VERTICAL SURFACE MOTIONS OF THE SOUTHERN U.K. DURING THE CENOZOIC

By

Philip George Smith

MSci Earth Sciences (University of Manchester), 2012

Thesis submitted for the degree of Doctor of Philosophy of the University of Leicester

Department of Geology

University of Leicester

United Kingdom

November, 2018

Abstract

The Cenozoic long wavelength uplift and subsidence patterns in the UK have been assumed to reflect the North Atlantic opening and Alpine |Orogenic sequences. Shorter wavelength variations are generally neglected and may give important clues to the processes driving vertical motions.

To understand the vertical surface motions of the south east UK a stratigraphic backstripping technique was applied which provides a record of long-term changes and can give indications of short term drivers or short wavelength variations. Traditionally backstripping has been applied to deep marine sequences but the Cenozoic onshore stratigraphic record consists of shallow marine and near shore deposits. This study shows that the use of shallow marine deposits provide effective constraints on interpreting palaeo-water depths.

Subsidence analysis of the Cenozoic succession indicates temporary uplift in the Paleogene, recorded between 56 and 55.8 Ma. This uplift may correlate with the 1 Myr duration uplift recorded in the Faroe-Shetland trough during North Atlantic opening, suggesting a long wavelength influence on the southern UK during the early Paleogene. The London Basin subsidence models suggested deposition most likely occurred above present day sea-level until sea-level began to fall around 54.7 Ma. Tectonic surfaces suggested south-eastern basement tilts were prevalent during the Paleogene and may be a result of magmatic underplating. Subsidence analysis also revealed larger subsidence rates and sediment accumulation in the Hampshire Basin than in the rest of southeast England. Reactivation of Variscan faults during the deposition of Cenozoic sediments appears to have taken place concomitantly with tectonic shortening and suggests phases of compression affected the UK from the mid-Paleogene and through the Neogene. Fault reactivation records a north-west strain during the Eocene as a result of Alpine orogenic phases that may have developed a WNW trajectory by the Oligocene.

From our data it seems likely the present-day topography of the Cretaceous Chalk in southern England began to develop during the Paleogene, while the short wavelength variations are a result of the older North Atlantic opening from the north-west and Alpine orogenic compression from the south-east.

Declaration

Whilst registered as a candidate for the above degree, I have not been registered for any other research award. The results and conclusions embodied in this thesis are the work of the named candidate and have not been submitted for any other academic award.

Acknowledgements

Firstly I would like to thank the IRSA project, Professor Paul Monks and the associated company Geospatial Insight for providing the financial pathway for this project. Without this and the subsequent college funding, the project would have not been possible to complete within the time-frame. I would like to thank my supervisors Prof Richard England and Prof Jan Zalasiewicz for their support and entrusting the original project idea to me. As the head of department for the duration of the PhD I appreciate the amount of time Richard England could give me. I would like to thank Dr. Annika Burns for producing the thin sections and suggesting fluorescence microscopy as a viable option for analysing the porosity. I would like to thank the rest of the Geology dept support staff equally, always on hand when needed.

I would like to thank my family for their academic support and continued parenting with the occasional embrace, perfect level of support without smothering. I have unending appreciation for my best friend and brother, Stephen, who will support me no matter the situation unless the cake is a lie. He also provided me with an overnight pit-stop for beer during my journey to the Isle of Wight for field work. I want to thank my lady Sophie for putting up with me and my nocturnal lifestyle, breakdowns, confusing rants and general disregard for pandas and umbrellas (raincoats don't turn inside out from a little wind).

I want to thank my office and friends Thomas 'it's not all about you' Clements, Joe 'fight club' Emmings, Leah 'vegan' Nolan, Tom 'U-boat Captain' Herring, A-Load and Dry Walker. Without them I think I would have struggled to finish less insane. Many friends from the north and south-west were detrimental and supported me the whole way, even if I missed huge life events. They are not gone and they are definitely not forgotten, not from lack of trying.

Finally I want to thank Manchester City F.C. and the plethora of games that were the ultimate distraction, but your transfer decisions and managerial changes have frustrated me this year creating an outlet for thesis related rage. But if I ever needed a 'Pep' talk or a pick me up I would sing Blue Moon and definitely not watch Claudio Bravo and his legs akimbo.

Contents

List of Figures

List of Tables

1 Introduction

1.1 Background

Much has been postulated and presented on the long wavelength vertical motions and their relation to the lateral configurations of Europe and the UK during the early Cenozoic, particularly focusing on North Atlantic opening, the Icelandic Plume, Alpine tectonic sequences and the igneous intrusive swarms in NW UK. The shorter wavelength motions have been studied across NW Europe using a variety of approaches. Short wavelength vertical motions can be extracted using techniques that isolate a rock's vertical history. It is hypothesised that long wavelength vertical motions from NE Atlantic opening and/or Alpine tectonic events during the Cenozoic are reflected in the stratigraphy of southern England and produce local shorter wavelength motions that may reflect the long wavelength motion. A backstripping approach is used in this study to test this hypothesis, which is unconventional for sediments formed at shallow water depth. Will the shorter wavelength vertical motions produced by this method, if at all, reflect the proposed early Cenozoic tectonic configuration for southern England? If so, will this method reveal the plausibility of these processes to influence basin development over long crustal wavelengths? This study aims to elucidate the short and/or long wavelength tectonic controls on basin development and the potential influences on the sedimentary sequences and cycles that have been extensively investigated in the London and Hampshire basins.

1.2 Project aims and chapter allocations

The overall aim of the project was to investigate the long wavelength and short wavelength variations in the vertical surface motions of the southern UK during the Cenozoic, identifying any relationships between the vertical movements of southern England and the vertical surface motions of NW Europe and its continental shelves. This was in order to isolate the most prevalent long wavelength mechanisms influencing vertical motions of the UK. To do this the project required detailed research on UK Cenozoic geology.

- The first objective was to assess and analyse the onshore UK sedimentary succession during the Cenozoic. This required the collation of existing literature, borehole and cliff section records varying in age and quality. This forms Chapter 2.
- The second objective was to collate the stratigraphy and constrain age ranges of the lithostratigraphic units used in this study. This forms chapter 3.
- The third objective was to interpret water depth values from the sedimentary facies of each lithostratigraphic unit and develop palaeobathymetric maps. This is crucial for the backstripping method used to isolate the vertical surface motions during the Cenozoic. Understanding the palaeogeography and palaeobathymetry helped to provide context of the evolving Cenozoic basins in the southern UK. This work corresponds to Chapter 4.
- The fourth objective was the backstripping of the Cenozoic succession from appropriate boreholes and sections from the southern UK. This produced water-loaded subsidence curves of the basement, and the temporal variations in vertical surface motions were analysed and correlated for the Cenozoic. This is presented in Chapter 5.
- The fourth objective involved the use of the water-loaded subsidence data to produce a series of tectonic surfaces throughout the Cenozoic so that spatial variations in vertical surface motions can be analysed more effectively. These surfaces are displayed in 3D to compare and contrast the vertical surface motions both spatially and vertically. This corresponds to Chapter 6.

- The final objective was to collate all interpretations of the data and relate them to the tectonic events of the UK during the Cenozoic and attempt to find any correlations between present-day vertical surface motions and the evolution of the basement during the Cenozoic. This study assesses both the long wavelength variations, but also the shorter wavelengths. This comprises the discussion in Chapter 7.

Chapter 2: Cenozoic geology of south-east England

2.1 Previous studies of the Cenozoic sedimentary sequences

This chapter examines existing knowledge of the geology of the London and Hampshire basin areas in which are exposed the best developed onshore sequences of Cenozoic rocks in the UK.

The immediate bedrock of the metropolitan area of London consists of Cenozoic strata, which has been widely studied for geotechnical and engineering purposes for over a hundred years, though there has been little petroleum exploration in comparison to the Hampshire region. The most notable early studies of the Cenozoic strata were by Prestwich (1852-1891) and Whitaker (1866-1889), and these provided a crucial background for later surveys and studies.

The recent volume from the late Chris King (2016) provides an extensive overview of the Cenozoic rocks in the UK, including the North Sea offshore strata and the Tertiary dyke swarms. It standardises the nomenclature of the rock formations in the London and Hampshire basins and its terminology has been adopted in this study. Previously 'The Geology of England and Wales' Brenchley and Rawson (2006) provided the best general background to the Cenozoic geology. Reviews of regional geology include the 'Stratigraphical framework for Palaeogene successions of the London Basin, UK' (Aldiss, 2012) and the 'Lithostratigraphical classification of the Hampshire Basin Palaeogene deposits' (Edwards and Freshney, 1987b). Numerous BGS memoirs, offshore reports, special sheets and maps provide information on local geology (Aldiss, 2002); (Aldiss et al., 2006); (Arthurton et al., 1994); (Barton et al., 2003); (Bristow, 1985); (Bristow et al., 1991); (Cameron et al., 1992); (Edwards and Freshney, 1987a); (Edwards and Scrivener, 1999) (Ellison and Wiliamson, 1999); (Ellison et al., 2002); (Ellison, 2004); (Hamblin et al., 1992); (Mathers and Smith, 2000); (Mathers and Smith, 2002); (Millward et al., 1987); (Moorlock et al., 2000); (Pattison et al., 1993); (Ritchie et al., 2011). These publications ranged across a century of study and some observations and subsequent interpretations may now be considered doubtful. Special sheets (Aldiss, 2002; Aldiss et al., 2006; Barton et al., 2003; Ellison and Wiliamson, 1999; Ellison et al., 2002; Mathers and Smith, 2000, 2002) only summarise the local geology and so lack the detail and depth needed for this study. However they did highlight reliable reference and type sections to search in the British Geological Survey online Geoindex.

While classification of the rock formations and correlation of the depositional sequences is important, the regional scope of this research and the extent of strata, both lateral and vertical, considered here precludes detailed correlation of the units analysed. The successions are mainly considered at formation level, with members locally used to infer depositional environments and their spatial distribution. Lithostratigraphical members are to take on more importance here where there is a particularly thick sequence such as the *London Clay Formation*, or where there is marked contrast laterally within a formation, such as the *Thanet Formation* and the *Ormesby Clay Member*.

Additional discussion of the stratigraphy will be covered in chapter 3 focusing on the weaknesses of and disparities between studies and the problems tackled in order to generate a stratigraphic model appropriate for this study. The tectonics will be discussed before to provide context for the environments in which the stratigraphy evolved in southern England.

2.2 Tectonic setting

This study comprises an analysis of sediment deposition, accumulation and distribution within the basins of Cenozoic south-east England, whilst attempting to unravel the possible mechanical influences for the patterns observed and whether they relate to tectonic or eustatic processes. First the tectonic and environmental evolution of the UK during the Cenozoic must be considered in order to understand the existing structures, structural state and terrestrial configuration of south-east England before the mechanisms that may have influenced them can be interrogated. The opening of the Atlantic Ocean to the north of the UK and the Alpine collisional sequences to the south-east are major tectonic events that may be implicated in the evolution of south-east England during the Cenozoic (Coward et al 2003; Brenchley and Rawson 2006). Therefore, the evidence for timing of these sequences of events is critical to understanding their influence, if at all, and answering the hypothesis as to whether they are the dominant mechanisms responsible for the south-east England outcrop..

Tectonic location of the UK

The UK at present lies within the western margin of the Eurasian plate, separated from the North American plate by a divergent plate boundary to the west while a convergent boundary separates the Eurasian plate from the African plate to the south (Figure 2.1). The relative motion of the Eurasian and African plates is south-eastwards and northwards, respectively. The basins and stratigraphic successions interrogated in this study have been modified or controlled by the tectonics and their related geological structures. The exact timing of many events in this tectonic scenario is disputed. Earlier tectonic events likely led to inherited structures, with subsequent possible influences on vertical crustal motions.

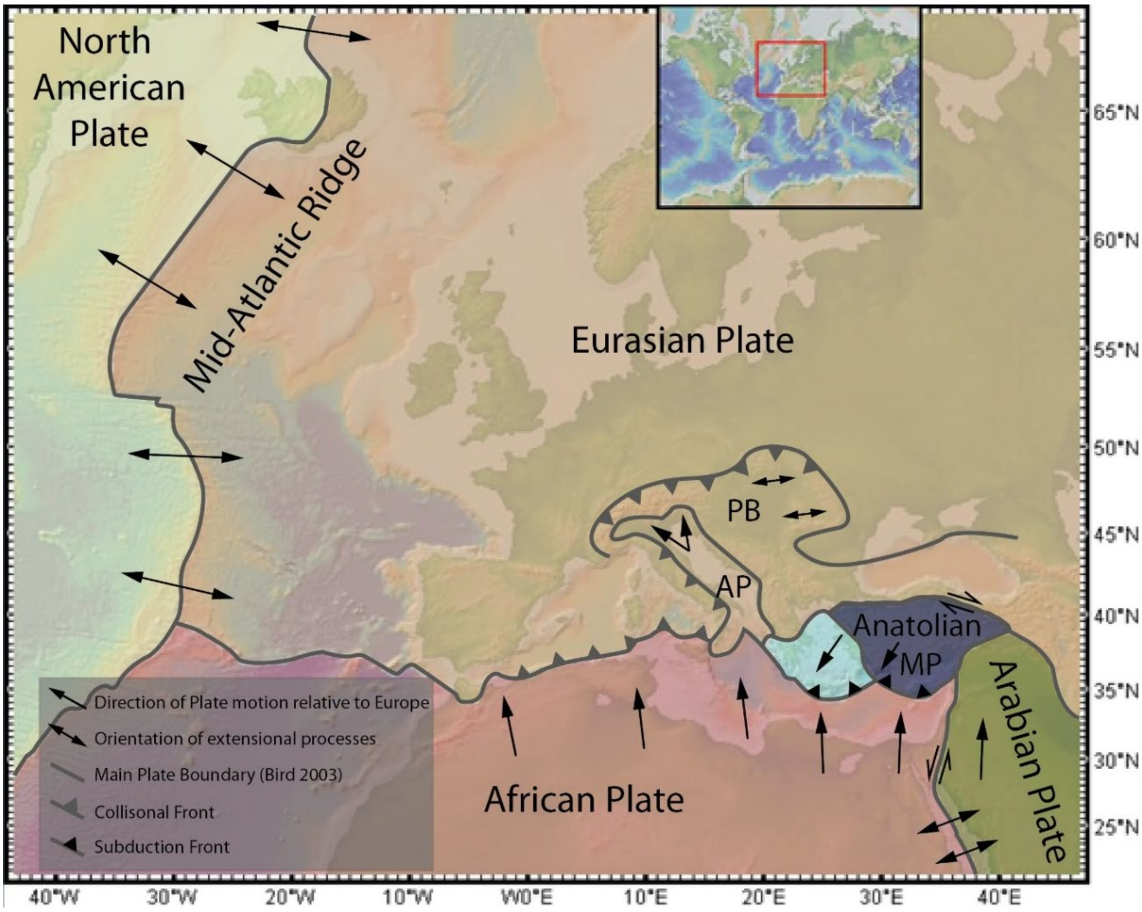
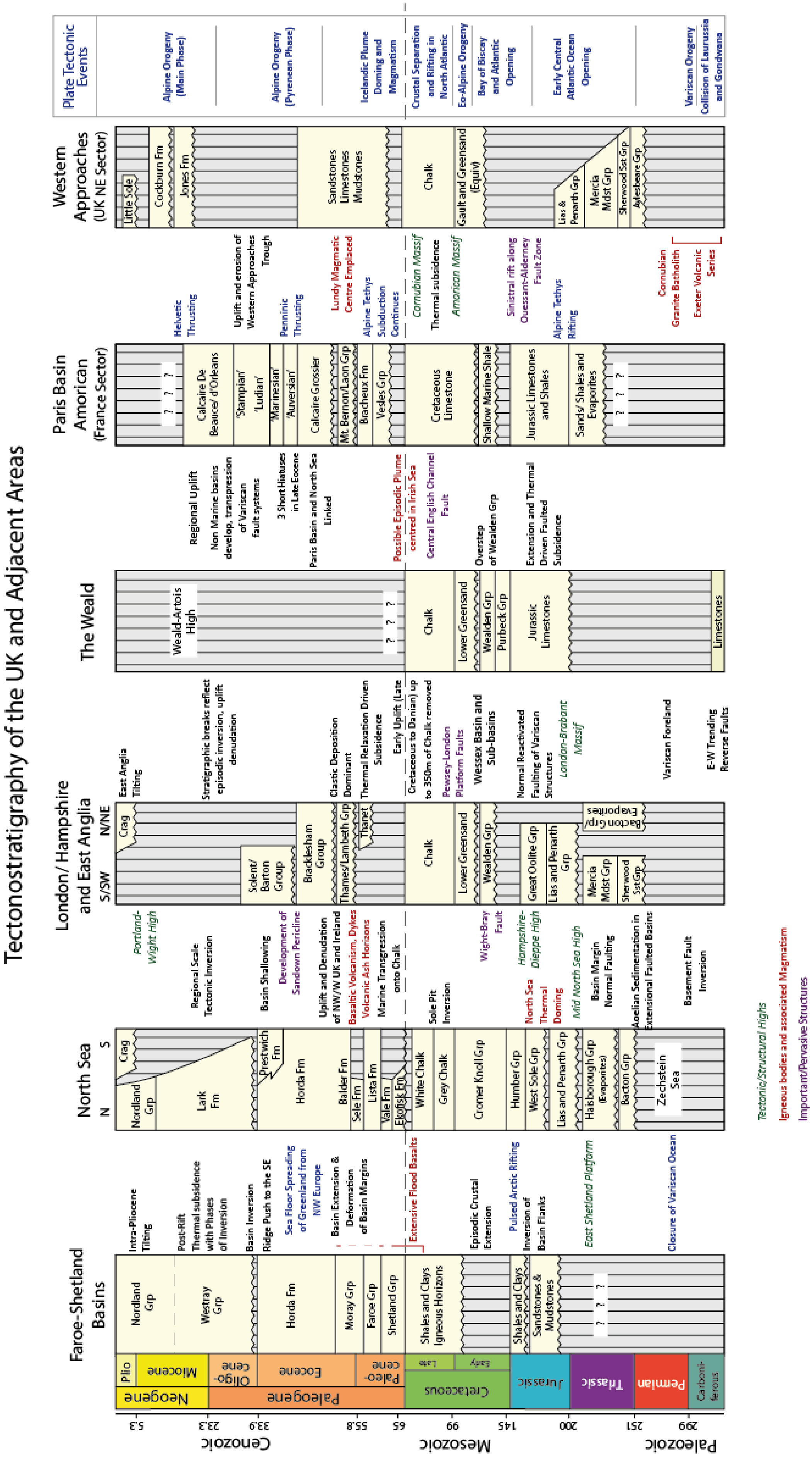


***Figure 2.1**: The position of the UK at the present day on the Eurasian plate. The Northern Mid-Atlantic ridge runs through Iceland. The relative motions show that the Eurasian plate is moving towards the northwards migrating African plate. Adapted from Grunthal and Stroymeyer (1992). Bird (2003) used for plate boundary layer.*

The tectonostratigraphy of the areas studied, and of the major basins adjacent to the UK compiled from literature, is shown in figure 2.2. The following sections of this chapter discuss the existing literature on the inferred tectonic and structural history of the UK from the end of the Carboniferous through to the end of the Pliocene, Late Cenozoic.

Figure 2.2 (Next Page)*: The tectonostratigraphy of the UK and adjacent regions from the Late Carboniferous to the Late Pliocene. The Hampshire and London basins are included as the main focus for the project, but basins surrounding the UK have also been included in order to show the tectonic setting and its effect on the stratigraphy regionally. Adapted from King (2016), Brenchley and Rawson (2006), (White and Lovell (1997); Ziegler (1982)).*


Tectonostratigraphy of the UK and Adjacent Areas
Faroe-Shetland Basins
North Sea
London/Hampshire and East Anglia
The Weald
Paris Basin American (France Sector)
Western Approaches (UK NE Sector)
Plate Tectonic Events
Cenozoic
Mesozoic
Paleozoic
Neogene
Paleogene
Cretaceous
Jurassic
Triassic
Permian
Plio
Miocene
Oligo-cene
Eocene
Paleo-cene
5.3
23.3
33.9
55.8
65
99
145
200
251
299
Tectonic/Structural Highs
Igneous bodies and associated Magmatism
Important/Pervasive Structures

2.2.1 Variscan tectonic phase and Mesozoic basin development in the UK

Prior to the deposition of Mesozoic and Cenozoic strata, NW continental Europe developed as Laurussia and Gondwana collided between 370-290 Ma, closing the Variscan Ocean to form Pangaea. The later stages of this compressional regime produced a major uplift event, the Variscan Orogeny, that affected the UK and that is marked by an extensive unconformity in the geological record (Holdsworth, 2000). Late Carboniferous limestones accumulated to form the basement of the Weald basin prior to the onset of the Variscan, but have been deformed following multiple compressional events (Brenchley and Rawson, 2006). The limit of deformation is marked by the Variscan foreland margin which extended across southern England, Cornwall, Wales and Southern Ireland (*Figure 2.3*). The orogeny led to the development of important widespread reverse faults that trend E-W, some being reactivated during inversion of post-Variscan basins (Chadwick and Evans, 2005). Many faults were developed from pre-Variscan extensional basins and their structural inheritance is a possible reason for the low effective stress required for failure during reactivation (Copley and Woodcock, 2016). These structures are of particular importance as they are suggested to have become reactivated again much later during the Cenozoic Alpine orogenic phases (Chadwick and Evans, 2005). During this time, the Cornubian Granite Batholith was intruded in Western England and linked to the 'Exeter Volcanic Series', signifying increased magmatism driven by evolving regional tectonism that lasted until the mid-Permian (Edwards and Scrivener, 1999). This region later formed a persistent tectonic high during development of the Western Approaches and Celtic Sea basins. The Permian and Triassic in the UK represents an interval of minimal marine influence, aoelian sedimentation and extensive deposits of evaporites (Brenchley and Rawson, 2006). An extensional tectonic regime is inferred in the south of the UK from rapid subsidence along normally faulted basin margins and an infill of coarse aoelian deposits, which will be the converse in Cenozoic times and explained later in this chapter. These deposits were later overlapped by finer grained sediments suggesting a gradual regional subsidence (Chadwick and Evans, 1995). The majority of Triassic deposits are proven in offshore basins, with some at depth in the Hampshire and London regions forming the basin margins at this time.

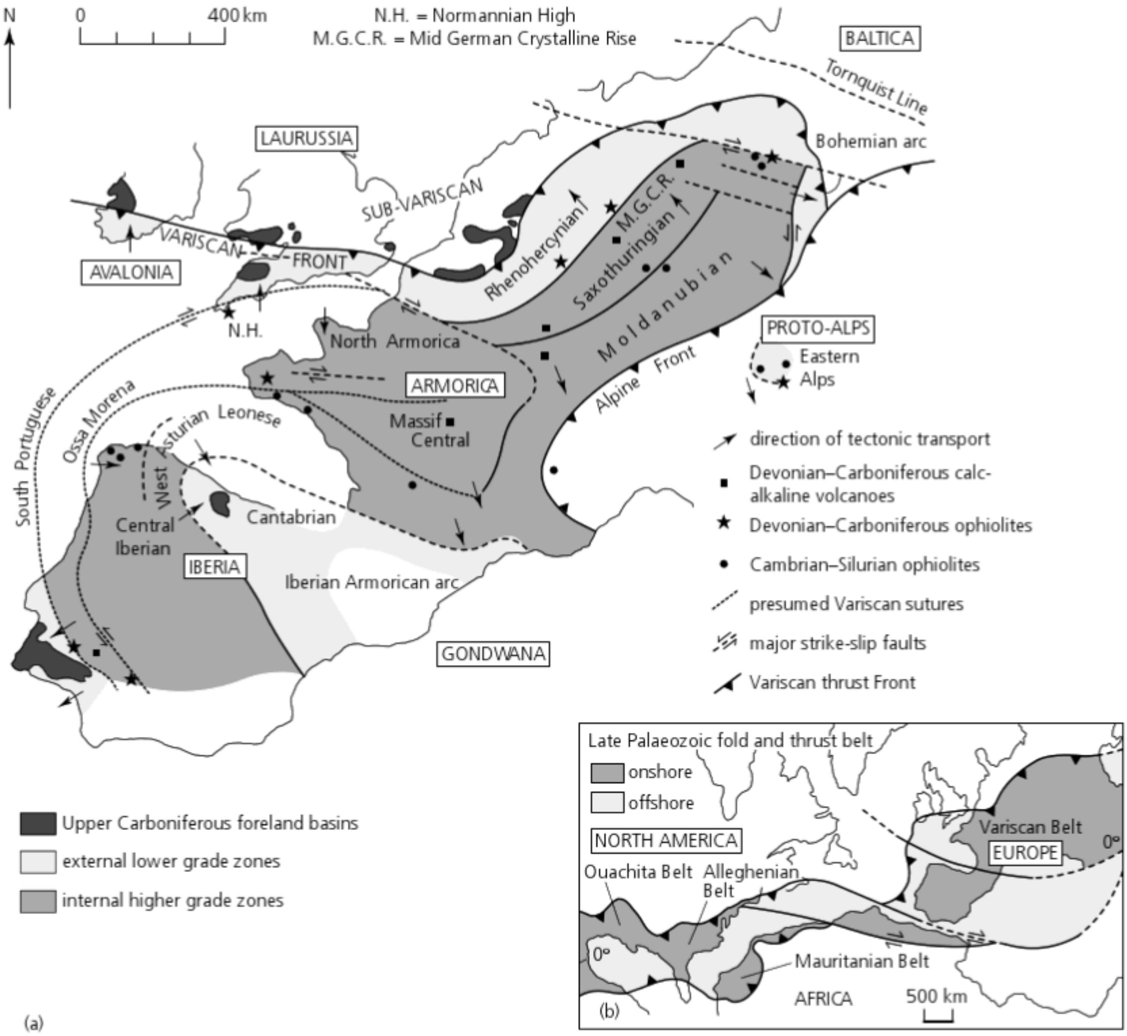


***Figure 2.3**: NW Europe and the tectonic zones during the Variscan Orogeny: reconstruction laid over the geography of Europe. The Bay of Biscay between Amorica and Iberia is closed. Gondwana and Laurussia are the major plates at this time, their collision resulting in the Variscan Orogeny. In the UK, the limit of the Variscan front is shown. Devon and Wales are locations of foreland basins. Important compressional fault structures developed in the external lower grade compressional zone. Taken from Holdsworth (2000)*

Towards the end of the Triassic the early stages of Central Atlantic Ocean opening had commenced. This resulted in a major marine transgression and a transition back to marine sedimentation in UK basins as they underwent renewed subsidence (Brenchley and Rawson, 2006). The Faroe-Shetland region experienced east-west extension until phases of Arctic rifting began in the early Jurassic, resulting in inversion in the flanks of the basin and a hiatus in sedimentation (Ritchie et al., 2011). Underhill and Partington (1993) showed that the mid Jurassic Unconformity in the east of the UK marked the onset of a thermal doming event centred in the Norwegian-Danish district of the North

Sea. A concentric area of uplift and erosion developed which was then followed by a basinward shift in facies on the fringes of the dome's thermal extent, preserved in Norway, Finland, Denmark and the Midlands of the UK (Underhill and Partington, 1993).

During the breakup of Pangaea, initiating in the early to mid-Jurassic through to the Cretaceous (Toarcian 180-80Ma), southern England experienced episodic crustal extension (Holdsworth, 2000). The large-scale basin development that followed was governed by the normal reactivation of the major reverse faults that had developed in the Variscan fold belt (Chadwick, 1986). A high volume of important large basin-controlling normal faults developed during the Jurassic through to the Late Cretaceous, with northwest-southeast and east-west trends (BGS, 1996). Their simple sinistral pull-apart structure controlled the location of sedimentary depositional centres (Chadwick, 1986; Newell, 2000). This is associated with the orientation of the major fault structures and the syntectonic sediment accumulation during the Mesozoic (Lake and Karner, 1987). The Wessex basin occupied large areas of south England with the comparatively smaller Portland-Wight and Wealden sub-basins to the south-west and south-east, respectively (BGS, 1996). Two relative highs were also associated with the large-scale Mesozoic extensional phases. The London Brabant Platform or Massif which later became the London basin existed as a topographic high north of the Wessex basin and, to the south, as the Hampshire Dieppe high, shown in figure 2.4 (Newell, 2000). The boundaries of both highs to the Wessex basin are marked by important faults, the Pewsey-London Platform faults in the north and the Wight-Bray and Portsdown Middleton faults in the south (Brenchley and Rawson, 2006; Ellison, 2004; Newell, 2000). It is possible these were a major control in the transition from a zone of high relief to a subsiding basin in the Cenozoic. The orientations of the Variscan fault structures consistently marks a boundary for basin development and inversion events during the Mesozoic in the London and Hampshire regions. The longer wavelength tectonic events in the Mesozoic appear to be reflected and localised in shorter wavelength variations marked by fault boundaries. In this study it would be appropriate for shorter wavelength variations to focus on areas identified to host Variscan fault structures recorded to have reactivated under compressional and extensional phases of deformation in the Mesozoic.

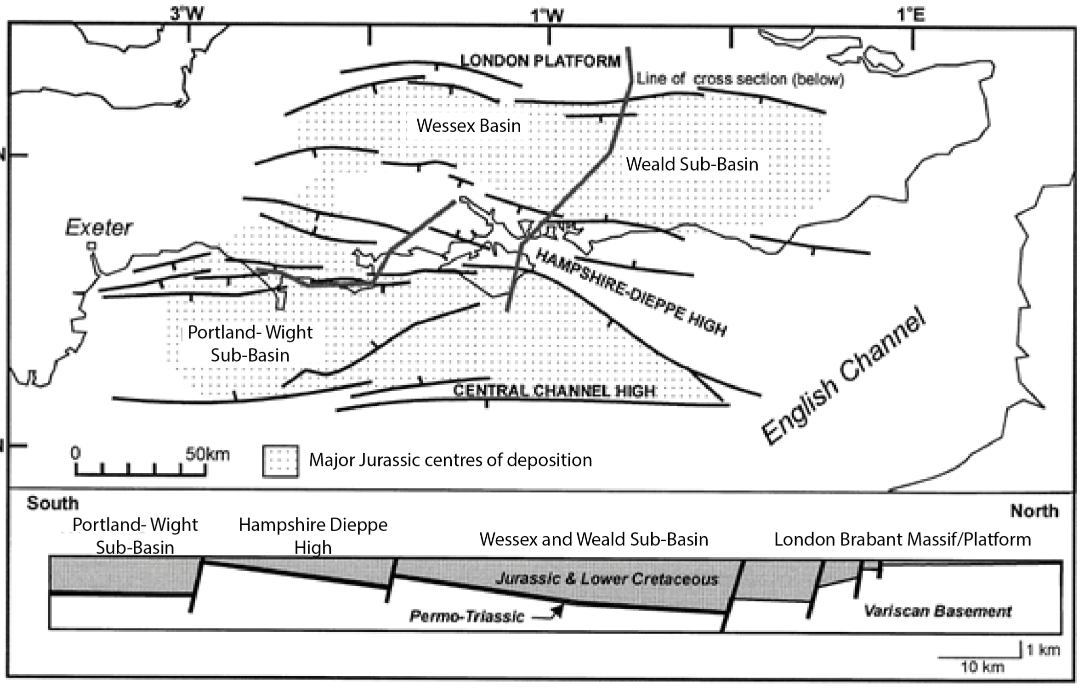


Figure 2.4*: Map of southern England during the Jurassic to Cretaceous. The Wealden and Wessex basin margins are bound by large-scale normal faults controlling basin extension, trending ESE-WNW. These are reactivated Variscan faults. The areas of sedimentary deposition during this time are shaded. The relative highs of the Hampshire-Dieppe and London Platform are also displayed. The North-South cross section represents a time in the early Cretaceous. Originally taken from Chadwick (1993). Adapted from Newell (2000)*

The earliest stages of Central Atlantic Ocean opening were marked by the separation of the Americas from Africa in the south and central regions during the Jurassic (Ziegler, 1982). By the Cretaceous, a rotation of Africa counter-clockwise pushed it northwards towards Eurasia causing an increase in the crustal strain, reflected in the development of numerous complex rift and strike-slip fault systems that spread to the Atlantic in the west (Coward et al., 2003; Dewey and Windley, 1988). The Bay of Biscay was also rifting at this time, separating the Iberian plate from the Eurasian during the Aptian at around 118 Ma (Handy et al., 2010). In the east, strain localised in the Eo-alpine Orogeny with a northwest vergence. The rotation and movement of Africa northwards also led to a narrowing of the Neotethys Ocean but it was not until the Late Cretaceous that Africa began to collide with Eurasia, resulting in the earliest of the Alpine orogenic phases (Holdsworth, 2000). The orientation of plate movements and recorded deformation could be related to the postulated stress regime of the UK and a precursor to events during the Cenozoic.

2.2.2 Alpine tectonic phases

The Alpine orogenic phases began in the Early Cretaceous with the rotation of the Adriatic/African plate north and eastwards, relative to the Eurasian plate (Ziegler, 1982). Shallow subduction of the Eurasian plate below the Adriatic/African plate led to the continued closure of the Alpine Tethys Ocean (Holdsworth, 2000). Rifting between the African and Adriatic plates produced the Ionian Sea during the Early Cretaceous, which was to later close again before the Quaternary (Handy et al., 2010). By the Aptian of the Early Cretaceous, the subduction of the Piemont-Ligurian Ocean below the now-separated Adriatic plate led to the early collisional event of the Eo-Alpine Orogeny in the Eastern Alps and was fully developed by the beginning of the Late Cretaceous at approximately 94 Ma (Handy et al., 2010). An accretionary complex on the Adriatic continental margin containing the Piemont-Ligurian ophiolites indicates the closing of this ocean in the east (Schmid et al., 2004). Large volumes of NW-verging thrusts developed during accretion and formed the Penninic nappes in the Austroalpine region (Schmid et al., 2004), the first in a series of high-strain events, as the African plate continued to collide with Eurasia and the Adriatic. The magnitude of these events and the low volume of magmatism found within the collisional zone suggests a very shallow subduction angle and this could have resulted in tectonic buckling with long wavelengths capable of influencing the vertical crustal motion of Western Europe and the UK at this time (Butler, 1986). Does the Cenozoic Alpine sequences follow a similar pattern of long wavelength buckling and will it be reflected on a short enough wavelength that can be identified by backstripping the Cenozoic sequence? It is clear that to isolate the signal, the timing of events and sedimentary facies need to be well constrained in order to be correlated. The later unconformable deposition of the Gosau beds (Turonian-Eocene) on the Austroalpine nappes and thrusts suggests the ending of the Eo-alpine orogenic event (*Figure 2.5a*) prior to the Cenozoic Alpine orogenic phases (Faupl and Wagreich (1996); Stern and Wagreich (2013)).

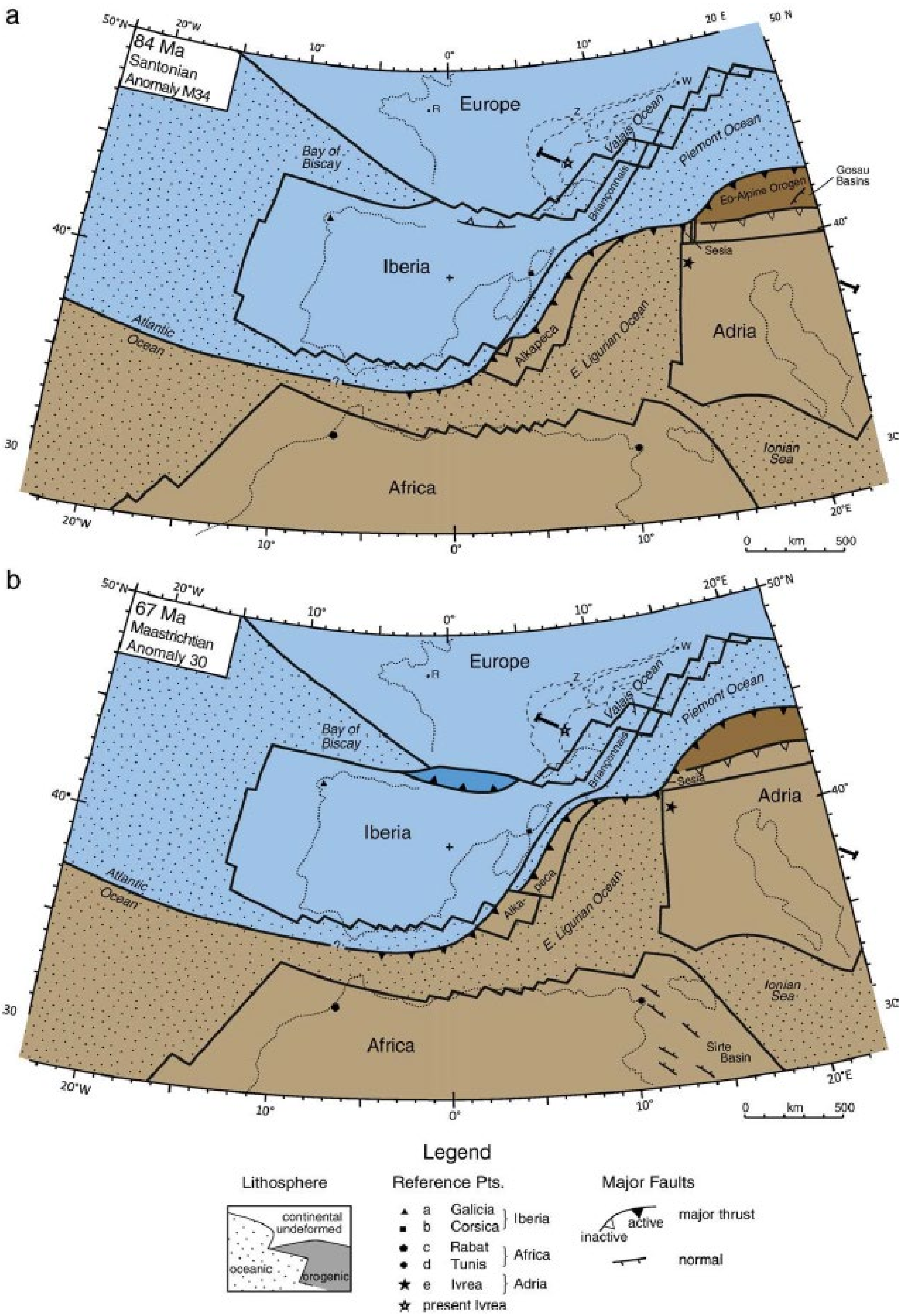


Figure 2.5*: Plate tectonic map displaying the Alpine Tethys and the arrangement of the Eurasian, Iberian, Adriatic and African plates in the Late Cretaceous. A) The latter stages of the Eo-Alpine Orogenic phases post Atlantic and Bay of Biscay opening. B) The continued closure of the Piemont, Valias and East Ligurian oceans, and very early phases of the Pyrenean Alpine orogenic phase. Taken from (Brenchley and Rawson (2006); Handy et al. (2010))*

The Pyrenean Alpine tectonic phase followed the opening of the Bay of Biscay, involving collision with a sinistral transform motion as the Iberian plate moved eastwards (Coward et al., 2003). Early collision commenced in the Maastrichtian, Late Cretaceous, at around 67 Ma and thought to have been completed by 55 Ma which may have influenced the Early Cenozoic tectonic configuration of the UK (*Figure 2.5b*). The Pyrenean phase eventually produced the Pyrenean Mountains that form the border between Spain and France. The eastward movement of the Iberian Plate also contributed to additional closing of the Ligurian Ocean and a compressional regime at this time (Handy et al., 2010).

Continued plate collision caused the narrowing of the Valais Ocean in Central Europe, north-east of the Pyrenean Mountains. In the Early Cretaceous the Valais Ocean was a centre of opening but continued plate convergence led to its eventual closure sometime towards the end of the Eocene which would suggest a compressional deformation state could have been inherited in the southern UK on a long wavelength (Coward et al., 2003; Froitzheim et al., 2008). The presence of unconformable flysch deposits that are Priabonian, approximately 35 Ma in the Late Eocene, on an older ophiolite sequence suggests the development of the Penninic Group accretion complex must have been completed during the Late Eocene (Schmid et al., 2004). Nappe stacking in the Penninic units is also observed in the northern Alpine region of the Helvetic nappes which are believed to have been active from approximately 37Ma and represent a large proportion of the main Alpine orogenic phases localised in the Western Alps (Steck and Hunziker, 1994). Nappe axial planes, thrust fault transport directions and stretching lineations in the Helvetic domain were shown by Steck and Hunziker (1994) to record a continuing NW vergence of the Adriatic plate at this time, towards the UK.

The main Alpine orogenic phases commenced in the very late Eocene, localised in the Western Alps. They were prominent for the rest of the Cenozoic, the majority of tectonic activity taking place across Central and Western Europe during the Oligocene and Miocene (Ziegler, 1982). Between 35-30Ma the collision of the Adriatic plate began to take a more westerly trajectory with a counter-clockwise rotation which would suggest a greater degree of compression which could have been translated to the southern UK (Handy et al., 2010). The presence of strike-slip faults and shear zones with a dextral sense of transpression is represented by the Periadriatic line, figure 2.6 (Schmid et al., 2004; Steck and Hunziker, 1994). The timing of this can be constrained by progressive

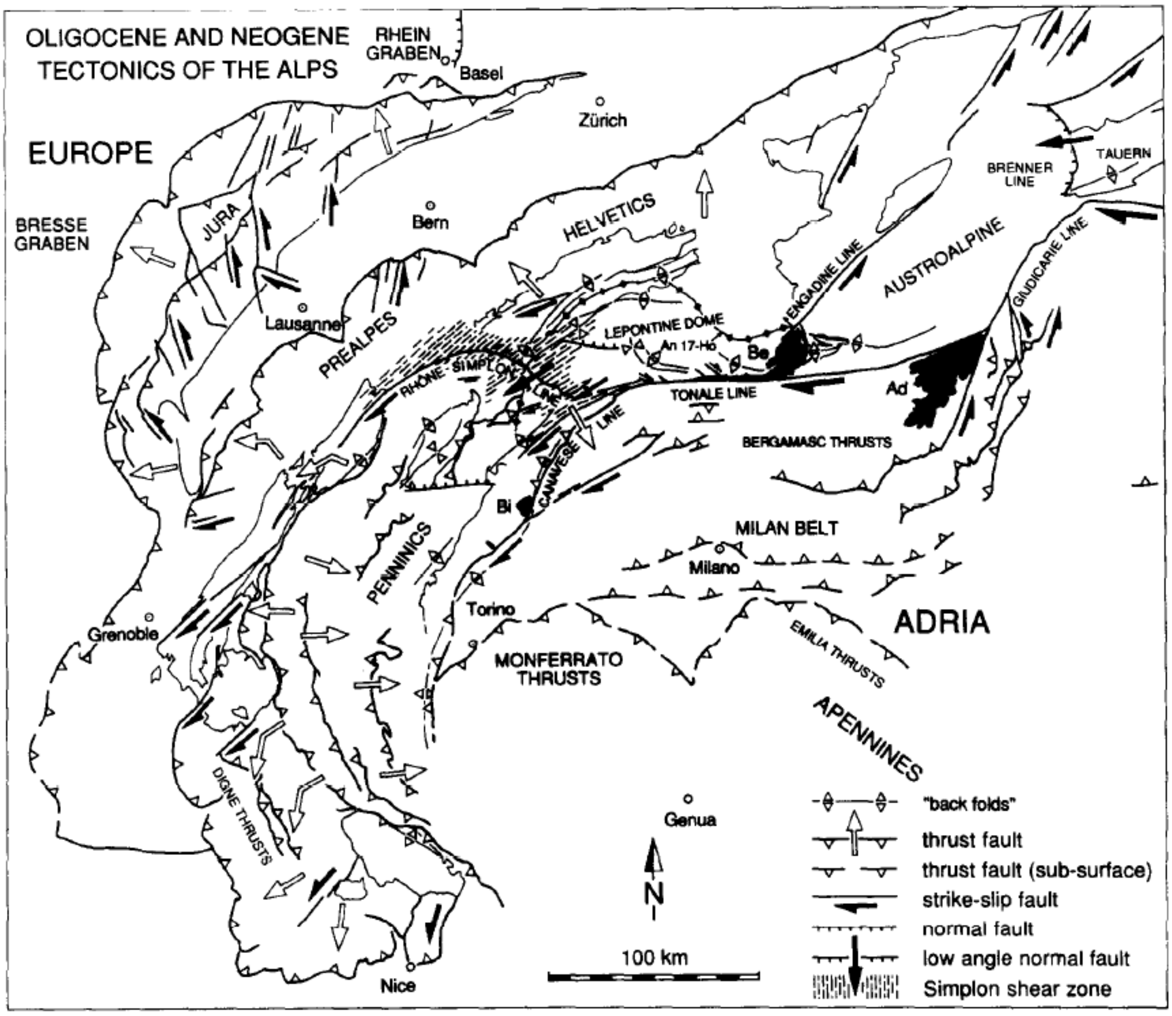


Figure 2.6: A map of Oligocene and Neogene tectonic developments in the Alps. The nappe regions are geographically represented with the Austroalpine in the east, the Helvetics in the north and the Penninics in the west. In the centre is the Simplon shear zone, exhibiting the transpressional component to the Adriatic indenter's counter-clockwise rotational collision. South of the Periadriatic line is the collection of thrust faults and back-folding with a southwards verging orientation. The overall vergence of the Alpine orogeny is between N and NW at this time. The position of the Rhine and Bresse grabens ahead of the thrust front and Jura Mountains is shown. Taken from Steck and Hunziker (1994)

deposition of syntectonic molasse, as shown in figure 2.6 (Reicherter et al., 2008). The structural position of the molasse relative to the western Alps and the overlying older Helvetic nappes demonstrates syntectonic deposition as the high-strain collisional zone continued movement in a NW direction (Zweigel et al., 1998). The molasse basin geometry within the foreland also exemplifies a region that was experiencing extensional stress in a NE-SW orientation normal to the NW-SE continental collisional orientation, again towards the UK (Bonnet et al., 2007; Froitzheim et al., 2008).

The dominant NW vergence of thrust fault systems has resulted in overall crustal thickening; however, areas adjacent to the sites of uplift and mountain building possess an extensional stress component parallel to the mountain belt, similar to the development of the previously discussed molasse which was deposited in extensional basins ahead of compressional zones. The Tertiary Piedmont Basin lies within the Southern Alpine region in NW Italy and during the Oligocene through to the mid Miocene it underwent a maximum subsidence rate of 2mm/year despite penecontemporaneously being under NW-SE compression (Carrapa et al., 2003). The Rhine Graben is an important feature that exemplifies an E-W and WNW-ESE extension direction normal to the vergence of the northern fringe of the Alpine thrust front, developing during the Oligocene from approximately 48 Ma (Dewey and Windley, 1988; Illies, 1972). Study of the SE German section of the molasse basin also revealed similar continued subsidence from the Late Eocene to the Miocene, with a possible visco-elastic relaxation of the lithosphere being responsible for the angular unconformity in the early Miocene (Zweigel et al., 1998). The overall formation of the Rhine Graben has been suggested to be a part of a larger fracture system, linked with the British dyke intrusion, although the timing of these intrusions is different (Dewey and Windley, 1988).

The sedimentary basins in Hampshire and London within the southern UK did not develop within or adjacent to an orogenic mountain building area. However, the timing of sediment deposition does parallel the later Cenozoic Alpine orogenic sequences and the regional stress from these sequences may have affected the vertical motions of the Mesozoic basement on a long wavelength. These motions, if present, may have resulted in in shorter wavelength motions in the UK. On a regional scale, the dominant compressional regime experienced throughout the Cenozoic during the Alpine orogenic phases had a sense of rotation from east to north-west (Handy et al., 2010). The NW trajectory of vergence and the tectonostratigraphic history of the southern UK recorded onshore and in offshore basins could represent a foreland to the thrust front, figure 2.1, albeit with lower strain rates than those recorded by the molasse basin. Nevertheless, the subsidence and inversion tectonics characterise an intra-plate deformational setting and may be linked to the Alpine Orogeny (Dewey and Windley, 1988). It has been postulated that minor Weald inversion resulted in early uplift and removal of up to 300m of Chalk which occurred during the Paleocene (Brenchley and Rawson, 2006), but the majority of the inversion is postulated to have taken place later in the Miocene at the same time as regional uplift associated with the main Alpine orogenic phases. The exact timing of inversion is problematic and is discussed later in this chapter. The English Channel, the Western Approaches and Celtic Sea are other Mesozoic basins that also record tectonic inversion at a similar time to the late Alpine phases, reactivating deep-set structures inferred from seismic sections and precluding extensive sedimentation (Ziegler, 1982, 1992). Reactivation of Variscan structures in other regions of the UK and the uplift along basin margins has also been proposed to be mainly influenced by Alpine tectonics. Gale et al. (1999) showed that uplift, erosion and reworking of younger Paleogene formations occurred as successive events in the region of the present-day Isle of Wight in the Late Eocene. This suggests that reactivation of the Sandown Fault and development of the Isle of Wight Monocline, figure 2.14, was synchronous with the Pyrenean collisional phases. Given the timing of inversion of these particular structures around the Western Approaches, English Channel and Celtic Sea and their proximity to the Hampshire and London basins, will the timing of any shorter wavelength variations in vertical motion within the areas in this study reflect this? If these are shorter wavelength structures that parallel the findings of Gale et al (1999) and Dewey and Windley (1988), will the method of backstripping be sensitive or robust enough to provide insight on the tectonic mechanisms or possible eustatic variations at work?

2.2.3 North Atlantic opening and magmatism and its effect on the UK

The Early Cretaceous marked the continued northward propagation of the Central Atlantic Ocean rifting, eventually separating the Americas from Greenland and NW Europe by the Late Cretaceous, and forming the Labrador Sea (Coward et al., 2003). Propagation north-east and the opening of the Norwegian Sea at approximately 57 Ma eventually led to the Mid Atlantic divergent boundary that separates the North American and Eurasian plates at the present day. Prior to the onset of Atlantic rifting, the region experienced pulses of Arctic rifting throughout the Jurassic, lasting approximately between 175 and 145 Ma (Ritchie et al., 2011). Atlantic rifting phases took over from the pulsed Arctic rifting during the Cretaceous and the Atlantic margin began to open from 55 Ma as shown by volcanic activity and fault movements in the Faroe region (Coward et al., 2003; Walker et al., 2011). Initial rifting is thought to have been primarily driven by a mantle plume that led to the upwelling of hot mantle, causing decompressional melting of the lower lithosphere, although it has been disputed whether a plume was indeed responsible (Mutter et al. (1988); Clift and Turner (1998a)). The early stages of crustal rifting and development of the north-east Atlantic margin is thought to have occurred between 60-56 Ma (Armitage and Allen, 2010), which would have produced a compressional strain towards the south-east from ridge push. Whether this would be on a wavelength long enough to affect the Hampshire and London basins has been suggested by reactivation of local structures (Gale et al 1999; Newell and Evans 2011). Prior to this, the Late Cretaceous basins of the Atlantic and North Sea were regionally subsiding (Coward et al., 2003). Crustal extension was a minor mechanism at this time but lithospheric cooling was responsible for the resulting thermal subsidence in the North Sea and Shetland regions (Mckenzie (1978); Sclater and Christie (1980)). Rifting resulted in accelerated early subsidence rates in the Rockall-Shetland-Faroe regions north and west of the UK but analysis of their vertical motions suggest that these basins had a lower total subsidence, despite the initial rate, than would be expected with uniform crustal extension (Clift and Turner, 1998a). Proposing that igneous underplating from the mantle plume during the Late Paleocene was up to 1-5km of crustal thickening, modelled from these Rockall Trough, Faroes and Northern North Sea areas (Clift and Turner, 1998b). These regions also contain thick flood basalts of

Paleocene to Eocene age extruded on to the basin floors (*Figure 2.7*), overlying the older Cenozoic and Mesozoic deposits, emphasising the large volume of magma that was erupted during the early Cenozoic rifting phases and the degree of tectonism at work (White and McKenzie, 1989). The extensive volcanism and igneous activity associated with the rift margin is also preserved onshore in NW Scotland, Wales, Ireland and the Faroe Islands, emplaced as part of the BTIP or British Tertiary Igneous Province (Brenchley and Rawson, 2006). The primary dyke swarms of the BTIP have a dominant orientation of NW-SE and occurred between 61 and 57 Ma (*Figure 2.7*) with some secondary dykes of E-W orientations in the early stages of crustal extension (Roberts et al., 1999). Their en echelon habit and dilation axis preserves a pattern of strain and the inferred minimum ($\sigma 3$) stress orientation is relatable to the late Paleocene extensional direction (England, 1988). Given the scale of tectonism during Atlantic opening, distance from the southern UK and amount of evidence recording the variations of stress orientation stretching as far as Greenland and the North Sea, an influence on the vertical motions in south-east England is likely. As to whether this is reflected in short wavelengths, is tested in this study.

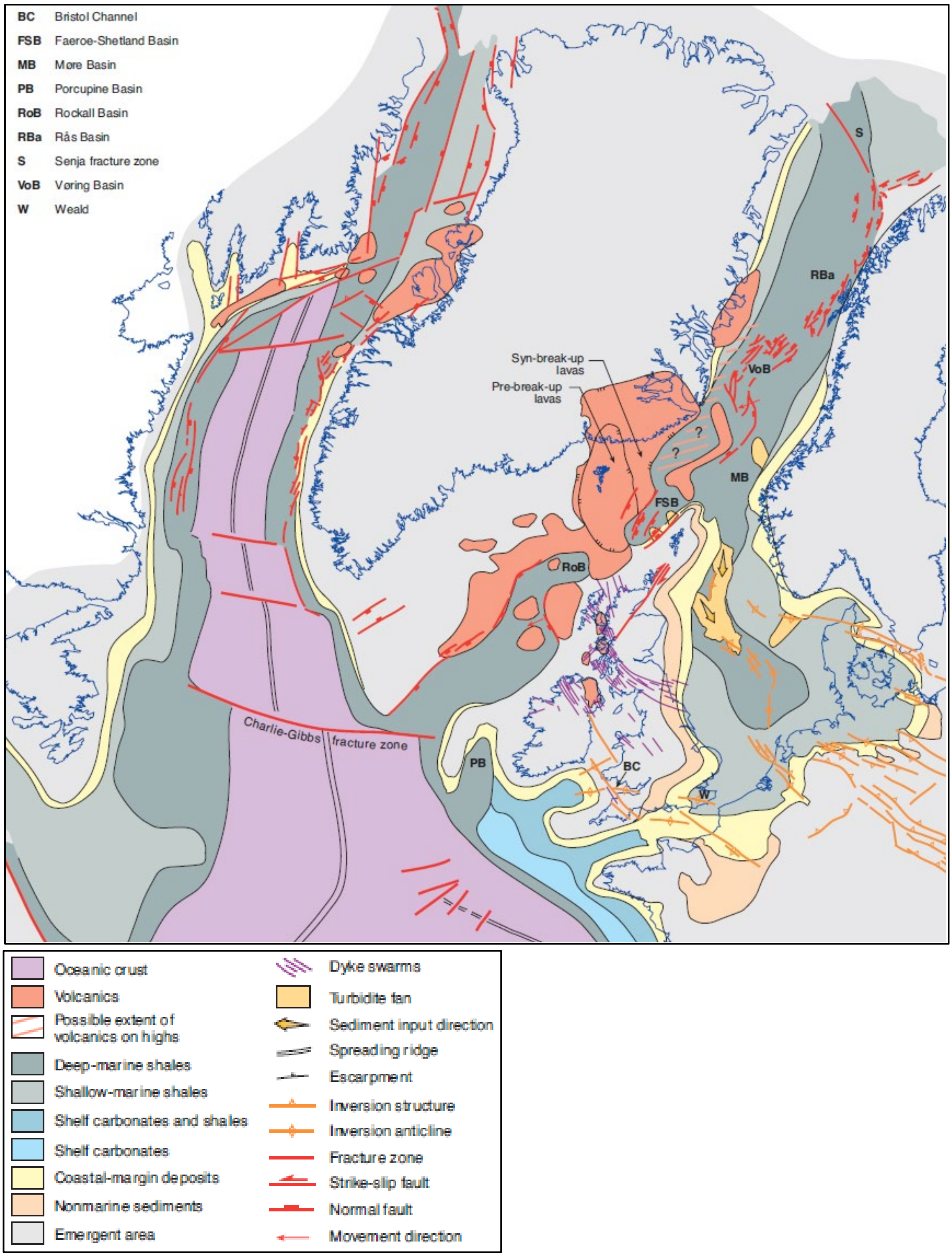


***Figure 2.7**: Map of the UK and Greenland during the Paleocene displaying the dominant tectonic structures and depocentres during the early rifting of the North East Atlantic Margin. The spreading ridge in the Labrador Sea, West of Greenland, is producing new oceanic crust and includes many extensional structures. The extent of flood lavas and volcanism associated with the Icelandic plume is shown to the south-east of Greenland. The subsequent uplift and sedimentation contributed to the basin subsidence by sediment loading of regions such as the Faroes/Rockall area and the North Sea. The major dyke swarms were intruded onshore into NW Scotland, Wales and Ireland at this time and the dominant orientation of NW-SE is displayed. The south of the UK and Northern Europe include many compressional structures trending NW-SE. Taken from Coward et al. (2003).*

Between 59-55Ma, the continued northward propagation of the NE Atlantic rift resulted in the localised extensional directions rotating counter-clockwise, identified using the onshore fault patterns in the Faroe Islands and the offshore rift-oblique lineaments (Moy and Imber (2009); Walker et al. (2011)). Basins in the North Atlantic margins at around 56 Ma experienced uplift above sea-level that lasted for up to 1 Myr before subsiding again, as shown by the existence of drainage networks and continental landforms (Hartley et al., 2011). Hartley et al. (2011) used three dimensional data to identify these landforms and attributed them to the transient convection of hot mantle under the Icelandic Plume. It is around this time that many unconformities preserved in the European geologic record formed, and these could be related to the Icelandic mantle plume development, figure 2.2. This could also be the case for southern England. The stress state of the crust is reflected in the basin margin deformation of the Hatton and Rockall troughs that were under compression (Ritchie et al., 2008). Asymmetrical anticlinal growth folds developed with thrust faults at the cores of the structures that verged to the south-east (Ritchie et al., 2011). Low strain rates are thought to be responsible for these structures and the transmission of ridge push stresses occurred while these margins were on hot recently stretched basement (Dore et al., 2008). The rate of spreading at the ridge is thought to have reduced around 52Ma and it can be inferred that the magnitude of stresses may have decreased concomitantly with this. The reduction in strain may also be attributed to the movement of the plume away from the UK at 54Ma, during the onset of the North Atlantic spreading (Blundell, 2002). The tectonic history of the UK Atlantic margin following successful North Atlantic spreading suggests frequent uplift and inversion events, with any sedimentation in the surrounding basins preserved by post-rift thermal subsidence, figure 2.2 (Ritchie et al., 2011). By 47.9Ma, seafloor spreading was inducing a NW-SE extensional regime; the centre of a large upwelling of asthenospheric mantle material resulted in lithospheric doming, in the present-day location of Iceland (Walker et al 2011). The UK at this time may have inherited a south-easterly compressional stress orientation as result of the Atlantic margin rifting. White and McKenzie (1989) suggested this was a result of gravity-driven ridge push away from the Icelandic plume as it continued to supply hot magmatic material to the rift margin.

2.2.4 Magmatic underplating, uplift and denudation of the UK

The dyke swarms emplaced in the UK record the timing of the voluminous magmatism associated with the impact of the proto-Icelandic plume on the base of the North Atlantic lithosphere and can be found preserved in Paleogene strata, figure 2.2. Their spatial extent is of particular importance. Centres of strong magmatic activity with large central complexes, dykes, sills and flood basalts date from the Paleocene through to the earliest Eocene and are preserved in northwest Scotland, the Irish Sea and the Isle of Lundy off the coast of north Devon, *figure 2.8 and 2.9* (King, 2016). Layers of ash are preserved in the Late Paleocene and Early Eocene strata of the North Sea and southern England, reflecting the high levels of magmatism and associated volcanism that coincide with the Icelandic plume emplacement, also exemplified by the dyke swarms in the NW UK of a similar age (Jolley, 1996). Uplift and erosion of large regions of the UK is believed to have occurred rapidly in the early Cenozoic, synchronously with the increase in magmatic and volcanic activity (Ziegler, 1982). It has been suggested that the upwelling centres of magmatism were accompanied by magmatism that underplated the UK (*Figure 2.8*). Deep seismic imaging of the present day structure suggests the presence of upwelling hot mantle material beneath the UK (Arrowsmith et al., 2005). It is uncertain whether the present-day deep seismic signals are related to the Paleocene emplacement.

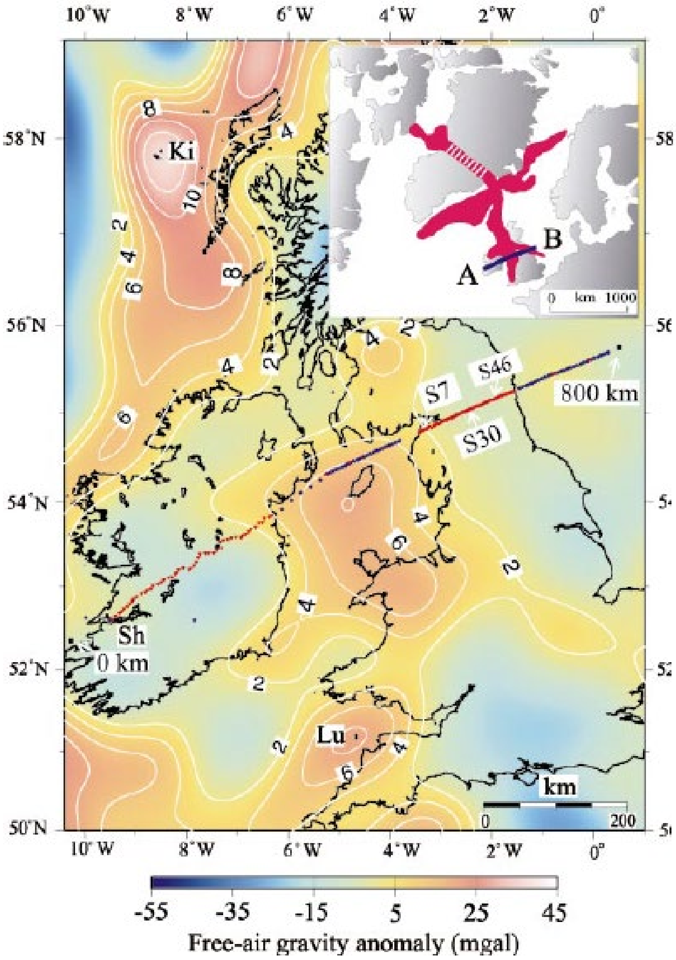


***Figure 2.8**: A long wavelength free air gravity map of the UK. The contours denote the predicted thickness of magmatic underplating based on the gravity data and seismic modelling. The red and blue dots denote sites of seismometers and shot explosions for the British and Irish Caledonian Suture Seismic Project (CSSP, ICSSP). It can be seen there are regions of positive results in the Irish Sea, NW Scotland and the Isle of Lundy. These correlate with areas of enhanced magmatism. The inset map suggests the proposed extent of underplating responsible for the magmatism across the UK, Iceland and Greenland. Taken from (Al-Kindi et al. (2003); Ziegler (1982)).*

The underplating may have led to variations in the vertical motion of the UK and a tilt to the south-east with the centre of uplift in the very Late Cretaceous proposed to be a very small mantle hotspot in the Irish Sea, NW of Anglesey (Cope, 1994). The degree of uplift from fission-track analysis and subsequent erosion in the adjacent areas is consistent with the transition from areas of sediment accumulation and subsidence to areas of uplift. Rowley and White (1998) inverse modelled the remaining stratigraphy of the basins surrounding the East Irish Sea and found that the minimum amount of uplift and erosion agreed with most vitrinite reflectance and fission-track studies (*Figure 2.9*). Heavy minerals of Scottish and Cornubian origin transported and deposited into the southern and eastern basins of Hampshire, London and The North Sea during the Paleocene also indicate the extent of uplift and its timing (Morton, 1982). The deposition and nature of submarine fans in the Faroe-Shetland and North Sea basins during the Paleogene indicate pulses of uplift, denudation and transport of clastics that may be correlated with episodic magmatic underplating (White and Lovell, 1997). The stratigraphic record across the UK is marked by a hiatus or by limited sedimentation during the very Late Cretaceous and in the Early Paleocene, which may be related to the Irish Sea hotspot or to an uplift/aerial exposure event (Cope, 1994). If this is the case, this occurred prior to the development of the Cenozoic Hampshire and London depocentres.

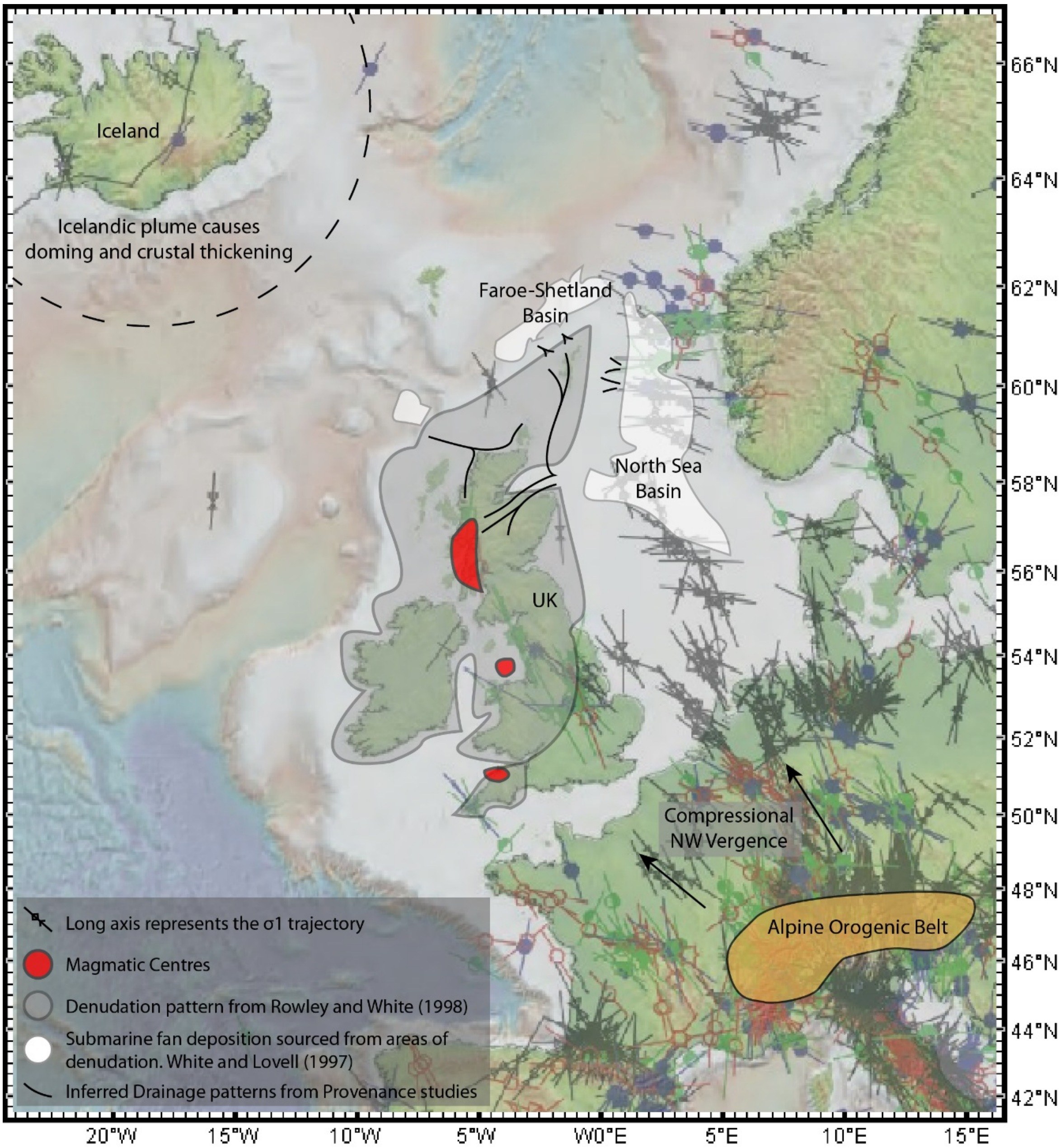


Figure 2.9: Map of the UK and its position between Iceland and the Alps at the present day laid over the world stress map. The grey shaded area depicts the region that underwent denudation during the Paleogene, from a minimum of 0.5km up to a maximum of 3km (Adapted from Rowley and White 1998). The red shaded polygons are regions of concentrated magmatism, inferred to be related to underplating and subsequent denudation. The drainage and sedimentation into submarine fans of the two marked basins at this time were sourced from the uplifted and denudated regions. Adapted from Brenchley and Rawson (2006) and White and Lovell (1997).

A study of the thickness of the underplate by (Al-Kindi et al., 2003; Tiley et al. (2004)) using free air gravity data shows that regions of greatest underplate thickness overlay the centres of magmatism in the Irish Sea and Lundy, with the NW Scotland centre in a similar location displaced farther NW over the Islands of Lewis and Harris. In any case, based on this data, there appears to be a link between the proposed emplacement of the mantle underplate, magmatism and the degree of uplift and volume of material subsequently removed from affected areas in the early Cenozoic. It was calculated from inverse modelling of the denudated regions that 15 km of crustal shortening would be required to remove up to 3 km of material and would rule out Alpine compression as the sole or dominant contributing factor (Brodie and White, 1994). The onset of epeirogenic uplift in the early Cenozoic as a result of the magmatic underplate would suggest a permanent thickening of the crust, rather than a transient uplift event due to heat flow. Underplating fits the rapid uplift and volume of exhumation suggested by apatite fission-track analysis (AFTA) and vitrinite reflectance (VR) estimates of the Atlantic margin and the surrounding basins' exhumation history (Green et al., 2002) more closely than do transient heat flow or Alpine compression. An isostatic adjustment of the lithosphere from the underplate would result in localised epeirogenic uplift and the denudation patterns observed, whilst areas not underplated may undergo relative subsidence as they accumulate the removed material, assuming a flexural response of the lithosphere of the UK that may have affected the geometry of drainage patterns in the proto-Solent and proto-Thames rivers during the Cenozoic (Rowley and White, 1998; Tiley et al., 2004). The variations in uplift and relaxation cycles in the Early Cenozoic can be inferred from the transgressive erosion of chalk and transportation into the proto-Solent and proto-Thames deposits ((Plint (1983); Ellison et al (2004).

Rather than magmatic underplating, Hillis et al. (2008) proposed that the UK Cenozoic exhumation pattern can be attributed to plate shortening and that phases of uplift were caused by incremental compression as the intra-plate stress field increased. There is no mention of deep convective processes as a control. However, studies of the UK crustal structure and underlying lithosphere favours a UK underplate model that would result in the uplift and denudation of the UK topography including the relation to unconformable surfaces and hiatuses in the stratigraphic record, fig 2.2 (Davis et al., 2012).

2.2.5 Crustal structure of NW Europe and the UK

There have been a series of investigations into the UK and European crustal structure, crustal thickness and depth to the Moho, partly funded by research councils and partly funded by the petroleum industry, given their interest of the latter in potential transient heat flow and its effect on deep hydrocarbon reservoirs. Commonly the studies have used seismic velocity models converted to density to image the crust and upper mantle structure.

The depth to the Moho below the UK from Ziegler and Dezes (2006) suggested the Moho is generally at greater depths when associated with topographically higher relief regions of the UK, such as central Scotland and central Wales (between 34 and 36km). In contrast, the topographically low areas of the UK, the London region and southern East Anglia also show great depths to the Moho. This data set suggests that topographic relief does not bear a strong correlation with depth to the Moho. The Moho depth map of Ziegler and Dezes (2006) suggests some interesting patterns but the discrepancies in the relationships may be a result of hand-contouring the data. The Moho depth map by Grad et al. (2009) proposes a similar pattern with a similar range of maximum and minimum depths in agreement with the results of Ziegler and Dezes (2006). Considering the degree of uncertainty in both datasets, the interpolation between data points and the hand-contouring method, the correlation between both studies is not adequate. Davis et al. (2012) used a wide distribution of seismometers across the UK and part of NW Europe to develop a model of crustal structure from velocity profiles. Their data showed that crustal thickness varied from 24 to 36 km in the UK, with thicker crust in central Scotland and north Wales. Their fastest P-wave velocities suggesting a complex Moho structure occurred below centres of Cenozoic magmatism and may be correlated with magmatic underplating (Davis et al., 2012).

It is important to note the depth to the Moho and the crustal thickness variations and their patterns across the UK as deep Earth structures and mantle dynamics may be a factor in influencing the vertical surface motion. For example, orogenic mountain belts such as the Himalayas are uplifting at high rates and have the largest crustal thicknesses and greatest depths to the Moho, and so topographic relief can be correlated to crustal thickness. Also, regions of thinner crust may produce more transient heat flow from the mantle and therefore may support an overall plastic response of the crust to deformational processes, either from tectonic events or mantle processes (Watts, 2001). The heat flow may influence the vertical response and flexure of the crust, but the temporal component of uplift and subsequent denudation is crucial evidence suggesting that this is not a dominant control. A relatively high influx of heat from the deep Earth may cause thermal expansion of material in the lower lithosphere. With a large enough thermal anomaly there could potentially have been a significant amount of uplift localised to certain areas without the injection of additional material, on bulk thermal expansion alone (Watts, 2001). Transient heat flow would result in brief variations of uplift, given that the size of the magmatic emplacement would result in long wavelength variations rather than shorter wavelength patterns. Would the long wavelength uplift patterns cause shorter wavelength deformation patterns in the crust observable via a vertical history analysis?

2.3 Distribution of Cenozoic rocks and structures

The majority of onshore Cenozoic sedimentary rocks of the UK are in the south of England. The oldest deposits are distributed across the Hampshire Basin, the London Basin and are not deposited northwards and north-westwards except for minor outliers. The majority of the Paleogene and Neogene onshore deposits at the present day are generally located in the axis of the large synclinal structures of the London Basin and the Hampshire Basin (*Figure 2.10).* Offshore, Cenozoic marine strata are preserved in the North Sea, the Faroe-Shetland Basin, the Western Approaches and the English Channel (*Figure 2.11*). The stratigraphic relationship is shown in Figure 2.2. Other non-marine deposits of Cenozoic age are in the west of the UK, preserved both onshore and offshore. Their thickness and spatial extent are limited, particularly onshore.

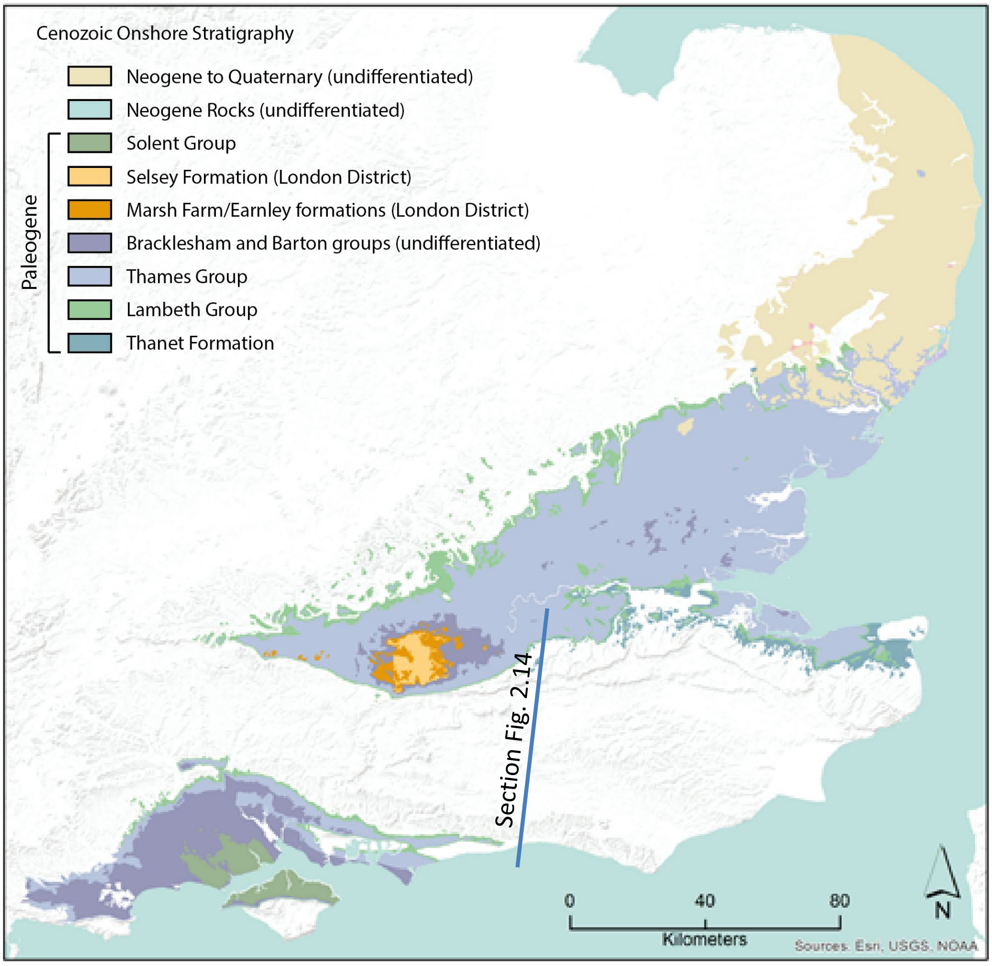


Figure 2.10*: The Cenozoic strata onshore are restricted to the London Basin, East Anglia and the Hampshire Basin; in pale yellow. Other Cenozoic deposits are of Igneous origin or too small to be shown this scale. Taken from the British Geological Survey (NERC 2014).*

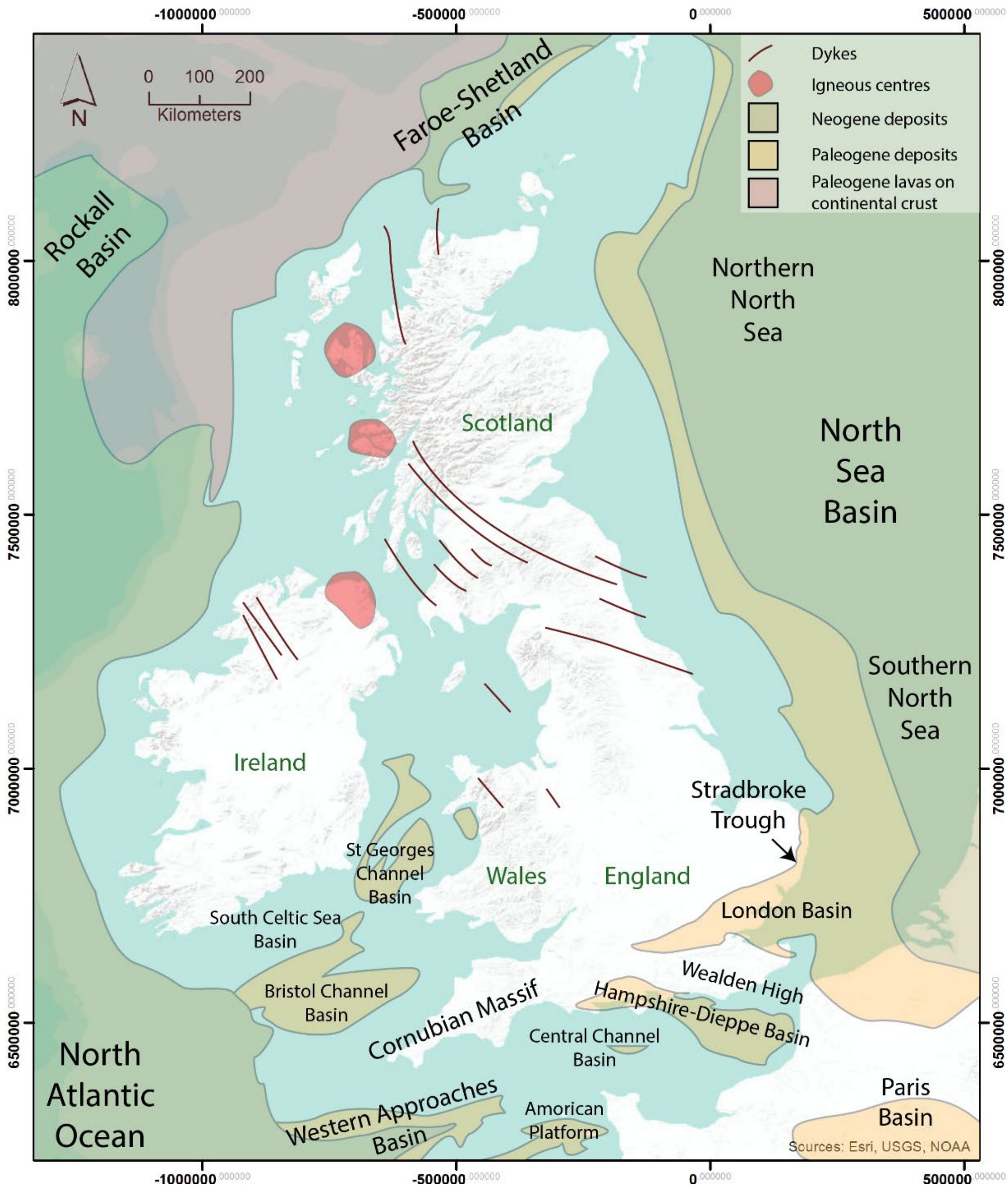


***Figure 2.11**: General distribution of Cenozoic rocks in the UK, offshore regions and northern France. The tectonostratigraphy of the thickest basins is shown in figure 2.1. Most Paleogene deposits are preserved near to the UK. Neogene deposits are preserved in deeper basins, farther offshore. The extent of the Paleogene submarine lavas NW of the UK are shown. Major dyke trends and igneous centres of Cenozoic magmatism are taken from Brenchley and Rawson (2006).The Irish Sea igneous centre is missing. Deposits and lava extents are adapted from King (2016) and White and Lovell (1997).*

2.3.1 London Basin and East Anglia

The London Basin preserves the oldest Cenozoic stratigraphy in the west which progressively youngs to the east along the synform's axis, figure 2.12a, with an overall ENE-WSW trend that plunges to the ENE (Royse et al., 2012). Generally, the older Paleogene rocks that are present at the surface in the west are proven at depth in the east by many boreholes drilled onshore and offshore (Brenchley and Rawson, 2006). However the outcrop is not simple, and large outliers occur along the fold axis, with the London Clay Formation being the most consistent due to its stratigraphic thickness (Aldiss, 2012; Clements, 2010). In Central London, the Wimbledon, Streatham and Greenwich faults in the Paleogene sequences modify the outcrop pattern. Their east-north-east strike has been suggested to be associated with later stages of Alpine tectonics and formed *en echelon* to the associated WNW principal compressive stress orientation (Ellison, 2004). It is possible the Alpine NW vergence has a more northern compressive orientation in the London region, as the strain radiates outwards from the dominant area of compression. There are deeper pervasive faults in the Mesozoic rocks that do have an effect on the outcrop patterns of the overlying Cenozoic strata, previously underrepresented in older geological maps of London (Aldiss, 2013). There are many small asymmetrical anticlines in central and east London that fold the Cenozoic and Cretaceous Chalk strata, such as the Greenwich and Purfleet anticlines. Both have fold axes striking ENE, similar to the faults in this area, and could also be described as *en echelon* structural features (Figure 2.12b). The shallow angle and thickness of the Cenozoic deposits north of the London Basin synclinal axis and thinner deposits in the south support an asymmetrical axial plane. The synclinal axis is deflected north in central and east London, possibly by the Wimbledon, Streatham and Greenwich faults but the trend overall remains NE-SW (Ellison, 2004). The faults themselves are not large controlling features on the London Basin. They form the southern margin of the Cenozoic rocks contacting with the underlying Cretaceous chalks (Royse et al., 2012). The deposits on the southern limb overstep onto the Cretaceous Chalk deposits of the Wealden Anticline, separating the Hampshire and London basins (Aldiss, 2012; Clements, 2010; Moorlock et al., 2000). The contact with the Chalk is a widespread unconformity, fig 2.2.

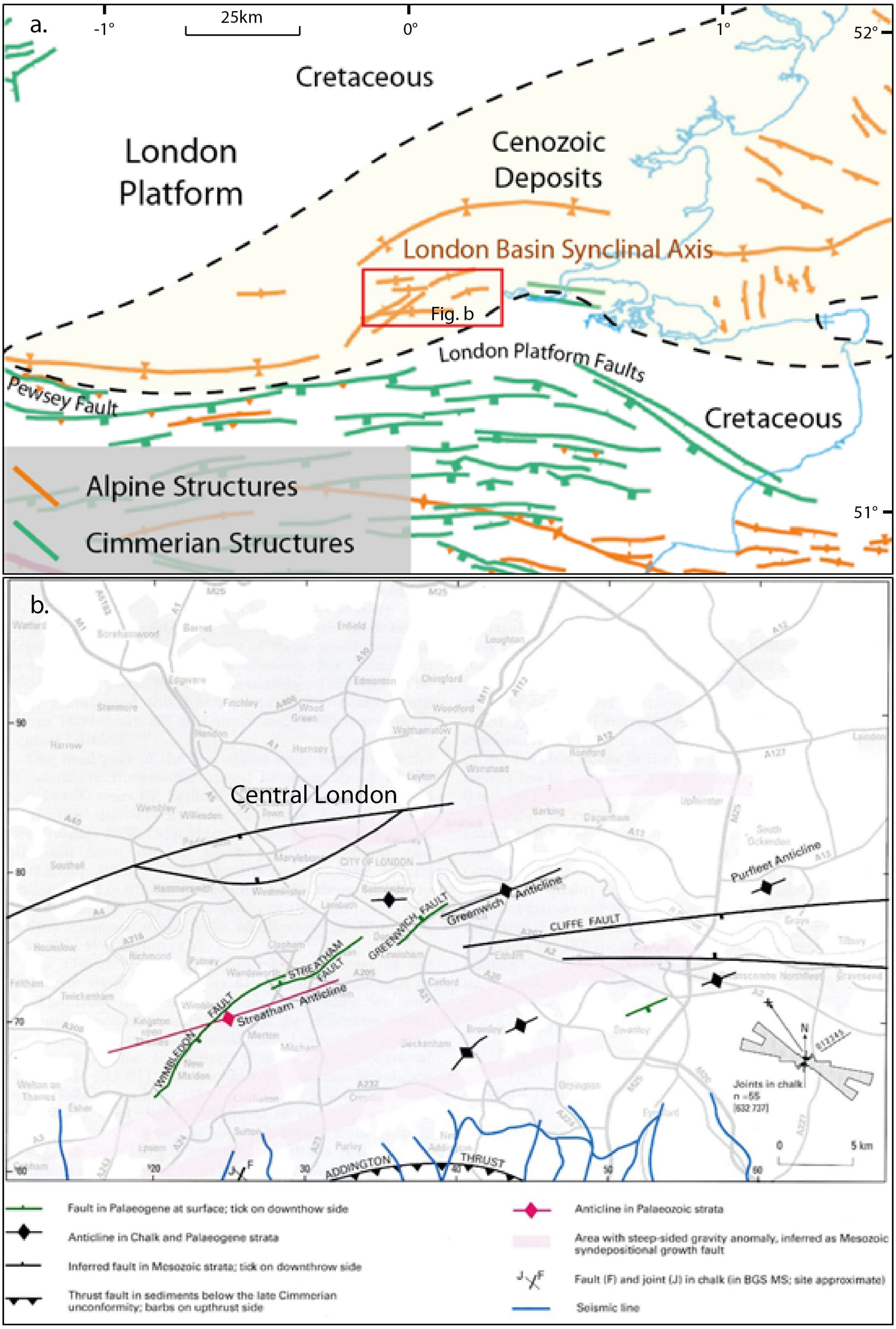


***Figure 2.12**: a: Map of the London Basin with the margin of Cenozoic deposits highlighted. The major structures formed during the Alpine deformation sequences and the Cimmerian sequences. The major bounding faults to the Cenozoic deposits are the Pewsey and London Platform faults. B: Map shows the fault structures present in the Cenozoic deposits (green), and fault structures inferred in underlying Mesozoic deposits (red). Adapted from Chadwick and Evans (2005) and Ellison (2004).*

The London Clay Formation extends into East Anglia and is the youngest formation exposed, of Eocene age, until is overlapped by the much younger Pliocene Coralline Crag Formation and latest Pliocene Red Crag Formation which mark the base of a large-scale unconformity (King, 2016). The London Clay is proved at depth by boreholes such as at Lowestoft, but with a reduced thickness of 48.8m (Moorlock et al., 2000). It has been suggested that the underlying, older Ormesby Clay thickens in the northern regions of East Anglia due to early Paleogene tectonic tilting to the north-east, prior to its deposition (Arthurton et al., 1994). The amount of Chalk removed from the region supports this model, which has been related to the earlier stages of Alpine tectonism, the Eo-Alpine phase (Chadwick, 1985). Relatively few geophysical and geotechnical surveys have been carried out in East Anglia, but large-scale fold or fault structures appear to be absent in comparison with the London Basin, with tilting and Cenozoic unconformities the most apparent evidence for tectonic motions.

2.3.2 Hampshire Basin

The Hampshire Basin and the outcrop of Cenozoic rocks within it are also controlled by a large synclinal axis trending NW-SE, plunging to the SE (Brenchley and Rawson, 2006; Edwards and Freshney, 1987a). The Cenozoic succession covers a smaller area by comparison with the London Basin but is thicker, as proved by the Sandhills 2 Borehole (SZ48NE55), which reaches the underlying Chalk at a depth of 668.7m (Edwards and Freshney, 1987b). The dominant features of the basin are large-scale fault-controlled monoclines that trend E-W; their influence is observed on the Isle of Wight, both in cliff sections and in the surrounding topography. The Needles Monocline is exposed at Alum Bay in the west and the Sandown Monocline can be observed at Whitecliff Bay in the east, both exposing tilted vertical strata. The Cenozoic rocks are bounded to the south by these two faults of Variscan origin, and are preserved in the underlying Cretaceous basin which was reactivated with a reverse sense of motion under a compressional regime, *figure 2.13* (Chadwick, 1985; Chadwick and Evans, 2005). Eastwards the basin extends into the English Channel connecting with strata of similar depositional age in the Dieppe Basin, off the coast of NW France (Hamblin et al., 1992). The Portsdown Anticline trends roughly parallel to the synformal axis of the Hampshire Basin, ENE-WSW, lying in the north-eastern reaches of the Hampshire Basin exposing the older Chalk in the core of the fold. It is non-cylindrical and plunges both to the WNW and ESE, where the crest line culmination produces a topographic high consisting of Cretaceous Chalk (Chadwick and Evans, 2005). For this reason there is a significantly thinner Cenozoic succession on and around the Portsdown Anticline. Therefore, the centre of the synformal structure in the west was chosen for the latter stages of the research. The many relict Variscan faults at depth that controlled the development of the monoclines have reactivated since Cenozoic deposition began. This produces a sharp contact between the Cenozoic strata and underlying Cretaceous marking the basal unconformity that can be observed in cliff sections at Alum Bay and Whitecliff Bay.

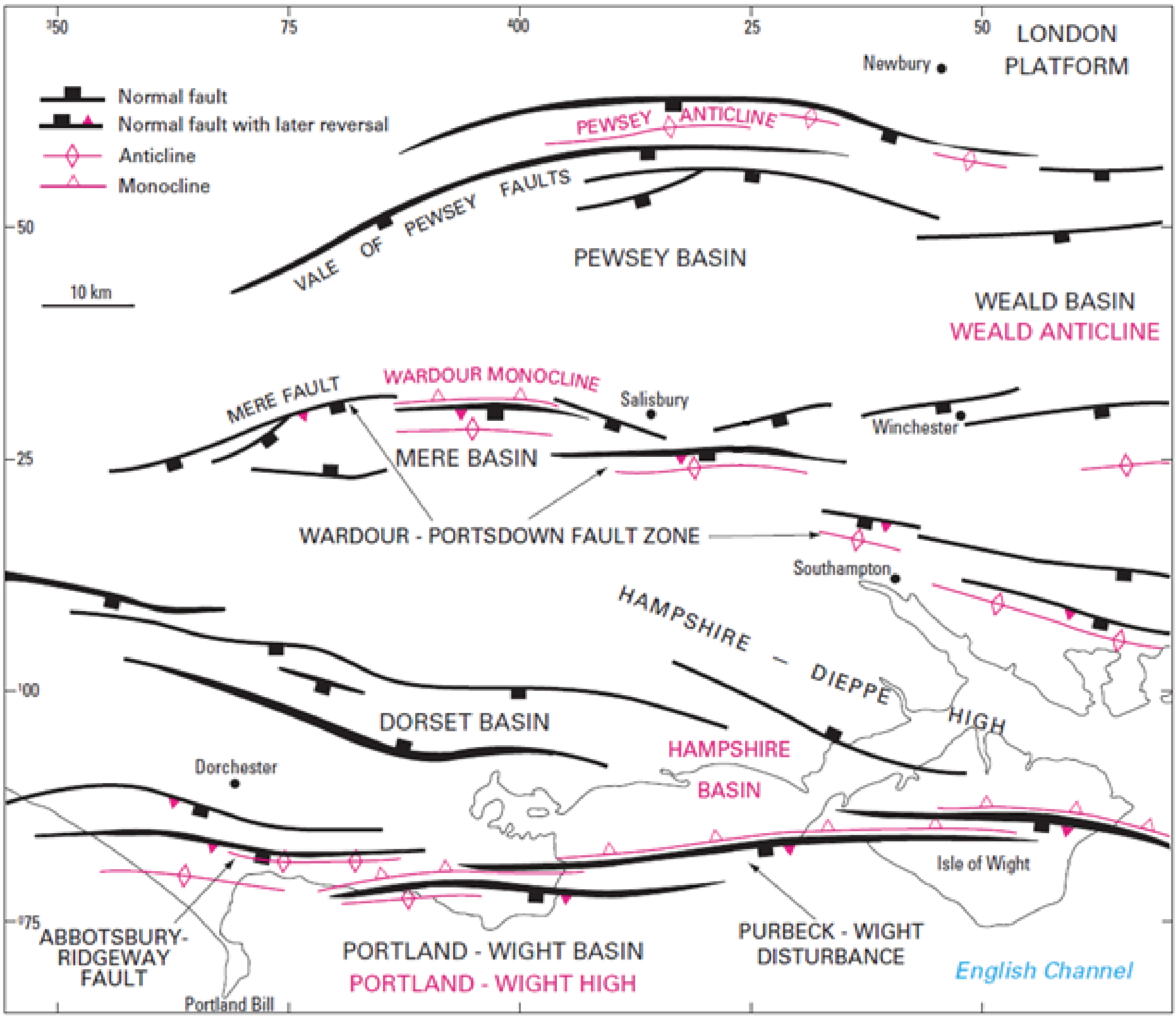


***Figure 2.13**: Map of the major fault and fold structures in the Hampshire region. Faults trend between WNW-ESE and E-W. The major faults were formed during Variscan compressional phases, reactivated as normal faults controlling basin development during intra-plate crustal phases and then finally reactivated under compression, most likely as a result of the Alpine orogenic phases. Black labels denote Mesozoic geographical regions, Pink labels and structures denote Cenozoic geographical regions of importance. Taken from (Brenchley and Rawson, 2006; Chadwick and Evans (2005))*

2.3.3 The Wealden High and Cenozoic outliers

The Wealden high formed as a result of Cenozoic inversion and forms a barrier between the preserved onshore Paleogene rocks of the Hampshire and London basins, figure 2.14. The timing of its inversion has been problematic with no Cenozoic material preserved and a large volume of the underlying Cretaceous rock removed. It has been postulated that inversion influenced the distribution of the stratigraphic units in southern England and is not just a recent structure (Chadwick, 1993; Murray, 1992). The numerous normal faults formed during its Mesozoic basin development have a similar trend to the major anticlinal fold axis and the London Basin fault structures (BGS, 1996). These faults may have been reactivated during tectonic compression along with other similar structures in the southern UK, such as the Sandown Fault on the Isle of Wight (Gale et al., 1999). This would support the degree of uplift and denudation that affected the Wealden area. Drainage patterns and erosion profiles on the Wealden, transportation of dateable overlying chalk, nodules and sedimentary material to the adjacent basins and their preservation have helped to estimate these motions to younger than the Cretaceous (Jones 1999). However as previously stated, the exact timing is unknown. It was postulated by Wooldridge and Linton (1955) that a mid-Cenozoic uplift event resulted in the uplift and denudation of the Weald, causing the observed peneplanation surfaces inferred to be of Miocene-Pliocene age. They also suggested a pre-Eocene inversion sequence, although more minor. Chadwick (1993) proposed the Miocene was the most likely age for the majority of inversion given the extent of missing strata and significant hiatuses across the UK, adjacent basins and parts of Western Europe. As such, constraining a more accurate timing is still uncertain.

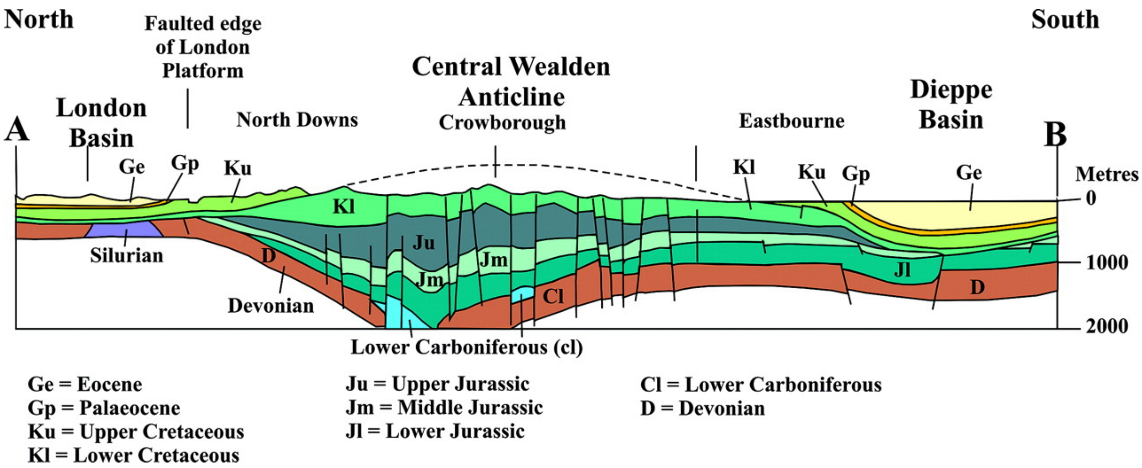


Figure 2.14: Generalised cross-section across the south-east of England traversing the inverted Wealden high. The distribution of onshore Cenozoic deposits is limited to the London Basin in the north-east and the Dieppe Basin in the south-west. The core of the Weald exposes the older Lower Cretaceous stratigraphy with upper Cretaceous Chalk missing. The vertical scale is greatly exaggerated relative to the horizontal scale. Adapted from Mortimore et al. (2011)

There are other onshore sites of Cenozoic strata in the UK but they are restricted to small outliers and temporally restricted deposits. In Derbyshire, there are localised pockets of deposits postulated to be of Miocene age, fluvial in origin, with material derived from the much older surrounding rocks. They may be related to the known uplift and widespread break in sedimentation that affected the UK at this time, suggested to be related to Alpine tectonism (Brenchley and Rawson, 2006). The Bovey Basin in Cornwall includes strata of a similar nature, fluvial in origin, within an erosional hollow carved into the surrounding older rocks, its margins being fault-controlled. Deposition continued into the late Oligocene (Campbell et al., 1998). The sediment is thought to have been derived from Devon, originally close to sea-level but now at least 75m above modern sea-level, representing a significant degree of uplift, post-Oligocene (Brenchley and Rawson, 2006).

2.4 Summary of stratigraphic relationships and tectonic events

A detailed account of regional Cenozoic sequence stratigraphy is beyond the scope of this project and is not necessary for the backstripping method. A discussion and summary of the major boundaries is beneficial as they provide geological context for the regional geology and may be related to tectonic events, as discussed in this investigation.

Throughout the Cenozoic, there were episodes of extensive marine incursions onto the land producing transgressive surfaces that are seen in the geological record, each being succeeded by marine shallowing events and subsequently by another major transgressive event. Formation boundaries commonly possess coarse to medium grained sands and flint pebble basal beds, marking these as marine transgressions (Edwards and Freshney 1987; Aldiss 2012: King 2016). The bases of these sequences represent deepening events with progressive shallowing up through the successions. A hiatus in sedimentation is usually representative of a lowstand and erosion may occur when previously submerged sediments are exposed subaerially. The origins of the flint pebbles could be from reworking or transportation from regions where the Chalk was bedrock at this time. The Cenozoic stratigraphy largely comprises shallow marine clastic successions with occasional carbonate and common flint pebbles. Flint gravel beds are more common in the lower marine formations of the Paleogene.

The deposition of the Cenozoic succession in the London and Hampshire basins occurs following the Eo-Alpine compressional events to the south-east and the onset of North Atlantic opening to the north-west during the Paleocene and Eocene. The onshore prerved sequence is no older than the Oligocene, prior top main Alpine compressional sequences which dominated Europe in the Miocene.

The use of all sedimentary information was instrumental in developing the palaeobathymetric surfaces and the detailed method is discussed in chapter 4. Chapter 3 discusses stratigraphic markers within the succession and the temporal constraints using this evidence.

Chapter 3: Cenozoic stratigraphy and chronostratigraphic relationships

In order to develop a model for the tectonic subsidence history described in chapter 5 using the Southern England Cenozoic record, the stratigraphic record needs to be assessed and correlated. Understanding the stratigraphic relationships across the London and Hampshire basins is a prerequisite to determining the palaeo water depths in chapter 4. To constrain the timing and temporal distribution of the evolving basins and water depths requires a model for the stratigraphic relationships across time and space.

This chapter focuses on the stratigraphy, the sedimentological and biostratigraphical constituents of each lithostratigraphic unit which are supplementary to the water depth determinations described in chapter 4, and the backstripping method in chapter 5. For both of these areas of the research, the stratigraphy must be assessed and correlated in order to build a robust chronostratigraphic framework which will be used in the displaying of the palaeobathymetric surfaces and the tectonic surfaces. In order to understand the regional tectonic and structural mechanisms that may be responsible for the evolution of southern England during the Cenozoic, constraining the timing of sedimentation in the depocentres is key. A study of the tectonic and palaeobathymetric evolution of the London and Hampshire basins requires a temporal constraint in the form of a chronostratigraphy. A range of palaeontological, magnetostratigraphic and tephrastratigraphic evidence was used to correlate and minimise the temporal error constraints on the age of the lithostratigraphic units studied, although uncertainties exist in each method and none give a numerical date. The tightest constraint on dating the stratigraphic succession came from oxygen isotopes obtained from the Barton Clay Formation, identifying an upper layer with an age of 39.9 Ma to 40.2 Ma. The London Clay Formation has been divided into three groups, the lower divisions A and B, the middle divisions C and D and the upper division E together with the overlying localised Claygate Member. Does the pattern of

evolving lithofacies and fossil assemblages in the lithostratigraphic succession reflect eustatic or tectonic control?

3.1 Cenozoic stratigraphy

One of the major challenges was in correlating and cross-referencing different generations of stratigraphic nomenclature and borehole/section descriptions into one coherent framework of the Cenozoic stratigraphy. The preserved stratigraphy of the London and Hampshire basins ranges from the Paleocene through to the early Oligocene, figure 3.1. Lithologies vary laterally throughout the formations and *Appendix 1* contains descriptions of all boreholes for each palaeobathymetric surface discussed within this chapter; references are included in the spreadsheets along with the water depths determined.

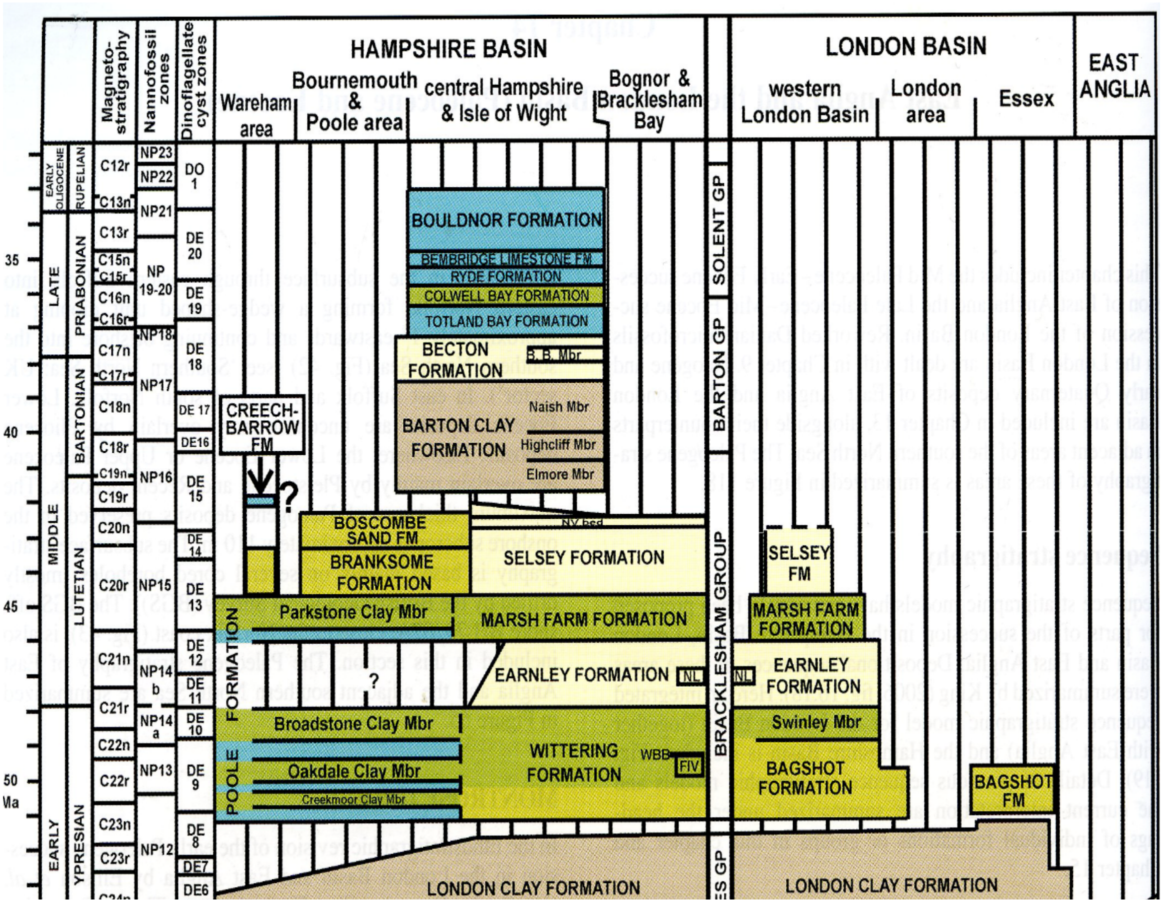


Figure 3.1: Eocene and Early Oligocene onshore stratigraphy of the London and Hampshire basins. The Thanet Formation is Paleocene and therefore missing from the figure. The Barton Clay is fully included in the Barton Group. Individual members reflect lateral and vertical variations in depositional systems. NL and NV refer to nummulite rich beds used later in the study. Taken from King (2016). A relevant higher resolution chronostratigraphic framework will be developed for the sections used in chapter 5.

3.2 Explanation of Cenozoic lithostratigraphic nomenclature

As noted above the major challenge was correlating the stratigraphic units given their evolving nomenclature. During the development of geology in the UK, these geological units have had their names amended many times or amalgamated into geographic counterparts of a similar age. This study was initiated prior to the release of the 'Revision of Tertiary rocks in the British Isles…' (King 2016). The report details a standardised framework for the UK Cenozoic (Tertiary) stratigraphy. *Table 1* shows the formation names used in earlier published papers/memoirs and the names used by King (2016). A full list of formation names used in the literature is featured in *Appendix 1*. The standardisation also led to minor alterations in the geological formation ages from earlier work.

Lithostratigraphic Nomenclature Amendments	
(Ellison *et al* 1996, Aldiss 2012 and Edward and Freshney 1987)	**Used in this study: 'Revision of Tertiary rocks on the British Isles…' Framework King (2016)**
Becton Sand and Chama Sand Formations	Becton Formation
Branksome Sand Formation	Branksome Formation
Camberely Formation (London Basin Only)	Selsey Formation
Windlesham Formation (London Basin Only)	Marsh Farm and Earnley formations
Oldhaven Formation and London Clay Basement Beds	Harwich Formation
Thanet Sand and Ormesby Clay formations	Thanet Formation and the Ormesby Clay Member

Table 1: Formation names used in this study, as interpreted by different authors.

3.2.1 Southern England Cenozoic stratigraphy

Table 2 and *table 3* give the summarised sedimentary geology compiled from the literature, boreholes and sections in the London Basin/East Anglia and Hampshire Basin, respectively. The sedimentary facies for each lithostratigraphic unit and range of water depths interpreted are displayed. Graphical displays of sedimentary facies for each borehole used in the backstripping in chapter 5 are shown in sections 1-5 (*figure 3.2 to 3.5*) within this chapter. The details of sedimentary facies for the remaining boreholes and sections used only in the palaeobathymetry section of the study in this chapter are in *Appendix 1.* The majority of boreholes used in the water depth investigation, unless specified as for research, were drilled by industry. These could be for petroleum or for geotechnical logging adhering to standards such as BS:5930 or Eurocode 7. In these, the clastic constituents are of the most importance, while fossil identification is of little to no importance and can therefore be commonly lacking. However, correlations can be made using other significant features via identifying lithofacies. The following section describes each lithostratigraphic unit, explaining the dominant lithologies, sedimentary structures, and depositional facies. The biostratigraphic content for each lithostratigraphic unit is listed, this being used to both constrain the age of each lithostratigraphic unit and assist in water depth determination. This also assisted in the establishing of the chronostratigraphic succession, presented at the end of this chapter, which is needed to providing likely ages and age error margins for the backstripping and subsidence history method described in chapter 5.

Summary of London Basin and East Anglia stratigraphy		
Geological Formation	**Basal Age (Ma)**	**Dominant lithology, common features and depositional facies**
Selsey Formation	44.5 Ma ±0.5	The lithostratigraphy displays dominant lithology of fine grained silt with **SAND** constituents. Glauconite is sparsely or moderately dispersed. Sub-horizontal laminations and cross-bedding. Commonly Bioturbated. The foraminifera *N.variolarius* and *N.lentipecten* present, provide water depth constraints.
Marsh Farm Formation	46.2 Ma ±0.5	Fine to very fine grained **SAND.** Clay beds and partings. Glauconite present with burrows, bioturbation and laminations. Burrows more common in clay-dominated beds. Shallow marine, inner neritic to shoreface.
Earnley Formation	51 Ma ±04	Medium grained **SAND.** Coarsens upwards. Glauconite abundant in lower beds, laminations, bioturbation also present. Burrows and lignite in the top beds. The foraminifer *N. laevigatus* present and is an important water depth indicator. Shallow marine, shore face.
Bagshot Formation	51.2 Ma ±0.4	Medium to fine grained **SAND.** Some silty parts. Sections typically have laminations, cross-bedding or ripples. Glauconite common. *Lingula sp* and bimodal cross-bedding suggests shallow marine, inner neritic, shoreface depositional environment.
London Clay Formation	53.2 Ma ± 0.4 to 52 Ma ±0.8 Ma	Dominantly **CLAY.** Some sand content. Laminations and cross-bedding present. Bioturbation and shelly remains common. *Terabratulina* and *Echinocythereis* present. Glauconite present with siderite concretions. Divisions A and B represent a shallow marine shelf, middle to inner neritic. Younger divisions such as C, D and E show a higher sand content and indicate shallower depositional conditions. *Portsmouth Sand Member* represents inner neritic to coastal depositional environments. *Nursling Sand Member* indicates inner neritic and wave base environments. *Christchurch Member* indicates the shallowest environments with rootlets and some palaeosol indicators. *Claygate Member* is synonymous with Division E.
Harwich Formation	55.5 Ma ±0.7	Very fine grained **SAND** to **CLAY.** Basal beds commonly marked by pebbles. Laminations fairly abundant with bioturbation and glauconite. Commonly contains layers of tuff. Dominantly middle to inner neritic conditions of deposition with some distal coastal facies. *Hales Clay member* represents the finer grain sizes of deeper marine conditions.
Reading/ Woolwich Formation	56 Ma ±0.2	**CLAY.** Fine grained to very fine grained sand constituents. Red, grey, brown mottling common. Laminations and cross-bedding present with abundant rootlets and carbonate nodules of pedogenic origin. Lignitic, palaeosols and molluscs common. *Reading Formation* represents deltaic and coastal plains with a low marine influence. *Woolwich Formation* is typically sandier with glauconite, bioturbation and a greater marine influence. Coastal shoreface depositional environment.
Thanet Formation/ Ormesby Member	58.5 Ma ±0.4	Very fine grained **SAND** and **CLAY.** Glauconite abundant, bioturbation and burrowing present. Red mottled horizon laterally traceable. Shallow marine, inner neritic. Limited to the London Basin. The *Ormesby Member* is dominated by **CLAY** with sporadic tephra layers. Represents a shallow marine shelf, deeper than the Thanet Formation. Limited to East Anglia.

Table 2: Compiled summary of London Basin and East Anglian Cenozoic Stratigraphy

Summary of stratigraphy limited to the Hampshire Basin		
Geological Formation	**Basal Age (Ma)**	**Dominant lithology, common features and depositional facies**
Bouldnor Formation	34.8 ±0.5 Ma	**CLAY** and **SILT.** Organic-rich clays with thin shell beds. Becomes mottled in colour up through the unit. Illite-rich clays. Interpreted as a restricted small sea or large lake with facies representing dominantly brackish or lagoonal conditions. Includes the *Hampstead* and *Cranmore members*. Both suggest a restricted depositional environment for the formation.
Bembridge Limestone and Marls	*35.2* ±0.5 Ma	Calcareous beds of **CLAY** and **SILT.** Some thin fine grained sand beds in eastern localities. Some limestone interbeds. Very shelly. Interpreted as a freshwater limestone. Very restricted sea/lake.
Headon Hill Formation	36.4 Ma ±0.6	**Groups stratigraphically thin formations and members together.** Dominantly **CLAY** with **SAND.** Some sandier sections and interbeds. Greenish grey. Shelly debris with gastropods and bivalves. Thick-shelled bivalves in some localised areas and rootlet beds. *Sinodia suborbicularis* is the bivalve used in dating the Formation. Some lignite. Heavy minerals in the sand have Cornubian, Scottish and American origin. Overall the formation is likely reflect a very shallow restricted sea. Some localities represent lagoonal/coastal facies and a transition through to fully marine conditions.
Becton Formation	38.5 Ma ±1.0	Fine to medium grained **SAND** with **CLAY.** Overall well sorted and shelly where unweathered. Localised glauconite and bioturbation. *Ophiomoprha* burrows are present. Localised sedimentary structures such as bidirectional cross-bedding. Interpreted as proximal marine facies. Inner neritic to upper shoreface. *Becton Bunny Member* laterally continuous thin clay layer helps stratigraphic correlation between sections and boreholes.
Barton Clay Formation	40.5 ±0.5 Ma	**CLAY and SILT.** Some sparse sand sections. Becomes finer and siltier upwards. Greenish grey to blue with glauconite present. Bioturbated. Shell fragments fairly common, of bivalves and gastropods. Presence of *Nummulites* foraminifera, *prestwichianus* and *variolarius*. Also present *Elphidium minitum.* Constrains the depositional environment to mid to inner neritic. Some marginal wave base facies. Devoid of any sedimentary structures.
Branksome Formation	44.5 Ma ±0.5	Fine to medium grained **SAND.** Some clay and silt parts. Commonly cross-bedded with dip towards the SE. Passes up into finer grain sizes, laminated silty clays with lignite and rootlet beds fairly common. General shallowing up sequence with cyclicity. Shallower cycles represent palaeosol horizons. Fluvial channels cut into older cycles. Interpreted as fluvial, coastal channels and coastal plain. Very shallow.
Wittering Formation	51.2 Ma ±0.4	Dominantly fine grained to medium grained **SAND** with **CLAY.** Glauconite present in some beds, sparsely distributed. Laminations and cross-beds fairly abundant with sparse lignitic material in basal sections of the formation. Cross-beds have a low angle, 10-17°. Laminations of clay and sand have regular spacings suggesting rhythmicity. Interpreted as coastal/marginal facies to shoreface. Intermediate water depth facies of the Lower Bracklesham Group.
Poole Formation	51.2 Ma ±0.4	**CLAY** and **SAND.** Coarsening up sequences of fine to coarse sand. Clays are laminated. Each member consists of sand and clay packages representing cyclicity. Interpreted as proximal/continental and tidally influenced, open to marine influence. Sedimentary structures suggest sediment transport eastwards. *Coleothrypta* dinoflagellate indicates tidal/salt marsh deposition. 4 Cyclic members through the formation. From oldest to youngest: *Creekmoor Clay, Oakdale Clay*, *Broadstone Clay* and *Parkstone Clay.* The Poole Formation is the lagoonal, brackish and shallowest unit of the lower Bracklesham Group.

Table 3: Summarised stratigraphy of formations only found in the Hampshire Basin.

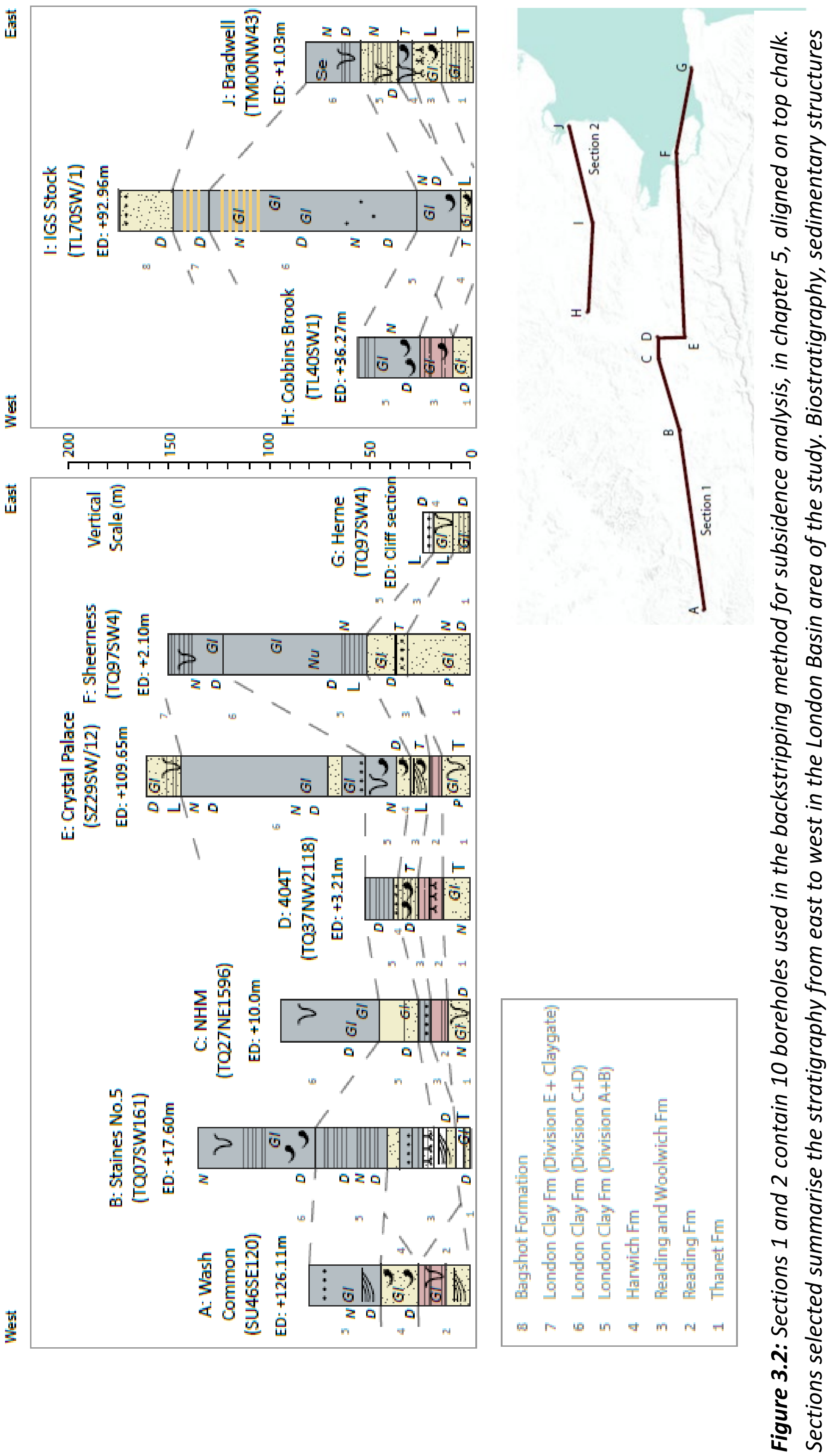


Figure 3.2: *Sections 1 and 2 contain 10 boreholes used in the backstripping method for subsidence analysis, in chapter 5, aligned on top chalk. Sections selected summarise the stratigraphy from east to west in the London Basin area of the study. Biostratigraphy, sedimentary structures and other notable observations are marked. The range of evidence displayed was used in developing the chronostratigraphy towards the end of this chapter. Detrimental to constraining lithostratigraphic timing. Other evidence marked was used in determining palaeo water depth, the focus of chapter 4 and the precursor to the subsidence analysis. Compilation of sections and relevant information derived from borehole logs. Initial sections from Edwards and Freshney (1987).*

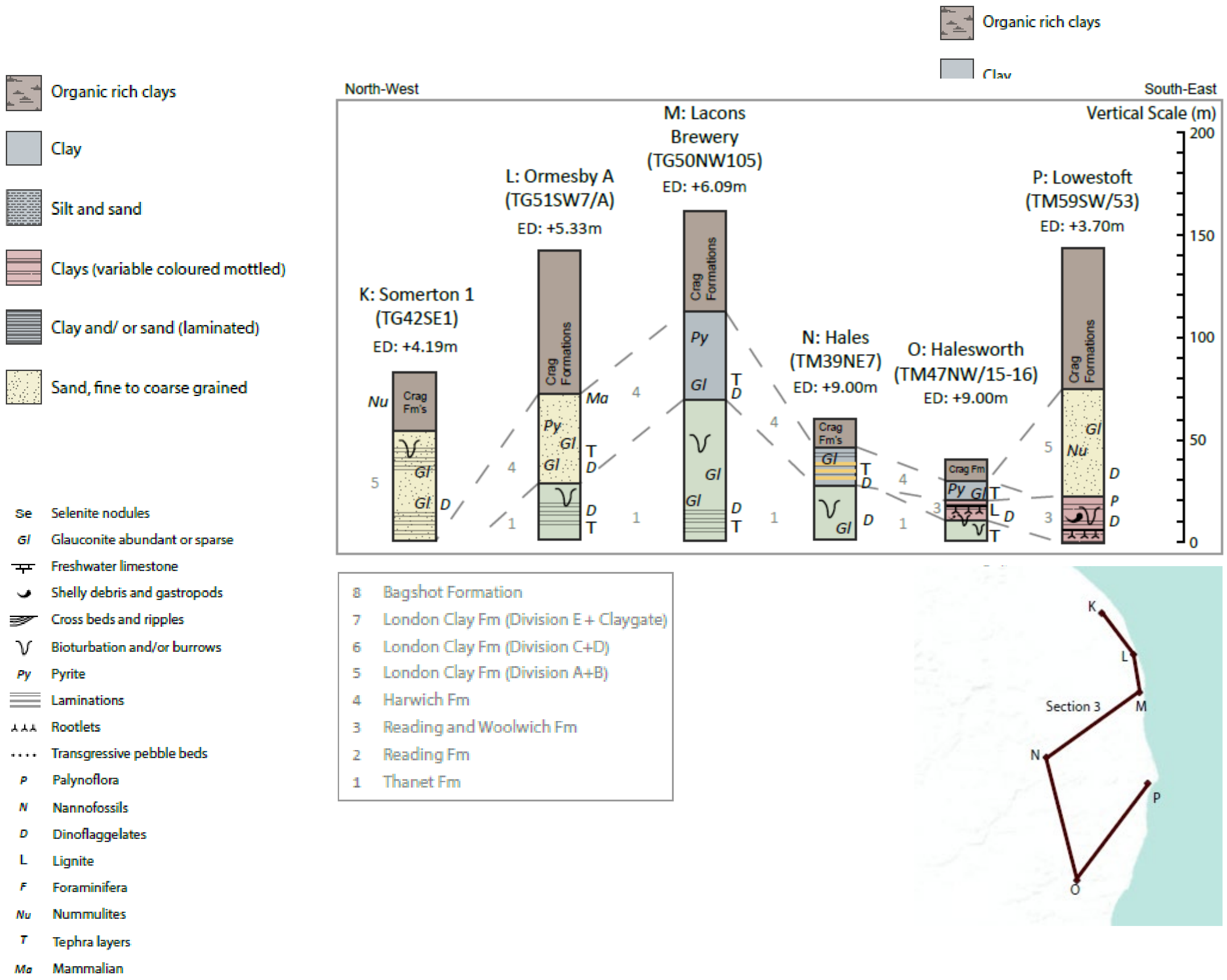
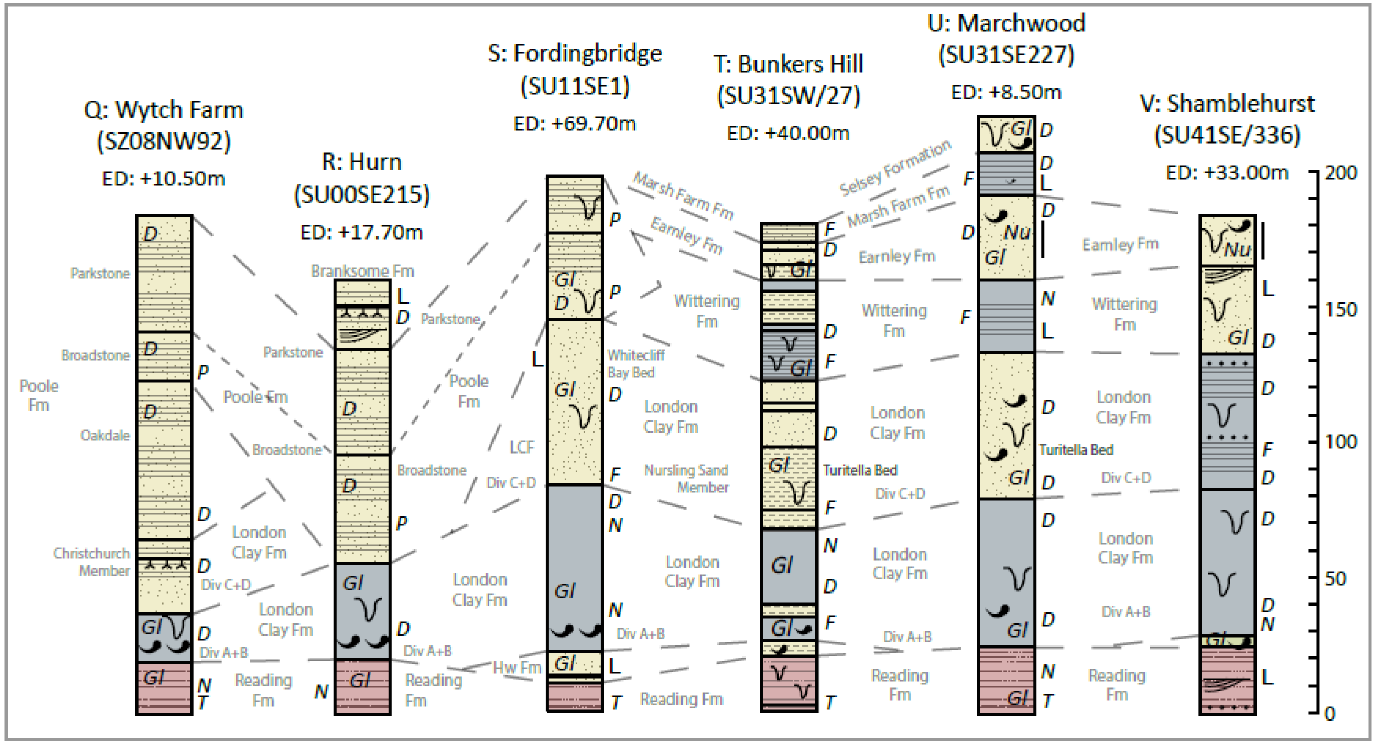


Figure 3.3: *Section 3 pertains to 6 borehole sections used in the subsidence analysis in chapter 5, aligned on top chalk. The section generally trends from north-west to south-east, summarising the early Cenozoic stratigraphic relations of the East Anglian study area. Again evidence for chronostratigraphic, water depth and subsidence analysis is marked.*



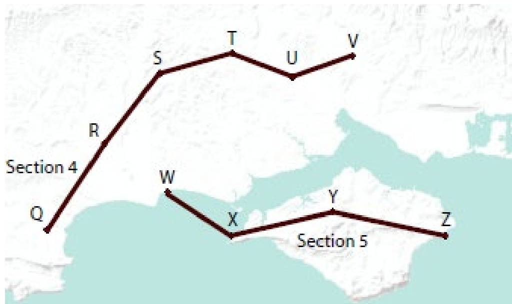
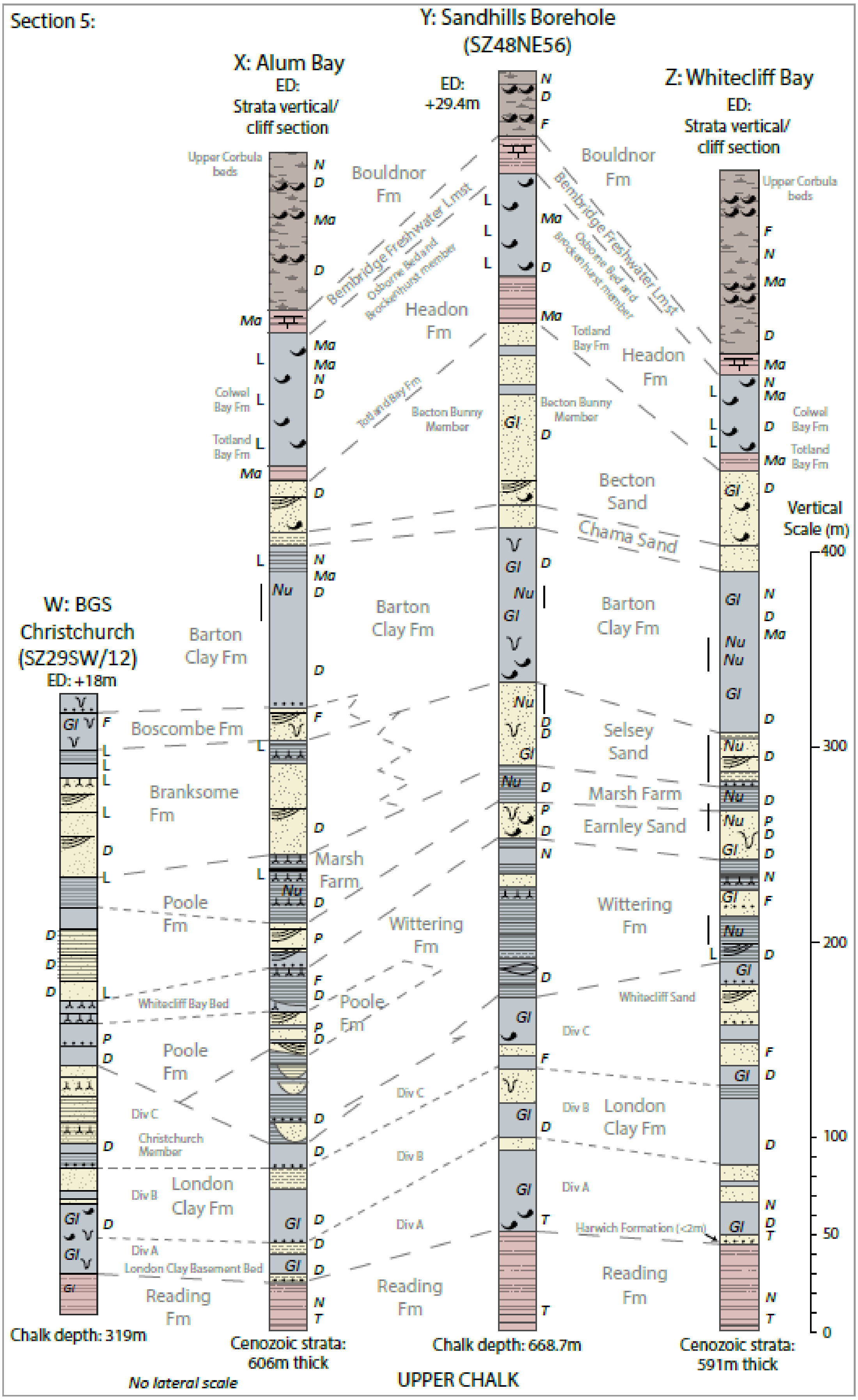


Figure 3.4: *Section 4 contains 6 borehole sections used in the subsidence analysis in chapter 5, aligned on top chalk. The section summarises the lithostratigraphy from the western to northern area of the Hampshire Basin study area.*

Figure 3.5 *(next page): Section 5 contains 4 borehole sections used in the subsidence analysis in chapter 5, aligned on top chalk. The section summarises the stratigraphic relationships from west to east of the central Hampshire Basin study area. These sections are the thickest sequences of Cenozoic stratigraphy studied.*


Section 5:
Y: Sandhills Borehole (SZ48NE56)
ED: +29.4m
X: Alum Bay
ED: Strata vertical/ cliff section
Z: Whitecliff Bay
ED: Strata vertical/ cliff section
W: BGS Christchurch (SZ29SW/12)
ED: +18m
Upper Corbula beds
Bouldnor Fm
Bembridge Freshwater Lmst
Osborne Bed and Brockenhurst member
Headon Fm
Colwel Bay Fm
Totland Bay Fm
Becton Bunny Member
Becton Sand
Chama Sand
Barton Clay Fm
Boscombe Fm
Branksome Fm
Selsey Sand
Marsh Farm
Earnley Sand
Poole Fm
Wittering Fm
Whitecliff Bay Bed
Whitecliff Sand
Div C
Christchurch Member
Div B
London Clay Fm
Div A
London Clay Basement Bed
Harwich Formation (<2m)
Reading Fm
Vertical Scale (m)
400
300
200
100
50
0
Chalk depth: 319m
Cenozoic strata: 606m thick
Chalk depth: 668.7m
Cenozoic strata: 591m thick
No lateral scale
UPPER CHALK

3.2.2 Thanet Formation (Thanetian, Late Paleocene)

The Thanet Formation is the oldest onshore Cenozoic lithostratigraphic unit in south-east England. It unconformably rests on Mesozoic Chalk and is restricted to the London Basin and East Anglia (Ellison 1994; Jolley 1998; Clements 2010; King 2016). A transgressive surface from the basal beds, characterised as sequence C2 and chronostratigraphically dated as C26n/NP7 after Jolley (1998), figure 3.1 and figure 3.2, using the presence of palynoflora: *Manipiles tenuipolis*. Tephrochronology was used to date the ash layers within the Thanet Formation, correlating within ash phase 1 (Knox and Harland 1979). The presence of the nannofossil *Heliothus redieli* constrains the base of the Thanet and Ormesby member to biozone NP6 in the early Thanetian (Hamilton and Hojgalzadach 1982). The dinoflagellate *Apectodinium* suggested that the upper and lower boundaries of the Thanet Formation lie within DP11b (Heilmann-Clausen 1985), which correlates with other evidence used despite the datum not being well defined (King 2016). Other dinoflagellates such as *Areoligera gippingensis* are much better constrained to dinoflagellate zone DP11b (Jolley 1992a; Powell et al 1996; Gradstein 2012) but limited to eastern areas of the London Basin and East Anglia. The numerical age has been constrained to 58.5 Ma ±0.4, due to the lateral continuity of the C2 horizon and the correlation of the biostratigraphically dated tephra layers. The Thanet Formation and Ormesby Member were deposited under shallow marine conditions and represent a transition between middle to inner neritic environments dominated by clay lithologies in northern East Anglia, characterised by the Ormesby Member (Ellison, 1994; Jolley, 1992). The coarser grain sizes and shallower water depth lithofacies are characterised by the Thanet Formation which is dominant in the London Basin and south East Anglia areas.

3.2.3 Reading and Woolwich formations (Early Eocene, Ypresian)

The Reading Formation crops out in the western and central areas of London, East Anglia and the Hampshire Basin. It is found at depth across the study area and represents an assortment of marine-influenced deltaic, coastal floodplain and terrestrial palaeosol environments (Edwards and Freshney, 1987b; Ellison, 1994). The Woolwich Formation crops out in the central and eastern regions of the London Basin. An influx of arenaceous and glauconite grain constituents suggests a shift to more marine depositional facies, along with the fossil assemblages (Ellison, 2004; Knox, 1996). The chronostratigraphic analysis suggests a basal age of 56 Ma ±0.2, based on the ranges of the top and basal layers from biostratigraphic, chronostratigraphic and tephrastratigraphic evidence and the confining likely ages of the overlying Harwich Formation and underlying Thanet Formation. The tephra analysis of argillized volcanic ash had a distinctive high titanium content and could be correlated within ash phase 2.1 but this reliant on communications between J.Skippers and C.King (King 2012) which is supported by the ash phase of 2.1 determined by Edwards and Freshney (1987) in the Hampshire Basin outcrops. The Woolwich Formation was dated within the dinoflagellate zone DE1 with the presence of *Apectodinium* in the London Basin but it is also present within the Reading Formation in the Hampshire Basin (Ellison 1996), and *Platycaryopollenites platycaryoides* in East Anglian deposits of the Reading Formation (Jolley 1996). Justifying the correlation of these two lithostratigraphies. Nannofossil zone NP9 was deduced from *Discoaster multiradiatus* in the Reading Formation in the Hampshire Basin (Siesser et al 1987). Magnetostratigraphic polarity has been determined to lie within the basal section of C24r in Hampshire and the London basin (Townsend and Hailwood 1985; Aubry et al 1986), however this provides little constraint given the long duration of this polarity interval. These age estimates suggest the Reading and Woolwich formations may have been deposited at the time of the Paleocene-Eocene Thermal Maximum (Gradstein 2012).

3.2.4 Harwich Formation (Early Eocene, Ypresian)

The Harwich Formation is primarily distributed across the London Basin and East Anglia with thinner deposits assigned to the Harwich formation in the Hampshire Basin (King 2016). Previously representing the most basal beds of the London Clay Formation, Division A, and also termed the Oldhaven Formation in the London Basin and East Anglia, it has now been defined as the Harwich Formation (Aldiss, 2012). The basal layer is dated at 55.5 Ma ±0.7 using tephrochronology (Gradstein et al., 2012; King, 2016) and can be correlated with volcanic activity, ash phase 2.2a across south east England, with some of ash phase 2.2b preserved in the upper Harwich Formation in East Anglia that can be associated with the Icelandic plume and North Atlantic opening, as discussed in chapter

2 (Knox and Harland 1979; Knox 1983; Knox 1996b). Further constraints are provided by the dinoflagellate assemblage of *Wetzeliella astra*, placing it at the top of dinoflagellate zone DE2, and *Apectodinium* at the boundary between DE1-DE2, younger the underlying Dinoflagellate DP zones (King 2016). The nannofossil zone is suggested to be within NP10 proven by *Dinoflandrea oebisfeldensis* (Jolley 1996) and the magnetostratigraphic polarity studies assign it as C24r (Ali and Jolley 1996). This can be correlated with thin beds in the Hampshire Basin assigned within subzone NP10b by the presence of *Tribrachiatus digitalis*, although this should be used cautiously due to its sporadic presence (Aubry et al 2003a). Additional constraints from East Anglian deposits use mammalian zones by Hooker (1991). *Pliolophus* suggests a biozonation of the upper Harwich Formation as MP8 to MP9 (Hooker at al 2005).

Parasequence 2 and its associated sequence Y4b dated from palynological studies (Jolley, 1996) were used as the laterally extensive layer representative of the Harwich Formation palaeobathymetry in chapter 4. It is dominantly comprised of inner neritic to mid-shelf depositional units (Edwards and Freshney, 1987b; Ellison, 1994; Jolley, 1996). All facies found are marine-influenced with nearshore facies more common in the southernmost localities.

3.2.5 London Clay Formation summary (Divisions A-E)

The London Clay Formation is one of the thickest units in the onshore Cenozoic stratigraphic record, up to 150 m in thickness. It was necessary here to use its subdivisions, Divisions A-E, for backstripping purposes, with Division C representing the bulk of the London Clay Formation in boreholes and cliff sections, hence its selection to represent the palaeobathymetric extent in chapter 4 (Aldiss, 2012; King, 1981). Divisions A-E show cycles of water depth shallowing with an overall progressive water depth shallowing through the succession, Division A is represented by the deepest facies. Divisions earlier than C possess similar lithologies and slightly deeper depositional facies but are limited in their extent as few of the boreholes drilled reach them. Division C is present in most sections and boreholes and outcrops in the London and Hampshire areas and in some parts of southern East Anglia. Here, the divisions are separated into A and B, C and D, and E with the Claygate Member. Due to the dominant lithotypes, divisions were grouped to reduce the number of intervals for the subsidence analysis in chapter 5. The resolution of using each division individually would result in chonostratigraphically determined ages that would have age error ranges greater than the maximum and minimum age of each lithostratigraphic division of the London Clay Formation.

3.2.6 London Clay Formation (Division A and B) (Early Eocene, Ypresian)

Divisions A and B of the London Clay Formation are preserved in 21 sections studied for subsidence analysis (Chapter 5), see figure 3.2 to 3.5. They comprise dominantly marine clays, interpreted as reflecting a dominantly shallow marine shelf environment across Southern England with the shallowest facies in the very western London Basin (Aldiss 2012; Edwards and Freshney 1987b). The assemblages from the base of Division A indicate a range of dinoflagellate zone DE3 to the base of DE4 with the presence of *Wetzelia astra* and *W. meckelfeldensis* (Bujak et al 1980; Ellison and King 2004. The magnetostratigraphy suggests a reverse polarity from studies in the Hampshire Basin, within the upper zonal division of C24r (Aubry et al (2003). To help constrain the age range, and the base of the overlying division C, it was necessary to obtain additional data for the upper parts of division A and division B. The uppermost division of A was suggested to span through to zone DE5 by the presence of *Draconidinium simile* (Knox 1983; Edwards and Freshney 1987). The base of the London Clay Division B can be constrained to the DE6-7 boundary suggested by the presence of *Pecten diplicatus* (King 1981), this being predominantly found in the London Basin. The top of division B includes a magnetic polarity change and lies within C24n (Aubry et al 2003). The range of nannofossils from the base of division of A through to division B are all proposed to be within zone NP11 (Aubry et al 2003), hence providing little constraint within these divisions. This does however help discern a boundary with the overlying division C.

3.2.6 London Clay Formation (Division C and D) (Early Eocene, Ypresian)

The basal bed of division C has been constrained to 53.2 Ma ± 0.4 using a range of evidence (King, 2016). The microfossil and macrofossil zonations are fairly well constrained in the London Clay formation as fossils are abundant. The presence of *Discocoaster lodensis* constrains division C to the NP12 zone. The dinoflagellate assemblage in C includes *Dracodinium varielongitudum*, present in the London and Hampshire basins, constraining this interval to the base of dinoflagellate zone DE7 (Newell 2001; Ellison et al 2004), with the appearance of *Charlesdonnia coleothrypta* and *Wetzeliella coleothrypta* constraining the overlying division D to the base of dinoflagellate zone DE8 (Eaton 1976; Bujak et al 1980).

The London Clay Formation Divisions C and D are interpreted in the London basin as reflecting a dominantly shallow marine shelf and inner neritic environment, with the shallowest facies limited to the Hampshire basin, consisting of coastal, nearshore and tidal zones of deposition (Aldiss, 2012; Burnett and Fookes, 1974; Edwards and Freshney, 1987b). This represents a shallower marine environment than the underlying divisions. Magnetostratigraphic correlation of the base of division D placed it within C23n (Aubry et al 1986). Additional water depth constraints are obtained from foraminifera, as exemplified by the *Subbotina* influx just above the C1 base (King 1991b).

3.2.7 London Clay Formation (Division E and Claygate Member) (Early Eocene, Ypresian)

Division E and the overlying Claygate Member are seen only in two borehole sections studied in the London Basin, later used for subsidence analysis. The spatial extent and stratigraphic thickness of the London Clay decreases following the deposition of division C deposits. This could be due to a eustatic variation, i.e. a sea-level drop, or a tectonic uplift. The result is limited preservation of deposits of Division E and the overlying Claygate Member, which are mostly restricted to the central and eastern London Basin, *figure 3.2* (borehole E and I). This is also reflected in a further reduced spatial extent of the younger overlying stratigraphic succession in the London Basin. The limited deposits studied indicated the dinoflagellate zone DE8 as shown by the presence *W. coleothrypta* (Eaton 1976). However, given the nature of these younger London Clay divisions, the shallower marine facies and their sporadic distribution, *W. coleothrypta* may have been reworked from the underlying divisions and therefore may be an unreliable constraint. Magnetostratigraphic evidence places division E from the C23r and C23n boundary upwards into the C23n polarity interval (Eaton 1976; Townsend 1982; Aubry et al 1986), constraining a possible age of 52 Ma ±0.8 Ma. There is, though, a significant hiatus between the youngest London Clay Formation and the overlying Bagshot Formation in the London Basin. The London Clay Division E may be a younger deposit and so the division has been assigned a higher error margin based on this and the limited available evidence for constraining a chronostratigraphic boundary. The greatest constraint is from the overlying basal deposits of the lower Bracklesham Group.

3.2.8 Lower Bracklesham Group (Early Eocene, Ypresian)

Lower Poole, Wittering and Bagshot formations

The Lower Bracklesham Group crops out in both the Hampshire and London regions and consists of three lithostratigraphic units reflecting varying depositional environments. The base of the Lower Poole, Wittering and Bagshot formations, form the base of the Bracklesham Group (King 2016), can be correlated using a combination of dinoflagellate, nannofossil, magnetostratigraphic and mammalian evidence, placing them within the Early Eocene at 51.2 Ma ±0.4 (Aldiss, 2012; King, 2016). The Bagshot Formation is distinctly marine, although restricted, being limited spatially to the London Basin (Clements, 2010), in contrast the Wittering Formation which represents a marginal marine depositional environment within the eastern areas of the Hampshire Basin (Edwards and Freshney, 1987b). The Poole Formation is interpreted as a coastal river and lagoonal depositional environment, with the facies cycles suggesting successive terrestrial flooding from transgressive events but with minimal to no marine-influenced deposits (Plint, 1983). During the deposition of the Poole Formation, successive stratigraphic layers show a transition from near-coastal to more inland deposits with a progressive decrease in marine influence, the facies and fossil assemblages reflecting this (Bristow et al., 1991; Plint, 1982). The presence of both *Impletosphaeridum cracens* and *Phthanoperidinuim comatum* suggest a dinoflagellate zonation of DE10 for the upper Wittering Formation (Eaton 1976). The basal surfaces of the Bagshot Formation can be correlated with the basal Poole Formation in the western Hampshire Basin and the lower Wittering Formation in the central and eastern Hampshire Basin by the presence of *Kisselovia coleothrypta* and *Dracodinium simile*, both suggesting a zonation of DE8 (Eaton 1976; Bujak et al 1980; Bristow 1991). *Triabrachiatus arthostylus* constrains a nannofossil level of NP12 for the Wittering Formation. *Nummulites* species preserved in the Poole and Wittering formations include *Palaeonummulites planalatus*, which also serves as a water depth constraint (Wrigley and Davis 1937; Chandler 1963).

A leaf bed found in the Poole Formation, within the Oakdale Clay can be correlated with NW European leaf floras (Gardner and Ettinghausen 1879 to 1882). All three lithostratigraphies that form the base of the Bracklehsam Group lie within the C23n magnetostratigraphic polarity, which is suggested to be correlated with the NP12-13 boundary (Ali et al 1993; Bristow 1999a; Vandenbergher et al 2012). The nature of the Bracklesham Group, the frequency of lithostratigraphic units allows relatively tight chronostratigraphic constraints given the rapidly evolving fossil assemblages and magnetostratigraphic patterns, potential reducing the error margin in age constraints.

3.2.9 Lower Bracklesham Group (Middle Eocene, Lutetian)

Earnley Formation and Upper Poole Formation

Above the Wittering Formation in the Hampshire Basin and its very localised exposures in the London Basin, is the Earnley Formation which can be correlated with the upper Poole Formation. The London Basin exposures were not included in this study as the deposits are thin and very localised. The limited assemblage suggests a dinoflagellate zonal level of DE10 in the London Basin for Earnley Formation (Islam 1983). However, the basal part of the Earnley Formation in the Hampshire Basin is suggested to be of DE9 zone age by the occurrence of *Areosphaeridium diktyoplokum*, giving some uncertainty over the relative ages of the Earnley Formation between the London and Hampshire basins. Relatively, less deposits of the Earnley Formation are preserved in the London Basin, and no boreholes from this study use the Earnley from the London Basin and is therefore does not affect the error margins for the Hampshire Basin. The constraints on the magnetostratigraphy from zone C22r to C21r has a wide chronological extent and does not help to solve the discrepancies in the age errors (Townsend 1982; Aubry et al 1986; Bujak 1980; Bristow 1991). Given the upper part of the Earnley Formation in the Hampshire Basin includes *Phthanthoperidium comatum*, which can be constrained to dinoflagellate zone DE10 (Bujak 1980), it may be that the limited outcrop in the London Basin preserves only the upper assemblages, and the lower units of that age were eroded away just following their deposition. The upper Poole Formation preserves *Pediastrum* in the Broadstone Member, also present in the upper Earnley Formation in the central and eastern Hampshire Basin (Eaton 1969; Bristow 1999). The very top of the Earnley Formation can be constrained to NP14 by the presence of a *Nummulites laevigatus* bed (Aubry 1983) and DE12 by the occurrence of *Enneadocysta arevata* (Islam 1983b). This provides a possible age on the basal surfaces as 51 Ma ±04 given the constraints from the underlying and overlying units. However, this error margin is increased in the London Basin given the limited fossil assemblages available. In terms of this project the data is unaffected as no section from the London Basin used in the backstripping method contained deposits of the Earnley Formation.

3.2.10 Upper Bracklesham Group (Middle Eocene, Lutetian)

Marsh Farm Formation

The Marsh Farm Formation is predominantly limited to the Upper Bracklesham Group in the Hampshire Basin with very limited deposits of similar age in the London Basin (Brenchley and Rawson 2005; King 2016). The lithostratigraphic succession comprises fine to very fine grained sands with clay beds representing shallow marine depositional environments, particularly inner neritic to shoreface, in the Hampshire Basin. Magnetostratigraphic studies suggest the Marsh Farm Formation is within the C21n polarity interval in the lower beds, with upper beds in the western Hampshire basin being suggested as C20r (Townsend 1982; Aubry et al 1986). The dinoflagellate assemblage preserves *Eatonicysta ursulae*, *Homotryblium oceanicum* and *Lanternopshaeridium vectense* constraining the lower Marsh Farm Formation to the upper part of dinoflagellate zone DE10 (Eaton 1976). Additional fossils such as *Triceratum kanayae* suggest a nannofossil age of NP15, and *Nummulites laevigatus* and *variolarius* further constrain the Marsh Farm Formation to the lower NP15 zone (Blondeau and Curry 1963). Chronostratigraphic correlations suggest a basal age of 46.2 Ma ±0.5.

3.2.11 Upper Bracklesham Group (Middle Eocene, Lutetian)

Branksome and Selsey formations

The Upper Bracklesham Group is limited to the Hampshire Basin and the western London Basin and consists of two lithostratigraphic units, the Branksome and Selsey formations, which are related genetically and spatially. The Selsey Formation represents a dominantly marine depositional environment, preserved in the western London Basin and in the eastern reaches of the Hampshire basin (Aldiss, 2012; Edwards and Freshney, 1987b; Plint, 1982). The outcrops of the Selsey Formation comprise the youngest Paleogene strata in the London Basin. The Branksome Formation is interpreted as representing coastal/marine influenced deltaic environments and may be used to constrain a likely palaeo-coastline in the Hampshire basin (Plint, 1983). A transgressive surface, dated with a numerical age of 44.5 Ma ±0.5 (King, 2016), was chosen. The lower sections of strata were easier to correlate across boreholes and sections, particularly units rich in *Nummulites variolarius,* lying within the nannofossil zone NP15, (Edwards and Freshney, 1987b), and these were also useful for inferences on water depth. From the eastern Hampshire Basin, a dinoflagellate zonation of DE15 was inferred from the presence of *Distatodinium craterum*, also present in the Selsey Formation along with *Cleistosphaeridium diversispisnosum* suggesting a range of zone DE14 to DE15 (Costa et al 1976; Eaton 1976, Bujak and Mudge 1994). This could be correlated with the western Hampshire boundary using magnetostratigraphic polarity to the C20r to C20n boundary found within the Selsey and Branksome formations (Townsend 1982). A widespread assemblage of *Nummulites variolarius* and *prestwichianus* found within the Selsey Formation constrains a nannofossil zone of NP16 (Aubry 1983).

3.2.12 Barton Clay Formation (Middle Eocene, Lutetian - Bartonian)

The Barton Clay is restricted to the Hampshire Basin. It is a dominantly clay lithostratigraphic unit which is of shallow marine origin with short phases of sand deposition preserved during periods of lowstand (Edwards and Freshney, 1987b; Hopson, 2011; Plint, 1988). The layers rich in *Nummulite prestwichianus* and *N. rectus* within the Barton Clay were used as lateral continuity markers between the cliff and borehole sections (Edwards and Freshney, 1987b). These foraminifera taxa can provide additional information on likely water depth maxima and minima, as well as constraining the age of the Barton Clay units via the presence of *Dipsiderella danvillensis* (Jorry et al., 2006). The foraminifera *Elphidium* is also fairly abundant in the Barton Clay Formation and also may be used to constrain likely water depth values (Leckie and Olson, 2003). The upper Barton Clay Formation was dated using $\delta^{18}O$ isotopes from benthic foraminifera, yielding an age range of 39.9 Ma to 42.2 Ma (Dawber et al 2011). This correlates with the MEBCO, Middle Eocene Climactic Optimum. Additional data from biostratigraphy is limited but does agree with the ages provided by $\delta^{18}O$ isotope data. Assessment of the magnetostratigraphy and dinoflagellates from the basal sections of the Barton Clay Formation suggest a polarity interval of C18n and constraining to the basal section of dinoflagellate zone DE16 as indicated by the presence of *Rhombodinium draco* and *Areoligera sentosa* (Bujak et al 1980; Bujak and Mudge 1994). The mammalian assemblages preserved were assessed by Hooker et al (1986) who proposed a Robiacian-Lautricense zone, MP16. The top of the Barton Clay Formation preserves *Spenolithus obtusus* suggesting the NP16 to NP17 nannofossil zones which is in agreement with the oxygen isotope dating (Dawber et al 2011). A date for the base of the Barton Clay Formation used in the subsidence analysis has been assigned as 40.5 ±0.5 Ma. The range of evidence used provides additional constraints on a lithostratigraphic succession which has a large temporal range.

3.2.13 Becton Formation (Middle Eocene, Bartonian – Late Eocene, Priabonian)

The thickest and most complete sequences of the Becton Formation are limited to the most central areas of the Hampshire Basin. The basal layers are dated as 38.5 Ma ±1.0 but are limited by their sporadic occurrence, the base of the overlying Headon Hill Formation providing better constraints, while the underlying upper Barton Clay Formation has been constrained by $\delta^{18}O$ isotope data (King, 2016). Mammal evidence in the form of *Chama* provides a possible constraint though the only occurrence is from Gardner et al (1888). The Becton Formation can be constrained to the Bartonian via the presence of *Rhondinium perforatum* and *R. porsum* found in the Becton Bunny Member (Bujak 1980; King 2016). This leaves the Becton Formation within the middle to upper DE18 dinoflagellate zone and therefore the age of the base could vary by up to 1 Ma. Dominantly composed of fine grained sands with subordinate clay, the continuity of the clay-dominated Becton Bunny Member helped correlate between the boreholes and sections (BGS, 2013; Edwards and Freshney, 1987a, b; Hopson, 2011).

3.2.14 Headon Hill Formation (Late Eocene, Priabonian)

The Headon Hill Formation is a succession of stratigraphically thin units with varying dominant clastic lithologies, capped by the Bembridge Limestone Formation which can be used as a marker. The Lyndhurst Member of Edwards and Freshney (1987a) was also used as a marker. The underlying and overlying units were difficult to correlate across sections and boreholes. However, their biostratigraphic assemblages helped constrain their likely age for the subsidence analysis. Within the Lyndhurst Member, the Venus Bed is laterally continuous across sections and easily distinguished by its abundant fossil fauna (BGS, 2013; Edwards and Freshney, 1987b; Hopson, 2011). The rapid variations in sedimentary facies are used for lithostratigraphic subdivision and are associated with unique fossil assemblages allowing good chronostratigraphic resolution. The base of the Headon Hill Formation is dated as 36.4 Ma ±0.6 using the bivalve *Sinodia suborbicularis* (Stinton, 1970). The lowest beds were also examined by Hooker et al (2005) who assigned a mammalian zone age of MP17a, within the Headonian. The overlying Colwell Bay Formation could be constrained to zone dinoflagellate DE19 or DE20 by the presence of *Rhombodinium perforatum* and *Thalassiphera fenestrata* (Liengjaren et al 1980). Although this is a coarse constraint, it does correlate with the overall stratigraphic age progression. Aubry (1983) noted the presence of *Cribocentrum reticulatum* which constrains the Headon Hill Formation lower beds to a similarly coarse resolution of NP19 to NP20. The upper sections of the Headon Hill Formation are better constrained by an array of mammalian assemblages: a *Microcherus* bed in the Ryde Member (middle Headon Hill Formation), followed by *psedosiderlithicus-thaleri* assemblages in the Osborne Member, all denoting the MP18 zone (Hooker et al 1992, 2005). The Headon Hill Formation is capped by the Bembridge Limestone, and although it is not stratigraphically significant in terms of subsidence analysis, being less than 2m thick, it provides an array of assemblages useful for chronostratigraphic correlation. Insole and Daley (1985) and Hooker et al (2004, 2009a) both assessed the assemblages, assigning them to the MP19 zone, showing age progression during deposition of the Headon Hill Formation.

The lithofacies and fauna suggest very shallow marine and coastal facies and the dominant depositional environments are interpreted as a shallow restricted sea to lagoonal setting. The disarticulation of shell parts suggests the coastal facies were of a notably high energy.

3.2.15 Bouldnor Formation (Late Eocene, Priabonian – Early Oligocene, Rupelian)

The Bouldnor Formation is the youngest preserved onshore Paleogene stratigraphic unit, limited to the very central areas of the Hampshire Basin. The Hampstead and Cranmore members were notable layers used to correlate across sections and boreholes (BGS, 2013; Edwards and Freshney, 1987a; Hopson, 2011). The organic-rich silts and clays and accompanying fauna suggest a very shallow environment, dominantly a restricted lake to brackish zones of deposition. The mineralogy and fossil assemblage suggest minimal to no full marine influence. The presence of *Rhombodinium perforatum* as described by Brown (1988) indicates the DE19 to DE20 dinoflagellate zone interval. Mammal evidence suggested the basal section can be assigned to the very Late Eocene MP20 zone (Hooker et al 2004). The upper beds can be constrained to the Rupelian (Early Oligocene) by the presence of *Phthanoperdinium flebile* and *Adnatospheridium reticulense* (Chateauneuf 1980) which can be compared with the Paris Basin assemblages of similar age, assigned to the dinoflagellate DO1 zone, further constrained to DO1b by *Wetzeliella symmetrica* and *Criboperidinium tenuitabulatum* (Chateauneuf 1980; Liengjaren et al 1980; Brown 1988). The presence of *Athleta rathreri* in deposits of similar age in Belgium suggest constraint to NP23 (King 2016). Assemblages of foraminifera are present that can help understand and constrain the palaeo-water depths, discussed in chapter 4 (Murray and Wright 1974).

3.3 Chronostratigraphic Correlation

Figure 3.6 presents a chronostratigraphic correlation between the Hampshire Basin, London Basin and East Anglia using the thickest sections available for use in the study as representatives of the maximum temporal extent of the Cenozoic succession in each region. The Hampshire Basin shows the greatest temporal extent, with the London Basin preserving a lesser stratigraphic succession of younger age, with even less farther north in East Anglia. The correlation constructed used the evidence described and assessed within this chapter.

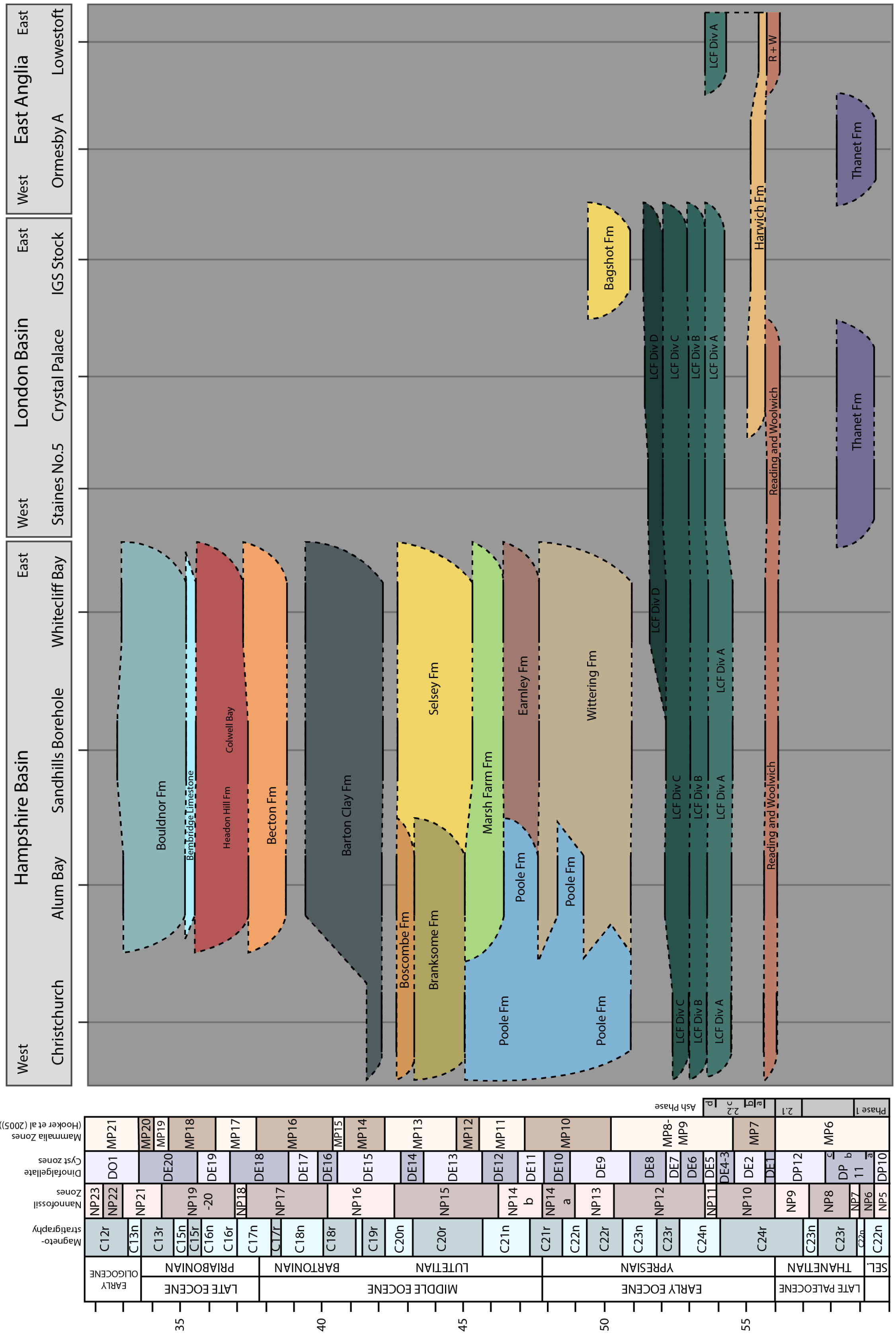


Figure 3.6: Chronostratigraphy diagram using the deepest sections from each area studied summarising the age ranges described within this chapter. Shallow sections preserve less stratigraphy and therefore provide less data but have been described in the text. The Hampshire Basin clearly preserves the longest duration of the onshore Cenozoic succession.

3.4 Chronostratigraphic Limitations

Correlation of a wide range of biostratigraphic markers, tephrostratigraphic and magnetostratigraphic methods allowed a robust correlation of lithostratigraphic units from the southern England Cenozoic succession. The age constraints and error margins produced are of suitable resolution for the units selected for subsidence analysis and palaeobathymetric reconstructions in the following chapters, 4 and 5. The resolution is appropriate as it allows overlying and underlying lithostratigraphic formations and members to be discerned from one another and arranged in a sequential order that also matches the arrangements of the stratigraphy in accordance with the law of superposition, suggesting that the method was sound, without placing any unit in an incorrect location in space and time. The nature of evolving stratigraphic patterns in East Anglia and the London and Hampshire basins, during approximately 33 Ma, in itself produces a temporal resolution of data points appropriate for correlating with regional tectonic events. The rapid variations in facies and evolving fauna help to constrain lithostratigraphic age ranges. The correlation method, though, relies on the accuracy of the observations and interpretations made in the literature, and on biostratigraphic data not being misidentified. This source of error has been dealt with by using a range of evidence and sources to constrain any likely erroneous observations. The frequency of facies changes and thus of accompanying fossil assemblage changes helps to constrain the upper and lower boundaries of the lithostratigraphic units selected. Furthermore, units with well-constrained boundaries will still provide a degree of temporal constraint with for adjacent, less well-constrained units.

3.5 Chronostratigraphy Conclusions

Constraining the ages of the lithostratigraphies is a complex process given the regional scope of the study and variations in lithostratigraphical members, so a combination of magnetostratigraphic, tephrostratigraphic and biostratigraphic evidence was used. Sparse oxygen isotope data was available to help constrain selected boundaries. The biostratigraphic evidence used to correlate and produce the chronostratigraphic succession include palynoflora, nannofossils, dinoflagellates and mammals. These were used to constrain the likely biozones, and when correlated with other evidence a likely age range with errors could be stated. The ages provided for the lithostratigraphic units in this study are for the purpose of constraining data points for the backstripping method and subsidence histories and are based on previous work by other authors. The ranges of zone fossils are subject to change based on additional evidence and are also dependent on correct identification by the author. Therefore, limitations exist in correlation and dating in producing any given chronostratigraphic succession. None of the methods prescribed produce absolute dates, necessitating the use of multiple lines of evidence to help constrain an age with a suitable error margin. Here a suitable chronostratigraphic is presented for the sections studied, providing error margins on the basal boundaries for each lithostratigraphic unit used in the palaeobathymetric mapping in chapter 4, and the backstripping and tectonic analysis in chapter 5. The use of tephra layers in the Paleocene and Early Eocene lithostratigraphic units was of particular importance, not only for the use of constraining depositional timing, but also as regards the pattern of appearance. It is clear that there was heightened volcanism in the Paleocene and Early Eocene as described in Chapter 2, from the Icelandic Plume and Atlantic opening processes. The abundance of preserved ash layers in these lithostratigraphic units shows there was an influence from these processes at this time. These ash layers become less abundant in the onshore Cenozoic stratigraphy during the Early Eocene and into the Mid-Eocene. The question of whether the tectonic signals deduced in chapter 5 also reflect an influence from the Icelandic Plume will be pursued below.

Chapter 4: Palaeo-water depth and bathymetry surface development

Determining palaeo-water depths from preserved stratigraphic successions is a prerequisite for accurate backstripping that will be conducted in chapter 5 hence, this part of the study produces interpreted palaeo-water depth values from sedimentary observations, these then being used to create palaeobathymetry maps for the Cenozoic geological units to provide additional context for the evolving tectonic patterns described in chapter 5. In this chapter the aim is to produce a systematic database of former water depths, noting both data quality and reliability and using the distribution of strata and depositional facies as the primary data source for the analysis of palaeobathymetry. This will in turn contribute to an assessment of the minimum extent and degree of water loading across southern England and provide clues as to the controls on the evolving basins, whether affected by sea-level rises and falls or by other mechanisms. The benefit of deriving a quantitative assessment of paleo-water depth is the subsequent production of quantified palaeobathymetric surfaces, previously unpublished for the Cenozoic UK. To date, there have been very few numerical values assigned to water depth allowing the production of palaeobathymetric surfaces of the Cenozoic strata that can help interpret early Cenozoic palaeogeography.

The analysis of palaeobathymetric variations poses hypotheses to be carried into the backstripping method: are the variations in water depth during the Cenozoic eustatically or tectonically influenced? Is this method of palaeo water depth determination and later backstripping appropriate for shallow marine sediments?

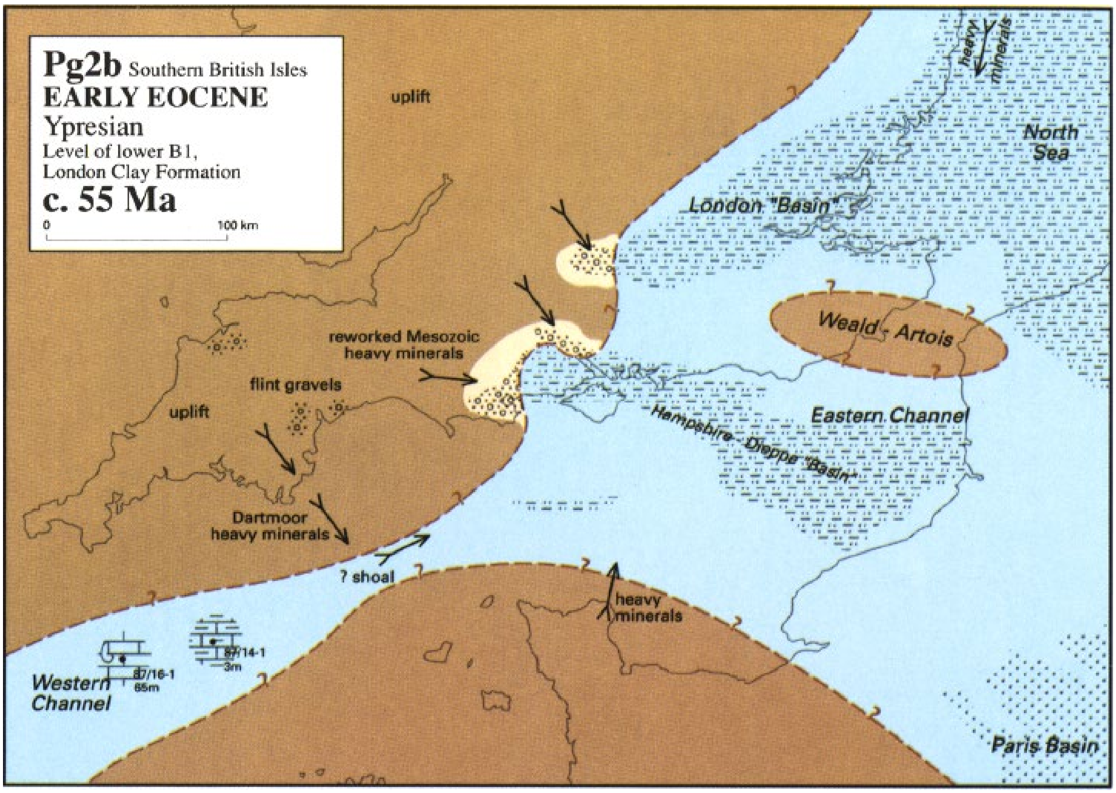
4.1 Aim of obtaining palaeo-water depths

To understand the amount of vertical motion of the basement in a basin, the loading must be calculated. The loading through time by the Cenozoic sedimentary units must be calculated and will be assessed in Chapter 5. Given these strata have been interpreted as being deposited in a shallow marine environment, the thickness of water column must be considered, stated as the determination of palaeo water depths. The water depth values are necessary for backstripping and assessing the basin evolution, while the palaeo-water depth data can be manipulated into palaeobathymetric surfaces. The use of quantitative modern techniques of surface development may provide additional information on Cenozoic basin evolution. The limitations of the palaeobathymetry maps displayed by Murray (1992) and in other hand-drawn studies has the potential for bias when gridding shorelines and boundaries, not to mention the limited quantitative assessment of potential deepening and shallowing trends. The recently released revised compendium of the Cenozoic succession (King, 2016) also justifies an updated series of palaeobathymetry maps. In this chapter, water depths are determined for use in the backstripping method in chapter 5 and are utilised to produce palaeobathymetry maps. These are developed to complement the hand-gridded method by using quantitative analysis, reducing the observer bias by using algorithms based on mathematical values and producing a graphical best fit surface representation. These representations can then be assessed, providing insight into the plausible basin geometry from point data distribution, potentially highlighting the changing volumes of water in the Cenozoic basins which can be correlated with sea-level fluctuations in order to help answer the hypothesis: is the Cenozoic succession in a eustatically or tectonically controlled system?

4.1.1 Regional and local palaeogeography during the Cenozoic

The Atlantic Ocean and adjacent basins west of the UK and in the North Sea have been continuously marine environments during the Cenozoic (see Figure 2.12 of Chapter 2). The strata preserved in these basins provide a thicker record of sedimentation than do the UK onshore strata (Brenchley and Rawson, 2006; King, 2016). Conversely, regions of sedimentation near to the continental UK, both (currently) offshore and onshore, particularly in the south of England, reflect more intermittent sedimentation than the Atlantic Ocean and North Sea sequences of strata. This has been interpreted in terms of phases of subsidence, sediment supply and basin accommodation alternating with phases of intermittent inversion and uplift (Newell and Evans 2011, Gale et al 2001). Such is the case in the Western Approaches and the southern North Sea (Brenchley and Rawson, 2006). The correlation between phases of uplift and their effect on Cenozoic stratigraphic sequences was discussed in chapter 1. The palaeogeography of southern England during the Cenozoic was suggested by Murray (1992) to be characterised by a continuous sea across the London and Hampshire basins in the early Paleogene (Figure 4.1a), as indicated by the consistently marine-influenced strata. It was suggested that both basins later became more restricted, in the Mid to Late Eocene, with dominant control by the Weald as a tectonic high, figure 4.1b. The interpretations of Murray (1992) are referred to as the 'semi-closed' Cenozoic palaeogeographic model. The evidence he presented suggests that the Weald was a land area or a palaeobathymetric high during the Paleogene,. It was also suggested that the presence of a tectonic high disrupted the connections between the eastern and western basins, and that the proto-Thames and proto-Solent drainage systems had developed as a result, with a similar distribution to the present day (Gibbard and Lewin, 2003). The disruption to sedimentation by a Wealden high was speculated on by Curry (1992) who provided additional stratigraphic evidence. This included the similarities in the stratigraphy across both basins throughout the Paleogene, with both including the London Clay (King, 1981, 2016) and the presence of heavy minerals of Scottish origin from the north, of Cornubian origin from the west, and of Amorican origin from the south deposited in both the Hampshire and London basins, suggesting more than intermittent connectivity (Morton, 1982). These studies argue for a more open palaeogeographical map with connectivity to the southern North Sea and Atlantic Ocean for longer durations during the Cenozoic, with the Weald existing as a bathymetric high rather than as a barrier.

The majority of studies agree on a palaeo-coastline existing across south-east England throughout the early to mid-Paleogene, with this coastline trending in a north-south orientation, bound dominantly by the Cornubian and Welsh massifs as topographic highs. The trend is largely inferred from near-shore and transitional sedimentary facies and a well-constrained palaeo-shoreline is limited to a few examples of marine-influenced successions that exist adjacent to coeval terrestrial and sub-aerial successions (Edwards and Freshney, 1987a). The transition of sedimentary facies in the Hampshire Basin from reflecting shallow marine to near-shore and then lacustrine environments during the Late Eocene through to the mid-Oligocene represents overall regression of the sea (Edwards and Freshney, 1987b). The missing Miocene stratigraphy prevents any interpretations of a palaeo-sea existing after the Oligocene, but a period of uplift is inferred from basins near to the UK and small preserved outliers onshore (Brenchley and Rawson, 2006). The interpretations made by these authors suggest evolution of the basins was mainly controlled by tectonic processes; however, the development of palaeobathymetric surfaces may indicate that variations in the volume of water held by the basins to be rather eustatically controlled.



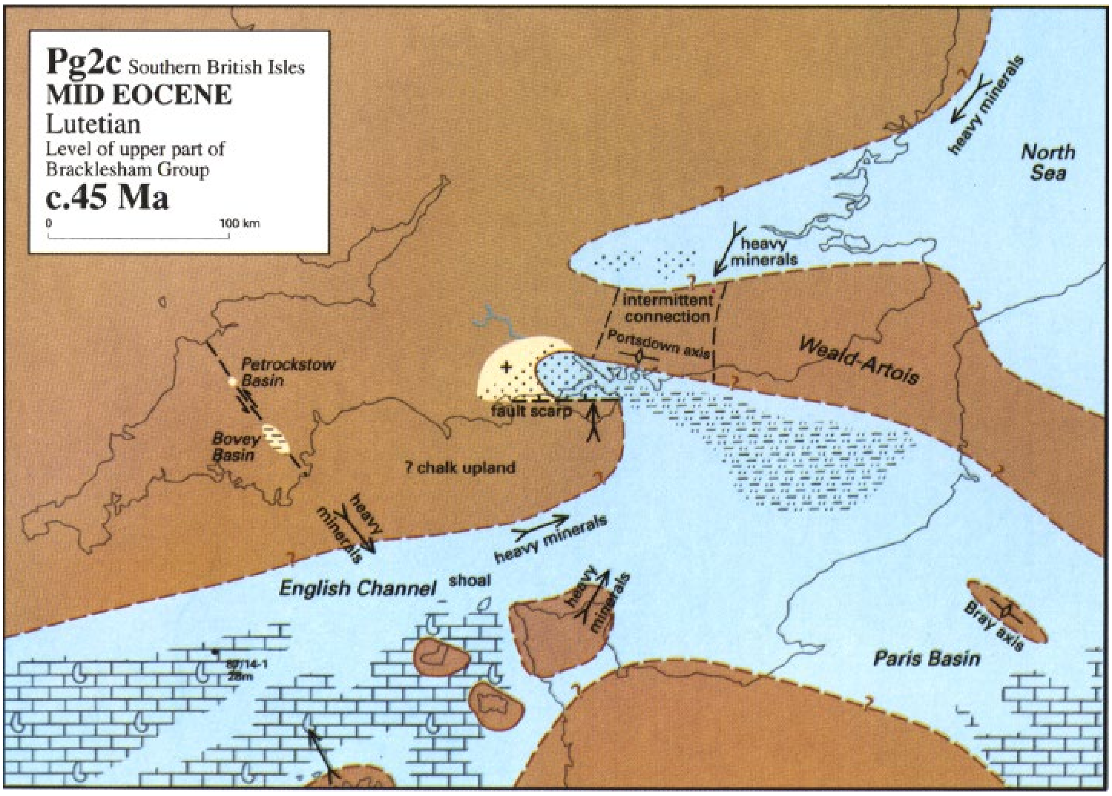


***Figure 4.1**: Palaeogeographical maps from two intervals of the Paleogene. A: Proposed palaeocoastlines show connectivity during the deposition of the London Clay but interpret the early onset of the Weald as a topographic high. B: During the Mid Eocene it is suggested the Weald was a substantial barrier and only intermittent connectivity between the basins occurred. The Hampshire basin is shown to have been highly restricted at this time. Taken from (Murray, 1992)*

4.2 Water depth determination

4.2.1 Introduction to the method and the water depth framework

The backstripping method that will be used to assess the vertical surface motions requires constraints on the water depth that the sediments studied were deposited in, to constrain the thickness of the water column and its contribution to loading of the basin basement which will be explored further in Chapter 5. Water depth determinations are very rarely absolute values and instead represent a semi-quantitative depth with error margins based on the constraints from the available lithofacies and fossil assemblages as suggested by Allen (1967). Some evidence is more reliable than others, and provides tighter constraints.

The main disciplines that provide the framework for constraining water depth are:

- Stratigraphy
- Sedimentology
- Palaeontology

The preliminary graphical framework for water depth determination was based on the Leckie and Olson (2003) study of the most likely water depth ranges of foraminifer taxa. This was the starting point and as the study progressed and additional parameters were applied to constrain water depth determination, an overall framework and starting point for the water depth method was developed using a combination of Leckie and Olson (2003) and the Gerard and Bromley (2008) practical guide to Ichnofacies. *Figure 4.2* displays a summary of Leckie and Olson's work with factors from Gerard and Bromley (2008). The approach by Kjennerud and Sylta (2001) has been used to constrain a framework for developing quantitative palaeo-water depths and its development to paleobathymetric surfaces. The next few sections describe and state the constraints applicable to a framework for the shallow marine strata of East Anglia, London and Hampshire Basins. This approach was deemed robust due to the focus of Kjennerud's (2001) studies on basin evolution in the North Sea, in close proximity to the study areas of this project. The limitations will be the use of coastal and nearshore facies that are not relatable to Kjennerud's (2001) approach, however, these have their own numerical constraints which will be discussed subsequently.

The first constraint on determining water depth is the maximum and minimum water depths for the study. Given the previous work and literature on the Cenozoic strata analysed, dominantly siliclastic deposition in a continental shelf environment is suggested as discussed in Chapter 3. Therefore, the maximum water depth would most likely not exceed 200 m, with literature suggesting facies water depths in southern England were not greater than 150 m (Edwards and Freshney 1987a; Coward et al 2009; Immenhauser 2009; King 2016). No deep marine sediments are preserved in the study area. This simplifies the significance of the error margin in determining relative water depth as the maximum water depth value is smaller than if the study consisted of deeper marine sediments; those used in the North Sea studied and described by Kjennerud (2001) and Kyrkjebo et al (2001) are deeper marine and as such have greater error margins. Deeper marine sediments within thicker successions are deposited in water greater than 200 m which incurs greater relative error margins based on the preservation of material on the ocean floor. The high frequency of shallow marine facies and their lithostratigraphic and lateral facies variations provides a finer resolution of water depth constraint than seen in deeper marine studies, which are usually fairly homogenous, relying on assemblages that preserve a range of fossils from within the water column that have percolated down into the sediments. Turbidite sequences may provide a water depth range or zonation and are localised events (allen 1967). Water depths in shallow marine environments show variations in current velocity and sea floor shear stress, which typically increase with proximity to coastal areas (Allen 1967). Unique to this study is the use of lithostratigraphic units that possess coastal or even terrestrial facies that can be correlated with marine environments. This lateral correlation increases the reliability of the water depth constraints, not only constraining a likely palaeocoastline with greater precision but also producing a zero value on the water depths of facies. This cannot be achieved in a wholly deep marine study; such data is absent farther offshore. This therefore underlines the strengths of this method for constraining palaeo-water depths and its appropriateness for this study. The reliability of both the chronostratigraphy and palaeobathymetry in this study is increased by the high frequency of Cenozoic lithostratigraphic units, their spatial distribution and the range of sedimentary facies and fossil assemblages that are present in southern England which are not commonly attributed to deep marine studies using the backstripping method.

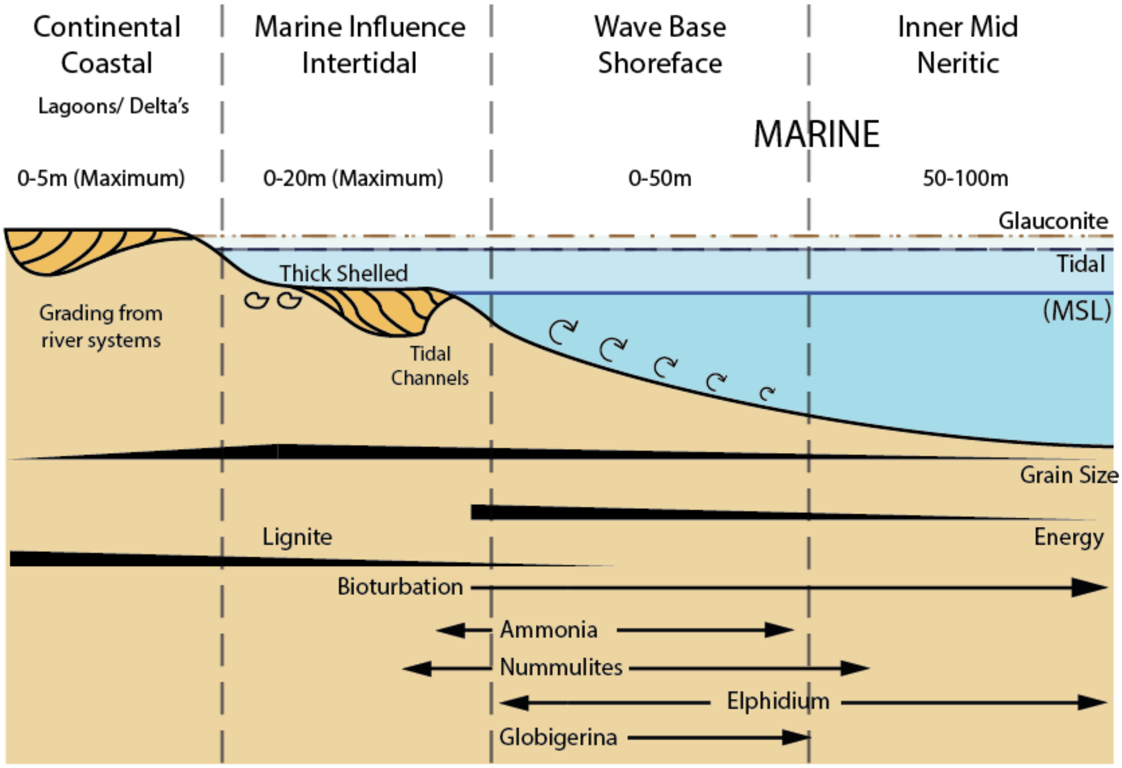


Figure 4.2: *Summary graphical framework adapted from Leckie and Olson (2003) explaining the an approach used. Foraminifera, although more sparsely distributed, provide an additional constraint on inferred water depth, alongside the primary evidence such as sedimentary structures, sequence stratigraphy and fossil assemblages.*

4.2.2 Stratigraphic constraints on water depth determination

The sequence stratigraphic and lithostratigraphic boundaries provide useful information on the most plausible regional to local palaeo-water depths and help correlate the likely palaeobathymetric estimates. The Cenozoic onshore stratigraphy reflects a succession of marine transgressive-regressive cycles and shallowing-up sequences (Edwards and Freshney 1987a, Ellison 2004, Aldiss 2012). The majority of the Hampshire and London basin successions are made up of late transgressive and highstand depositional sequences, with little early transgressive and almost no lowstand systems tract sequences preserved (King, 2016). Boundaries between lithostratigraphic units also mark the sequence boundaries and represent these transitions, with divisions and members also representing localised cyclicity as shown by Plint (1983a) in the Bracklesham Group. A few exceptions, such as the Boscombe and Marsh Farm formations, mark a solely transgressive event and not the full sequence (Edwards and Freshney, 1987b). The bases of the units above marine transgression events reflect the greatest water depths and so were used to provide maximum water depths. A maximum water depth is important for the later backstripping exercise to show when the basin was at its deepest during sedimentation. A maximum water depth is also important for understanding the possible maximum extent of the palaeosea at the time of each lithostratigraphic unit when developing the palaeobathymetric surfaces. The Reading and Poole formations were the most marginal/continental units and their spatial distributions as previously discussed provide valuable constraints on water depth and can be used to determine the likely orientation of basin deepening and the geometry of palaeo-coastlines, constraining the maximum extent of the palaeosea. During the deposition of a lithostratigraphic unit, the facies and water depth could vary. For simplicity, only one point was taken to represent each unit.

Each palaeobathymetric surface was derived from a well-constrained interval, representative of the dominant lithology and depositional environment. Ideally, a palaeobathymetric map is developed using a laterally continuous, chronologically well-constrained horizon or sedimentary division. Chapter 3 achieved this using a range of sedimentological or palaeontological evidence. Therefore, the chronostratigraphically constrained boundaries were used to correlate and contrast facies variations across lithostratigraphies preserved in boreholes and sections

4.2.3 Sedimentological constraints on water depth determination

Sedimentary structures, grain size, grain type and mineralogy are useful evidence for inferring depositional environments and determining local relative water depth values. The presence of sedimentary structures such as laminations, high-angle cross-stratification or ripples alongside the dominant sediment type and mineralogy contributed to referring each sedimentary facies to depositional environments. These were divided into one of five main categories: Outer Neritic, Mid to Inner Neritic, Wave base/Shoreface, Marine-Influenced intertidal and marginal, and Continental/Coastal (Figure 4.2). Each category of marine shelf facies was assigned an initial upper and lower boundary of water depth, the error bars on the data are therefore within 50 to 20 m so a likely relative water depth could be further determined. The presence of multiple lines of evidence of sedimentary features and biostratigraphic markers and fossil assemblages could be used to further constrain the likely water depths. Again, the nature and distribution of shallow water depth facies helped to constrain palaeobathymetry with a finer resolution than is possible in deep-water settings.

The coarsest sedimentological constraint used was the mudline, described by Immenhauser (2009) as the boundary between the siliciclastic dominant lithotypes and the deeper marine clay particle-dominated lithotypes commonly approximating to a 60 m water depth boundary. This is relevant to this study as the Cenozoic succession in southern England preserves dominantly siliciclastic facies, so a maximum high energy shallow sea environment mudline is stated to be 40 to 60 m water depth (Immenhauser 2009). There is variability depending on the other water depth-related facies present but this provides an initial constraint on lithofacies dominated by granular coarse materials rather than finer grain sizes such as silt and clay. *Table 4* presents the structures present and the constraints on the water depth they provided.

The majority of the Cenozoic deposits assessed are clastic, with the exception of the Bembridge Limestone Formation from which palaeobathymetric surfaces were not developed due to limited spatial data and limited stratigraphic thickness. The grain size ranges from coarse sand and gravel beds through to clays and silts. Many lithostratigraphic units include lithofacies comprising fine-grained sand with varying clay proportions which was significant for resolving compactional histories, as discussed in chapter 5.

The presence of particular minerals provides additional constraints on the marine influence within the palaeo-basin both regionally and locally, providing evidence for semi-quantitative boundaries in marine or more marginal and coastal facies. Pellets of glauconite or glauconite-coated grains are abundant in the Cenozoic succession and reinforce the dominant shallow marine interpretation (Triplehorn, 1964). Glauconitization dominantly requires a silicate parent material with iron and potassium sources in sea water with local reducing conditions (Thompson and Hower, 1975; Triplehorn, 1964). Lithostratigraphic units that represent more continental or marginal depositional conditions generally include little to no glauconite or selenite mineralisation. Other sedimentological evidence to help constrain water depth includes organic matter content. Darker units rich in lignite verging on coal-bearing are also usually accompanied by rootlets and palaeosol horizons. These observations alongside the profile of the strata build an ecological profile similar to a deltaic or flood plain environment, to which are assigned the lowest water depth values of zero as explained in section 4.2.1. It would be useful using alternative methods to assess the likely elevation of terrestrial fluvial palaeosol facies, but given the rarity of these deposits it is not feasible to explore this. To produce a negative palaeobathymetric value would provide a better elevation profile helping to better constrain the palaeocoastline when used with water depth points. This is a weakness of this approach in shallow marine settings with coastal deposits.

As with any proxy used, such as palaeontology or the physical rock record, limitations exist in estimating an ancient water depth from modern observations that may not be completely comparable as discussed by Immenhauser (2009). This can be combated by the use of many forms of evidence for determining water depth, leading to tighter constraints. The shallow marine settings, although providing additional constraints in comparison to a deeper marine setting, will have a higher relative error margin due to the complexity of coastal facies and varying water depths. Immenhauser (2009) states that an average wave base is difficult to constrain across fossil settings. This is countered in this study by the use of all of evidence available, but also via stratigraphic facies as previously discussed to help constrain plausible water depths and minimise errors. A compilation from Walker and Plint (1992) of modern siliclastic seas averages the fair weather base at 10 ±5 m, and a storm wave base at 20 ±5 m. This will be used as a baseline analogue for comparative purposes but as the study areas are paleo-seas, conditions may still exceed these boundaries if other evidence suggests so. Given the paleogeographic model of Murray (1992) and the analogue of the Cenozoic North Sea Basin, studied in detail, which is thought to have more connection to open marine deeper conditions and was suggested as low energy and minimal storm influence, the adjacent more restricted shallower conditions of the London and Hampshire basins are assumed to be of a similar energy and storm influence (Kjennerud 2001; Coward et al 2003; Immenhauser 2009). This means error margins can be adjusted accordingly in the interpretations of palaeo-water depth from sedimentary structures as stated in table 4.

A list of sedimentary structures and their relation to fluctuations in hydrodynamic conditions is found in Reineck and Singh (1986) and modern analogues for sedimentary facies and their water depths were used for comparison from Allen (1967) and Immenhauser (2009).

Semi to quantitative sedimentological constraint	Observations and characteristics	Output and Limitations	Depth Range	Reference
Sand to mud marine transition (mudline in siliciclastic seas).	*Transition from granular to cohesive dominated lithofacies*	*Limitations narrowed by the Cenozoic stratigraphy constrained to a shallow marine and dominantly siliclastic setting.*	*40 to 60m for a high energy shallow marine setting; 11 to 30m for low energy setting.*	*Immenhauser (2009)*
Subaerial exposure surfaces	*Palaeosol, calcretes, silcretes and desiccation cracks*	*Small error bars, providing above sea-level evidence. Elevation cannot be provided.*	*0m (for backstripping)*	*Immenhauser and Scott (2002); Hillgartner et al (2003)*
Intertidal Facies	*Bi-modal bedforms, coarse grained tidal channels and tidal flats*	*Tidal range varies but maximum defined by presence of type bed forms.*	*0.5m to >4m*	*Allen (1967); Reineck and Singh (1986)*
Average fair weather wave base	*Winnowing of fine grained material*	*Fair-weather wave base, variation proximally and laterally*	*Siliciclastic basin: 10 ±5m Protected coastal setting: 2-3m ±0.5m*	*Allen (1967); Shipp (1984)*
Shoreface facies	*Presence of peat or lignite. Cross lamination and sub-horizontal trough laminations with heavy minerals in laminae*	*Small error bars near to or above sea-level.*	*0 to 20m*	*Makaske and Augustinus (1998); Immenhauser (2009)*
Ripple bedforms	*In accompaniment with similar bedforms, flat-topped and ladderback ripples*	*Within the tidal range with medium error margins. Compaction may affect the interpretation of ripple bedforms.*	*0-50m*	*Allen (1967); Reddering (1987)*

Table 4: Sedimentological and sedimentary structural evidence used in determining palaeo-water depths.

4.2.4 Palaeontological constraints on water depth determination

Palaeontological evidence is particularly useful in constraining palaeo-water depth values as long as the fossil evidence is found in situ. The abundance and distribution through a stratigraphic unit is a key observation in this method. Again the method relies on published observations and Murray and Wright (1974) describe the process in detail, in which assemblages for the Paleogene strata in the Hampshire Basin were identified and characterised. Large sample sizes were used by Murray and Wright (1974) to identify abundant groups of fauna in each lithostratigraphic unit before the dominant species could be constrained and minor or isolated appearances of identified fauna were usually disregarded if their consistent appearance was not certain. In one case modern fauna was identified as a contaminant and removed. As such, given the breadth of assemblages, only representative abundant fossils were used to determine depositional conditions and assign numerical values to palaeo-water depth, table 5. Full assemblage analysis of the Hampshire Basin Paleogene strata are detailed in Murray and Wright (1974) and their correlations to the environments and assemblages of the Paris Basin increase the validity of their results and relevance to this study. A recent palaeontological approach to determine palaeo-water depth is outlined in Gillmore et al (2001) but this focuses on micropalaeontological evidence alone; here we expand to macrofauna and ichnofacies to support the sedimentological constraints.

Particular fauna provide interpretations on possible water depth zonations, based on their interpreted salinity conditions and mode of life. Cumulative dominance in an assemblage is a key observation for a representative sample and thus can lead to a robust interpretation of palaeo-water depth. The presence of fossils or trace fossils also provides additional data on the sedimentary conditions of the depositional system. The larger fossils such as bivalves and their degree of disarticulation reflect current strengths during deposition. Whether particular species had a freshwater or marine mode of life is also useful in water depth determination. The presence of particular ichnofacies, such as of *Ophiomorpha*, and the degree of bioturbation provides further evidence on the likely setting of deposition, see table 6 (Gerard and Bromley, 2008). However as discussed by Ekdale (1988), the presence of similar ichnofacies in different lithostratigraphic units does not necessarily indicate correlation. Ekdale (1988) noted that environmental shifts of particular trace fossils have occurred through time, for instance as regards varying salinity and oxygenation levels. Therefore care must be taken, as using these traces alone may result in errors when assessing the environment of deposition.

In summary, the use of palaeontological evidence in determining water depth values, when used in conjunction with sedimentological and stratigraphical observations, reduces the errors in the assessments and the fauna displayed in table 5 and table 6 with interpreted ranges supports this. Correlation across boreholes and lithofacies is needed when using palaeontological data for determining water depth. Where possible the collation of fossil assemblages will help to build a palaeoecological interpretation of the depositional environment supporting the inferred water depth zonation. Equally, hiatuses in the biostratigraphic record when coupled with sedimentary structures indicating subaerial exposure will support an inferred bathymetry of 0 m, representing a level at or above sea-level.

Palaeontology Fauna	Type	Interpreted environment	Depth Range	Reference
Angulogerina germanica	*Foraminifera*	*Non-marine to lagoonal hyposaline*	*0-20m*	*Keen (1971); Murray and Wright (1974)*
Brizalina cookei	*Foraminifera*	*Non-marine to lagoonal hyposaline*	*0-10m*	*Cushman (1922); Keen (1971); Murray and Wright (1974)*
Cibicides ungerianus	*Foraminifera*	*Inner to mid shelf, coarser sediment some hyposaline increased currents*	*0-50m*	*Murray and Wright (1974)*
Dipsidrella danrillensis	*Foraminifera*	*Inner neritic shallow marine*	*0-50m*	*Bronnimann et al (1968); Norvick (1969); King (2016)*
Elphidium hiltermanni	*Foraminifera*	*Hyposaline shallow near shore*	*0-30m*	*Hagn (1952); Murray and Wright (1974)*
Elphidium latidorsatum	*Foraminifera*	*Shelf to mid-shelf within mud line*	*0-100m*	*Reuss (1864); Gardner et al (1888) Murray and Wright (1974)*
Globigerina aquiensis	*Foraminifera*	*Hyposaline shallow near shore*	*0-20m*	*Loeblich and Tappan (1957); Murray and Wright (1974)*
Globulina gibba	*Foraminifera*	*Near shore shelf, high salinity*	*0-50m*	*D'Orbigny (1846); Bhatia (1957); Murray and Wright (1974)*
Nummulites laevigatus	*Foraminifera*	*Nearshore shelf, hyposaline and fine substrate*	*0-50m*	*Bruguiere (1792); Murray and Wright (1974)*
Nummulites planalatus	*Foraminifera*	*Marine estuary with low to moderate salinity*	*0-10m*	*Lanarck (1894); Murray and Wright (1974); Wrigley and Davis (1937)*
Nummulites prestwichianus	*Foraminifera*	*Shelf to mid-shelf, hyposaline and fine mud substrate*	*0-100m*	*Fisher (1862); Gardner et al (1888); Murray and Wright (1974)*

Nummulites rectus	*Foraminifera*	*Mid-shelf, hyposaline and fine mud substrate*	*0-50m*	*Curry (1937); Murray and Wright (1974); Wrigley and Davis (1937)*
Nummulites Variolarius	*Foraminifera*	*Nearshore shelf, hyposaline and fine substrate*	*0-50m*	*Curry (1966); Murray and Wright (1974W*
Protelphidium roemeri	*Foraminifera*	*Hyposaline Lagoon*	*0-20m*	*Bhatia (1957); Murray and Wright (1974)*
Pullenia quinqueloba	*Foraminifera*	*Shelf, hyposaline and fine substrate*	*20-100m*	*Reuss (1851); Murray and Wright (1974)*
Quinqueloculina seminulum	*Foraminifera*	*Nearshore, Hyposaline lagoon*	*0-20m*	*Linne (1758); Strahan; (1889); Murray and Wright (1974)*
Subbotina	*Foraminifera*			*King (1991b)*
Turrilina acicula	*Foraminifera*	*Lagoonal and subtidal*	*0-20m*	*Andreae (1884); Bhatia (1957); Murray and Wright (1974)*

Table 5: Details of foraminifera used for determining palaeo-water depths.

Other fauna and Ichnofacies	Type	Description	Depth Range	Reference
Pholadomya cuneata	*Mollusc*	*Shallow marine inner neritic*	*0-50m*	*Sowerby (1821-1834); Waterhouse (1969)*
Corbula regulbiensis	*Mollusc*	*Intertidal to brackish waters*	*0-10m*	*Olivi (1792); Holmes and Miller (2006)*
Ostrea vectensis	*Mollusc*	*Intertidal to brackish waters*	*0-10m*	*Curry (1958); Daley (1999d)*
Vetustocytheridea lignitarium	*Ostracod*	*Shallow inner shelf marine*	*0-30m*	*King (2016)*
Cytheretta nurva	*Ostracod*	*Mid to outer shelf*	*50-100m*	*Jolley and Spinner (1989); King (2016)*
Crassostrea longirostris: Oyster Bed (Headon Hill Formation)	*Mollusc*	*Freshwater with marine influence*	*0-10m*	*Reid and Strahan (1889); Brown (1988); Gale et al (2006); King (2016)*
Leaf Bed in Poole	*Flora correlated in NW Europe*	*Fluvial flood plain, sub aerial exposure*	*0m (in terms of backstripping)*	*Gardner and Ettinghausen (1879); King (2016)*
Intense bioturbation cohesive sediment	*Ichnofacies*	*Inner to mid neritic. Genetically related to mudline interpretations (see table 4)*	*20-70m*	*Allen (1967)*
Abundant bioturbation granular and cohesive sediment	*Ichnofacies*	*Inner to mid neritic. Genetically related to mudline interpretations (see table 4)*	*5-60m*	*Allen (1967)*
Ophiomorpha	*Ichnofacies*	*Marine, sublittoral or upper neritic, abundant refers to shoreface; brackish in sandy subtrates*	*0-30m*	*Lundgren 1891; Vaziri and Fursich 2007*
Chondrites	*Ichnofacies*	*Fully marine, possible low oxygenation*	*40-100m*	*Strenberg (1833); Fursich (1974a); Ekdale (1988)*

Table 6: Details of ichnofacies and organism-influenced evidence used for determining palaeo-water depths.

A limiting factor on the use of fossils is whether they are in situ. It is common for sediments to be reworked with larger clasts such as fossils surviving this process. In chronostratigraphic correlation, this limitation may be assessed to a degree by noting the abundance and distribution of fossils across different basins. If a biostratigraphic marker suggesting a particular temporal range is found within a stratigraphic level but it does not match other evidence, then this suggests possible reworking. More often than not such erroneous biostratigraphic indicators are abundant in the underlying unit, suggesting preservation and reworking.

4.3 Outcomes and limitations in developing palaeo-water depths into palaeobathymetric surfaces

The limitations of the palaeo-water depth determination method has been discussed in the previous sections, noting the error margins in the evidence used and the amalgamation of this data in each borehole to provide values that could be developed into palaeobathymetric surfaces. Here the outcomes and inherent errors are described as to whether the palaeobathymetric surface method is appropriate for this study.

The interpreted depositional environments are largely based on published observations, including British Geological Survey memoirs. Interpretations of palaeobathymetry are influenced by the literature and inherit errors reflecting author interpretation and observation. Discussions of sedimentology, stratigraphy and facies variations are described in detail in the BGS memoirs, and compiled in King (2016), while biostratigraphic assessments are reliant on the judgement of the author. To limit this factor in the data, discrepancies in the literature were assessed and cross-compared, and multiple sources were used where possible. The age of borehole/section description was also taken into consideration. Generally more recent IGS/BGS or industry-sourced borehole reports provided apt and concise lithological descriptions that could be correlated with the stratigraphy and with samples taken from field localities. Care has to be taken with all published borehole data based on the purpose of the investigation. Logging may inherit bias relating to the contractor and to the needs of the client and the project. Engineering geology standard BS:5930 allows variations in observational logging depending on the needs of the project, in most cases structures associated with and including fossils are of little importance unless specified. Such descriptions are less useful as fossils are critical to constraining possible palaeo-water depth values. For this reason academic or BGS boreholes from sites without an external client were preferred, to minimise the potential for industrial/client influence/bias or data exemption. The detail and range of data used for this chapter was acceptable for constructing detailed palaeobathymetric maps, though some sections were not appropriate for backstripping, as explained in chapter 5.

The amount of data required to produce a series of high-density palaeobathymetric surfaces for each geological unit is beyond the scope of this study given the regional aim. The palaeo-bathymetry needs to be relatable to the regional variations, either eustatically or tectonically. Localised structural variations 100 km away are irrelevant and therefore this level of data resolution is not required. However, where resolution can be increased this will reduce the error margins on data points.

Palaeobathymetric surfaces are developed from palaeo-water depth values determined from stratigraphic, sedimentological and palaeontological observations and therefore gridding is independent of any topographic or structural feature, unless a water depth is specifically provided from them. The development of palaeobathymetric surfaces can be used to assess the relationships, if any, of the evolution of palaeobathymetry and of the tectonic basement through the Cenozoic. This may provide clues to the degree of eustatic influence and tectonic influence on basin evolution in the south-east England.

Considering all the limitations and possible errors described, an error margin maximum of ±50m has been proposed based on the classification used. This is because each facies is first constrained to a zone of deposition using the water depth framework. Each palaeo-water depth can be constrained further by the amalgamation of all the evidence available as described above.

4.3.1 Water depth ranges

Tables 7 and 8 below are the adapted summary tables 2 and 3 from chapter 3, with maximum and minimum water depths for each lithostratigraphy and their error margins added to it. The raw data displaying each section or borehole and their interpreted water depth value is in appendix 1.

London Basin/ Hampshire and East Anglia stratigraphy and water depth values			
Geological Formation	**Age Range (Ma)**	**Dominant lithology, common features and depositional facies**	**Water Depth (max/min and max error)**
Selsey Formation	*44.8-42*	The lithostratigraphy displays dominant lithology of fine grained silt with **SAND** constituents. Glauconite is sparsely or moderately dispersed. Sub-horizontal laminations and cross-bedding. Commonly Bioturbated. The foraminifera *N.variolarius* and *N.lentipecten* present, provide water depth constraints.	20 – 40m ± 20m
Bagshot Formation	*53.2-51.6*	Medium to fine grained **SAND.** Some silty parts. Sections typically have laminations, cross-bedding or ripples. Glauconite common. *Lingula sp* and bimodal cross-bedding suggests shallow marine, inner neritic, shoreface depositional environment.	30 – 60m ± 30m
London Clay Formation	*54.7-51.8*	Dominantly **CLAY.** Some sand content. Laminations and cross-bedding present. Bioturbation and shelly remains common. *Terabratulina* and *Echinocythereis* present. Glauconite present with siderite concretions. Divisions A and B represent a shallow marine shelf, middle to inner neritic. Younger divisions such as C, D and E show a higher sand content and indicate shallower depositional conditions. *Portsmouth Sand Member* represents inner neritic to coastal depositional environments. *Nursling Sand Member* indicates inner neritic and wave base environments. *Christchurch Member* indicates the shallowest environments with rootlets and some palaeosol indicators. *Claygate Member* is synonymous with Division E.	5 – 80m ± 40m
Harwich Formation	*55-54.1*	Very fine grained **SAND** to **CLAY.** Basal beds commonly marked by pebbles. Laminations fairly abundant with bioturbation and glauconite. Commonly contains layers of tuff. Dominantly middle to inner neritic conditions of deposition with some distal coastal facies. *Hales Clay member* represents the finer grain sizes of deeper marine conditions.	10 - 120m ± 50m
Reading/ Woolwich Formation	*56-58*	**CLAY.** Fine grained to very fine grained sand constituents. Red, grey, brown mottling common. Laminations and cross-bedding present with abundant rootlets and carbonate nodules of pedogenic origin. Lignitic, palaeosols and molluscs common. *Reading Formation* represents deltaic and coastal plains with a low marine influence. *Woolwich Formation* is typically sandier with glauconite, bioturbation and a greater marine influence. Coastal shoreface depositional environment.	0 – 30m ± 20m
Thanet Formation/ Ormesby Member	*59.5-57.8*	Very fine grained **SAND** and **CLAY.** Glauconite abundant, bioturbation and burrowing present. Red mottled horizon laterally traceable. Shallow marine, inner neritic. Limited to the London Basin. The *Ormesby Member* is dominated by **CLAY** with sporadic tephra layers. Represents a shallow marine shelf, deeper than the Thanet Formation. Limited to East Anglia.	20 – 80m ± 40

Table 7 (above): Compiled summary of London Basin and East Anglian Cenozoic Stratigraphy

Table 8 (next page): Summarised stratigraphy of formations only found in the Hampshire Basin.

Summary of stratigraphy limited to the Hampshire Basin			
Geological Formation	**Age Range (Ma)**	**Dominant lithology, common features and depositional facies**	**Water Depth (max/min and max error)**
Bouldnor Formation	*34.8-33*	**CLAY** and **SILT.** Organic-rich clays with thin shell beds. Becomes mottled in colour up through the unit. Illite-rich clays. Interpreted as a restricted small sea or large lake with facies representing dominantly brackish or lagoonal conditions. Includes the *Hampstead* and *Cranmore members*. Both suggest a restricted depositional environment for the formation.	5– 10m ± 5m
Headon Hill Formation	*36.4-35.2*	**Groups stratigraphically thin formations and members together.** Dominantly **CLAY** with **SAND.** Some sandier sections and interbeds. Greenish grey. Shelly debris with gastropods and bivalves. Thick-shelled bivalves in some localised areas and rootlet beds. *Sinodia suborbicularis* is the bivalve used in dating the Formation. Some lignite. Heavy minerals in the sand have Cornubian, Scottish and American origin. Overall the formation is likely reflect a very shallow restricted sea. Some localities represent lagoonal/coastal facies and a transition through to fully marine conditions.	5 – 20m ± 10m
Becton Formation	*38.6-37.4*	Fine to medium grained **SAND** with **CLAY.** Overall well sorted and shelly where unweathered. Localised glauconite and bioturbation. *Ophiomoprha* burrows are present. Localised sedimentary structures such as bidirectional cross-bedding. Interpreted as proximal marine facies. Inner neritic to upper shoreface. *Becton Bunny Member* laterally continuous thin clay layer helps stratigraphic correlation between sections and boreholes.	10 – 40m ± 20m
Barton Clay Formation	*41.8-38.6*	**CLAY and SILT.** Some sparse sand sections. Becomes finer and siltier upwards. Greenish grey to blue with glauconite present. Bioturbated. Shell fragments fairly common, of bivalves and gastropods. Presence of *Nummulites* foraminifera, *prestwichianus* and *variolarius*. Also present *Elphidium minitum.* Constrains the depositional environment to mid to inner neritic. Some marginal wave base facies. Devoid of any sedimentary structures.	30 – 70m ± 30m
Branksome Formation	*44.8-43.4*	Fine to medium grained **SAND.** Some clay and silt parts. Commonly cross-bedded with dip towards the SE. Passes up into finer grain sizes, laminated silty clays with lignite and rootlet beds fairly common. General shallowing up sequence with cyclicity. Shallower cycles represent palaeosol horizons. Fluvial channels cut into older cycles. Interpreted as fluvial, coastal channels and coastal plain. Very shallow.	0 – 5m ± 5m
Wittering Formation	*51.2-48*	Dominantly fine grained to medium grained **SAND** with **CLAY.** Glauconite present in some beds, sparsely distributed. Laminations and cross-beds fairly abundant with sparse lignitic material in basal sections of the formation. Cross-beds have a low angle, 10-17°. Laminations of clay and sand have regular spacings suggesting rhythmicity. Interpreted as coastal/marginal facies to shoreface. Intermediate water depth facies of the Lower Bracklesham Group.	10 – 20m ± 20m
Poole Formation	*51.2-44.7*	**CLAY** and **SAND.** Coarsening up sequences of fine to coarse sand. Clays are laminated. Each member consists of sand and clay packages representing cyclicity. Interpreted as proximal/continental and tidally influenced, open to marine influence. Sedimentary structures suggest sediment transport eastwards. *Coleothrypta* dinoflagellate indicates tidal/salt marsh deposition. 4 Cyclic members through the formation. From oldest to youngest: *Creekmoor Clay, Oakdale Clay*, *Broadstone Clay* and *Parkstone Clay.* The Poole Formation is the lagoonal, brackish and shallowest unit of the lower Bracklesham Group.	0 – 5m ± 5m

4.4 Surface method using GIS

The purpose of the palaeobathymetric surfaces is to illustrate the orientations of basin deepening interpreted from the water depth data. The distribution of data points is too sparse to provide any further interpretations other than possible correlations with tectonic motions which is the main focus of this study.

Gridding of the palaeobathymetric surfaces was digitally rendered using the nearest/neighbour interpolation method and was achieved using the Surfer 10 software, which was preferred as it griddeds with less bias than kriging or hand gridding. Extrapolation of water depth reduces exponentially as distance from the data point increases in order to reduce the occurrence of artificial architecture in areas with fewer data points. The spatial distribution of the Cenozoic succession is in two dominant regions, the East Anglia and London Basin area and the Hampshire Basin area. The Weald region between the two study areas preserves no Cenozoic stratigraphy. Limited inferences on the possible palaeobathymetry in these proximal regions have been made based on the patterns observed.

Water depth values were attributed to the z-axis of the data in preparation for developments of palaeobathymetry profiles and later 3D rendering in ArcScene. The .grd data was inserted into ArcGIS 10.3 and was projected with British National Grid (NGR) referencing, geographically projected in Ordnance Survey Great Britain 1936 co-ordinates. ArcGIS was preferred for interface and data manipulation; however, a range of freeware such as QGIS would also be reliable and acceptable for modelling. Data sets contain UTM latitude and longitude information allowing a change in projection to world Mercator if a scale outside the UK is required. Accordingly the BGS coordinate converter was used to produce the NGR from lat/long and vice versa. This was necessary for offshore sections. Point data was created from borehole and cliff sections and determined as such, and polygons of formation outcrop were obtained and isolated from *Edina*'s 1:50,000 and 1:625,000 British Geological Survey data sets.

Palaeobathymetry profiles were selected to represent a cross-section of the maximum variation of water depths across the surface displaying significant areas of accommodation space for each lithostratigraphic unit. As profiles were selected based on these criteria and surface extents vary based on the outcrop extent, the orientation of profiles vary. Each profile was generated in ArcGIS using the 3D analyst extension and the interpolate line tool.

4.5 Results: Palaeo-water depths and palaeobathymetric surfaces

The aim of palaeo-water depth data is a precursor to the backstripping method. The point data alone in a table format provides data for the water loading component of the tectonic subsidence in chapter 5. As point data this provides little context for a study that is analysing eustatic and tectonic controls on a regional scale. As such, it is advantageous for a robust analysis that will complement the tectonic subsidence data in chapter 5; the results are presented as rastered palaeobathymetric surfaces. This provides a regional context of the evolving palaeobathymetry that can be compared with the supplementary tectonic subsidence data whilst also presenting the data in a graphical format.

The generalised lithologies of the lithostratigraphic units and stratigraphic correlations between members/divisions are displayed in Chapter 3, summarised by Tables 2 and 3, the boreholes and sections used for backstripping (figures 3.2 to 3.5) and the chronostratigraphic correlation chart, figure 3.6. Raw data of boreholes and sections, their descriptions and the subsequent palaeo-water depth determinations are included in Appendix 1. Figures 4.3 and 4.4 show all boreholes and sections used to develop all 10 palaeobathymetry maps. The ages of the lithostratigraphic units have been amended from the correlations proposed by Curry et al. (1978) using King (2016), cross-referenced with Gradstein et al. (2012). The list of memoirs and special sheets used for depositional environment interpretation and water depth determination comprises: (Aldiss, 2002; Aldiss et al., 2006; Aldiss, 2012; Arthurton et al., 1994; Barton et al., 2003; Bristow, 1985; Bristow et al., 1991; Edwards and Freshney, 1987a; Ellison, 2004; Ellison and Wiliamson, 1999; Ellison et al., 2002; Mathers, 1993; Mathers and Smith, 2000, 2002; Millward et al., 1987; Moorlock et al., 2000; Pattison et al., 1993).

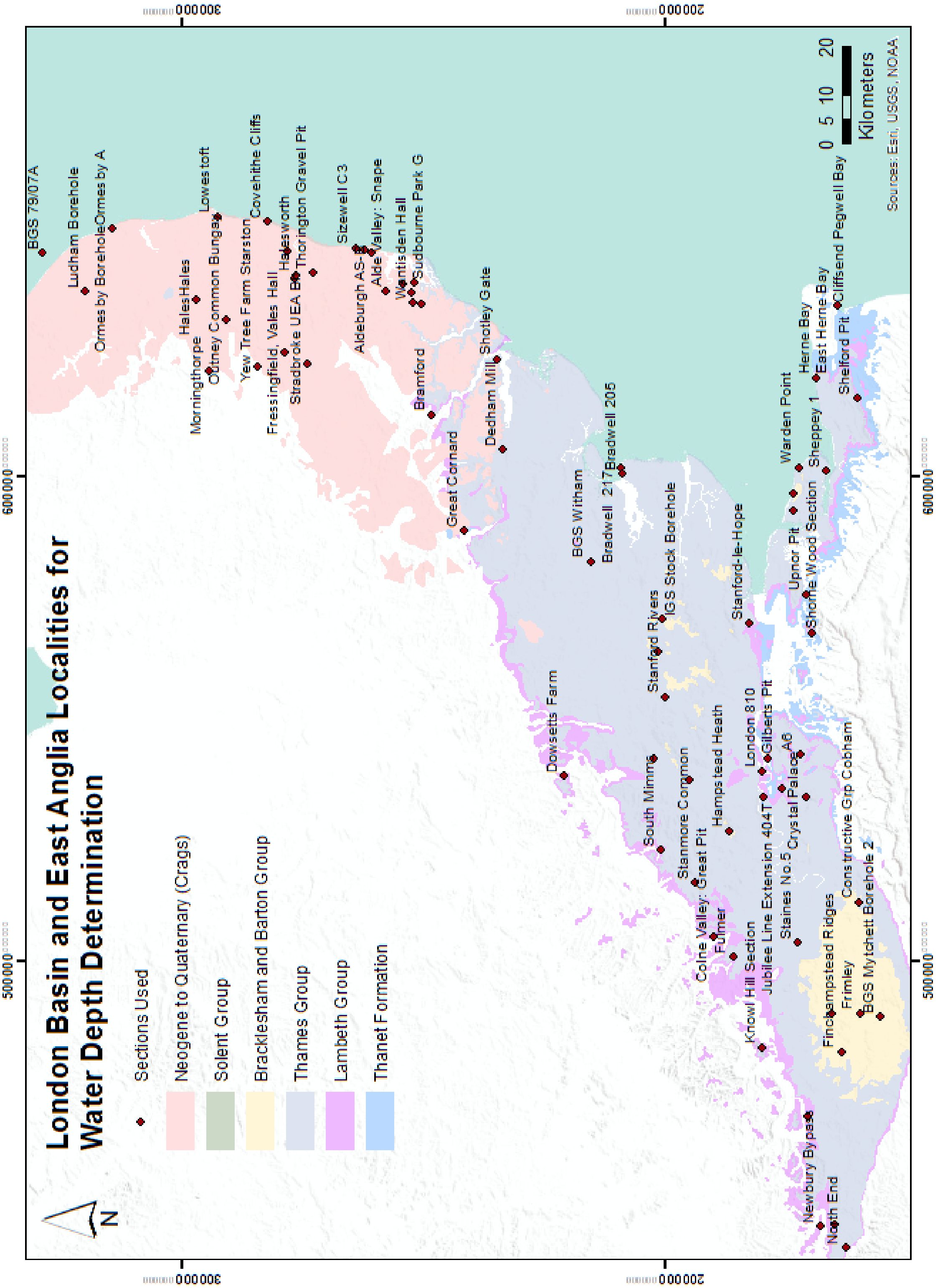


Figure 4.3: *Map of the London area and East Anglia displaying all the boreholes and cliff sections used in developing palaeobathymetric surfaces. Not all sections reach the underlying Chalk. Boreholes have been drilled for various purposes and may not penetrate the complete Cenozoic stratigraphic sequence.*

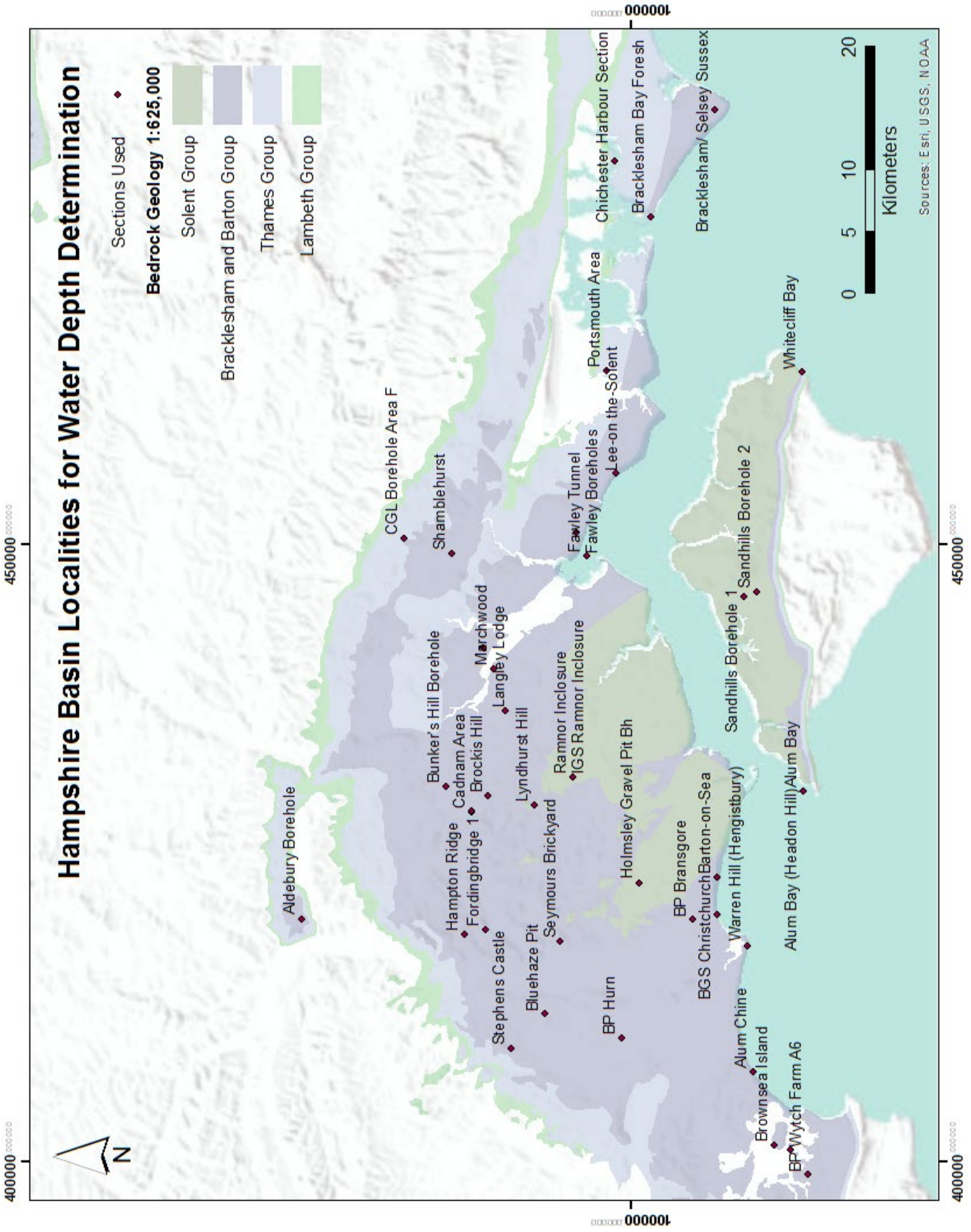
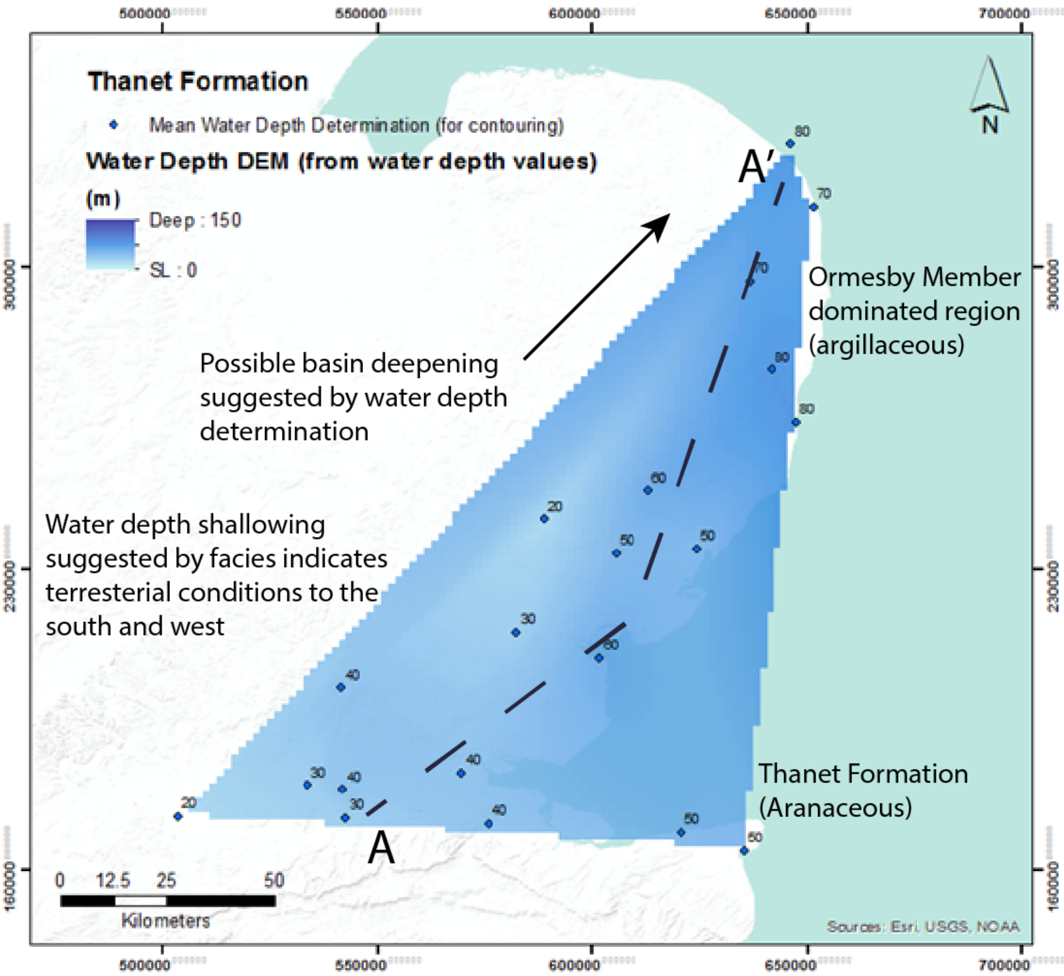


Figure 4.4: *Map of the Hampshire area displaying all the boreholes and cliff sections used in developing palaeobathymetric surfaces. As with the sections used in the London area and East Anglia, an even distribution of reliable boreholes and sections was attempted.*

4.5.1 Thanet Formation (Late Paleocene)

The gridded data suggest that the basin deepened towards the north-east and east, though the palaeobathymetric relief is a little more complex. The shallowing trend suggests a palaeo-coastline existed to the south and west. The transition from the Thanet Formation to the deeper Ormesby Member appears to show a marked influence of the proposed Ipswich-Felixstowe High at this time (Jolley, 1998; Knox, 1996). The succession is missing or highly reduced in thickness in this area and a progressive onlap relationship on either side of this structure is suggested by the stratigraphical evidence. However, the palaeo-water depth values are point data and determined independently of this stratigraphic relationship: the gridding of this region suggests a plateau existed in an orientation and geometry consistent with the Ipswich-Felixstowe High of Jolley, (1998) suggesting it is a syn-depositional feature. The profile shows the mid-basin high and the extent of shallowing across the area of the Ipswich-Felixstowe High. The transition to deeper marine conditions north-eastwards of the basin high is also clearly shown in the profile. *Figure 4.5* displays the palaeobathymetry map rastered and gridded from the Thanet Formation water depth point data.



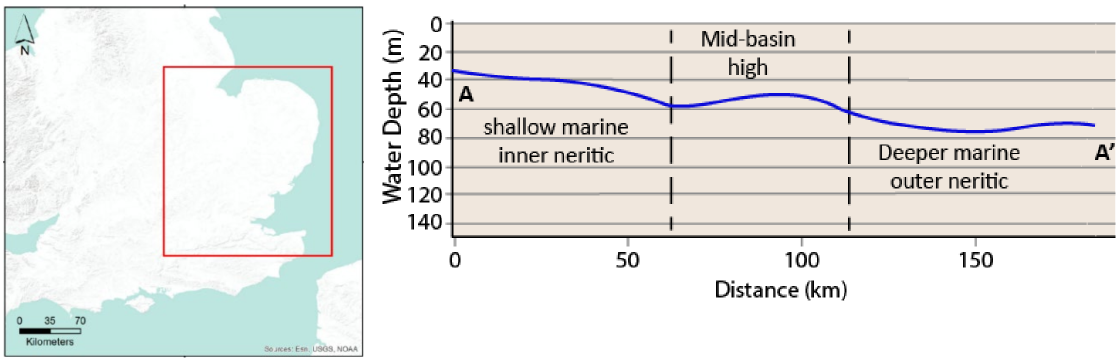


Figure 4.5: *The palaeobathymetry map for the Thanet Formation correlates with a shallow marine environment that prevailed across the London and East Anglia area following the end of the Mesozoic. Shallower facies are found in the London region where sand-dominated lithofacies are abundant. Farther north in East Anglia, a transition to deeper marine environments is indicated by the dominance of the Ormesby Member, consisting primarily of continental shelf clay strata. Gridding suggests a possible bathymetric high that trends generally east-west, located in a similar position to the earlier-proposed Ipswich-Felixstowe High. The profile across the basin clearly shows the extent of the mid-basin high while the general transition to deeper marine conditions is to the north-east.*

4.5.2 Reading and Woolwich formations (Early Eocene, Ypresian)

The boundary between the Reading and Woolwich formations suggests a transitional palaeo-coastline for the UK at this time, trending NE-SW across the London Basin, which appears to have deepened towards the south-east as suggested by the point data. A shallowing in the north-eastern areas of the surface in East Anglia suggests a deviation in form to the transitional palaeo-coastline. This feature is notably similar to that shown in the Reading/Woolwich map of Murray (1992) and lies in a similar location to the underlying Ipswich-Felixstowe High described from the Thanet Formation palaeobathymetry. Its precise geometry is uncertain given the lack of data points in this area. The E-W oriented profile shows the above sea-level facies of the Reading Formation, and the gradual transition to very shallow marine conditions represented by the Woolwich Formation.

The Hampshire Basin suggests a possible deepening to the south; however, this inference is based on point data only from the Reading Formation, where there is small variance within the water depth values. The Reading and Woolwich facies together display overall shallowing from the conditions of the Thanet Formation, though preserved marine-influenced sediments were deposited in the Hampshire Basin at this time. *Figure 4.6* shows the palaeobathymetry map rastered and gridded from the Reading Formation and Woolwich Formation water depth point data.

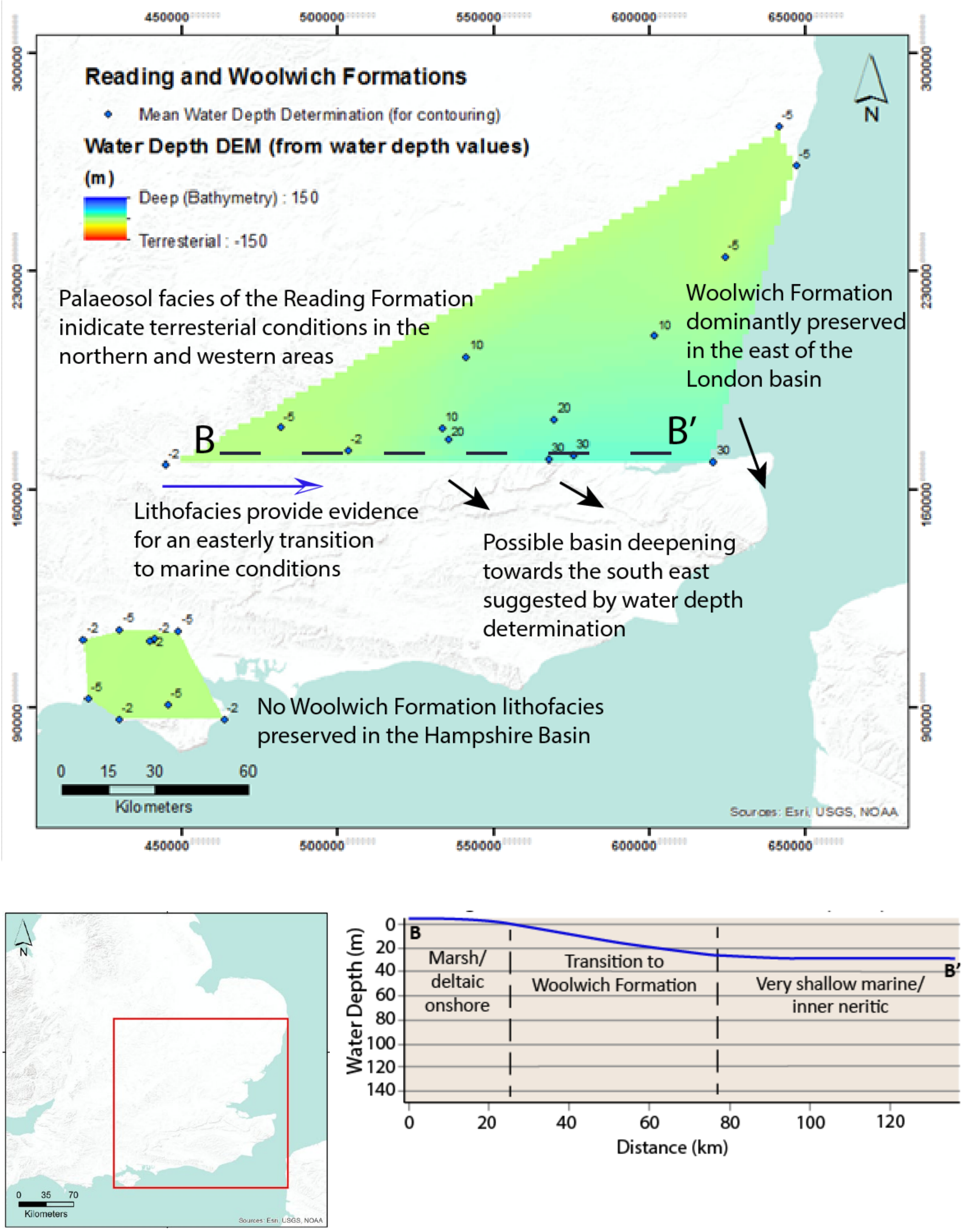


Figure 4.6: *The palaeobathymetry map for the Reading/Woolwich Formation indicates there was overall shallowing from the time of the Thanet Formation. The location of the Reading and Woolwich formations to each other and their stratigraphic relationship helped constrain a likely palaeo-coastline domain which can be seen as a colour change from blue to green. The location and shape of a palaeo-coastline cannot easily be constrained because of the transitional nature of the component lithofacies and because of the sparse distribution of the data. The profile is oriented E-W showing a cross-section of the basin's deepest regions at this time. The majority of the facies during deposition of the Reading Formation reflect a position above or close to sea-level.*

4.5.3 Harwich Formation (Early Eocene, Ypresian)

That pattern of basin deepening is similar to that suggested by the data produced for the Thanet Formation (4.5.1), trending distinctly to the north-east with a palaeocoastline present in the west and possibly in the south as indicated by the most proximal facies present in the southern data points. In the Hampshire Basin, the most distal facies are in the east, suggesting dominant basin deepening to the east and south. A palaeocoastline may be inferred to the west of the Hampshire Basin area, but its spatial position is speculative. The gridded palaeobathymetry suggests that a large-scale transgressive event occurred between the deposition of the Reading and Woolwich formations and that of the Harwich Formation. The sedimentology and biostratigraphy suggest a basinwards shift. The palaeobathymetric surface and profile suggest that there was a basin high in the central regions of the London Basin during the deposition of the Harwich Formation. The westernmost facies indicate a shift back to deeper facies. From the palaeobathymetry profile, a palaeo-sea may be inferred to have extended across southern England, and the basin high may not be in close proximity to a coastline as the data suggests deepening on both sides of the high. It possibly coincides with the inferred palaeo-coastline to the northwest. A north-easterly steep transition to deeper marine conditions is shown by the profile across the basin. *Figure 4.7* displays the palaeobathymetric surface developed from the Harwich Formation water depth point data.

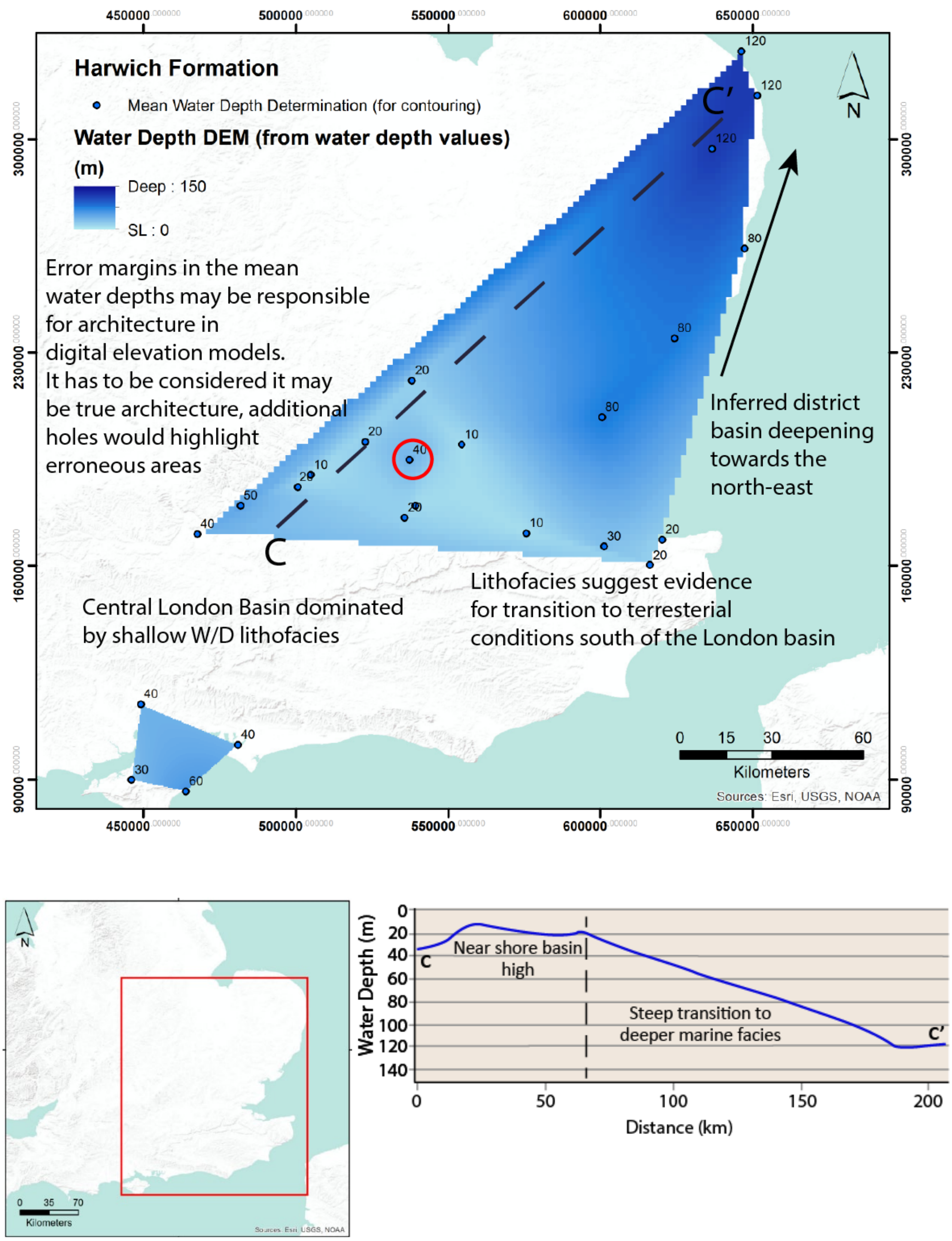


Figure 4.7: *The palaeobathymetry map for the Harwich Formation shows a flooding event relative to deposition during the Reading and Woolwich Formation deposition. The sea has been inferred to extend from East Anglia, through to the western reaches of the London Basin and on the east side of the Isle of Wight. It is likely that the palaeo-coastline was a little farther inland but deposition and removal of these coastal facies via erosion has removed any such strata. The profile shows an extensive basin high near to the inferred north-western palaeocoastline, with deepening in the far west.*

4.5.4 London Clay Formation (Division C) (Early Eocene, Ypresian)

The London Clay at the time of deposition of Division C has been gridded, showing a basin that deepens northwards and eastwards, in a similar trend to that of the underlying Harwich Formation. The basin overall shows a transition to deeper marine facies and the position of the palaeo-coastline has been inferred to be farther inland to the west in the London Basin, trending NE-SW. Some additional proximal facies are present in central London hinting at a possible shallowing to the south and south-west. The Hampshire Basin possesses an inferred coastline to the west and more distal basinward facies to the east. The palaeobathymetric surface and profile across the basin suggest that the water depths were fairly consistently middle to outer neritic. Although the profile across the basin does show a marine shallowing to the south-west, the degree of shallowing is not substantial enough to infer a palaeo-coastline between the Hampshire and London basins. It is fair to assume, from the data, that a palaeo-sea was continuous across south-east England during the deposition of Division C of the London Clay Formation. *Figure 4.8* shows the palaeobathymetry map developed from the Harwich Formation water depth point data.

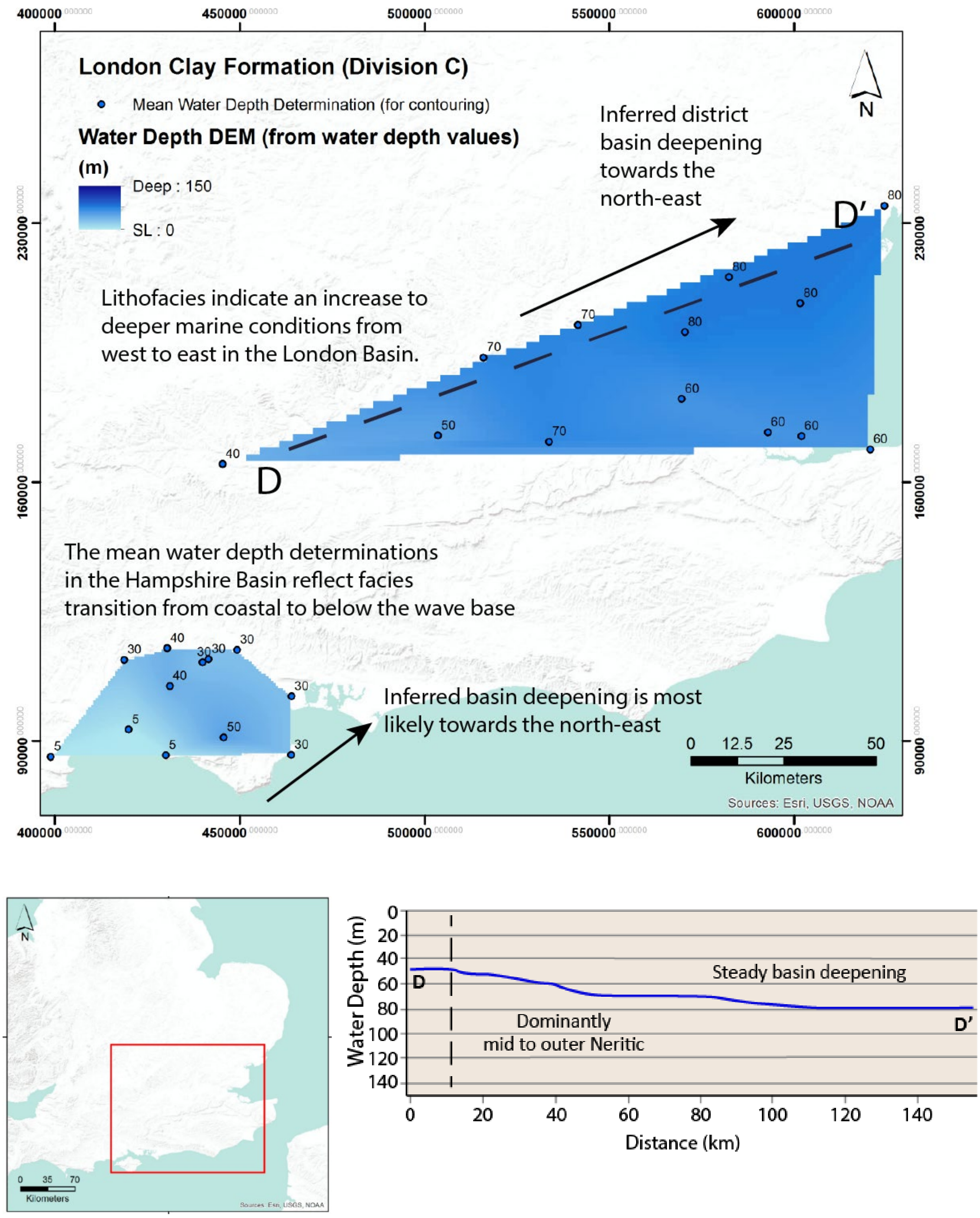


Figure 4.8: *The London Clay Formation (Division C) palaeobathymetry map suggests that a moderately extensive basin existed across most of south-east England when extrapolating the missing strata in the Wealden region. Basin deepening appears to occur NE-wards across the region with only the western reaches of the Hampshire Basin qualitatively constraining a reliable palaeo-coastline position and trend. It can be inferred from the data that there was marine connection both to the south and to the east. Whether it was an extensive palaeo-sea cannot be determined definitively due to missing strata.*

4.5.5 Lower Bracklesham Group (Early Eocene, Ypresian)

Lower Poole, Wittering and Bagshot formations

The overall palaeobathymetry may be interpreted as a marine regression from the previous London Clay palaeobathymetric surface. The London Basin is dominantly within mid-neritic shallow marine conditions but there is a sparse distribution of data points in the eastern areas. Basin deepening is suggested to deviate slightly from the older London Clay Formation from NE to ENE, and the data suggests a palaeo-coastline most likely existed to the west and north. The proximity of the palaeo-coastline in the London Basin is uncertain. All lithofacies suggest shallower zones of deposition, particularly in the Hampshire region in which a palaeo-coastline is well-constrained in the west. A marine influence is still pervasive in this region and it deepens to the east and northeast; the most distal lithofacies are restricted to the eastern Isle of Wight and Bracklesham Bay sections. The profile of the palaeobathymetry cuts across the plateau of shallow inner neritic facies before gradually transitioning to deeper marine conditions in the north-east. The relief of the palaeobathymetric surface is not hugely varied, as is apparent from the profile across the London basin. *Figure 4.9* displays the palaeobathymetry map developed from the water depth point data.

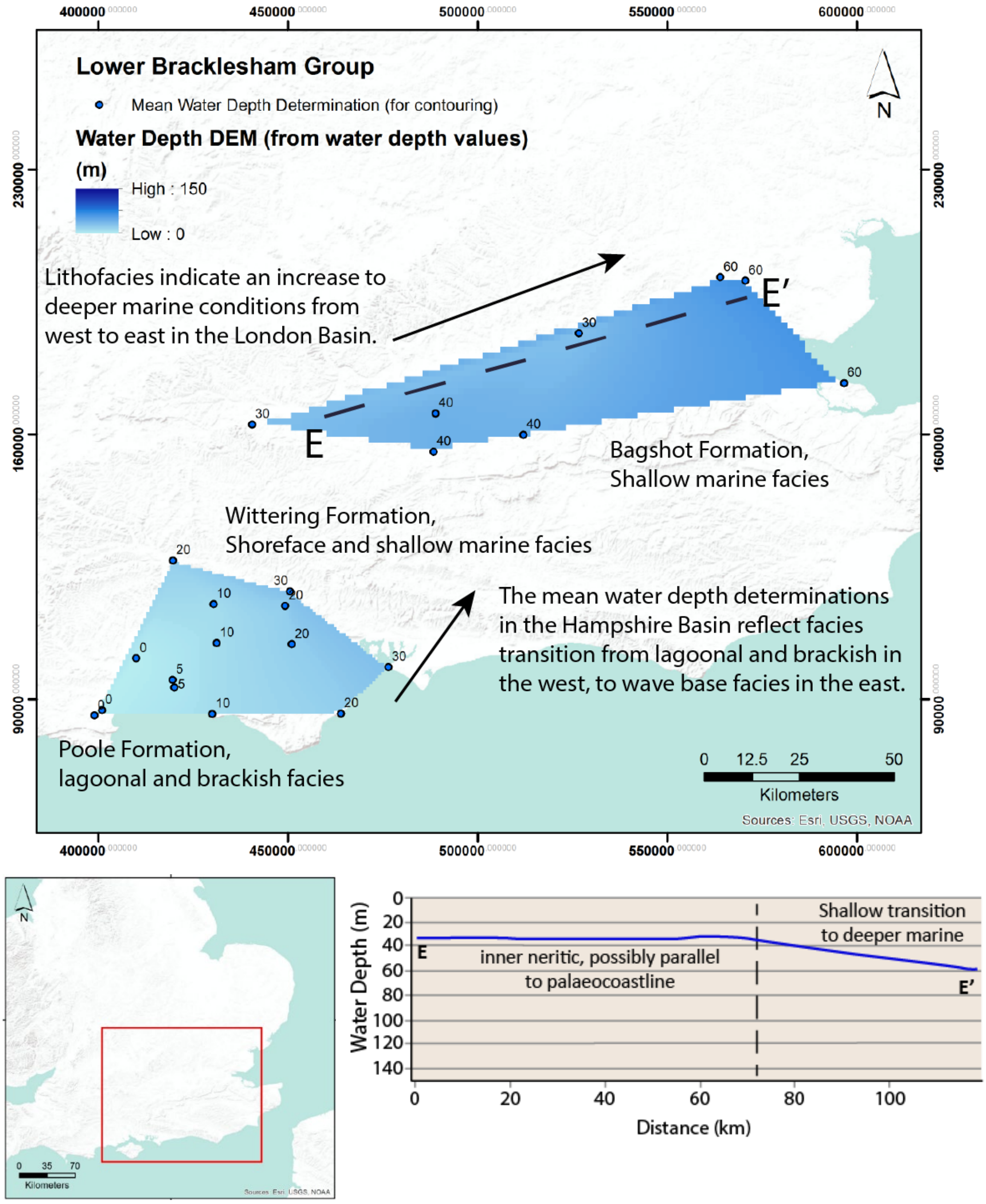


***Figure 4.9**: The Lower Bracklesham Group palaeobathymetry map suggests there is a strong presence of a shallow marine palaeo-sea in the London and Hampshire basins, however it has been inferred that an overall shallowing has occurred since the deposition of the Harwich Formation. Coastal facies have been preserved in the western reaches of the Hampshire Basin and suggest an overall shallowing water depth trend towards the SW. The profile reflects the overall inner neritic facies and its consistency in the central London Basin, before deepening towards the northeast.*

4.5.6 Upper Bracklesham Group (Mid Eocene, Lutetian)

Branksome and Selsey formations

The limited volume of deposits preserved in the London Basin allow minor interpretations of basin geometry and deepening to be made. The presence of data points in the London basin and their similarity to the older Lower Bracklesham Group palaeobathymetry suggest a possible basin deepening trend towards the north-east. This inference is speculative given the limited data available. The Hampshire Basin indicates reliable constraints on a palaeo-coastline existing in the western reaches of the district, trending NW-SE, similar to the previous Lower Bracklesham Group palaeobathymetric surface. All facies in the Hampshire Basin indicate deeper water depths than the previous surface with basin deepening trending north-eastwards. The most distal and deepest marine facies are preserved in the farthest northern and eastern boreholes and sections. The profile presents the distribution and continuity of coastal facies and likely position of the palaeo-coastline in the west. The shallow shape and gradual transition to deeper marine conditions eastwards is also apparent. An overall slight regression of the sea from the previous Lower Bracklesham surface could be interpreted. *Figure 10* displays the palaeobathymetry map rastered from the Upper Bracklesham Group water depth point data.

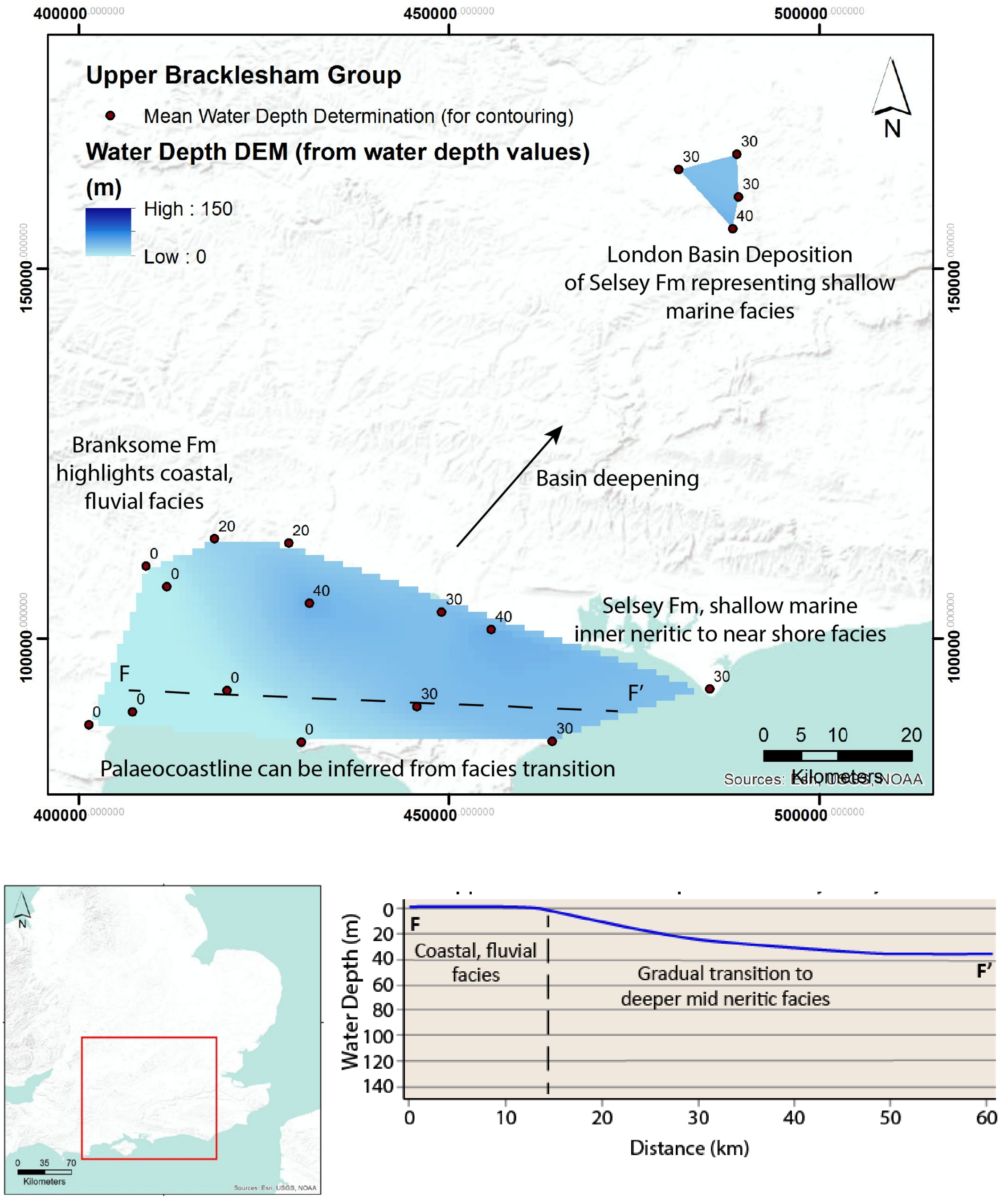
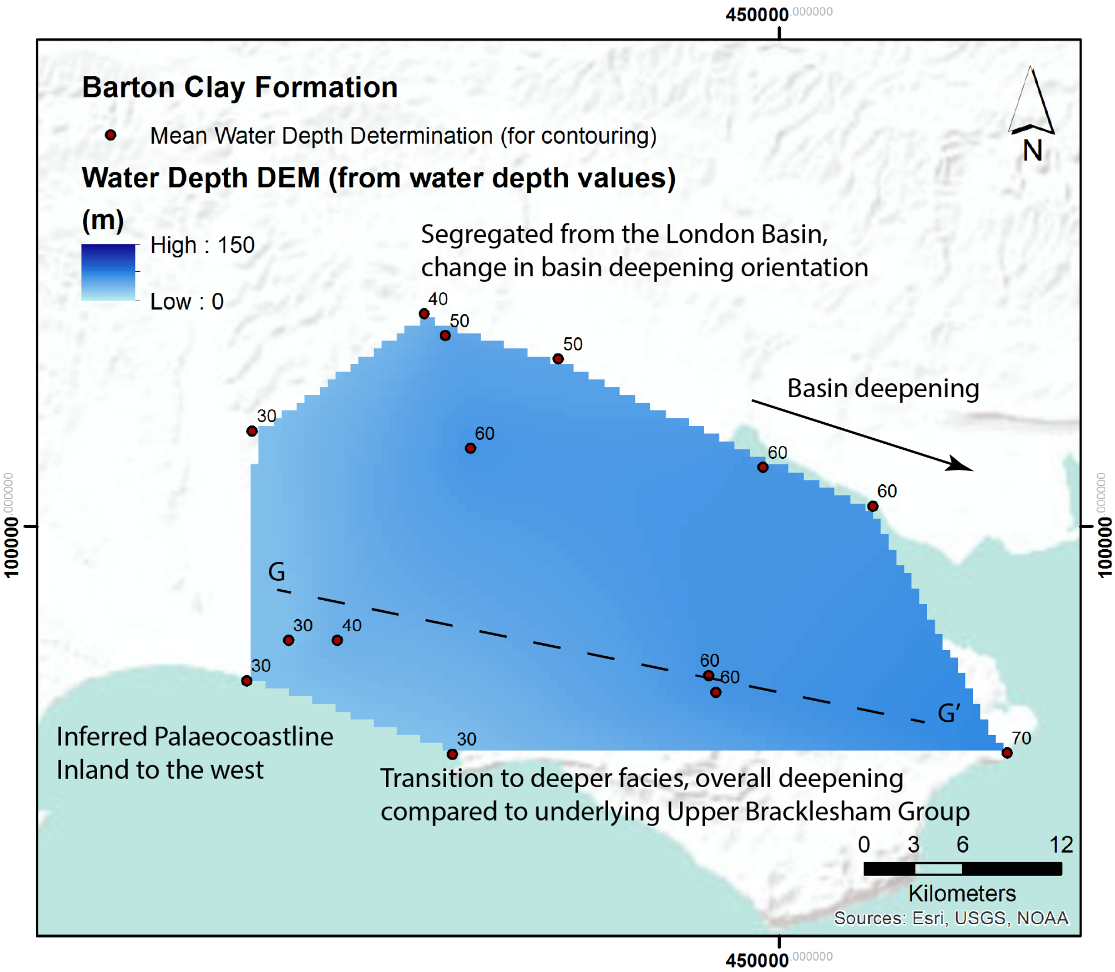


Figure 4.10: *The palaeobathymetry map for the Upper Bracklesham Group shows a similar trend to shallowing patterns seen in the Lower Bracklesham Group surface. However the distribution of near shore facies and deeper marine environments appears to have shifted slightly landward. The locations on the Isle of Wight are a point of reference for this slight variation and shift to shallower facies. There is an overall shallowing, but a more rapid eastward transition to deeper water environments than in the older Lower Bracklesham Group lithostratigraphic units. The profile is perpendicular to the palaeo-coastline suggested by onshore and coastal sedimentary facies. The western palaeo-coastline of the basin is clearly defined in the palaeobathymetry profile.*

4.5.7 Barton Clay Formation (Mid Eocene, Lutetian - Bartonian)

At this point, no deposits of Paleogene, mid-Eocene age or younger are preserved in the London Basin and so no data is available for rendering palaeobathymetry. In the Hampshire Basin consistent shallow marine depositional environments are interpreted from the sections. There is a progressive transition to deeper marine facies with no marginal/coastal deposits suggesting a large basin wide transgressive event in comparison to the deposits in the older Upper Bracklesham surface. The most distal facies are in the eastern areas, consistent with the easterly basin deepening trend. By extrapolating the shallowing trends of the griddeds a palaeo-coastline may have existed to the west and northwest and possibly to the south-west. The profile across the palaeobathymetric surface from west to east reflects a gradual transition from inner neritic to mid neritic marine conditions. The steeper gradient of shallowing in the western areas of the profile supports the existence of a possible coastline in close proximity. The consistent shallow marine water depths across the profile supports the idea that a transgressive event flooded inland from the previous, older Upper Bracklesham Group. *Figure 4.11* displays the palaeobathymetry map for the Barton Clay Formation rastered from the water depth point data.



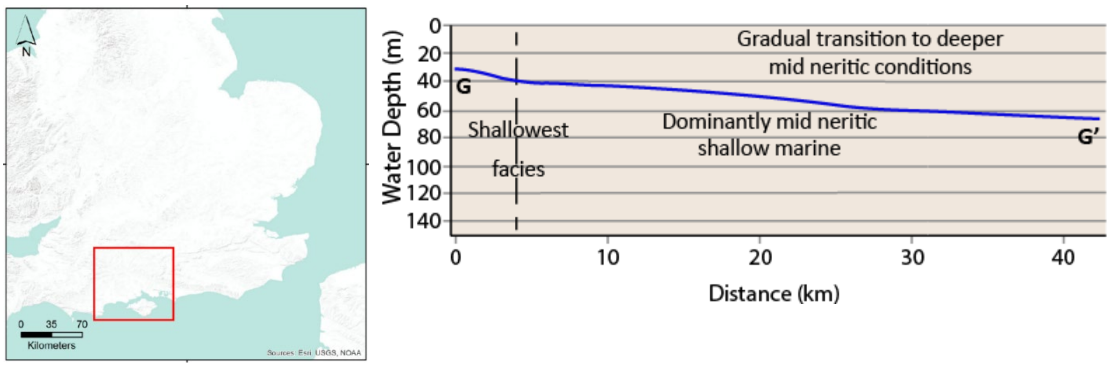


Figure 4.11: *The palaeobathymetry map for the Barton Clay Formation is completely restricted to the Hampshire Basin and the deposits lie in the axis of the large-scale syncline trending NW-SE (Chapter 2). Foraminifera present were used to quantitatively constrain a likely water depth range and easily correlate between boreholes and sections. The transition from the shallower older Upper Bracklesham Group lithostratigraphic units to deeper marine facies reflects a basin-wide deepening. The result was a migration of the palaeo-coastline farther inland, flooding coastal regions. The coastal facies are not preserved. The profile of the palaeobathymetry exhibits a shallow marine basin that is deepening to the east, with possible palaeo-coastlines in the west and north.*

4.5.8 Becton Formation (Mid Eocene, Bartonian – Late Eocene, Priabonian)

The deepest marine facies have been interpreted in the south and western areas of the Hampshire Basin. The pattern of griddeds suggest basin deepening is towards the south-west. This is a contrast to the previous palaeobathymetric surfaces which inferred basin deepening trends to the north-east and east. The pattern of shallowing suggests a likely palaeo-coastline existed to the NE and NW, but also in the south. However, with no distal and/or marginal facies preserved the position and trend of the palaeo-coastline can only be postulated.

An overall shallowing of the marine facies from the previous Barton Clay Formation suggests a regression of the sea led to this transition. The profile of the palaeobathymetry suggests the existence of a palaeocoastline can be inferred to the northwest, and that from the data the basin was dominantly deepening to the south-west. This contrast in basin deepening orientation from the older Barton Clay Formation suggests an alternative mechanism would be responsible rather than fluctuations in sea-level from eustatic variations. It is possible the sparse amount of data available and the error margin of water depth determinations could have produced an artificial orientation change. *Figure 4.12* displays the palaeobathymetry map for the Becton Formation rastered from the water depth point data.

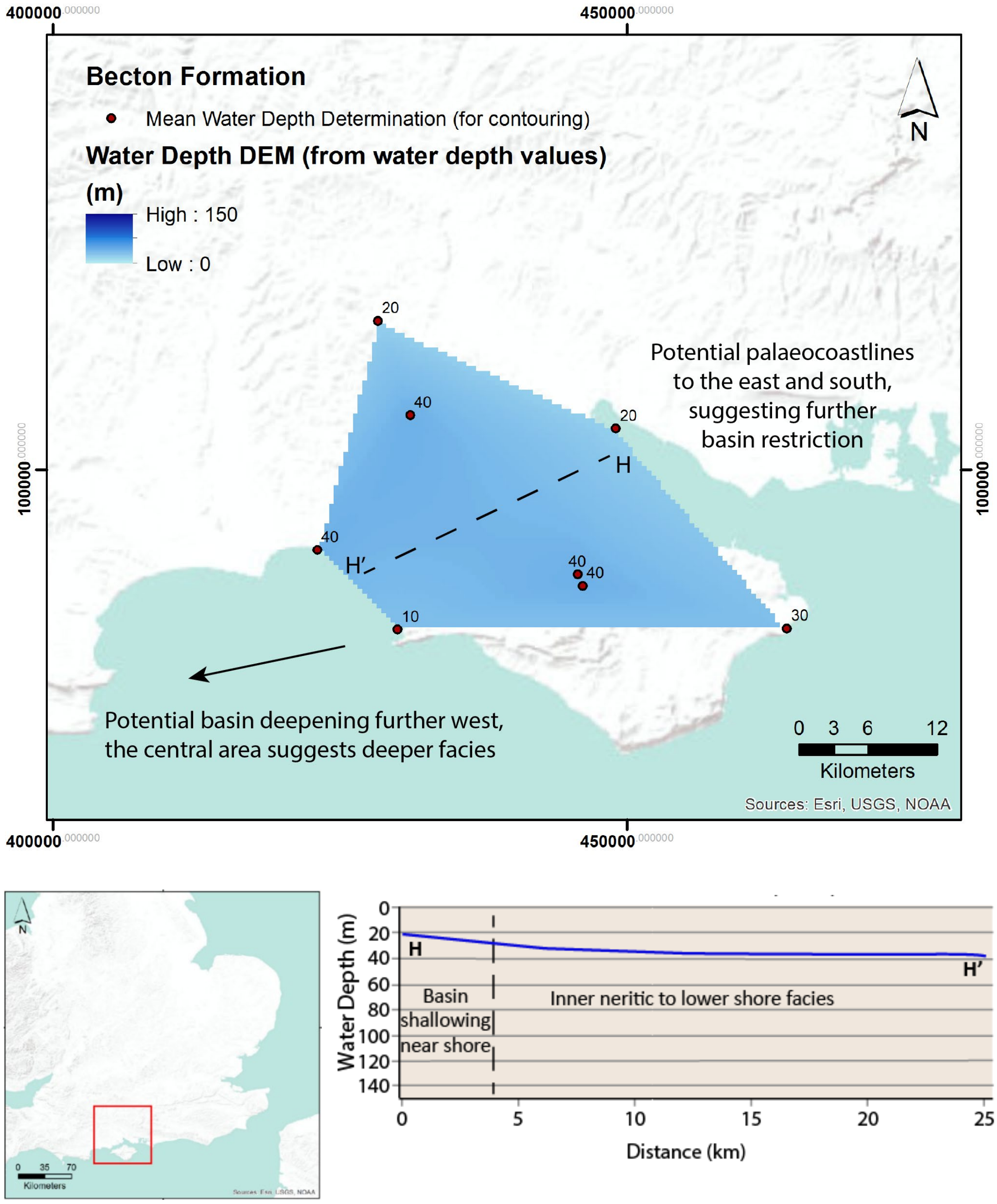
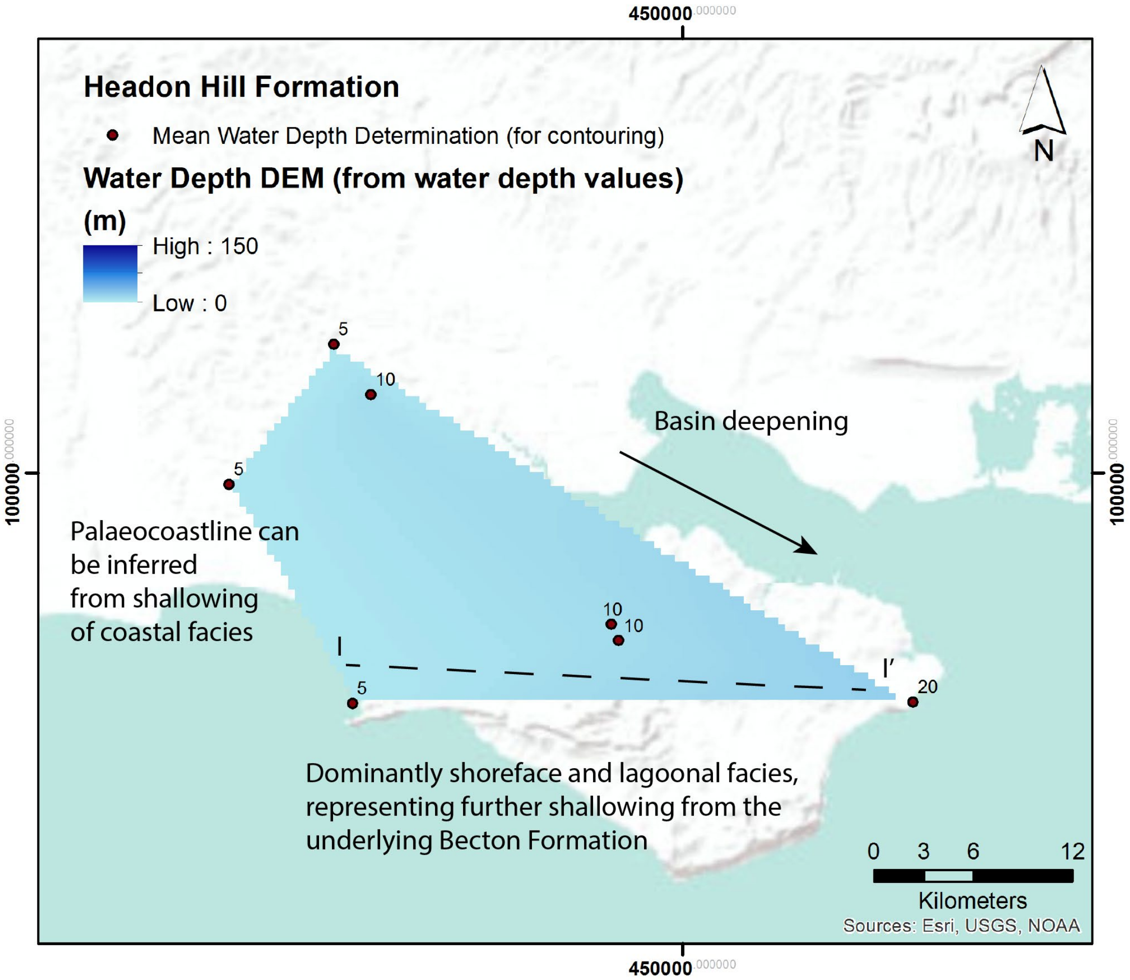


Figure 4.12: *The palaeobathymetry map for the Becton Formation shows an overall shallowing from the older Barton Clay Formation. The contrast is the possible basin deepening suggested to the SW. Still dominantly marine but the influence is reduced and a possible palaeocoastline could be inferred to be in the NE and NW which is still concordant with depositional environments of older geological formations analysed. The basin deepening profile is also similar, but has developed in a contrasting orientation. The basin is consistently shallower.*

4.5.9 Headon Hill Formation (Late Eocene, Priabonian)

The facies and assemblages preserved are all very shallow marginal deposits with the palaeobathymetry suggesting a basin deepening to the south-east. Despite the shallow nature of the facies preserved, the mineralogy is similar to that of the Paris Basin (Murray 1992) suggesting connection to a larger sea, possibly to the south-east suggested by the basin deepening trend. A palaeo-coastline may have existed in the very western fringes of the Headon Hill outcrop, extrapolated from shallowing griddeds. Extrapolation of the profile also suggest a possible palaeo-coastline in close proximity to the north-west of the surface. A very shallow basin deepening to the east and south-east is exemplified by the palaeobathymetry profile. Since the deposition of the Becton Formation, a further marine regression can be inferred during the deposition of the Headon Hill Formation. The basin deepening orientation to the south east, although shallow, is in contrast to the underlying Becton Formation basin deepening orientation. *Figure 4.13* displays the palaeobathymetry map for the Headon Hill Formation rastered from the water depth point data.



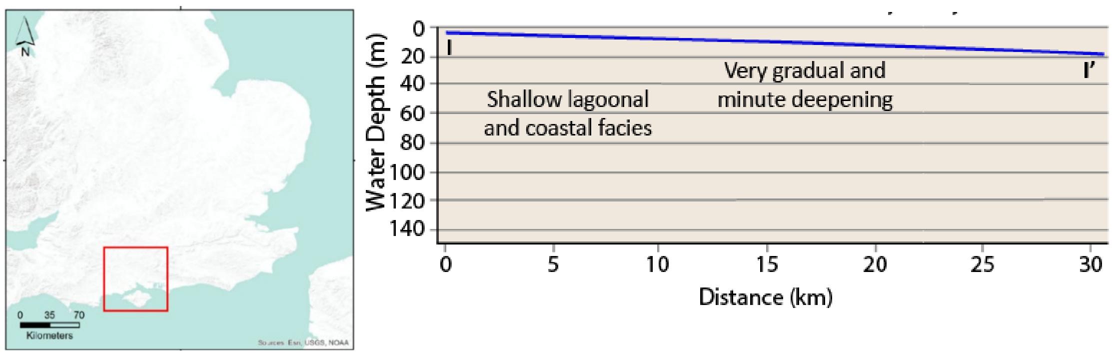


Figure 4.13: *The palaeobathymetry map for the Headon Hill Formation shows a basin deepening to the SE. All facies reflect a water depth shallowing with even less marine influence than the older Becton Formation. A definitive palaeo-coastline is difficult to constrain but the transition in lithofacies and extrapolation of the determined gridded s suggests it is farther to the west and north-west. Unfortunately these deposits have been eroded. Extrapolation of the palaeobathymetry profile supports the presence of a western palaeo-coastline in close proximity to the extent of the surface. This orientation and spatial distribution would be consistent with older formations in the Hampshire Basin.*

4.5.10 Bouldnor Formation (Late Eocene, Priabonian – Early Oligocene, Rupelian)

All lithofacies of the Bouldnor Formation reflect consistent shallow water depths with no or very minimal marine influence. Biostratigraphic evidence supports a shallow marine to freshwater environment. The error margins in water depth determination complicate the inference on definitive basin deepening trend or transitions to continental environments. From the raster data and transition of lithofacies, it can be suggested the margins of a restricted lake are in close proximity to the south, west and east. The lithofacies preserved suggest possible deepening continues northwards, similar to the south, west and east. The shallow water depths are consistent across the Hampshire Basin and preferential shallowing in the south east is apparent from palaeobathymetry profile. The full palaeobathymetric surface suggests a further regression of the palaeosea from the deposition of the older Headon Hill Formation. *Figure 4.14* displays the palaeobathymetry map for the Bouldnor Formation rastered from the water depth point data.

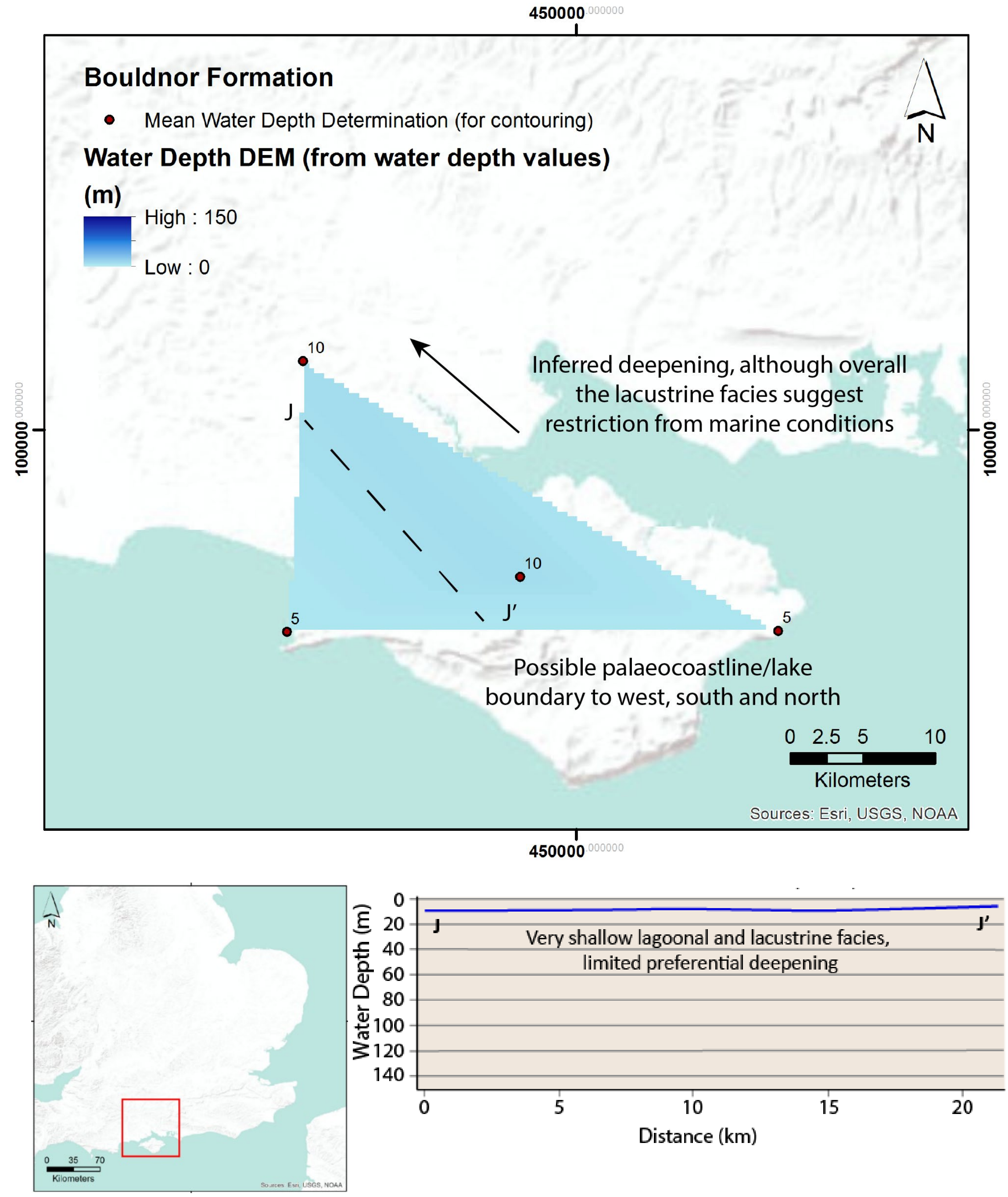


Figure 4.14: *The palaeobathymetry map for the Bouldnor Formation. Very limited and restricted zones of deposition and analysis of lithofacies suggests a further shallowing of the Hampshire Basin from the older Headon Hill Formation. Gridding and nature of depositional environments suggest a restricted lacustrine environment most likely bound on all sides. The exact position of the northern margin is more difficult to infer. Extrapolation of the griddeds suggest a deepening of the lacustrine environment towards the northern reaches of the Hampshire Basin.*

4.6 Discussion

Palaeo-water depths were interpreted from the sedimentary stratigraphy in south-east England for use in the subsidence analysis in chapter 5. The data was manipulated into palaeobathymetric surfaces for additional context. The purpose of developing palaeobathymetric surfaces is to understand and interpret the potential extent of marine conditions across the south-east of England during the Cenozoic and assess the evolution of the basins, basin margins and possible palaeo-coastlines. The range of palaeontological, sedimentological and stratigraphic evidence for the Cenozoic succession supports the interpretation of a shallow marine shelf depositional environment in south-east England. The range of environments displayed by the lithostratigraphic units within shallow marine conditions was advantageous for identifying palaeocoastlines and possible basin deepening. Analysis of the palaeobathymetric surfaces and the bathymetry deepening trends and geometry has proposed some interesting questions that may pertain to influences other than sea level variations. Short wavelength variations in basin margins can be a result of changing sea-level, the accumulation of sediments, or deformation of the basin itself.

4.6.1 Basin geometry and deepening trends

If accommodation space in south-east England basins during the Cenozoic was purely controlled by sea-level changes and assuming sediment loading was uniform, basin geometry should theoretically not vary on a short wavelength. However deepening trends may be affected by irregular sediment supply leading to a development of varying bathymetric relief. Analysis of the varying thickness of the sedimentary column may help constrain the possible influences on basin geometry from sediment supply and deposition. Analysing the dominant basin deepening trends from the palaeobathymetric surfaces can provide insight into possible mechanisms responsible for basin deepening changes other than eustatic sea-level variations. However, basin deepening trends are dependent on the spatial extent of the palaeobathymetric surface and a larger area covered will provide more information on a dominant basin deepening trend. Taking into consideration error margins, data density and gridding of the palaeobathymetric surfaces, a basin deepening orientation varying more than 90°

suggests a mechanical influence; any less than this value are most likely limitations in the palaeobathymetric data and surface extent. The evolution of basin deepening trends, position of proximal facies and drastic localised changes in basin bathymetry suggests a possible control other than eustasy. Whether these variations are short wavelength that can be attributed to crustal deformation and tectonic motions can then be explored in chapter 5 using the water depth information.

Figure 4.17 shows the change in dominant basin orientation trends during the Cenozoic interpreted from the development of the palaeobathymetric surfaces. The Early Paleogene palaeobathymetry suggests a predominant north-east deepening is consistent across the London and Hampshire basins from the base of the Thanet Formation through to the deposition of the Upper Bracklesham Group. After this time the sedimentary and stratigraphic evidence suggests the connection between the London and Hampshire Basins began to close (Murray 1992) with the exception during deposition of the Reading and Woolwich formations which trend more towards the east. The shift of the Reading and Woolwich Formation is particularly marked, displaying a drastic shallowing from the underlying deeper palaeo-water depths of the Thanet Formation and the subsequent Harwich Formation, also suggesting deeper palaeo-water depths. The rest of the data from the Cenozoic succession does not display shallowing of a similar magnitude, rather progressive cycles of transgression and regression culminating in the eventual regression to marine conditions during the deposition of the Bouldnor Formation.

The consistent north-east basin deepening orientation in the Hampshire and London basins suggests both were connected to each other and the Paleogene North Sea basin, and this is supported by the heavy mineral transport described by Morton (1982) and the similarities in taxa as described by Aldiss (2012), Edwards and Freshney (1987b) and Curry (1992). The very shallow restricted environments in the Hampshire Basin from the base of the Barton Clay Formation display drastic changes in the deepening orientation exceeding the variance in the data from the surface extent limitation. This can be paralleled with the increase in frequency of palaeo-water depth shallowing facies and taxa in the younger Paleogene lithostratigraphic units limited to the Hampshire Basin. This is also simultaneous with the regression and limited spatial distribution of marine facies in the London Basin, which may reflect their limited present-day outcrop. This suggests sea-level change had cyclic controls on the water depth variations; however, the regression almost entirely from the London Basin and not from the Hampshire Basin, particularly during relative palaeo-water depth deepening during the deposition of the Barton Clay Formation, points towards an alternative mechanism for segregation of the basins. From the Late Eocene to the Early Oligocene (between 38.5 Ma and 36.4 Ma) the orientation of basin deepening appears to change from south-west to south-east. Either this is an anomalous result, or this variation suggests a control other than eustatic variations. The palaeo-water depth data for south east England supports a semi-closed model for the Hampshire and London basins during the early Paleogene as suggested by Murray (1992). However, the palaeo-water depth data supports segregation of the basins and disruption of marine conditions by the Weald as a topographic barrier by the time the Barton Clay Formation was deposited. The timing of these variations in palaeo-water depth and basin deepening are comparable to that of the proposed development of the Weald and associated inversion structures and subsequent segregation of the proto-Solent (Hampshire) and proto-Thames (London) basins as suggested by Gibbard and Lewin (2003). Therefore palaeo-water depth data and the production of palaeobathymetric surfaces have provided potential evidence supporting the timing of basin segregation in south east England and indirectly suggests that although there is eustatic control on local basin bathymetric variations, basin geometry variations are most likely due to the development of inversion structures. These structures are on a shorter wavelength than the tectonic processes occurring during the Eocene in the North Atlantic region.

The basin deepening orientations of the Late Eocene to Early Oligocene lithostratigraphic units is of little value given the context of their progressively shallowing depositional conditions and their limited spatial extent as palaeobathymetric surfaces. Most importantly the data proposes conditions of the Becton Formation through to the younger Bouldnor Formation (Late Eocene to Early Oligocene) reflect no connectivity to the London Basin to the north-east and restricted connection to the south-east, if at all, as shown by the reduction of marine-influenced sedimentology and taxa. The reactivation of the Isle of Wight structures was suggested to commence during the Mid-Eocene and shown by the reworking of older sediments into the Barton Clay and younger lithostratigraphic units (Gale et al., 1999). The changes in basin geometry suggest a possible development of a barrier to the south of the Hampshire Basin depocentre. The progressive shallowing to a restricted sea/lake during the deposition of the Early Oligocene Bouldnor Formation is synchronous with the basin geometry changes. It could be postulated that while sea level progressively fell, the reactivation of the Sandown and Portland-Wight faults were producing a barrier that eventually further restricted the marine conditions of deposition. If this is not an artificial construct of the gridding of palaeo-water depths, then the tectonic subsidence curves should parallel and demonstrate similar structural influences in the following chapters.

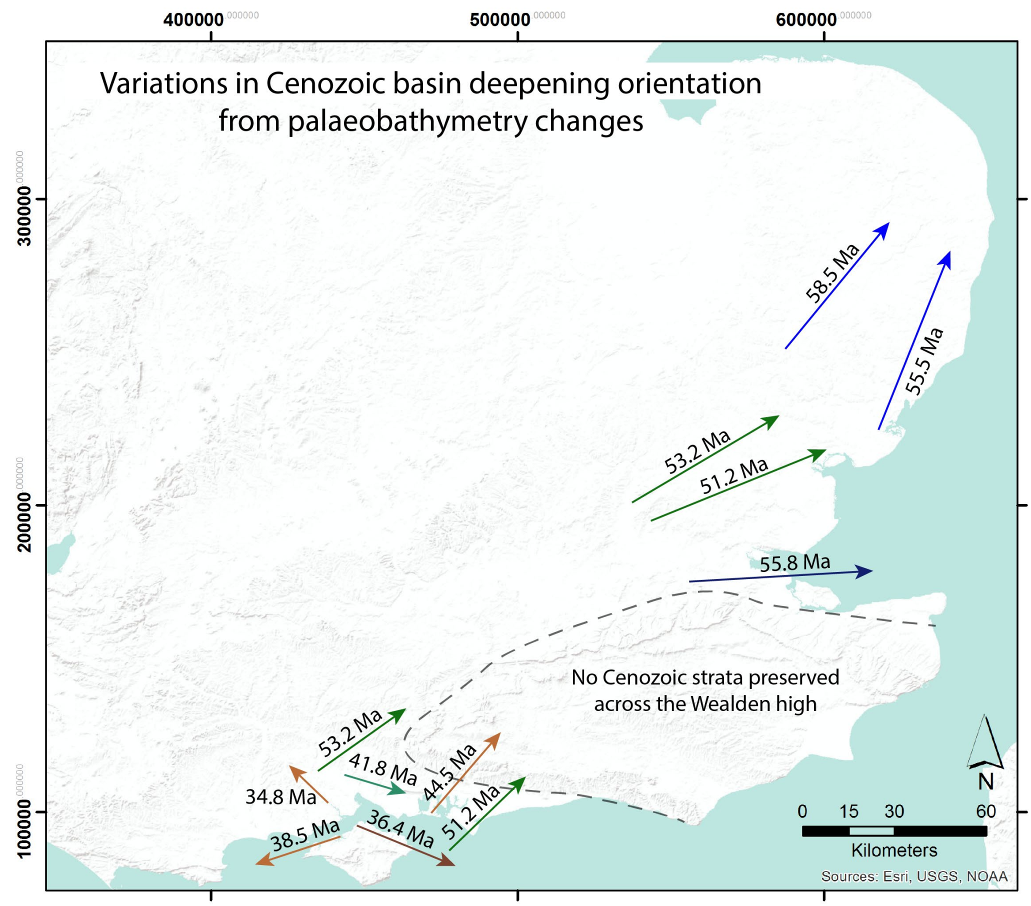


***Figure 4.17**: Interpreted dominant basin deepening trends extracted from each palaeobathymetric surface. The Paleogene is dominated by north-easterly azimuths across East Anglia, London and Hampshire basins. From the Mid to Late Eocene, the basin deepening trend begins to change, (41.8Ma onwards) which reflects the timing of inversion structures such as the reversal of the Isle of Wight faults.*

4.6.2 Implications for tectonic subsidence analysis

The palaeobathymetric surfaces developed suggest a drastic water deepening during the early Paleogene, and that the palaeo-water depths then, through cycles of regression and transgression, progressively shallowed until the marine conditions finally gave way to deposition of the lacustrine Bouldnor Formation. The timing of Wealden uplift is highly disputed but its existence as a bathymetric high or barrier can be postulated. The regular presence of a shallow marine environment of deposition in both the London and Hampshire basins which both show deepening trends consistently towards the north-east suggests connectivity and supports deeper water conditions. This is supported by the transport of heavy minerals from the north into both southern England basins (Morton, 1982). The Weald as a tectonic high and major barrier between both basins is not apparent from the deepening trends and basin geometry of the palaeobathymetric surfaces until after the onset of deposition of the Barton Clay Formation in the Mid-Eocene. This is supported by the correlation of biostratigraphic, sedimentary and stratigraphic histories. Though, because of the limitations of the data, it cannot be definitively stated when the Wealden high began uplifting and therefore it may still have existed as a barrier farther east towards the Paris Basin. This does however suggest the influence of a crustal structure on the development of basin geometry. Given the increase in palaeo-water depths during the deposition of the Barton Clay Formation but the apparent influence of a tectonic high on the connectivity to the north-east to the London Basin, it can be postulated that a short wavelength variation in basin deepening was affected by development of the Wealden structure and was not a control from eustasy. This can be inferred by the evolving palaeo-water depths and change in basin geometry as inferred from the palaeobathymetric maps.

4.7 Palaeobathymetry conclusions

The palaeobathymetric surfaces were developed with additional parameters to quantify water depth and justify the interpretations. The timing of each lithostratigraphic unit was updated to the newly assigned dates from King (2016) and the use of modern techniques of producing gridded surfaces is a new addition to the existing literature on southern England's Cenozoic palaeobathymetry and palaeogeography. The configuration of the palaeobathymetric surfaces are not too dissimilar to the maps produced by (Murray (1992)). The extent of palaeo-seas, orientations of palaeo-coastlines and geometry of coastal facies can be correlated. The advantage of the palaeobathymetric surfaces is the quantification of the basin geometry variations and the subsequent inferences made on basin trends that suggest that connectivity between the London and Hampshire basins was prolonged. It also suggests that the Weald existing as a significant bathymetric barrier was not apparent in the western regions of southern England until the Mid to Late Eocene. The palaeobathymetric surfaces developed have shown features that suggest additional controls on basin geometry and bathymetry other than eustasy. These other controls reflect shorter wavelength variations that temporally correlate with North Atlantic developments. Although fluctuations in palaeo-water depth can be attributed to variations in sea-level when correlated with the long term global sea level curve of Miller *et al* (2005), the Reading and Woolwich formations suggest other, tectonic, influences are acting upon basin development and shallowing trends.

Chapter 5: Tectonic subsidence curves and porosity analysis

The method of backstripping is predominantly used on deep marine sedimentary basin successions; whether the approach is appropriate for shallow marine sediments is tested here. The key strength in determining palaeo-water depths in the study area was the shallow marine depositional environment as discussed in chapter 4. The backstripping method analyses the vertical motions of the basement by removing the effects of sediment loading from the Cenozoic succession. The pre-requisites for this were discussed in chapter 3 and 4. First the temporal constraints on each lithostratigraphic unit was assessed as discussed in chapter 3. The next phase was to determine the thickness of the water column for each unit by analysing the depth of water the sediments were deposited in, which was the determination of palaeo-water depths described in chapter 4. This determines the degree of water loading and the elevation of sea-level can then be 'hung' from a eustatic sea-level curve. In this chapter the compaction history of the sediments in the Cenozoic succession is calculated using their temporal and palaeo-water depth constraints. Following decompaction water loaded subsidence curves are calculated to remove the effects of eustatic sea level change and varying sediment density on basement elevation, thus revealing the tectonic mechanisms, if any, which may be responsible for varying vertical motions.

The determination of palaeobathymetric surfaces (Chapter 4) revealed shorter wavelength variations controlling basin geometry that are unlikely to be attributed to eustasy and seem to be synchronous with structural inversions as described in the literature. An example of this is the suggested reactivation and inversion of the Isle of Wight faults during the deposition of the Barton Clay Formation, as shown by reworking of older sediments (Gale et al 2009).

5.1.1. Studying vertical motions

To understand the short wavelength variations of the southern UK during the Cenozoic and their relation to longer wavelength tectonic mechanisms the vertical motions need to be quantified. Following the determination of the palaeo-water depths the compaction history of the strata within the basins must be constrained in order to remove the effects of sediment loading on the crust during the Cenozoic. This will reveal the degree of vertical motion as a tectonic uplift or subsidence signal. The method of backstripping is commonly used in basin analysis to investigate the tectonic evolution of a basin and its margins but predominantly focus on deep marine basins. In this chapter, the appropriateness of applying a backstripping method to a shallow marine continental shelf environment is discussed and tested.

Previous studies on vertical motions have focused on the northern and western areas of the UK's uplift history. These studies use the fission track dating method which requires partially annealed apatites or zircons that are common in the rocks of Scotland, Ireland, northern Wales and the Atlantic margins (Cogné et al., 2016; Green et al., 2002; Holford et al., 2010; Jones et al., 2001; Look, 2007; Persano et al., 2007; Wagner and Van den Haute, 1992). This has been particularly useful in constraining exhumation and uplift of the northern and western regions of the UK. The specific conditions for fission track dating are not appropriate in the sedimentary basins of the southern UK because of the presence of apatites and zircons in the sediments have not been heated or buried sufficiently to anneal them to a level that gives a clear record (Wagner and Van den Haute 1992; Guo and Chen 2012). Fission track analysis is a more appropriate method for modelling uplift patterns whereas backstripping focuses on compaction histories of clastic sequences for tectonic subsidence analysis. Given the assessment in chapters 3 and 4, applying a backstripping method to the dominantly siliciclastic shallow marine Cenozoic succession in southern England is justified and is a more appropriate method for analysis of vertical motions and plotting tectonic subsidence than is fission track analysis.

5.1.2 Introduction to the method of backstripping

There are many parameters that need considering in order to calculate the subsidence history of the tectonic basement. The Cenozoic succession rests on Mesozoic units of which the top surface of the Cretaceous Chalk is the youngest preserved. This forms the initial surface that the Cenozoic sediments were deposited on, and will be used as the basement; justification for this is discussed in the latter parts of section 5.2. The deposition of Cenozoic sediments onto the basement and their loading effect will be analysed using the backstripping method of Watts and Ryan (1976). The main areas of the method will be explained in detail in the subsequent sections 5.1.3-5.1.6;

- Compaction history - The compaction history of the sediments and their subsequent loading effects on the basement can be removed. This includes determining the likely surface porosities at deposition, the grain density and bulk lithology, and an appropriate compaction coefficient (5.1.3).
- Water depth - The depth of water the sediment was deposited in for each unit. The thickness of the overlying water column in each section can be incorporated into the backstripping method (5.1.4). Paleo-water depths have been produced for the backstripping and were subsequently developed into the palaeobathymetric surfaces (Chapter 4).
- Eustatic sea-level change - The variations in global sea-level relative to the present day, taken from Miller et al. (2005) using backstripped sea-level records (5.15).

By determining and constraining all the parameters for the backstripping equation (*eq.1*) from Watts and Ryan (1976), Sclater and Christie (1980), Watts (2001), Allen and Allen (2013), the tectonic subsidence (Y) can be isolated. The sediment, mantle and water density terms are based on bulk densities (Watts, 2001).

Eq. 1:

$$Y = W_d + S^* \left[\frac{(\rho_m - \rho_s)}{(\rho_m - \rho_w)} \right] - \Delta_{sl} \frac{\rho_m}{(\rho_m - \rho_w)}$$

Y = Tectonic Subsidence — *P_m = Mantle Density*

W_d = Water Depth — *P_s = Sediment density*

Δ_{sl} = Change in Sea-level (Eustasy) — *P_w = Water column density*

S = Decompacted stratigraphic layer*

5.1.3 Decompacting a lithology: extracting surface porosity and grain density

Vertical motions of the crust can be affected by sediment loading, water loading and tectonic movements. The aim of backstripping is to isolate the tectonic subsidence or uplift signal from the vertical motions caused by sediment loading. The degree and history of sediment loading needs to be understood in order to remove its effect (Sclater and Christie (1980); Watts, 2001). This requires the preserved thickness of the strata to be used to estimate its unconsolidated state at the time of deposition, process of compaction and deposition of overlying units; prior to lithification. The original method developed by Watts and Ryan (1976) strips the entire sequence to assess the adjusted depth of the basement layer. In this study we use a more detailed technique of stripping each layer and modelling the compaction in sequence, thus modelling the vertical motions of basement at each interval in time.

The sediments in the onshore UK Cenozoic succession were deposited in a predominantly shallow marine or fluvial/lacustrine setting, with sedimentological evidence described in chapters 3 and 4 demonstrating fluid saturation. The nature of the sediments would be classed as unconsolidated at the time of deposition and assumptions made in soil mechanics can be utilised. Thus, an assumption is made that prior to compaction the host sediments will have possessed a higher porosity and fluid saturation than do the preserved strata at the present day. Sorby (1908) noted that unconsolidated sediments lose porosity through the applied loading from overburden, the weight of the overlying water column and gravitational compaction. A simplified relationship is assumed between sediment burial depth and the change in porosity volume. The process is a little more complicated due to the effects of compressive stress, the fluid pressure in the void spaces and possible chemical alterations, but the overall mechanical relationship that is active can be expressed through Terzaghi's law, *equation 2* (Terzaghi, 1936).

Eq.2:

$$\text{Effective stress } (\sigma') = \text{vertical compressive stress } (\sigma) - \text{fluid pressure } (\rho)$$

As the vertical compressive stress overcomes the fluid pressure in the pores and the mechanical strength of the grain framework, the effective stress will increase (Terzaghi 1936). The effective stress also increases as the load of overlying accumulating sediment increases, a function of increasing mass and acceleration to gravity plus the mass of the water column (Terzaghi 1951). The resultant reduction in porosity, expulsion of fluid from the pore spaces and reduction in pore volume in the underlying sediment can be mechanically described as compaction because a shortening of the unit occurs in the vertical direction with little to no change in the horizontal. To summarise, the process of compaction under uniaxial strain results in decreasing porosity and an increase in the bulk density which can be related to an increase in the overall effective strength of the strata (Terzaghi 1951; Sclater and Christie 1980; Allen and Allen 2013), *figure 5.1*.

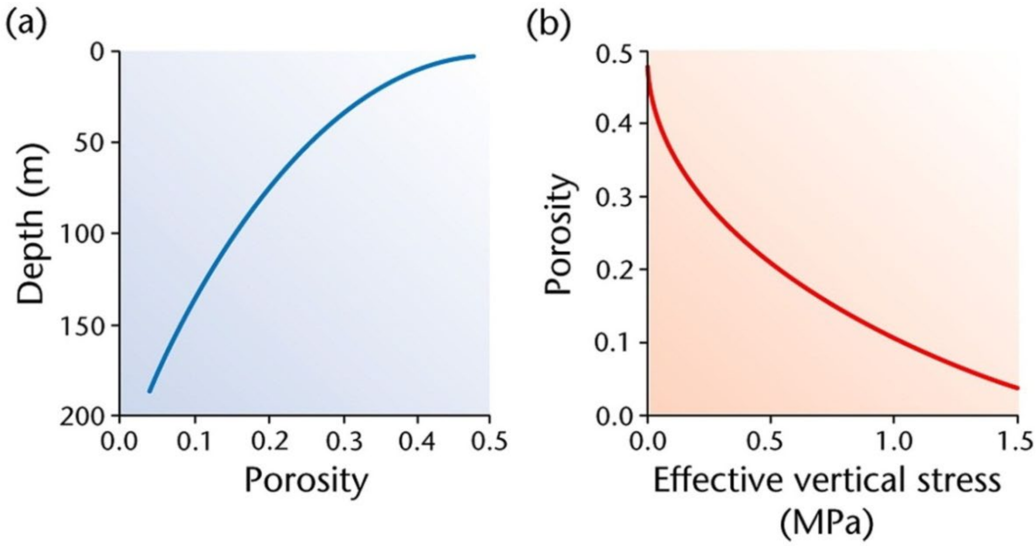


Figure 5.1: *A. Graph shows the generalised relationship between depth and porosity during burial of sediments. An exponential relationship is demonstrated by a rapid reduction in porosity within the first kilometres of burial. Greater depth increments are required to further reduce the smaller volume of porosity that has been retained. B. Graph showing the reduction in porosity will reduce the fluid pressure acting against the vertical compressive stress. Therefore increasing the effective vertical stress. Taken from (Allen and Allen, 2013; Jones et al., 2001).*

The compaction history of clastic sediments reflects a relationship of progressive density increase and porosity loss with an increase in depth over time. To increase the accuracy of deriving a compaction history for a full stratigraphic section, units can be classified into lithologies. Lithologies will have a varied response to applied stress and will exhibit contrasting compaction pathways. The primary control in porosity loss of clastic lithotypes is predominantly attributed to grain size and the grain framework (Pettersen, 2007). Secondary controls include the distribution of sedimentary structures and fossils; the facies could potentially affect the compaction pathways but this would depend on the quantifying the volume, abundance and pervasive nature of the structures but modelling these for a bulk model for use in backstripping is highly complex and the effect of the bulk properties of the lithology may be mimimal (Stonecipher and May, 1990). Lithologies containing a regular coarse grained framework with minerals of a low compressibility, such as an arenitic sand will retain porosity under a greater compressive stress than a clay or silt dominated lithology (Hough, 1969; Scherer, 1987). Generally sand dominated lithologies will show a linear relationship in their compaction history as compressive stress increases and overwhelms the compressive strength of the grain framework leading to porosity loss, figure 5.2a. There is variation between sand dominated lithologies and the gradient of the linear porosity-depth relationships. Clay and silt dominated lithologies such as shale (figure 5.2b) are much more compressible under lower compressive stresses and shallower depths with rapid expulsion of large volumes of fluid and rapid reduction in porosity, the majority of which occurs within the first kilometre of burial (Rieke and Chilingarian 1974). The dominantly platy shape of the clay minerals allow a tight packing of the framework under relatively low compressive stresses (Rieke and Chilingarian, 1974). These laboratory-tested pathways are consistent with the application of soil mechanical theory in the engineering and petroleum industries This is of particular importance in the southern UK Cenozoic record as the field observations summarise a succession that is notably friable, which as such been the focus of geotechnical engineering studies (Yuangdetkla 2013 Thesis). Also noteworthy is the burial depth. The thickness of the full succession at the present day does not exceed 1km, highlighting the application of soil mechanical modelling but this is assuming the rocks were not buried to a depth greater than 1 km and subsequently exhumed. Given their undeformed states, friable nature and mineral and chemical compositions matching an unmetamorphosed sequence, as discussed in chapter 3 and 4, this is highly unlikely. Carbonates are a lot more complex in terms of their compaction due to the variation of lithotypes and cementation (Allen and Allen, 2013), however this is not an issue as the Cenozoic basins studied are composed almost entirely of siliciclastic sediments except for very stratigraphically thin very infrequent carbonate beds that are not representative of individual lithostratigraphic units let alone of the succession as a whole. The basement Chalk layer is composed of carbonate rocks and these are assumed not to undergo further or drastic compaction during the Cenozoic, being modelled essentially as incompressible relative to the Cenozoic sediments during deposition (Hillis, 1995); this assumption is discussed in section 5.2. Using existing data on the compaction history of clastic rocks, decompacting a lithostratigraphic unit may be achieved by 'sliding' the preserved sediment toward the surface along a relatable porosity-depth curve, producing likely porosity values at the time of deposition, i.e. of surface porosity (Watts and Ryan 1976: Watts 2001).

In terms of the method within this study, once a bulk lithology has been determined for a lithostratigraphic unit, an associated average grain density and surface porosity can be assigned using the plethora of existing data. Table 9 shows the data used in this study to assign porosity and density to bulk lithology. The compressibility and the resulting density of the unit following compaction are associated with these values. Only one representative value is used for grain density so the lithological unit was required to consist of at least 60% of that sediment type. Examples of backstripping studies classify clastic lithostratigraphic units using grain density and porosity, into two or three

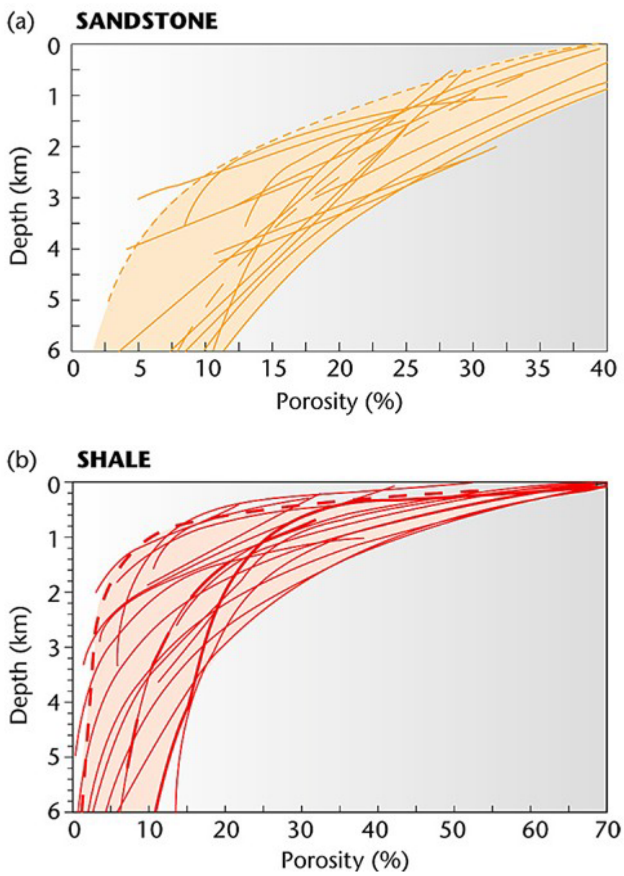


Figure 5.2: *Generalised porosity-depth graphs based on lithology. a: The porosity loss of a sandstone within the first few kilometres of burial results in a linear relationship. The porosity loss rate decreases at less than 10% due to the progressive mechanical strengthening from the grain framework in most sandstones. b. Shale is much more easily compacted in the early stages of burial; porosity loss is rapid within the first kilometre of burial. Taken from Allen and Allen (2013).*

categories. For example Allen and Allen (2013) and Zweigel et al. (1998) use two categories: 'sandstone' and 'shale' assigning two porosities and grain densities for the sequences in their studies. Sclater and Christie (1980) is a key study and used three clastic categories for backstripping: sand, shale and shaley-sand. The shaley-sand in Sclater and Christie (1980) is utilised as an intermediate category comprising clastic sediments of containing roughly equal amounts of shale and sand and this approach was adopted. Sand and silt proportions can vary substantially within sediments and this will have an effect on the likely initial porosity. In this study a total of 7 categories for likely surface porosity was utilised: table 9. Surface porosity is a representative value of unconsolidated sediment, or soil in engineering literature. Therefore soil engineering terms and data was taken from a range of geotechnical texts, studies and tests (Hough, 1969; Look, 2007; Sowers, 1979). Each clastic sediment type has a surface porosity, grain density and compaction coefficient assigned to it. Once again, the compaction coefficient is related to the dominant grain type, their compressibility under compaction, and the likely pathway of porosity loss and fluid expulsion from a wide range of studies and as such represents a best fit of a sediment's burial history, figures 5.2a-b (Watts, 2001). To determine additional compaction coefficients, lab tests on each lithostratigraphic unit would need to be carried out which would be beyond the scope of this study. Ideally each lithology could be lab tested to represent the preserved porosity at the present day, therefore constraining the potential error in the compaction model. Temperature can also affect diagenetic processes and therefore the resulting porosity. However, the friable nature of the succession suggests it has not been buried to depths of more than 1 km and hence it is unlikely it will have been subjected to higher temperatures (Yuangdeltka 2013). There also appears to be little evidence for high thermal anomalies within the study area, e.g. high geothermal gradients or shallow intrusions, that would be sufficient to skew the output porosity values (Surdam et al., 1989; Wilson, 1994a).

Lithological Description	Mean Initial Porosity ϕ_{si} (Decimal %)	Grain Density ρ_{gi} (kg/m^3)	Compaction Coefficient (km^{-1})
SAND, fine to coarse grained.	50	2650	0.27
SAND, very fine to medium grained. Some clay and silt.	56	2650	0.27
SAND, fine grained to medium grained. Silty and clay.	47	2650	0.27
SAND/CLAY. 50/50 parts sand and clay grain sizes ±20%	64	2650	0.4
CLAY, SILT, SAND. Some fine to coarse grained sand.	64	2600	0.4
CLAY, SILT. Dominantly clay.	71	2600	0.51
CLAY, organic rich.	75	2600	0.51

Table 9: *The lithological classifications used to assign surface porosity and grain density values to clastic sedimentary categories. Compaction coefficients are a reflection of both these values and the likely degree of compaction each category will undergo. Data is taken from lab and in situ soil testing and collated by (Hough (1969); Jones et al., 2001) and (Jones et al., 2001; Sowers (1979)). Combining geotechnical, petroleum and soil engineering principles.*

Grain density values are taken from Batzle (2007) and an average value was used to represent the bulk grain density of each lithological type. Lithostratigraphic units dominated by sand sized grains were assigned a density of quartz, 2650 kg/m^{3,} which can be shown by thin section and hand specimen analysis from field work (see Chapter 5, section 5.1.4 and Appendix 4). Most importantly the mineralogy has been extensively studied and documented in the literature, as discussed in chapters 3 and 4; the Cenozoic succession comprises a dominantly siliciclastic succession (Edwards and Freshney 1987b; Aldiss 2012; King 2016). Lithostratigraphic units dominated by clay could have a range from 2200-2700 kg/m^3. This is based on the dominant clay mineral constituent and whether the clay minerals have been hydrated, which can increase their volume following swelling, but lowers the bulk density (Sowers 1979; Look 2007). This is a well-studied area in geotechnical engineering as swelling clays can be problematic to foundation design (NHBC 2011). Despite this an average grain density value of 2600 kg/m^3 is common to previous studies and was assigned as it uses the upper boundary densities of illite, montmorillonite, smectite and in some parts glauconite, the most abundant clay minerals in the Cenozoic succession (Aldiss, 2012; Batzle, 2007; Edwards and Freshney, 1987; King, 2016). Ideally each lithostratigraphic unit should be evaluated for its mineralogy to provide quantitative data on the mineralogical constituents. However, this degree of accuracy would not affect the output backstripped data to the same degree as improving the determination of sediment porosity, as compaction in this regard is a function of porosity loss. To quantify the appropriateness of using porosity as a function of burial depth and the accuracy of the method proposed a short laboratory study was conducted.

5.1.4 Laboratory study on porosity as a function of burial depth

As a quality control for the backstripping method, a sample from the Isle of Wight was used to measure the preserved porosity at the present day and then compared to the output theoretical porosity from the backstripping equation. The Branksome Formation was used for its homogenous nature consisting of a dominantly fine to medium grained quartzose sandstone that could be successfully cored. Samples of other formations were obtained but these were insufficiently consolidated to allow them to be cored or sectioned. A combination of methods including optical microscopy, fluorescence microscopy and Computed Tomography (CT) X-ray scanning was utilised to quantify the preserved porosity. The methods, limitations, assessment and data development are described in Appendix 5.

The thin section analysis of porosity appears conclusive with minor error margins. The mean resin filled porosity value of 31.2 ±5% is very similar to the compaction history output porosity of 31%. The preserved porosity from the CT scan of the entire core suggested a similar value of 32%, which is within 0.8% of the mean porosity from the thin section analysis. The variance in the porosity (Appendix 5, figure 8.5.4) was greater in the orientation of compaction. The measured porosity values suggest the choice of initial porosity and compaction coefficient were appropriate for the Branksome Formation and support the approach used for this study. It is important to note that if a standard three or two lithology classification for initial porosity was used, studies such as those of Zweigel et al. (1998) and (Sclater and Christie (1980)), would have categorised the Branksome Formation as a sandstone with an initial porosity of 50% and not the 56% assigned for this study. This justifies the use of using more than three classifications for bulk lithology and the assumed initial porosities in the backstripping method. This is not conclusive for each category and ideally each lithology would need to be tested to the same degree to check that the initial porosities and compaction coefficients were appropriate. The similarities in the average porosity values and the variance in porosity across the regions of interest analysed does suggest there are limitations in assigning a single value to represent a bulk lithology. It also supports the use of an average porosity as being representative, which seems paradoxical. Figure 5.1.5 shows where the assigned initial porosity and output porosity of the Branksome Formation lies on an adapted depth/ porosity plot, falling within the upper tested boundaries of other sandstones. This short investigation supports the use of soil mechanical data to provide additional porosity values to increase the accuracy of the backstripping method in this study. Ideally, to be more conclusive an entire assemblage of samples should be tested but this preliminary study is promising in demonstrating the reliability of the method used to quantify the compaction histories of the Cenozoic sequence.

Considering the vertical tilting of the Alum Bay strata, the proximity of the samples to the fault in the Mesozoic Chalk, and their subsequent exhumation and exposure as cliff sections, a degree of uncertainty in the porosity results may exist and could be explored further in terms of a tandem laboratory subsidence analysis study. The Sandhills borehole would be an ideal section for sampling and testing away from the structure but samples were not available and as such will be considered for further work.

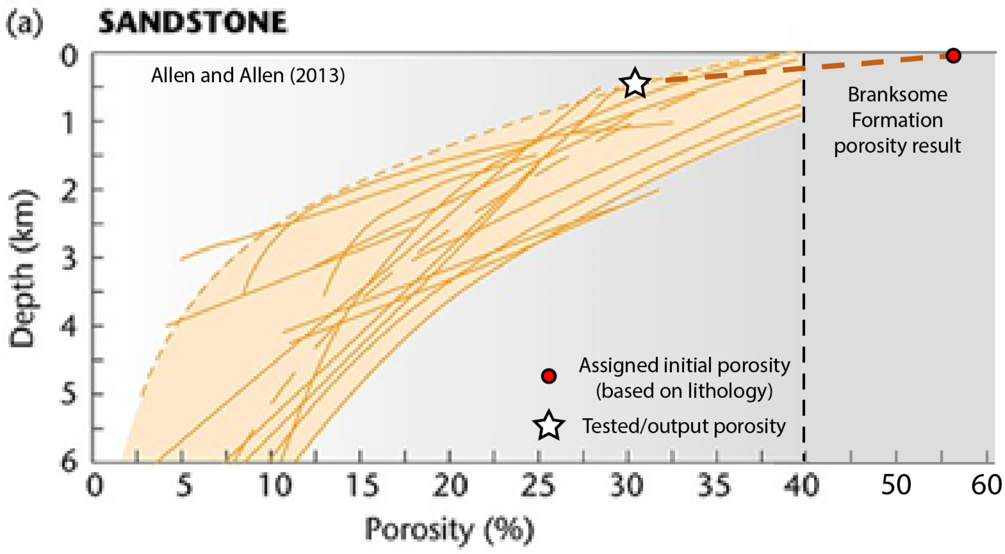


Figure 5.1.5: *An extended plot showing the compaction pathway as suggested by the preserved tested porosity/ output porosity and assigned initial porosity of the Branksome Formation. Adapted from Allen and Allen (2013)*

5.1.5 Water depth determinations

The method of palaeo-water depth determination was described and evaluated in Chapter 4. Values of water depth for each of the 28 sections studied were used from the palaeobathymetric data. The palaeo-water depths used for backstripping are essential to correcting the depth to the basement at the time of deposition for each stratigraphic layer. This can then also be corrected for eustatic sea-level variations (*Section 5.15*). The depth of the water column acts as an additional load and must be considered when correcting for the isostatic effect from sediment and water loading in order to isolate the total tectonic movement (Allen and Allen, 2013; Sclater and Christie, 1980; Watts, 2001).

5.1.6 Eustatic sea-level change

Changes in the configuration of plates, particularly spreading rates, will change the extent to which the continental shelves will be flooded leading to variations in global sea-level. Sea-level can also be affected by climate and temperature variations, such as the formation of ice caps. Any increases or decreases in the volume of water in ocean basins will be isostatically compensated and will produce a new sea-level datum (Allen and Allen, 2013). The eustatic variation must be used in the backstripping calculation as this corrects the determined depths to the basement for this change in sea-level elevation which is suggested to have fluctuated during the Cenozoic. There are many studies on eustatic sea-level variations that use different methods. The Miller et al. (2005) study was selected as it uses a similar stratigraphic backstripping method to previous studies and produces similar patterns of sea-level rise and fall. There is a broad agreement that studies such as that of Haq et al. (1987) although having similar temporal variations, are displaced by up to 100m in comparison to more recent studies figure 5.1.6, thus would result in displacing the elevation of the basement and water depths by larger than the vertical error margin (Kominz, 2001). The use of a eustatic sea-level curve that is lower will produce more conservative elevations. A series of eustatic sea-level long term and short term curves have been compared.

Sea-level curves from Miller (2005), Kominz (1998), Kominz (2008) and Watts (1979) have similar amplitudes and wavelengths, and are unlike the Haq et al (1987) curve, figure 5.1.6. Further to this the water depth interpretations from the deepest sections were compared with the short term and long term sea-levels from each curve, figure 5.1.6. The plotting of the interpreted water depths shows good agreement in sea-level fluctuations with the short term Miller (2005) curve. Not only do the water depth variations reflect each other, they also show similarities in variations to reflect the sea-level fluctuations of Miller (2005). This would highlight any particular stronger tectonic signals without bias from the sea-level variations of the Haq et al (1987) curve, which would also produce an amplitude 100m higher than that of other sea-level studies. Although figure 5.1.6 shows comparisons between the water depths and the sea-level variations of Miler (2005), it also suggests local variations in water depth that maybe attributed to alternate mechanisms, for example short wavelength tectonic variations.

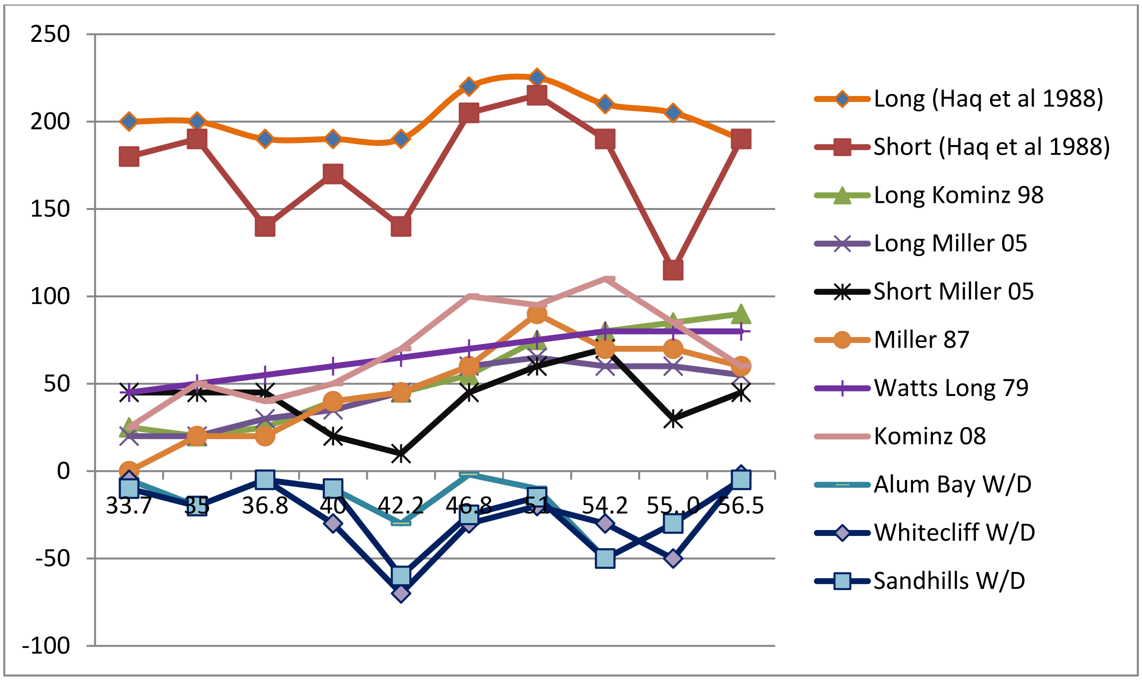


Figure 5.1.6: *Plot of short term and long term eustatic sea-level curves. The Haq et al (1988) curve is up to 100m higher than the other sea-level curves studied. All other curves show a similar amplitude in sea-level maximum and minimum. The palaeo-water depths taken from the deepest borehole sections to be backstripped have been compared with water levels of the sea-level curves.*

5.1.6 Applying backstripping to a stratigraphic sequence

When all rock properties were estimated, each unit in each borehole/ section was backstripped to produce a water-loaded tectonic subsidence curve. Once the complete compaction history has been determined for a multi-layered section, as schematically shown by figure 5.3a, the effects of sediment loading can be removed by replacing the sediments with a column of water so the vertical motions of the basement can be analysed (Watts and Ryan 1976). The resulting water-loaded tectonic subsidence curves allow an effective comparison of different basins and areas of the same basin without the complications from lateral variations in sediment types. The use of water-loaded subsidence curves for analysis in this study is crucial given the regional distribution of the London and Hampshire basin depocentres, the lateral variation of sediment types and the eventual spatial analysis of the subsidence values. Figure 5.3a and 5.3b is a schematic demonstration of backstripping a section and the effects from eustatic variations have not been applied to these examples. The curves from backstripping a basin of accumulated sediments will provide information on the rates of tectonic subsidence from the shape and gradient of the subsidence curves. Backstripping is not only limited to tectonic subsidence signals and can present signals that suggest phases of uplift. A significant increase in sea floor elevation, a eustatic control, and a reduction in palaeo-water depth, figure 5.3c, and sedimentation could result in an isostatic adjustment of the basement with a net vertical motion producing an uplift signal in a subsidence curve (Watts 2001). Conversely, it is also possible if the sea-level datum remains constant but there was a reduction in water depth and minimal sedimentation, an isostatic adjustment would produce an uplift signal in a tectonic subsidence curve, figure 5.3d (Watts and Ryan 1976; Watts 2001). Uplift signals are reliant on the constraints on palaeo-water depth or sea-level variations. A unit that underwent little to no compaction during deposition can reduce the accommodation space but not result in a net uplift and it is especially important to be critical of the error margins when the data presents an uplift signal.

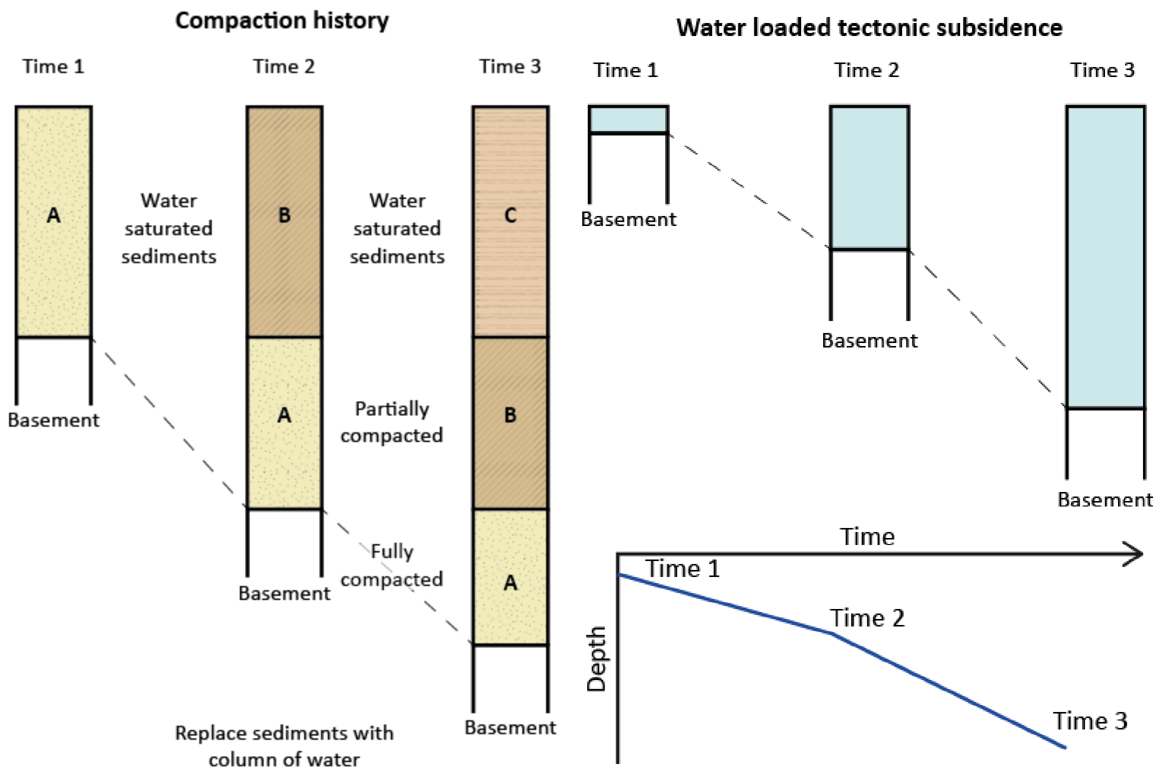


Figure 5.3a: *Determining a compaction history. Unit A is the first to be deposited, directly onto the basement at Time 1. The column of sediment is unlithified and water saturated and loads the basement causing subsidence. At Time 2, unit B is deposited as unlithified water saturated sediments. This further loads the basement and partially compacts the underlying sediments of Unit A. Time 3 is the deposition of unit C, once again unlithified and water saturated it further loads the basement to greater depths. Unit C also forces the partial compaction of Unit B and by this point Unit A is further compacted. Unit A is thinner here than at Time 1.*

Figure 5.3b: *The subsequent removal of sediment loading from the basement to plot the amount of subsidence caused by tectonic subsidence. Once the full compaction history has been determined and the compaction pathways of each unit within a section has been applied the most likely effects of sediment loading can be removed. This leaves the amount of subsidence of the basement attributed to tectonic mechanisms. In this example, the sediment has been replaced by water and reflects a basement that was tectonically subsiding from Time 1 through to Time 3. The simplified graph shows how this data is presented in the results section. Corrections are subsequently made for global sea-level for each time.*

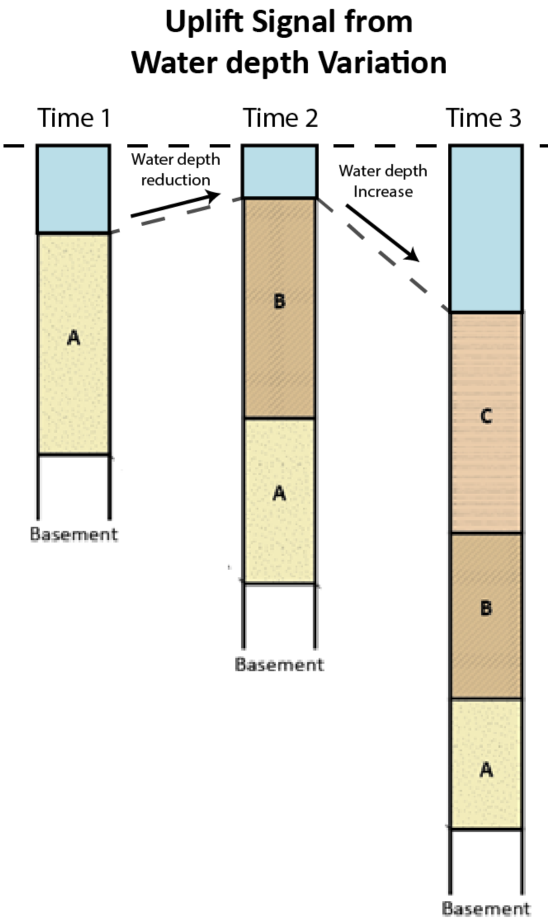


Figure 5.3c: *This diagram displays how an uplift signal can be produced from water depth variations. Once the sediment loading has been removed the basement will give vertical motion variation reflecting an uplift and subsequent subsidence event. In this example the sea-level remains constant.*

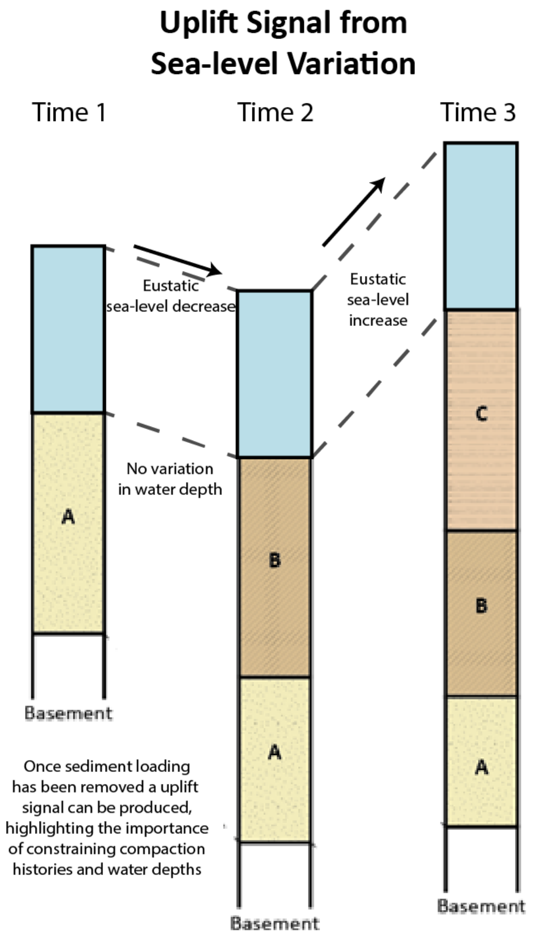


Figure 5.3d: An uplift signal can be produced from variations in the sea-level. This diagram suggests water depth remains constant and variations in the eustatic sea-level would result in an uplift signal within this sequence. Therefore it is important to use appropriate sea-level curve data when backstripping sequences. Relating the sea-level fluctuations to the stratigraphy is a way of quality controlling the data used.

5.1.7 Applying backstripping: Isostasy models

Backstripping has been completed for each stratigraphic surface using the Airy model of isostatic compensation due to loading. Two models of isostatic response are generally used, the Airy model and the Flexure model (Watts, 2001). Both model the isostatic response of the crust to loading from water and sediment; this results in crustal thickening and in their simplest form both models assume the underlying basement crust and mantle are of a uniform density throughout. The first model is named after G.B Airy (1855) and his idea that the outer layers of the crust lie on a fluid of greater density and he related this to the principals of icebergs. This has been developed into the Airy model, representing a local isostatic compensation of the crust to an applied load, sediments or water, as shown by the block diagram in *figure 5.4a*. Before and after loading the lithosphere maintains isostatic equilibrium despite crustal thickening. The flexural model of isostasy follows a similar pattern, but assumes the lithosphere has rigidity as developed from initial ideas by Vening Meinesz (1941) and followed by Walcott (1970). When a load is applied the compensation is spread across the lithosphere laterally, decreasing in magnitude away from the focal point of loading and producing a pattern of less localised compensation and more regional compensation (*Figure 5.4b*). Tiley et al. (2003) suggested the elastic thickness of the crust below the British Isles is 5 ± 2 km. This a low value and they concluded the lithosphere beneath the north-western European continental shelf, and thus beneath the UK, was weak. The crustal thickness of the southern UK averages 34 km with minimal significant variation in crustal thickness (Ziegler and Dezes, 2006). Considering these two factors of the crustal strength and thickness and the long wavelength distribution of sediment loading in the southern UK, the Airy model of support is more appropriate for this study. If a flexural model was used the degree of variation in the resultant data would not be too dissimilar based on the crustal elastic thickness and long wavelength of loading. Considering this factor, a more complex approach with additional varying parameters to reach a similar result given the assumed crustal thickness and strength of the UK, would be an unnecessary methodical pathway.

Following the backstripping of each stratigraphic surface the tectonic subsidence and uplift can be plotted as a subsidence curve against time. Rates of subsidence and uplift recorded in the subsidence history can then be correlated to the regional tectonic events.

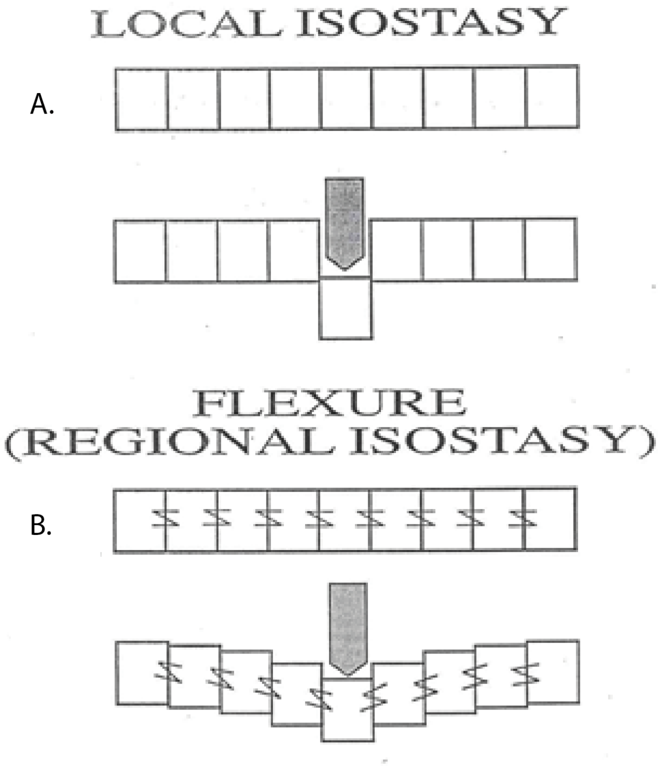


Figure 5.4: *Two models of isostatic compensation. A: Is Airy local isostatic compensation in which the load applied is compensated by the area it is applied to. This assumes little to no rigidity to the crust. B: Flexural compensation model assumes rigidity of the crust. As such the load applied is distributed across an area and not localised. However this method is considerably more complicated to plot accurately and requires additional detail of the variations in crustal thickness and density in order to model the likely isostatic compensation. The output of this model is not necessary when considering the volume of sediment load being dealt with.*

5.2 Assumptions and limitations of backstripping

As previously discussed, to minimise the assumptions and limitations of this method external data from soil engineering sources has been used to further constrain the likely porosity at the time of clastic deposition, based on modern analogues. It is important to note that all sections analysed were assumed to have experienced compaction via a vertical compressive stress only. The migration of fluids will be in the orientation of least compressive stress following expulsion from the closing pores (Terzaghi 1951). The action of compaction requires a greater change in volume in the vertical orientation than the horizontal orientation (Terzaghi, 1936) and for this reason a closed system of compaction is deemed appropriate for each backstripped section. However, compressive stress from overburden can vary based on lithology changes, rate of sedimentation and planes of weakness within a unit (Jolly and Lonergan, 2002). This could result in the retention of pore fluids, and lead to slower rates of fluid expulsion that can lead to overpressure within the void spaces, as described by Jolly and Lonergan (2002). The preserved Paleogene succession at its thickest is less than 700 m thick on the Isle of Wight (Edwards and Freshney, 1987; King, 2016). The majority of the preserved Cenozoic succession across the southern UK is less than 200m thick (Aldiss, 2012). The maximum sedimentation rate is 23 ± 5 m/Myr, calculated from the duration of time and maximum thickness of preserved strata. If this is the case then the rate of sedimentation and depth of burial is too low to produce significant overpressure. One complication is whether the sequence was subject to additional deposition which was subsequently removed via erosion. Overpressure will increase with depth as overburden or lithostatic pressure increases, figure 5.5 (Jolly and Lonergan, 2002). Eventually the hydrostatic pressure in the overpressure voids will exceed the lithostatic pressure leading to hydrofracturing. This is most likely at depths greater than 2 km, which is much greater than the most likely maximum burial depth of the Cenozoic succession which is probably less than 1 km (Appendix 3).

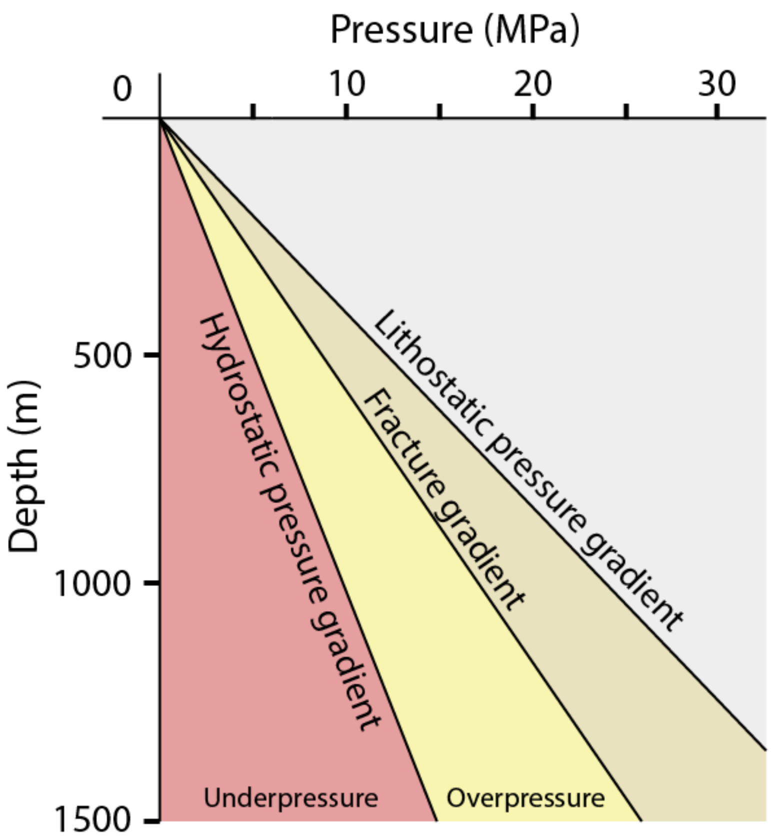


Figure 5.5: *Plot of depth against pressure showing the relationships between fluid pressure and the lithostatic pressure. Hydrofracturing may not be a factor as this requires depths greater than 2 km which the Cenozoic succession most likely did not reach. Adapted from Jolly and Lonergan (2002).*

Backstripping can only provide data on the vertical motions of the basement from preserved strata; as such, it is quite likely that during deposition a larger column of sediment may have accumulated which was eroded between lithostratigraphic intervals. Essentially the sequence is backstripping the minimum amount of sediments/rock following erosion through time and so will provide a minimum vertical motion history.

The subsidence data is generated from points in time of existing lithostratigraphic units. As many divisions of the Cenozoic succession were used as possible to increase the temporal resolution of the subsidence curves and each unit backstripped was assigned its basal age based on existing literature. The errors in the ages of the stratigraphy were discussed in detail in chapter 3; this error is carried into the backstripping. The backstripping does assume sedimentation is instantaneous at the basal age, which in reality is not the case as it would span from the oldest to the youngest age. By using the basal age the tectonic subsidence can be assumed for the oldest ages of sediment loading and the next age input is determined by the following lithostratigraphic unit and its basal layers. The method used to backstrip the sections assumes both instantaneous deposition and isostatic adjustment. Neither is the case but the short time intervals represented by each formation mitigate this limitation, which is much less in the well constrained shallow water succession which is the focus of this study than the more poorly constrained more conventional backstripping of deeper water successions.

Grain densities determined for backstripped layers are non-wetted. This is not an issue for quartz-rich lithologies but it may add a degree of uncertainty for clay-dominated lithologies as their density may increase by up to 40% by water absorption and swelling as previously mentioned (Rieke and Chilingarian, 1974). As the focus of the starting layers is within water-saturated columns it is highly likely that the clay particles will have at least partial absorption. The compaction history also assumes the sediments do not regain porosity and that at no point is compaction reversed. Through some diagenetic processes or unloading/removal of overburden a layer may be able to regain thickness or reverse-compact prior to lithification.

There are limited sections and boreholes that meet all the criteria in the onshore geological records. Most sections used in the assessment of palaeobathymetry were unusable for backstripping as they did not preserve thick enough sequences or multiple lithostratigraphic units. The vertical uncertainty is a summation of the water depth errors, chapter 4: section 4.3, and the variables in compaction coefficients, initial porosity and grain density. The maximum preserved thickness of the Cenozoic succession is in the Sandhills borehole which is less than 700m. By applying the Sclater and Christie (1980) lithological classifications of compaction coefficient, initial porosity and grain density an uncertainty maximum of 20m was determined. Therefore all other sections backstripped which are thinner than the Sandhills borehole will have a vertical uncertainty of less than 20m. The summation of the water depth errors and the backstripping is a total of ± 70m.

Lastly, the backstripping method assumes the Mesozoic Chalk is appropriate as a basement layer and has undergone burial and exhumation of overlying units prior to Cenozoic deposition (Brenchley and Rawson, 2006; Hillis et al., 2008). Studies such as

Hillis (1995) analysed the sonic velocities in offshore UK basins such as the southern North Sea and Western Approaches to determine the degree of burial and exhumation. This can be applied to the onshore regions in this study. It was suggested that exhumation occurred after the Cretaceous Chalk had undergone compaction and reached its maximum burial depth. From Hillis (1995) it can be assumed that the Mesozoic Chalk was fully compacted prior to Cenozoic deposition and as such appropriate as a basement layer which is assumed to be incompressible with no further accommodation space being created by additional compaction during loading by the Cenozoic succession. Conversely, a backstrip of the Chalk and older Cretaceous sequences would provide additional information on the likely state of compressibility; however, this would go beyond the time constraints of this project and evidence so far suggests the assumption of minimal compressibility is justified.

5.3 Results: Tectonic subsidence curves

A total of 28 sections/boreholes that met the criteria outlined in section 5.2 were backstripped. For this reason, there are sparse areas of data in parts of southern England. In some areas boreholes were stratigraphically too thin (<30m), descriptions lacked detail or did not consist of more than one lithostratigraphic unit. Figure 5.6 shows the location of all sections/boreholes used in this study, initially separated into areas A-E to display the subsidence results more clearly but also allowing correlations between sections with a local spatial context. All water-loaded subsidence curves are corrected for eustatic sea-level using Miller (2005). For all sections to be directly compared, the last section of the results will display all water-loaded subsidence curves and the eustatic sea-level curve for correlation and assessment of the data in a regional context. *Appendix 2* contains the raw input files for backstripping, compiled spreadsheets and individual borehole curves.

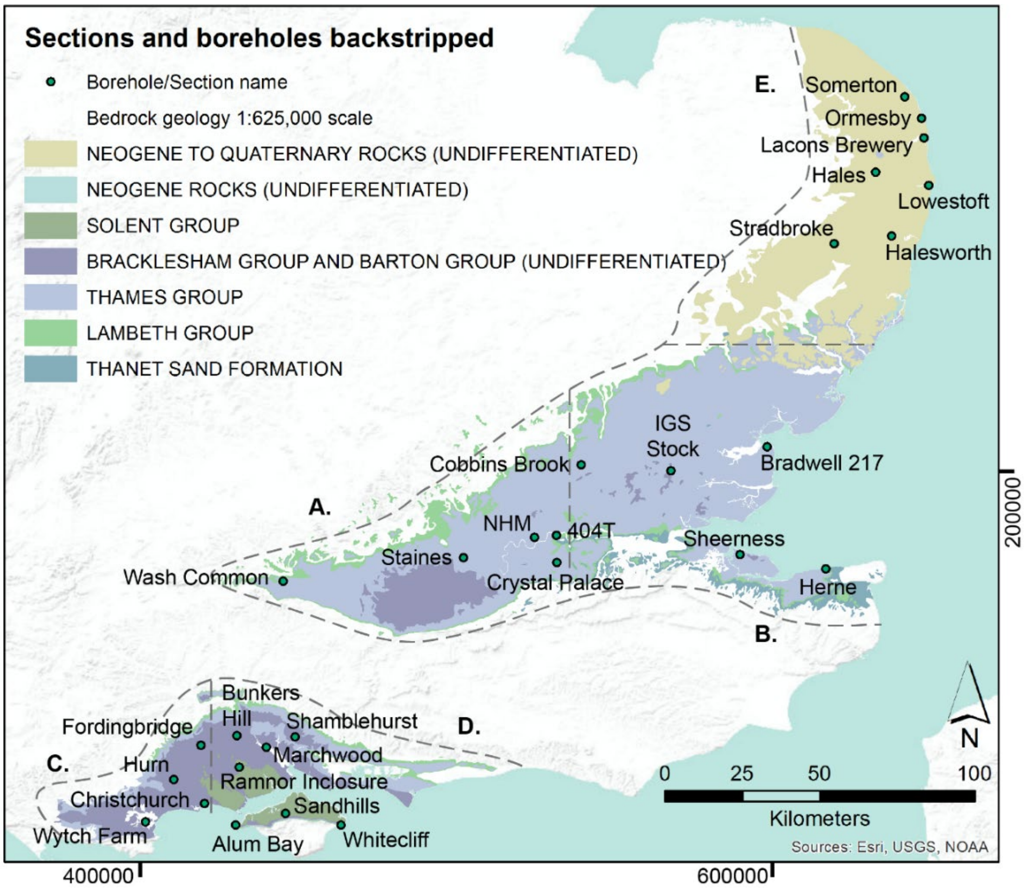


Figure 5.6: *Map shows the location of sections and boreholes backstripped and show how the region has been divided into five areas, A-E. This is for comparative reasons and prevents details being lost in the areas of high-density data. It also provides spatial context to some local and regional patterns. Southern East Anglia is limited in viable sections and boreholes. Many selected did not meet the criteria required but were appropriate for palaeobathymetry analysis.*

5.3.1 Region A: West London Basin curves

Sections and boreholes in figure 5.7 are from the western London Basin (Figure 5.6: Region A.) which includes the data-rich area of Central London. The deposition of the Late Paleocene Thanet Formation is spatially limited to the London Basin and East Anglia but is critical to providing data on the vertical history of southern England from 58.5 Ma. The youngest Paleogene rocks preserved in the sections of Region A (Figure 5.6) of the London Basin are dated at 51.8 Ma.

There are two phases of uplift and subsidence signals suggested to occur between 58.5 and 51.8 Ma that are common to most sections, figure 5.7. All backstripped sections of Region A show a similar degree of uplift between 58.5 and 56 Ma. The most rapid tectonic subsidence signal from 55.8 to 54.7 Ma is recorded by the Staines borehole in the central area of Region A. All sections show very similar vertical motions of the basement, except for Wash Common. The Staines and NHM sections record an uplift event through to approximately 53.2 Ma. The Crystal Palace section is the only subsidence curve recording subsidence through to 51.8 Ma and the maximum net tectonic subsidence is shown to be up to 50 m, despite the intervals of uplift the periods of tectonic subsidence are longer lasting.

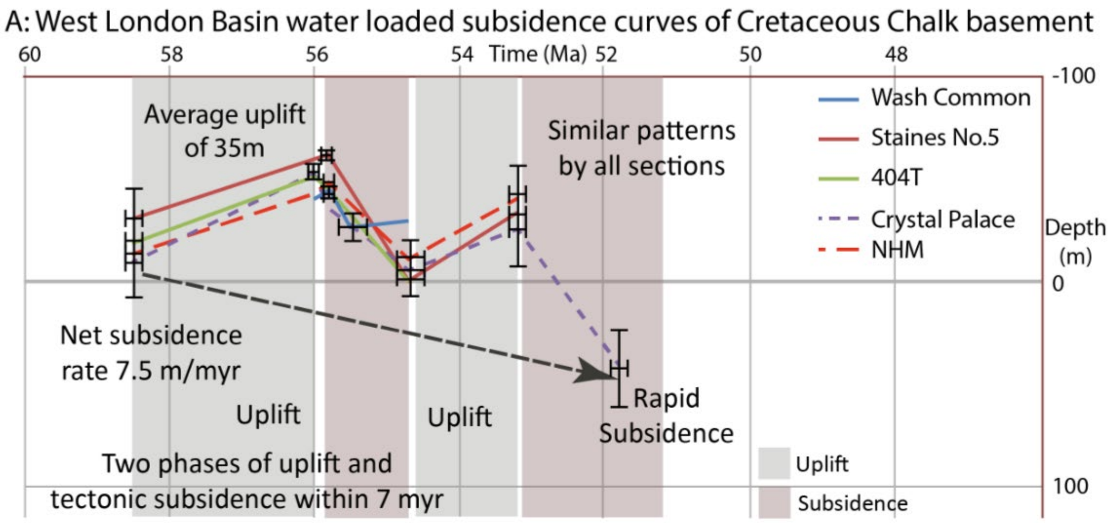


Figure 5.7: *Water-loaded subsidence curves corrected for eustasy from Region A of figure 4.5, the western London Basin. Two phases of uplift and subsequent subsidence are suggested by the backstripping of 5 boreholes and sections in this region. Error bars are displayed for each data point.*

The Wash Common section is the most westerly and stratigraphically thin, possessing little temporal data, but it is spatially important for generating the later tectonic surfaces discussed in Chapter 5. The Wash Common section displays minor uplift from 56 to 55.8 Ma followed by a period of subsidence from 55.8 to 55.5 Ma. This is then finally followed by minor uplift from 55.5 to 54.7 Ma. These phases of uplift and subsidence occur on a shorter time frame than do the other sections in the west London Basin area. The Wash Common section is the most western data point in the London Basin area and may be the reason for the variation in vertical motions, given that the preserved facies also represent a more marginal area to the basin. The elevation of all sections is consistently above or close to present-day sea levels, when the potential error margins are considered. The duration of time for all sections is approximately 6.7 ±1.0 myr and reflects vertical motions that were fluctuating in a relatively short space of time.

5.3.2 Region B: East London Basin curves

Figure 5.8 shows the water-loaded subsidence curves of Region B in the eastern London Basin area (Figure 5.6: Region B). There is a greater spatial distribution of the sections in Region B and so the less consistent nature of the data provides additional information on the movement of the basement across the area.

The data shows two phases of tectonic uplift and subsidence between 58.5 and 51.2 Ma, from the Late Paleocene to the Early Eocene displaying a net tectonic subsidence of the basement. The first phase uplifts and subsides from approximately 58.5 to 54.7 Ma. Phase 2 is suggested to be from 54.7 to 51.2 Ma lasting approximately 3.5 myr. The IGS Stock borehole preserves the youngest strata through to 51.2 Ma which suggests the north-eastern district of the London Basin continued to subside beyond 51.8 Ma as suggested by the Central London boreholes. The Bradwell borehole is the north-easternmost section backstripped in the London Basin area and shows very rapid subsidence between 55.8 and 55.5 Ma. The Sheerness borehole exhibits a similar pattern to the Central London sections of Region A (figure 5.5 and 5.6), but with a greater degree of tectonic subsidence. However the most easterly section backstripped in the London basin, Herne, shows uplift continuing to as late as 55.5 Ma before subsidence begins. This is the easternmost section studied in this area and the continued uplift may be related to its location.

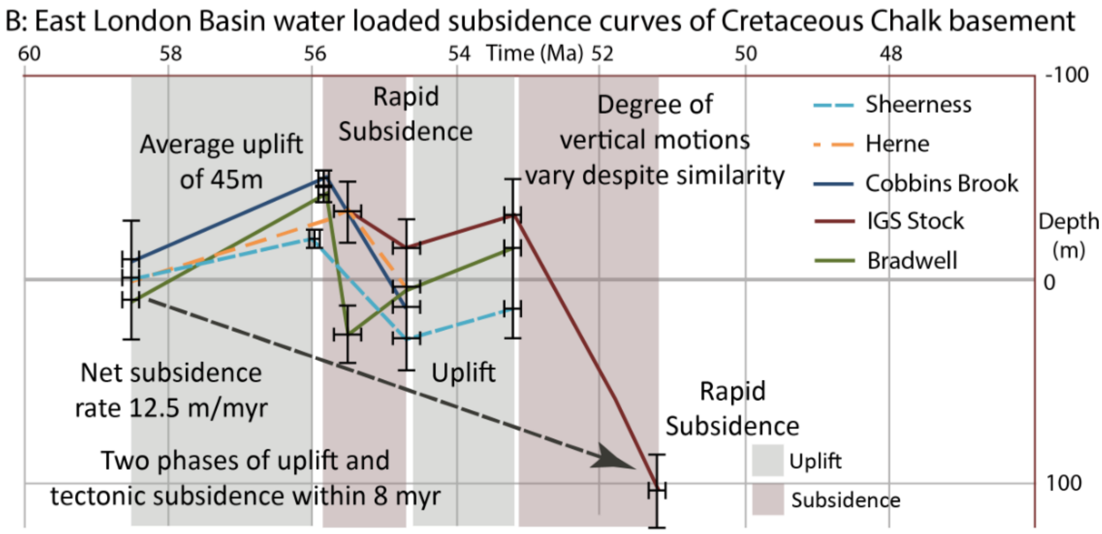


Figure 5.8: *Water-loaded subsidence curves corrected for eustasy from Region B of figure 5.5, the eastern London Basin. Two phases of uplift and subsequent subsidence are again suggested by the backstripping of 5 boreholes and sections in this region. Error bars are displayed for each data point.*

5.3.3 Region C: West Hampshire basin curves

The western Hampshire Basin boreholes and sections (Figure 5.6: Region C.) show a net subsidence from 55.8 to 42 Ma, Early Eocene to Mid Eocene. Figure 5.9 shows the water-loaded subsidence curves of Region C in the western Hampshire basin area.

The subsidence curves from the Early Eocene suggest initial tectonic subsidence of the basement followed by a phase of uplift and subsequent subsidence from 56 to 51.2 Ma. From 51.2 Ma, the basement in the western areas of the Hampshire Basin exhibit a respite in tectonic vertical motions, with the most western and north-western sections of Wytch Farm and Fordingbridge suggesting slow tectonic subsidence rates. Most sections resume an increased rate of tectonic subsidence from 48 Ma, with only the most western Wytch Farm section reflecting minor uplift. From 46.2 Ma a faster rate of subsidence is suggested by the Hurn and Christchurch boreholes. The Christchurch borehole is the only section in the western Hampshire Basin region that preserves tectonic subsidence of the basement through to 41.8 Ma. The Hurn borehole seems to suggest minimal vertical motions during the mid-Eocene; however, there is a gap in the stratigraphy for erosional and transgressional reasons between 54.7 and 48 Ma and so no data constraints are provided for this period. It is likely, given the consistent shallow

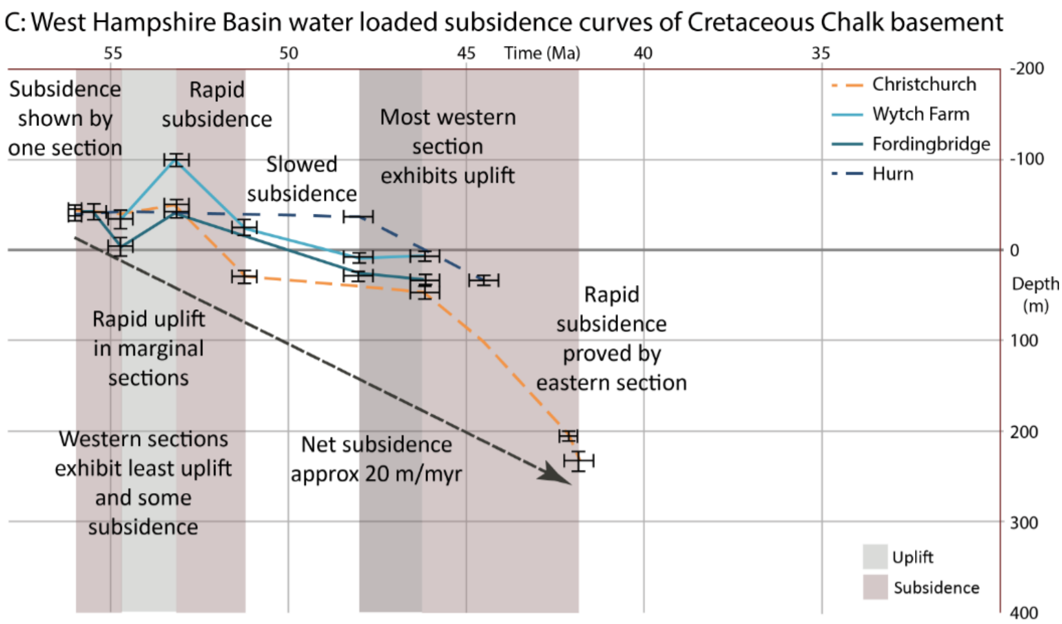


Figure 5.9: *Water-loaded subsidence curves corrected for eustasy from Region C of figure 5.5, the western Hampshire Basin. Early subsidence followed by a phase of uplift and subsequent subsidence in the Early Eocene is suggested by the backstripping of 2 of the 4 boreholes and sections in this region. Error bars are displayed for each data point.*

water depths and consistent near-shore and terrestrial depositional environments, this area of the subsidence curve represents the margins of the basin.

5.3.4 Region D: East Hampshire basin curves

The eastern sections of the Hampshire Basin (Figure 5.6: Region D.) preserve the thickest and most complete sequences of UK Cenozoic strata and provide a valuable constraint on tectonic vertical motions in the Paleogene. Three sections from the Isle of Wight span from 56 through to 34.8 Ma, Early Eocene to very Late Eocene/Early Oligocene. Figure 5.10 shows the water-loaded subsidence curves of Region D in the eastern Hampshire Basinarea.

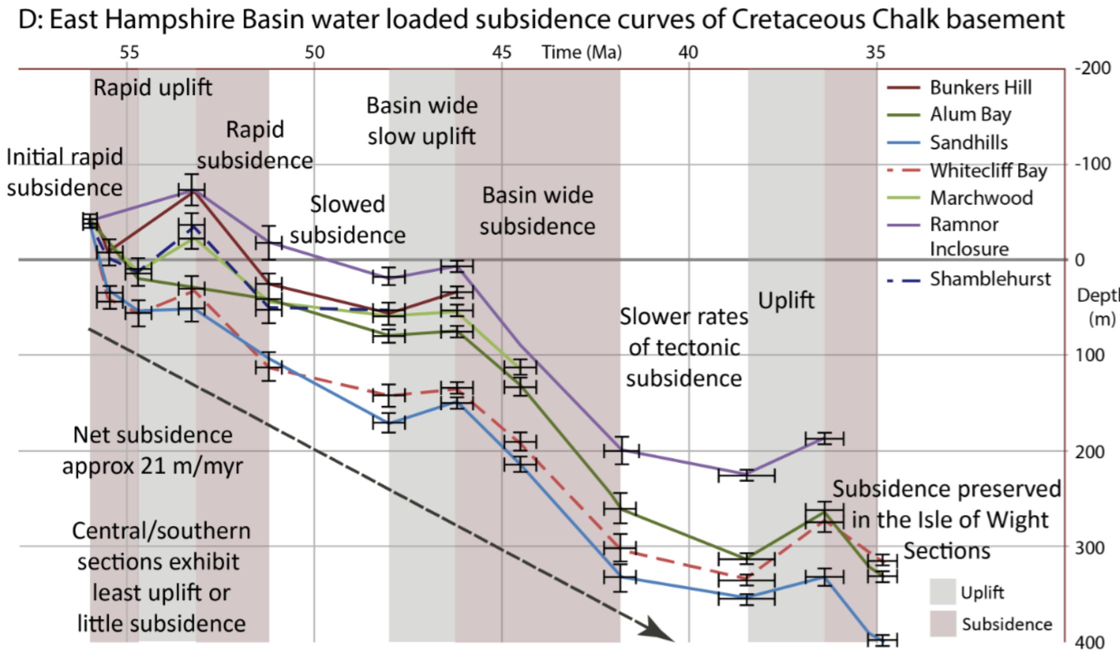


Figure 5.10: *Water loaded subsidence curves corrected for eustasy from Region D of figure 5.5, the eastern Hampshire Basin. Early subsidence and a phase of uplift and subsequent subsidence is suggested by the backstripping of 6 of the 7 boreholes and sections in this region.*

The net vertical motion is subsidence as shown by the three Isle of Wight curves and these models are in good agreement with each other. The spatial distribution of the east Hampshire Basin sections provide a good range of the local tectonic motions. All sections suggest a cycle of uplift and subsequent rapid subsidence between 56 and 51.2 Ma, except for Alum Bay. The interval of slow subsidence rates experienced by all sections from 51.2 Ma is not shown by the north-easternmost Shamblehurst borehole. From 48

Ma all sections show some magnitude of basement uplift until 46.2 Ma which then suggests basin-wide rapid tectonic subsidence until 38.5 Ma. The relative rate of tectonic subsidence slowed for all sections from 41.8 Ma. A late Mid to Late Eocene period of tectonic uplift is suggested by all three Isle of Wight sections and the Ramnor Inclosure borehole. The most easterly Whitecliff section and central Sandhills borehole show similar patterns of vertical basement motions, with a greater magnitude of subsidence suggested by the Sandhills borehole from 48.5 Ma. A late phase of uplift and subsequent subsidence is indicated by the Isle of Wight sections and the Ramnor Inclosure borehole. The rate of tectonic uplift and subsequent subsidence is similar in all four sections, despite varying depths to the basement.

5.3.5 Region E: East Anglia

The backstripped sections and boreholes of East Anglia (Figure 5.6: Region E.) preserve the oldest onshore stratigraphy of the UK in the Cenozoic, from the base of the Thanet Formation. The earliest onshore Paleocene and Eocene strata is preserved, but the Mid to Late Eocene, Oligocene and Miocene deposits are missing. Figure 5.11 shows the water-loaded subsidence curves of Region E in the East Anglia area.

Tectonic subsidence is exhibited by all the East Anglia sections from 58.5 Ma through to 54.7 Ma. The Ormesby borehole displays rapid tectonic subsidence between 55.8 Ma and 55.5 Ma. None of the other sections display this rapid subsidence. The Halesworth borehole dataset records subsidence between 55.8 and 55.5 Ma but shows slower rates of subsidence.

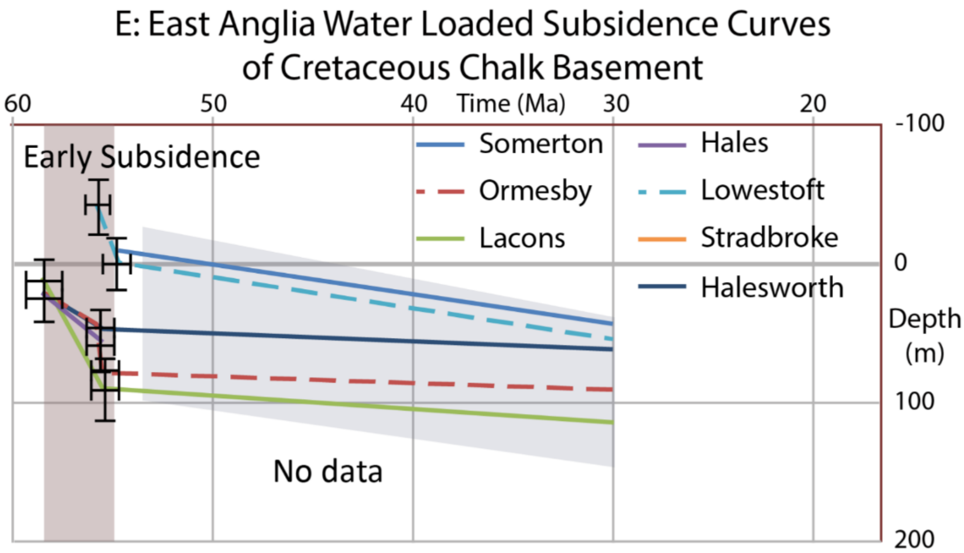


Figure 5.11: *Water-loaded subsidence curves corrected for eustasy from Region E of figure 4.5, East Anglia. An initial phase of subsidence is suggested by 5 of the 7 sections that preserve Early Paleogene strata.*

5.3.6 Summary of backstripped sections and dominant vertical surface motions

Analysing short wavelength and long wavelength variations by directly comparing all section across all areas is complicated and makes identifying patterns spatially difficult, figure 5.12 and 5.13. Chapter 6 attempts to solve the lack of spatial context when presenting the data. Two phases of subsidence and uplift can be observed in the Late Paleocene through to the Mid-Eocene. Most sections across southern England reflect this, with Late Paleocene uplift 58.5 Ma to 56 Ma predominantly preserved in the London Basin sections. Following this, rapid initial tectonic subsidence of the basement was predominantly accommodated in the central and eastern Hampshire Basin. Slower subsidence rates and magnitudes of subsidence were observed in the west Hampshire Basin and London Basin regions. The East Anglia sections suggest tectonic subsidence of the basement during a time when the London Basin is proposed to be undergoing uplift. Considering all sections, the net vertical motion is dominantly a tectonic subsidence regime with three uplift events, each lasting from 2-4 Myr and in most sections followed by longer durations of rapid subsidence. Long-term correlations with the eustatic curve of Miller *et al* (2005) shows a progressive decrease in sea-level as the basement subsided. The greatest overall subsidence is in the central Hampshire Basin.

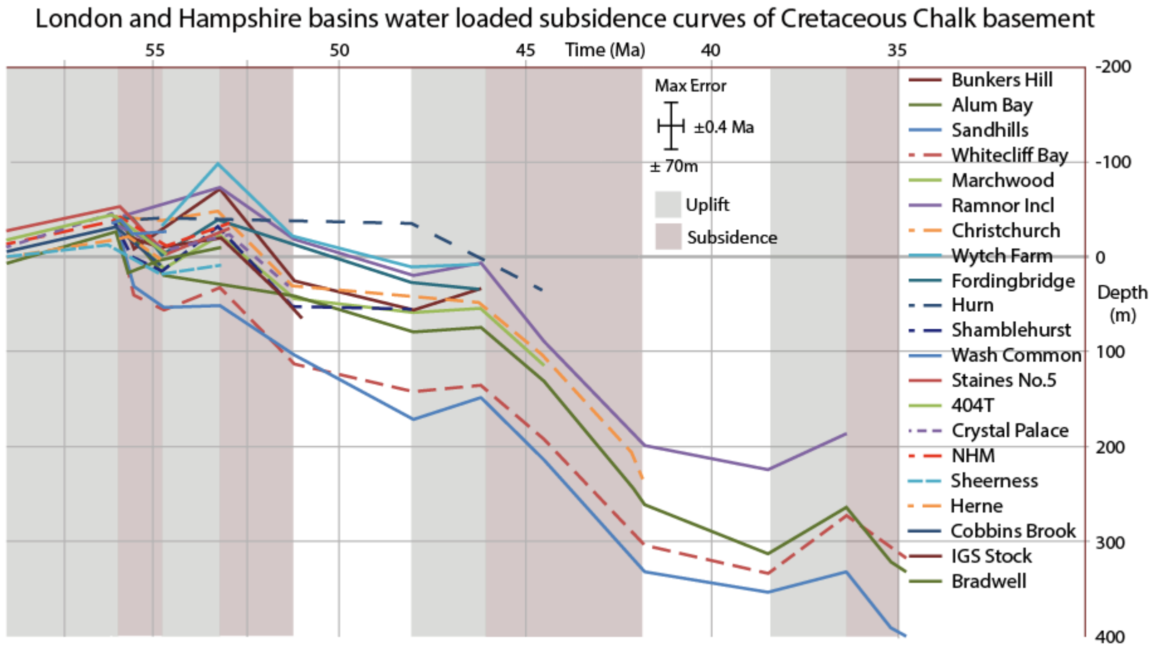


Figure 5.12: The London and Hampshire basin water-loaded subsidence curves corrected for eustasy, compiled into one graph. East Anglia curves are included alongside all other data in figure 5.13. Patterns of uplift and subsidence can be observed when all sections are directly compared. This graph shows the importance of dividing the curves into regions to assess them. The overall events can be observed but localised variations could be determined by dividing the data.

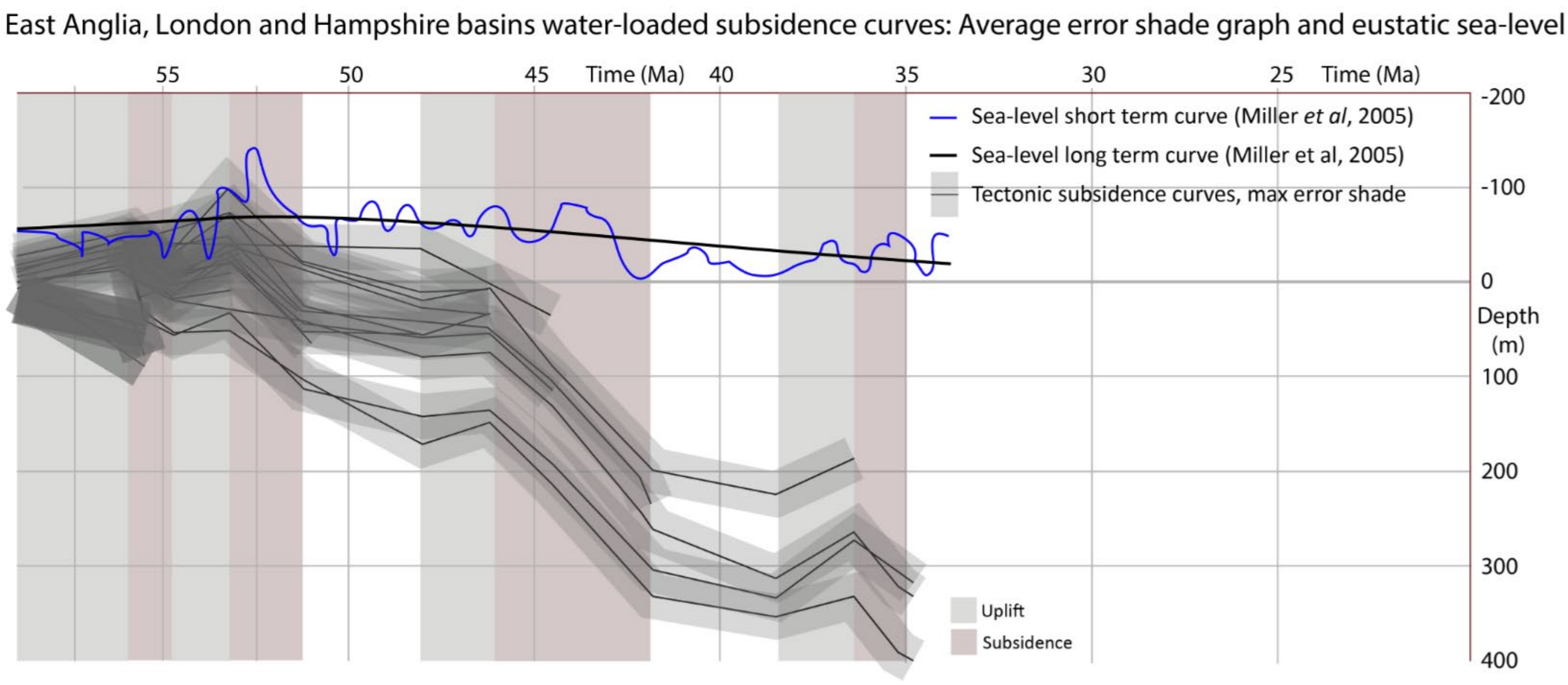


***Figure 5.13*:** The water loaded subsidence curves of south England using data from East Anglia and the London and Hampshire basins. The shading shows the maximum error. The subsidence of East Anglia while the rest of south England suggests uplift is shown between 58.5 and 56 Ma. The major uplift event shown from 54.7 and 53.2 Ma coincides with a regional water depth decrease. The comparison with the short and long term sea-level curves of Miller *et al* (2005) displays a correlation between progressive sea-level decline and the reduction of preserved sedimentary marine facies in the onshore Cenozoic record of the UK. The large time gap with no data between the Paleogene successions and the Pliocene/Pleistocene Crag deposits is very apparent. Correlating and contrasting the data across this time gap contains a large degree of uncertainty.

5.4 Discussion of vertical motions, sedimentation and eustasy

5.4.1 West London Basin subsidence curve discussion

Both areas (Region A and B) in the London Basin represent a relatively short amount of time, under 8 Myr, in comparison to the later Hampshire Basin sections. However they are important for correlation of regional events and localised tectonic signals during the Late Paleocene (58.5-56 Ma).

The net vertical motion is subsidence, as shown by the Crystal Palace section. All sections are in good agreement with each other but the spatial distribution is less than those sections of other areas studied. The most westerly and thinnest section studied, Wash Common, shows similarities in the vertical history but the total subsidence and temporal duration of the uplift and subsidence is greatly reduced when compared with the Central London sections. This suggests that the most westerly area of the London Basin endured lower degrees of uplift and subsidence. Taking into consideration the sea-level curve used, the majority of sedimentation during the Late Paleocene through to the Early Eocene could have been on a seabed up to 50m above the present-day sea level.

5.4.2 East London Basin subsidence curve discussion

The eastern boreholes and sections of Region B show similar patterns to the western district of Region A (Figure 5.6: Region B.). There is less conformity between the eastern backstripped sections and comparatively increased rates of uplift and subsidence are apparent. The general trends suggest that the net tectonic subsidence increases to the east in the London Basin and the comparison of all London Basin sections suggests that tectonic uplift of the basement occurred between 58.5 and 56/55.8 Ma, commencing in the Late Paleocene.

The very rapid and large amount of subsidence within less than 0.3 Myr suggested by the Bradwell borehole and its location in the north-east could be an anomaly, but other sections do show significant subsidence, though perhaps not of the same magnitude. There is a possibility this is a localised rapid subsidence event or the degree of subsidence is not as severe, as it is within the error margin and may more closely resemble the other sections. Conversely, it is possible the Stock borehole shows slower subsidence rates at this time and could be the anomaly.

The longer duration of uplift (continuing until 55.5 Ma) for the Herne Bay section suggests the basement in the most eastern areas of the London Basin was above present day sea-level. Again the correction for eustasy suggests that the majority of sedimentation occurred above present day sea level.

5.4.3 West Hampshire Basin subsidence curve discussion

The west Hampshire Basin subsidence curves cover an extended period of 12 Myr in comparison to the London Basin subsidence curves. There is consistency to the subsidence curve trends but the spatial distribution of sections provides insight into the relative motions across the western Hampshire Basin region. The Early Eocene initial subsidence that is followed by a phase of uplift and subsidence is comparable to the Early Eocene phase 2 seen in the London Basin sections. However, the initial uplift observed in the London Basin subsidence curves cannot be inferred, as the Thanet Formation was not deposited in the Hampshire Basin.

The Hurn section preserved no data between 54.7 and 53.2 Ma. When compared to other sections this interval occurs during uplift recorded by the most westerly sections. It is possible that the missing strata is a result of this uplift resulting in removal of some preserved strata and the limited sedimentation. The Wytch Farm and Christchurch boreholes to the south preserve some of the strata missing in the Hurn section. The Christchurch borehole is the easternmost backstripped section in Region C and suggests tectonic subsidence of the basement accelerated during the mid-Eocene from 46.2 Ma. The geographical position of the western sections and reduced subsidence can be related to the margins of deposition. The stratigraphy and depositional environments are dominantly near-shore or almost terrestrial suggesting the western Hampshire sections mark the margins of the basin which appear to have undergone less deformation than the central and eastern areas.

5.4.4 East Hampshire Basin subsidence curve discussion

The Sections backstripped resemble the most eastern Christchurch borehole of the western Hampshire Basin with similar vertical motions of the basement in the Early to Mid Eocene: initial subsidence followed by a cycle of uplift and further subsidence. The initial subsidence from 56 Ma is rapid, particularly in the eastern Isle of Wight sections which also displayed the deepest marine facies. This could suggest a tectonic control on basin accommodation at this point. The degree of tectonic uplift experienced appears to be greater in the more northern sections.

The missing strata at 53.2 Ma in the Alum Bay section does not produce an uplift signal similar to the other sections in this area. This could be a result of more uplift in this area preventing the preservation of strata or removing them shortly after deposition. This cycle of relatively rapid uplift and subsidence is similar to the western Hampshire Basin and London Basin backstripped curves. The degree of basement uplift shown by all sections from 48 Ma until 46.2 Ma is comparatively greater than the western Hampshire Basin subsidence curves, particularly in the south-eastern sections. The most easterly Whitecliff section and central Sandhills borehole show similar patterns of vertical basement motions, with a greater magnitude of subsidence suggested by the Sandhills borehole from 48.5 Ma. Spatially this suggests the centre of the Isle of Wight underwent the greatest net tectonic subsidence across all sections in the eastern Hampshire Basin. The very last cycle of uplift and subsidence between 48.5 and 34.8 Ma, from Early to very Late Eocene/ Early Oligocene, coincides with the progressive drop in global sea-level. Sedimentation may have continued beyond the youngest Bouldnor Formation from 34.8 Ma or an immediate sequence of uplift, or the sea-level drop may be responsible for the missing strata or the lack of extensive sedimentation.

5.4.5 East Anglia subsidence curve discussion

The tectonic subsidence signal suggested by all sections in East Anglia does not fit the cycles of Late Paleocene to Early Eocene uplift and subsidence shown by the southern London and Hampshire basin sections. All sections suggest East Anglia was dominated by subsidence, from the Paleocene to the Early Eocene. Overall there is limited data but figure 5.13 shows the subsidence from 58.5 to 54.7 Ma.

5.4.6 Subsidence curve discussion

From the correlation of backstripped sections of the onshore UK Cenozoic successions, the data suggest a strong agreement in dominantly regional subsidence of the Mesozoic Chalk basement from 58.5 to 34.8 Ma. However, the tectonic history is not straightforward as multiple phases of uplift are reflected in the curves during deposition of the Cenozoic succession. Two phases of uplift and subsequent subsidence during the Late Paleocene to Early Eocene have been extracted, between approximately 58.5 to 51.2 Ma (figure 5.12), common to most subsidence curves across south-east England with the exception of East Anglia. East Anglia sections suggest steady subsidence between 58.5 to 56 Ma at a time when the rest of the data suggests the basins were experiencing uplift, figure 5.11. The greatest amount of accommodation space is shown in the Hampshire Basin, also reflected by the preservation of the thickest of the Cenozoic successions. Data from the eastern area of the Hampshire Basin reflects the greatest subsidence rates, greatest amount of tectonic subsidence and the greatest sediment accumulation compared to western areas. The Early Paleogene rates of subsidence in the Hampshire Basin are greater than in the London Basin. This suggests that the Hampshire Basin produced additional accommodation space via tectonic motions during the Paleogene and may be the reason for the continued preservation of strata. After the correction for eustatic sea level change, the London Basin subsidence curves suggest the basement was consistently above present-day sea level and, as the eustatic sea level dropped, a reduction in the accommodation space would have occurred. This may be the reason younger Paleogene sediments were not deposited or preserved. Whether the London Basin continued to subside post 51.2 Ma is unknown. It may be that the London basin was starved of sediments, or less accommodation space developed but the comparison with the Hampshire Basin suggests sedimentation may have been more extensive when comparing the palaeobathymetry trends from chapter 4. The lithofacies also suggest a progressive shallowing of water depth in the London Basin from 54.7 Ma up until 51.2 Ma, after which no more strata are preserved.

A relationship between the progressive sea-level decline and transition of lithofacies to shallower water depth environments during the Paleogene in the Hampshire Basin is apparent prior to backstripping. This agreement suggests eustasy as a contributing factor to the starvation of sediment supply and reduction of marine conditions. Many sea-level curves present a progressive fall in sea-level from the Paleocene-Eocene Thermal Maximum (PETM) onwards (Brenchley and Rawson, 2006; Miller et al., 2005). This coincides with a reduction in tectonic subsidence rates and a sequence of uplift from 38.5 Ma as there is a basin-wide water depth reduction. A combination of both factors may have led to the reduction in accommodation space and the preservation of lithofacies that reflect a progressive transition to shallower water depths from the Late Eocene to Early Oligocene. The eustatic inferences are dependent on the sea-level curve used. The use of the Miller et al. (2005) sea-level curve suggests the basement in the London Basin was fairly consistently up to 100 m above present day sea level. If the Haq et al. (1987) sea-level curve was used the tectonic vertical motions after isostatic adjustment would have been up to 100 m higher. Given the additional data and agreement of other studies, this amount of additional height appears to be extreme (Kominz, 2001). This supports the care needed when considering the global sea-level changes through time.

Studies that use backstripping of wells and boreholes to develop a model of the spatial developments of tectonic motions usually use very few sections, such as the study of Sclater and Christie (1980). Therefore direct comparisons between their spatial positions and the pattern of subsidence can be made. However with the amount of sections analysed in this study an additional method is applied to profitably compare and discuss the spatial relationships of the tectonic basement during the Cenozoic. The evolution of the basement is represented by developing the subsidence values from points to surfaces in chapter 6. A full discussion of the implications of the suggested vertical motions is compiled with the palaeobathymetric and tectonic subsidence surface data in chapter 7.

5.5 Subsidence curve conclusions

The water-loaded subsidence curves corrected for eustasy suggest that two phases of uplift and subsidence occurred between 58.5 to 51.2 Ma and were common to sections in the London and Hampshire basins. East Anglia records only subsidence from 58.5 to 54.7 Ma. Beyond this, the Hampshire Basin continued to subside alongside progressive sea-level fall until 34.8 Ma, after which no more data is available. Prior to this an uplift event is suggested in the eastern area of the Hampshire Basin between 38.5 and 36.2 Ma. The subsidence curves from the London Basin suggest the Chalk basement was predominantly above present-day sea level during the Early Paleogene. This temporal assessment provides little information on spatial patterns and so the data needs to be manipulated for analysis on short and long wavelengths patterns. To fully quantify the spatial relationships of contrasting tectonic motions of the Chalk basement, a 2D and 3D analysis is essential.

Chapter 6: Tectonic subsidence surfaces

The method of backstripping is essentially a point data technique, with each water-loaded subsidence curve providing the vertical motion history for a single locality. To assess the vertical variations across an area, multiple sections are used to provide interpretations on the evolving deformation in a region of interest. In this study 28 sections from across south-east England have been analysed on a regional scale to constrain the potential changes in vertical surface motions. Chapter 5 contained the backstripping data that was predominantly analysed temporally, providing trends for subsidence and uplift during the Paleogene. These were grouped into areas relating to the Cenozoic outcrop to provide some spatial context to these patterns. In doing so chapter 5 highlighted the limitations of discussing the spatial variations in vertical surface motions across a large geographical area using only a graphical format.

As the temporal component has been successfully analysed, in this chapter the merits of developing a spatial context of basement vertical motions will be tested by developing the data into water-loaded subsidence surfaces that represent tectonic surfaces, showing the spatial variations. The suggestion is that the spatial variations will provide clues to shorter wavelength variations and potential long wavelength variations in vertical surface motions that are not easily recognisable using a traditional graph format. In this chapter it is proposed that relying on water-loaded subsidence curves to assess the potential for analysing short wavelength variations and constraining tectonic mechanical interpretations is inefficient and a cartographic approach is greatly superior, informing and furthering interpretation with minimal data manipulation.

6.1 Previous studies using the spatial distribution of tectonic subsidence data

The water-loaded subsidence curves produced in Chapter 5 were appropriate for analysing the rates of vertical surface motions, total subsidence and the degree of uplift, particularly for correlating the vertical motions temporally and contrasting the subsidence patterns of all boreholes and sections used across south-east England. To understand the movement of the Chalk basement during the Cenozoic and understand the possible influences on the vertical surface motions, a spatial analysis is conducted by developing surfaces from the water-loaded subsidence data. The advantage of creating tectonic surfaces is the cartographic display of the comparative variation of vertical motions with spatial context, thus leading to interpretations on short wavelength and long wavelength variations. Additionally, the Cenozoic movements can be superimposed on to known geological structures and features. Relating the geometry and relief of the Mesozoic Chalk basement to known structures and features can lead to regional inferences and interpretations of the tectonic regime of south-east England and the possible mechanisms influencing the development of the UK basins during the Cenozoic. The backstripping of the Alpine Molasse by Zweigel et al. (1998) was mentioned in Chapter 4 and 5 and the method used is relevant to the spatial use of backstripped sections and the development of surface models in this study. Zweigel et al. (1998) used backstripped sections and their spatial distribution to infer the likely tectonic regimes; they used three backstripped wells with one in the north, one in the south, and one central well in order to compare the evolving tectonic responses across the Alpine Molasse. Direct comparisons between subsidence curves are made in order to infer the most likely tectonic mechanisms. This direct correlation method is suitable for a study using three wells and a localised area. A total of 28 sections were backstripped in this study and temporal correlations were completed in Chapter 5. Although the subsidence curves were divided into regions of interest, this method has limitations in analysing the spatial relationships between backstripped sections. Therefore the method using tectonic surfaces to understand the basement evolution during the Cenozoic is appropriate and adds context to the data, furthering and refining the interpretations on short wavelength variations. Previous studies using 2D approaches in backstripping are becoming more common but the use of 3D modelling is rare. Studies that employed a 2D or 3D approach to backstripping a study area and multiple wells recognised the need to understand the possible lateral variations of the data, not limiting interpretations to direct point to point correlations (Roberts et al., 1998; Zhou, 1993). The limitations of backstripping in 1D were also particularly recognised by studies focused on salt diapirs due to their fluid nature and mobility in geological time in comparison to the surrounding stratigraphy. To truly restore their flow and likely distribution through backstripping, 2D and 3D approaches were applied (Ismail-Zadeh et al., 2001; Scheck et al., 2003).

6.2 Basement surface method using GIS

A similar approach to that used for developing the palaeobathymetric surfaces was used to produce the tectonic basement surfaces (Chapter 4, section 4.4). Contouring of the tectonic subsidence surfaces was digitally rendered using a nearest/neighbour gridding method using the Surfer 10 software. Extrapolation from each data point is exponentially reduced as the distance from between the grid node and data point increases. The areas of fewest data points have the greatest uncertainty. The spatial distribution of the Cenozoic succession is in two dominant regions: the London Basin and the Hampshire Basin. East Anglia has a comparitvely limited spatial extent and relates more to the London Basin, both geographically and stratigraphically. As was the case with the palaeobathymetric surfaces, this leaves an area lacking in data across the Weald where no Cenozoic deposits are preserved. Extrapolation across these regions devoid of Cenozoic deposits has been limited. The surfaces produced also do not extrapolate outside the furthest data points. The result of these factors produces a surface represented by data with less artificial architecture than other interpolation techniques. Surface gridding was by using a digital method, preventing personal bias. The raw data is inputted independently of vertical surface motion interpretation and extrapolation between data points is reduced to within the proximity of data points. A surface with a high density of data points will be more reliable than a data surface with few points. However the region of interest for most surfaces scales down with reduction of data points.

Water-loaded basement depth values were assigned to the z-axis of the data in preparation for development of tectonic subsidence profiles and later 3D rendering in ArcScene, which is discussed in section 5.6. The .grd data was inserted into ArcGIS 10.3 and was projected with British National Grid (NGR) referencing, geographically projected in Ordnance Survey Great Britain 1936 co-ordinates.

In this case, contours are layered on to tectonic surfaces to highlight the gradient of slope and elevation variations. This was not acceptable in the palaeobathymetry as it suggested architecture within the bathymetry extrapolated from the data. As the palaeobathymetric surfaces were representation of a surface that existed in space and time a conservative approach to surface generation was taken, showing variations in palaeobathymetry limited to the proximity of data points. As such the contours were removed to prevent additional interpretation of bathymetric variations away from data points. However, the tectonic surfaces generated in this chapter represent a theoretical digital elevation model (DEM) of the vertical surface motions of the basement Chalk surface with the effects of sediment loading removed. The surfaces themselves did not exist in space-time and therefore any additional data rendered are from the same extrapolated data with similar calculated error margins, complementing the cartographical representation.

6.3 The limitations in constraining basement surfaces

The tectonic surfaces are developed from the water-loaded subsidence data corrected for eustasy using the backstripping method, and assuming Airy isostatic compensation. Ideally when analysing the sections in 2D or 3D it has been recognised to be advantageous to apply a flexural mode of backstripping to other localised studies (Roberts et al., 1998); however, the reasons for taking an Airy approach are discussed in Chapter 5, section 5.1.7.

Backstripped sections use water depth values determined from the palaeobathymetric data (Chapter 4). The palaeo-water depth determination and backstripping contain a maximum uncertainty and so the surface development inherits the uncertainties and these are outlined in Chapter 5. In terms of developing these basement motions into surfaces, the main areas of limitation are the density of available data points and the areas of no data. As previously discussed, sections selected for backstripping were required to meet a set of criteria to be suitable for use in this study. This reduced the volume of available data spatially suitable for surface development and led to some areas of poor data cover. To counter this limitation, quantitative inferences on the development of the Mesozoic Chalk basement are restricted to data points and close proximity to neighbouring data points. As such the basement geometry and gradient is inferred only in data-rich areas.

The inference of basement deepening trends from the tectonic surfaces is limited to their spatial extent and are representative of the area covered. It is fair to assume that the overall basement deepening trends may vary if additional data was available for the tectonic surfaces. The tectonic surfaces are used as spatial context for the variations in the Chalk basement during the Cenozoic alongside the tectonic subsidence curves described in Chapter 5. The 3D rendering and stacking of all tectonic surfaces in section 6.5 of this chapter provide additional spatial context in the horizontal and vertical planes. All data are analysed and fully discussed in Chapter 7.

6.4 Results: Tectonic subsidence surfaces

Tectonic surfaces are developed from the water-loaded subsidence curves of the Chalk basement in Chapter 5. All 28 backstripped boreholes and sections used in the previous chapter were used to develop the tectonic surfaces. The compiled water-loaded subsidence values for every section was used to compile spreadsheets of basement elevation for each time interval, appendix 4. Figure 6.1 is the map used in Chapter 5 to show the distribution of the data points and as such reflects the maximum extent of the tectonic surfaces developed. Not all sections and boreholes will contain the full sequence of lithostratigraphies due to the outcrop of pattern of the Cenozoic succession and localised stratigraphic hiatuses. This will reduce the extent of some tectonic surfaces as a surface cannot be generated from point data if the stratigraphic unit is missing for aforementioned reasons.

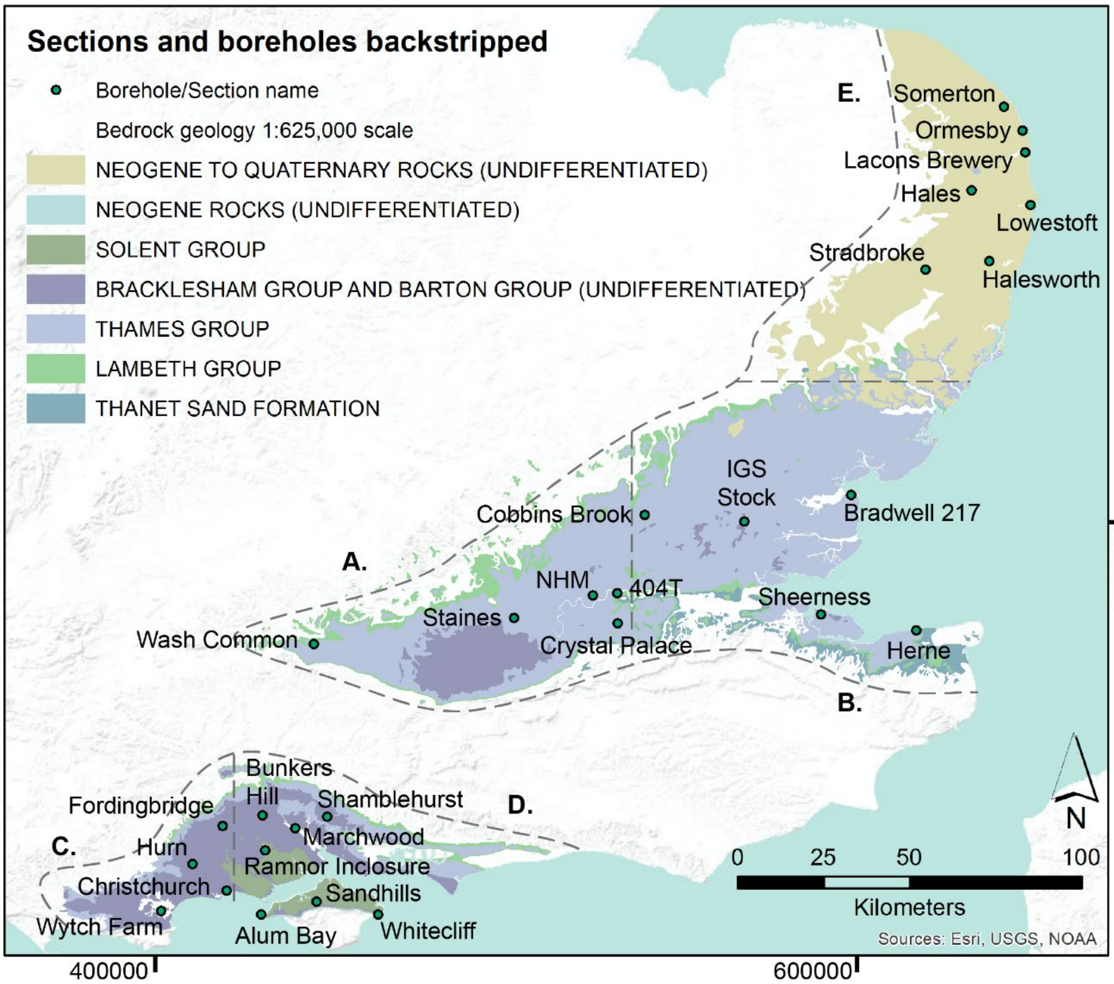


Figure 6.1: *Map shows the location of sections and boreholes backstripped. Details of the regions A-E are discussed in Chapter 5 (figure 5.5). The distribution of data points and the absolute maximum of tectonic surface extent can be seen. Not at all backstripped sections, (i.e. boreholes) preserve a full sequence and so the extent of tectonic surfaces is reduced.*

6.4.1 Thanet Formation - 58.5Ma (Late Paleocene)

The tectonic surface of the Mesozoic Chalk basement during the deposition of the Thanet Formation, 58.5 Ma, is represented in figure 6.2. It is the oldest lithostratigraphic unit and is deposited on the top of the Mesozoic basement, so the relief of the water-loaded subsidence surface should resemble the palaeobathymetric surface developed in chapter 4. This assumes that the Chalk is an incompressible unit.

The tectonic surface shows the Mesozoic basement reflecting a tilt towards the north-east and east-north-east. This basement tilt is suggested to exist as the earliest Cenozoic lithostratigraphic unit with its basal surface dated at 58.5 Ma. The northern areas of East Anglia reflect a basement depth up to 50 m deeper than the south-western areas in central London. The central London data points are of a Mesozoic basement existing above present day sea-level (up to 30m higher). These points demonstrate consistent water-loaded subsidence values above the present-day sea-level, with the highest relief at the western point. The basement depth increases eastwards in the Central London area. Boreholes and sections preserving the Thanet Formation are sparse in the southern areas of East Anglia, so inferences on the depth to the water-loaded basement are unreliable from the surface alone. Contouring in this area is limited to representing a shallow gradient progressing to greater basement depths in the north-east.

The tilt spans from the western London basin to the northern East Anglian data points, the data suggesting a wavelength pattern longer than intra basin variations. Variations within the London Basin are not pronounced enough to suggest any shorter wavelength patterns.

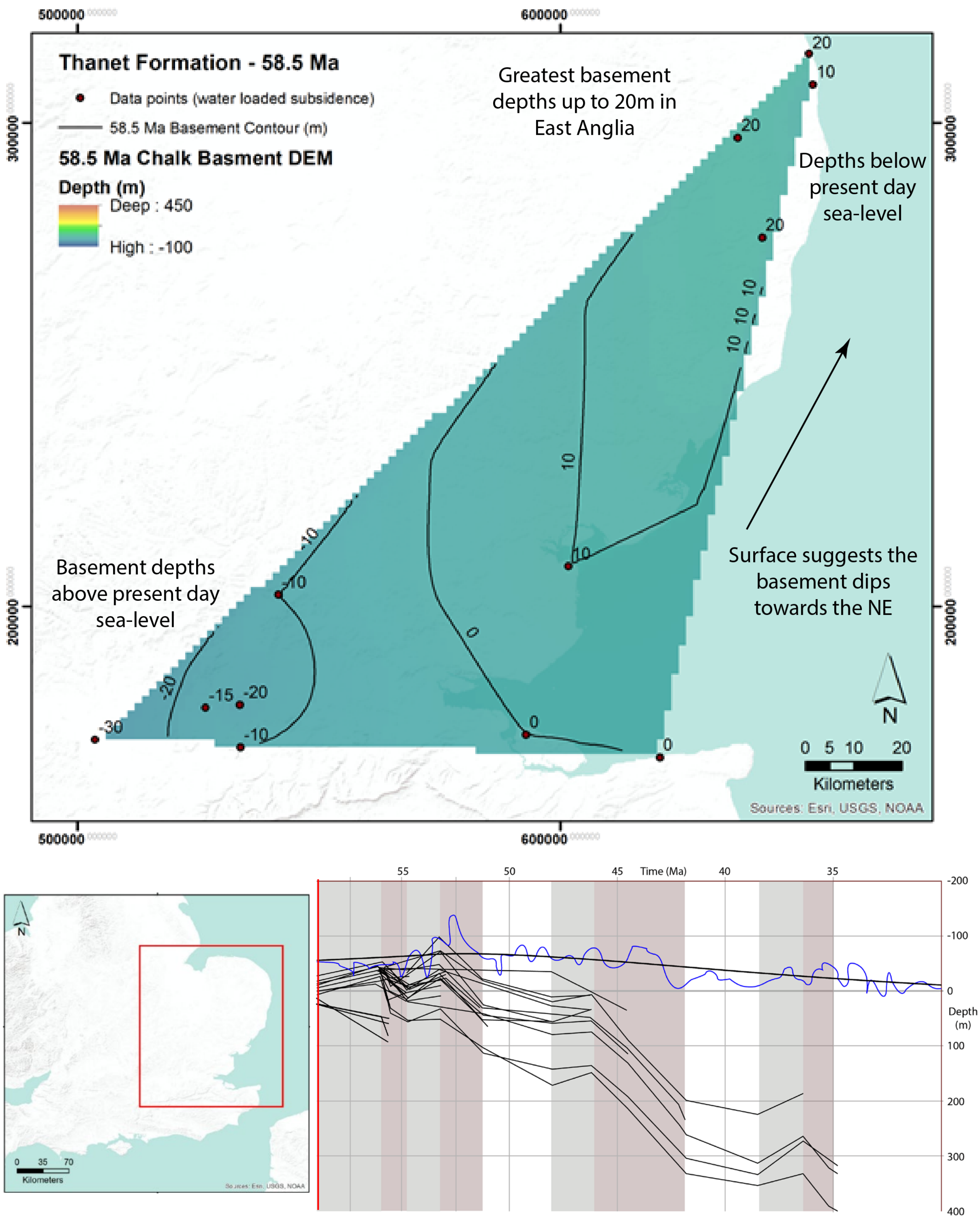


Figure 6.2: *The water-loaded subsidence surface for the Mesozoic Chalk basement as the Thanet Formation was deposited, 58.5 Ma. It is the oldest lithostratigraphic unit and is preserved on top of the Mesozoic Chalk and so the water-loaded subsidence surface should reflect the palaeo-sea floor. Given the regional scale, the surface suggests the basement was dipping towards the north-east, with south-west water-loaded subsidence data points suggesting the basement was up to 30 m higher than present-day sea-level. The red box outlines the area of the tectonic surface analysed. The red line on the subsidence curves shows the time level used for the tectonic surface.*

6.4.2 Lower Reading Formation - 56 Ma (Early Eocene, Ypresian)

The water-loaded subsidence data points are limited to the southern and eastern areas of the London Basin and the western and central areas of the Hampshire Basin, at a level of approximately 56 Ma, figure 6.3. The spatial extent is reduced in the London Basin surface due to available data. The Mesozoic basement is suggested to be up to 54 metres above the present day sea-level in the London Basin and up to 44 metres above in the Hampshire Basin. The backstripping suggests there is a basement high in the Central London area which has a shallow dip to the west and has a steeper slope towards the east. The surface in the London Basin has a thin spatial extent and so inferences on dominant basement tilt orientations are restricted. The data suggests the basement high in the London Basin is more marked in the western areas of the London Basin; it is possible that the basement was a greater depth farther east based on the contouring.

With no deposits of the Thanet Formation present in the Hampshire Basin, the Lower Reading Formation was deposited onto the Mesozoic Chalk basement. Therefore the Hampshire Basin tectonic surface should reflect the relief of the Chalk basement at 56 Ma and the palaeobathymetry. Although a palaeobathymetric surface was not developed for the Lower Reading Formation, the sedimentary facies and water depths in the Hampshire area for 56 Ma are in backstripped sections in Appendix 2. The Hampshire Basin has similar water-loaded subsidence values across the basement, with a possible high in the central areas. All data points in the Hampshire Basin have similar water-loaded subsidence values of the Mesozoic Chalk basement that are consistent with the central and western London Basin data points.

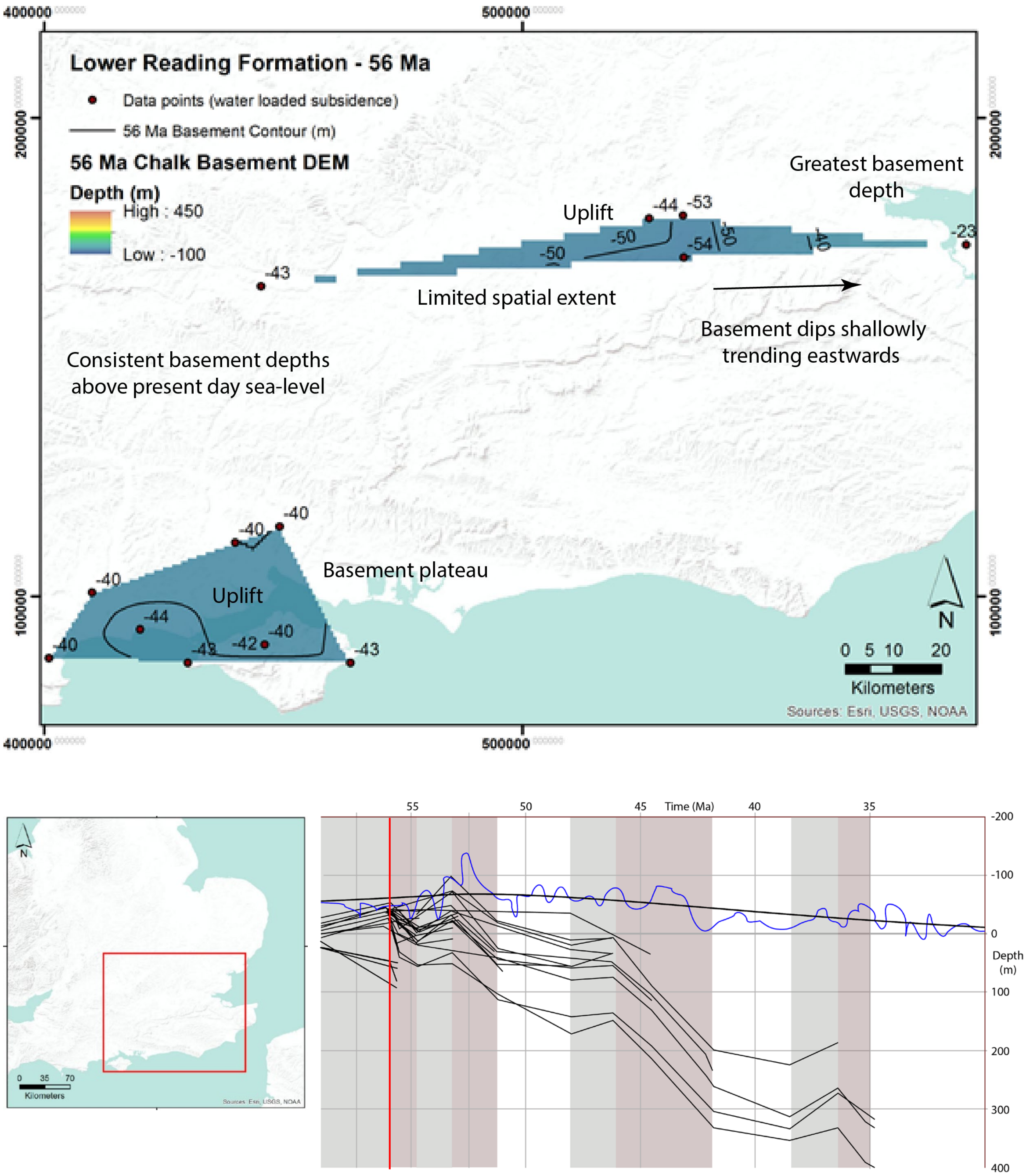


Figure 6.3: *The water-loaded subsidence surface for the Mesozoic Chalk basement as the Reading/ Woolwich Formation was deposited, 56 Ma. It is the oldest lithostratigraphic unit and is preserved on top of the Mesozoic Chalk and so the water-loaded subsidence surface should reflect the palaeo-sea floor. Given the regional scale, the surface suggests the basement was gently dipping towards the north-east, with south-western water-loaded subsidence data points suggesting the basement was up to 30 m higher than present-day sea-level. The red box outlines the area of the tectonic surface. The red line on the subsidence curves shows the time level used for the tectonic surface.*

6.4.3 Reading and Woolwich formations - 55.8 Ma (Early Eocene, Ypresian)

The tectonic surface of the water-loaded Mesozoic Chalk basement at 55.8 Ma, figure 6.4, shows data points lie predominantly in East Anglia and the London Basin. Dividing the Reading and Woolwich formations from the Lower Reading Formation was difficult for the Hampshire Basin as the Woolwich Formation is not present and the lithofacies are more uniform in the older 56 Ma Reading Formation strata.

A basement maximum high of 61 metres above present-day sea-level is suggested in the Central London area. To the east of this data point are similar water-loaded subsidence values between 45 and 50 metres above present-day sea-level. The tectonic surface shows a basement high existed in Central London and in eastern East Anglia with comparable subsidence values up to 54 metres above present-day sea-level. There is a lack of data in southern East Anglia.

The eastern London Basin points reflects a basement at a greater depth than Central London. The marine lithofacies of the Woolwich Formation preserved in the eastern London Basin suggests that subsidence of the Mesozoic Chalk basement created the accommodation space, allowing the deposition of these units. The most northern data point in East Anglia suggests a water-loaded subsidence value of 43 metres depth. This is the only data point reflecting a depth to basement below the present-day sea-level at the time the Reading and Woolwich formations were being deposited. It is 86 m lower than the neighbouring data point in East Anglia. It is either an anomalous data point or there is a shift in depth to the Mesozoic Chalk basement in northern East Anglia within close proximity to a shallower basement depth.

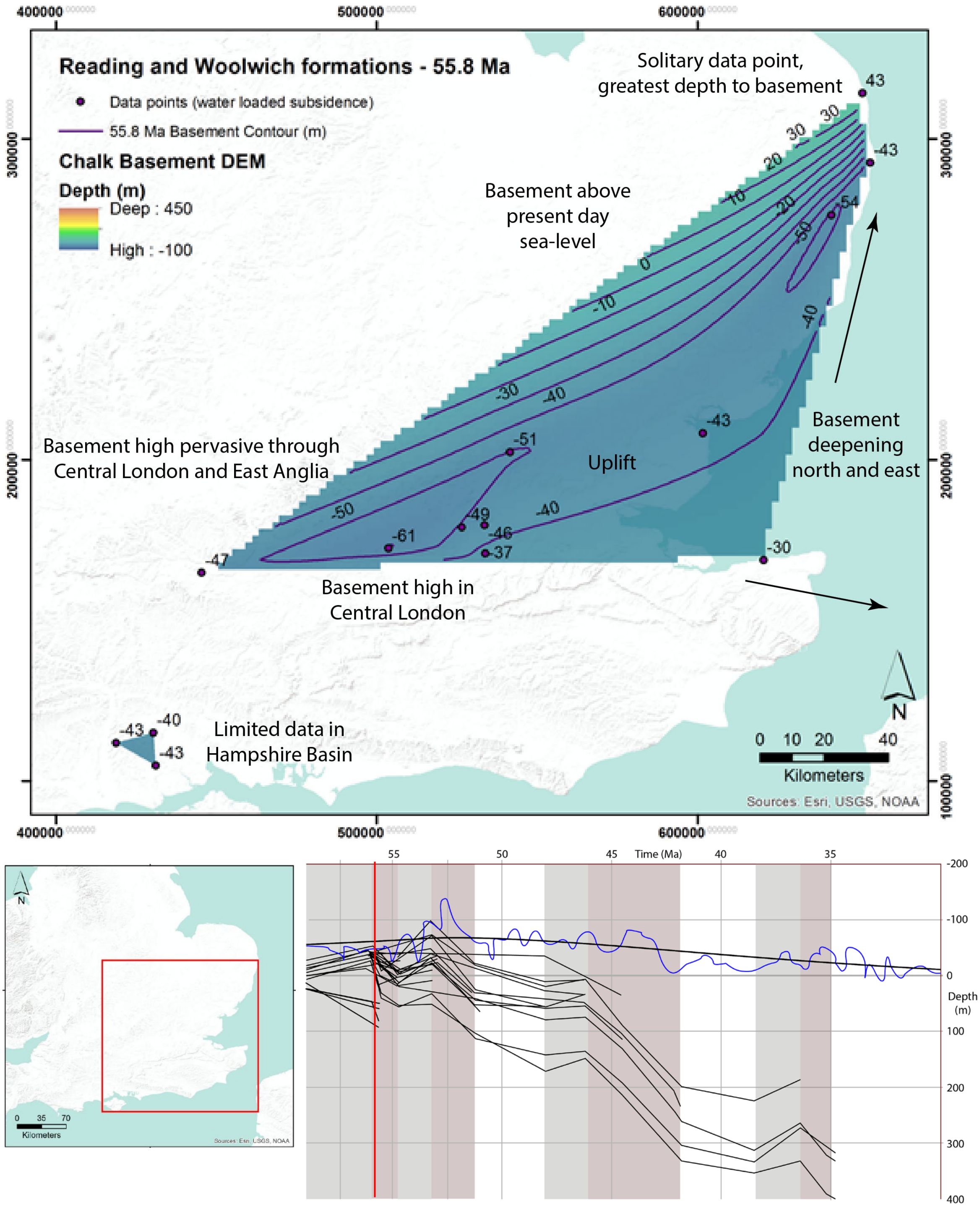


***Figure 6.4:** The tectonic surface for the Mesozoic Chalk basement as the Reading and Woolwich formations were deposited, 55.8 Ma. The tectonic surface reflects tectonic high values, particularly in Central London and East Anglia. The depths to the water-loaded basement are fairly consistent with a maximum high of up to 61 metres above present-day sea-level. The most northerly data point in East Anglia suggests the only value below present-day sea-level. This water-loaded subsidence value could be an outlier in the data. The red box outlines the area of the tectonic surface analysed. The red line on the subsidence curves shows the time level used for the tectonic surface.*

6.4.4 Harwich Formation - 55.5 Ma (Early Eocene, Ypresian)

The general pattern of the water-loaded Mesozoic Chalk basement at 55.5 Ma, figure 6.5, suggests large depths in East Anglia, and the southern Hampshire basin. Conversely the surface suggests that the London Basin and northern Hampshire Basin areas reflect a tectonic high in which the basement was above present-day sea-level. The maximum depth of the basement in the London area is up to 35 metres above present-day sea-level and in the Hampshire Basin it is up to 43 metres above present-day sea-level. The data point distribution in northern East Anglia shows the consistent water-loaded basement depths of up to 90 metres below present-day sea-level.

The tectonic surface suggests a north-easterly tilt of the Mesozoic Chalk basement at 55.5 Ma from Central London towards East Anglia. Inferences on the basement relief in Central London are uncertain as the data is sparse in this area. There is a transition between the London Basin area and southern East Anglia from a basement high of -35 metres to 26 metres depth within a distance of 20-30 km. The linear shape of this feature is most likely a result of the data point distribution; additional data points could show a different geometry to the shallowing of the contours.

The Hampshire Basin data suggests the Mesozoic Chalk surface was tilted towards the south-east at approximately 55.5 Ma. The northern margins are consistently shallower at basement depth. The tectonic surface reflects an overall subsidence from the previous tectonic surface at 55.8 Ma. The largest amount of net subsidence is seen in the eastern London Basin and East Anglia. Considering there is a time gap of 0.3 Myr between the previous tectonic surfaces of 55.8 to 55.5 Ma, this a rapid transition in the subsidence of the Chalk basement, highlighting shorter wavelength variations in vertical motions in the London Basin area.

Some of the selected backstripped sections in the Central London area do preserve the Harwich Formation; however, the strata are too thin (<1m) to be backstripped effectively, for example in the Crystal Palace and 404T boreholes. There are thicker sequences in East Anglia. These deposits remain useful and are discussed in chapter 7.

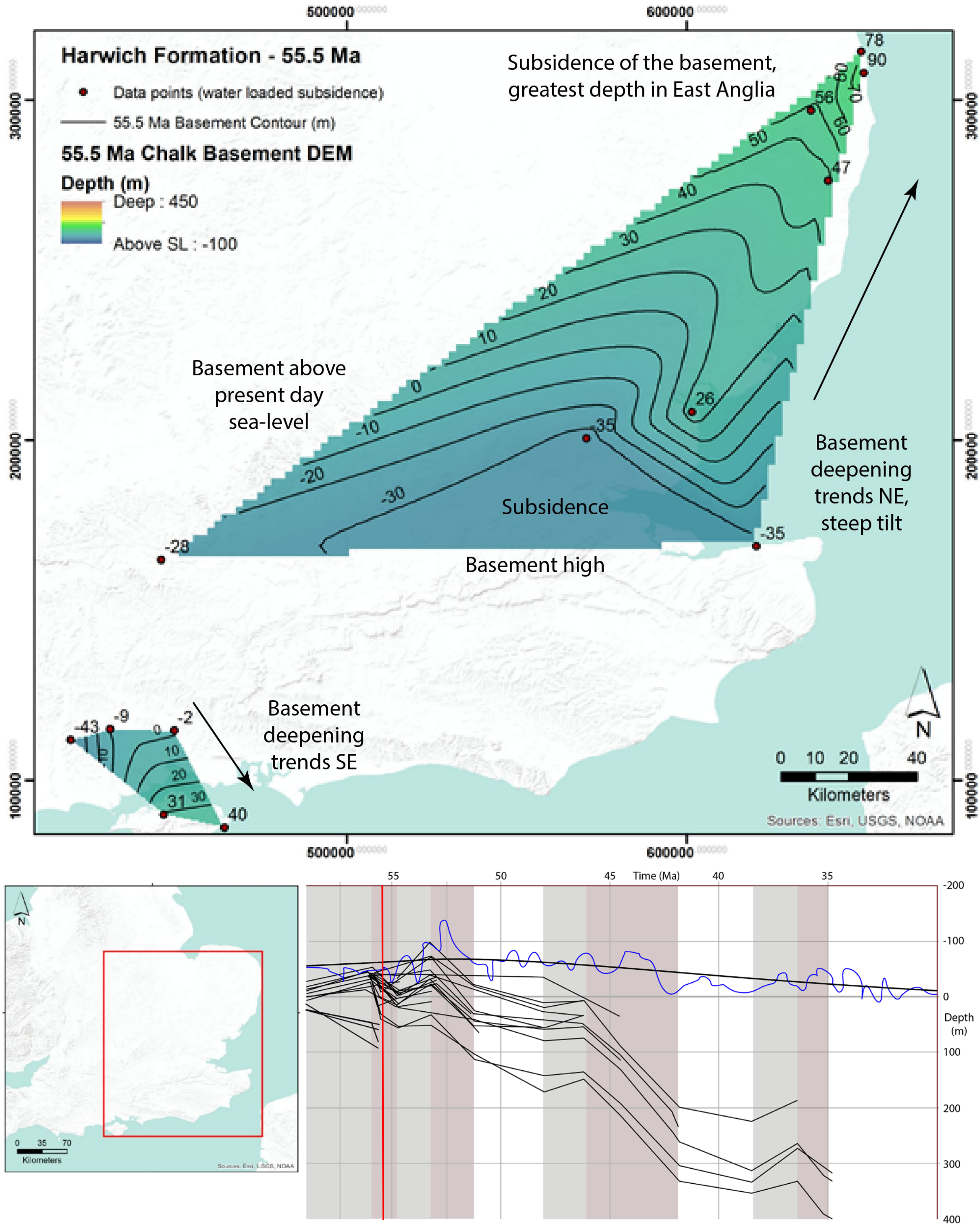


Figure 6.5: *The tectonic surface for the Mesozoic Chalk basement as the Harwich Formation was deposited, 55.5 Ma. The tectonic surface reflects an overall subsidence from the previous tectonic surface at 55.8 Ma. The red box outlines the area of the tectonic surface. The red line on the subsidence curves shows the time level used for the tectonic surface.*

6.4.5 London Clay Formation (Div A + B) - 54.7 Ma (Early Eocene, Ypresian)

The tectonic surface of the Mesozoic Chalk basement at 54.7 Ma, figure 6.6 shows that the most western and northern areas of both the London and Hampshire basins are above or close to present-day sea-level with the Central London area exhibiting basement depths lower than present-day sea-level. The eastern London Basin data points suggest greater depths to the water-loaded basement at a maximum of 13 metres depth on the Isle of Sheppey. Fewer data points are available in East Anglia, with two points suggesting the water-loaded basement was up to a maximum of 10 metres above the present-day sea-level.

A comparatively greater density of data points than the previous surface are available for the Hampshire Basin at 54.7 Ma. The water-loaded basement depths are not too dissimilar to the previous basement surface of 55.5 Ma. The Hampshire Basin suggests further subsidence of the basement, of up to a maximum depth of 56 metres in the central areas, geographically centred on the present-day Isle of Wight. The basin margins in the west and north-west may have been up to a maximum water-loaded basement high of 43 metres above present-day sea-level. Transecting across the Hampshire Basin, the surface suggests that the Mesozoic basement dips to the east, transitioning from above to below present-day sea-level. Extrapolation of this pattern may suggest an eastwards increase of basement depth.

The geometry of the Mesozoic basement at 54.7 Ma reflects a similar pattern to the outcrop pattern. The largest basement depths are suggested in the eastern sections and the tectonically highest basement values in the sections farthest west. The Central London data points suggest a tectonic high with basement deepening to the east and west. Extrapolation of the contours suggest that the basement depth would increase farther east. There is a greater temporal range of data points are present in the Hampshire Basin than in the London Basin, potentially revealing short wavelength variations in vertical motions that cannot be determined in the London Basin due to the lack of data. Given the lower density of the data in the London Basin, it is likely shorter wavelength variations may not be represented at a high enough resolution.

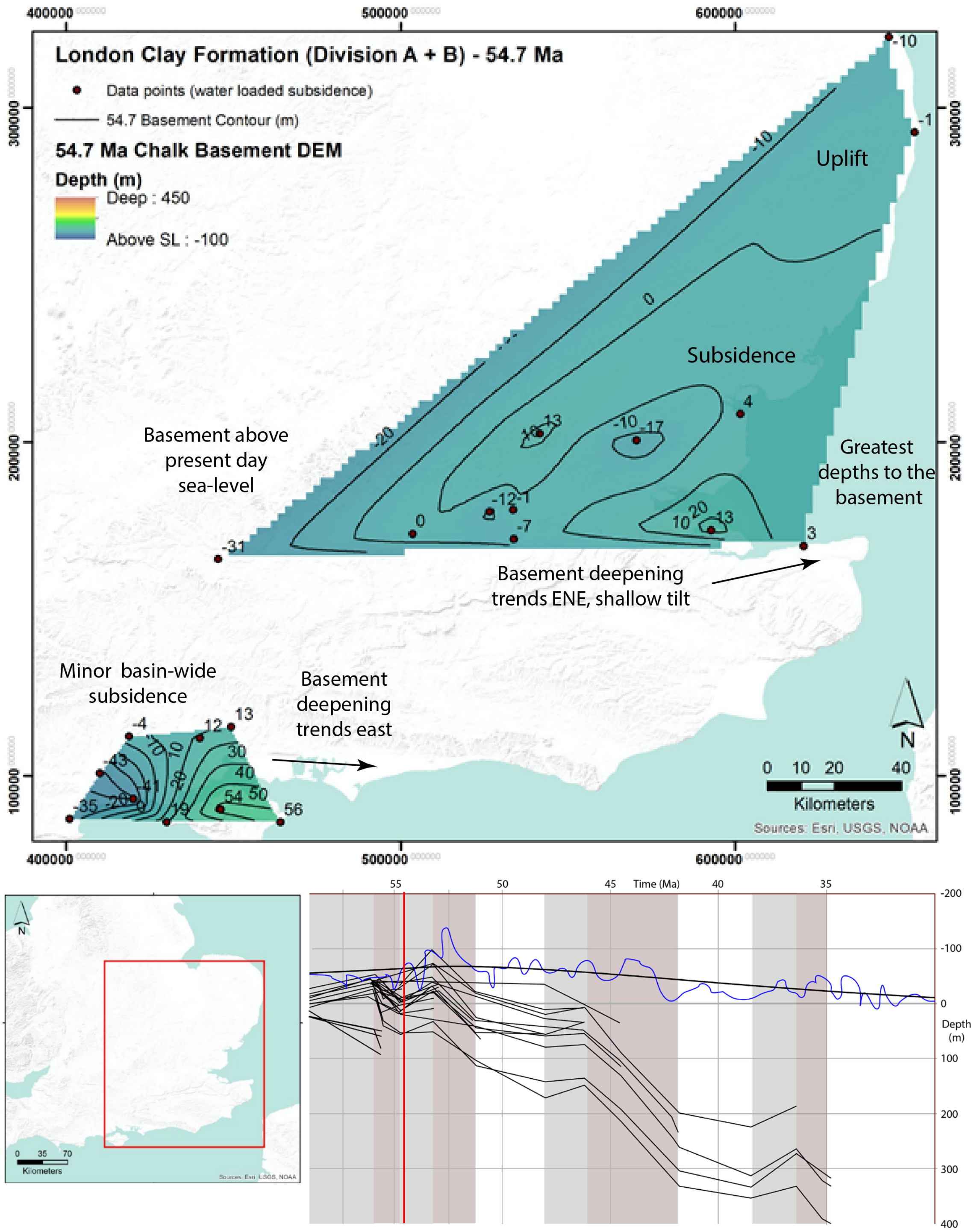


Figure 6.6: *The tectonic surface for the Mesozoic Chalk basement as the London Clay Formation (Division A + B) was deposited, 54.7 Ma. An overall reduction in depth to the water-loaded basement has occurred between the 55.5 Ma tectonic surface and the 54.7 Ma surface. The red box outlines the area of the tectonic surface. The red line on the subsidence curves shows the time level used for the tectonic surface.*

6.4.6 London Clay Formation (Div C + D) - 53.2 Ma (Early Eocene, Ypresian)

The tectonic surface at 53.2 Ma as the London Clay Formation (Division C+D) was deposited shows a reduced spatial extent than the previous surface at 54.7 Ma as no useful data was available in East Anglia, figure 6.7.

The surface suggests the basement in the London Basin was dominantly above present-day sea-level by up to 42 metres in the central and western regions. A reduction in basement high eastwards and northwards is observed in the data which falls below present-day sea-level in the easternmost data point on the Isle of Sheppey and indicates the greatest depth to the water-loaded Mesozoic Chalk basement. The data points produce a tectonic surface of the basement reflecting an east-south-east dip. Comparing the London Basin area of the basement surface at 53.2 Ma to the older 54.7 Ma surface shows a widespread uplift event seen in all data points, with a maximum of 30 metres in the central areas of London. This phase of uplift can be clearly seen in the subsidence curves of chapter 5. Importantly, this highlights the need for a spatial representation of this data.

The water-loaded basement data from the Hampshire Basin at 53.2 Ma shows an easterly trend of basement dip with the water-loaded basement high of 101 metres above present-day sea-level in the most westerly data point. It has a similar pattern to the older 54.7 Ma surface. All data points suggest that up to 70 metres of basement uplift has occurred between the older 54.7 Ma surface and the 53.2 Ma surface. All northern and western data points indicate water-loaded basement depths above present-day sea-level. The greatest depth to the Chalk basement is shown by the Sandhills borehole data point at 51 metres. This appears to be the centre of a tectonic depression as the basement depth shallows farther east. With no additional data to the east and north-east, it is uncertain as to whether the basement continues to deepen away from the projected tectonic surface.

This is the last tectonic basement surface covering the London Basin and interpretations on possible vertical developments of the basement are made in chapter 7 using the subsidence curves and surfaces discussed in this chapter 4 and in chapter 5.

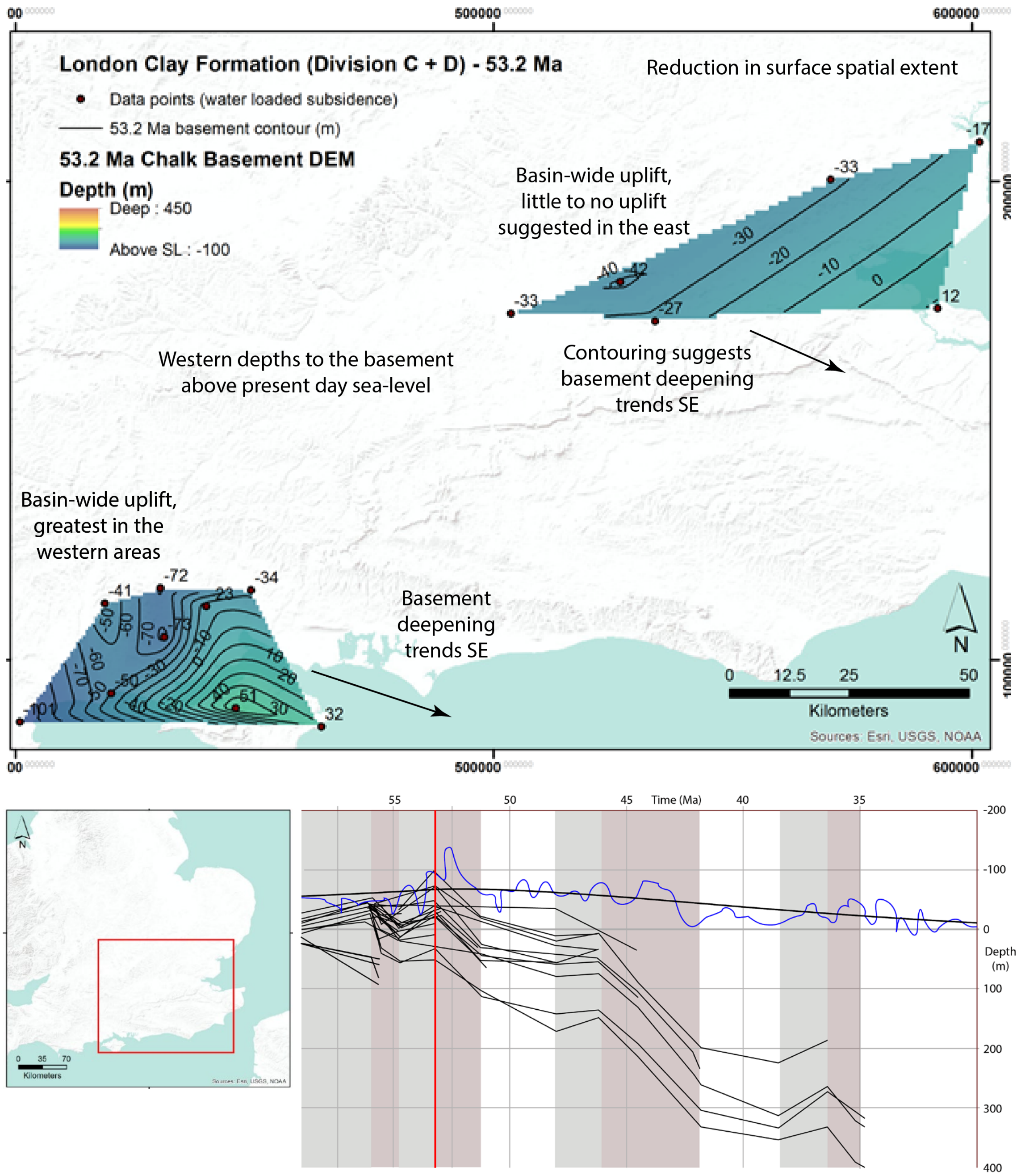


__Figure 6.7:__ The tectonic surface for the Mesozoic Chalk basement as the London Clay Formation (Division C + D) was deposited, 53.2 Ma. An overall reduction in depth to the water-loaded basement has occurred between the 54.7 Ma tectonic surface and the 53.2 Ma surface suggesting a period of uplift. The red box outlines the area of the tectonic surface. The red line on the subsidence curves shows the time level used for the tectonic surface.

6.4.7 Lower Bracklesham Group - 51.2 Ma (Early Eocene, Ypresian)

Lower Poole, Wittering and Bagshot formations

The tectonic surface of the Mesozoic Chalk basement at 51.2 Ma is limited to the Hampshire Basin area and reflects an interval of subsidence, figure 6.8. The small volume of Bagshot Formation preserved in useable backstripped boreholes and sections which are limited to the London Basin did not produce a spatially extensive surface that could be used effectively to assess the basement development.

The westernmost data point and one data point in the north-west suggest the basement was above present-day sea-level in these areas. The majority of the surface reflects an eastwards increase in basement depth. The easternmost data point suggests a maximum depth of 113 metres for the water-loaded Mesozoic basement. This is an additional subsidence of up to 81 metres in the farthest extent of the 51.2 Ma tectonic surface from the previous surface at 53.2 Ma. The degree of subsidence in the eastern area of the Hampshire Basin is less than in the central areas when comparing the 51.2 Ma and 53.2 Ma tectonic surfaces. The northern data points show a maximum amount of subsidence of 84 metres. This results in a tectonic surface composed of water-loaded data points predominantly below present-day sea-level. Extrapolation of the surface eastwards would suggest a further increase in depth to the water-loaded Chalk basement. However additional useable backstripped sections would be required to test this inference.

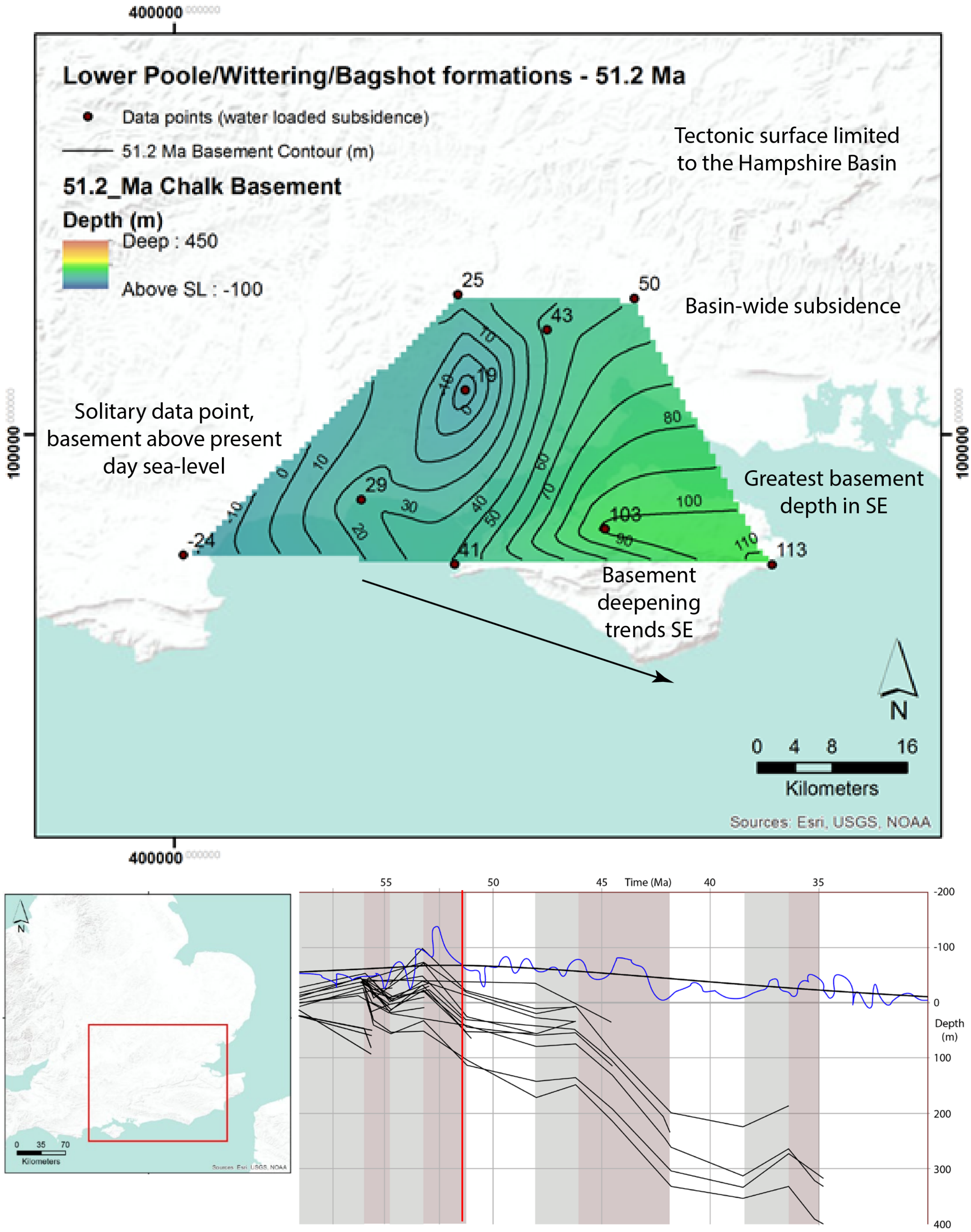


Figure 6.8: *The tectonic surface for the Mesozoic Chalk basement during the deposition of the Lower Bracklesham Group, 51.2 Ma. From 51.2 Ma until 34.8 Ma, the tectonic surfaces are limited to the Hampshire Basin area. The surface reflects a subsidence of the Chalk basement with depths increasing towards the east. The red box outlines the area of the tectonic surface. The red line on the subsidence curves shows the time level used for the tectonic surface.*

6.4.8 Lower Bracklesham Group - 48 Ma (Early Eocene, Ypresian)

Middle Poole and Earnley formations

The tectonic surface of the Mesozoic Chalk basement at 48 Ma is limited to the Hampshire Basin area and is shown in figure 5.9. A continued subsidence of the area from 51.2 Ma is shown in the subsidence curves.

One data point in the central western area of the surface suggests the water-loaded Mesozoic basement was above present-day sea-level. This is a maximum basement high of -37 metres depth. Considering the error margin of the subsidence data and the neighbouring data points this appears to be a plausible value and not erroneous. The rest of the surface is projected below present-day sea-level with depths of up to 171 metres in the central Hampshire Basin. The north and western data points suggest shallower depths to the water-loaded basement than in the southern and eastern areas of the Hampshire Basin. The transition to greater basement depths trends dominantly east to west. However the maximum water-loaded depth of the Chalk basement is centred on the Sandhills borehole at the centre of the Isle of Wight. This produces a trough-like geometry to the tectonic surface with the basement shallowing to the north and east. The easternmost data point at Whitecliff Bay reflects the second greatest depth to the water-loaded basement at 142 metres below present day sea-level. This is 29 metres shallower than the depth to the basement in the Sandhills borehole to the west. It could suggest shallower depths to the basement if additional data was available to the east and west of the tectonic surface developed.

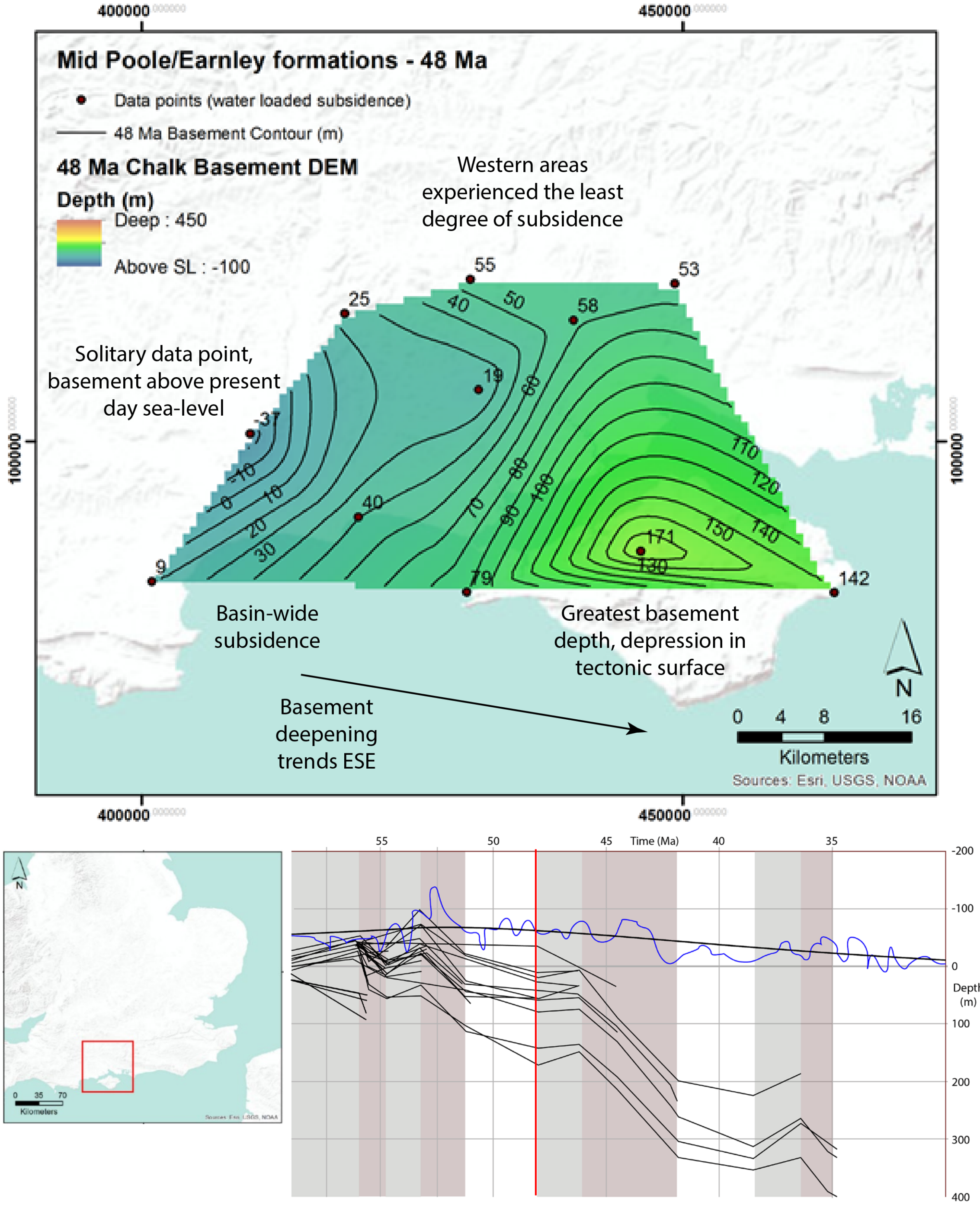


Figure 6.9: *The water-loaded subsidence surface for the Mesozoic Chalk basement during the deposition of the Lower Bracklesham Group, 48 Ma. The majority of the tectonic surface reflects water-loaded basement below the present-day sea-level, except for a solitary western data point at 37 metres above present-day sea-level. The red box outlines the area of the tectonic surface. The red line on the subsidence curves shows the time level used for the tectonic surface.*

6.4.9 Upper Bracklesham Group – 46.2 Ma (Middle Eocene, Lutetian)

Upper Poole and Marsh Farm formations

The Hampshire Basin tectonic surface at 46.2 Ma, figure 6.10, suggests the water-loaded Mesozoic Chalk basement did not have a marked difference in vertical surface motions when compared with the older surface of 48 Ma. The vertical surface motions from the previous surface reflect minor uplift across the Hampshire Basin area. Two data points, in the west and north-west, suggest subsidence when compared with the surface at 48 Ma. However, the difference in depth to the basement between 46.2 Ma and the older 48 Ma surface is a maximum of 7 metres. Considering the error margins of the backstripping method it is difficult to distinguish between uplift and subsidence. The possible uplift of these western data points would not be unreasonable as they represent the margins of the sedimentary basin, and basement deformation and uplift could be a controlling factor.

The eastern areas of the Hampshire Basin tectonic surface suggest minor uplift with a maximum basement depth change of 23 metres. This is suggested by the Sandhills borehole data in the centre of the Isle of Wight. When contoured, this data point produces a basement depression in the water-loaded tectonic surface which reflects an eastwards shallowing of basement depth. This depression and the geometry of the basement is similar to that suggested by the contouring of the 48 Ma water-loaded subsidence data. Again, the main difference between the two tectonic surfaces pertains to the shallowing of the water-loaded subsidence values that could be attributed to uplift of the basement.

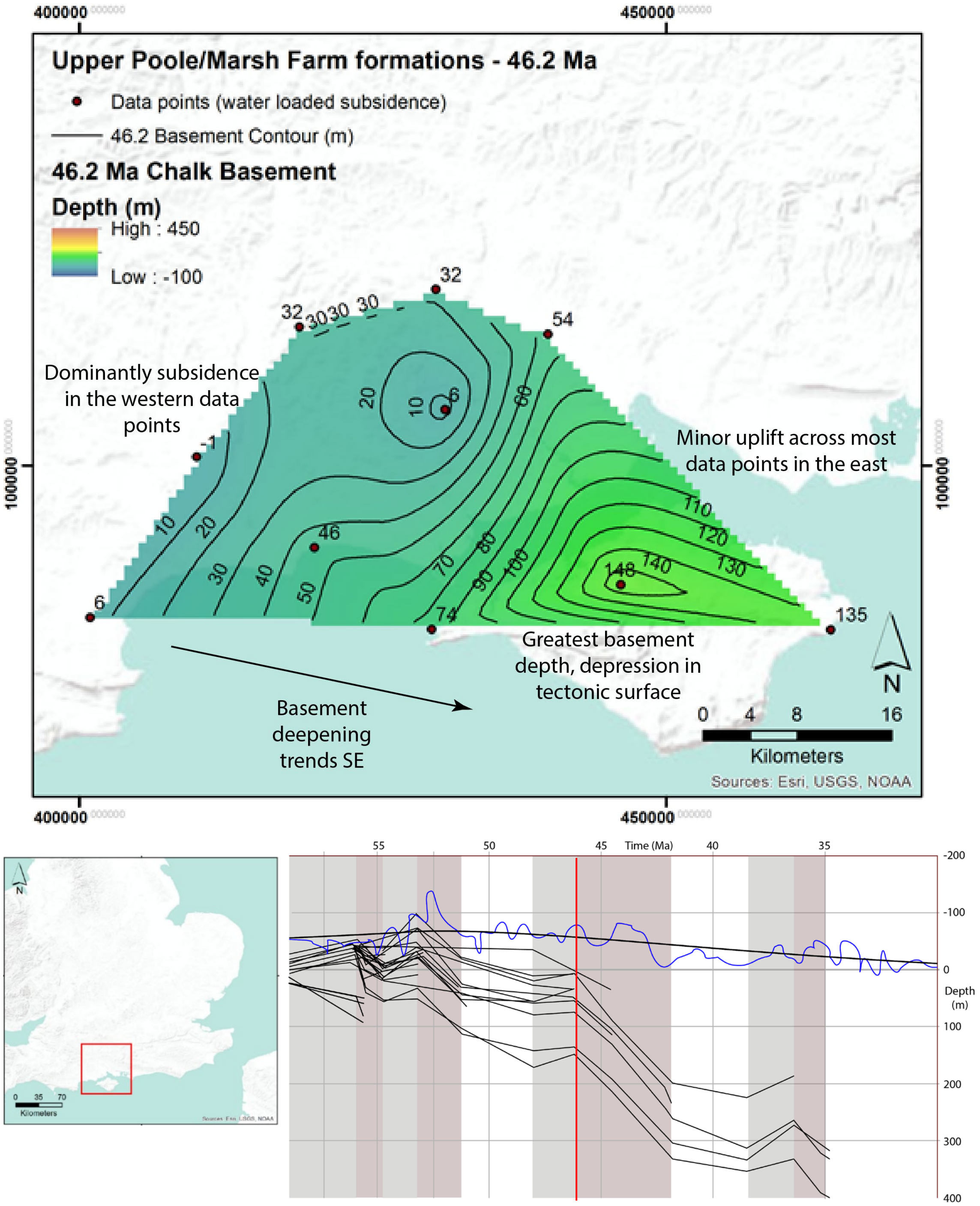


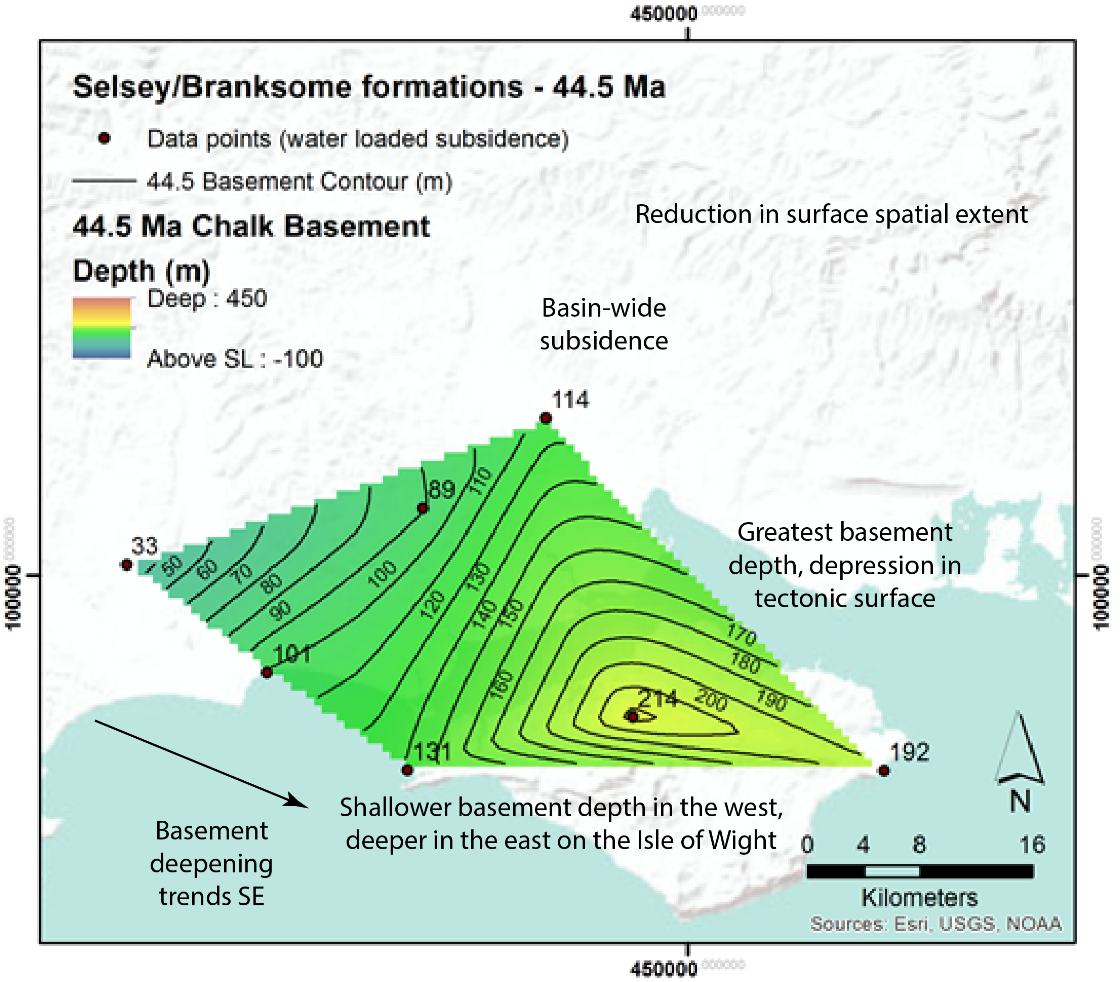
Figure 6.10: *The tectonic surface for the Mesozoic Chalk basement during the deposition of the Upper Bracklesham Group, 46.2 Ma. The tectonic surface reflects a water-loaded basement below the present-day sea-level, except for a solitary western data point at 1 metre above present-day sea-level. The red box outlines the area of the tectonic surface. The red line on the subsidence curves shows the time level used for the tectonic surface.*

6.4.10 Upper Bracklesham Group - 44.5 Ma (Middle Eocene, Lutetian)

Branksome and Selsey formations

The tectonic surface of the water-loaded Mesozoic Chalk basement at 44.5 Ma, figure 6.11, reflects a reduction in the extent of available data in the Hampshire Basin. There is reduction in the spatial extent of the lithostratigraphic units used for backstripping, reducing the number of useable sections available. Each subsequent surface from 44.5 Ma to 34.8 Ma displays a reduction in the tectonic surface spatial extent. It is important to note the relative changes in vertical motion of the western margins in comparison to the rest of the Hampshire Basin.

The depth to the water-loaded basement reaches a maximum of 214 metres in the centre of the Isle of Wight and a minimum of 33 metres below present-day sea-level in the westernmost data point. Overall there is an easterly trend of increasing depth to the water-loaded basement across the tectonic surface at 44.5 Ma. The tectonic surface reflects an overall subsidence of the basement from the previous surface of 46.2 Ma. The maximum difference in water-loaded subsidence is up to 83 metres as suggested by the Ramnor Inclosure data point in the north-west. The least additional subsidence of 34 metres was suggested by the westernmost data point. This pattern is consistent with the previous tectonic surfaces developed in this area. The deepest water-loaded subsidence value of 214 metres suggested by the Sandhills data produces a depression in the tectonic surface with depths to the basement shallowing eastwards, similar to the previous two surfaces developed, at 48 and 46.2 Ma. This suggests a tectonic depression in the basement surface was still present. The tectonic surface indicates that the shallowing of the depth to basement had a comparatively steeper gradient south of Sandhills at 44.5 Ma.



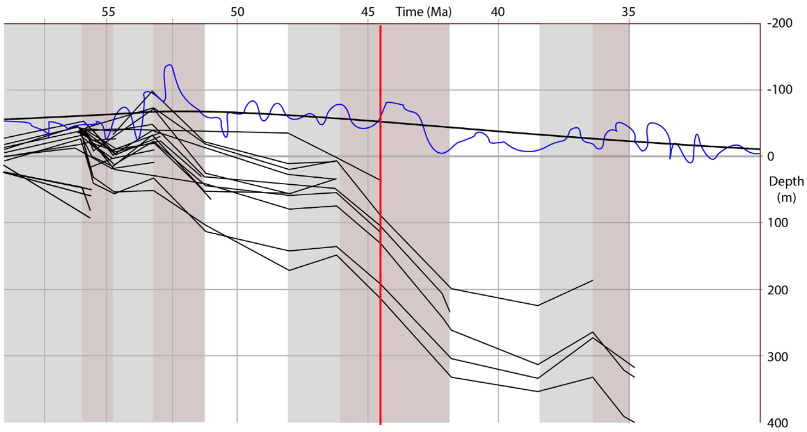
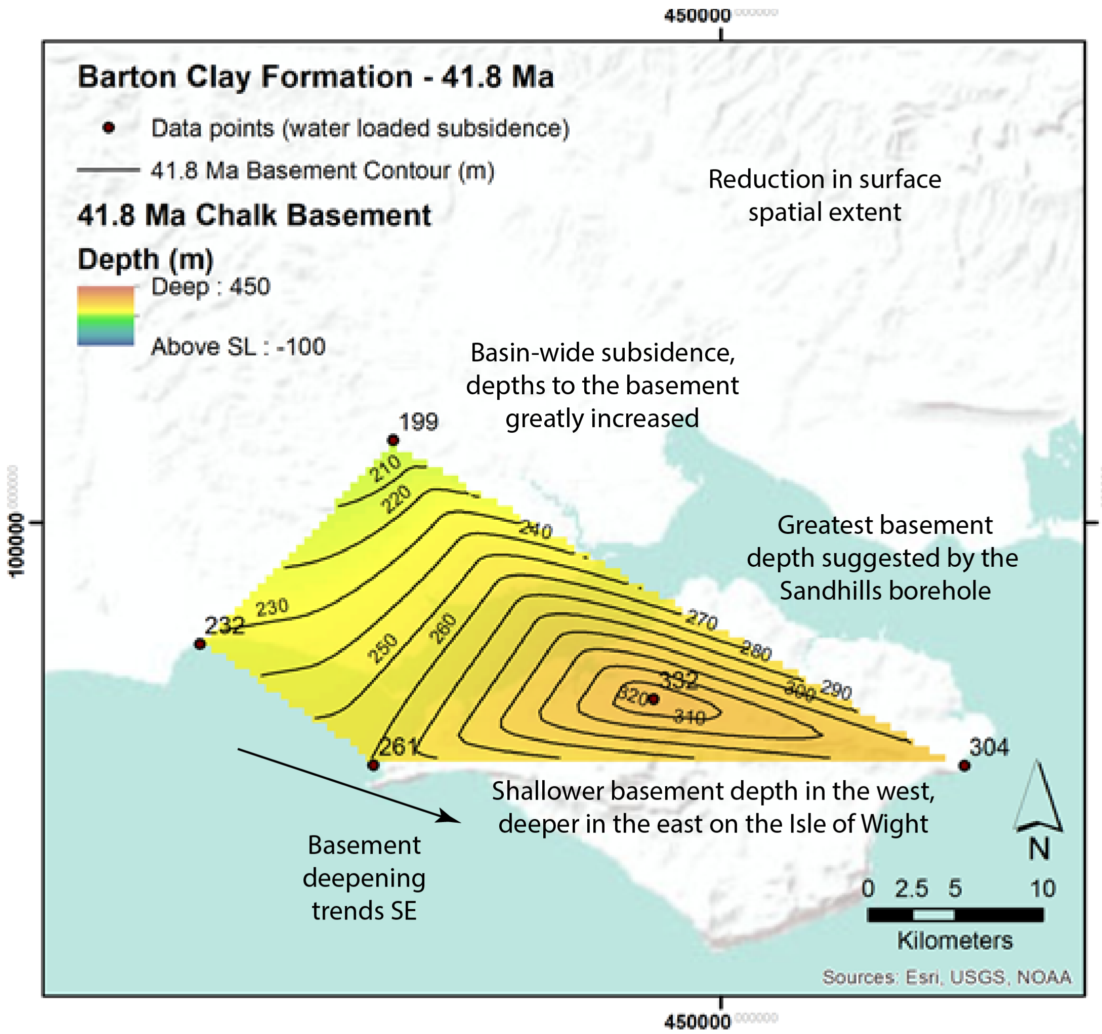


Figure 6.11: *The tectonic surface for the Mesozoic Chalk basement during the deposition of the Upper Bracklesham Group, 44.5 Ma. The spatial extent of the surface has been reduced. The water-loaded depth values suggest an interval of subsidence of the basement between 46.2 Ma and 44.5 Ma. The red box outlines the area of the tectonic surface. The red line on the subsidence curves shows the time level used for the tectonic surface.*

6.4.11 Barton Clay Formation - 41.8 Ma (Mid Eocene, Lutetian - Bartonian)

The tectonic surface rendered from the water-loaded subsidence values at 41.8 Ma, figure 6.12, is limited to data points from the central areas of the Hampshire basin, the majority of which lie on the Isle of Wight. The water-loaded Mesozoic Chalk basement suggests a continued period of subsidence at 41.8 Ma from the previous tectonic surface at 44.5 Ma. There is a 2.7 Myr time gap between the tectonic surfaces and a substantial increase in the total amount of subsidence proposed by all data points, all suggesting the basement subsided at least an additional 100 metres. The maximum additional water-loaded subsidence of the basement from the previous tectonic surface is suggested to be up to 130 metres, shown by the south-western data point at Alum Bay. The least amount of additional tectonic subsidence is suggested to be 110 metres in the most north-westerly data point at Ramnor Inclosure.

Overall the tectonic surface reflects an increase in depth to the water-loaded Chalk basement from north-west to south-east. The Sandhills data point in the centre of the Isle of Wight suggests the greatest depth to the basement at 332 metres, consistent with previously described tectonic surfaces. The south-eastern Whitecliff Bay point reflects a shallowing of basement depth towards the east, suggesting the tectonic depression in the Chalk basement is still present.



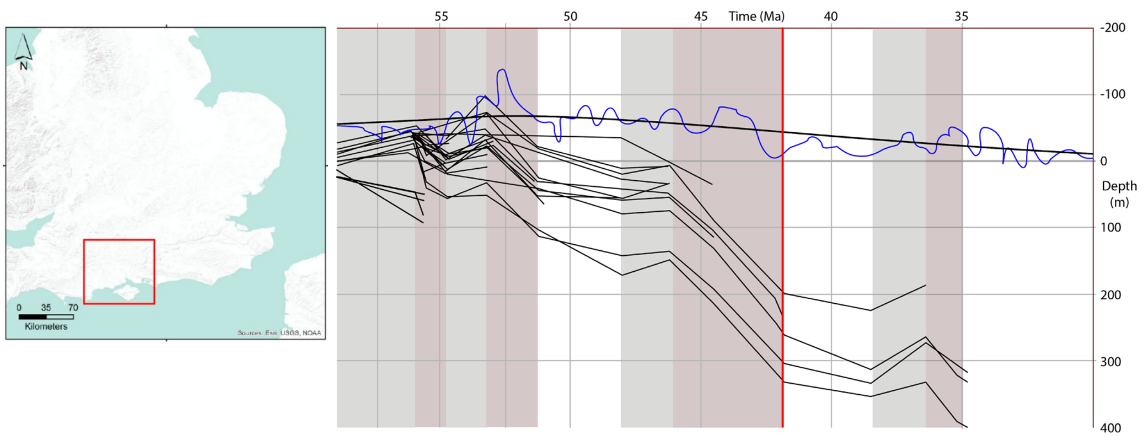


Figure 6.12: *The tectonic surface for the Mesozoic Chalk basement during the deposition of the Barton Clay Formation, 41.8 Ma. The pattern of the surface is similar to the previous 44.5 Ma and reflects a further subsidence of Chalk basement across the Hampshire Basin. The red box outlines the area of the tectonic surface. The red line on the subsidence curves shows the time level used for the tectonic surface.*

6.4.12 Becton Formation - 38.5 Ma (Mid Eocene, Bartonian – Late Eocene, Priabonian)

The next three tectonic surfaces are limited to the Isle of Wight boreholes and sections and the Ramnor Inclosure borehole to the north-west.

The overall water-loaded tectonic surface of the Mesozoic Chalk basement at 38.5 Ma is shown in figure 6.12, reflecting an increase in tectonic subsidence in the central Hampshire Basin. The water-loaded basement is suggested to be at its minimum at a depth of 224 metres in the north-west. This is a net subsidence of 25 metres from the older 41.8 Ma tectonic surface, suggesting tectonic subsidence rates have slowed. The greatest additional subsidence is suggested to have occurred in the south-west, by up to 52 metres. The greatest depth to the water-loaded Chalk basement is displayed by the Sandhills borehole at a depth of 353 metres below present-day sea-level. This data point continues to produce a depression in the tectonic surface centred on the Isle of Wight. The Sandhills borehole shows 21 metres of additional subsidence relative to the previous 41.8 Ma tectonic surface. This is the smallest amount of subsidence for the 38.5 Ma tectonic surface and may suggest a relative reduction in the subsidence rate in the Sandhills area.

Depth to the water-loaded basement increases towards the south-east. Minor shallowing of the basement depth is suggested by the easternmost data point at Whitecliff Bay.

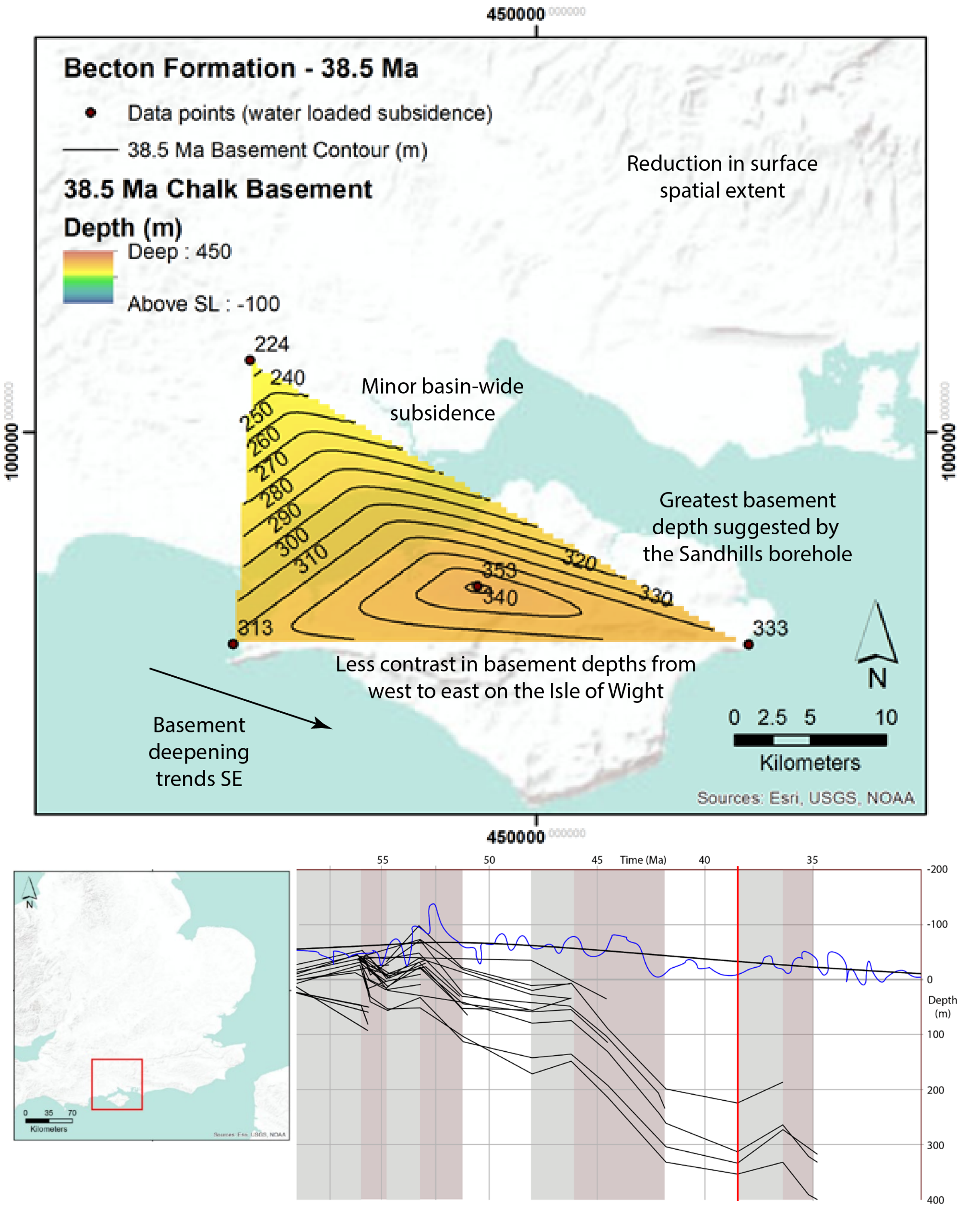


Figure 6.12: *The water-loaded subsidence surface for the Mesozoic Chalk basement during the deposition of the Becton Formation, 38.5 Ma. The tectonic surface reflects further subsidence of the Chalk basement from the older 41.8 Ma tectonic surface. The red box outlines the area of the tectonic surface. The red line on the subsidence curves shows the time level used for the tectonic surface.*

6.4.13 Headon Hill Formation - 36.4 Ma (Late Eocene, Priabonian)

The tectonic surface rendered for the water-loaded Mesozoic Chalk basement at 36.4 Ma uses the same points as the older 38.5 Ma surface and has a similar spatial extent, figure 6.13.

The tectonic surface records a reduction in the depth to the water-loaded basement across all data points. This suggests an interval of uplift between the older 38.5 Ma tectonic surface and the 36.4 Ma tectonic surface which is present in the central Hampshire Basin. The greatest basement shallowing of up to 61 metres is suggested to have occurred in the easternmost data point at Whitecliff Bay. The northern and western data points suggest a similar degree of uplift, 38 metres and 49 metres respectively. The Sandhills borehole records the greatest depth to the water-loaded basement and suggests the centre of the Isle of Wight at 36.4 Ma had experienced the least amount of uplift, the difference between the depth at 38.5 Ma and 36.4 Ma being 21 metres. The differential uplift experienced by the surrounding points is reflected by the steepening of the contours in the tectonic surface. The southern points are at very similar water-loaded depths that are well within the error margin, suggesting the basement dips northwards towards the centre of the Isle of Wight. A pattern of basement shallowing towards the northwest is also obvious at 36.4 Ma.

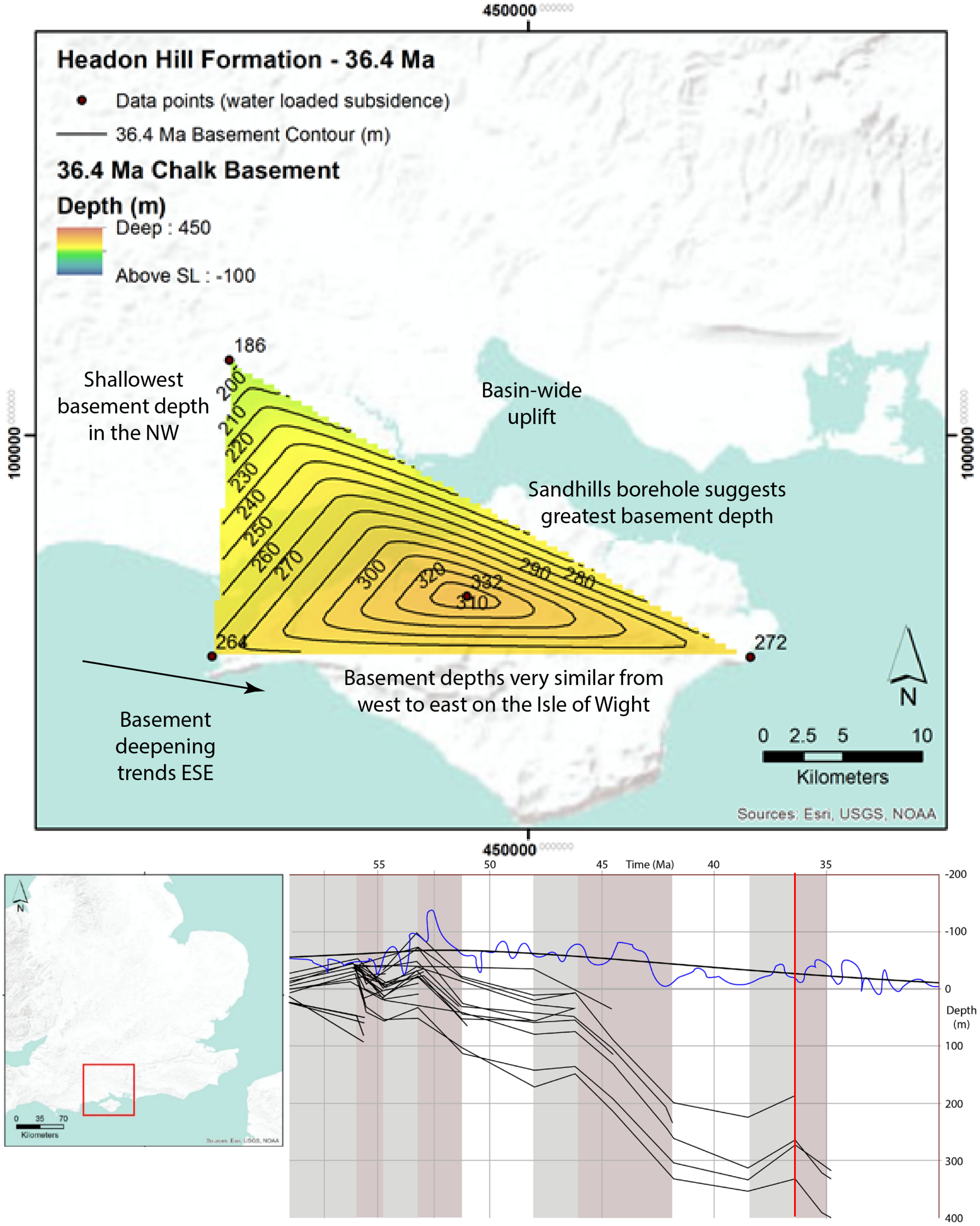


Figure 6.13: *The water-loaded subsidence surface for the Mesozoic Chalk basement during the deposition of the Headon Hill Formation, 36.4 Ma. The surface reflects an interval of uplift of the basement between 38.5 and 36.4 Ma. The red box outlines the area of the tectonic surface. The red line on the subsidence curves shows the time level used for the tectonic surface.*

6.4.14 Bouldnor Formation - 34.8 Ma (Late Eocene, Priabonian – Early Oligocene, Rupelian)

The tectonic water-loaded basement surface at 34.8 Ma is the last one of Paleogene age, figure 6.14. It is limited to the three data points on the Isle of Wight and has a smaller spatial extent than the surface constructed for 36.4 Ma.

The data points reflect tectonic subsidence of the basement relative to the previous surface. The greatest subsidence of 73 metres is suggested to have occurred at the westernmost point. The central and eastern points suggest subsidence of 67 and 65 metres, respectively. The depth to the water-loaded Chalk basement is shallowest in the south, particularly in the east at a depth of 317 metres. The water-loaded basement has a deepest value of 399 metres suggested by the Sandhills borehole in the centre of the Isle of Wight. This pattern produces a northwards basement deepening trend. More inferences on the geometry of the water-loaded basement would be possible if additional useable data was available in the north of the Hampshire Basin.

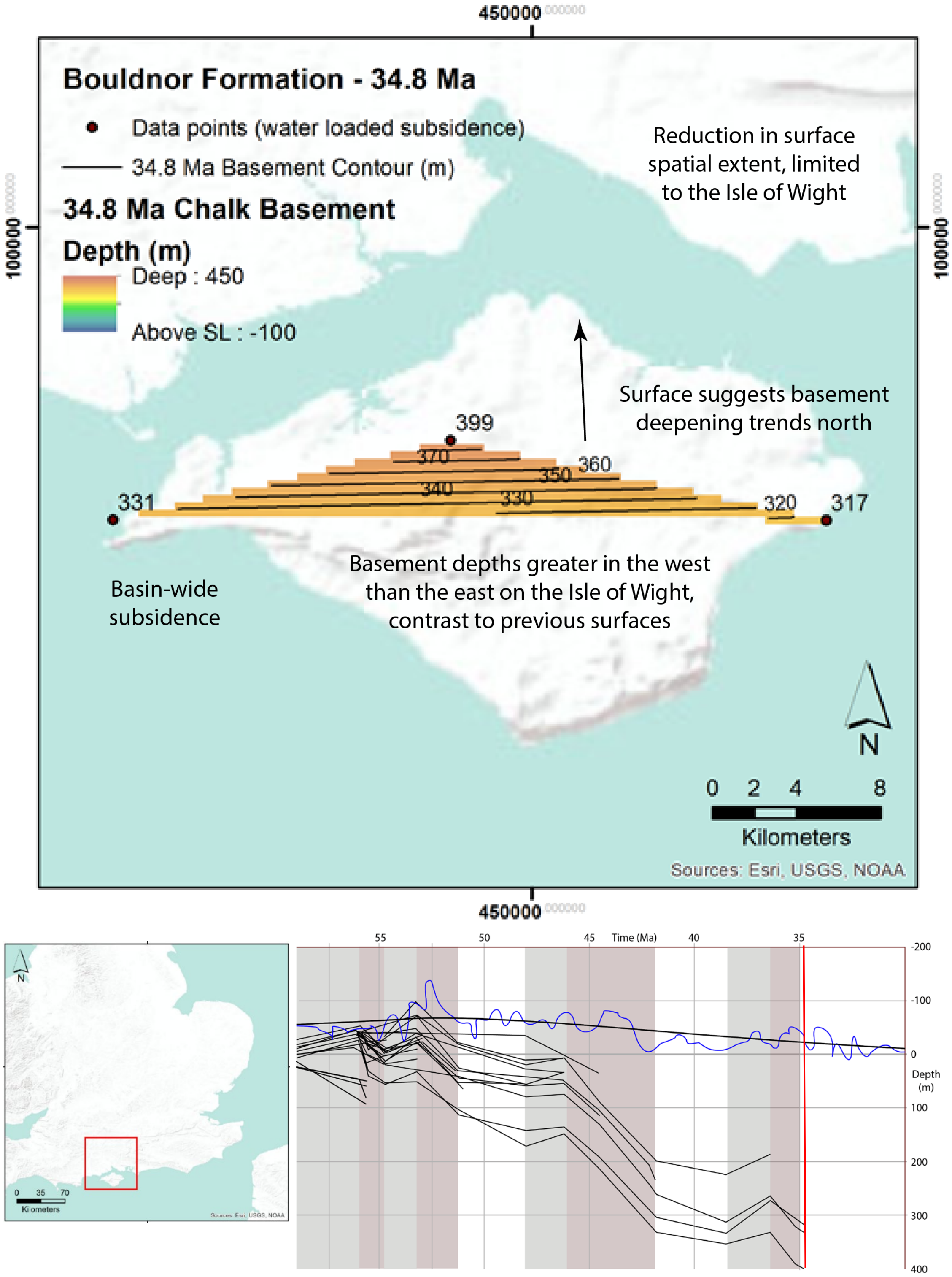


Figure 6.14: *The tectonic surface for the Mesozoic Chalk basement during the deposition of the Bouldnor Formation, 34.8 Ma. The youngest Paleogene tectonic surface developed and the extent of the surface has been further reduced and limited to data points on the Isle of Wight. The red box outlines the area of the tectonic surface. The red line on the subsidence curves shows the time level used for the tectonic surface.*

6.4.17 Summary of tectonic surface patterns

All tectonic surfaces suggests that the periods of uplift and subsidence are mostly consistent across each tectonic surface, with only a few points reflecting contrasting basement motions. These points are usually isolated and could either be a result of uncertainties in the method or in the local variations in geology.

The tectonic surfaces developed in the London Basin range from 58.5 Ma to 53.2 Ma and the tectonic surfaces developed that cover East Anglia span 58.5 to 54.7 Ma. The tectonic surfaces from 58.5 to 53.2 Ma project the London Basin water-loaded Chalk basement existing above the present-day sea-level. Contouring of these subsidence points consistently suggests the basement prominently dipped towards the north-east in the Late Paleocene and eventually eastwards by the Early Eocene. The most eastern and northern sections reflect the greatest depths to the basement in the East Anglian and London Basin areas.

Considering all points across all surfaces, the greatest depths to the water-loaded basement are consistently in the Hampshire Basin, particularly the easternmost data points. The western and northern sections in the Hampshire Basin suggest relative basement highs that are consistent throughout the Paleogene with an easterly dip to the basement surface reflected in the tectonic surfaces from 55.5 to 36.4 Ma. From 36.4 to 34.8 Ma a northerly dip to the basement is more prominent but the spatial extent of the surfaces is reduced due to the lack of data. The Sandhills borehole suggests that a tectonic depression in the Chalk basement was present from to 53.2 to 34.8 Ma. The Whitecliff Bay section in the east of the Isle of Wight shows consistently deeper basement depths until 36.4 and 34.8 Ma, after which the western Alum Bay section suggests similar and deeper basement depths, respectively.

6.5 Strengths and limitations of tectonic surface development

The greatest constraining factor for the limitation on tectonic surface development and reliability for tectonic interpretations is that the method is inherently reliant on the source data. The number of borehole locations that can be backstripped will increase the validity of the data, but also aid in constraining the wavelength of short wavelength vertical variations. The disparity between the London Basin and Hampshire Basin regions is highlighted by the apparent occurrence of short wavelength patterns that can be observed across the Isle of Wight. This level of data density was not achieved in the London Basin and overall basement highs may have shown greater variations in vertical motions had a more focused approach on particular localities been taken. The spatial representation of the data clearly showed some patterns that can be attributed to short-wavelength variations and lead to tectonic interpretations. Ideally a larger data set of boreholes could be used, or a more focused area of study would help to increase the validity and quantify the wavelength of the vertical motions.

6.6 Tectonic surface ground modelling

The tectonic surfaces of the Mesozoic top-Chalk basement during the Cenozoic have been rendered in ArcScene for 3D visualisation providing spatial context for the 3D geometry of the evolving water-loaded basement during the Cenozoic. Up until this point, each tectonic surface has been described individually in chronological order. The advantage of a 3D model is that the relative variation between the tectonic surfaces, spatially and temporally, can be viewed more clearly. The following figures 6.17-6.20 are screenshots of the ground model developed from the tectonic surfaces. Appendix 5 contains a digital copy of the model that can be explored using the appropriate software. The regional extent of the tectonic surfaces has led to exaggeration of the vertical scale so that basement spatial variations in the topography can be seen more clearly. The boreholes and sections that were backstripped form linear features on the ground model. These linear features show the depths of the boreholes that reach the Chalk basement at the present day and so display the preserved thickness of the Cenozoic succession across the study area. This of particular interest as it shows the relative elevations of the water-loaded Chalk basement surfaces in relation to the depth they

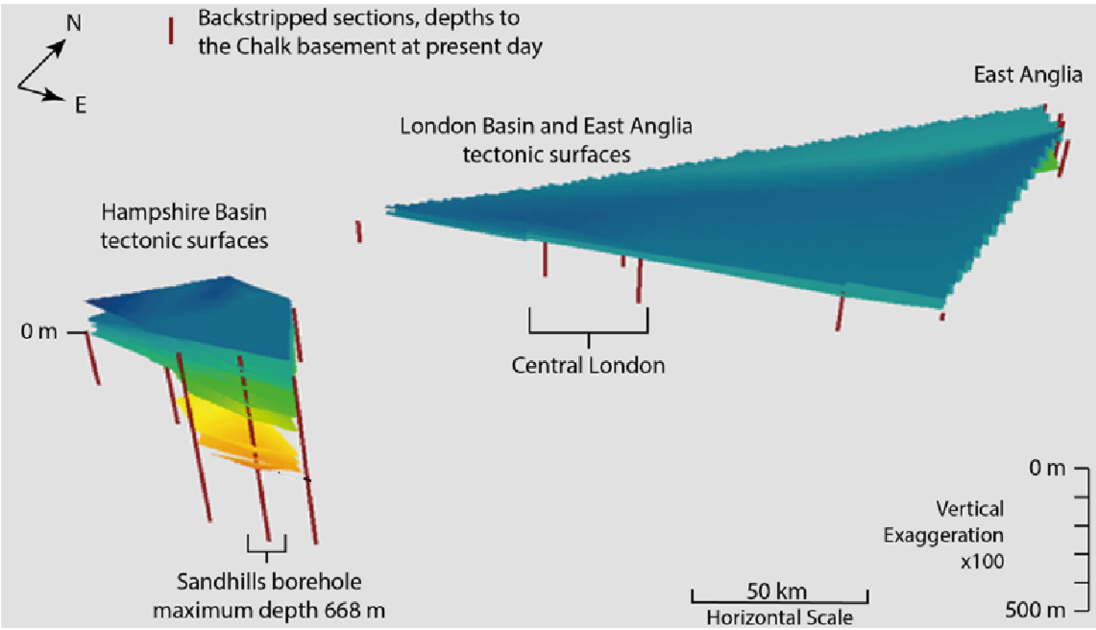


Figure 6.17: *The 3D ground model for the Cenozoic evolution of the water-loaded Chalk basement. All tectonic surfaces discussed have been stacked so that the spatial and temporal relationships can be observed more clearly. This image looks north-westerly onto the East Anglia, London and Hampshire basin areas. The variations in basement depths is clearly seen. Shallow depths are shown in the London Basin surfaces which are projected above present-day sea-level. The Hampshire Basin shows the greatest depth to the basement and a higher density of data.*

are preserved at the present day. The tectonic surfaces from the London Basin, figure 6.18, show the top Chalk basement surface above the present-day sea level. A dip of the surfaces towards East Anglia can be seen. In figure 6.19a an intersection between the 56 Ma and 53.2 Ma surfaces suggest a large amount of uplift in the western areas of the Hampshire Basin while the eastern areas experienced subsidence. Also in figure 6.19a the deepest 34.8 Ma surface shows the shallower basement depth in the eastern Whitecliff Bay section: a contrast to the younger surfaces above.

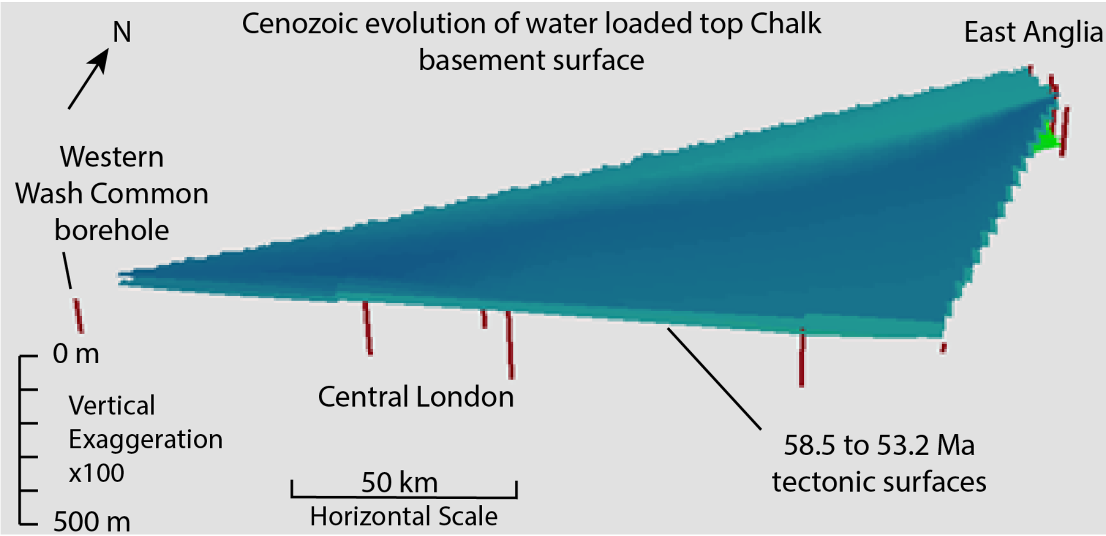


Figure 6.18: *Image of the East Anglia and London Basin tectonic surfaces in the 3D ground model, which reflects the Cenozoic evolution of the water loaded top Chalk basement surface.. The Central London and East Anglia areas have the greatest density of data points and stacked surfaces. The surfaces from 58.5 to 53.2 Ma suggest consistent depths to the Chalk basement that were dominantly above present day sea-level. The areas of East Anglia reflect greater depths to the basement during these times.*

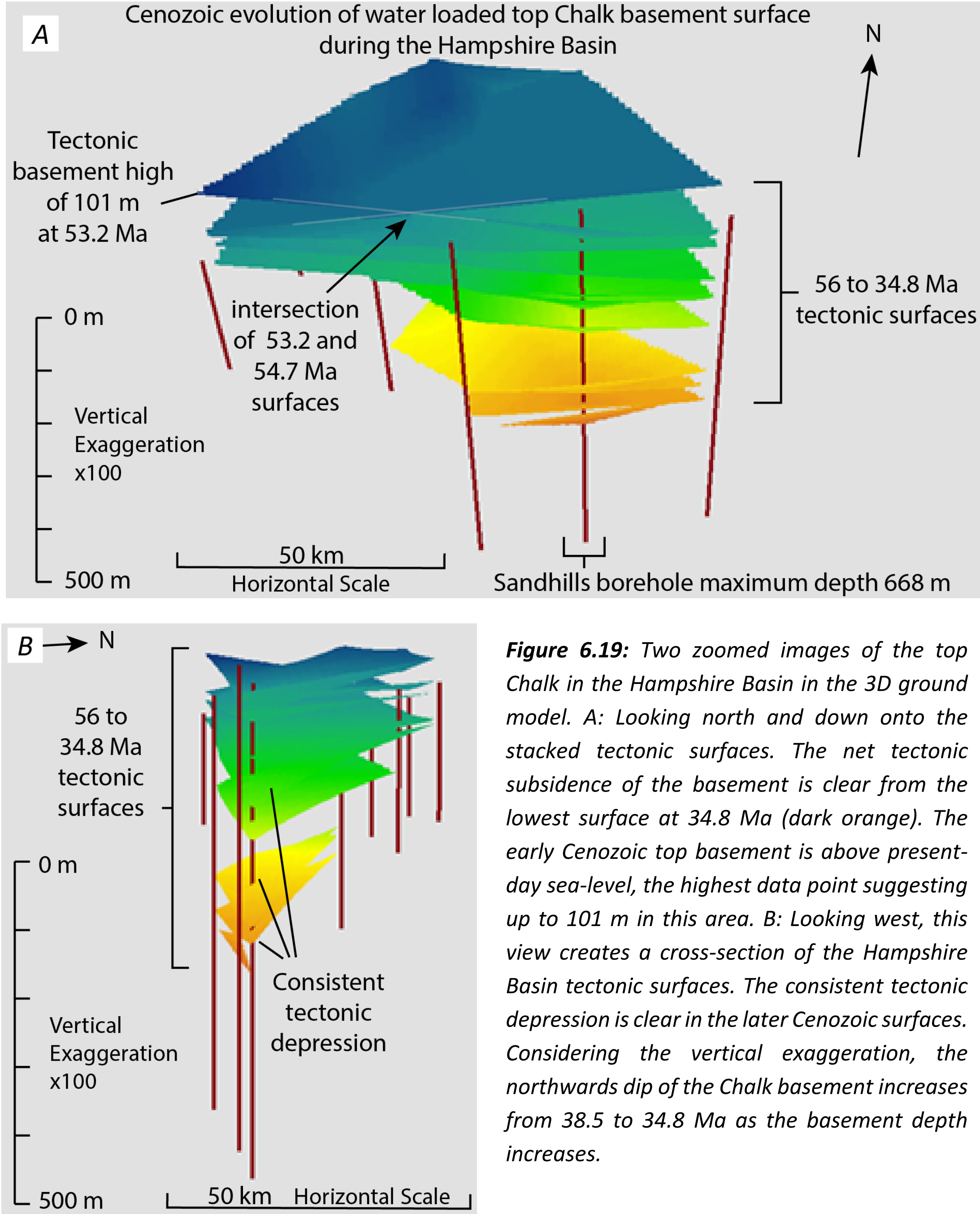


Figure 6.19: *Two zoomed images of the top Chalk in the Hampshire Basin in the 3D ground model. A: Looking north and down onto the stacked tectonic surfaces. The net tectonic subsidence of the basement is clear from the lowest surface at 34.8 Ma (dark orange). The early Cenozoic top basement is above present-day sea-level, the highest data point suggesting up to 101 m in this area. B: Looking west, this view creates a cross-section of the Hampshire Basin tectonic surfaces. The consistent tectonic depression is clear in the later Cenozoic surfaces. Considering the vertical exaggeration, the northwards dip of the Chalk basement increases from 38.5 to 34.8 Ma as the basement depth increases.*

6.7 Tectonic surface discussion

6.7.1 Cenozoic top Chalk basement evolution

The tectonic surfaces and ground modelling revealed that the Chalk basement experienced mostly subsidence during the Paleogene and early Neogene. During the early Paleogene, the London Basin is suggested to have been above present day sea-level while the East Anglian area experienced relative subsidence. At 53.2 Ma both the Hampshire and London basins experienced a large amount of uplift, particularly the western area of the Hampshire Basin which must have suffered a reasonable amount of strain. The possible reasons for this will be discussed in Chapter 7.

The Hampshire Basin surfaces showed a dominant south-eastern tilt until 34.8 Ma. The western areas of the basement had shallower depths for much of the Paleogene. The eastern Hampshire Basin data suggested a tilt toward the north east to the top Chalk surface during the Mid-Eocene to Early Oligocene. However the data becomes increasingly spatially limited and could be the cause for this orientation. The fact the data is limited relates to the water depth shallowing which is suggested by the evolving depositional conditions from marine to lacustrine. The Sandhills borehole was a common point in the tectonic surfaces and records the greatest basement depths in relation to the two Isle of Wight points to the south-east and south-west. A seismic section at the present day taken N-S across the Isle of Wight, figure 6.20, shows a slight tilt to the top Chalk basement closer to the Sandown fault. The surfaces produced for the Hampshire Basin in the Paleogene produced an even tilt across the area from one point to the other. This is a limitation of the surface development from point data and suggests the use of an additional borehole between the Sandown fault and the Sandhills borehole may produce a pattern that would more closely resemble the present-day configuration observed in seismic section. Interpretations of vertical surface motions from the tectonic surfaces are best close to the data points. The seismic section also shows a large fault at depth in the Mesozoic strata that uplifts the full Cenozoic succession below the Sandhills borehole and was most likely activated post-Oligocene (why? – reference Gale paper?). An additional backstripped section between the Sandhills and Sandown fault would help constrain the possible timing of this fault movement. This highlights some limitations of interpreting from the tectonic surfaces away from points. The dip of the basement surfaces does reflect the Cenozoic succession sequence stratigraphy. However, faulted uplift of the Cenozoic succession most likely occurred following the Paleogene sedimentation. Backstripping and surface development therefore suggest that a northwards basement tilt towards the Sandhills borehole existed before later deep fault reactivation shifted the Sandhills borehole upwards, figure 6.20 a-b. The seismic in figure 6.20b reflects this change.

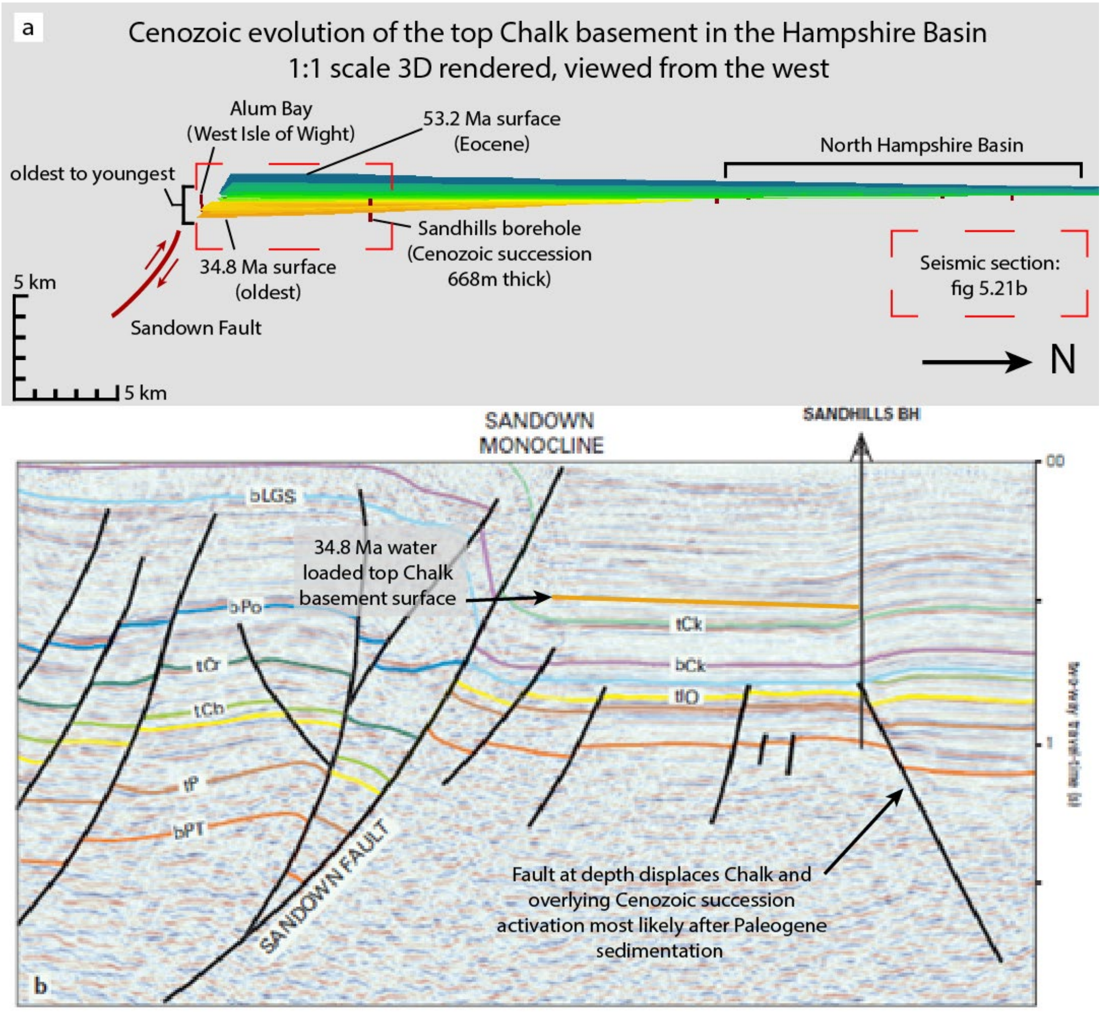


Figure 6.20: a: *View of the top Chalk basement evolution from the west at a 1:1 horizontal and vertical scale. b: Seismic section is N-S on the Isle of Wight showing the Sandown fault in the subsurface causing the monocline. The Sandhills borehole is north of this fault along the seismic line and preserves a thick Cenozoic succession. The seismic section shows a deeper fault below the Sandhills borehole that appears to have activated and uplifted following the deposition of the Cenozoic succession. Taken from Chadwick and Evans (2005)*

6.7.2 Water-loaded basement deepening trends

The approach used to assess the Cenozoic palaeobathymetric deepening orientations, in Chapter 4, was used to compare the variation in basement deepening. Figure 6.21 shows the Cenozoic Chalk basement deepening trends inferred from the tectonic surfaces. The basement deepening trends suggest the Chalk basement in East Anglia was tilted towards the north-east during the Late Paleocene (58.5 to 55.8 Ma). The younger tectonic surfaces in the London Basin, 55.8 to 53.2 Ma, produced easterly and westerly basement tilt trends with Central London forming a consistent tectonic high. This pattern was also reflected in the Hampshire Basin as the basement progressively slopes downward towards the east-south-east. The Hampshire Basin surfaces suggest the basement is dominated by east-south-east deepening trends from 54.7 to 36.4 Ma. At 34.8 Ma the basement deepening trends solely to the north. This could be a result of the reduction in available data points. However, it may be that this is a feature of basement development. Evidence can be taken from relative shallowing of the easternmost data point at Alum Bay from 38.5 to 34.8 Ma. The sedimentological and palaeobathymetric variations suggest a change from open marine to a lacustrine environment during this time. Whether this is the case and interrogation of the possible causes for this will be discussed in detail in Chapter 7.

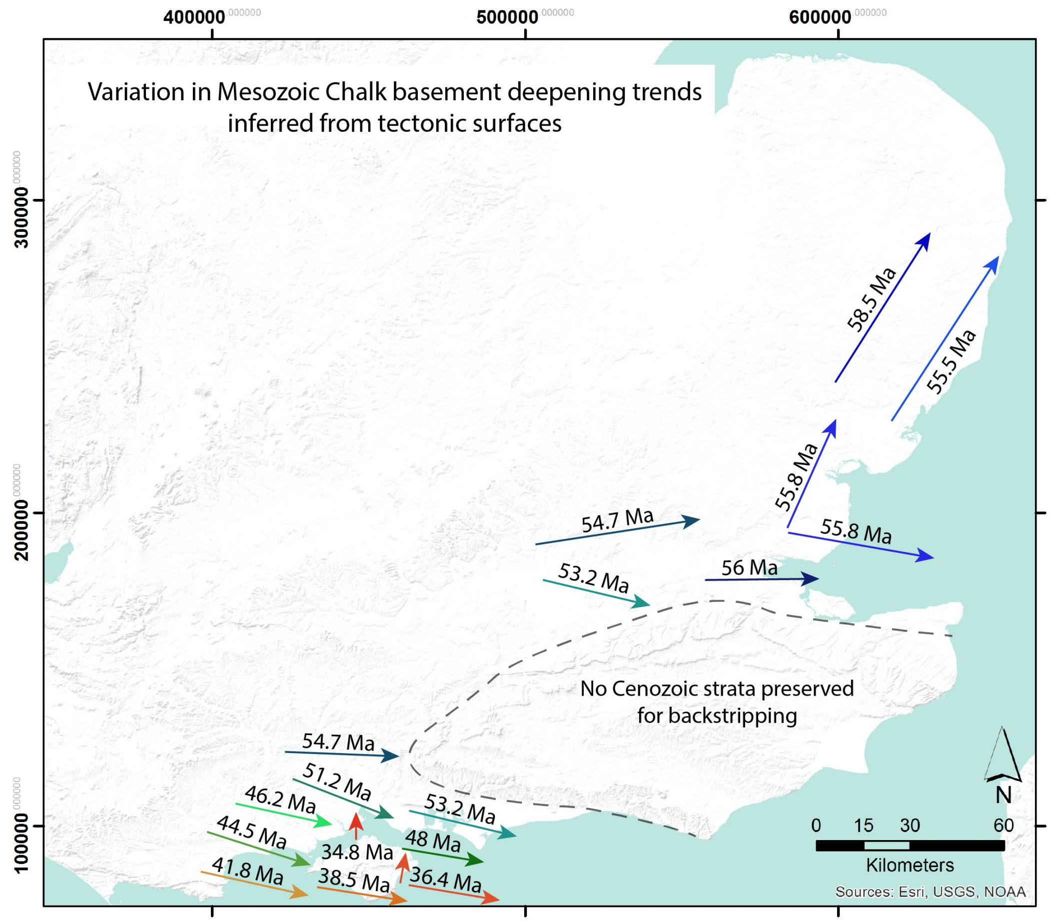


Figure 6.21: *Map compiling the Cenozoic water-loaded basement deepening trends. The basement appears to consistently dip strongly towards the east and north-east during the Cenozoic. The north-east trends are most common in East Anglia. The central London Basin and Hampshire suggest basement dips commonly oriented towards the east. From 53.2 Ma an ESE trend is very prominent until 36.4 Ma when the surfaces suggest basement dips are predominantly towards the north. The colours of the arrows refer to the basement depth keys used in each surface, cold colours represent shallow depths to the basement. Warm colours represent greater depths to the basement.*

6.7.3 Tectonic surface interpretations

The subsidence curves are produced from backstripped boreholes that have uncertainties associated with the method. The tectonic surfaces developed also possess these uncertainties. The simultaneous analysis of the subsidence values in both the subsidence curves and the construction of the tectonic surfaces reduces the uncertainties. This is because erroneous results can be identified and correlated with the initial interpretations of the stratigraphy. For example the south easterly tilt of the

Chalk basement with the western regions showing shallower depths than the eastern Hampshire Basin areas can be correlated with coastal facies in the west and open marine facies in the east. The stratigraphy and water depth interpretations can be synthesised to support the interpretations made from the tectonic surfaces. However, as discussed in section 6.7.1, the tectonic surfaces may resemble the possible top Chalk topography during the Cenozoic, and so additional points are required to create a more robust model. Therefore interpretations should be restricted to a proximity to a node point and some inferences may be made on the surface topography depending on the density of points.

6.8 Conclusions

Traditionally, vertical surface motions of basins and their basement are assessed using a series of backstripped water-loaded subsidence curves. Their spatial distribution helps to infer the patterns of tectonic movements. The generation of regional tectonic surfaces mapping the developing water loaded basement alongside the use of subsidence curves helps to provide spatial and temporal context to the data. The production of tectonic surfaces revealed patterns of tectonic subsidence that would be otherwise difficult to isolate and display when analysing 28 backstripped sections across a large area.

The London Basin tectonic surfaces suggested that the water-loaded basement was above present-day sea-level from 58.5 to 53.2 Ma. Basin deepening trends were dominantly towards the east and north-east and to the west, with Central London forming a tectonic high. The Hampshire Basin tectonic surfaces suggested the western margins were above present-day sea-level until 46.2 Ma. The eastern area of the Hampshire Basin consistently suggests greater depths to the Chalk basement with a south-east deepening trend prominent throughout the Paleogene until 36.4 Ma. From 36.4 to 34.8 Ma the tectonic surfaces suggest the Chalk basement developed a northwards basement deepening.

In order to fully understand the evolution of the Chalk basement and the features observed in the tectonic surfaces developed, data from all chapters will now be compiled, compared and discussed with the existing literature to try to understand the mechanisms and processes responsible for the patterns.

Chapter 7: Discussion

7.1 Early phases of the method and stratigraphy nomenclature

To fulfil the aims of the project effectively, an intensive study of the onshore UK Cenozoic successions was conducted. This included correlation, organisation and standardisation of lithostratigraphic names in order to build a regional framework of the stratigraphic relationships. This work pre-dated the release of the unified revision of Tertiary geology by King (2016). Upon its release, minor amendments to dates, boundaries and lithostratigraphic nomenclature were applied to the datasets. The understanding of the Cenozoic successions, their sedimentology and stratigraphic relationships were necessary to interpret water depths and the compaction histories of the lithologies in order to complete the backstripping of the sections studied and to produce the tectonic subsidence curves and surfaces. The temporal correlation of the units used in the subsidence analysis proved successful given the vast array of available dating methods and the relative temporal thickness of overlying units, creating a maximum and minimum age based on the law of superposition. For example, the Becton Formation which possessed a reduced assemblage of available data was temporally constrained by the boundaries of the underlying Barton Clay Formation, which are constrained by oxygen isotope data. This indirectly increases constraints on the possible oldest ages of the Becton Formation. The overlying unit indirectly constrains its youngest possible age.

7.2 Palaeobathymetry discussion

7.2.1 Palaeobathymetry surface extent and sediment thickness

Correlations can be made between the spatial extent of preserved strata and variations in water depths. The London Clay Formation is extensive in terms of outcrop and produced the greatest palaeobathymetric extent showing greater water depths. Those lithostratigraphic units with shallower water depths record/preserve a reduced spatial extent, with the exception of the Reading and Woolwich formations. These crop out across southern England and consist of very shallow marine/marginal or onshore deposits and preserve relatively thick strata and reflect the very proximal areas of a basin with little accommodation space. This is unlike the rest of the Cenozoic lithostratigraphic units studied**.** An increase in basin accommodation space and the increase in basin extent could be attributed to sea-level variations (figure 7.1). Once again the exception to this is the Reading and Woolwich formations' palaeobathymetry, which shows uncharacteristically thicker sequences of strata considering the proportionally shallower water depths.

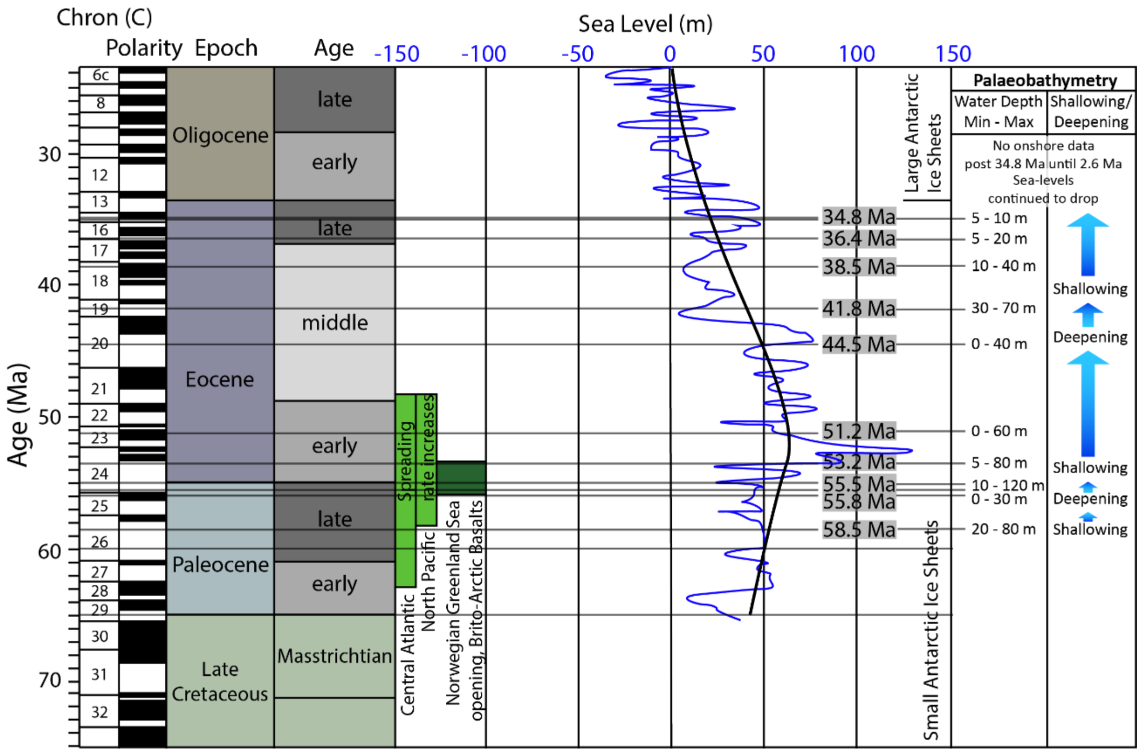


Figure 7.1*: Global sea-level curves of Miller et al. (2005) with the palaeobathymetric map minimum and maximum water depths. The shallowing and deepening trends were determined by the water depth variations. The black line denotes the long term curve, the blue and black is the short term. Red denotes oxygen isotope variations. Black horizontal lines and ages are of each palaeobathymetric surface analysed.*

The general consistent deepening across the London Basin in the Paleocene and Early Eocene can generally be correlated with the long term sea-level curve of Miller (2005). However, from 55.8 to 55.5 Ma the long term eustatic curve indicates sea-level rise while the palaeobathymetric surfaces of these units suggest a basin-wide reduction in water depths. Sediment accumulation of the Reading and Woolwich formations is uncharacteristically high given these parameters in comparison to other lithostratigraphic units in the Cenozoic succession. This is consistent with vertical uplift of the basin floor suggested by the subsidence curves, section 7.3. The lithostratigraphies show cycles of progressive shallowing in the Hampshire Basin occurs during the period of 51.2-34.8 Ma and can also be correlated with the long term curve of Miller (2005). This suggests a good agreement with eustatic variation as a control on water depth variation. However, the change in geometry of the basins and increased transition to shallow conditions from the Late Eocene to Early Oligocene suggests a tectonic control. An interesting question for further work and to increase the resolution of the data would be to investigate the water depth variations and cyclicity in shallowing events within lithostratigraphic units and comparing these to the short term sea-level curve of Miller (20005).

7.2.2 Palaeocoastline inferences and sea-level transgression and regression

A series of sea-level rises and falls can be interpreted from the palaeobathymetry maps by comparing the water depth variations and tracing the migration of inferred palaeocoastlines. In some instances a palaeo-coastline was well defined by the preservation of coastal facies adjacent to shallow marine facies, such as the Branksome and Selsey formations, respectively. Their spatial distribution permits an interpretation of a palaeocoastline location and helps constrain the most likely orientation. The deposition of the Barton Clay Formation has a similar spatial extent in the Hampshire Basin but the coastal facies are replaced by shallow marine lithofacies. In this case, all data points are succeeded by a deeper lithofacies (figure 3.11), suggesting a deepening event. Extrapolating the contour shallowing trend suggests a likely palaeocoastline position and trend, but it is not definitive due to the missing coastal facies. A movement of the palaeocoastline to the west can be confidently inferred based on the water depth data and the palaeobathymetry surfaces and supports the interpretation of a transgressive event that is preserved in the stratigraphy. Whether this flooding of the land surface is related to tectonic subsidence of the basin and its margins or a eustatic control may be determined by discussing the backstripping. The stratigraphy records a number of flooding events, commonly marked at the base of lithostratigraphic units by coarse pebble beds (Aldiss, 2012; Edwards and Freshney, 1987; King, 2016). These coarse beds signifying transgressive events are frequently logged in the boreholes and sections studied.

Considering the flooding events recorded by the stratigraphy, the palaeobathymetry reflects a net shallowing of water depths in Southern England during the Paleogene. The area of deposition reduces over time and may be related to this shallowing. This is exemplified by the earlier deeper marine Paleogene lithofacies which culminates with the eventual deposition of the restricted lacustrine shallow water depths of the Bouldnor Formation at 34.8 Ma. Whether a transgressional event and subsequent deposition occurred post-Bouldnor Formation is unknown but given the trend of the sea-level curve this is unlikely.

Variations of bathymetric deepening and migration of palaeocoastlines landward and basinward provide vital information on sea-level changes that may be a result of global or local eustatic variations. However, changes in the palaeocoastline orientation and deepening trend suggest additional processes other than marine flooding and shallowing events. Variations in basin shape and geometry suggest deformation or uneven basin fill. Using the long-term eustatic variations of Miller *et al* (2005), figure 6.1, and comparing them to water depth variations in the data a general correlation can be seen, figure 6.1 and 5.1.6. The progressive shallowing of the Hampshire Basin fits with long term sea-level trends for the Mid to Late Eocene. The extensive deep water marine conditions in the Late Paleocene and Early Eocene can be correlated with a sea-level high, which could be attributed to the timing of the Paleocene Eocene Thermal Maximum (PETM) (Brenchley and Rawson, 2006; Kominz, 2001). The deposition of the Reading and Woolwich formations between 55.8 and 55.5 Ma is atypical as it occurred during a global sea-level high, but data on the basin geometry and accommodation space shows consistently very shallow coastal water depths across large areas up until the deposition of the succeeding Harwich Formation from 55.5 Ma. According to Miller *et al* (2005) the Norwegian-Greenland Sea opening and the eruption of Brito-Arctic basalts occurred between 55.8 and 55.5 Ma. The constrained deposition of the Reading and Woolwich formations coincides with this. This suggests there could be a tectonic or thermal influence, and these possibilities are explored later in this chapter. The presence of tephra layers in the early Paleogene lithostratigraphic units, the Thanet Formation, and Reading, Woolwich and Harwich formations coincides with the most volatile and volcanic phases in NW Europe, from Icelandic plume development and the emplacement of Brito-Arctic basalts. It is necessary to consider that the long-term eustatic data may not be appropriate in this regard or that using the short-term curve in backstripping the data was justified. The good agreement of the Miller et al (2005) sea-level curve and the variation in water depths reflected in the palaeobathymetry maps suggests the sea-level curve was appropriate for the study. The Miller et al (2005) study used stratigraphy from New Jersey in North America and the agreement of the derived eustatic sea-level curve with the water depths in this study from south-east England supports its use, as demonstrated and described by figure 5.1.6 in chapter 5.

7.3 Tectonic subsidence curves and surface discussion

Following the development of water depth values, appropriate sections were selected for backstripping. The backstripping produced curves of water-loaded vertical motions of the Chalk basement during the Cenozoic. It was critical that the selected boreholes or sections preserved more than one lithostratigraphic unit or were thicker than 30 m to produce resolution in the data required, as discussed in Chapter 5, section 5.2. It was also preferable they reached the Chalk basement. This limited the number of available boreholes or sections that could be backstripped. The western London Basin and southern East Anglia were the most sparsely populated in terms of suitable freely available appropriately detailed boreholes and sections that could be backstripped into data points. The Central London, northern East Anglia and Hampshire basin regions produced the highest density of data points. Subsequent interpretations of the vertical motions of the Chalk basement during the Cenozoic and the possible causes for these patterns are more definitive in the higher density areas. The next few sections of this chapter discuss the three main areas and the most important subsidence patterns from the curves and surface models before discussing a regional context for the tectonic patterns suggested in this study.

7.3.1 Hampshire Basin: Isle of Wight tectonic subsidence and surfaces

The Paleogene tectonic subsidence curves suggest a dominant south-east tilt of the basement between 55.5 to 36.4 Ma in the Hampshire Basin. The central and eastern areas of the Hampshire Basin consistently produced greater depths to the basement than the western and northern areas that were backstripped.

In the early Paleogene between 54.7 and 53.2 Ma, all subsidence curves suggest a basin-wide uplift event. The south-easterly tilt of the basement was suggested by the 54.7 and the 53.2 Ma surfaces despite the similar amount of uplift experienced across all sections. The northern and north-western areas of the Hampshire Basin tectonic surfaces consistently produced the shallowest depths to the basement together with tectonic highs when compared with the eastern and south-eastern data points. The evolution of the basement during the Cenozoic, interpreted from the tectonic surfaces, suggests a tectonic control by structures at depth in the Hampshire Basin (figure 2.14: Chapter 2).

The backstripped data from the eastern areas of the Hampshire Basin produced the greatest tectonic subsidence values from the 28 sections studied in the southern UK. The water-loaded basement produced a maximum depth value of 399 metres at 34.8 Ma, from the Sandhills borehole in the centre of the Isle of Wight. The two cliff sections south of this produced shallower basement depths at this time. The Alum Bay section in the west produced a maximum basement depth value of 331 metres and the Whitecliff Bay section in the east, a shallower maximum basement depth value of 317 metres by 34.8 Ma. From 54.7 to 36.4 Ma the eastern section, Whitecliff Bay on the Isle of Wight, showed greater basement depths which produced a local north-easterly tilt to the basement for 18.3 Ma in this area of the Isle of Wight (figure 6.2a-b). At 36.4 Ma the Whitecliff Bay data suggests a change in the subsidence of the basement. The west and eastern sections have similar basement depths at 36.4 Ma and the subsequent surface at 34.8 Ma shows a shift to a north-north-west tilt as the western section at Alum Bay suggests a greater basement depth than in the east (figure 6.2d). At the present day the Whitecliff Bay and Alum Bay sections preserve the Cenozoic strata at a near-vertical dip, measured in the field as 095/88 N (Appendix 3). It is interpreted from seismic sections and the tilted strata that two large E-W trending faults, the Sandown fault in the east and the Needles fault in the west, cut the underlying Mesozoic strata (Chadwick and Evans, 2005). These faults are believed to be Variscan in origin (Chadwick, 1986). They do not crop out at the surface but their reactivation is proposed to be responsible for tilting of the Cenozoic succession to near vertical during the Miocene and the development of the large monoclinal structure preserved at the present day (Brenchley and Rawson, 2006). These structures existed as part of pervasive extensional basin faults across south-east England during the Mesozoic (figure 2.4) and are believed to have been reactivated as thrusts during the Miocene, post-Bouldnor Formation 34.8 Ma. However, stratigraphic and fossil evidence suggests earlier minor reactivation events during the Mid to Late Eocene (Gale et al., 1999), highlighted in Chapter 2. Assessment of the syntectonic stratal thickening of the Becton Formation north of these faults also suggests an early phase of reactivation and inversion, constrained to the Bartonian-Priabonian boundary (Late Eocene) by Newell and Evans (2011). They suggested thickening of strata north of the faults post-deposition of the Barton Clay Formation. This stratigraphic thickening (Newell and Evans 2011) is consistent with the water-loaded subsidence values in this study. Disparity in basement depths increases from the deposition of the Barton Clay Formation and decreases following the Headon Hill Formation. The lateral variation in stratal thickness of the youngest Bouldnor Formation as assessed by Newell and Evans (2011) is reduced, this is also reflected in the subsidence values as the difference in basement depths from north to south have decreased in magnitude. Although the gradient of the basement's northward dip is fairly shallow, it becomes steeper throughout the mid-Eocene through to the Early Oligocene at 34.8 Ma (figure 7.2a-d).

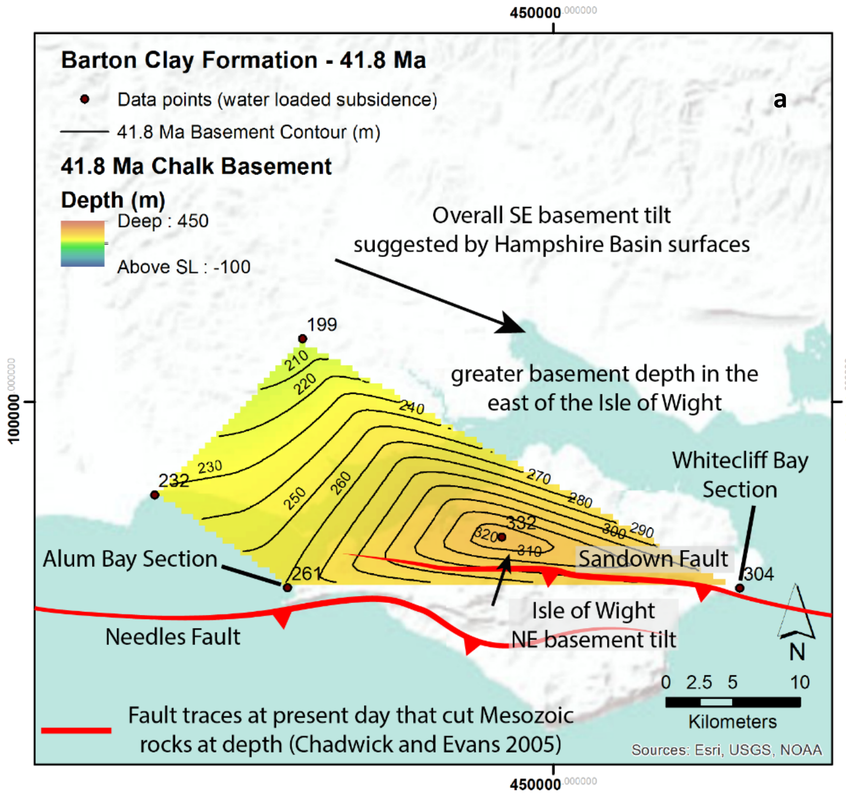
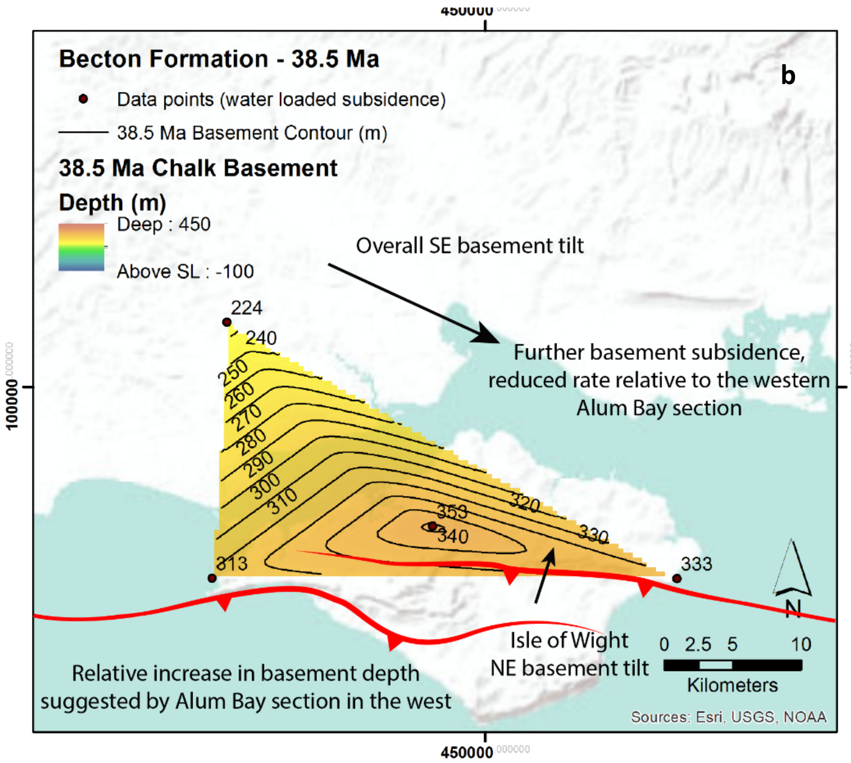


***Figure 7.2:** The tectonic surfaces of the Chalk Mesozoic basement developed from the subsidence data. A south-eastern tilt to the Chalk basement can be seen with a tectonic depression centred on the Sandhills borehole on the Isle of Wight. The northward tilt of the basement on the Isle of Wight can be compared with the known traces of the faults preserved at depth. **a**: 41.8 Ma tectonic surface showing shallower depths to the basement in the west. **b**: 38.5 Ma tectonic surface showing an increased rate of deepening in the western Isle of Wight basement depth compared to the east.*



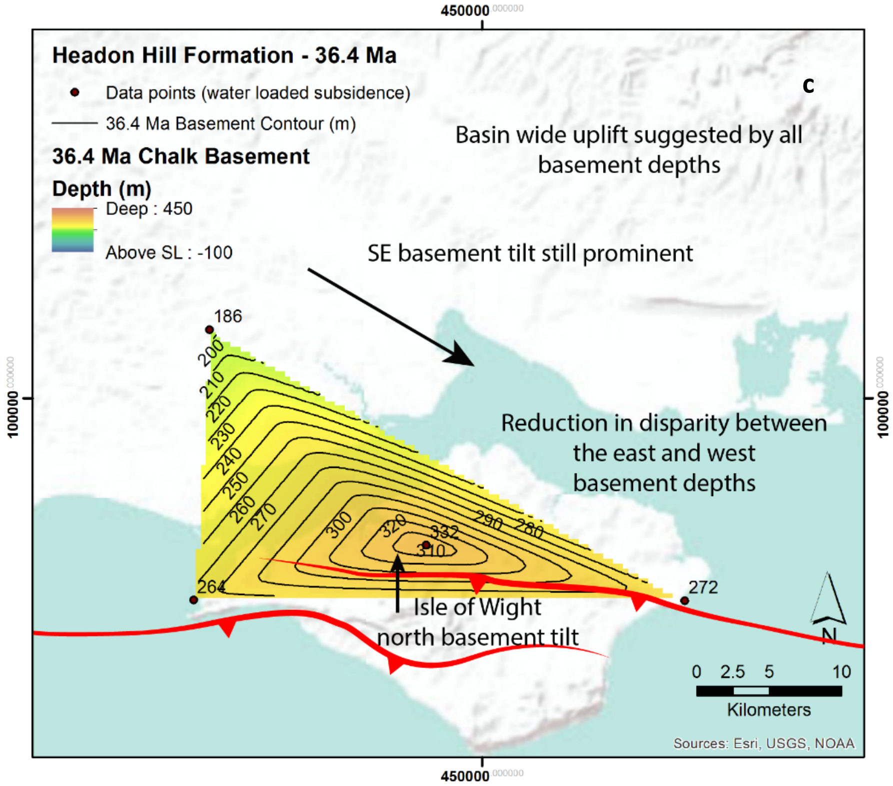
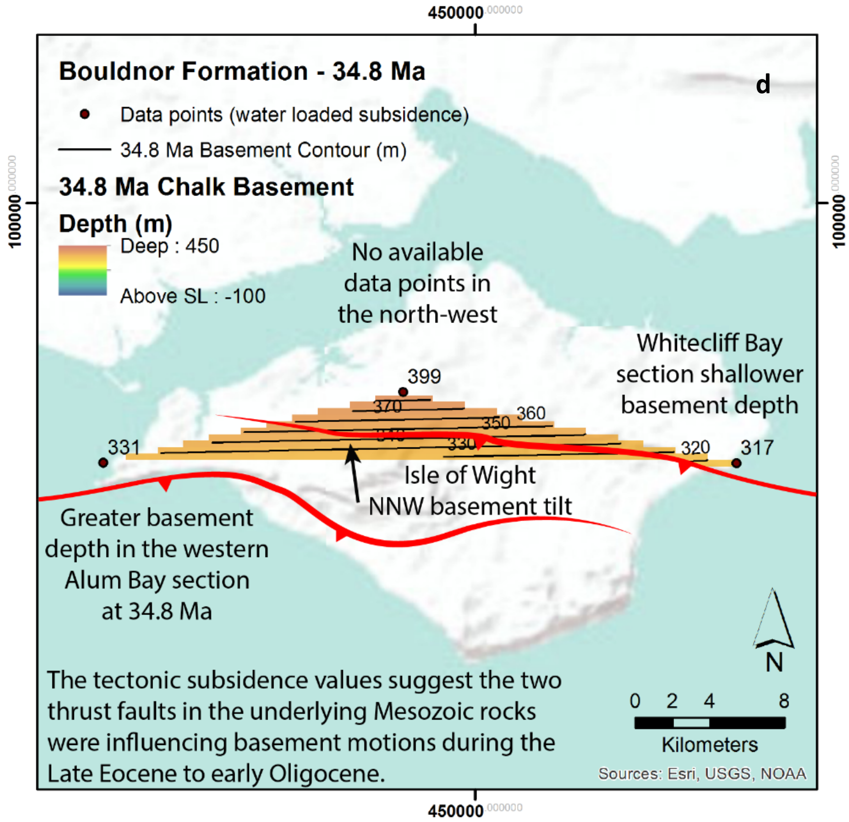


Figure 7.2: *The tectonic surfaces of the Chalk Mesozoic basement developed from the subsidence data. The south-eastern tilt to the Chalk basement and a tectonic basement exist; however, there is a reduced difference in the eastern and western subsidence values.* ***c****: 36.4 Ma tectonic surface showing very similar depths to the basement in the west and east.* ***d****: 34.8 Ma shows the western Alum Bay data point has exceeded the eastern Whitecliff Bay with a greater depth to the basement. The progression and the comparison to fault traces suggests differential slip from east to west.*



The changes in maximum basement depths from east to west and the relationship of these to the consistently greater basement depths in the centre of the Isle of Wight suggests that fault reactivations may have an influence on the geometry of the basement in this area during the Paleogene. The proposed thrust fault reactivation uplifted and eroded the southern areas of the Isle of Wight and the areas north of the faults were subsiding, relatively. This is suggested and shown by stratigraphic and sedimentological evidence combined with seismic data by Gale et al (2009) and Newell and Evans (2011). The deformation from the southern block thrusting upwards could be responsible for the northern tilt to the basement similar to the geometry produced in the tectonic surfaces of the Hampshire Basin and this can be seen in seismic sections trending N-S (Chadwick 2001). The tectonic surface at 41.8 Ma suggests that the northerly basement tilt began to develop during the Mid Eocene (figure 7.2a) which correlates with analysis of the reworking of the younger sediments into the Barton Clay Formation, of Mid to Late Eocene in age (Gale et al 2009). Newell and Evans described the timing of inversion to have occurred within the Bartonian, Late Eocene, during the deposition of the Barton Clay Formation. This is shown by the thickening of sequences within the Bouldnor syncline, north of the Needles Fault. The changes in subsidence values occur within the Late Eocene, correlating with the work of Newell and Evans (2011) and Gale et al (2009). The change in orientation of the basement tilt in this area from 36.4 to 34.8 Ma could reflect a reduction in the amount of displacement experienced by the eastern Sandown fault in comparison to the western Needles fault. Figure 7.2a-d highlights the progressive increase of basement depths in the west relative to the northern and eastern Hampshire Basin sections. This may be a result of the Needles Fault reactivating more readily than the eastern Sandown Fault and influencing the increased rate of tectonic subsidence observed in the data. This change in dominant fault displacement could be recording a variation in the stress orientation that favours the western Needles Fault. The reactivation of these faults as thrusts during the existence of continued deposition to the north and their development during the Eocene and Oligocene suggests the Hampshire Basin developed under a compressional regime at this time. The orientation of stress can also be determined based on the localisation of strain. The record of strain changing from east to west during the Paleogene suggests an orientation of stress that has a western trajectory. As the structures are reactivated as thrust faults there must also be a northern component to the stress orientation which fits with areas of compression studied across the UK and also in Europe. Fault movements in SE Ireland reflect a similar pattern, displaying short wavelength variations in crustal deformation that reflect a principal stress orientation with a northerly trajectory (Cunnnigham and Philips 2004). This is not unlike the Hampshire Basin; unfortunately, kinematic indicators of the same quality cannot be obtained. A WNW transpression is suggested to be dominant in the Variscan fault systems south of the Hampshire Basin, but the data suggests a NW-SE principal stress (Hamblin et al., 1992). This is discussed regionally in section 7.4 of this chapter. When analysing the change in palaeobathymetry and sedimentology throughout the Paleogene, a correlation exists between the basement depths and the transition of the Hampshire Basin from a restricted sea with connection to the south-east to a lacustrine depositional environment from 36.4 to 34.8 Ma (figure 7.2c-d). The relative reduction in basement depths may have been a contributing factor in the restriction of marine conditions if combined with the reduction in global sea-level at this time seen in Miller et al (2005).

The progressive development of a northerly basement tilt from 41.8 to 34.8 Ma during the Eocene through to the Early Oligocene records a progressive deformation of the Chalk basement with a potentially low strain rate, calculated as 0.0097 mm/yr from the tectonic subsidence points on the Isle of Wight. This rate is averaged for the duration of the Late Paleogene and it is possible strain build up could have led to short lived faster fault slip events rather than a progressive creep of 0.0097 mm/yr for the duration of the Paleogene. This value of strain rate also suggests the amount of movement post-Bouldnor Formation 34.8 Ma must have had faster strain rates to tilt the Cenozoic succession to its near-vertical state at the present day. The faults are believed to cut the Cenozoic succession at depth but do not appear to reach the surface. They tilt the strata to almost vertical but produce a monocline at the surface which may also suggest a low strain rate and could be attributed to the competence of the Cenozoic strata which are predominantly a series of clays and poorly consolidated sand-dominant lithologies with weak engineering properties. From field observations, the vertical strata at the surface did not show any clear signs of brittle deformation or fault planes. Supplementary to this, to backstrip the Whitecliff and Alum Bay sections, they were assumed as boreholes with horizontal strata prior to the vertical tilting. The tectonic surfaces produced a development of basement tilt and deformation independent of structural information that supports the Late Eocene to Early Oligocene reactivation of these fault structures. Analysis of the lateral stratal thickness variations reflects the influence of the Sandown and Needles fault structures. The thickness variations during the early inversion event of the Late Eocene and the pervasive syntectonic thickening of the strata north of the faults also supports a lower strain rate inversion shown by seismic data (Newell and Evans 2011).

The water-loaded subsidence data presents shorter wavelength structures within the Hampshire Basin developed during the Late Eocene and Oligocene, and suggests a timing for structural inversion that correlates with studies on these areas using other methodologies, such seismic analysis (Newell and Evans 2011) and sedimentological and biostratigraphical analysis (Gale et al 2009). As such, despite the limitations and error margins in the data, the method of backstripping shallower sequences appears robust. However these data points are minima as the sediment loading can only be calculated by the sequence of existing overburden. Therefore it is possible additional tectonic uplift may have occurred leading to additional removal of sediments that cannot be quantified. The signal produced from backstripping is a conservative quantifiable value that is consistent with results of published studies using other methods. These indicate the strengths of the method applied to the Hampshire Basin.

7.3.2 London Basin: tectonic subsidence and surfaces

There are fewer available data points, both spatially and temporally, in the London Basin which means the detail that was attained in the Hampshire Basin is not possible here. This is because the Cenozoic succession in the London Basin is stratigraphically thinner and the youngest Paleogene deposits are limited to small localised exposures. The Paleogene subsidence patterns in the Hampshire Basin are used as a comparator for the structural and tectonic evolution of the London Basin during the Paleogene.

A basement tilt towards the east and north-east is suggested to take place during the Paleogene from 58.5 to 55.5 Ma (figures 6.4a-c). The data points of this age in East Anglia continue this pattern northwards and eastwards and will be discussed later. The oldest Thanet Formation was deposited onto the underlying Mesozoic Chalk surface with a north-east tilt from 58.5 Ma. The subsequent tectonic surfaces from 56 to 55.8 Ma suggest uplift of the area occurred. Eastern and north-eastern basement tilts are still suggested by the tectonic surfaces. The Early Paleogene phases of uplift in the data suggest that the western and central areas of the London Basin were consistently above present-day sea level and predominantly formed basement highs. The most eastern and northern backstripped sections suggest the area was subsiding below present-day sea level from 56 to 53.2 Ma. The tectonic surfaces from 56 to 54.7 Ma consistently show basement highs to exist in the central London area. Despite the very shallow water depths of the Reading and Woolwich formations in central London (max 20 metre water depth), up to 20 metre of strata is preserved while there is a pervasive basement high in this area at 55.8 Ma. The subsequent Harwich Formation represents deeper marine conditions across the London Basin and East Anglia. However in central London a maximum of 15m of strata is preserved, the majority of the area preserving less than 2 metre-thick sequences of Harwich Formation, figure 6.4b. This resulted in all boreholes and sections containing insufficient preserved strata to be backstripped. The tectonic surface at 55.5 Ma (figure 7.4b) suggests that a tectonic high may have existed across Central London at this time, extrapolated from neighbouring data points. A strong link may exist between the shallow marine facies in the palaeobathymetry of Central London and the reduced thicknesses of strata preserved in this area. Perhaps there is a tectonic control on the bathymetric high observed in the data and this affected the water depth and the subsequent accumulation of sediments of the Harwich Formation. This could be the reason for thinner strata and shallower marine lithofacies. The tectonic surface at 54.7 Ma shows that the basement high in Central London is still present, with basement depths increasing towards the west and east. Similarities exist when comparing the Early Paleogene tectonic surfaces of the Chalk basement to the present-day distribution of Cenozoic strata and the topography of the underlying Chalk in Central London (figure 7.5). It is possible this pattern of sedimentation and preserved strata was influenced by the basement developments during the Paleogene. The last tectonic surface at 53.2 Ma in the London Basin again reflects this pattern of a basement high in Central London with greater basement depths to the east and west.

In Central London, three major faults have been recorded to cut the Paleogene succession to the surface, figure 7.3, others are more disputed (Aldiss, 2013; Ellison, 2004). The Wimbledon, Streatham and Greenwich faults all trend NE-SW forming the

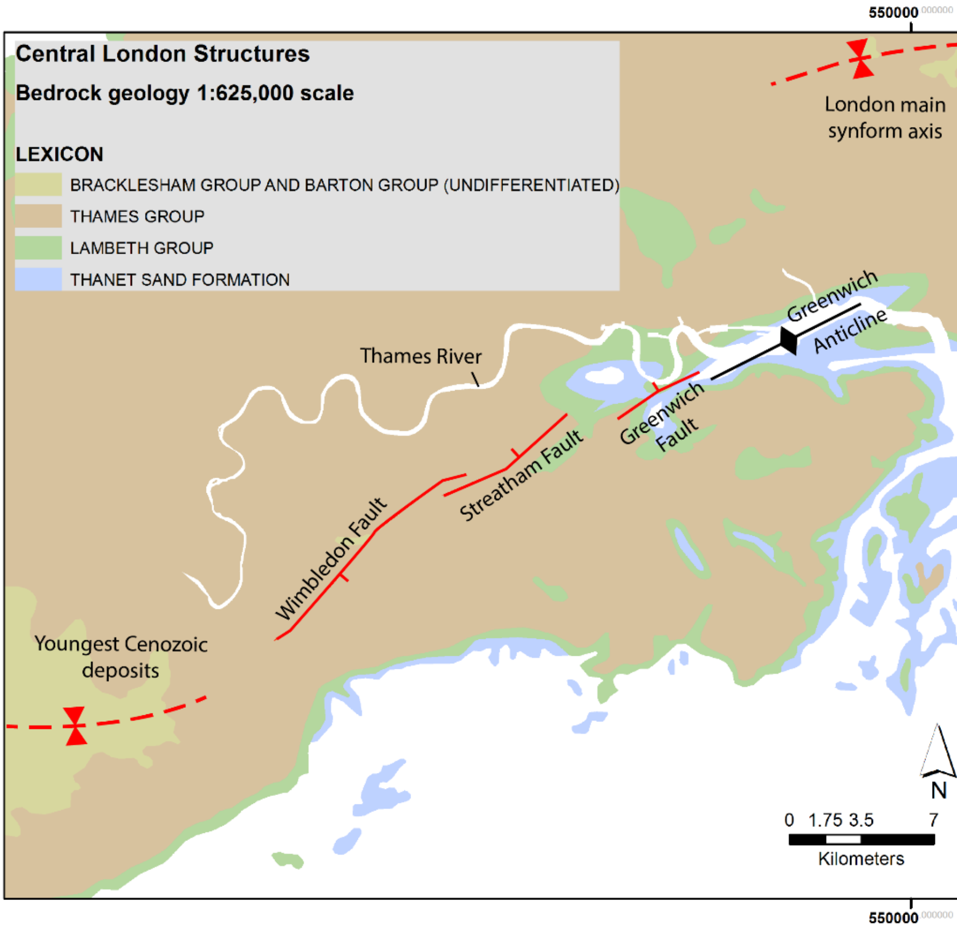
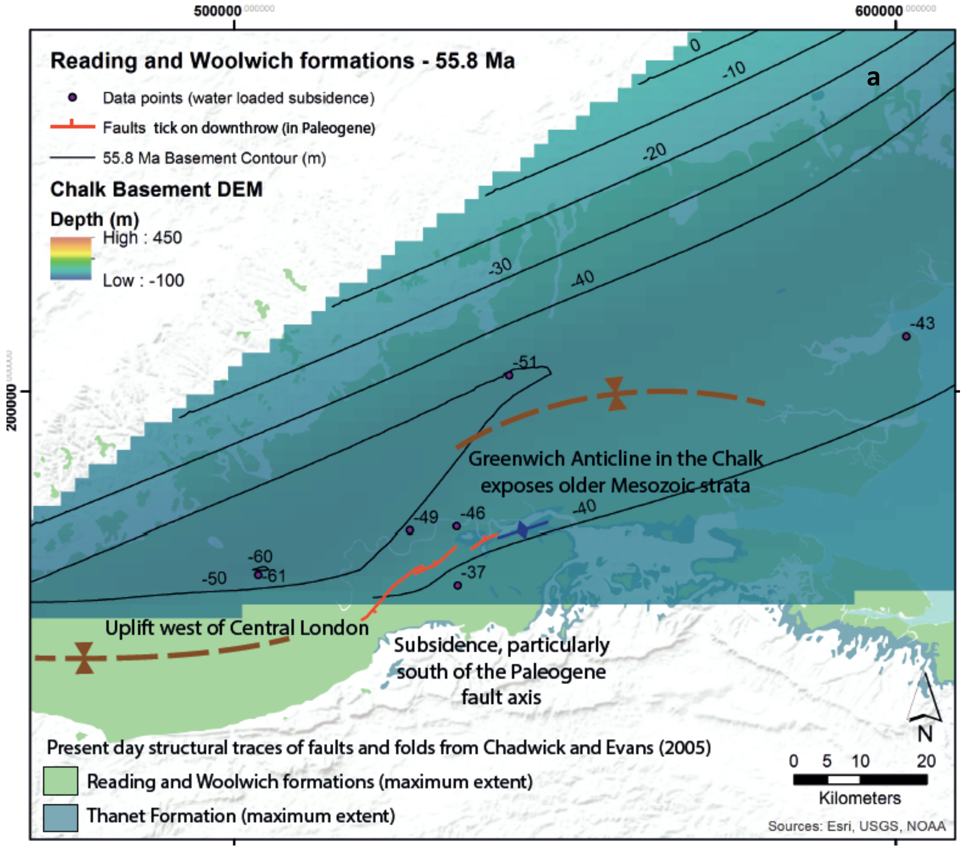
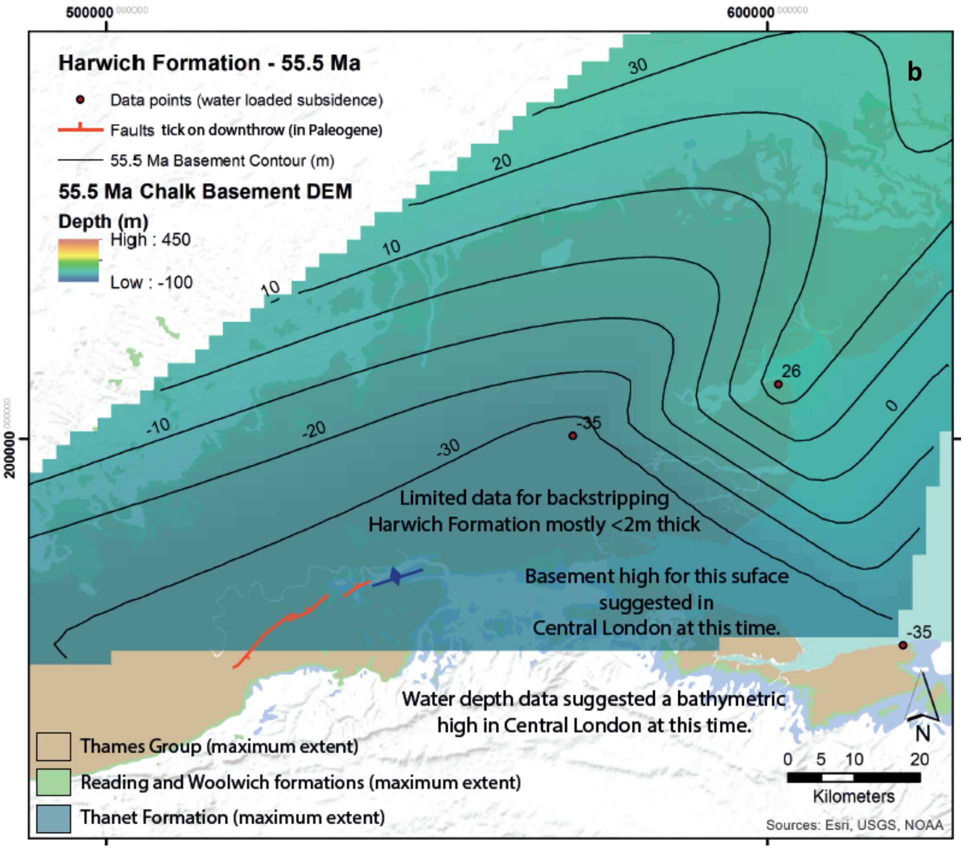


Figure 7.3: *The faults in the Central London area. The faults and fold trend NE-SW forming the Greenwich and Wimbledon axis. Structures taken from Ellison (2004). The large-scale London synformal axis is also shown but is deflected around Central London. The youngest Cenozoic deposits are preserved east and west of Central London.*

Greenwich-Wimbledon axis. The Greenwich and Purfleet anticlines in the underlying Chalk also trend in this orientation folding the overlying Paleogene strata, the former is in the northwest tip of the Greenwich-Wimbledon axis. The most south-western (Wimbledon) fault in the axis has a downthrow towards the south-east. The Streatham and Greenwich faults have a downthrow to the north-west. All are located in an area of shallow Chalk basement depths at the present day. The tectonic surface for 56 to 55.8 Ma shows a high in Central London during this time, figure 7.4a. The major faults are suggested to have activated between the Oligocene and the Miocene, forming en echelon to Alpine stress (Ellison, 2004). These may have activated as early as the Mid-Eocene as suggested by the 54.7 Ma tectonic surface which shows greater basement depths on the downthrown side of the Greenwich-Wimbledon axis. The greater basement depths to the east and west also preserve less faulting and folding structures but to determine whether this is really the case, additional boreholes and data from central London should be studied. It may be that Central London was a tectonically high area as a result of strain localisation and the areas of younger deposits preserved to east and west of Central London were a result of greater basement depths. This suggests the outcrop pattern at the present day is not necessarily a large synformal structure as suggested by published maps (BGS, 1996).


Reading and Woolwich formations - 55.8 Ma
Data points (water loaded subsidence)
Faults tick on downthrow (in Paleogene)
55.8 Ma Basement Contour (m)
Chalk Basement DEM
Depth (m)
High : 450
Low : -100
a
Greenwich Anticline in the Chalk exposes older Mesozoic strata
Uplift west of Central London
Subsidence, particularly south of the Paleogene fault axis
Present day structural traces of faults and folds from Chadwick and Evans (2005)
Reading and Woolwich formations (maximum extent)
Thanet Formation (maximum extent)
Kilometers
Sources: Esri, USGS, NOAA


Harwich Formation - 55.5 Ma
Data points (water loaded subsidence)
Faults tick on downthrow (in Paleogene)
55.5 Ma Basement Contour (m)
55.5 Ma Chalk Basement DEM
Depth (m)
High : 450
Low : -100
b
Limited data for backstripping Harwich Formation mostly <2m thick
Basement high for this suface suggested in Central London at this time.
Water depth data suggested a bathymetric high in Central London at this time.
Thames Group (maximum extent)
Reading and Woolwich formations (maximum extent)
Thanet Formation (maximum extent)
Kilometers
Sources: Esri, USGS, NOAA

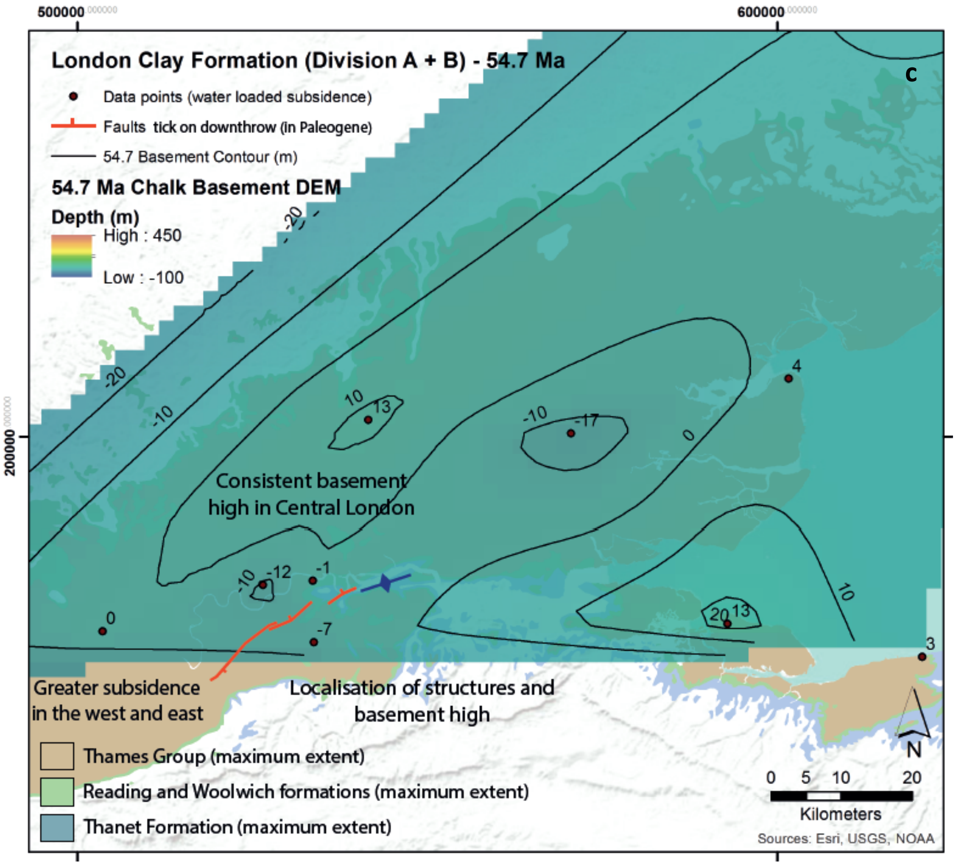


***Figure 7.4:** The tectonic surfaces of the Chalk basement developed for the London Basin during the early Paleogene. Subsidence curves show consistent tectonic highs particularly in Central London. The Greenwich-Woolwich tectonic axis of faults and folds has been added to each surface. The proposed synclinal axes are added to the 55.8 Ma surface. **a**: At 55.8 Ma highs existed in the central and western London area. **b**: The tectonic surface at 55.5 Ma has contouring that suggests Central London was a tectonic high. Deposits were too thin to be backstripped in Central London. **c**: Central London at 54.7 Ma exhibits a tectonic high and the Chalk basement deepens to the east and the west.*

The Harwich Formation at 55.5 Ma follows the Reading and Woolwich formations and preserves mostly thin deposits, commonly <2 metres in Central London. The facies of the Harwich Formation indicate shallower water depths in Central London than to the west and the north-east. The palaeobathymetry also suggests a shallowing or bathymetric high was centred on Central London at the time of Harwich Formation deposition at approximately 55.5 Ma. These strata are either missing or not thick enough for backstripping. This area of London produced a tectonic high in the tectonic surface but a more sensitive localised investigation could reveal whether it reflects a very localised event (figure 7.4b). Deeper water conditions were prevalent northwards and eastwards during the Harwich Formation deposition but a period of subsidence must have occurred between 56 and 55.5 Ma, though not significant enough to preserve thicker strata.

Although a net subsidence of the London Basin is shown by the subsidence curves, the rate of basement subsidence, unlike the Hampshire Basin, was not as rapid in the early Paleogene. The possible reasons for this variation are discussed in section 7.4. It also suggests the water-loaded basement was above present-day sea level. With the decline in global sea level shown by Miller et al. (2005) the sea most likely progressively regressed from the land surface with shallowing water depths leading to a reduction in accommodation spaced and thus in preserved strata. The London Basin may have been a tectonic high with areas of increased localised deposition until connection with the North Sea Basin and the Hampshire Basin was restricted by continuing falling sea-levels during the Paleogene. A comparison can be made with the present-day depth to the Chalk in Central London, which is shallow but deepens to the east and the west.

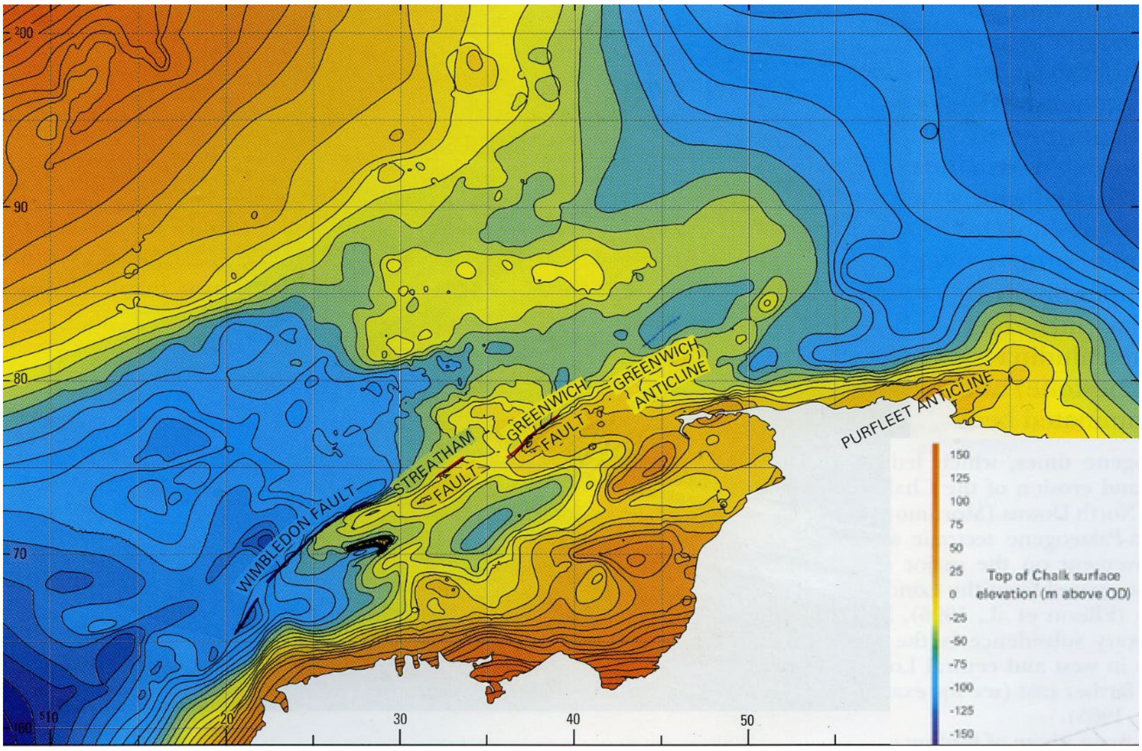


Figure 7.5: *The relief of the Chalk underlying Central London at the present day. Depths to the Chalk are shallowest in Central London, increasing in depth towards the east and west. The major faults trend NE-SW in the Greenwich-Woolwich axis and coincide with the shallowest depths to the Chalk in Central London (Ellison 2004).*

7.3.3 Summary of Cenozoic tectonic surfaces and inferred strain

- Progressive slip of the IOW faults is suggested by water-loaded surfaces and also previous stratigraphic evidence. To tilt strata to vertical requires a large amount of displacement. The fact the fault at depth reactivated and tilted the overlying strata to vertical without cutting the full Cenozoic succession to the surface suggests fairly low strain rates and supports progressive reactivation and slip along the faults. The water-loaded surfaces and subsidence curves suggest a progressive reactivation and that the eastern and western faults, Sandown and Needles respectively, became activated and slipped at different times/rates during the Paleogene. The eastern Sandown fault may have contributed to the restriction of marine conditions. The tectonic surfaces and stratigraphic evidence suggest multiple events and record a relatively slow strain rate for the Cenozoic.
- The Central London structures, particularly the shallow faults that cut the thin Paleogene strata, show a maximum of 30 m of displacement along the fault plane during their movement in the Cenozoic. They cut the succession along the Greenwich anticlinal axis that trends NE-SW and may have activated from the Mid Eocene. Strain appears to have localised in Central London with the depths to the basement increasing to the east and west, similarly to the present-day depths to the Chalk. The thinnest Cenozoic strata in the London Basin preserved at the present day are in Central London; east and west the Cenozoic succession is thicker, particularly in the west. Thinner deposits were preserved during the deposition of the Harwich Formation at 55.5 Ma. This tectonic configuration of the basement is supported by the shallower marine facies and shallower depths to the basement in Central London during the very Early Eocene. Overall it appears the London Basin was a consistent tectonic high with deposition controlled by areas of additional accommodation space until sea-levels dropped and Central London may have been an area in which strain localised.

7.4 Regional tectonics

The water-loaded subsidence curves suggest that the basins of south-east England underwent net subsidence during the Paleogene but with intervals of transient uplift. This pattern may agree with the long wavelength uplift pattern expected if the area was influenced by magmatic underplating associated with the Icelandic Plume, as has been argued to be a possible cause of permanent uplift in the NW of the UK. With the addition of material to the lithosphere and a resultant isostatic adjustment, the magmatic underplating would produce a permanent uplift pattern rather than the transient and intermittent signals observed in the subsidence data. However the backstripping data is a minimum quantification based on the preserved strata. Uplift may have led to erosion and denudation of the material and so a greater uplift signal may have been present but subsequently removed. Areas across Europe and the UK studied show periods of uplift and denudation within the Late Paleocene and the Late Eocene, as in Scotland, the Faroe Islands, Ireland and parts of Western Europe (Lovell and White 1997; Naylor et al 1999; Dore et al 2002; Cunningham and Philips 2004). Therefore this pattern would not be unlikely, but does express a limitation in the backstripping technique. Supplementary to this, these studies have been suggested to be attributed to the North Atlantic processes and so support this possibility as an influence on the Hampshire Basin. The south-east and eastern basement tilts may be a result of a long wavelength effect from the underplate existing in the NW of the UK where magmatic centres and intrusive dyke swarms were abundant and related to the overall Paleogene stress of north-western Europe (Dewey and Windley 1988). This does appear to reflect the shorter wavelength variations observed in the tectonic surfaces.

The independent variations of subsidence values on a 20 km wavelength as revealed in south-east England could be attributed to the reactivation of existing structures, given their proximity to features such as the reverse faults on the Isle of Wight. The timing also falls into line with sedimentological studies dating reactivation and inversion commencing from the Mid to Late Eocene (Gale et al 2009). The reworking of older units into Late Eocene facies is also reflected in the thickening of the younger units following inversion as shown by the seismic data (Newell and Evans 2011). This deformation suggests an area under compression which may be localising near faults but also the basin margins as reflected by lower subsidence rates and larger amounts of uplift, such as the Christchurch borehole in the western Hampshire Basin. The sedimentology and biostratigraphy consistently reflect facies of near-shore and terrestrial environments, consistent with an area experiencing less subsidence. The evolving palaeobathymetry suggests that the basement subsidence rates, intervals of uplift and synchronously decreasing sea-levels during the Eocene resulted in the restriction of marine conditions and the possible disappearance of large water bodies entirely by the early Oligocene may have been influenced by the deforming basement. The Headon Hill Formation displays channelling features that support the timing and nature of inversion, suggesting that the reactivation of these faults had a large control on the basin (Newell and Evans 2011).

The transpression of Variscan fault systems in the Late Eocene in the Amorican region, south of the Hampshire Basin (Hamblin et al., 1992), correlates with the subsidence patterns on the Isle of Wight; whether these are directly related is unknown. The reactivation of Variscan faults as thrusts as proposed by Gale et al (2009) and Newell and Evans (2011) was determined using sedimentological and seismic assessments and not by backstripping. As such the good agreement on the possible timing of the reactivation as suggested by the variations in subsidence rates constrains reactivation and deformation of the basement to have occurred within the Mid to Late Eocene, agreeing with studies using other methods. The disparity and variation in vertical motions produce a shorter wavelength pattern displaying a possible distribution of strain from east to west on the Isle of Wight suggesting a possible WNW stress trajectory. The strain recorded by both faults reactivating would most likely show less disparity between basement subsidence values if the stress direction had a more northern trajectory.

The timing of the apparent fault reactivation on the Isle of Wight coincides with the development of fault-controlled small depocentres in SW England such as the Bovey Basin, controlled by strike-slip faulting from the Mid Eocene to the Oligocene (Brenchley and Rawson, 2006; Campbell et al., 1998). Further to the south-west of the UK, the Western Approaches is suggested to have experienced periods of uplift and erosion during the Late Eocene and into the Oligocene. The subsidence data from across the

Hampshire Basin suggests short wavelength variations. Decreasing rates of subsidence during the Mid to Late Eocene varied across the basin. The basin margins to the north and west subsided at slower rates exhibiting relative uplift when compared with the central areas of the Hampshire Basin. This suggests the area experienced compressional driven subsidence in the Late Eocene through to the Oligocene, not unlike the Western Approaches (figure 7.7).

The south-eastern tilt of the Chalk basement in the Hampshire Basin was dominant until the subsidence rates slowed during the Mid to Late Eocene, with falling sea-levels, as shown by numerous sea-level curves (Miller 2005; Kominz 2009), led to a restriction of the marine conditions. The subsidence data suggests the restriction on the basin is mostly tectonically controlled, supported by the seismic inferences made on the Headon Hill Formation (Newell and Evans 2011). This is synchronous with the Pyrenean Phase of the Alpine orogeny (Handy et al., 2010). The orogenic belt was developing generally E-W, suggesting a long wavelength N-S tectonic compression. A northward component on a long wavelength may be responsible for the fault displacement and increased strain in the Hampshire Basin and the shorter wavelength variations in vertical motions seen from the data in the Mid to Late Eocene. The African plate moved northwards relative to Europe during the Cenozoic (Capitanio & Goes, 2006) while the Adriatic plate moved NW from the beginning of the Paleogene. By 35 Ma, it had developed a WNW direction of movement. The timing of this change in movement may explain the reduction in subsidence rates in the eastern Isle of Wight relative to the west but the data provided are inconclusive. The movement of both plates can be correlated with the development of compressional depocentres forming in the southern UK.

The movement on thrust faults, development of anticlines and uplift of areas between periods of basement subsidence support a hypothesis that basin development in the southern UK, such as the Hampshire Basin (figure 7.6), occurred in a compressional tectonic regime. The orientation of fault activation, folding and uplifted areas in the basement, records a strain with a north-west to west-north-west compression during the Eocene to Early Oligocene. A NW vergence from the Alpine collisional event was demonstrated to have occurred from 37 Ma by the Penninic and Helvetic Nappe stacking (Steck and Hunziker, 1994) and correlates with the timing of increased strain suggested by the subsidence data in the Hampshire Basin. The south-east basement tilt may represent a long wavelength pattern and the shorter wavelength deformation of the Hampshire Basin during compression is demonstrated by the possible reactivation of fault structures and margin uplift. The timing of these compressional structures being activated whilst the basin was also tectonically subsiding is similar to the SE German Molasse basin during the Late Eocene (Zweigel et al., 1998). Forming in the Alpine foreland under compression, the basin experienced a higher degree of subsidence than the Hampshire Basin but this may be due to its proximity to the orogen but the timing constrained by various studies and the degree of deformation make it plausible. An analysis of the closer Paris Basin may provide additional clues. The subsidence models suggest the Hampshire Basin developed under compression and movement of the fault structures during the mid-Eocene to Oligocene, which can be correlated with the uplift events of the South Celtic Sea and Western Approaches basins west and south-west of the Hampshire Basin (Evans, 1990). The timing of these events and their correlation to the Hampshire Basin tectonic subsidence models supports the hypothesis that the Alpine tectonic phases were a stronger influence from the mid-Eocene than has previously been thought

The development of the Greenwich anticline and Greenwich-Wimbledon faults and their orientation suggests a degree of shear and uplift that localised in the Central London area during the Paleocene and early Eocene, 58.5 to 53.2 Ma. NW-SE trending joints in the underlying chalk may have also facilitated this movement during the Cenozoic (Ellison, 2004). The London tectonic surfaces were consistently above present-day sea level with the phases of uplift and subsidence between 58.5 and 53.2 Ma. During this time the North Atlantic opening had commenced and basins surrounding the margin at around 56 Ma experienced up to 1 Myr of uplift above sea-level (Hartley et al., 2011). This correlates with the tectonic high between 56 and 55.8 Ma in the London Basin. The Hampshire Basin also demonstrates this tectonic high between 56 and 55.8 Ma. Stratigraphically, the sedimentological facies represent a subaerial unconformity surface, not dissimilar to the uplift and denudation pattern observed north of the UK in the Faroe-Shetland Islands (Stoker et al 2018). Although the degree of uplift is comparatively lower, the magnitude of compressive stresses from North Atlantic processes would be much lower, given the long wavelength. The rapid uplift in the NW of the UK and resulting denudation during the early Paleocene has been attributed to magmatic underplating and the timing is supported by fission-track studies (Green et al., 2002). It is unlikely it reached the London area given the outcrop pattern, however a combination of gravity-driven crustal push towards the south-east and the possible associated elevated mantle temperatures may have resulted in the early Paleogene uplift signals from 56 to 55.8 Ma recorded in the subsidence data of the London and Hampshire basins, reflected in the fission-track studies closer to the north Atlantic ridge. (Hartley et al 2011). The second phase of uplift in the London Basin is recorded at 53.2 Ma in the subsidence curves. The tectonic models of the London Basin area suggest it was not folded into a large scale synform but rather a tectonically high area with lows to the east and west. The tectonic high in Central London localised the faulting and folding. The tectonic lows formed the depocentres that accumulated sediments under deeper water conditions until sea-level fell. Although the Hampshire Basin continued to

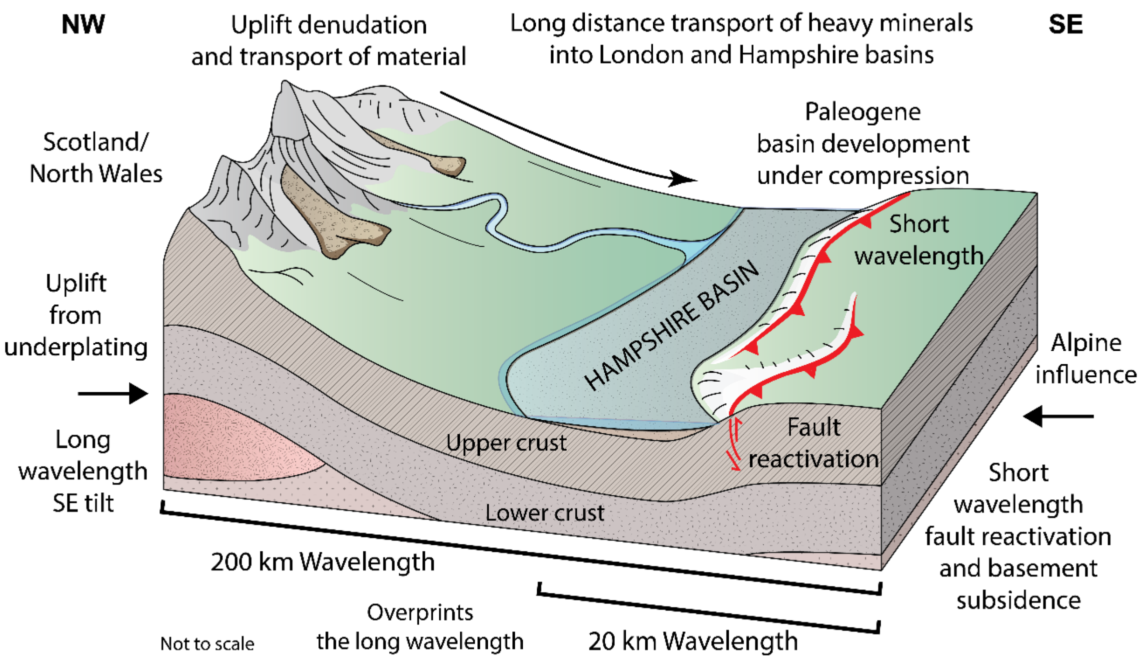


Figure 7.6: *A schematic diagram of the long wavelength and short wavelength influences on the Hampshire Basin. Uplift of the northern areas of Scotland from underplating may have caused the south-eastern tilt observed in the tectonic surfaces. With Alpine compression, the Hampshire Basin was depressed. Incremental strain was compensated by reactivation of Variscan faults causing subsidence of the basin although under compression. Periods of uplift in the Hampshire Basin may have been a result of strain build-up before continued fault movement took place to accommodate the strain and produce shorter wavelength variations and a non-transient pattern of uplift events.*

subside at faster rates during the Paleogene in comparison to the London region, ultimately the sea-level fall across both basins was synchronous with reducing rates of subsidence across south-east England, leading to the restriction of full marine conditions but local fault controlled inversion controlled the geometry of existing basins.

The trajectory and timing of this basement deformation correlates with the Pyrenean and early stages of main phase Alpine tectonism. The relatively low magnitude of deformation suggested by the tectonic subsidence reflects the early development of structures that most likely developed further during the Miocene and the onset of the main Alpine orogenic phases. When assessing the shorter wavelength variations observed in the tectonic surfaces, the possible Alpine influence on the Paleogene basin development of the southern UK is more appropriate than magmatic underplating which most likely occurred in the Paleocene, 65-60 Ma, as suggested by fission-track studies (Holford et al., 2010). It could be that the magmatic underplate and increased magmatism in the western and northern UK regions led to uplift and a plate tilt creating a crustal push towards the south-east, producing higher strain in the Paleocene and Early Eocene, before forming essentially a tectonic boundary for the Alpine processes to push against from the mid Eocene onwards, figure 7.6. What the range of evidence from previous studies and the subsidence data presented in this study suggest is that pervasive structures related to the Variscan front may be responsible for localising crustal deformation. The London Basin developing on the southern edge of the stable Midland Craton, appears to show fewer short wavelength variations in vertical motions.

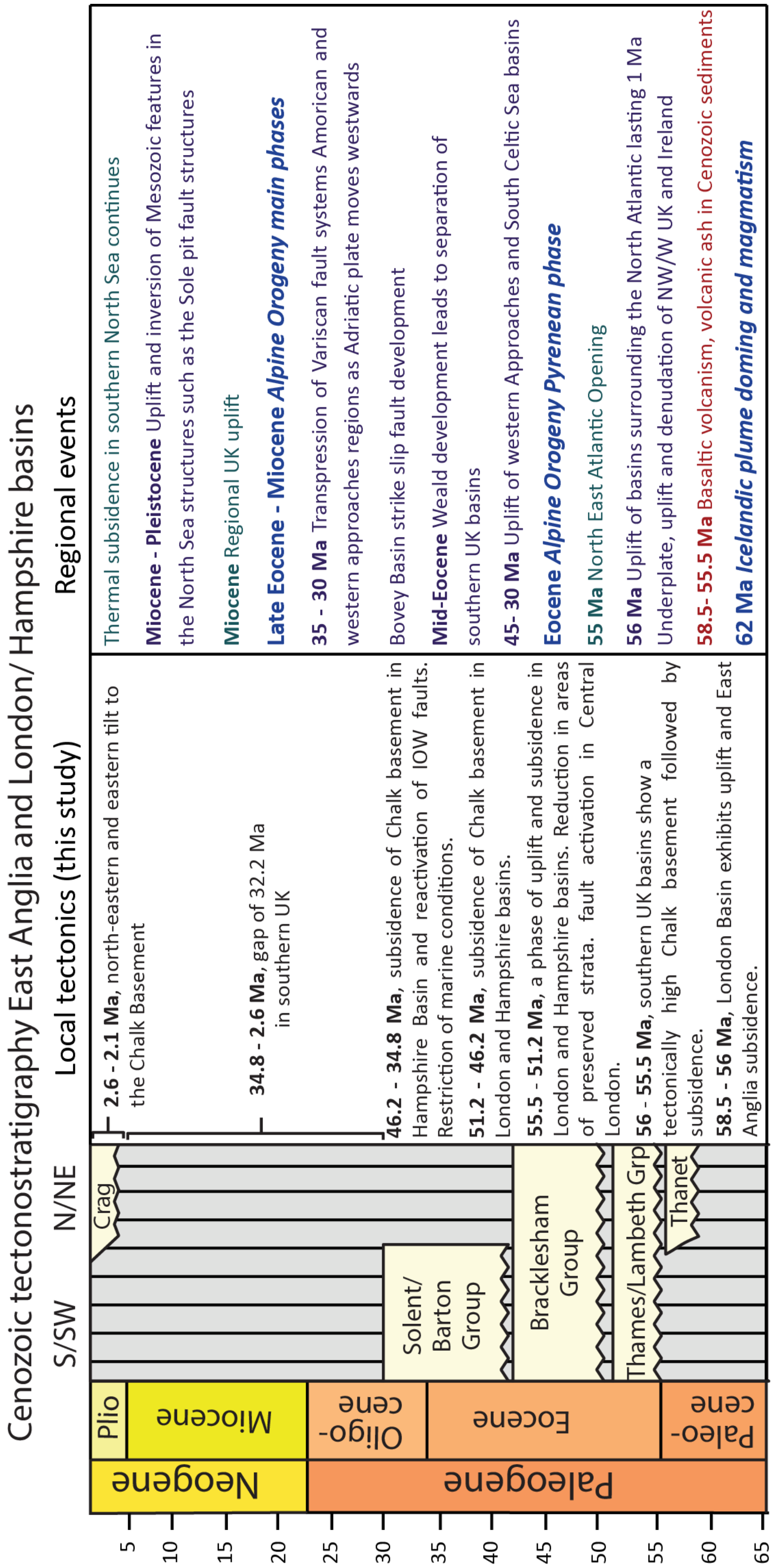


Figure 7.7: *The Cenozoic tectonics of East Anglia and Hampshire and London basins from this study correlated with major regional tectonic events.*

7.5 Tectonic zones of southern UK during the Cenozoic

Overall it appears that the influence of Alpine tectonism was dominant during the Cenozoic and the major control on crustal deformation. The three regions of East Anglia and the London and Hampshire basins record compressional structures with short wavelengths (figure 7.8). The Hampshire Basin appears to be dominantly controlled by the reactivation of pervasive Variscan fault structures. The London Basin lies north of the Variscan front and was a consistent high in the Mesozoic and the vertical surface motion suggests this was still the case in the Cenozoic. East Anglia represents the fringe

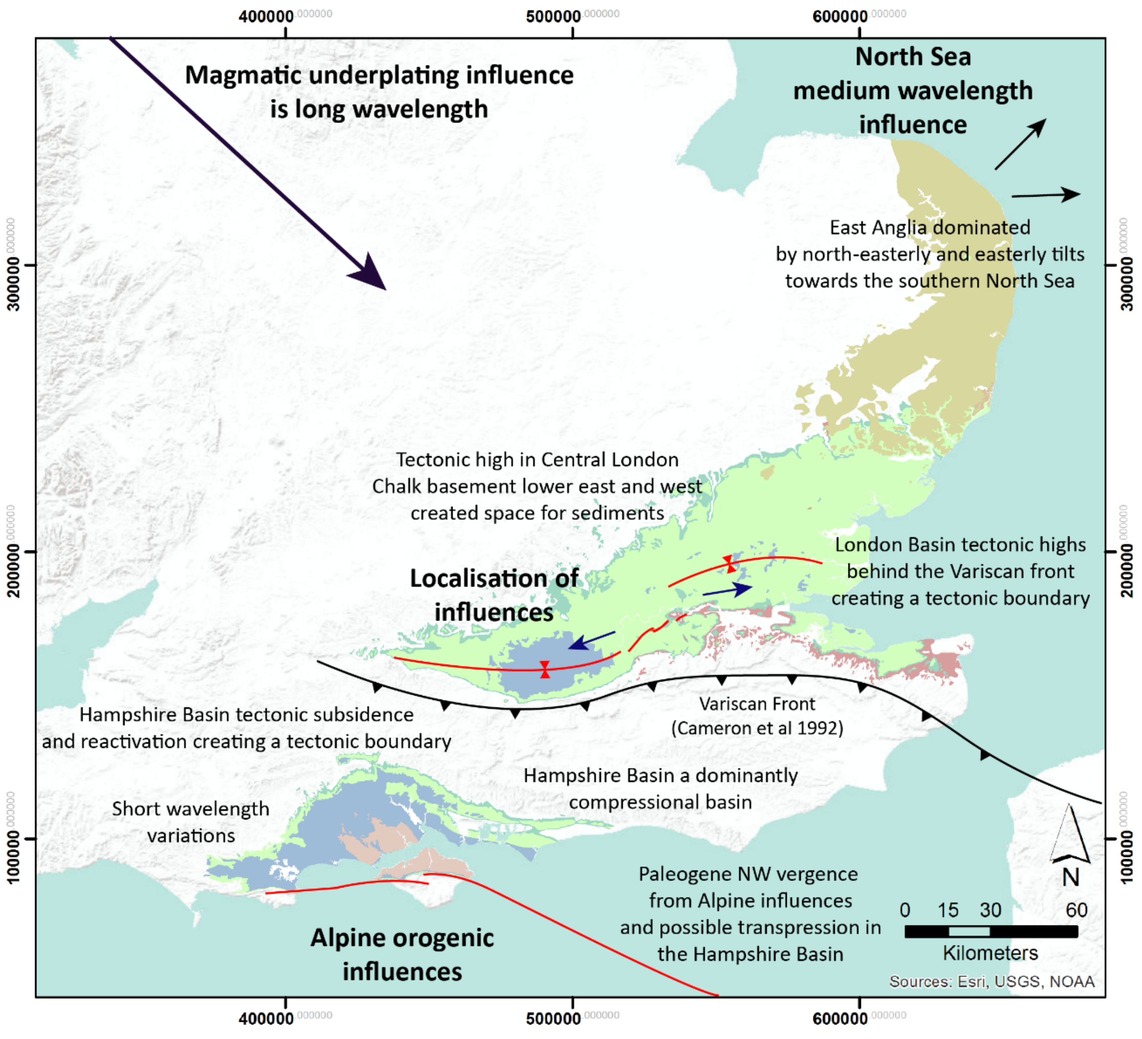


Figure 7.8: *The Cenozoic geology of the UK, and the main structures and tectonic influences on the vertical motions of the Chalk basement. The shorter wavelength changes in basement topography across the London and Hampshire basins appear to be influenced by tectonics to the east and west. The suggestion of magmatic underplating tilting the UK and influencing the Cenozoic geology in southern UK appears to be to be a very long wavelength in comparison to the short wavelength variations suggested by the tectonic surfaces developed in this study.*

of the North Sea basin affected by extension and subsidence to the north and north-east during the early Cenozoic.

7.6 Outcomes of the subsidence analysis method

The subsidence analysis method is predominantly applied to deep marine sequences hundreds of metres thick with fairly homogeneous sequences thereby creating a larger error margin in the uncertainty in water depth and age constraints such as those used by Sclater and Christie (1980) in the North Sea. This study used shallow marine deposits with a high frequency of alternating lithofacies temporally well constrained within a period of 33 myr. These sedimentary facies and fossil assemblages varied significantly laterally and temporally with a higher resolution than a traditional deep marine basin study with the challenge of a limited outcrop extent. This did allow interpretations on the likely palaeo-water depth and chronostratigraphic placement to be made at finer resolution. The varying lithostratigraphic units provided maximum and minimum constraints at a finer resolution given the rapid variation in facies within short durations of time, none of which possessed an error margin greater than a million years. This led to a maximum of 13 data points, which was achievable in the Sandhills Borehole, characterising the likely subsidence history at a finer resolution than a traditional deeper marine study that could produce fewer data points for thicker sequences of deposit. The result is a subsidence history that displayed multiple phases of uplift, not limited solely to subsidence. The method is robust for shallow marine stratigraphy because of the nature of the sedimentary succession possessing a high chronological frequency of lithostratigraphies and members and associated biostratigraphic and sedimentological evidence further constraining the sequence. The results are plausible and the resulting subsidence curves can be correlated to significant regional events, such as the uplift signal produced by the Reading and Woolwich formations.

Chapter 8: Conclusions

8.1 Project aim and hypothesis

The project and thesis set out to analyse and discuss the vertical surface motions of the southern UK during the Cenozoic focusing on whether shorter wavelength variations would reflect the long wavelength patterns and tectonic mechanisms. Secondary to this, the appropriateness for using a backstripping technique in a shallow marine sequence was assessed. The research conducted fulfilled these objectives.

8.2 Conclusions of Cenozoic vertical surface motions in the southern UK

The project was developed from the analysis of vertical surface motions of the UK assessing the shorter wavelength variations in the southern UK and relating them to the long wavelength mechanisms. In order to isolate the vertical surface motions and tectonic signals, the onshore Cenozoic record from the UK was successfully analysed using the method of backstripping.

Determining palaeo-water depths was necessary for the backstripping method; however, the development of these water depths into palaeobathymetric surfaces proved vital for understanding the palaeogeography and distribution of lithofacies and more crucially the evolution of the onshore basins. The palaeobathymetric surfaces produced patterns of basin deepening in the early Paleogene (Palaeocene to Early Eocene) which could be correlated to the sea-level rise described by Miller et al (2005).

The Reading and Woolwich formations from 56 to 55.8 Ma showed basin shallowing during sea-level rise demonstrating an outlier in the data when compared with the other lithostratigraphic units. This highlighted a period of uplift that can be correlated with uplift events observed from fission-track studies in the NW UK and stratigraphically the facies may represent a subaerial exposure and denudation event. This lasted for 1 Myr and can be attributed to transient uplift associated with North Atlantic opening/Icelandic plume tectonic processes suggesting that south-east England was also affected at this time. This transient uplift can be correlated with the 1 Myr duration uplift events recorded in the Faroe-Shetland islands and trough at this time (Hartley et al., 2011; Stoker et al 2018).

During the Paleogene, from the Mid Eocene, the marine conditions began to shallow, disappearing from the London Basin as sea level fell. In the Hampshire Basin, water depths continued to shallow from the Mid Eocene through to the Early Oligocene. The early Oligocene marked the restriction of the basin from marine conditions and it became a lacustrine environment.

The London Basin vertical surface motions during the early Paleogene, corrected for eustasy, suggest that the water-loaded Chalk basement most likely existed above present-day sea level. The data suggest also that Central London existed as a tectonic high and a possible localisation of regional stress while the basement deepened both to the east and the west. This created the accommodation space for deposition in these areas, influencing the outcrop pattern of these sediments at the present day. The eventual sea-level fall led to the restriction of marine facies in the London Basin.

The Hampshire Basin vertical surface motions, corrected for eustasy, suggested marine conditions continued long after sediment supply had been reduced in the London Basin. Tectonic surfaces indicate a Chalk basement with a south-easterly tilt during the Paleogene. The data from the Isle of Wight demonstrated suggested increased strain leading to reactivation of pervasive Variscan faults cutting through the underlying Mesozoic sequences. This led to the deformation of the Chalk basement which the data suggests began in the Mid Eocene lasting through to the Oligocene; this in agreement with the findings of Newell and Evans (2011). This also fits the patterns of uplift and denudation across the UK, particularly drawing parallels with reactivation of Variscan faults studied in south-east Ireland (Cunningham and Philips 2004). Variations in subsidence rates from west to east on the Isle of Wight may be attributed to the two Variscan faults reactivating at different rates. The activation of these faults, which eventually tilted the Cenozoic strata to vertical, began to develop prior to the Miocene. The evolution of these short wavelength structures can be related to the large scale processes, with the stress orientation to be inferred within a NW-SE orientation fitting the long wavelength processes of the Icelandic plume and NE Atlantic opening dominating the Paleocene and Early Eocene and Alpine Events from the south west. Eventual continued deformation of the basin margins alongside continued sea-level fall restricted the initially open marine Hampshire Basin to a lacustrine environment.

8.3 Final Conclusion

The use of the backstripping method in shallow marine and near-shore sequences is effective, producing signals of uplift and subsidence events that can be correlated with fission-track dating, and seismic and stratigraphic methods, for assessing the timing of inversions and basin development. Interpretations of palaeo-water depths and timings of deposition within the south-east England Cenozoic record, particularly in the Hampshire Basin, are well constrained and the use of backstripping, given the error margins, is appropriate. Uplift events in the Late Paleocene and Late Eocene were revealed by the data that correlated with patterns observed across the UK and NW Europe, suggesting a predominant NW-SE principal stress orientation reflected by shorter wavelength variations. These can be attributed to the long wavelength mechanisms of the Alpine orogenic sequences and phases from the North Atlantic opening processes influencing the patterns in the Paleocene and Early Eocene.

Secondly, in order to successfully assess the short wavelength variations that can be related to long wavelength tectonic patterns, the regional scale of the data points required a spatial assessment and the production of tectonic surfaces displaying the evolving water-loaded Chalk basement. These surfaces quantify the spatial distribution of vertical motion variations. These reveal the London Basin as a basin within a tectonic high that subsided more slowly than the rate of sea-level fall. The Hampshire Basin subsided under compressive stress causing inversion of structures, but again deposition within the basin finally ceased as the subsidence rate was slower than the rate of sea-level fall. This was reflected in the changes in facies from shallow marine to a lacustrine environment.

8.4 Further Work

The research project raised interesting questions and areas that could form the foundation for additional research.

- The method of using backstripping was appropriate for the area studied. In order to increase the detail of the data, a few parameters could be improved. The use of more boreholes from across the UK onshore would increase the spatial resolution of the data and additional boreholes from offshore areas such as the English Channel, the Western Approaches and the southern North Sea would increase the extent of the data. Modelling the development of the Hampshire and London basins offshore would be useful for confirming extrapolated basement depths. Additionally some lithostratigraphic units could be divided further to increase the temporal resolution of the data. The London Clay Formation could be subdivided into each division and some lithostratigraphic units could be divided further into localised members. This may result in a reduced spatial extent of the data if developed into tectonic surfaces but may provide a better picture of detail patterns.
- For the Harwich Formation, the backstripping method could be adjusted to accommodate these thin deposits for an individual study of its evolution in the London Basin. To do this, additional boreholes would be used in Central London and the lateral variations in the Harwich Formation and the Chalk basement variations at 55.5 Ma could be analysed more accurately.
- A more detailed localised investigation into the Crag formations would be beneficial to the knowledge of vertical motions of the UK during the Pliocene and Pleistocene. Some areas are data-poor, but additional boreholes for the Coralline Crag Formation to the south-east could be added alongside offshore sections to increase the resolution of Neogene vertical motions.
- The porosity investigation provided interesting constraints on assigned initial porosity in backstripping and its relation to the preserved porosity and compaction coefficient values. This was done using fluorescence microscopy and CT scanning. Ideally, additional non-friable samples could be tested from the Alum Bay section. The application and appropriateness of these values could

then be evaluated for the full succession at this locality. Samples collected at depth would be useful to compare and contrast with exhumed sediments studied here against confined sediments from the Cenozoic succession. Additionally, the study of porosity and compaction coefficients could be extended to the lithostratigraphic units in the areas of both the London Basin and East Anglia.

- Increasing the data points in the London Basin could also be related to the increased density of present-day vertical and lateral motion data that is currently being analysed by Dr Ghail (personal communication) and a joint investigation has been proposed into the uplift and shear patterns observed both in the Cenozoic record and at the present day.

8.5 References

Airy, G. B., 1855, On the computation of the effect of the attraction of mountain-masses, as disturbing the apparent astronomical latitude of stations of geodetic surveys: Phil. Trans. R. Soc. London, v. 145, p. 101-104.

Akin, S., and Kovscek, A., 2003, Computed tomography in petroleum engineering research, in Mees, F., Swennen, R., Van Geet, M., and Jacobs, P., eds., Applications of X-ray Computed Tomography in the Geosciences, Volume Special Publications 215: London, Geological Society, p. 23-38.

Aldiss, D. T., 2013, Under-representation of faults on geological maps of the London region: reasons, consequences and solutions: Proceedings of the Geologists' Association, v. 124, no. 6, p. 929-945.

Aldiss, D. T., 2012, The Stratigraphical Framework for the Palaeogene Successions of the London Basin, UK: British Geological Survey.

Aldiss, D., 2002, Geology of the Chichester and Bognor District: Sheet Description, Keyworth, Nottingham, British Geological Survey.

Aldiss, D., Burke, H., Chacksfield, B., Bingley, R., Teferle, N., Williams, S., Blackman, D., Burren, R., and Press, N., 2014, Geological interpretation of current subsidence and uplift in the London area, UK, as shown by high precision satellite-based surveying: Proceedings of the Geologists' Association, v. 125, no. 1, p. 1-13.

Aldiss, D., Newell, A., Smith, N., and Woods, M., 2006, Geology of the Newbury District: Sheet Description, Keyworth, Nottingham, British Geological Survey.

Ali, J. R. & Jolley, D. W. 1996. Chronostratigraphic framework for the Thanetian and lower Ypresian deposits of southern England. In: Knox, R. W. O'B., Corfield, R. M. & Dunay, R. E. (eds) Correlation of the Early Paleogene in Northwest Europe. Geological Society, London, Special Publications, 101, 129–144.

Ali, J. R., King, C. & Hailwood, E. A. 1993. Magnetostratigraphic calibration of early Eocene depositional sequences in the southern North Sea Basin. In: Hailwood, E. A. &Kidd, R. B. (eds) High Resolution Stratigraphy. Geological Society, London, Special Publications, 70, 99–125.

Al-Kindi, S., White, N., Sinha, M., England, R., and Tiley, R., 2003, Crustal trace of a hot convective sheet: Geology, v. 31, no. 3, p. 207-210.

Allen, J.R. 1967. Depth indicators of clastic sequences. Marine Geology. 5. pp429-446.

Allen, P., and Allen, J., 2013, Basin Analysis: Principles and Application to Petroleum Play Assessment, Wiley-Blackwell.

Armitage, J. J., and Allen, P. A., 2010, Cratonic basins and the long-term subsidence history of continental interiors: Journal of the Geological Society, v. 167, no. 1, p. 61-70.

Arrowsmith, S. J., Kendall, M., White, N., VanDecar, J. C., and Booth, D. C., 2005, Seismic imaging of a hot upwelling beneath the British Isles: Geology, v. 33, no. 5, p. 345.

Arthurton, R., Booth, S., Morigi, A., Abbott, M., and Wood, C., 1994, Geology of the Country Around Great Yarmouth, London HMSO, British Geological Survey.

Aubry, M.P. 1983. Biostratigraphie du Paleogene epicontinental de l'Europe du Nordouest. Etude fondee sur les nannofossiles calcaires. Documents des Laboratories de Geologie de Lyon, 89, 1–317.

Aubry, M.-P., Hailwood, E. A. & Townsend, H. A. 1986. Magnetic and calcareous-nannofossil stratigraphy of the lower Palaeogene formations of the Hampshire and London Basins. Journal of the Geological Society, London, 143, 729–735.

Barton, C., Hopson, P., Newell, A., and Royse, K., 2003, Geology of the Ringwood District: Sheet Description, Keyworth, Nottingham, British Geological Survey.

Batzle, M., 2007, Petroleum Engineering Handbook: Chapter 13 Rock Properties, Society of Petroleum Engineers.

Beck, R. B., Funnell, B. M., and Lord, A. R., 1972, Correlation of Lower Pleistocene Crag at Depth in Suffolk: Geological Magazine, v. 109, no. 2, p. 137-&.

Becker, A., 2000, The Jura Mountains -- an active foreland fold-and-thrust belt?: Tectonophysics, v. 321, p. 381-406.

BGS, 1996, Tectonic Map of Britain, Ireland and Adjacent Areas.

BGS, 2013, Isle of Wight.: British Geological Survey.

Bird, P., 2003, An updated digital model of plate boundaries.: Geochemistry Geophysics Geosystems, v. 4, no. 3, p. 1027.

Blondeau, A. & Curry, D. 1963. Sur la presence de Nummulites variolarius (Lmk) dans les diverses zones du Lutetien des bassins de Paris, de Bruxelles et du Hampshire. Bulletin de la Societe Geologique de France, 7, 275–277.

Blundell, D., 2002, Cenozoic inversion and uplift of southern Britain: Geological Society, London, Special Publications, v. 196, p. 85-101.

Bonnet, C., Malavieille, J., and Mosar, J., 2007, Interactions between tectonics, erosion, and sedimentation during the recent evolution of the Alpine orogen: Analogue modeling insights: Tectonics, v. 26, no. 6, p. n/a-n/a.

Bradley, S. L., Milne, G. A., Teferle, F. N., Bingley, R. M., and Orliac, E. J., 2009, Glacial isostatic adjustment of the British Isles: new constraints from GPS measurements of crustal motion: Geophysical Journal International, v. 178, no. 1, p. 14-22.

Brenchley, P., and Rawson, P., 2006, The Geology of England and Wales, London, The Geological Society.

Bristow, C., 1983, The stratigraphy and structure of the Crag of mid-Suffolk, England: Proceedings of the Geologists' Association, v. 94, p. 1-12.

Bristow, C., 1985, Geology of the Country Around Chelmsford, London HMSO, British Geological Survey.

Bristow, C., Freshney, E., and Penn, I., 1991, Geology of the Country Around Bournemouth, London HMSO, British Geological Survey.

Brodie, J., and White, N., 1994, Sedimentary Basin Inversion Caused by Igneous Underplating - Northwest European Continental-Shelf: Geology, v. 22, no. 2, p. 147-150.

Brown,S. 1988. A Palynological Investigation of the Eocene/Oligocene boundary problem in the west European context. PhD thesis, University of Sheffield.

BS EN 1997-2:2007 Eurocode 7 – Geotechnical Design Part 2: Ground investigation and testing

BS EN ISO 14688-2:2004 Geotechnical investigation and testing – Identification and classification of soil – Part 2: Principles for a classification

BS EN ISO 14689-1:2003 Geotechnical Investigation and testing – Identification and classification of rock – Part 1: Identification and description

BS 5930:2015 Code of Practice for ground investigations

Bujak, J. P. & Mudge, D. C. 1994. A high-resolution North Sea Eocene dinocyst zonation. Journal ofthe Geological Society, London,151,449–462.

Bujak, J. P., Downie, C., Eaton, G. L. &Williams, G. L. 1980. Dinoflagellate cysts and acritarchs from the Eocene of southern England. Special Papers in Palaeontology, No. 24, 100.

Burnett, A. D., and Fookes, P. G., 1974, A Regional Engineering Geological Study of the London Clay in the London and Hampshire Basins: Quarterly Journal of Engineering Geology and Hydrogeology, v. 7, no. 3, p. 257-295.

Burruss, R., 1991, Practical aspects of fluorescence microscopy of petroleum fluid inclusions, in Barker, C., and Kopp, O., eds., Luminescence Microscopy and Spectroscopy: Qualitative and Quantitative Applications, Volume 25, SEPM Special Publications.

Butler, R. C., 1986, Thrust tectonics, deep structure and crustal subduction in the Alps and Himalayas: Journal of the Geological Society, v. 143, p. 857-873.

Cameron, T. D. J., Bonney, A., Gregory, D. and Harland, R., 1984, Lower Pleistocene dinoflagellate cyst, foraminiferal and pollen assemblages in four boreholes in the Southern North Sea: Geological Magazine, v. 121, no. 2, p. 85-97.

Cameron, T., Crosby, A., Balson, P., Jeffrey, D., Lott, G., Bulat, J., and Harrison, D., 1992, United Kingdom offshore regional Report: The Geology of the Southern North Sea, London HMSO, Britsh Geological Survey.

Campbell, S., Hunt, C., Scourse, J. D., Keen, D., and Stephens, N., 1998, Quaternary of South-west England, Joint Nature Conservation Committee.

Carrapa, B., Bertotti, G., and Kijgsman, W., 2003, Subsidence, stress regime and rotation(s) of a tectonically active sedimentary basin within the western Alpine Orogen: the Tertiary Piedmont Basin (Alpine domain, NW Italy Geological Society, London, Special Publications, v. 208, p. 205-227.

Chadwick, R. A., 1986, Extension Tectonics in the Wessex Basin, Southern England: Journal of the Geological Society, v. 143, no. 25, p. 465-488.

Chadwick, R., 1985, Cenozoic sedimentation and subsidence and tectonic inversion, in Whittaker, A., ed., Atlas of onshore basins in England and Wales: Keyworth, Glasgow and London, British Geological Survey, p. 61-63.

Chadwick, R., 1993, Aspects of basin inversion: Journal of the Geological Society, v. 150, p. 311-322.

Chadwick, R., and Evans, D., 2005, A Seismic Atlas of Southern Britain - images of subsurface structure, Keyworth, Nottingham, British Geological Survey, v. Occasional Publication No.7.

Chadwick, R., and Evans, D., 1995, The timing and direction of Permo-Triassic extension in southern Britain: From Boldy, S. A. R. (ed.) Permian and Triassic rifting in Northwest Europe., v. Geological Society Special Publication No.91, p. 161-192.

Chandler, M. E. J. 1963. The Lower Tertiary Floras of Southern England. III. Flora of the Bournemouth Beds, the Boscombe & the Highcliffe Sands. British Museum (Natural History), London.

Chateauneuf, J. J. 1980. Palynostratigraphie et paleoclimatologie de l'Eocene superieur et de l'Oligocene du Bassin de Paris. Memoire du Bureau des Recherches. Geologiques et Minieres (BRGM), 116, 1–360.

Clegg, B., and England, R., 2003, Velocity structure of the UK continental shelf from a compilation of wide-angle and refraction data: Geological Magazine, v. 140, p. 4537-4567.

Clements, D., 2010, The Geology of London, CityPrint Ltd, Geologists' Association, The Curry Fund.

Clift, P., and Turner, J., 1998a, Paleogene igneous underplating and subsidence anomalies in the Rockall-Faeroe-Shetland area: Marine and Petroleum Geology, v. 15, p. 223-243.

Clift, P., and Turner, J., 1998a, Paleogene igneous underplating and subsidence anomalies in the Rockall-Faeroe-Shetland area: Marine and Petroleum Geology, v. 15, p. 223-243.

Cnudde, V., and Boone, M. N., 2013, High-resolution X-ray computed tomography in geosciences: A review of the current technology and applications: Earth-Science Reviews, v. 123, p. 1-17.

Cogné, N., Doepke, D., Chew, D., Stuart, F. M., and Mark, C., 2016, Measuring plume-related exhumation of the British Isles in Early Cenozoic times: Earth and Planetary Science Letters, v. 456, p. 1-15.

Cope, J. C. W., 1994, A latest Cretaceous hotspot and the southeasterly tilt of Britain: Journal of the Geological Society, v. 151, no. 6, p. 905-908.

Copley, A., and Woodcock, N., 2016, Estimates of fault strength from the Variscan foreland of the northern UK: Earth and Planetary Science Letters, v. 451, p. 108-113.

Costa, L. I. & Downie, C. 1976. The distribution of the dinoflagellate Wetzeliella in the Palaeogene of North-Western Europe. Palaeontology, 19, 591–614.

Coward, M., Dewey, J., Hempton, M., and Holroyd, J., 2003, Tectonic Evolution, in Evans, D., Graham, C., Armour, A., and Bathurst, P., eds., Millennium Atlas: Petroleum Geology of the Central and Northern North Sea: London, The Geological Society.

Curry, D. 1937. The English Bartonian Nummulites. Proceedings of the Geologists' Association, 48, 229–246.

Curry, D., 1992, Tertiary, in Duff, P., and Smith, A., eds., Geology of England and Wales, Volume 1st Edition, Geological Society, p. 389-411.

Curry, D., Adams, C., Boulter, M., Dilley, F., Eames, F., Funnell, B. M., and Wells, M., 1978, A Correlation of Tertiary Rocks in the British Isles, London, Geological Society.

Davis, M. W., White, N. J., Priestley, K. F., Baptie, B. J., and Tilmann, F. J., 2012, Crustal structure of the British Isles and its epeirogenic consequences: Geophysical Journal International, v. 190, no. 2, p. 705-725.

Dawber, C. F., Tripati, A. K., Gale, A. S., MacNiocaill, C. I. &Hesselbo, S. P. 2011. Glacioeustasy during the middle Eocene? Insights from the stratigraphy of the Hampshire Basin, UK. Palaeogeography, Palaeoclimatology, Palaeoecology, 300, 84–100.

Desbois, G., Urai, J. L., Hemes, S., Schröppel, B., Schwarz, J.-O., Mac, M., and Weiel, D., 2016, Multi-scale analysis of porosity in diagenetically altered reservoir sandstone from the Permian Rotliegend (Germany): Journal of Petroleum Science and Engineering, v. 140, p. 128-148.

Dewey, J., and Windley, B., 1988, Palaeocene-Oligocene tectonics of NW Europe: From MORTON, A. C. & PARSON, L. M. (eds),Early Tertiary Volcanism and the Opening of the NE Atlantic, Geological Society Special Publication., v. No. 39, p. 25-31.

Dore, A. G., Lundin, E. R., Kusznir, N. J., and Pascal, C., 2008, Potential mechanisms for the genesis of Cenozoic domal structures on the NE Atlantic margin: pros, cons and some new ideas: Geological Society, London, Special Publications, v. 306, no. 1, p. 1-26.

Eaton, G. L. 1976. Dinoflagellate cysts from the Bracklesham Beds (Eocene) of the Isle of Wight, southern England. Bulletin of the British Museum (Natural History) (Geology), 26, 225–332.

Edwards, R., and Freshney, E., 1987a, Geology of the Country Around Southampton, London HMSO, British Geological Survey.

Edwards, R., and Freshney, E., 1987b, Lithostratigraphical classification of the Hampshire Basin Palaeogene Deposits (Reading Formation to Headon Formation): Tertiary Research, v. 8, no. 2, p. 43-73.

Edwards, R., and Scrivener, R., 1999, Geology of the Country Around Exeter, London, HMSO, British Geological Survey.

Ellison, R. A., Knox, R., Jolley, D. and King, C., 1994, A Revision of the Lithostratigraphical Classification of the Early Palaeogene Strata of the London Basin and East Anglia: Proceedings of the Geologists' Association, v. 105, p. 187-197.

Ellison, R., 2004, Geology of London, Keyworth, Nottingham, British Geological Survey.

Ellison, R., and Wiliamson, I., 1999, Geology of the Windsor and Bracknell District: Sheet Description, Keyworth, Nottingham, British Geological Survey.

Ellison, R., Williamson, I., and Humpage, A., 2002, Geology of the Guildford District: Sheet Description, Keyworth, Nottingham, British Geological Survey.

England, R. W., 1988, The Early Tertiary Stress Regime in NW Britain: Evidence from the Patterns of Volcanic Activity: Geological Society Special Publication, v. 39, p. 381-389.

Faupl, P., and Wagreich, M., 1996, Basin analysis of the Gosau Group of the Northen Calcareous Alps (Turonian-Eocene, Eastern Alps): EAGE Special Publication, v. 5, p. 127-135.

Froitzheim, N., Plasienka, D., and Schuster, R., 2008, Alpine Tectonics of the Alps and Western Carpathians, in T.McCann, ed., The Geology of Central Europe, Volume 2: Mesozoic and Cenozoic: London, The Geological Society, p. 1142-1232.

Gale, A. S., Jeffery, P. A., Huggett, J. M., and Connolly, P., 1999, Eocene inversion history of the Sandown Pericline, Isle of Wight, southern England: Journal of the Geological Society, v. 156, p. 327-339.

Gardner, J. S. & von Ettinghausen, C. 1879–1882. A monograph of the British Eocene Flora. Volume 1. Monograph of the Palaeontographical Society London. Part 1 (1879), pp. 1–38, pls 1–.5 (Issue 151, part of Volume 33); Part 2 (1880), pp. 39–58, pls 6–11 (Issue 157, part of Volume 34); Part 3 (1882), pp. 59–86, pls 12–13, title page (Issue 168, part of Volume 36).

Gardner, R., and Pincus, H., 1968, Fluorescent dye penetrants applied to rock fractures: International Journal of Rock Mechanics and Mineralogical Society, v. 5, p. 155-158.

Gerard, J., and Bromley, R., 2008, Ichnofabrics in Clastic Sediments: Applications to Sedimentological Core Studies, Madrid, Spain, Gerard, J., 100 p.

Gibbard, P., and Lewin, J., 2003, The history of the major rivers of southern Britain during the Tertiary: Journal of the Geological Society, v. 160, p. 829-845.

Gibbard, P., Zalasiewicz, J., and Mathers, S., 1998, Stratigraphy of the marine Plio-Pleistocene crag deposits of East Anglia: Mededelingen Nederlands Instituut voor Toegepaste, v. 60, no. Dawn of the Quaternary, p. 239-262.

Gozzard, J., 1981, The sand and gravel resources of the country around Newbury, Berkshire, London, Institute of Geological Sciences.

Grad, M., Tiira, T., and Group, E. W., 2009, The Moho depth map of the European Plate: Geophysical Journal International, v. 176, p. 279-292.

Gradstein, F., Ogg, J., Schmitz, M., and Ogg, G., 2012, The Geologic Timescale 2012, Elsevier.

Green, P. F., Duddy, I. R., and Hegarty, K., 2002, Quantifying exhumation from apatite fission-track analysis and vitrinite reflectance data: precision, accuracy and latest results from the Atlantic margin of NW Europe, in Dore, A. G., Cartwright, J., Stoker, M. S., Turner, J., and White, N., eds., Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration., Volume 196: London, Geological Society Special Publication, p. 331-354.

Grunthal, G., and Stroymeyer, D., 1992, The recent crustal stress field in central Europe - Trajectories and finite-element modelling: Journal of Geophysical Research, v. 97, no. 11, p. 805-820.

Shi-Lun Guo, Bao-Liu Chen, 2012 Chapter 4: Solid-state Nuclear Track Detectors pp 233-240 From Durrani, S. 2012, Handbook of Radioactivity Analysis (Third Edition) Elsevier Academic Press.

Hamblin, R., Crosby, A., Balson, P., Jones, S., Chadwick, R., Penn, I., and Arthur, M., 1992, United Kingdom Offshore Regional Report: The Geology of the English Channel, London HMSO, British Geological Survey.

Hamilton, G. B. & Hojjatzadeh, M. 1982. Cenozoic calcareous nannofossils–a reconnaissance. In: Lord, A. R. (ed.) A Stratigraphical Index of Calcareous Mannofossils. Ellis Horwood, Chichester, 136–167.

Handy, M. R., M. Schmid, S., Bousquet, R., Kissling, E., and Bernoulli, D., 2010, Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological–geophysical record of spreading and subduction in the Alps: Earth-Science Reviews, v. 102, no. 3-4, p. 121-158.

Haq, B., Hardenbol, J., and Vail, P., 1987, The chronology of fluctuating sea level since the Triassic: Science, v. 235, p. 1156-1167.

Harland, R., Bonny, A., Hughes, M., and Morigi, A., 1991, The Lower Pleistocene stratigraphy of the Ormesby Borehole, Norfolk, England: Geological Magazine, v. 128, no. 6, p. 647-660.

Hartley, R. A., Roberts, G. G., White, N., and Richardson, C., 2011, Transient convective uplift of an ancient buried landscape: Nature Geoscience, v. 4, no. 8, p. 562-565.

Hayward, B., 2014, World Foraminifera Database.

Hillgartner, H., van Buchem, F.S., Gaumet, F., Razin, P., Pittet, B., Grotsch, J. & Droste, H. 2003. The Barremian/Aptian evolution of the eastern Arabian carbonate platform margin, (northern Oman): sedimentology, sequence stratigraphy and environmental change. Journal of Sedimentary Research. 73. pp756-773.

Hillis, R. R., 1995, Regional Tertiary exhumation in and around the United Kingdom, in Buchanan, J., and Buchanan, P., eds., Basin Inversion, Geological Society Special Publication No. 88, p. 167-190.

Hillis, R. R., Holford, S. P., Green, P. F., Doré, A. G., Gatliff, R. W., Stoker, M. S., Thomson, K., Turner, J. P., Underhill, J. R., and Williams, G. A., 2008, Cenozoic exhumation of the southern British Isles: Geology, v. 36, no. 5, p. 371.

Holdsworth, R., 2000, Geological Framework of Britain and Ireland, in Woodcock, N. a. S., R., ed., Geological History of Britain and Ireland, Volume 1: Oxford, Blackwell.

Holford, S. P., Green, P. F., Hillis, R. R., Underhill, J. R., Stoker, M. S., and Duddy, I. R., 2010, Multiple post-Caledonian exhumation episodes across NW Scotland revealed by apatite fission-track analysis: Journal of the Geological Society, v. 167, no. 4, p. 675-694.

Hooker, J. J. 1991. The sequence of mammals in the Thanetian and Ypresian of the London and Belgian Basins. Newsletters on Stratigraphy, 25, 75–90.

Hooker, J. J. 1992. British mammalian paleocommunities across the Eocene-Oligocene transition and their environmental implications. In: Prothero, D. R. &Berggren, W. A. (eds) Eocene–Oligocene Climatic and Biotic Evolution. Princeton University Press, Princeton, NJ, 494–511.

Hooker, J. J., Cook, E. & Benton, M. 2005. British Tertiary fossil mammal GCR sites. In: Benton, M. J., Cook, E. &Hooker, J. J. (eds) Mesozoic and Tertiary Fossil Mammals and Birds of Great Britain. Geological Conservation Review Series, 32. Joint Nature Conservation Committee, Peterborough, 69–124.

Hooker, J. J., Grimes, S. T., Mattey, D. P., Collinson, M. E. &Sheldon, N. D. 2009b. Refined correlation of the UK Late Eocene–Early Oligocene Solent Group and of its climate history. In: Koeberl, C. & Montanari, A. (eds) The Late Eocene Earth–Hothouse, Icehouse, and Impacts. Geological Society of America, Special Papers, 452, 179–196.

Hopson, P., 2011, The geological history of the Isle of Wight: an overview of the 'diamond in Britain's geological crown': Proceedings of the Geologists' Association.

Hough, B. K., 1969, Basic Soils Engineering, New York, The Ronald Press Company.

Illies, J., 1972, The Rhine graben rift system plate tectonics and transform faulting: Geophysical Surveys, v. 1, p. 27-60.

Immenhauser, A. & Scott. R.W. 2002. An estimate of Albian sea-level amplitudes and its implications for the duration of stratigraphic hiatuses. Sedimentary Geology. 152. pp19-28.

Immenhauser, A. 2009. Estimating palaeo-water depth from the physical record. Earth-Science Reviews. 96. pp107-139.

Immenhauser, A. 2009. Estimating palaeo-water depth from the physical rock record. Earth-Science Reviews. 96. pp107-139.

Insole, A. N. & Daley, B. 1985. A revision of the lithostratigraphical nomenclature of the late Eocene and early Oligocene strata of the Hampshire Basin, southern England. Tertiary Research, 7, 67–100.

Islam, M. A. 1983a. Dinoflagellate cysts from the Eocene cliff sections of the Isle of Sheppey, southeast England. Revue de Micropaleontologie, 25, 231–250.

Islam, M. A. 1983b. Dinoflagellate cyst taxonomy and biostratigraphy of the Eocene Bracklesham Group in southern England. Micropaleontology, 29, 328–353.

Islam, M. A. 1983c. Dinoflagellate cysts from the Eocene of the London and Hampshire Basins, southern England. Palynology, 7, 71–92.

Islam, M. A. 1984. A study of early Eocene palaeoenvironments in the Isle of Sheppey as determined from microplankton assemblage composition. Tertiary Research, 6, 11–2

Ismail-Zadeh, A., Talbot, C., and Volozh, Y., 2001, Dynamic restoration of profiles across diapiric salt structures: numerical approach and its applications: Tectonophysics, v. 337, p. 23-38.

Jolley, D. W. & Spinner, E. G. 1989. Some dinoflagellate cysts from the London Clay (Paleocene–Eocene) near Ipswich, Suffolk, England. Review of Palaeobotany and Palynology, 60, 361–373.

Jolley, D. W., 1992, Palynofloral association sequence stratigraphy of the Palaeocene Thanet Beds and equivalent sediments in eastern England: Review of Palaeobotany and Palynology, v. 74, p. 207-237.

Jolley, D. W., 1996, The earliest Eocene sediments of eastern England: an ultra-high resolution palynological correlation, in Knox, R., Corfield, R., and Dunay, R., eds., Correlation of the Early Paleogene in Northwest Europe, Volume Geological Society Special Publication No. 101: London, The Geological Society, p. 219-254.

Jolley, D. W., 1998, Palynostratigraphy and depositional history of the Palaeocene Ormesby/Thanet depositional sequence set in southeastern England and its correlation with continental West Europe and the Lista Formation, North Sea: Review of Palaeobotany and Palynology, v. 99, p. 265-315.

Jolly, R., and Lonergan, L., 2002, Mechanisms and controls on the formation of sand intrusions: Journal of the Geological Society, London, v. 159, no. 605-617.

Jones, S. M., White, N., and Lovell, B., 2001, Cenozoic and Cretaceous transient uplift in the Porcupine Basin and its relationship to a mantle plume: Geological Society, London, Special Publications, v. 188, no. 1, p. 345-360.

Jorry, S. J., Hasler, C.-A., and Davaud, E., 2006, Hydrodynamic behaviour of Nummulites: implications for depositional models: Facies, v. 52, no. 2, p. 221-235.

Kelly, A., England, R. W., and Maguire, P. K. H., 2007, A crustal seismic velocity model for the UK, Ireland and surrounding seas: Geophysical Journal International, v. 171, no. 3, p. 1172-1184.

King, C., 1981, The Stratigraphy of the London Clay and associated deposits: Tertiary Research Special Paper, v. 6, no. Bakhyus, Rotterdam.

King, C., 2016, A Revised Correlation of Tertiary Rocks in the British Isles and Adjacent Areas of NW Europe, The Geological Society, Special Report No. 27.

Knox, R., 1996, Tectonic controls on sequence development in the Palaeocene and earliest Eocene of southeast England: implications for North Sea stratigraphy: Geological Society, London, Special Publications, v. 103, no. 1, p. 209-230.

Kominz, M. A., 2001, Sea Level Variations Over Geologic Time, p. 2605-2613.

Kyrkjebo, R., Kjennerud, T., Gillmore, G., Faleide, J. & Gabrielsen, R.H.2001. Cretaceous-Tertiary palaeo-bathymetry in the northern North Sea; integration of palaeo-water depth estimates obtained by structural restoration and micropalaeontological analysis. Sedimentary Environments Offshore Norway - Palaeozoic to Recent edited by O.J. Martinsen and T. Dreyer. NPF Special Publication 10, pp. 321-345, Published by Elsevier Science B.V., Amsterdam. 9 Norwegian Petroleum Society (NPF), 2001.

Lake, S. D., and Karner, G. D., 1987, The Structure and Evolution of the Wessex Basin, Southern England - an Example of Inversion Tectonics: Tectonophysics, v. 137, no. 1-4, p. 347-&.

Leckie, A., and Olson, H., 2003, Micopalaeontologic proxies for sea-level change and stratigraphic discontinuities: SEPM Special Publication, v. 75, p. 5-19.

Liengjaren, M., Costa, L. & Downie, C. 1980. Dinoflagellate cysts from the Upper Eocene–Lower Oligocene of the Isle of Wight. Palaeontology, 23, 475–499.

Look, B., 2007, Handbook of geotechnical investigation and design tables, London, UK, Taylor & Francis.

Makaske, B. & Augustinus, P.G. 1998. Morphologic changes of a micro-tidal, low-wave energy beach face during a spring-neap tide cycle. Rhone-Delta, France. Journal of Coastal Research. 14. Pp632- 645.

Martini, E. 1972. Die Gattung Eosphaeroma (Isopoda) im europa ¨ischen Alttertia ¨r. Senckenbergiana Lethaea, 53, 65–79.

Mathers, S., 1993, Geology of the Country Around Diss, London HMSO, British Geological Survey.

Mathers, S., and Smith, N., 2000, Geology of the Reading District: Sheet Description, Keyworth, Nottingham, British Geological Survey.

Mathers, S., and Smith, N., 2002, Geology of the Woodbridge and Felixstowe District: Sheet Description, Keyworth, Nottingham, British Geological Survey.

Mathers, S., and Zalasiewicz, J., 1988, The Red Crag and Norwich Crag formations of southern East Anglia: Proceedings of the Geologists' Association, v. 99, no. 4, p. 261-278.

Mckenzie, D., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25-32.

Miller, K. G., Kominz, M. A., Browning, J. V., Wright, J. D., Mountain, G. S., Katz, M. E., Sugarman, P. J., Cramer, B. S., Christie-Blick, N., and Pekar, S. F., 2005, The Phanerozoic record of global sea-level change: Science, v. 310, no. 5752, p. 1293-1298.

Millward, D., Ellison, R., Lake, R., and Moorlock, B., 1987, Geology of the Country Around Epping, London HMSO, British Geological Survey.

Moorlock, B., Hamblin, R., Booth, S., and Morigi, A., 2000, Geology of the Country Around Lowestoft and Saxmundham, London HMSO, British Geological Survey.

Mortimore, R., Newman, T. G., Royse, K., Scholes, H., and Lawrence, U., 2011, Chalk: its stratigraphy, structure and engineering geology in east London and the Thames Gateway: Quarterly Journal of Engineering Geology and Hydrogeology, v. 44, no. 4, p. 419-444.

Morton, A., 1982, The provenance and diagenesis of Paleogene sandstones of southeast England as indicated by heavy mineral analysis: Proceedings of the Geologists' Association, v. 93, p. 263-274.

Moy, D., and Imber, J., 2009, A critical analysis of the structure and tectonic significance of rift-oblique lineaments (‘transfer zones’) in the Mesozoic–Cenozoic succession of the Faeroe–Shetland Basin, NE Atlantic margin: Journal of the Geological Society, v. 166, p. 1-14.

Murray, J. W. & Wright, C. A. 1974. Palaeogene Foraminiferida and Palaeoecology, Hampshire and Paris Basins and the English Channel. Palaeontology, Special Papers, 14.

Murray, J. W., 1992, Palaeogene and Neogene: Geological Society, London, Memoirs, v. 13, no. 1, p. 141-147.

Mutter, J. C., Buck, W. R., and Zehnder, C. M., 1988, Convective Partial Melting .1. A Model for the Formation of Thick Basaltic Sequences during the Initiation of Spreading: Journal of Geophysical Research-Solid Earth and Planets, v. 93, no. B2, p. 1031-1048.

Newell, A. J. 2001. Construction of a Palaeogene tide-dominated shelf: influence of Top Chalk topography and sediment supply (Wessex Basin, UK). Journal of the Geological Society, London, 158, 379–390.

Newell, A. J., 2000, Fault activity and sedimentation in a marine rift basin (Upper Jurassic, Wessex Basin, UK): Journal of the Geological Society, v. 157, p. 83-92.

Newell, A. and Evans, D. 2011. Timing of basin inversion on the Isle of Wight: New evidence from geophysical log correlation, seismic sections and lateral facies change in the Paleogene Headon Hill Formation. Proceedings of the Geologists’ Association. v. 122, p. 868-882.

Norvick, M. S. 1969. An analysis of the microfauna and microflora of the Upper Eocene of the Hampshire Basin. PhD thesis, Imperial College, University of London.

Pattison, J., Berridge, N., Allsop, J., and Wilkinson, I., 1993, Geology of the Country Around Sudbury (Suffolk), London HMSO, British Geological Survey.

Persano, C., Barfod, D. N., Stuart, F. M., and Bishop, P., 2007, Constraints on early Cenozoic underplating-driven uplift and denudation of western Scotland from low temperature thermochronometry: Earth and Planetary Science Letters, v. 263, no. 3-4, p. 404-419.

Pettersen, Ø., 2007, Sandstone compaction, grain packing and Critical State Theory: Petroleum Geoscience, v. 13, p. 63-67.

Plint, A., 1982, Eocene Sedimentation and Tectonics in the Hampshire Basin: Journal of the Geological Society, v. 139, no. May, p. 249-254.

Plint, A., 1983, Facies, environments and sedimentary cycles in the Middle Eocene, Bracklesham Formation of the Hampshire Basin: evidence for global sea-level changes?: Sedimentology, v. 30, p. 625-653.

Plint, A., Global eustasy and the Eocene sequence in the Hampshire Basin, England: Basin Research, v. 1, no. 1, p. 11-22.

Powell, A. J., Brinkhuis, H. & Bujak, J. P. 1996. Upper Paleocene-Lower Eocene dinoflagellate sequence biostratigraphy of southeast England. In: Knox, R. W. O'B., Corfield, R. M. &Dunay, R. E. (eds) Correlation of the Early Paleogene in Northwest Europe. Geological Society, London, Special Publications, 101, 145–183.

Reddering, J.S.V. 1987. Subtidal occurences of ladder-back ripples: their significance in palaeo-environmental reconstruction. Sedimentology. 34. pp 253-257.

Reicherter, K., Froitzheim, N., and Jarosinski, M., 2008, Alpine Tectonics north of the Alps, in McCann, T., ed., The Geology of Central Europe, Volume 2: Mesozoic and Cenozoic: London, The Geological Society, p. 1233-1285.

Reineck, H.E & Singh, I.B. 1986. Depositional Sedimentary Environments. Springer, Berlin. pp551.

Rieke, H., and Chilingarian, G., 1974, Compaction of argillaceous sediments, Amsterdam, Elsevier.

Ritchie, J. D., Johnson, H., Quinn, M. F., and Gatliff, R. W., 2008, The effects of Cenozoic compression within the Faroe-Shetland Basin and adjacent areas: Geological Society, London, Special Publications, v. 306, no. 1, p. 121-136.

Ritchie, J., Ziska, H., Johnson, H., and Evans, D., 2011, Geology of the Faroe-Shetland Basin and adjacent areas, Keyworth, British Geological Survey, BGS/Jardfeingi Research Report RR/11/01.

Roberts, A., Kusznir, N. J., Yielding, G., and Styles, P., 1998, 2D flexural backstripping of extensional basins: the need for a sideways glance: Petroleum Geoscience, v. 4, no. 327-338.

Roberts, D., Thompson, M., Mitchener, B., Hossack, J., Carmichael, S., and Bjornseth, H. M., 1999, Palaeozoic to Tertiary rift and basin dynamics: mid-Norway to the Bay of Biscay - a new context for hydrocarbon prospectivity in the deep water frontier, in Fleet, A., and Boldy, S., eds., Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference: London, The Geological Society, p. 7-40.

Rowley, E., and White, N., 1998, Inverse Modelling of Extension and Denudation in the East Irish Sea and Surrounding Areas: Earth and Planetary Science Letters, v. 161, p. 57-71.

Royse, K. R., de Freitas, M., Burgess, W. G., Cosgrove, J., Ghail, R. C., Gibbard, P., King, C., Lawrence, U., Mortimore, R. N., Owen, H., and Skipper, J., 2012, Geology of London, UK: Proceedings of the Geologists' Association, v. 123, no. 1, p. 22-45.

Scheck, M., Bayer, U., and Lewerenz, B., 2003, Salt redistribution during extension and inversion inferred from 3D backstripping: Tectonophysics, v. 373, no. 1-4, p. 55-73.

Scherer, M., 1987, Parameters influencing porosity in sandstones: a model for sandstone porosity prediction: AAPG Bulletin, v. 71, no. 5, p. 485-491.

Schmid, S. M., Fugenschuh, B., Kissling, E., and Schuster, R., 2004, Tectonic map and overall architecture of the Alpine orogen: Eclogae Geologicae Helvetiae, v. 97, no. 1, p. 93-117.

Sclater, J. G., and Christie, P. A. F., 1980, Continental stretching: An explanation of the Post-Mid-Cretaceous subsidence of the central North Sea Basin: Journal of Geophysical Research, v. 85, no. B7, p. 3711.

Siesser,W. G.,Ward,D.J.& Lord,A.R.1987. Calcareous nannoplankton biozonation of the Thanetian Stage (Palaeocene) in the type area. Journal of Micropalaeontology, 6, 85–102.

Sorby, H., 1908, On the application of quantitative methods to the study of the structure and history of rocks: Quarterly Journal of the Geological Society, London, v. 64, p. 171-232.

Sowers, G., 1979, Introductory Soil Mechanics and Foundations, Geotechnical Engineering.

Steck, A., and Hunziker, J., 1994, The Tertiary structural and thermal evolution of the Central Alps-compressional and extensional strctures in an orogenic belt: Tectonophysics, v. 238, p. 229-254.

Stern, G., and Wagreich, M., 2013, Provenance of the Upper Cretaceous to Eocene Gosau Group around and beneath the Vienna Basin (Austria and Slovakia): Swiss Journal of Geosciences, v. 106, no. 3, p. 505-527.

Stinton, F., 1970, Field Meeting in the New Forest, Hants: Proceedings of the Geologists' Association, v. 81, p. 269-274.

Stoker, M., Holford, S. and Hillis, R. 2018. A rift-to-drift record of vertical crustal motions in the Faroe-Shetland Basin, NW European margin: establishing constraints on NE Atlantic Evolution. Journal of the Geological Society. 175. Pp263-274.

Stonecipher, S., and May, J., 1990, Facies controls on early diagenesis: Wilcox Group, Texas Gulf Coast, in Meshri, D., and Ortoleva, P., eds., Prediction of Reservoir Quality Through Chemical Modeling, I, Volume 49, AAPG Memoir, p. 25-44.

Surdam, R., Dunn, T., MacGowan, D., and Heasler, H., 1989, Conceptual models for the prediction of porosity evolution with an example from the Frontier Sandstone, Bighorn basin, Wyoming, in Coalson, E., Kaplan, S., Heighin, C., Oglesby, L., and Robinson, J., eds., Sandstone Reservoirs, Rocky Mountain Association of Geologists, p. 7-21.

Teferle, F. N., Bingley, R. M., Orliac, E. J., Williams, S. D. P., Woodworth, P. L., McLaughlin, D., Baker, T. F., Shennan, I., Milne, G. A., Bradley, S. L., and Hansen, D. N., 2009, Crustal motions in Great Britain: evidence from continuous GPS, absolute gravity and Holocene sea level data: Geophysical Journal International, v. 178, no. 1, p. 23-46.

Terzaghi, K., 1936, A fundamental fallacy in Earth pressure computations: J. Boston Society of Civil Engineers, v. 23, p. 71-88.

Thompson, G., and Hower, J., 1975, The Mineralogy of Glauconite: Clays and Clay Minerals, v. 23, p. 289-300.

Tiley, R., Mckenzie, D., and White, N., 2003, The elastic thickness of the British Isles: Journal of the Geological Society, London, v. 160, p. 499-502.

Tiley, R., White, N., and Al-Kindi, S., 2004, Linking Paleogene denudation and magmatic underplating beneath the British Isles: Geological Magazine, v. 141, no. 3, p. 345-351.

Townsend, H. A. 1982. Magnetostratigraphy of early Palaeogene sediments from southern England. PhD thesis, University of Southampton

Triplehorn, D., 1964, Origin and Significance of Glauconite in the Geologic Sequence: Tulsa Geological Society Digest, v. 33, p. 282-283.

Underhill, J., and Partington, M., 1993, Jurassic thermal doming and deflation in the North Sea: implications of the sequence stratigraphic evidence, in Parker, J. R., ed., From Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference: London, The Geological Society., p. 337-345.

Vandenberghe, N., Hilgen, F. J. 2012. Chapter 28-The Paleogene Period. In: Gradstein, F. M., Ogg, J. G., Schmitz, M. D. &Ogg, G. M. (eds) The Geologic Time Scale 2012. Elsevier, Amsterdam, 855–921.

Vening Meinesz, F., 1941, Gravity over the Archipelago and over the Madeira Area; conclusions about the Earth's crust: Pro. Kon. Ned. Akok, p. 44.

Wagner, G., and Van den Haute, P., 1992, Fission-Track Dating, Kluwer Academic Publishers.

Walcott, R., 1970, Flexural rigidity, thickness, and viscosity of the lithopshere: Journal of Geophysical Research, v. 75, p. 3941-3953.

Walker, R. J., Holdsworth, R. E., Imber, J., and Ellis, D., 2011, Onshore evidence for progressive changes in rifting directions during continental break-up in the NE Atlantic: Journal of the Geological Society, v. 168, no. 1, p. 27-48.

Watts, A., 2001, Isostasy and Flexure of the Lithosphere, Cambridge, Cambridge University Press.

Watts, A., and Ryan, W., 1976, Flexure of the lithosphere and continental margin basins: Tectonophysics, v. 36, no. 1-3, p. 25-44.

White, N., and Lovell, B., 1997, Measuring the pulse of a plume with the sedimentary record: Nature, v. 387, p. 888-861.

White, R., and McKenzie, D., 1989, Magmatism at rift zones: The generation of volcanic continental margins and flood basalts: Journal of Geophysical Research, v. 94, no. B6, p. 7685.

Wilson, M., 1994a, Non-compositional controls on diagenetic processes, in Wilson, M., ed., Reservoir Quality Assessment and Prediction in Clastic Rocks, Volume SEPM short course 30, p. 183-208.

Wooldridge, S., and Linton, D., 1955, Structure, Surface and Drainage in Southeast England: George Philip, London.

Wrigley, A. G. &Davis, A. G. 1937. The occurrence of Nummulites planulatus in England, with a revised correlation of the strata containing it. Proceedings of the Geologists' Association, 48, 203–228.

Zalasiewicz, J., and Mathers, S., 1985, Lithostratigraphy of the Red and Norwich Crags of the Aldeburgh-Orford Area, south-east Suffolk: Geological Magazine, v. 122, no. 3, p. 287-296.

Zalasiewicz, J., Mathers, S., Hughes, M., Gibbard, P., Peglar, S., Harland, R., Nicholson, R., Boulton, G., Cambridge, P., and Wealthall, G., 1988, Stratigraphy and palaeoenvironments of the Red Crag and Norwich crag formations between Aldeburgh and Sizewell, Suffolk, England: Phil. Trans. R. Soc. Lond., v. 322, p. 221-272.

Zhou, S., 1993, A 3-D Backstripping Method and Its Application to the Eromanga Basin In Central and Eastern Australia: Geophysical Journal International, v. 112, no. 2, p. 225-243.

Ziegler, P., 1982, Geological Atlas of Western and Central Europe, The Hague, Netherlands, Shell Internationale Petroleum Maatschappij B.V., 130 p.:

Ziegler, P., 1992, European Cenozoic rift system: Tectonophysics, v. 208, p. 91-111.

Ziegler, P., and Dezes, P., 2006, Crustal evolution of Western and Central Europe: From: Gee, D. & Stephenson, R. (eds) European Lithosphere Dynamics. Geological Society, London, Memoirs, v. 32, p. 43-56.

Zweigel, T., Aigner, T., and Luterbacher, H., 1998, Eustatic versus tectonic controls on Alpine foreland basin fill: sequence stratigraphy and subsidence analysis in the SE German Molasse, in Mascle, A., Puigdefabregas, C., Luterbacher, H., and Fernandez, M., eds., Cenozoic Foreland Basins of Western Europe, Volume 134, Geological Society Special Publications, p. 299-323.

8.6 Appendices

8.6.1 Appendix 1

- Digital copies of water depth spreadsheets are on the attached pen drive. *Appendix > Appendix 1 > Sheets*

Boreholes used to develop the palaeobathymetric surfaces that were not obtained from the BGS Geoindex, memoirs, journals or text books have been added to the attached pen drive. These additional borehole records are mostly from industry and have been requested from the companies named on each file. Therefore these should not be printed or distributed and are included for reference purposes. The digital copies should be deleted following examination.

These are included in the folder Appendix > Appendix 1 > Boreholes

8.6.2 Appendix 2

- Boreholes and sections used for backstripping. Input spreadsheets are on the attached pen drive. *Appendix > Appendix 2 > Sheets*

Backstripped output data used for developing water loaded subsidence curves and tectonic surfaces

Thanet Formation

Name	Easting	Northing	WLSUB
Halesworth	641780	276270	20
Ormesby	651450	314250	20
Hales	636710	296870	20
Staines	503633	172405	-30
Crystal_palace	533790	170820	-10
404T	533638	179604	-20
Cobbins	541600	202380	-10
Herne	620582	168730	0
Bradwell	601669	208256	10
NHM	526550	179000	-15
Lacon	652290	307930	10
Sheerness	592900	173470	0

Lower Reading Formation

Name	Easting	Northing	WLSUB
Sandhills_bh	446129	89840	-40
Alum Bay	430032	86053	-43
Marchwood1	439910	111180	-40
Whitecliff	464021	86020	-43
Shamblehurst	449270	114560	-40
Christchurch	420020	93010	-44
Wytch	400939	87049	-40
Hurn	409988	100714	-40
Crystal_palace	533790	170820	-54
404T	533638	179604	-53
Sheerness	592900	173470	-23
NHM	526550	179000	-44
Wash	445380	164780	-43

Reading and Woolwich formations

Name	Easting	Northing	WLSUB
Halesworth	641780	276270	-54
Ormesby	651450	314250	43
Staines	503633	172405	-61
Crystal_palace	533790	170820	-37
404T	533638	179604	-46
Cobbins	541600	202380	-51
Herne	620582	168730	-30
Bradwell	601669	208256	-43
Lowestoft	653800	292600	-43
NHM	526550	179000	-49
Wash	445380	164780	-47
Bunkers_hill	430380	114980	-40
Adj_Ramnor_inclosure	431140	104750	-43
Fordingbridge	418760	111800	-43

Harwich Formation

Name	Easting	Northing	WLSUB
Hales	636710	296870	56
Halesworth	641780	276270	47
IGS_Stock	570540	200450	-35
Herne	620582	168730	-35
Bradwell	601669	208256	26
Ormesby	651450	314250	78
Lacon	652290	307930	90
Wash	445380	164780	-28
Sandhills_bh	446129	89840	31
Bunkers_hill	430380	114980	-9
Whitecliff	464021	86020	40
Shamblehurst	449270	114560	-2
Fordingbridge	418760	111800	-43

London Clay Formation (Divisions A+B)

Name	Easting	Northing	WLSUB
IGS_Stock	570540	200450	-17
Staines	503633	172405	0
Crystal_palace	533790	170820	-7
404T	533638	179604	-1
Cobbins	541600	202380	13
Herne	620582	168730	3
Bradwell	601669	208256	4
Sheerness	592900	173470	24
Lowestoft	653800	292600	-1
Somerton	646070	321201	-10
NHM	526550	179000	-12
Wash	445380	164780	-31
Sandhills_bh	446129	89840	54
Alum Bay	430032	86053	19
Marchwood1	439910	111180	12
Whitecliff	464021	86020	56
Shamblehurst	449270	114560	13
Christchurch	420020	93010	-41
Wytch	400939	87049	-35
Hurn	409988	100714	-43
Fordingbridge	418760	111800	-4

London Clay Formation (Divisions C+D)

Name	Easting	Northing	WLSUB
IGS_Stock	570540	200450	-33
Staines	503633	172405	-33
Crystal_palace	533790	170820	-27
Bradwell	601669	208256	-17
Sheerness	592900	173470	12
NHM	526550	179000	-42
Sandhills_bh	446129	89840	51
Bunkers_hill	430380	114980	-72
Marchwood1	439910	111180	-23
Adj_Ramnor_inclosure	431140	104750	-73
Whitecliff	464021	86020	32
Shamblehurst	449270	114560	-34
Christchurch	420020	93010	-50
Wytch	400939	87049	-101
Fordingbridge	418760	111800	-41

Lower Bracklesham Group

Name	Easting	Northing	WLSUB
Sandhills_bh	446129	89840	103
Alum Bay	430032	86053	41
Bunkers_hill	430380	114980	25
Marchwood1	439910	111180	43
Adj_Ramnor_inclosure	431140	104750	-19
IGS_Stock	570540	200450	103
Whitecliff	464021	86020	113
Shamblehurst	449270	114560	50
Christchurch	420020	93010	29
Wytch	400939	87049	-24

Lower Bracklesham Group

Name	Easting	Northing	WLSUB
Sandhills_bh	446129	89840	171
Alum Bay	430032	86053	79
Bunkers_hill	430380	114980	55
Marchwood1	439910	111180	58
Adj_Ramnor_inclosure	431140	104750	19
Whitecliff	464021	86020	142
Shamblehurst	449270	114560	53
Hurn	409988	100714	-37
Christchurch	420020	93010	40
Wytch	400939	87049	9
Fordingbridge	418760	111800	25

Upper Bracklesham Group

Name	Easting	Northing	WLSUB
Sandhills_bh	446129	89840	148
Alum Bay	430032	86053	74
Marchwood1	439910	111180	54
Adj_Ramnor_inclosure	431140	104750	6
Bunkers_hill	430380	114980	32
Whitecliff	464021	86020	135
Hurn	409988	100714	-1
Christchurch	420020	93010	46
Wytch	400939	87049	6
Fordingbridge	418760	111800	32

Upper Bracklesham Group

Name	Easting	Northing	WLSUB
Sandhills_bh	446129	89840	214
Alum Bay	430032	86053	131
Adj_Ramnor_inclosure	431140	104750	89
Marchwood1	439910	111180	114
Whitecliff	464021	86020	192
Christchurch	420020	93010	101
Hurn	409988	100714	33

Barton Clay Formation

Name	Easting	Northing	WLSUB
Ramnor_inclosure	431140	104750	199
Sandhills_bh	446129	89840	332
Whitecliff	464021	86020	304
Christchurch	420020	93010	232
Alum Bay	430032	86053	261

Becton Formation

Name	Easting	Northing	WLSUB
Sandhills_bh	446129	89840	353
Alum Bay	430032	86053	313
Ramnor_inclosure	431140	104750	224
Whitecliff	464021	86020	333

Headon Hill Formation

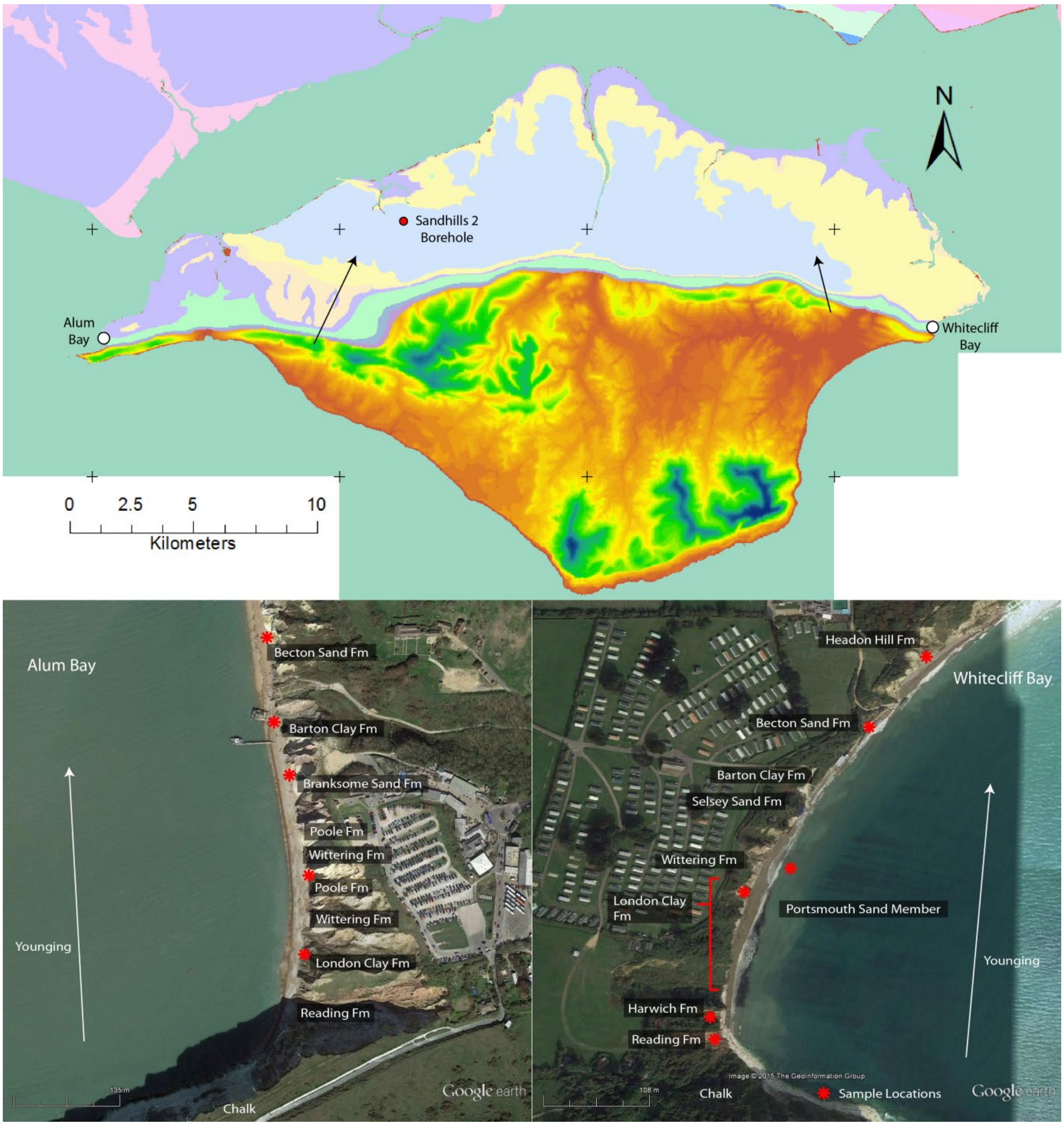
Name	Easting	Northing	WLSUB
Sandhills_bh	446129	89840	332
Alum Bay	430032	86053	264
Ramnor_inclosure	431140	104750	186
Whitecliff	464021	86020	272

Bouldnor Formation

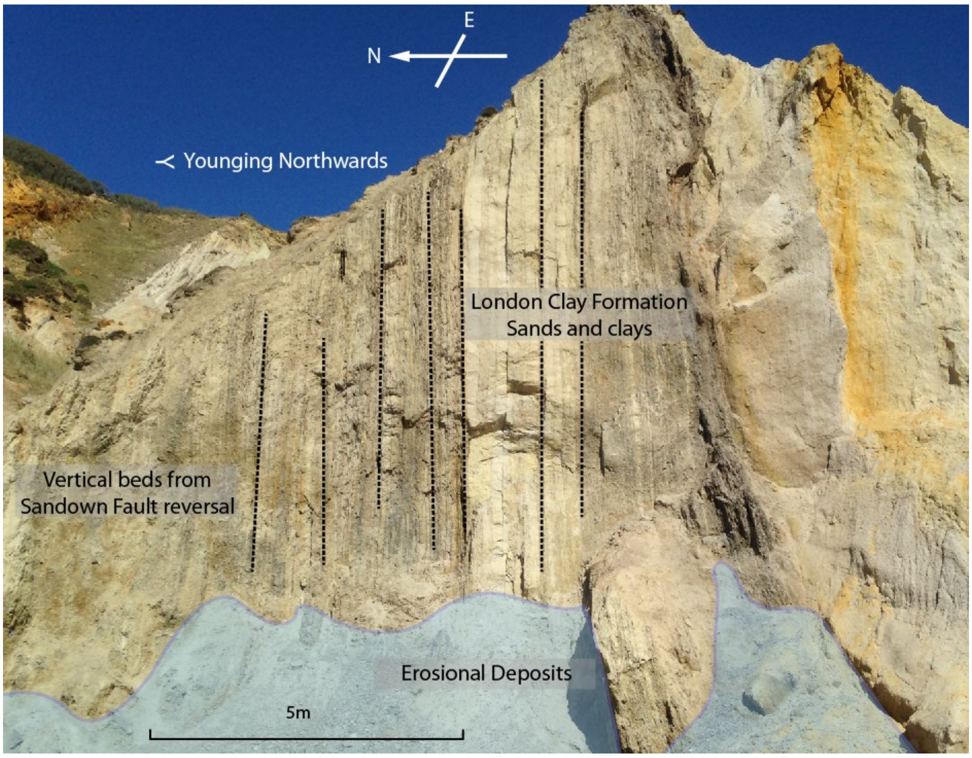
Name	Easting	Northing	WLSUB
Alum Bay	430032	86053	331
Sandhills_bh	446129	89840	399
Whitecliff	464021	86020	317

8.6.3 Appendix 3

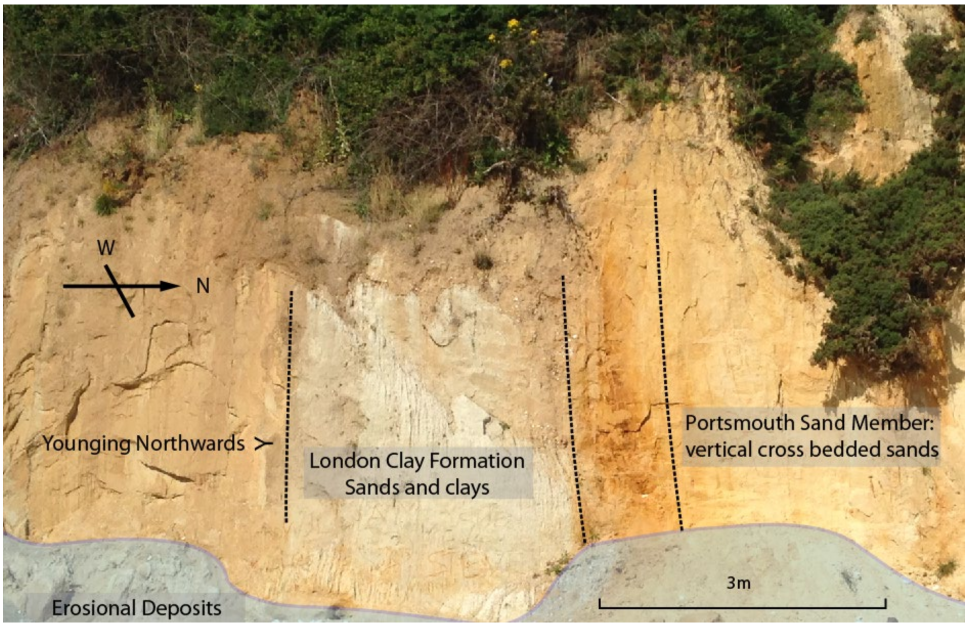
Map of the Isle of Wight showing the topography of the cretaceous rocks in the south and the Cenozoic geology overlayed in the north. The backstripped section of the Sandhills borehole is shown in relation to the to field localities visited. Both cliff sections show similar thicknesses and stratigraphy to the Sandhills borehole. Satellite imagery shows the important geological formations at both field sites and the locations samples were taken from.



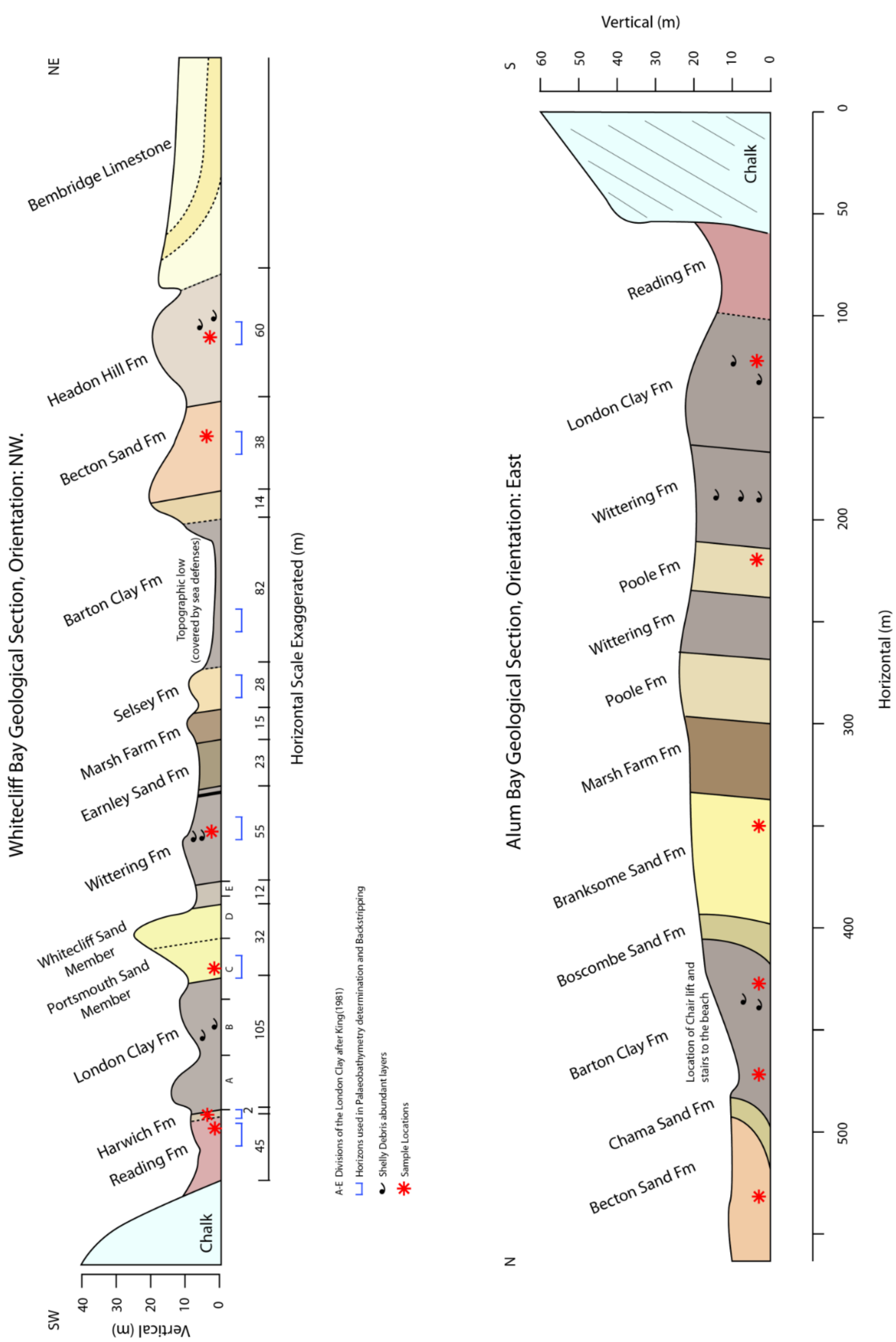
Isle of Wight location map for field work to study the Hampshire Basin Cenozoic succession. Red stars were sample locations for study and porosity testing selection.



Alum Bay annotated section of the lower London clay beds (Division A +B). Vertical strata and friable nature is clear.



Whitecliff Bay annotated section of the middle London Clay formation, (Division C + D) and localised Portsmouth Sand Member.. Vertical strata and friable nature is still clear.



Simplified cross sections of exposed Cenozoic succession of the Whitecliff and Alum Bay sections on the Isle of Wight. Once again sample locations are shown.

Notice of proposal to carry out an operation on an SSSI

Section 28E (1)(a) Wildlife and Countryside Act 1981 (as amended and inserted by section 75 and Schedule 9 of the Countryside and Rights of Way Act 2000)

Name of Site of Special Scientific Interest (SSSI)

Headon Warren and West High Down, Alum Bay
Whitecliff Bay and Bembridge Ledges

Name and address of owner(s) or occupier(s)

Owned by National Trust, Isle of Wight
isleofwight@nationaltrust.org.uk
Longstone Farmhouse
Strawberry Lane
Mottistone
Isle of Wight
PO30 4EA

[I/We] give notice under Section 28(E)(1)(a) of the Wildlife and Countryside Act 1981 of [my/our] proposal to carry out, cause or permit to be carried out the operation(s) specified below on the land specified below.

Specified operations (summary of proposal):

The operations will include field observations sedimentary logging of the cliff sections plud rock sampling from each Paleogene geological formation along the Whitecliff Bay and Alum Bay exposures.

Details of proposed operations (continue on separate sheet if necessary or attach additional information, documents etc):

The research project focuses on the tectonic vertical motions of South East England during the Cenozoic and heavily involves the study of the stratigraphy from this time.

Sedimentary logging and field observations will be to identify the dominant lithologies, important horizons in the stratigraphic sections and notable variations in the lithology. This is to justify the layers that have been selected to represent a geological formation in the research. These methods will not be invasive or destructive to the sites of interest. To fully document the rocks, fossils and important features, photography will be included in the field observations.

The samples taken will be used for porosity measurements and strength testing for use in determining the compaction histories of the Paleogene stratigraphy. In order to quantify the porosity of each geological formation and therefore further constrain the compaction pathway of the clastic lithologies found on the Isle of Wight. The samples will be needed for porosimetry tests using fluorescence microscopy. There are ten major geological formations of interest and both sites display this stratigraphy and up to 1kg ±500g will be required for each selected lithology. The maximum amount of rock removed from the site for full testing purposes will not exceed 20kg.
Samples are planned to be taken from below the high tide mark and within the intertidal zone. The reason for this is samples are likely to be fresher and more representative of the geological formations properties within this zone but supplementary a preference can be made on the type of material taken and the method used to extract it i.e. samples taken via recently loosened sections rather than requiring more invasive and destructive techniques such as hammering or drilling.

The two localities of Whitecliff Bay and Alum Bay localities need to be sampled for two reasons: 1. The sedimentary facies do vary within geological formations from the east to the west of the Isle of Wight. Therefore varying properties can be fully quantified between lithologies.
2. East to West, some geological formations terminated and are replaced by different stratigraphically adjacent formations with contrasting lithologies and structures. Again affecting their potential

compaction history pathway and subsidence properties.
3. New samples are required as the British Geological Survey (BGS) does not want to destroy their examples of each geological formation or boreholes, as the porosimetry technique is fairly invasive and requires the samples to be broken down to smaller sizes.

Care has been taken to acknowledge the personal risk both sites may possess. A hard hat and high visibility jacket will be worn at all times during logging and sample taking. When samples are to be taken, an inspection will be made to identify the safest way of extracting relevant material without complications. The coastal position of both sites and their exposure to the sea has also been taken into consideration and procedures will take place during times of lower tide.

No vehicles will need access to the site as samples removed will be small enough to be easily carried away to the nearest car park by foot. There will be now chemical involvement or materials left behind. As previously stated, the plan is to remove material already loosened by natural weathering.

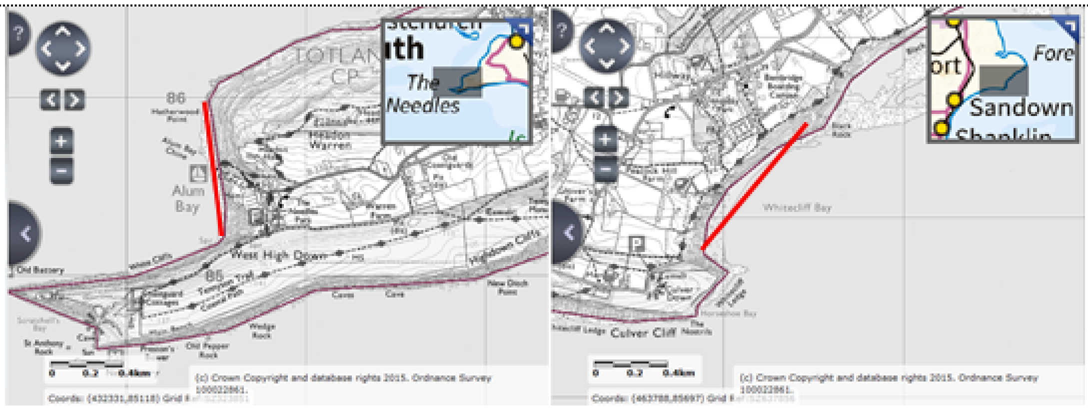
Timing of proposed operations:

31/07/2015

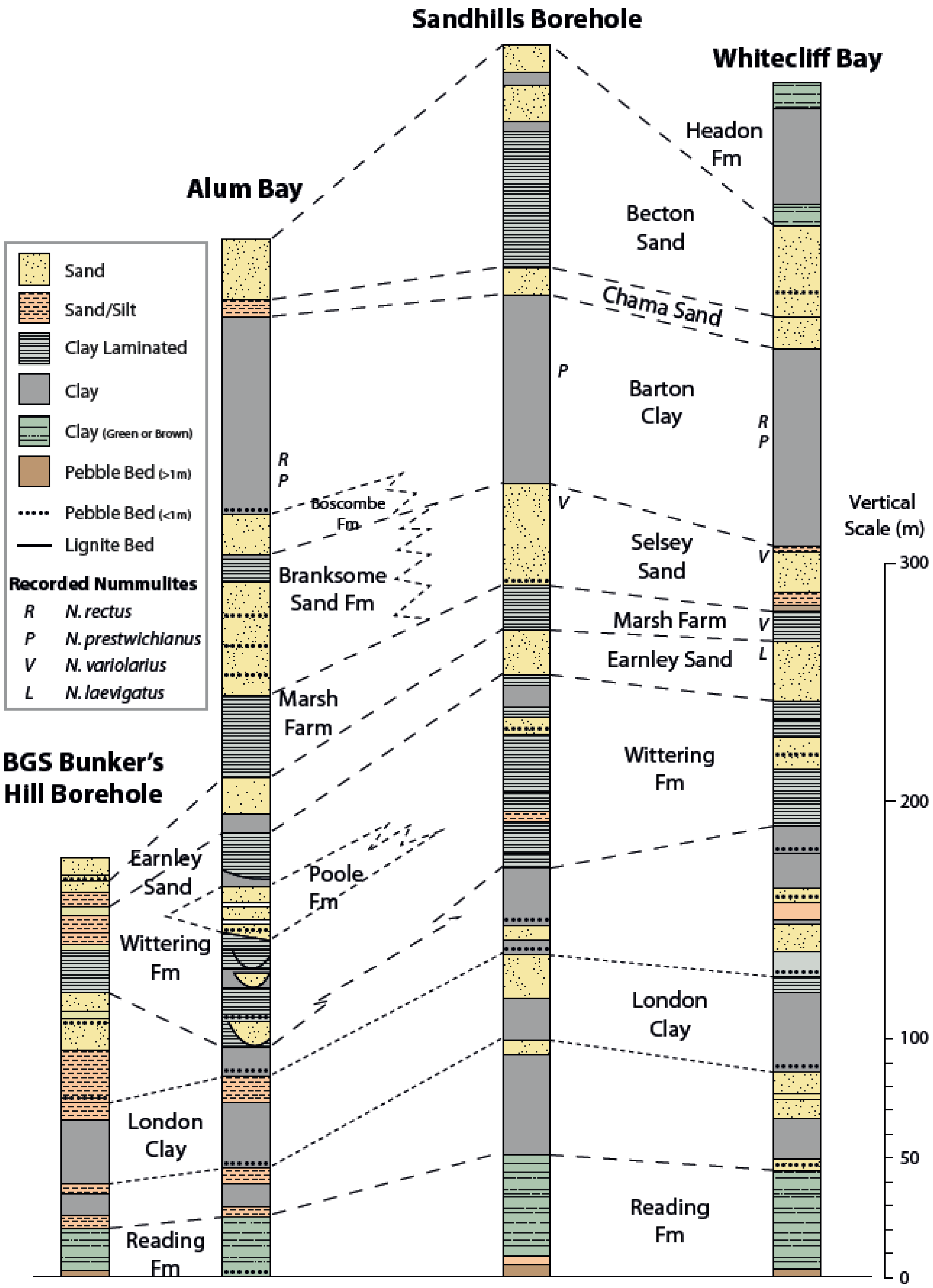
End date of proposed operation:

7/08/2015

Land on which operations are to be carried out (or attach map):



Images are maps of both localities for proposed operations and logging. Red lines denote the location and area's that proposed logging and samples would like to be carried out.



Logs from the Isle of Wight and central Hampshire Basin. The Bunkers Hill is the most NW log. The Whitecliff Bay log is the most eastern in the area. These were used to correlate facies and familiarise and identify the key stratigraphy preserved in the field. Adapted from Edwards and Freshney (1985).

Field work image showing the Lower London Clay Formation at Alum Bay, looking 078° E. More resistance beds of higher sand content are more likely to form escarpments and clay dominant lithologies form topographic lows. Yellow hard hat for scale.

Field work image showing the Middle London Clay Formation at Whitecliff Bay, looking 310 NW°. As was the case at Alum Bay, more resistance beds of higher sand content form topographic high escarpments and clay dominant lithologies form topographic lows.

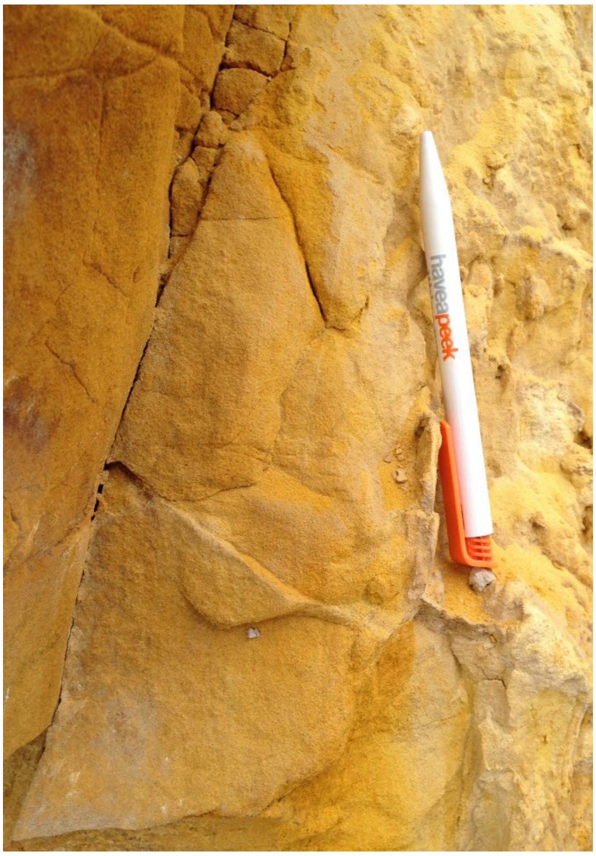
Variocoloured sands and silts of the Poole Formation at Alum Bay. Truncation of laminations is also shown. Photo is looking 058° ENE. Pen for scale.

The Cretaceous Chalk and the Needles viewed from the Cenozoic succession at Alum Bay and the photo was taken looking south west.

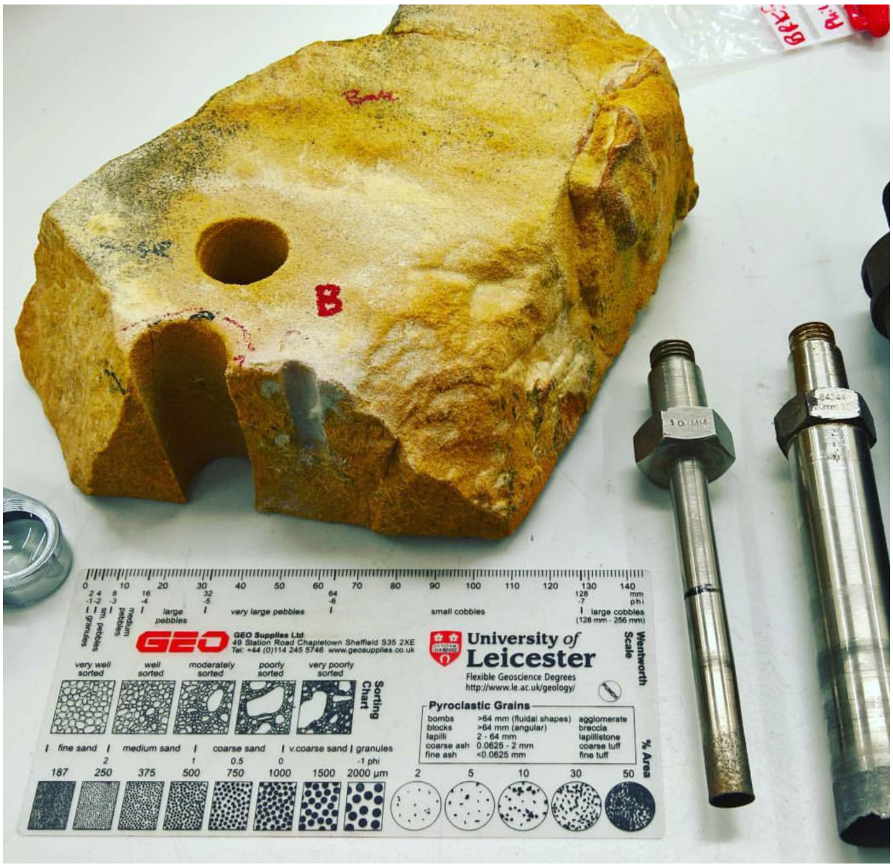
Whitecliff Bay, sample collection from the Portsmouth Sand Member of the London clay Formation. Looking 260° W, bag for scale.

Portsmouth Sand Member of the London Clay Formation. Sample Block was taken just above the hammer. Cross bedding and laminations can be seen. Geological hammer for scale.

Alum Bay sample collection for the Branksome Formation, used in the porosity analysis section of chapter 4. Looking 065 ENE.



Alum Bay sample collection for the Branksome Formation, used in the porosity analysis section of chapter 4. Pen used for scale. Bedding is 087/82 N.



Branksome Formation sample from Alum Bay being cored with 20mm and 10 mm drill bits. Cores were used for CT scanning and thin sections were taken from the cores. Orientation was key for the correlating porosity to the compaction models. B denotes the base of the bedding plane.

8.6.4 Appendix 4

CT scanning and fluorescence microscopy method and data

Porosity as a function of burial depth laboratory methods and limitations

This section discusses the initial porosity and modelled output porosity values from backstripping and compares them to the preserved porosity using laboratory measurements on samples collected from the field. As previously discussed, the initial porosity is stated as one value and assigned based on the bulk lithology. Whether this is a fair representation and the use of values from the literature is appropriate will be assessed using modern techniques. The compaction of sediments and subsequent porosity loss is a very complex process with many parameters that have been widely studied and correlated. The initial porosity at deposition and the compaction coefficient values take this into account, whether they are appropriate for this study is the purpose of this discussion. The errors in determining percentage compaction based on the porosity-depth relationship may have more of an effect on sections that are stratigraphically thinner. The majority of boreholes and sections do not exceed 200m in thickness, with the exception of a few sections from the Hampshire Basin. Backstripping studies more commonly focus on very thick stratigraphic sequences from deep marine environments, nonetheless the majority of compaction for clastic sediments occurs within the first 1-2 Km and so initial porosity is equally important.

5.5.1 Field localities and samples

Samples were taken from Alum Bay and Whitecliff Bay. Location map, field photos and cliff sections are shown in *Appendix 3.* These sections were chosen to provide a comparison with the Sandhills borehole. Both cliff sections expose vertical sequences of Paleogene strata above sea-level. They preserve strata deposited between 56 to 34.8 Ma. These rocks have been buried and returned to the surface, undergoing compaction, loading and unloading. The vertical dip is interpreted as being the result of reactivation at depth of the Variscan Sandown and Needles faults in the underlying Mesozoic rock. This can be seen in N-S oriented seismic sections (Chadwick and Evans, 2005). The fault plane does not cut the overlying Cenozoic succession but is clearly seen as a strong reflector in seismic surveys in the Mesozoic sequences. The Cenozoic strata is dominantly horizontal to sub-horizontal across the Hampshire Basin, except close to the E-W trending fault structures of the Isle of Wight and the Portsdown Anticline in the north-east of the Hampshire Basin.

5.5.2 Method: Sample selection and CT scanning

The Branksome Formation (BRKS) from Alum Bay was selected as a test sample to investigate the output preserved porosity using a combination of optical and fluorescence microscopy, and Computed Tomography (CT) X-ray scanning. The Branksome Formation was selected because it is a moderately sorted, homogenous quartz dominated fine grained sand that was most importantly well consolidated, allowing coring and thin section collection without deforming or destroying the structure of the rock which would affect the results. Unfortunately most other samples collected are lithofacies that are too friable or too fine to produce acceptable cores or thin sections. This does not bias the data, as the Branksome Formation was assigned an initial porosity using the same classification as the other lithotypes studied. Theoretically the output porosity from the backstripped Alum Bay section should be similar to the preserved porosity of the sample. Once the laboratory tests have been completed, the preserved porosity of the sample will be compared with the output porosity and compaction coefficient. If they are not correct or too dissimilar the compaction coefficient and assigned initial porosity will be modified based on this information.

CT scanning is a non-invasive technique that permits multiple scans and retesting of the samples used. Mercury porosimetry was going to be used to measure the porosity directly but does not measure the non-connected pore spaces and commonly results in destruction of the samples. This is why CT scanning was conducted. Cores are preferred over blocks or rock chips for CT experiments as the geometry reduces the effects of beam hardening, reducing the errors in the imaging from CT-scanning. Reviews by Akin and Kovscek (2003) and Cnudde and Boone (2013) discuss x-ray computed tomography in geosciences and its application, limitations and possible errors. Desbois et al. (2016) conducted a study on reservoir sandstones from the Permian Rotliegend and this was used as an analogue for the method employed here and possible errors that may be encountered.

A 20x57mm core was used initially, cut normal to the bedding plane, figure 7.5.1. It was dried ensuring the majority of pore spaces were filled with gas and to minimise the volume of pores containing any aqueous material as it complicates the imaging. Discerning between high density and lower density areas is less complex if the voids are filled with gas. If some voids are filled with (aqueous) fluids a contrast between the high density grains and low density voids is still obvious, it is just preferable to limit uncertainties. This is because the boundary between a grain and a void filled with fluid would have a lower contrast than if the void was filled with a gas. If the sample was highly saturated in fluid, this could amount to a high volume of porosity characterised as grain boundary or vice versa. Non-connected pores may contain aqueous fluid but the error margin is too low for any significant effects on bulk porosity volume and these pores may still possess 'grey' values that allow a definitive contrast to be made. Completely drying a sample of fluid would require a very high permeability. CT-scanning revealed the preserved porosity was easily detectable as the lower density areas in the sample, both qualitatively and using the defect analysis tool in VGstudio. An 8x29mm core, figure 7.5.1, was subsequently drilled in an attempt to increase the resolution of CT scans and further discern the void to material ratio. Smaller samples allow them to be closer to the x-ray source and increases the magnification and a higher resolution image of the pore spaces can be generated.

5.5.3 Method: Optical microscopy

The use of optical microscopy in conjunction with smaller core sizes was proposed to further constrain the definitive porosity analysis. Thin sections were cut parallel to the bedding (xy) and normal to the bedding plane (xz), figure 7.5.1. The xz plane was of particular importance as the z-axis is parallel to the orientation of compressive stress that results in sediment compaction during subsidence analysis. The thin sections were impregnated with resin so an initial qualitative assessment of porosity in cross section could be conducted. The quartz grains and the resin displayed similar refractive index. A resin with blue dye was initially used to highlight pore spaces, figure 7.5.1, but this proved ineffective on the smaller void spaces, coagulating only in the large pore spaces. The dye failed to produce consistent impregnation and filling of the pore spaces, figure 7.5.2a. The Logitech Ltd resin without the dye is low viscosity and had a penetration of < 5 µm. It was suggested that the composition of the resin in the pore spaces would have a strong reaction under a fluorescence microscope and reflected light, removing the dye as a factor, figures 7.4b-d. The method and application of fluorescence to geoscience is discussed by Burruss (1991) and Gardner and Pincus (1968). Photos of thin sections were taken using a ZEISS Axio imager Msm microscope and an Axio Cam Mrm. Using Image J the areas of resin infiltration were isolated in order to quantitatively assess a minimum porosity area. The software analyses the image based on colour and shade variation from pixel to pixel which represent 4 x 4 µm, applying a threshold based on the infiltrated resin in the pore spaces. Therefore the limitation at this point is the penetration of the resin which is slightly greater than the pixel dimensions and so micro-porosity would be more challenging, requiring a resin viscosity on the nano-scale. ImageJ version FIJI with the Nucleus Counter Plugin was used to analyse the thin sections and estimate their preserved porosity. A colour threshold was applied to fluorescence composite images, figures 7.5.2c and 7.5.2d, to isolate the resin infiltrated pores. For each slide and plane the percentage area of resin was measured and compared with randomly selected regions of interest.

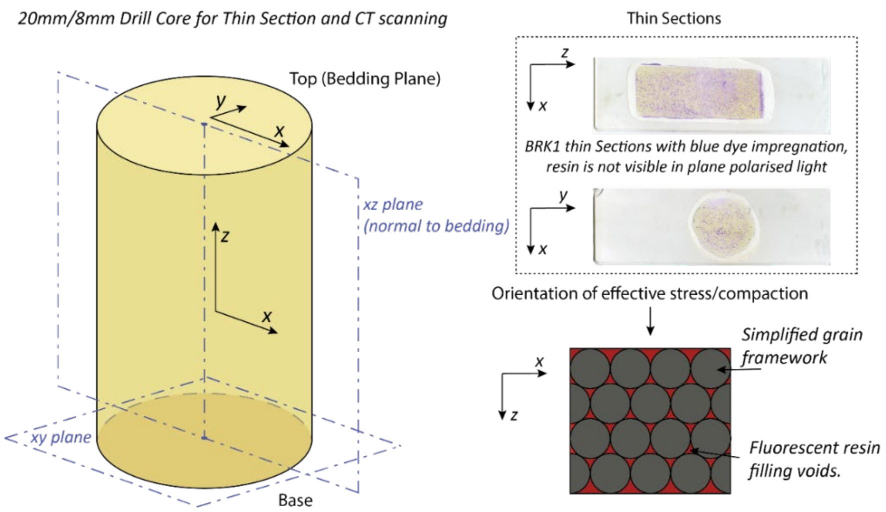
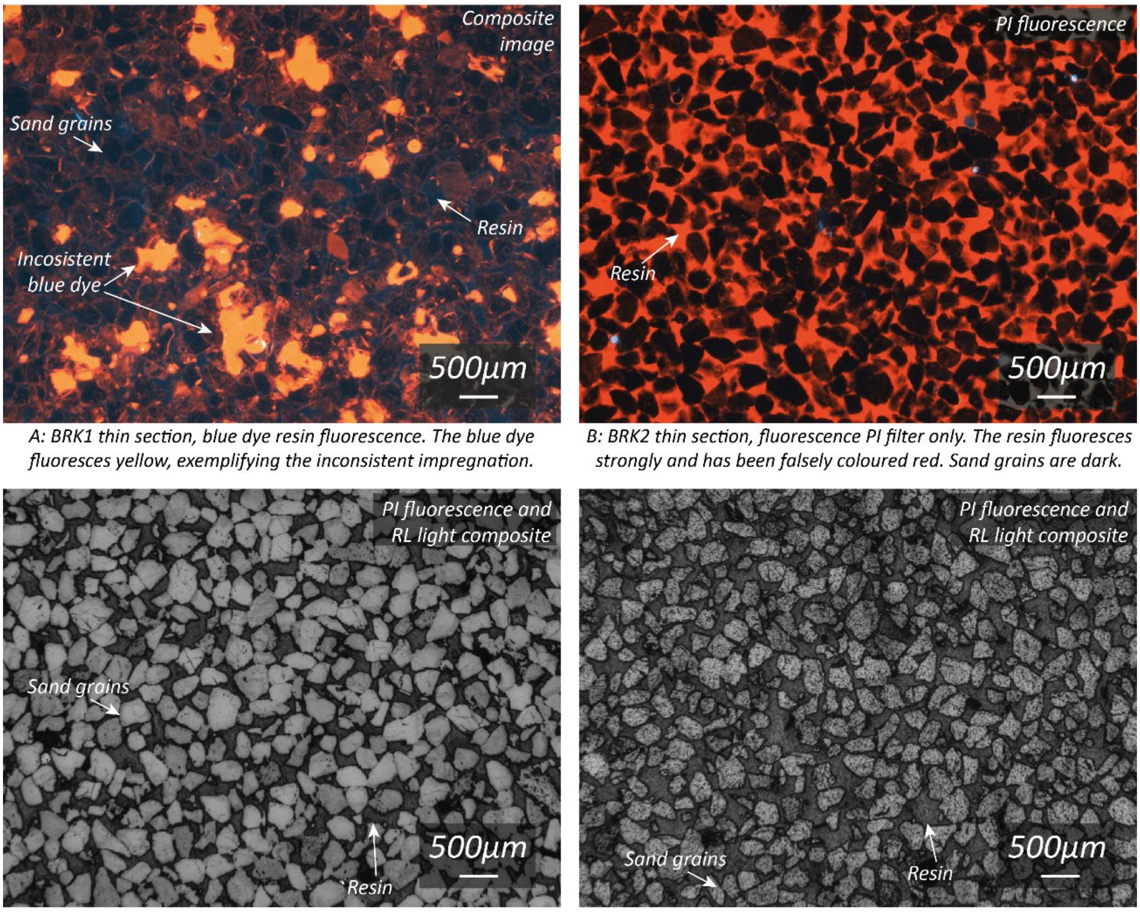


***Figure 7.5.1**: The orientation diagram of the core used and the orientation of the thin sections taken to quantitatively analyse the preserved porosity of the Branksome Formation at Alum Bay. Thin sections show the blue dye impregnation, however the resin was used without dye for fluorescence microscopy as the dye would fluoresce at a different wavelength to the resin making an image threshold more difficult to constrain.*

An average for the minimum porosity in cross section is calculated using multiple thin sections. The likely area of porosity lost to diagenetic processes, such as post depositional mineralisation appeared to be minimal as determined by assessing the grain shapes, boundaries and comparing to the fluorescence of the resin in the void areas, figures 7.5.2b-d. The average minimum porosity gained from fluorescence microscopy was used to guide the lowest surface determination between material and void space on the CT scans. This is the rendered 3D surface that defines the boundary between the higher density grains and void space or porosity. The 20x57mm core was cut so that two planes of thin sections could be made, the xz and xy planes. A reliable quantitative analysis of varying porosity through the scanned sample and could be representative of the 3D framework. The measured porosity values in the xz plane is directly relatable to the output porosity value from the compaction equations. The addition of the xy plane is useful for the CT scanning and surface determination but also provides data on the plane that, in terms of determining a compaction history, is not considered to undergo compaction.



A: BRK1 thin section, blue dye resin fluorescence. The blue dye fluoresces yellow, exemplifying the inconsistent impregnation.

B: BRK2 thin section, fluorescence PI filter only. The resin fluoresces strongly and has been falsely coloured red. Sand grains are dark.

C: BRK2 top bedding (xy) plane, resin fluorescence. Bedding plane. Threshold image allows isolation of resin impregnating void spaces

D: BRK2 side normal to bedding (xz) plane, resin fluorescence. Normal to the bedding plane. Void spaces quantified by area %.

***Figure 7.5.2**: Examples images of the Branksome Formation thin sections under the PI fluorescence filter and reflected light. A: Composite image of reflected light, and three wavelengths of fluorescence highlighting the inconsistent impregnation of the blue dye. B: PI Fluorescence image of the Branksome Formation highlighting the resin impregnation of the void spaces. C: Fluorescence and reflected light composite image on the bedding (xy) plane of the Branksome Formation. Composite helps further discern the resin and areas porosity from grain boundaries. D: Fluorescence and reflected light composite image normal to the bedding (xz) plane.*

5.5.4 Limitations

Due to exhumation and possible higher strains associated with nearby fault movement, it can be inferred that the porosity of the rocks may not be representative of the same lithostratigraphies found at depth in other boreholes e.g. the Sandhills borehole further north in central Isle of Wight. The grain framework may have additional deformation due its proximity to the Sandown Fault zone, resulting in additional varying amounts of strain that could influence the degree of compaction. However, samples taken from cliff sections did not show pervasive brittle deformation and/or low grade metamorphism. Ideally, samples would be taken from a freshly drilled borehole of the Paleogene stratigraphy in order to constrain the porosity under the existing confining pressure. However borehole samples were not available for this study. As a result removal of overburden and a reduction in the confining pressure following exhumation, the grain framework may have regained some thickness as a result of the elasticity in the grains. This may lead to a recovery of some porosity. The lithologies at depth may be under a greater confining pressure from the overburden and are most likely be more representative of the preserved porosity. These parameters have been taken into consideration, and porosity measurements will be assumed to be a maximum and that the lithostratigraphies at depth would most likely possess lower preserved porosity.

5.5.5 Results

The Branksome Formation from the Alum Bay section was assigned an initial porosity of 56% (Decimal porosity ϕ = 0.56), prior to backstripping, based on the bulk grain size and mineral constituents of the compacted rock. The compaction history indicated the Branksome Formation at Alum Bay had an output porosity of 31% (Dec. ϕ = 0.31). This should theoretically match the preserved porosity of the samples.

5.5.5.1 CT scan defect analysis

BRK2 8mm core was used to constrain a possible porosity percentage. Within the core, various regions of interest were selected and analysed using the defect analysis tool which determines the high density from the low density areas of the sample. The scans were conducted at 175 KeV, 65 mA and with a voxel size of 14 µm. As the stage of the CT scanner rotates to produce a full 3D image, a cylindrical core prevents shadowing and reduces the effects of beam hardening and reduces the data noise.

CT scanning produced void ratios of Region A= .32%, B= .29 % and C=

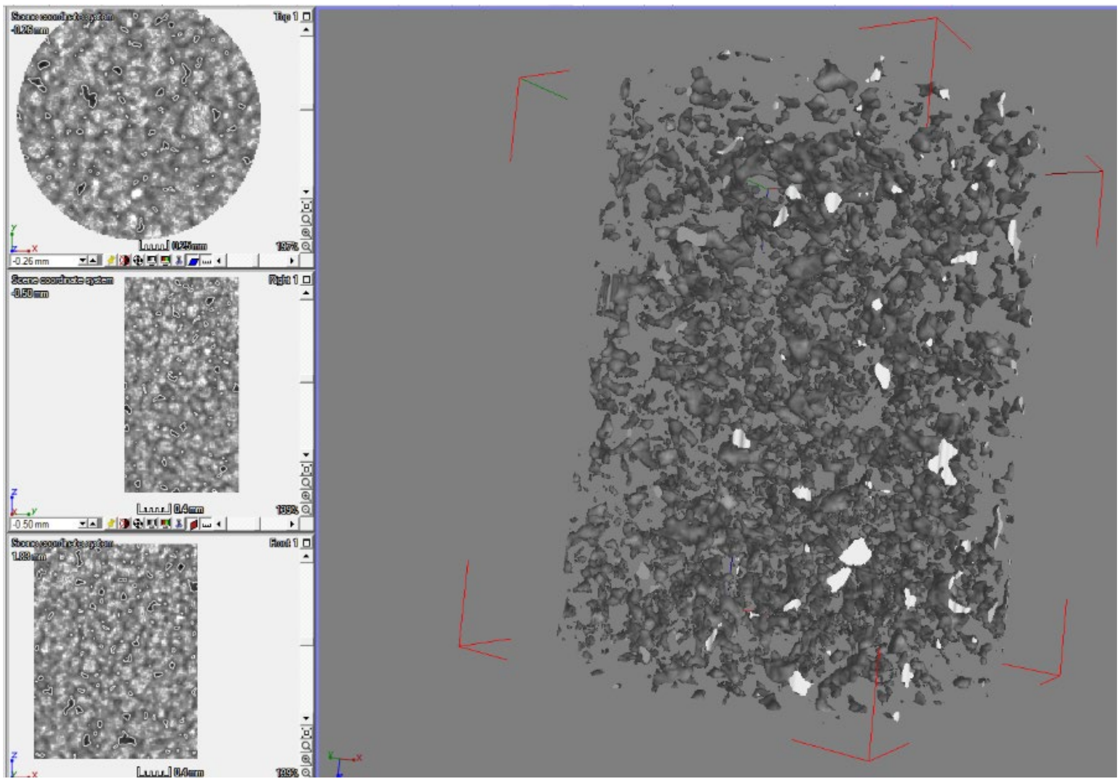


Figure 7.5.3: *Example CT data showing the distribution of low density values in the sandstone that have been inferred as porosity. The high density values interpreted as the grain framework has been removed and a 3D rendering of the voids is left.*

7.5.6 Thin Section Fluorescence analysis

The PI fluorescence filter under reflected light was used to create composite images highlighting the resin in the pore spaces and the texture of the grain boundaries. 12 assorted regions of interest were selected and measured for percentage porosity. 6 regions of interest (ROI) for bedding plane (xy) and 6 regions of interest (ROI) for normal to the bedding (xz). An average porosity for each orientation was determined and an average of both reflects a possible 3D porosity value.

Orientation	Region of Interest	Porosity %	Variance
xy- top	ROI 1	33.01	8.00
xy- top	ROI 2	31.2	1.04
xy- top	ROI 3	28.69	2.22
xy- top	ROI 4	29.1	1.17
xy- top	ROI 5	28.8	1.90
xy-top	ROI 6	30.26	0.006
Mean xy		30.18	2.39
Standard	**Deviation xy**		1.546
xz- side	ROI 1	34	3.24
xz- side	ROI 2	32.2	0
xz- side	ROI 3	30.5	2.89
xz- side	ROI 4	29.10	9.61
xz- side	ROI 5	31.94	0.07
xz- side	ROI 6	36.06	14.90
Mean xz		32.30	5.12
Standard	**Deviation xz**		2.262

Average: *xy plane = 30.18%* *xz plane = 32.30%* *3D = 31.2%*

Table 7.1: *The 12 randomly selected regions of interest (ROI) and the percentage porosity determined from fluorescence microscopy. 6 for each orientation, xy and xz planes. The variance in porosity has been determined for all regions of interest analysed. The mean porosity and standard deviation have been derived for each orientation*

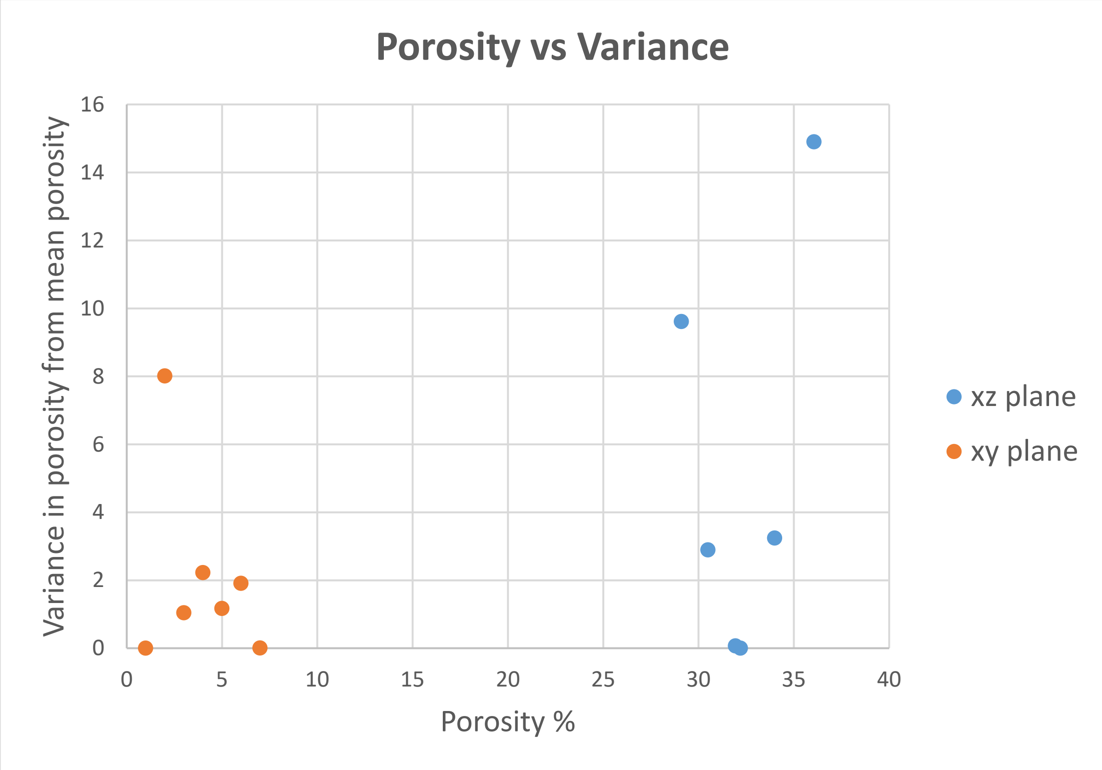
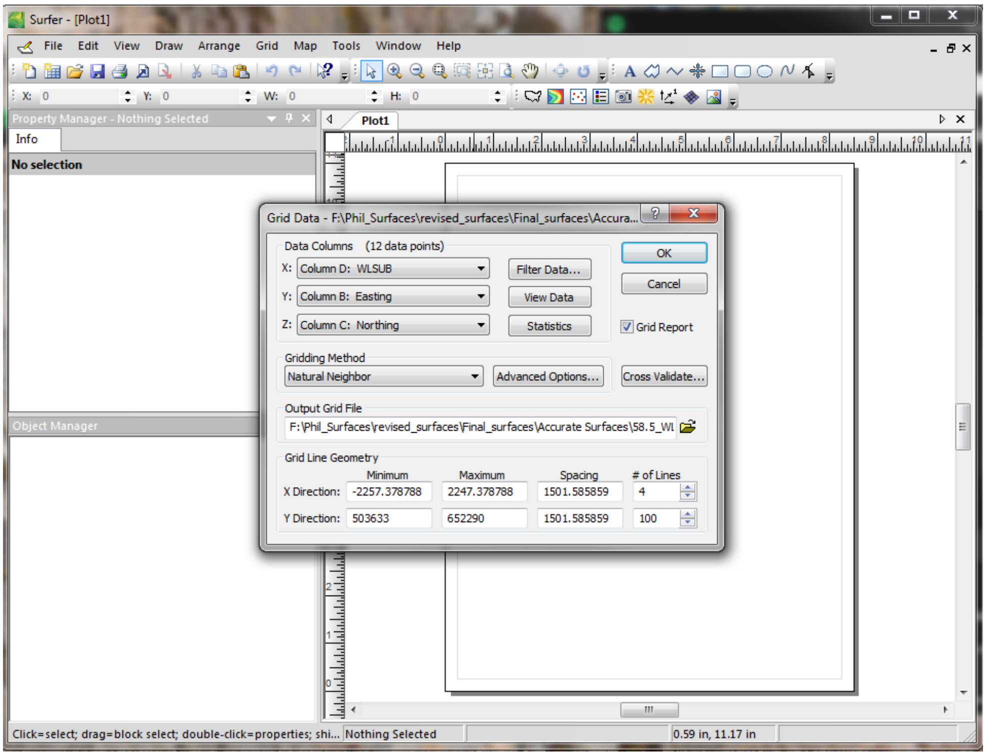


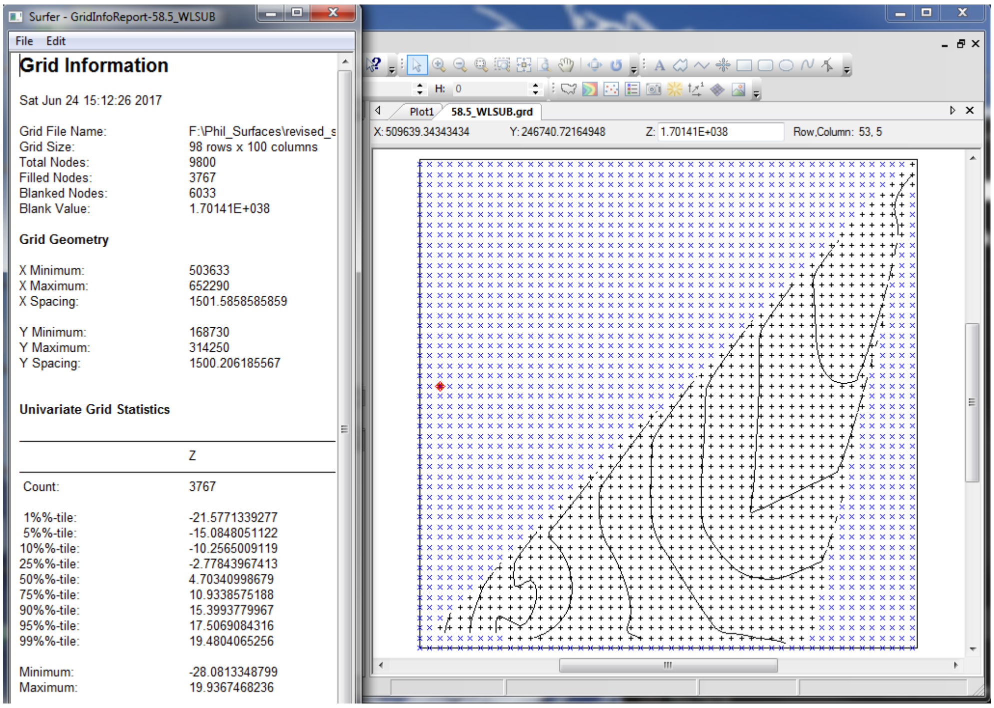
Figure 7.5.4: *Percentage porosity plotted against the variance for each region of interest (ROI). Blue are the xz plane and red are the xy plane taken from table 4.2. There is a greater variance and distribution from the xz plane data. Less variance and distribution can be seen from the xy plane data.*

Qualitatively, the resin appeared to consistently impregnate the pore spaces on a micrometre scale. The porosity values for each slide and region of interest were within ±5% of each other. The mean resin filled porosity was 2.12% less in the xy plane than the xz plane. This is within the ±5% margins for all 12 regions of interest suggesting the resin filled porosity is close to isotropic in orientation, but a possible reduced volume of porosity in the xy plane. There is a greater variance in the xz plane porosity values, table 4.2 and figure 7.5.4 show the distribution in variance. There is a lower standard deviation in the xy orientation and figure 7.5.4 shows the clustering of data in comparison to the xz plane data. Using the mean porosity values for the xz and xy planes an assumed 3D porosity value of 31.2% can be derived.

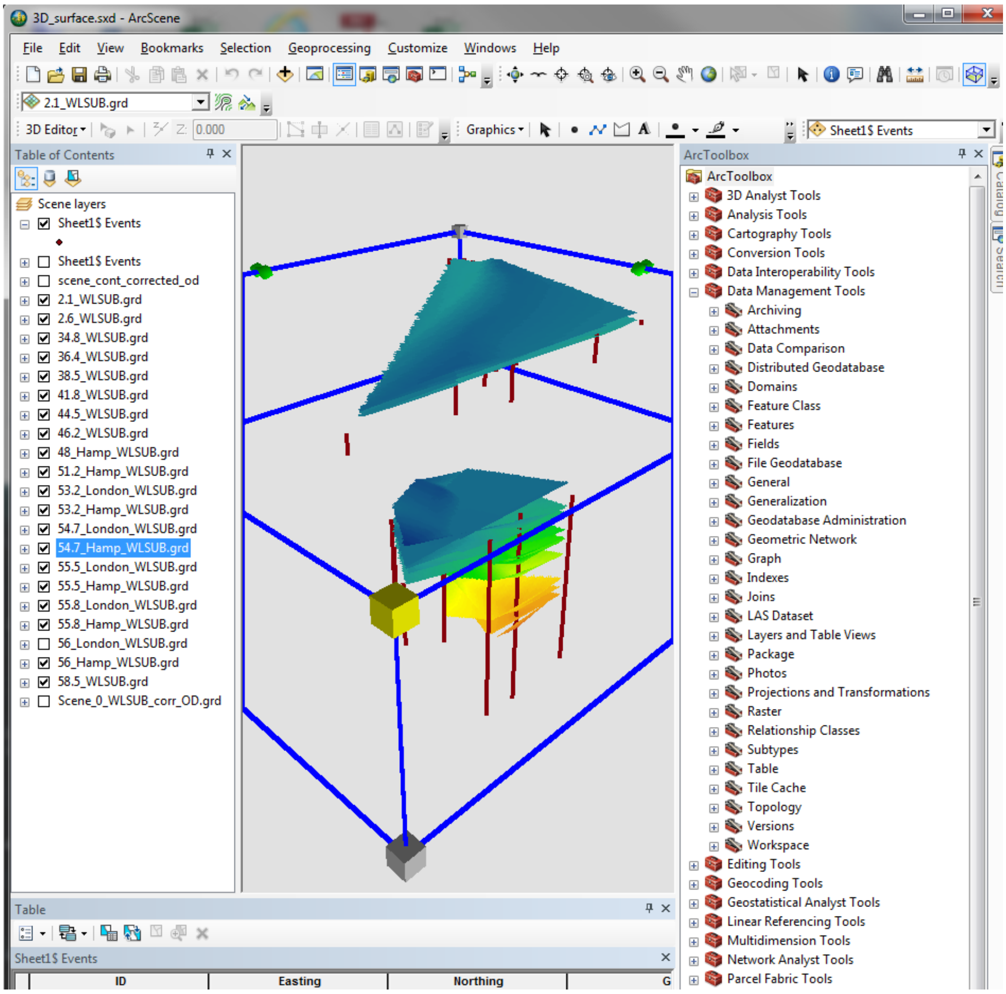
8.6.5 Appendix 5



Gridding interface of the Surfer 10 software. The 58.5 subsidence data was used as an example for the following images. The input functions for x, y and z are shown with the gridding method.



Surface generation in Surfer 10 software and the statistics produced for each surface. 58.5 Ma surface is shown as an example. These .grd files were used in Arc GIS



3D rendering and modelling of tectonic surfaces in ArcScene. List of surfaces opened and displayed in this screengrab are shown in the left hand layer toolbar.