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Loess and Bee-Eaters I: Ground properties affecting the nesting of European bee-eaters (*Merops apiaster* L.1758) in loess deposits

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All bee-eaters nest in earth holes. - C.H. Fry

Abstract

The European bee-eater (*Merops apiaster* L.1758) nests in tunnels in loess deposits. The properties of loess make it particularly suitable for tunnel nesting birds (a major factor is the metastable nature of the ground). The 'Heneberg Compromise' operates whereby the conflicting requirements of tunnel stability and ease of excavation dictate the optimum particle size for usable ground. The open structure of loess deposits, due to particle shape and airfall sedimentation, allows gas movement in nesting tunnels. It also allows local compaction during nest building which strengthens tunnel walls. The short range nature of the interparticle bonds in the ground material provides an almost ideal construction environment, ensuring a low plasticity index, which appears to be critical for tunnel building birds. Bee-eaters and sand martins dig tunnels in loess as 'primary nesters'. These loess tunnels are used by many 'secondary nesters'. The bee-eater is an efficient ecosystem engineer.

Distribution maps of European bee-eater nesting, and of loess deposits, show some coincidence. A concentration of loess and nest regions is observed to the north of the Black Sea where the rivers Dnepr and Don deliver loess material, and to the west of the

Black Sea in the Danube basin. The birds nest to the north of the demarcated Meigs arid/semi-arid zones in Africa, but spend winters to the south of these regions. They fly long distances from wintering zones to loess nesting regions, the longest migration of the bee-eaters. Even relatively minor loess deposits on the fringes of the breeding range, as in southern Poland, have their bee-eater inhabitants.

Keywords: European Bee-Eater; tunnel nests; loess deposits; ground properties; primary tunnel nesting birds; nest and loess coincidence.

1. Introduction

The European Bee-Eater (*Merops apiaster*) (Fig.1) has been observed nesting in the loess deposits in south-eastern Poland, in the region of the Poland-Ukraine border. The EBCC Atlas of European Breeding Birds (Hagemeijer and Blair, 1997) shows a great concentration of bee-eater nesting in Central and Eastern Europe, but there is a distinct outlier on the Poland-Ukraine border. The birds appear to have a strong preference for nesting in loess, and their distribution is, to some extent, controlled by the existence of loess deposits.

Loess is a particular type of ground which has proved attractive to certain bird species that can dig tunnels in the relatively soft material and construct satisfactory nests. The sand martin is perhaps the best known of the loess-living birds (and has been studied at length by, in particular, Heneberg 2003, 2009). This paper is about the ground rather than the birds, and the birds might be seen as experimental operators who manipulate the ground thus enabling its properties to be assessed.

The European bee-eater (*Merops apiaster* L.1758)(Fry, 1984) is another well known loess-living bird and its treatment of loess ground provides a nice contrast to the results concerning the sand martins. It might be useful to also consider the kingfisher as a tunnel living bird: although it does not live in loess deposits, it provides some interesting comparative granulometric data. How do the properties of the ground affect the nesting behaviour? What properties are sought by the tunnel nesting birds? Some simple ideas from the fields of soil mechanics and sedimentology are used to elucidate the bird/ground interaction. The ‘Heneberg compromise’ which underpins nesting behaviour has been discussed (Smalley et al., this volume), and this paper progresses from that discussion.

2. Birds in loess

Bee-Eaters and Sand Martins dig nesting tunnels in loess deposits. These are ‘primary nesters’ who build their own tunnels. They can be followed by a considerable number of ‘secondary nesters’ who use the ready-made nesting tunnels. Casas-Criville and Valera (2005) listed rock sparrow, house sparrow, Spanish sparrow, tree sparrow, sand martin, little owl, European roller, pied wagtail, European starling, hoopoe, African pied starling and African hoopoe as a selection of secondary nesters who move into bee-eater nests. There can be no doubt that bee-eaters act as ‘ecosystem engineers’ and shape their immediate environments and influence the life-styles of many other species, not only birds: lizards and beetles live in bee-eater tunnels. Large scale tunnelling can cause slope failure and ground changes on the geotechnical scale. Whether bee-eaters possess a ’theory of mind’ is still being discussed (Smitha et al., 1999).

The European bee-eaters have utilised the European loess to good effect. Where there is plentiful loess and an acceptable climate and environment they have flourished (e.g. in Vojvodina in northern Serbia, where the loess is particularly well developed [Purger 2001]). The remarkable properties of the loess provide a serendipitous fit to bee-eater requirements.

3. Ground property variables

A loess deposit is essentially a silty deposit, with usual particle size in the range 20-50μm. There can be a modest clay mineral content. There will be a fairly open packing texture because of the airfall mechanism by which the loess deposit formed. In many deposits there is a significant carbonate content, and this can have an effect on strength and stability.

From the nest-builder point of view, two major properties are critical: it must be possible to dig a tunnel in the loess, and the tunnel once built should be stable. The need to balance these two factors is recognized in the Heneberg Compromise, and is illustrated in Fig.2. Tunnel stability is enhanced by increased cohesion in the ground material, which is produced by reducing the particle size.

Clay mineral content of ground material has an effect on nesting properties because it confers plasticity to the soil. Plasticity is measured by plasticity index (PI). A discussion of plasticity involves a consideration of interparticle bonding in the ground system. At the most basic it is the interparticle bonding which controls the nesting properties. A relatively weak bond allows tunnel excavation, whereas a relatively strong bond offers strong walls and stable structures. A useful conceptual approach to bonding in ground systems can be developed using the concepts of 'short-range bonding' and 'long-range bonding', and these ideas can be applied to nesting milieu.

4. The nest tunnel

The tunnel has a length L, which is fairly easy to define. It also has a transverse dimension which is a bit more difficult to define, called W (width). The shape of the tunnel is defined by L/W: the length/width ratio.

European Bee-eaters largely nest and breed in southern Europe and North Africa (see fig.3), spending the Northern Hemisphere winter in southern Africa. The ground properties in the breeding region must be suitable for tunnel construction, and this is presumably the main control on the breeding range. Sandy and silty grounds with a predominance of short range interparticle bonding are required.

There are certain other architectural requirements for the tunnel (Lill and Fell, 2007). It should be excavated to a depth for the correct temperature and humidity conditions to be achieved. The wide variation in surface temperature must be nullified and the correct thermal environment produced, which may require a long tunnel (White et al., 1978). Diffusion of gases through the porous ground and along the tunnel can maintain tolerable levels of O_2 and CO_2. Wind movements improve the internal conditions via gas vortices which penetrate via the nest tunnel and displace gases from inside. The piston effects of birds moving in the relatively narrow tunnel help with ventilation. A combination of permeable soil materials and nest design gives good results. The airfall structure of the loess ground and the relative absence of pore-filling clay make loess an ideal ground material from the atmosphere control point of view.

The chemistry and mineralogy of the ground may have some consequences relative to the production of waste material by the birds and the development of bacterial environments. Fry (1984 p.234) noted that the only concession to hygiene is that nestlings defaecate usually not on the floor but against the earthen walls. It may be that the walls are slightly better at adsorbing some waste materials, possibly less compact than the floor. Bacterial decomposition in the nest tunnel produces ammonia, which does not appear to have an adverse effect on the nestlings. There may be some cyano-bacterial activity. Cyano-bacterial activity in loess in general is beginning to be studied (Smalley et al., 2011) but will possibly be more relevant to deposit formation actions rather than post-depositional events.

Some interesting tunnel profiles in Romania have been shown by Petrescu (1998). These are long tunnels dug apparently in the Danubian loess, and they have L/W values in excess of 10. The bee-eaters favour loess in Romania, and this region falls within the great Danubian loess/bee-eater region (see Fig.3).

5. The nature of ground

It has been proposed that five basic types of particulate material make up ground (see Fig.4, Jefferson and Smalley 1997). In very basic soil mechanics, it is usual to recognise two ground types: cohesive and cohesionless, essentially clayey and sandy. These are distinguished by particle size and the nature of the interparticle interaction- the bond. It is possible to postulate a bond/weight ratio[BWR] which gives an indication of the predominance of bond type.

A simple distinction can be made in bond nature, with division into long range bonds and short range bonds. Short range bonds produce a brittle system, whereas long range bonds produce the phenomenon of plasticity, one of the most interesting and important of ground properties. A very simple interpretation of bond nature is shown in Fig.5. The complexity in the bonding system derives from the fact that clay mineral particles have electrical charges.

The five distinctive particulate ground materials are active clay minerals (smectite group), inactive clay minerals (kaolinite group), very fine silt (associated with glacierized terrain, in particular in Canada and Scandinavia), ‘ordinary’ silt (quartz silt with a mode size around 30 m) and sand (quartz sand with a mode size of perhaps 300 μm). This is a basic, simplified list (more fully discussed elsewhere; Jefferson and Smalley 1997) but it contains the essential ground material particles, certainly those involved in tunnel nest construction.

The clay particles have electrical charges, and their interaction with polarised water molecules in the ground water and dissolved cations leads to the system of long-range interparticle bonding, and to the phenomenon of plasticity. Some birds are brilliant exploiters of plastic clay. Very plastic clay is sometimes called mud, and certain birds (e.g. among the Hirundinidae) can construct elaborate and structurally sound nests from mud. However, for tunnel builders it can be a problem, and the ground used by tunnel builders is low in clay and has a low plasticity index (PI<5-6, see e.g. Yuan et al., 2006).

Tunnel builders favour silt (near zone D in Fig.4), commonly silt in the form of loess deposits. In a loess deposit it is not just the ideal nature of the particles that facilitates building, but also the fact that the loess deposit, having been deposited as an open structure by wind, has some very acceptable structural properties. The bonding is essentially a classic short range bond: the sort of bond that would exist between two primary mineral particles in a sediment or soil. It is a contact bond and can be quite strong, particularly when enhanced by some cementation, but the essential property is that when the system is deformed and the bonds are broken, all strength is lost. With long range bonding strength is retained, which is the essence of plasticity, the ability to retain strength after deformation.

The loess deposit consists largely of silt-sized quartz particles which have a very tabular shape (Rogers and Smalley, 1993; Howarth, 2010, 2011) and form a very open packing, held in position by simple short-range contact bonds. The open packing can be measured in terms of packing density or, as in conventional soil mechanics, by voids ratio. Voids ratio (e) is simply the ratio of space to solid in a soil system. A voids ratio of 1.0 is the same as a packing density of 0.5 (Rogers et al., 1994). A characteristic property of loess is the open packing (e >1.0) which is produced by the airfall method of deposit formation. The airfall sedimentation puts the loess in useful places (from a bee-eater viewpoint) and produces the open structure which allows gas movement through the ground. Another packing factor may be important: as the bird tunnels in loess it produces local compaction and the tunnel walls are subtly strengthened. The ground around the tunnel has a slightly elevated packing density and is thus more stable (the bonding is enhanced). Many factors combine to make loess a close-to-ideal material for bee-eater nesting, and particle packing is very important.

Two dimensional models of loess deposit structures can be made by simple Monte Carlo methods (Dibben et al., 1998; Assallay et al., 1997). These demonstrate the very high voids ratio in an ideal loess deposit, and the disposition of very large pores which must assist considerably in tunnel excavation and produce the high beneficial permeability. Kingfishers, nesting in more sandy ground, face a different packing regime. The quartz sand particles are more bulky and more equi-axial, forming a somewhat closer packing with a lower voids ratio. However, they still excavate relatively easily because of the predominance of short range bonding and the relative lack of clay minerals. Clay minerals can be a problem for tunnel nesting birds because they fill the pores and reduce permeability and they introduce possible plasticity, the high PI which should be avoided.

The co-ordination number (CN) is a useful concept to consider when discussing ground systems which are essentially particle packings. The co-ordination number defines the mean number of nearest neighbour particles. A tight packing of ideal equal spherical particles has a CN of 12, a number which is not likely to be approached in real ground systems. In the 'simple' system of sphere packing (see Rogers et al., 1994) the range of packing densities varies from 0.52 (the so-called cubic 600 packing, with a CN of 6), to 0.74 (the rhombohedral packing 204, CN 12, see fig.8). The packing density of loess is around 0.5 (e = 1), with a low CN. A cohesive system with very small particles can have a very low CN. The wall strength (see fig.1) can decline at very small sizes as the CN becomes very small. Cohesive forces hold the particles apart in a very loose packing.

6. Kaiserstuhl

The Kaiserstuhl, in the Rhine, is a well known nesting site for bee-eaters, and provides an excellent study example. It is a volcanic landform covered in loess. It has a particularly benign climate which is attractive to bee-eaters. It is believed to be the warmest place in Germany. It is in effect a low mountain range, a Mittelgebirge, with a height of around 500 m. It sits in the rain shadow of the Vosges Mountains and has a modest rainfall, about 600-700 mm/y, mild winters and warm/hot summers with a mean annual temperature of about 10°C, and a rich flora and fauna.

This is an excellent nesting place for bee-eaters. The ground conditions and the climatic conditions would appear to be about ideal. Fig. 6 shows nests in the Kaiserstuhl loess.

The nesting pattern clearly indicates the property variation within the loess ground. Removal of softer material in the tunnel building process has revealed the zones of harder ground where carbonate precipitation has occurred. The periodic arrival of the loess material is reflected in the variation in ground properties.

The Kaiserstuhl loess is classic loess (Smalley et al., 1973), formed from Alpine material carried to the north by the Rhine. Loess deposits tend to be associated with rivers (Smalley et al., 2009), and thus rivers have a secondary effect on bird distribution. Bee-eaters and sand martins nest in loess which has been placed in the landscape by two major sedimentological processes. The silt material has been transported from source region by river action, and then finally emplaced by aeolian action to form the open-structured loess deposit. Kingfishers nest in material which has only undergone stage 1 of this process. The aeolian transport has a sorting action, so that the loess deposit is largely silt. The river has some sorting action but the kingfisher will expect to encounter clay and sand in addition to silt.

7. Comparisons

Kingfishers dig tunnels: they are also primary tunnel nesting birds. There have been some interesting studies of ground nature relative to kingfisher tunnelling and nesting behaviour (e.g. Heneberg, 2004; Kafutshi and Komanda, 2011), and these might be compared to sand martin and bee-eater results. In particular, the kingfisher is digging into a fluvial sediment, ground material deposited by rivers, which consists largely of sand and silt and clay. The observations by Heneberg (2004) are particularly interesting: he noted that Eurasian kingfishers avoided large particles and small particles, working in the compromise region (as shown in fig.2). The birds appear to favour particulate ground with a mode size in the sand region.

The Malachite kingfishers studied by Kafutshi and Komanda (2011) favoured sand-sized particles with low clay. They described a ground material with a BWR of around 1.0. It has been observed that kingfishers like to build their nests at about 0.5m from the ground surface. It is possible that there is a change in ground properties at about 0.5m. Assallay et al. (1998) have described a mechanism by which a pedogenic hard layer can develop in granular soils in a relatively damp environment, at around 0.5m depth. This is largely due to changes in soil structure via compaction. This form of ground deformation, known as hydroconsolidation, is the classic deformation mode of in-situ loess deposits. It depends on the presence of an open soil structure- something which occurs in loess deposits via the airfall deposition mechanism and could occur in recently deposited river bank sediments. There may be an element of hard layer control in kingfisher nesting as there almost certainly is in bee-eater nesting (see Kaiserstuhl situation in fig.5).

The bee-eater is a larger bird (see fig.7): sand martins and kingfishers are about 10cm long, wheras a European bee-eater is about 25cm. A larger tunnel is required for the bee-eater. It may be that the larger tunnels are somewhat less stable than the smaller tunnels, with more chance of random ground defects occurring in the larger circumference of the bee-eater tunnel. This might suggest that they could favour a smaller size ground material to give increased cohesion (Fig.2), as observed by Heneberg and Simecek (2004).

8. Commentary and conclusions

Fry (1984, p.148) writing about habitat, stated that the European Bee-eater, "nests mainly in sandy cliffs or steep slopes: river and canal banks, gullies, ravines, quarries and cuttings; sandstone, sand sea-cliffs reported in South Africa." The ground material involved in each situation is a granular material with relatively small particle size, with a predominance of short range bonding, often with an open packing texture and a low clay mineral content. The tunnel disposition and creation largely depends on the 'Heneberg compromise', the balance between ease of tunnelling and stability of the tunnel.

Loess appears to be an ideal material for bee-eater nests, and an attempt to relate bee-eater nesting regions and European loess distribution has been made in Fig.3. Neither distribution map is particularly precise: the loess distribution is from Scheidig (1934), and the bee-eater nesting distribution from Fry (1984), and from the EBCC Atlas of European Breeding Birds (Hagemeijer and Blair 1997). Two interesting loess regions are favoured by bee-eaters: the loess zone to the north of the Black Sea and the region to the east of the Black Sea which is dominated by the Danube basin, as is particularly well shown in the EBCC Atlas.

Loess is not the only ground material used by bee-eaters for nesting purposes. They can cope with a variety of particulate systems, and if the conditions are suitable can build in a variety of grounds. There seem to be a few limitations which might be applied. The basic Heneberg compromise has to be applicable: the ground must be easily excavated and strong. Short range bonds must predominate, the PI must be fairly low, the packing must not be too tight, and a small amount of bond enhancement by cementation is acceptable.

However, the loess has an additional advantage, by virtue of its metastable nature. Loess has the capacity to collapse into a more compact packing. It is this property which causes many engineering problems, but which may be of great advantage to primary nesters. A bee-eater building its nest will tend to compact the floor, and it appears that bee-eaters like to work over a solid floor, rather than under a solid roof (see Fig.6 of tunnels over hard layers in the Kaiserstuhl loess). The collapse of ideal systems is shown in Fig.8. On initial aeolian deposition the loess can have a very open structure (e = 2) which collapses immediately into a metastable structure with an e value of about 1.0. This structure is capable of further collapse, but is relatively strong. This is material that the bee-eaters can exploit. It is the same property which is utilised by the human inhabitants of loess houses in China.

A climatic factor might be commented on. Fig.9 is based on the aridity maps of Meigs(1953). Bee-eater distribution, as in Fig.3, is applied to the Meigs map of Africa and Europe. Sandy, arid regions offer nesting opportunities, the short range bond requirement will operate, but it appears that bee-eaters prefer to travel further and populate the metastable loess in Europe. Two loess regions appear to be favoured: regions supplied with loess material by large river systems. North of the Black Sea, there are large deposits of glacial loess (see Smalley et al., 2009), which are delivered into place by the rivers flowing into the north of the Black Sea and the Caspian Sea. The Dnepr, Don, and Volga are great loess rivers. The Danube delivers loess material from the Alps and Carpathians. The Danube basin represents a great loess deposit to the west of the Black Sea. The bee-eaters like to nest well to the north of the major arid zones of North Africa.

There are nesting sites indicated in Spain and Italy, and these may prove to be very interesting and critical to the study of the relationship between bee-eaters and ground. Stuut et al. (2009) have indicated regions in Italy and Spain where windblown material from Africa makes a significant contribution to soils. It may be that soils in Spain and

Italy are more loess-like than is usually acknowledged, and that with acceptable climatic conditions, they offer good nesting sites for bee-eaters. These possible loess regions on the fringe of accepted deposits need more investigation, as does the great band of material across Africa shown as possible loess in Fig.3. This seems to correspond quite closely to the living and nesting region of the Northern Carmine Bee-eater (*Merops nubicus*) and offers another aspect of the bee-eater and loess situation.

In Africa, Fry (1984 p.57) has noted that the Little Bee-eater (*Merops pusillus*) likes to nest in the roofs of dens excavated by aardvarks (*Orycteropus afer*). This must be a textural selection, as the ground excavated by the aardvark reveals soil of the right texture for bee-eater nesting. The aardvark removes crusting and cementation which would make nest building more difficult. This might be a factor affecting bee-eater distribution in Europe. Fry (1984 p.154) reported a serious decline in bee-eater numbers from about 1875 to the end of the nineteenth century, but then they recovered. They are known to be sensitive to environment, but the early twentieth century recovery may have been somewhat influenced by improved access to nesting ground. As urban development proceeded, more bricks were required and this meant that more loess quarries were opened. Sand martins appear to respond to the growing availability of quarry sites, and it is possible that bee-eaters are similarly affected. The working quarry is a place where fresh loess faces are being steadily provided, and a bird which likes to build a fresh nest tunnel every season would find this agreeable.

Bee-eaters nest in the major loess deposits of Europe, but they are sufficiently attracted to the ideal loess nesting environment to also head slightly north and utilize the more modest deposits in Poland. The Bee-eater nesting in loess is a European phenomenon, and a Polish phenomenon.

References

Assallay, A.M., Rogers, C.D.F., Smalley, I.J. 1997. Formation and collapse of metastable particle packings and open structures in loess deposits. Engineering Geology 48, 101-115.

Assallay, A.M., Jefferson, I., Rogers, C.D.F., Smalley, I.J. 1998. Fragipan formation in loess soils: development of the Bryant hydroconsolidation hypothesis. Geoderma 83, 1-16.

Casas-Criville, A., Valera, F. 2005. The European bee-eater (*Merops apiaster*) as an ecosystem engineer in arid environments. Journal of Arid Environments 60, 227-238.

Dibben, S.C., Jefferson, I.F., Smalley, I.J. 1998. The 'Loughborough Loess' Monte Carlo model of soil structure. Computers and Geosciences 24, 345-352.

Fry, C.H. 1984. The Bee-eaters. T.and A.D.Poyser, Calton. 304p.

Hagemeijer, W.J.M., Blair, M.J., 1997. EBCC Atlas of European Breeding Birds: their distribution and abundance. T.and A.D. Poyser, Calton 920p.

Heneberg, P. 2003. Soil particle composition affects the physical characteristics of Sand Martin *Riparia riparia* holes. Ibis 145, 392-399.

Heneberg, P. 2004. Soil particle composition of Eurasian Kingfishers' (*Alcedo atthis*) nest sites. Acta Zoological Academaiae Scientiarum Hungaricae 50, 185-193.

Heneberg, P. 2009. Soil penetrability as a key factor affecting nesting of burrowing birds. Ecological Research 24, 453-459.

Heneberg, P., Simecek, K. 2004. Nesting of European bee-eaters (*Merops apiaster*) in Central Europe depends on the soil characteristics of nest sites. Biologia (Bratislava) 59, 205-211.

Howarth, J.J. 2010. The shape of loess particles reviewed. Central European Journal of Geosciences 2, 41-44.

Howarth, J.J. 2011. A commentary on the shape of loess particles assuming a spatial exponential distribution for cracks in quartz. Central European Journal of Geosciences 3, 231-234.

Jefferson, I., Smalley, I.J. 1997. Distinctive particle types in ground materials: implications for engineering geology. In Wang Siying and P. Marinos, ed., Engineering Geology: Proceedings of 30th International Geological Congress 23, 303-313.

Kafutshi, R.K., Komanda, J.A. 2011. The impact of soil texture on the selection of nesting sites by the Malachite Kingfisher (Alcedinidae: *Alcedo cristata* Pallas 1764). Ostrich 82, 243-246.

Lill, A., Fell, P.J. 2007. Microclimate of nesting burrows of the Rainbow Bee-eater. Emu 107, 108-114.

Meigs, P. 1953. World distribution of arid and semi-arid homoclimates. In Reviews of Research on Arid Zone Hydrology (UNESCO Arid Zone Programme), 203-210.

Petrescu, A. 1998. Study on the placement and architecture of the nests of *Merops apiaster* L.(Aves, Coracilformes) in colonies from Southern Romania. Travaux Museum Natural History 'Grigore Antipa' 40, 383-402.

Purger, J.J. 2001. Numbers and breeding distribution of the Bee-eater (*Merops apiaster*) in province Voivodina (northern Serbia) between 1987 and 1990. Vogelwelt 12, 279-282.

Rogers, C.D.F., Smalley, I.J. 1993. The shape of loess particles. Naturwissenschaften 80, 461-462.

Rogers, C.D.F., Dijkstra, T.A., Smalley, I.J. 1994. Particle packing from an Earth Science viewpoint. Earth Science Reviews 36, 59-82.

Scheidig, A. 1934. Der Loess und seine geotechnischen Eigenschaften. Theodor Steinkopff Dresden Leipzig. 233p.

Smalley, I.J., Krinsley, D.H., Vita-Finzi, C. 1973. Observations on the Kaiserstuhl loess. Geological Magazine 110, 29-36.

Smalley, I.J., O'Hara-Dhand, K., Wint, J., Machalett, B., Jary, Z., Jefferson, I. 2009. Rivers and loess: the significance of long river transportation in the complex event-sequence approach to loess deposit formation. Quaternary International 198, 7-18.

Smalley, I.J., Markovic, S.B., Svircev, Z. 2011. Loess is [almost totally formed by] the accumulation of dust. Quaternary International 240, 4-11.

Smalley, I.J., Blake-Smalley, R., O'Hara-Dhand, K., Jary, Z., Svircev, Z., this volume. Sand martins favour loess: how the properties of loess ground facilitate the nesting of Sand Martins/ Bank Swallows/ Uferschwalben (*Riparia riparia* Linnaeus 1758). Quaternary International.

Smitha, B., Thakar, J., Watve, M. 1999. Do bee-eaters have a theory of mind? Current Science 76, 574-577.

Stuut, J-B., Smalley, I.J., O'Hara-Dhand, K. 2009. Aeolian dust in Europe: African sources and European deposits. Quaternary International 198, 234-245.

White, F.N., Bartholemew, G.A., Kinney, J.L. 1978. Physiological and ecological correlates of tunnel nesting in the European Bee-Eater *Merops apiaster*. Physiological Zoology 51, 140-154.

Yuan H-W, Wang M-K, Chang W-L, Wang L-P, Chen Y-M, Chiou C-R. 2006. Soil composition affects the nesting behaviour of blue tailed bee-eaters (*Merops phillipinus*) on Kinmen Island. Ecological Research 21, 510-512.

Figure captions

1. European Bee-eater (*Merops apiaster* L.1758); "one of the largest and most aerial of bee-eaters, a robust bird with long pointed wings and short, acutely pointed tail streamers" (Fry 1984, p.147).

2. The Heneberg compromise: conflicting requirements of tunnel stability and ease of excavation. There is a delineated compromise zone (in terms of ground particle size) where ground has the optimum properties. CN is co-ordination number [relating to soil particle packing]. BE bee-eater, SM sand martin, KF kingfisher, e: voids ratio.

3. Distribution of European bee-eater nesting zones and the distribution of loess in Europe. There is a large concentration of bee-eater nests to the north of the Black Sea where large rivers deliver loess material, and to the west of the Black Sea, in the Danube basin. These are approximate distributions based on Scheidig (1934) for loess and Fry (1984) and Hagemeijer and Blair (1997) for bee-eaters.

4. Five particle types in soil; the granulometry of ground. Approximate plasticity indices are indicated. Bond/weight ratio [BWR] is plotted against particle size. The favoured region is around zone D, the silty ground. (after Jefferson and Smalley 1997).

5. Basic nature of (a) long range bonds and (b) short range bonds. The short range bond can be augmented by cementation, but its essential short range nature remains. The long range bond system (with charged particles) retains strength on deformation; the short range bond system(with uncharged primary mineral particles) does not.

6. Bee-eater nest tunnel openings in the Kaiserstuhl loess. The nest distribution is complex due to property variations in the loess. The birds appear to choose to nest on top of the cemented, harder layers. A solid floor is preferred to a strong roof.

7. Bird sizes: bee-eater, sand martin and kingfisher, respective lengths 25cm, 10cm, 10cm. Therefore, two mode tunnel diameters are produced. The bee-eater is a much larger, more robust bird and builds the largest tunnels.

8. Packing density (PD) and voids ratio(e) in ideal granular materials. Relationship e = (1 – PD)/PD is plotted, and region of nest building by primary nesters is indicated. CN is co-ordination number; 600 and 204 are designations for simple packings (see Rogers et al 1994).

9. Meigs (1953) maps of aridity in Africa and Europe, with approximate distribution of bee-eater nest sites.

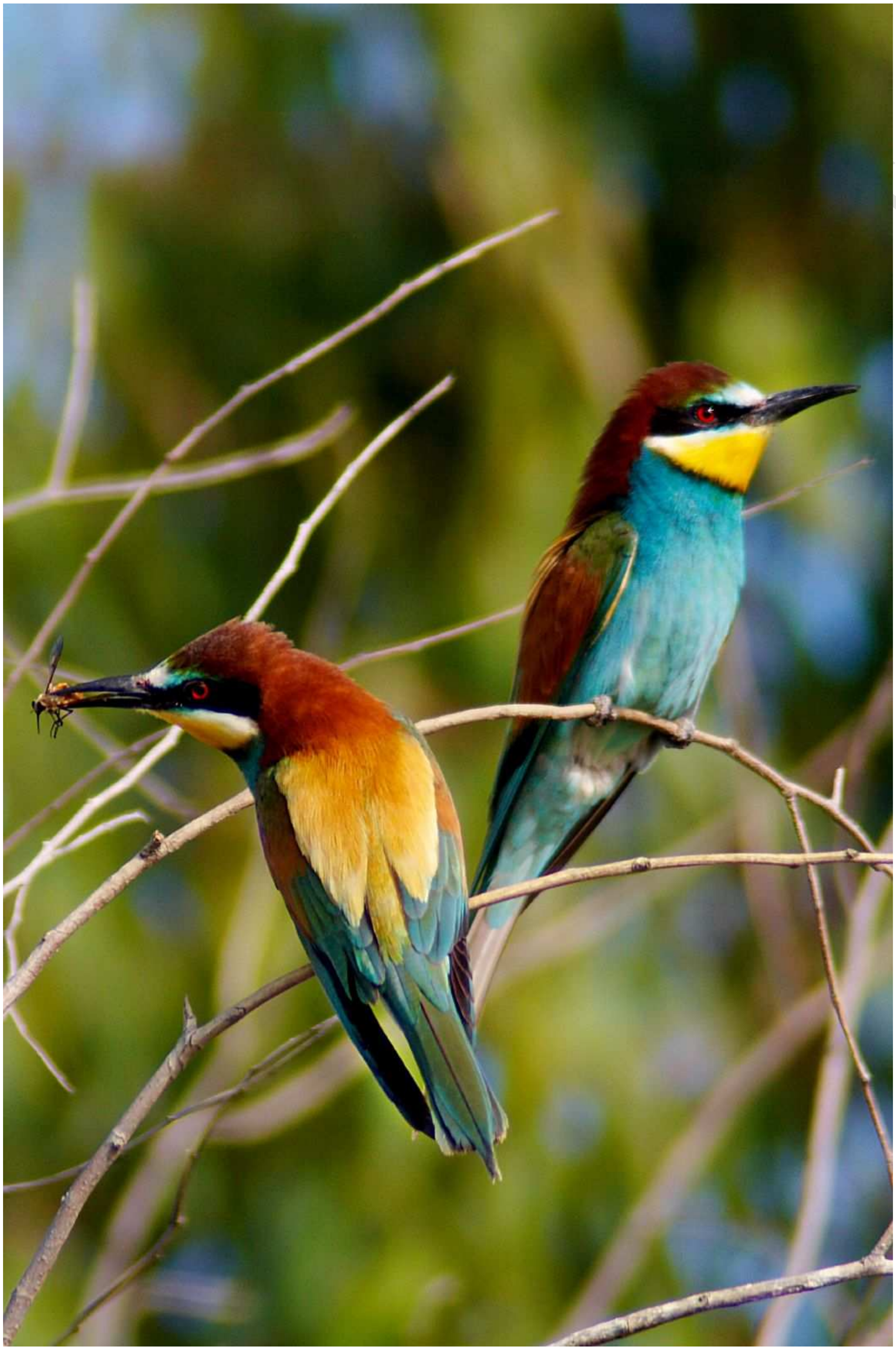


Figure 1

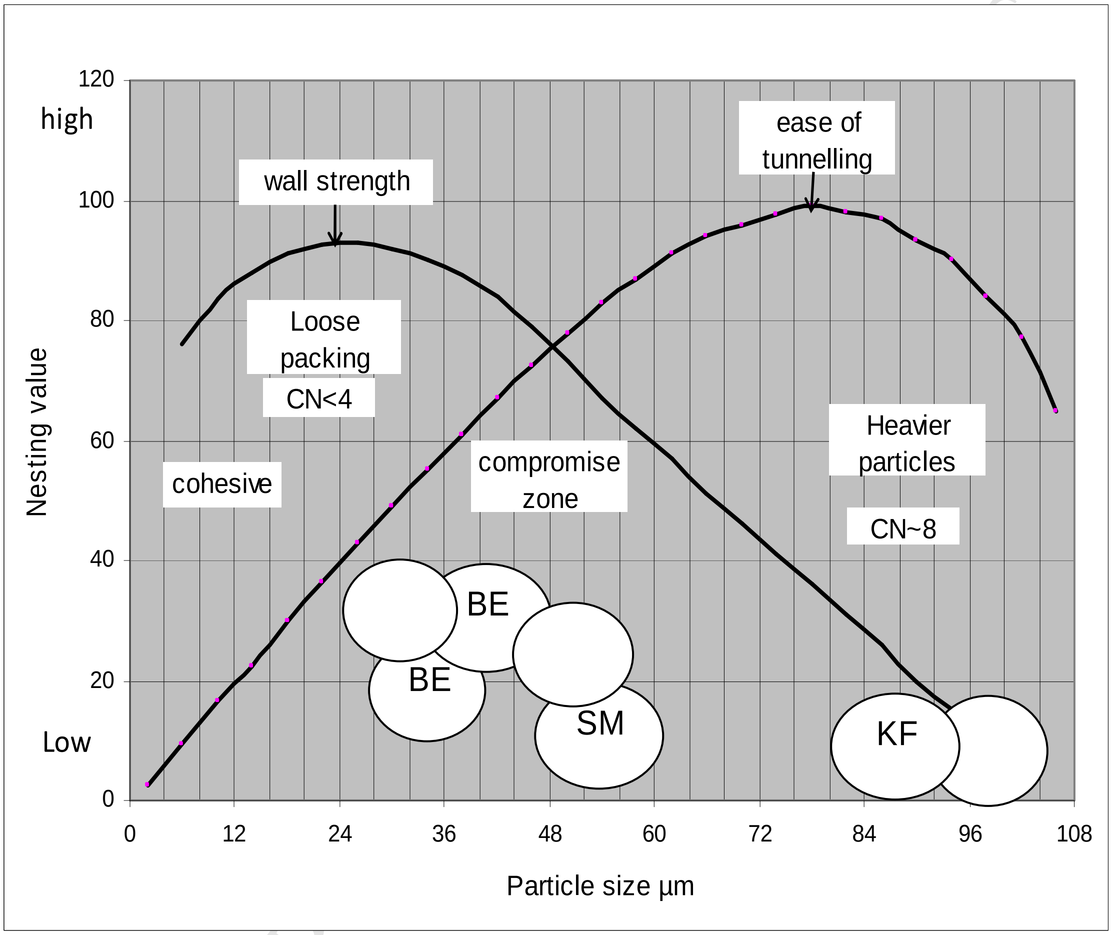

120
high
100
80
60
40
20
Low
0
Nesting value
wall strength
ease of
tunnelling
Loose
packing
CN<4
cohesive
compromise
zone
Heavier
particles
CN~8
BE
BE
SM
KF
0
12
24
36
48
60
72
84
96
108
Particle size µm

Figure 2

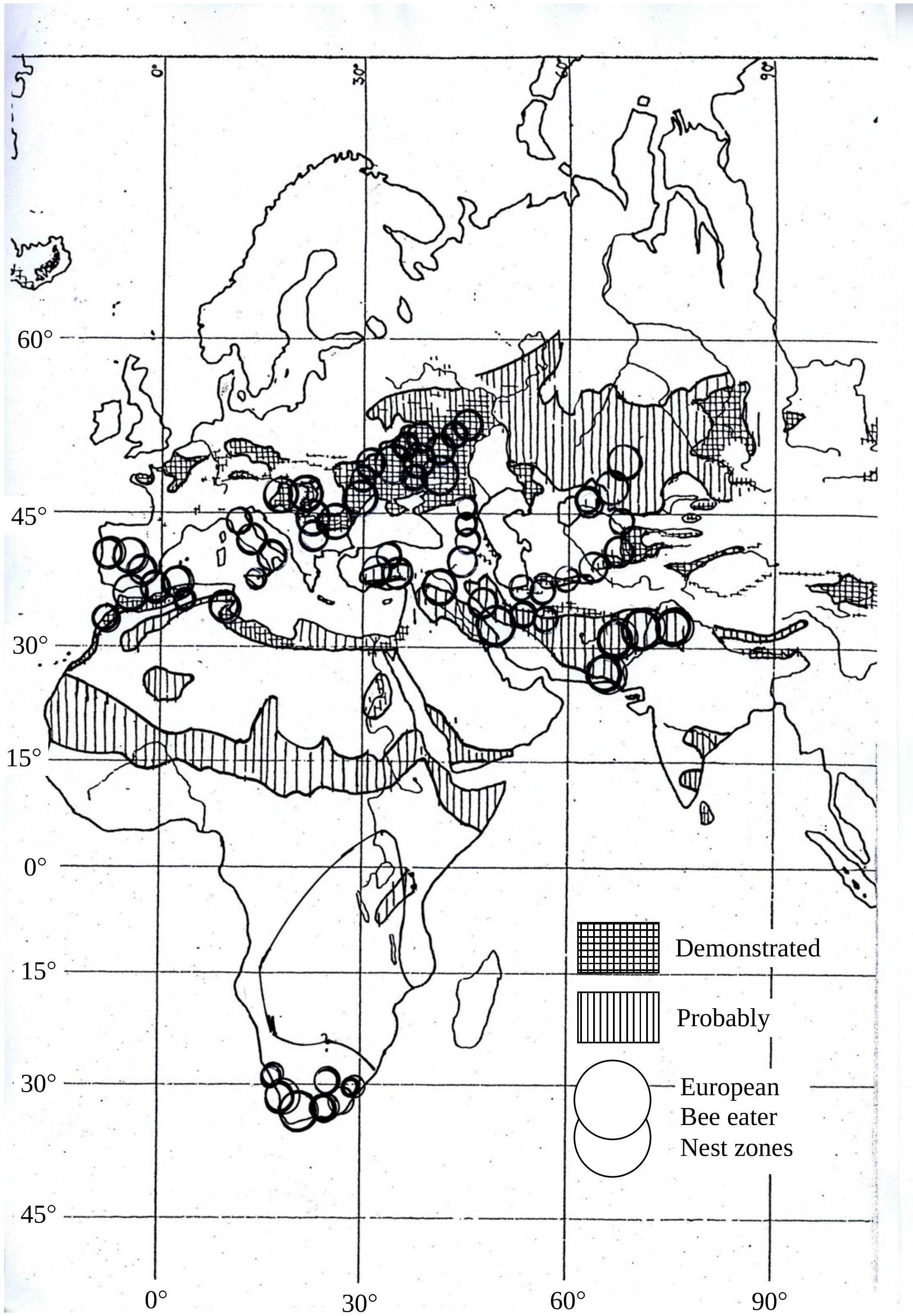

60°
45°
30°
15°
0°
15°
30°
45°
0°
30°
60°
90°
Demonstrated
Probably
European
Bee eater
Nest zones

Figure 3

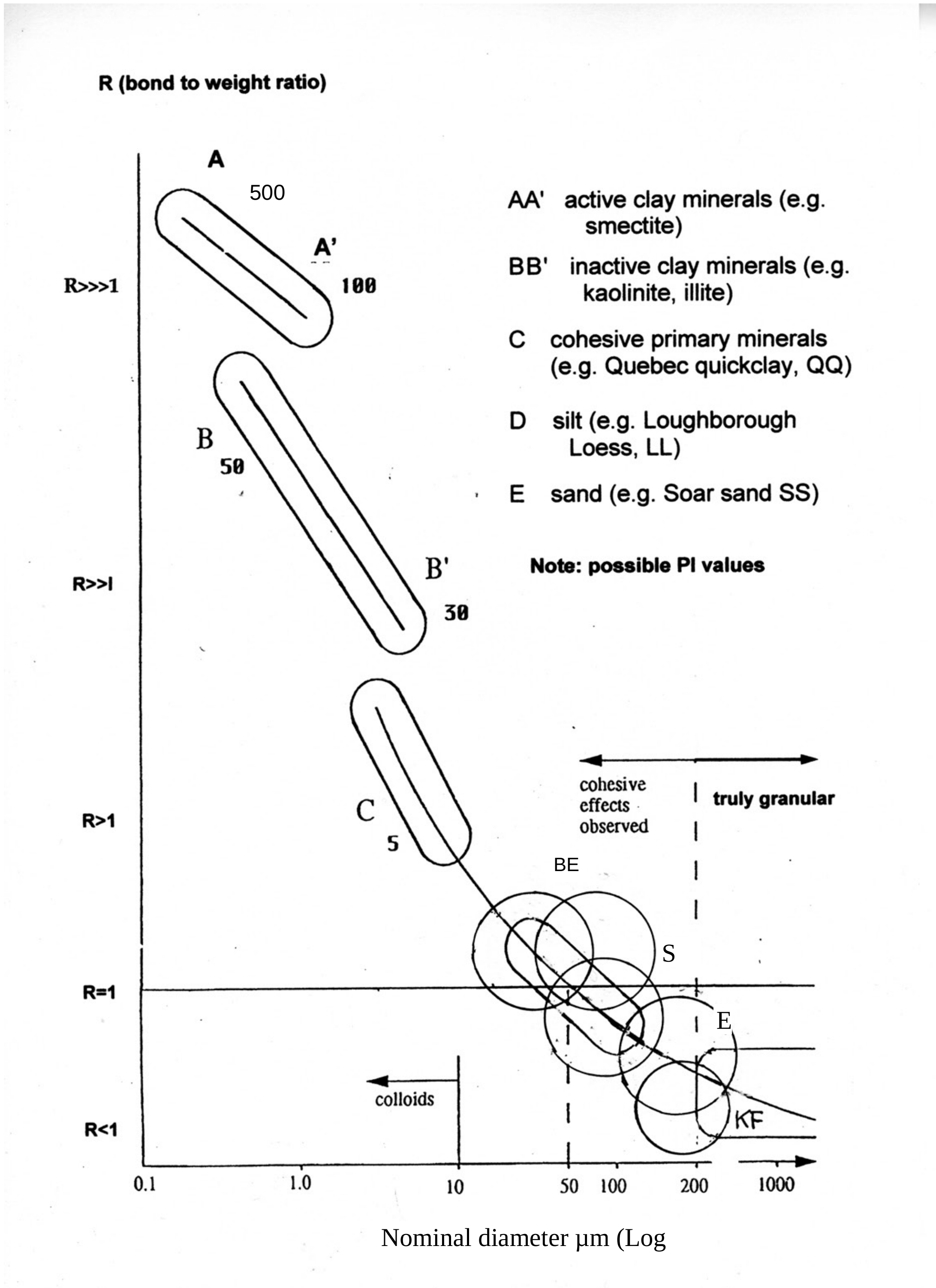

R (bond to weight ratio)
A
500
A'
100
R>>>1
B
50
B'
30
R>>I
C
5
R>1
R=1
R<1
BE
S
E
KF
colloids
cohesive
effects
observed
truly granular
AA' active clay minerals (e.g. smectite)
BB' inactive clay minerals (e.g. kaolinite, illite)
C cohesive primary minerals (e.g. Quebec quickclay, QQ)
D silt (e.g. Loughborough Loess, LL)
E sand (e.g. Soar sand SS)
Note: possible PI values
0.1
1.0
10
50
100
200
1000
Nominal diameter µm (Log

Figure 4

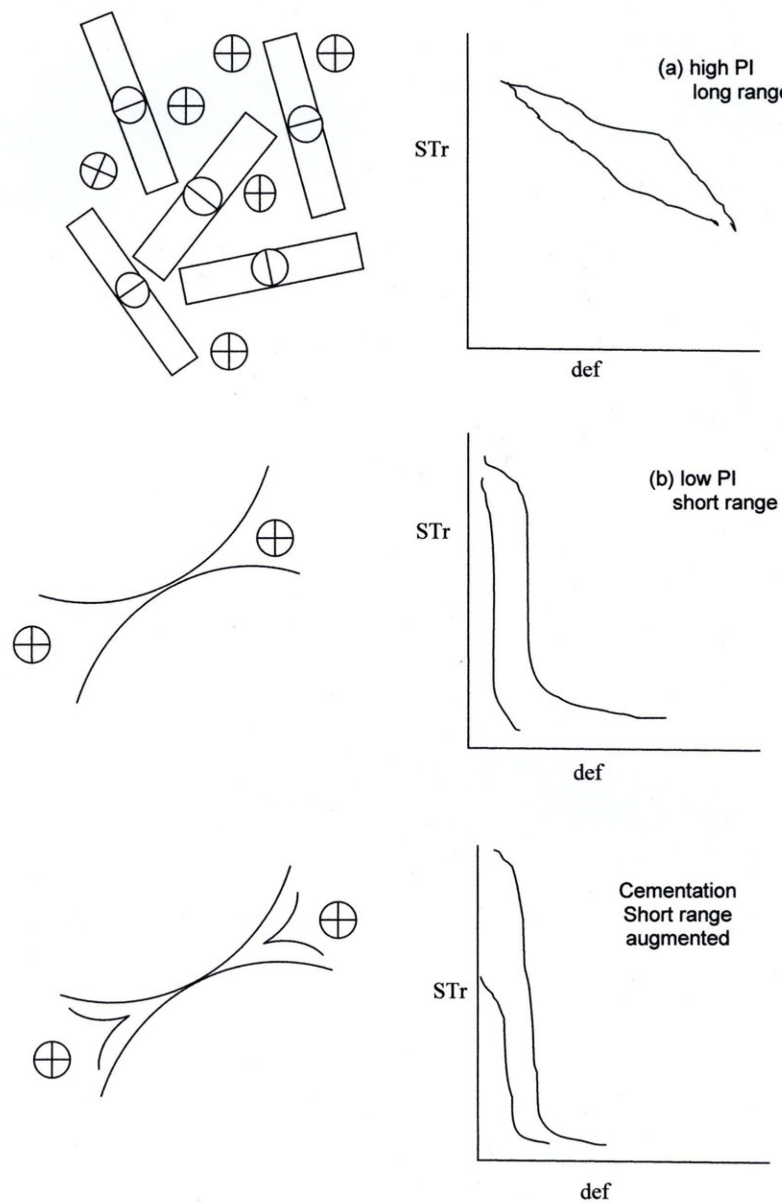
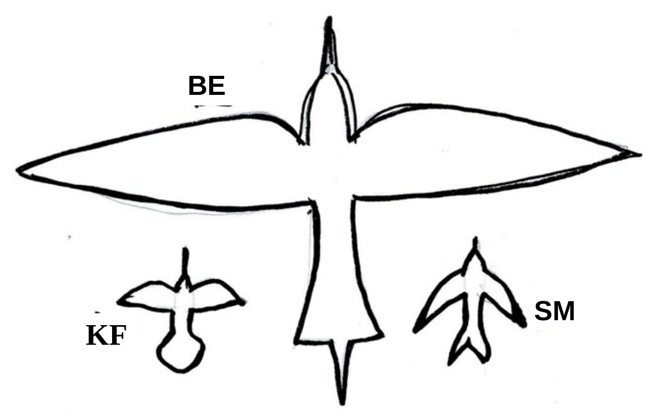
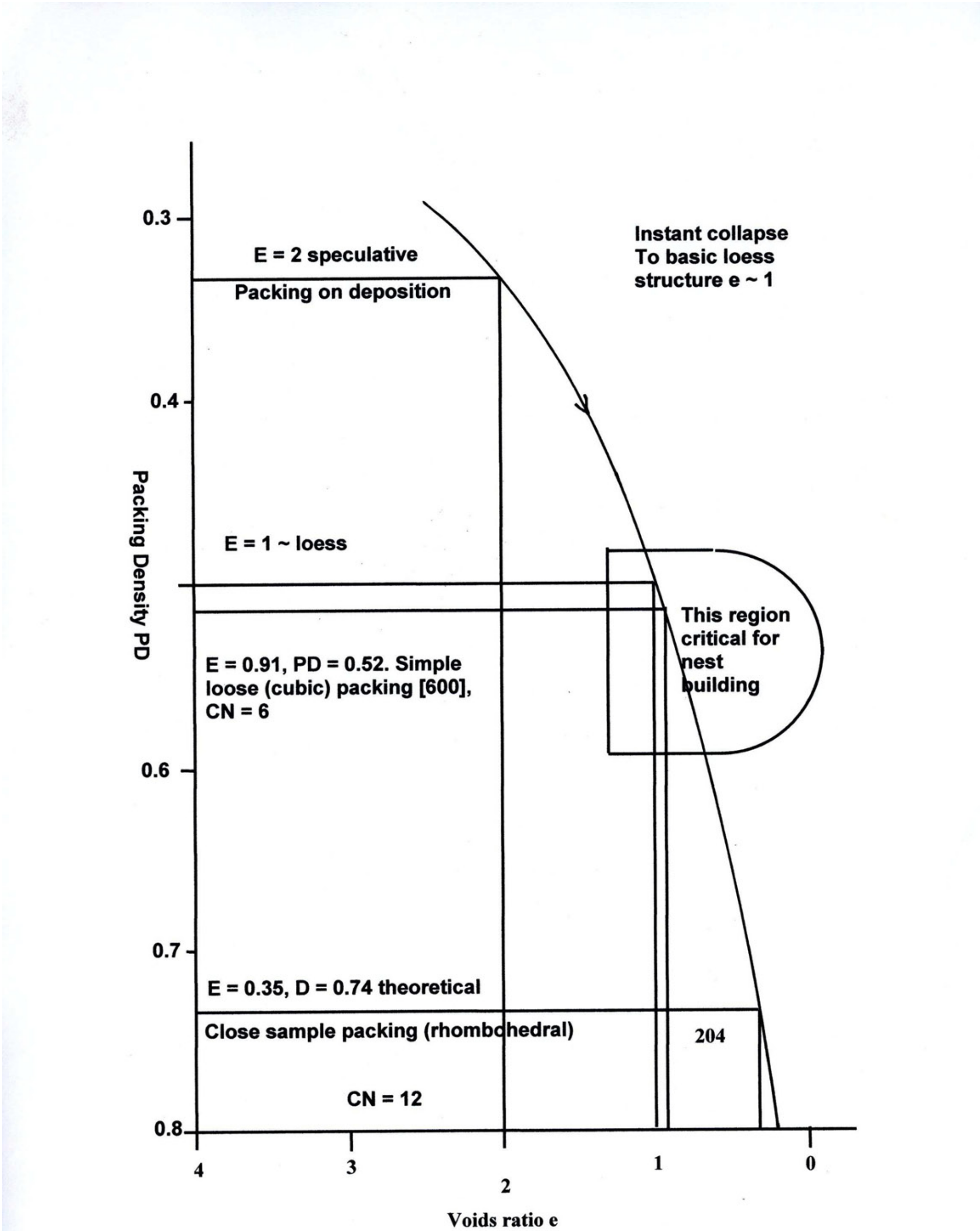

(a) high PI
long range
STr
def
(b) low PI
short range
STr
def
Cementation
Short range
augmented
STr
def

Figure 6



Comparative sizes of primary nesters.
Bee eater body length about 24 cm, Kingfisher and Sand Martins about 10 cm body length.

Figure 7



0.3
0.4
0.6
0.7
0.8
Packing Density PD
E = 2 speculative
Packing on deposition
Instant collapse
To basic loess
structure e ~ 1
E = 1 ~ loess
This region
critical for
nest
building
E = 0.91, PD = 0.52. Simple
loose (cubic) packing [600],
CN = 6
E = 0.35, D = 0.74 theoretical
Close sample packing (rhombohedral)
204
CN = 12
4
3
2
1
0
Voids ratio e

Figure 8

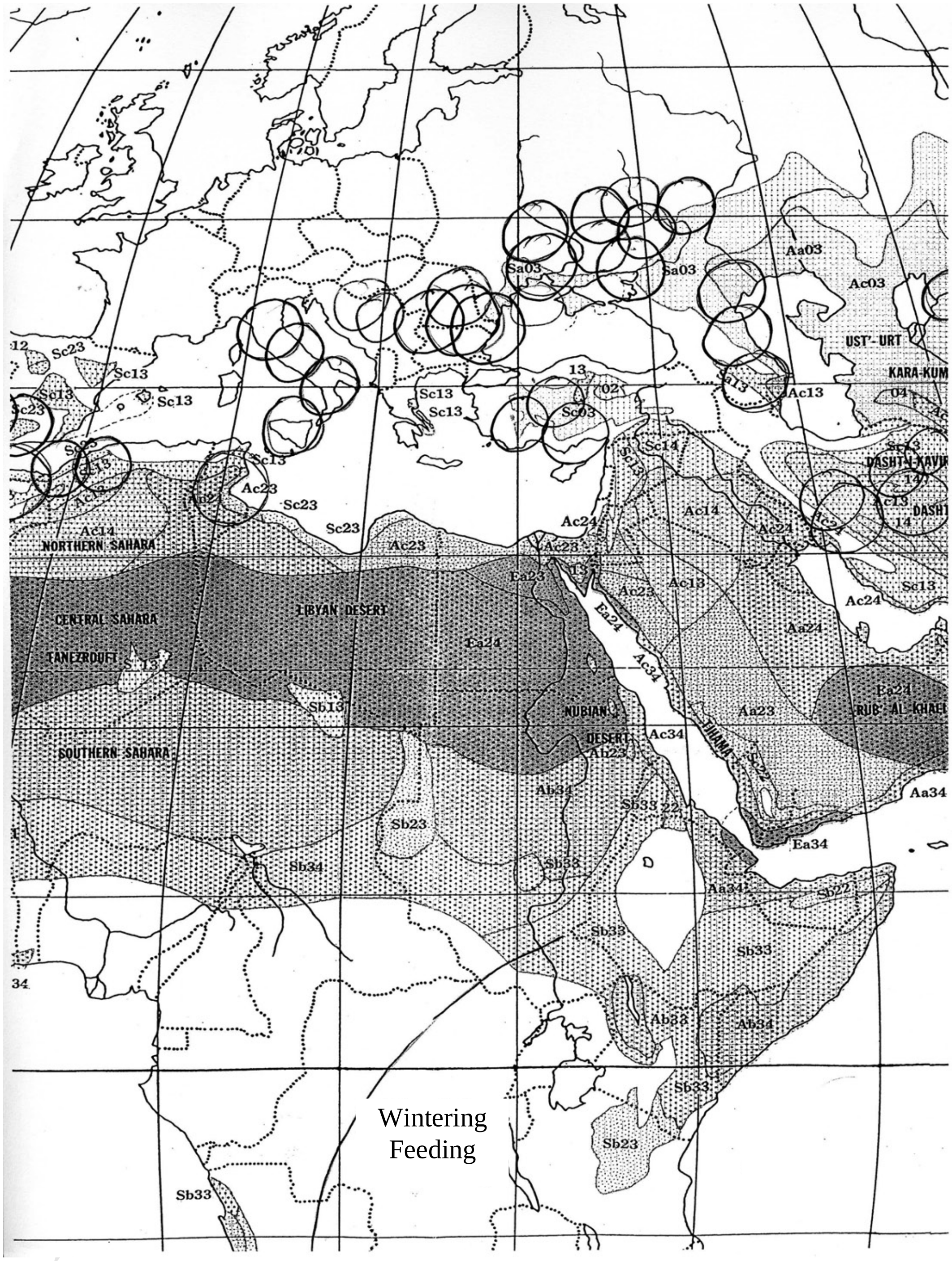

Sa03
Sa03
Aa03
Ac03
UST'-URT
KARA-KUM
Sc23
Sc13
Sc13
Sc13
Sc13
Sc03
Ac13
Sc14
DASHT-I-KAVIR
Sc13
Ac23
Sc23
Sc23
Ac14
NORTHERN SAHARA
Ac23
Ac24
Ac23
Ea23
Ac23
Ac13
Ac24
Ac24
Sc13
CENTRAL SAHARA
LIBYAN DESERT
TANEZROUFT
Ea24
Ea24
Ac34
Aa24
Ea24
NUBIAN
DESERT
Ac34
Aa23
TIHAMA
Ab23
Sb13
SOUTHERN SAHARA
Ab34
Sb33
Sb23
Aa34
Ea34
Sb34
Sb33
Aa34
Sb22
Sb33
Sb33
Ab33
Ab34
Sb33
Sb23
Sb33
Wintering
Feeding

Figure 9