Supplemental Material 1: Bedrock Unit Descriptions

Pre-Extensional Rock Units: The Death Valley region has a well-known stratigraphy (Figure 2), but the Ibex Hills contain complex lateral facies changes in many of the units. Thus, lithostratigraphic units vary across the mapped area requiring some description of the stratigraphic units used in our mapping.

The pre-Neogene bedrock includes Mesoproterozoic basement and overlying Mesoproterozoic, Neoproterozoic, and Paleozoic sedimentary rocks with several unconformities bounding sequences within the stratigraphic assemblage (Figure 2). The most extensive and complex stratigraphic assemblage in the study area is the Pahrump Group which forms the base of the sedimentary cover across much of the region. The Pahrump Group is comprised of four formal lithostratigraphic units (Figure 2): the Crystal Springs Formation, Horse Thief Springs Formation, Becks Spring Formation, and Kingston Peak Formation (Wright et al., 1974; Mahon and Link, 2013). Overlying the Pahrump group are the Neoproterozoic Noonday, Johnnie, and Stirling Formations followed by Ediacran-Cambrian strata of the Wood Canyon Formation and overlying Paleozoic rocks (Figure 2) (Wright et al., 1974). In general, these formal units are sufficiently thick that they are insufficient as map units for the scale of this study. Thus, the units were subdivided into informal members described here.

The Crystal Springs Formation is the oldest sedimentary unit in the mapped area and is made up of carbonate and siliciclastic rocks intruded by mafic sills ranging up to 450-m in thickness (Wright et al., 1974). The sills are medium to coarse grained diabase and gabbro which have been dated to 1.084 Ga, and these intrusive contacts have created talc deposits throughout the area (Heaman and Grotzinger, 1992). The Crystal Springs Formation has traditionally been divided into three informal members, the lower, middle, and upper units, in addition to the Mesoproterozoic intrusions (e.g. Wright et al., 1974). Diabase intrusions are abundant in the lower and middle Crystal Springs members but their presence in the upper member has been controversial. Calzia et al., (2008) cited intrusions within the upper Crystal Springs member in the Kingston Range, implying the upper member is a part of the same depositional sequence as the lower and middle members. In contrast, Mahon et al., (2014) recently redefined what had been mapped as the upper member of the Crystal Springs Formation as a separate, distinctly younger rock unit, the Horse Thief Springs Formation which spans ~150 m. This redefinition was based on detrital zircon studies which yielded Neoproterozoic zircons in the unit, indicating a maximum depositional age of 770 Ma, much younger than the ~1.1Ga dates of the mafic intrusions within the lower and middle members of the Crystal Springs Formation. We found no indications of intrusion into the upper Crystal Springs/Horse Thief Springs Formation, however, and use the terminology of Mahon et al. (2014).

In this study we mapped a Lowerand Upper Member of the Crystal Springs, with further subdivisions made locally where possible (Plate 1). The lower member of the Crystal Springs begins with a 1-10m thick basal conglomerate marking the nonconformity with the underlying basement rock (Figure 2; Plate 1). Above the conglomerate lies the bulk of the lower Crystal Springs which is dominated by white to gray, cross-bedded and planar bedded quartzite (Figure 2). These quartzitic rocks of the lower Crystal Springs can commonly be mapped as a subunit (pCcsl1)that grades upward into a reddish brown to purple sandstone that fines upward into maroon and green shales, resulting in a color change that can allow for the distinction of a separate unit (pCcsl2). The units of the Crystal Springs Upper member are more difficult to separate because of large volumes of plutonic rock that permeate this part of the section. The sedimentary units in the upper member consist of two layers of maroon to green-black shales which sandwich a unit of orange to tan dolomite (Plate 1). The upper unit of maroon shales marks the top of the Crystal Springs Upper Member; however, this space is also occupied by the diabase intrusive in some places.

The overlying Horse Thief Spring Formation is marked by a thin, 5-10 meter, layer of chert-pebble conglomerate which contains clasts of the Crystal Springs Formation. The unit is described in detail by Mahon et al. (2013).

The Becks Springs Formation reaches ~400-m thick in the southern portion of the mapped area and is dominated by grey-blue dolomite interpreted to have been deposited in a shallow platform environment (Wright et al., 1974; Mahon et al., 2013). However, in the central to northern Ibex Hills the Beck Spring Dolomite thins to less than 100 meters and eventually is cut out of the section completely along overlying unconformities (Plate 1). The basal Beck Springs Formation is a gradational contact with the underlying Horse Thief Springs. For mapping purposes (Plate 1) the contact between the Horse Thief Springs and Beck Springs Formation is marked by the first presence of the blue-grey dolomite of the Beck Springs Formation.

The Kingston Peak Formation overlies the Beck Springs Formation and contains a diverse range of rock types including siltstones, sandstones, and conglomerates (Wright et al., 1974; Corsetti and Kaufman, 2003). In this work the terminology of Macdonald et al., (2013) is used to map the members of the Kingston Peak Formation. Macdonald et al. (2013) mapped four members in the southern Death Valley region, KP1-4, and all four were recognized in the mapped area (Plate 1). KP1 consists of thinly bedded shales and sandstones (Macdonald et al., 2013) and reaches ~250 m in thickness at the southern end of the mapped area (Plate 1). The contact with the underlying Beck Springs Formation was mapped at the base of the first thick sequence of thinly bedded shales (Plate 1). KP2 is unconformably above the lower KP1 member and consists of poorly bedded diamictites, predominately with a dark colored mudstone matrix in the mapped area, which contains clasts of the Crystal Springs Formation and basement rock (Macdonald et al., 2013). The KP2 member reaches ~375 m in thickness in the southern Saratoga Hills (Plate 1). The KP2 diamictites are overlain by a mixed clastic unit, KP3, which contains interbedded sandstones and shales, commonly as graded beds, along with layers of diamictite (Plate 1). KP3 is only exposed as a partial section in the Saratoga Hills within the mapped area (Plate 1). Rocks correlated to KP4 are seen as a thin layer beneath Noonday formation in the northern Ibex Hills but rest unconformably on Crystal Springs. Elsewhere, KP4 is only seen in the northern Saddlepeak Hills beneath Noonday dolomite and consists of conglomerates, sandstone-shale couplets showing graded beds and minor diamictite, consistent with descriptions of Macdonald et al. (2013) for KP4.

The ~200-m thick Noonday Formation overlies the Kingston Peak Formation. Recent work by Petterson et al., (2011) divided the Noonday Dolomite into three members, based in part on exposures of what Wright and Troxel, (1984) had originally defined as the Ibex Formation with a type section in the southern Ibex Hills. The Petterson et al. (2011) stratigraphy includes the Sentinel Peak Member, Radcliff Member, and the Mahogany Flats Member, divisions that are retained in this study (Plate 1). Noonday stratigraphy varies dramatically across the mapped area. We recognized a thick section carrying all of the subunits to the north, in the Ibex Hills, yet only the lower, Sentinel Peak member and a thin layer of Radcliff member (aka Noonday 2 of Wright and Troxel, 1984) is observed when the units re-emerge from below Tertiary cover in the northern Saddlepeak Hills. This attenuated section in the northern Saddlepeak Hills is presumably a Precambrian structural high, however, because the thick basinal assemblage (Ratcliff and Mahogany flat members) reappear to the south in the central Saddlepeak Hills (e.g. Mahon et al., 2013).

The Noonday Formation is overlain by two thick Neoproterozoic units: Johnnie and Stirling Formations. These units have a well known regional stratigraphy (Stewart, 1972; Wright et al., 1974; Summa, 1993; Corsetti and Kaufman, 2005) and crop out extensively in the eastern and southeastern Ibex Hills (Figure 4). In this study the Johnnie Formation was divided into four informal members: 1) a lower mixed clastic-carbonate member (pCjl) with a sharp contact between uppermost sandstone of the unit and overlying shales, 2) a lower-middle shale-rich member (pCjm1) with a top recognized as the first 1m dolomite layer, 3) an upper-middle carbonate-dominant member (pCjm2) with a top marked by the base of the distinctive Oolite marker bed well known in this unit; and 4) a mixed carbonate-shale member with complex stratigraphy (pCju). In some areas we did not distinguish pCjm1 and pCjm2 because of structural complexity. Much of the Johnnie Formation in the northern Ibex Hills is extensively faulted and attenuated and only the middle and upper members were exposed in that portion of the mapped area (Plate 1). Similarly, the Stirling Formation was divided into three members following Wright and Troxel (1984): a lower quartzite member, a middle mixed clastic unit with extensive purple, green and brown shales, and an upper quartzite member.

The youngest pre-Cenozoic units in the mapped area are the Ediacran-Early Cambrian aged Wood Canyon and Zabriskie Formations (Corsetti and Kaufman, 2003) with exposures limited to the northeast edge of the Ibex Hills (Plate 1). Following local mapping conventions (e.g. Wright and Troxel, 1984), the Wood Canyon Formation was divided into a lower member, middle member, and upper member (Corsetti and Kaufman, 2003): a lower mixed clastic (predominantly shale)-carbonate member; a middle coarse clastic member; and an upper mixed clastic-carbonate member. The Zabriski Quartzite overlies the Wood Canyon and is a distinctive unit comprised primarily of pink quartzite with abundant scholithos trace fossils near the base.

Neogene Rock Units: Pre-extensional to syn-extensional Miocene deposits are exposed between the Ibex and Saddlepeak hills in two distinct areas separated by a large area of Quaternary deposits (Plate 1). The most extensive deposits are in the east, in the Ibex Pass area between the northern Saddle Peak Hills and the eastern flank of the Ibex Hills (Figure 4). A smaller, more poorly exposed assemblage is exposed in the southern Ibex Hills (Figure 4). We describe these rocks in detail because they relate closely to the Cenozoic structure.

The angular unconformity at the base of the Neogene section is exposed over significant areas in the northern Saddlepeak Hills and northern Ibex Hills, but is limited to a few small outcrops in the southern Ibex Hills area (Figure 4). The rocks immediately above the unconformity are different in each of these areas and the sub-unconformity geology is also distinctly different. In both the southern Ibex Hills and northern Saddlepeak Hills, the unconformity is directly overlain by a basal conglomerate that ranges in thickness from 0 to ~30m. In both areas the conglomerates vary from matrix supported to clast supported with variably rounded clasts. Clasts are predominant quartzite and at both localities appear to be derived from directly underlying rocks which range from Crystal Spring Formation to Johnnie Formation in the southern Ibex Hills and Johnnie to Stirling Formations in the northern Saddlepeak Hills. We interpret these rocks as alluvial fan deposits deposited along paleotopography on the unconformity.

Above these scattered gravels is a composite volcanic section. In the Saddle Peak Hills (Figure 4), the basal volcanic unit is an ~100-m thick, altered andesitic to dacitic unit that is probably comprised of several flows. Above the dacite is ~250-300-m of volcanogenic strata dominated by pyroclastic deposits that include volcanic breccias, matrix supported conglomerates/breccias, and ash beds as well as intermittent flows (Canalda, 2009). Lithologically this sequence ranges in composition from trachyandesite to rhyolite and is interpreted as a sequence of pyroclastic flows, lahars and lava flows (Canalda, 2009). Interbedded near the top of the pyroclastic sequence is a conspicuous white to buff colored, 1-10m thick tuff (Figure 4). Topping (1993) correlated this unit with the ~9-10 Ma Rhodes Tuff (Topping, 1993), but Luckow et al., (2005) and Canalda (2009) correlated this tuff with a similar tuff in the 12-14 Ma Wingate Wash volcanics of the Panamint and Owlshead Mountains. We amplify the Wingate Wash correlation based on three observations (Canalda, 2009): 1) the physical appearance and thickness of the tuff; 2) the physical stratigraphy associated with the tuff where the tuff is a horizon within a volcanic section dominated by pyroclastic rocks; and 3) a similarity in the geochemistry of the volcanic assemblage with a distinctive alkaline trend through a broad compositional range.

In the southern Ibex Hills a similar volcanic section overlies the basal gravels (Figure 4) but unit thicknesses are distinctly different. It is unclear if these distinctions are due to structural complications, depositional differences, or both (Figure 4), because exposures of the lower volcanic section are limited to a few outcrops less than 20-30m across. Nonetheless, within the section a conspicuous 1-10m white tuff lies within the volcanic section and is indistinguishable from the tuff seen in the Ibex Pass area (Figure 4). Assuming these tuffs are the same unit, the apparent thickness of the volcanic units below the tuff in the southern Ibex Hills is far less than Ibex Pass, but the overlying volcanic succession is much thicker. The increase in thickness of the volcanics above the tuff in the southern Ibex Hills may be a primary depositional feature because this unit is a massive, dacitic unit that probably represents a lava dome or thick flow succession. Nonetheless, more work is needed on these units to clarify correlations because the upper volcanics are undated and could be significantly younger (Figure 4).

The lower volcanic assemblage at Ibex Pass was clearly tilted and partially eroded prior to deposition of an overlying upper Neogene assemblage forming a prominent angular unconformity (Figure 4 and Plate 1). This observation is consistent with the regional observations of Fridrich and Thompson, (2011) for a significant Neogene transition at this stratigraphic level; their Hells Gate/Owlshead to Navadu sequence boundary. Above this angular unconformity the sequence is capped by a thick megabreccia sheet comprised primarily of granite clasts. Topping (1993 and 1995, in Holm et al., 1994) interpreted this granitic megabreccia as a landslide deposit derived from a Kingston Peak granite source and correlated it with similar deposits to the north, in the Amargosa Chaos. Lauren Wright (personal communication to Pavlis, 1995) inferred that the rocks had a local source east of Ibex Pass, but we found no rocks consistent with that interpretation in our reconnaissance.

In the Ibex Pass area the granite megabreccia is the base of a poorly exposed, upper Neogene section that is not well understood. It is poorly understood because the apparent section is distinctly different within three structural-stratigraphic domains (Figure 4). In addition, because none of the contacts are exposed it is unclear if domain boundaries are faults, facies variations, or both. In the eastern part of the mapped area (Domain 1, Figure 4), for example, the basal granite megabreccia is clearly stratigraphically overlain by a poorly exposed gravel. To the east of this gravel, however, a second granite megabreccias unit is exposed, yet it is unclear if the contact is stratigraphic; i.e. this contact could be a fault, repeating the lower granite megabreccia. Our mapping in this area is too incomplete to assess this contact relationship, but shifts in volcanic units to the south seen in satellite imagery suggest the latter hypothesis is likely. Just to the north in Domain 3 (Figure 4), the same basal granite megabreccia overlain by a gravel is observed, but here two distinct megabreccias containing sedimentary clasts occur within the gravels above the granite megabreccia (Figure 4): a lower Crystal Springs derived breccia and an upper Beck Springs derived breccia. The top of these megabreccias is poorly exposed with gravel rubble covering an interval ~500 m across until gravels with depositional dips are exposed and continue to the north where they lie in angular unconformity on the Precambrian strata of the Ibex Hills (Figure 4). This contact relationship virtually requires that there is a fault beneath the upper Neogene-Quaternary cover in this domain, somewhere between the megabreccias exposures and the Ibex Hills themselves, because the entire Ibex Pass volcanic section is missing beneath the unconformity in the northern Ibex Hills (Plate 1). Instead, upper Neogene gravels lie directly above the unconformity with steeply dipping Stirling, Johnnie, and Crystal Springs formations beneath the unconformity. These gravels are poorly exposed but contain a thin, stratabound monolithologic megabreccia/mega-clast-conglomerate comprised of Kingston Range granite type clasts (Figure 4 and Plate 1). Finally, the gravels themselves are overlain by a second megabreccia sheet(s) that lies against the boundary fault of the Ibex Hills (Tmb2, Figure 4). This megabreccia sheet contains Beck Springs Dolomite clasts as well as Noonday clasts. Similar megabreccias of Beck Spring Dolomite are exposed in the northern Ibex Hills and central Ibex Hills (Plate 1), but these megabreccias do not clearly lie on sediments of the Ibex Pass basin. Finally, in Domain 2 the section is again distinct and requires a fault or highly unusual stratigraphic relationship along a NNW trending dry wash (Figure 4 and Plate 1). Specifically, although the upper part of the section is indistinguishable from the upper gravels in Domain 1 (Tg2, Figure 4) the rocks below the gravel are distinct. The base of this partial section is not exposed but fine-grained clastic rocks comprised of interbedded sandstones, shales and siltstone comprise the lower part of the section and are, in turn, overlain by a Crystal Springs and Beck Springs derived megabreccia similar to breccias just to the east in Domain 3 (Figure 4). This stratigraphic change is too abrupt for a normal facies change indicating either a fault between domains 2 and 3 or an unusual depositional manifestation of the rock avalanche that formed the megabreccia; e.g. damming of streams by the landslide to form the fine-grained section. We suggest a fault is most likely given that there is other evidence for a fault to the north where the unconformity beneath the gravels is shifted by down to the east slip (Figure 4).

Citations

Calzia, J.P., Ludington, S., Miller, C.F., and Ramo, O.T., 2008, Miocene magmatism and coeval crustal extension in the Colorado River and Death Valley extensional terrains (IGCP-510) (R. G. Raynolds, Ed.): GSA Field Guide, v. 10, p. 111–138, doi:http://0-dx.doi.org.lib.utep.edu/10.1130/2008.fld010(07).

Canalda, S.M., 2009, Magnitude of right-lateral offset on the southern Death Valley fault zone from Miocene volcanic assemblages [M.S.]: The University of Texas at El Paso, 155 p., http://0-search.proquest.com.lib.utep.edu/pqdtglobal/docview/305068006/abstract/FFFE661790334E34PQ/2?accountid=7121 (accessed February 2015).

Corsetti, F.A., and Kaufman, A.J., 2003, Stratigraphic investigations of carbon isotope anomalies and Neoproterozoic ice ages in Death Valley, California: Geological Society of America Bulletin, v. 115, p. 916–932, doi:10.1130/B25066.1.

Corsetti, F.A., and Kaufman, A.J., 2005, The relationship between the Neoproterozoic Noonday Dolomite and the Ibex Formation; new observations and their bearing on “snowball Earth” (J. P. Calzia, Ed.): Earth-Science Reviews, v. 73, p. 63–78, doi:http://0-dx.doi.org.lib.utep.edu/10.1016/j.earscirev.2005.07.002.

Fridrich, C.J., and Thompson, R.A., 2011, Cenozoic tectonic reorganizations of the Death Valley region, southeast California and southwest Nevada: U. S. Geological Survey Professional Paper, p. 36, 1 sheet.

Heaman, L.M., and Grotzinger, J.P., 1992, 1.08 Ga diabase sills in the Pahrump Group, California: Implications for development of the Cordilleran miogeocline: Geology, v. 20, p. 637–640, doi:10.1130/0091-7613(1992)020&lt;0637:GDSITP&gt;2.3.CO;2.

Holm, D.K., Pavlis, T.L., and Topping, D.J., 1994, Black Mountains crustal section, Death Valley region, California (S. F. McGill, Ed.): Geological Society of America, Cordilleran Section, Annual Meeting, Guidebook., v. 27, p. 31–54.

Luckow, H.G., Pavlis, T.L., Serpa, L.F., Guest, B., Wagner, D.L., Snee, L., Hensley, T.M., and Korjenkov, A., 2005, Late Cenozoic sedimentation and volcanism during transtensional deformation in Wingate Wash and the Owlshead Mountains, Death Valley: Earth-Science Reviews, v. 73, p. 177–219, doi:10.1016/j.earscirev.2005.07.013.

Macdonald, Prave, A.R., Petterson, R., Smith, E.F., Pruss, S.B., Oates, K., Waechter, F., Trotzuk, D., and Fallick, A.E., 2013, The Laurentian record of Neoproterozoic glaciation, tectonism, and eukaryotic evolution in Death Valley, California: Geological Society of America Bulletin, v. 125, p. 1203–1223.

Mahon, R.C., Dehler, C.M., Link, P.K., Karlstrom, K.E., and Gehrels, G.E., 2014, Geochronologic and stratigraphic constraints on the Mesoproterozoic and Neoproterozoic Pahrump Group, Death Valley, California: A record of the assembly, stability, and breakup of Rodinia: Geological Society of America Bulletin, p. B30956.1, doi:10.1130/B30956.1.

Mahon, R.C., and Link, P.K., 2013, EdMap geologic map of the Saddle Peak Hills 7.5’ quadrangle, Death Valley National Park, San Bernardino County, California: Abstracts with Programs - Geological Society of America, v. 45, p. 372.

Petterson, R., Prave, A.R., Wernicke, B.P., and Fallick, A.E., 2011, The Neoproterozoic Noonday Formation, Death Valley region, California: Geological Society of America Bulletin, p. B30281.1, doi:10.1130/B30281.1.

Stewart, J.H., 1972, Initial Deposits in the Cordilleran Geosyncline: Evidence of a Late Precambrian (<850 m.y.) Continental Separation: Geological Society of America Bulletin, v. 83, p. 1345–1360, doi:10.1130/0016-7606(1972)83[1345:IDITCG]2.0.CO;2.

Summa, C.L., 1993, Sedimentologic, stratigraphic, and tectonic controls of a mixed carbonate-siliciclastic succession : neoproterozoic Johnnie formation, southeast California [Thesis]: Massachusetts Institute of Technology, http://dspace.mit.edu/handle/1721.1/12447 (accessed July 2016).

Topping, D.J., 1993, Paleogeographic reconstruction of the Death Valley extended region: Evidence from Miocene large rock-avalanche deposits in the Amargosa Chaos Basin, California: Geological Society of America Bulletin, v. 105, p. 1190–1213, doi:10.1130/0016-7606(1993)105<1190:PROTDV>2.3.CO;2.

Wright, L., and Troxel, B., 1984, Geology of the northern half of the confidence hills 15-minute quadrangle, death valley region, eastern california; the area of the amargosa chaos: California Division of Mines and Geology.

Wright, L.A., Troxel, B.W., Williams, E.G., Roberts, M.T., and Diehl, P.E., 1974, Precambrian sedimentary environments of the Death Valley region, eastern California: Death Valley Publ. Co.; Shoshone; CA, http://0-search.proquest.com.lib.utep.edu/georef/docview/52351472/2DAD0567B15240FFPQ/2?accountid=7121 (accessed February 2015).