I. GLACIGENIC AND RELATED STRATA OF THE NEOPROTEROZOIC KINGSTON PEAK FORMATION IN THE PANAMINT RANGE, DEATH VALLEY REGION, CALIFORNIA

II. THE BASAL EDIACARAN NOONDAY FORMATION, EASTERN CALIFORNIA, AND IMPLICATIONS FOR LAURENTIAN EQUIVALENTS

III. RIFTING OF SOUTHWEST LAURENTIA DURING THE STURTIAN-MARINOAN INTERGLACIAL: THE ARGENTA OROGENY

Thesis by

Ryan Petterson

In Partial Fulfillment of the Requirements

For the Degree of

Doctor of Philosophy

California Institute of Technology
Pasadena, California
2009

ACKNOWLEDGEMENTS

I would like to thank my many field assistance over the years; J.D. Godchaux, Nathan and Nicole Downey, Elisabeth Nadin, Allison Randall (RIP), Natalia Deligne, and Auna Moser and Maggie Osbourne. I would also like to thank my Riverside friends, Damon DeYoung, Dave Mrofka, Karl Thomson and Camille Partin, whose company in the field and many discussions helped immensely. Charlie Verdel was invaluable in the years of work, from helping in the field to countless discussion on Neoproterozoic geology. I thank Brian Wernicke for introducing me to the Panamints and for his continued support over the years. This work could not have been completed without the selfless time and guidance of Anthony Prave, who showed me the many nooks and crannies of Death Valley and its geology, taught me stratigraphy and helped in the final preparations of my dissertation. I would also like to thank Lauren Edgar and my parents for constant support.

ABSTRACTS

I.

Glacigenic deposits in the Death Valley region occur within the Neoproterozoic Kingston Peak Formation. In the Panamint Range, immediately west of Death Valley, these strata are ≥1000 m thick and are continuously exposed for nearly 100 km along the strike of the range. Although these strata are variably metamorphosed and locally exhibit pronounced ductile strain, original sedimentary textures are well preserved throughout the range. Diamictic strata occur in two distinct intervals, a lower one comprising the Limekiln Spring and Surprise Members, and an upper one known as the Wildrose Sub-member of the South Park Member. Each of these intervals are succeeded by well defined cap carbonates, which, from oldest to youngest, are the Sourdough Member of the Kingston Peak and the Sentinel Peak Member of the overlying Noonday Formation. Between the two glacial successions, the Sourdough and sub-Wildrose South Park units comprise a ~300 m thick interglacial succession that includes platform carbonate deposition. Sparse lonestones and striated clasts, along with the impressive lateral continuity of diamictic units, support a glacial origin. Chemostratigraphic profiles of $\delta^{13}C$ through the Sourdough (-3‰ to +2‰, increasing upward) and Sentinel Peak (-3‰ +/- 1‰) suggest correlation with the Sturtian and Marinoan caps, respectively. Potentially economic U deposits (secondary brannerite) occur in graphitic schists of the Limekiln Spring Member and sub-economic U and Th (hosted by detrital monazite) occur within quartz-pebble conglomerates in the South Park Member. The strata contain no fossils, radiometric age control, or primary magnetizations.

II.

The Neoproterozoic-Cambrian succession in the Death Valley region of SW Laurentia is among the best exposed and easily accessible in the world, and comprises one of the most complete sections in Laurentia. The largest single exposure of these strata occurs in the Panamint Range on the west flank of Death Valley, but this area has received little attention in comparison to numerous exposures to the east of Death Valley, primarily because of structural complexity and metamorphism. The eastern strata, although unmetamorphosed, occur in isolated fault-bounded exposures and are relatively thin and incomplete compared to the Panamint stratigraphy. These factors, combined with a lack of fossil or radiometric age control, has hindered confident regional correlation, as well as placement in the context of hallmark Neoproterozoic events observed in the South Australian, Namibian and other successions around the globe. New geological mapping, measured sections and high-resolution C-isotope data reported here from the Noonday Formation in the Panamint Range delineate its regional stratigraphic architecture and establish its age through correlation with section with radiometric age control. Carbon isotopic trends in the Panamint Range match to within 1-2‰ reproducibility previous results obtained for correlative strata in the eastern sections, indicating that metamorphism did not significantly alter C isotopic ratios.

The combined lithostratigraphic and chemostratigraphic data form the basis for a revised, more complete stratigraphic framework for the Noonday Formation. A composite section shows that, where most complete, the Noonday consists of three members, from the base upward, the Sentinel Peak, Radcliff, and Mahogany Flats members. New mapping and chemostratigraphic data permit robust regional correlation of a thin dolostone marker horizon at the base of the Noonday in the Panamint Range as little as 2 m thick (Sentinel Peak Member) with a tube-bearing microbial dolostone in the eastern Death Valley region more than 200 m thick. The data also reveal that the Radcliff Member is bounded by disconformable surfaces and their correlative conformities. These surfaces are recognizable throughout the region and are used to construct a regionally unified stratigraphic nomenclature.

A key finding of this study is the construction of a chemostratigraphic profile spanning most of Noonday time. This was greatly aided by the discovery of carbonate-bearing strata in the lower part of the Radcliff Member in the Tucki Mountain area of the Panamints, and relating their stratigraphic position to upper Radcliff and younger Noonday strata in the Wildrose Canyon area. The chemostratigraphic profile is a remarkable match for the Maiberg cap carbonate sequence in Namibia, including the decline to a minimum at -5‰, a recovery to near 0‰, and then subsequent decline to -2‰. Globally, profiles through many post-Marinoan sequences are either too condensed or lack sufficient carbonate to record these features, including the sections in the eastern Death Valley region. (Halverson et al. 2005). As such, the Panamint profiles represent the first relatively complete record of the post-Marinoan C-isotopic recovery outside of southern Africa. Correlation of these curves (1) firmly places the Noonday at the base of the Ediacaran Period, (2) indicates deposition of ~200 m of Sentinel Peak and Radcliff strata occurred between 635 and 632 Ma, (3) supports the hypothesis that the Wildrose Diamictite of the Kingston Peak Formation, which lies in sharp contact below the Sentinel Peak Member, represents at least part of the Marinoan glacial interval; (4) helps identify correlative cap carbonate sequences in key Laurentian sections, which include the Ravensthroat Formation in the MacKenzie Mountains, dolostones capping the upper diamictite of the Pocatello Formation in eastern Idaho, and the middle part of the Mina el Mezquite Formation in Sonora. The Noonday C-isotopic profile confirms that the details of relatively rapid, complex variations in ocean chemistry observed in basal Ediacaran strata in Namibia are globally reproducible.

III.

The Kingston Peak Formation in the Panamint Range represents the stratigraphically most complete section of Cryogenian strata along the SW margin of Laurentia. Two glacigenic diamictites and their associated cap carbonates, the older Surprise Member and Sourdough Member and the younger Wildrose Member and Noonday Formation (Sentinel Peak Member), provide timing constraints to bracket the inter-glacial succession to between *ca*. 713 Ma and 635 Ma, the ages of inferred correlative glacial-cap carbonate rocks dated elsewhere. This timing constraint is further strengthened by the presence of a sharp decline in C isotopes in the Thorndike Member, which occurs immediately beneath the Wildrose Member; this decline is readily correlated with the global Trezona anomaly.

Within the inter-glacial succession, new mapping in the northern Panamints has documented the presence of a previously unrecognised suite of coarse sedimentary rocks herein defined as the Argenta Member of the Kingston Peak Formation. The Argenta consists largely of poorly-sorted breccias and conglomerates containing an assemblage of gravel-sized clasts dominated by granitic gneiss, schist, feldspar augens, vein quartz and quartzite fragments, and locally carbonate rocks. These compositions indicate derivation from a basement provenance and record deposition in alluvial-fan to coarse-braided fluvial settings; their textural and compositional immaturity implies relatively short distances of transport. Mapping shows that the Argenta defines wedge-shaped packages as much as 200 m thick and that the base of the Argenta is a significant angular unconformity. Combined, these features are evidence that deposition occurred during a phase of extensional tectonism interpreted as recording the initial dismemberment of the Rodinia supercontinent. Best estimates place the timing of this tectonism at *ca*. 650 – 700 Ma.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER I

CHAPTER II

CHAPTER III

I. GLACIGENIC AND RELATED STRATA OF THE NEOPROTEROZOIC KINGSTON PEAK FORMATION IN THE PANAMINT RANGE, DEATH VALLEY REGION, CA

ABSTRACT

Glacigenic deposits in the Death Valley region occur within the Neoproterozoic Kingston Peak Formation. In the Panamint Range, immediately west of Death Valley, these strata are ≥1000 m thick and are continuously exposed for nearly 100 km along the strike of the range. Although these strata are variably metamorphosed and locally exhibit pronounced ductile strain, original sedimentary textures are locally well preserved throughout the range. Diamictic strata occur in two distinct intervals, a lower one comprising the Limekiln Spring and Surprise Members, and an upper one known as the Wildrose Sub-member of the South Park Member. Each of these intervals are succeeded by well-defined cap carbonates, which, from oldest to youngest, are the Sourdough Member of the Kingston Peak and the Sentinel Peak Member of the overlying Noonday Formation. Between the two glacial successions, the Sourdough and sub-Wildrose South Park units comprise a ~300 m thick interglacial succession that includes platform carbonate deposition. Sparse lonestones and striated clasts, along with the lateral continuity of diamictic units, support a glacial origin. Chemostratigraphic profiles of $\delta^{13}C$ through the Sourdough (-3‰ to +2‰, increasing upward) and Sentinel Peak (-3‰ +/- 1‰) suggest correlation with the Sturtian and Marinoan caps, respectively. Potentially economic U deposits (secondary brannerite) occur in graphitic schists of the

Limekiln Spring Member and sub-economic U and Th (hosted by detrital monazite) occur within quartz-pebble conglomerates in the South Park Member. The strata contain no fossils, radiometric age control, or primary magnetizations.

INTRODUCTION

The Neoproterozoic strata considered to be glacigenic in the Death Valley region of eastern California were first described by Murphy (1932) for ≥1000 m of conglomeratic strata exposed in the Telescope Peak area of the Panamint Range, a major Basin and Range fault block on the western flank of Death Valley (Figs. 1 and 2). Subsequently, Hewett (1940) documented equivalent rocks in the Kingston Range, about 50 km east of Death Valley, and named them the Kingston Peak Formation, the youngest of three formations he assigned to the newly defined Pahrump Group. This general nomenclature has since been adopted and used throughout the Death Valley region. However, in general Kingston Peak strata are highly variable in thickness and sedimentary facies owing to syn-depositional tectonism in the region. Therefore, regional correlation of units at the sub-formational level has proved challenging (Miller *et al.* 1988; Prave 1999).

The strata east of Death Valley are generally well exposed and have experienced only minor metamorphism. Owing to stratigraphic variability, structural deformation and erosion it is difficult to follow any given section of these strata in the eastern Death Valley Region for more than a few kilometers along strike. The eastern sections are generally preserved in relatively small fault blocks isolated by large areas of alluvium, making lateral correlations between sections difficult. In contrast, Kingston Peak strata in the Panamint Range are continuously exposed for nearly 100 km along strike. This outcrop belt is the largest single exposure of Cryogenian strata in the southwestern portion of Laurentia, providing an unusual opportunity to examine in detail lateral transitions in facies and thickness. Although these strata are variably metamorphosed (up to amphibolite facies) and locally exhibit pronounced ductile strain, original sedimentary textures are locally well preserved throughout the range.

STRUCTURAL FRAMEWORK

The Panamint Range is a N-S trending, east-tilted range block within the Basin and Range extensional province. The main structural features affecting exposures of Kingston Peak strata include 1) a NNW-trending anticline cored by 1.7 Ga gneissic basement which is locally intruded by a 1.4 Ga porphyritic quartz monzonite, which runs through the southern half of the range (Albee *et al*. 1981); and 2) an east-directed thrust fault and underlying recumbent fold in the Tucki Mountain area (Wernicke *et al.* 1993). These basement rocks, collectively called the World Beater Complex, are non-conformably overlain by the Pahrump Group and younger strata (Labotka *et al.* 1980). Syn-depositional faulting and mafic magmatism have been identified within the Kingston Peak Formation and is generally interpreted to be a manifestation of continental rifting (e.g., Wright *et al.* 1974; Prave 1999). Regional contractile deformation affected the Panamint Range during Mesozoic time, accompanied by granitic magmatism and metamorphism in Jurassic and Cretaceous time (Labotka *et al.* 1985). The final major deformation event was west-side down normal faulting and accompanying eastward tilting in Late Tertiary time, accompanied by intrusion of granitic plutons and associated dikes (Labotka *et al.* 1980; Hodges *et al.* 1989).

STRATIGRAPHY

In the Panamint Range, the Kingston Peak Formation has been subdivided into four members, from oldest to youngest the Limekiln Spring, Surprise, Sourdough, and South Park (Labotka *et al.* 1980; Miller 1985). Diamictic strata occur throughout the Limekiln Spring and Surprise Members, and within the uppermost sub-member of the South Park Member, named the Wildrose Sub-member. In contrast to the lithologically variable Limekiln Spring and the Surprise Members, the Sourdough and all four sub-members of the South Park are lithologically persistent and distinct, and can be traced along most of the length of the range block. The four sub-members of the South Park, originally named by Murphy (1932), from oldest to youngest are the Middle Park, Mountain Girl, Thorndike, and Wildrose Sub-members (Fig. 1).

The Limekiln Spring Member

The Limekiln Spring is the most stratigraphically complex member of the Kingston Peak in the Panamint Range, and despite continuity of exposure of the Kingston Peak as a whole, mapped exposures of the Limekiln Spring are limited to a small area in the southern part of the range and a larger area to the north in the vicinity of Telescope

Peak (Fig. 2). Its stratigraphic architecture is accordingly not well understood. In the southern exposures, which are not strongly deformed or metamorphosed, it consists of laterally and vertically variable interbedded diamictite, sandstone and siltstone (Miller *et al*., 1988). In the northern exposures, which are strongly deformed and metamorphosed, it is mostly immature sandstone, pelitic schist, amphibolite, minor dolomitic marble, and discontinuous lenses of metaconglomerate and breccia (Miller 1985). Structural thicknesses in both areas are highly variable, ranging from 0 to >1000 m. At large scale the unit appears to thin eastward beneath the overlying Surprise Member, apparently filling depressions around a local topographic high underlain by crystalline basement (Labotka 1978; Labotka *et al.* 1980; Miller 1985).

The Surprise Member

The Surprise Member is poorly bedded to massive diamictite in the southern Panamints but appears to pass northward into finer-grained facies consisting of argillite and immature sandstone (Labotka *et al.* 1980; Miller 1985). Locally, it contains a few tens of meters of tholeiitic pillow basalts (Hammond 1983). The Surprise Member ranges from 35 m in thickness near Goler Wash in the southern Panamints (Miller 1985) to locally as much as 1,300 m west of Telescope Peak, although this may be partly the result of structural thickening or duplication (Labotka *et al.* 1980). The diamictic facies is dominated by quartzite and carbonate clasts supported by an argillaceous, sandy matrix. Clasts range in size from pebbles to boulders, with the quartzite clasts generally rounded to sub-rounded whereas the carbonate clasts are subangular (Miller 1985).

North of the latitude of Telescope Peak, diamictite is uncommon and the dominant lithology is dark grey to black argillaceous siltstone and fine sandstone. Argillite is also present in minor amounts to the south, but unlike the southern sections there is a significant amount of interbedded laminated limestone and argillaceous limestone (Labotka *et al.* 1980; Harding 1987). The transition between these two facies occurs in a well exposed but structurally complex area (Labotka 1978; Labotka *et al.* 1980), leading to uncertainty as to whether the two facies are coeval. Assuming that they are coeval, the association implies a significant interval of simultaneous deposition of diamictite and carbonate.

The Sourdough Member

The Sourdough overlies the Surprise Member with a conformable, generally sharp contact (Labotka 1978; Miller 1985), though locally diamictite and limestone are interbedded at the contact (Miller 1985; Partin *et al.* 2007). It is a 0.5 to 45 meter-thick grey to dark grey laminated limestone. Typically, the Sourdough exhibits strong internal deformation, inhibiting confident identification of primary structures (Miller 1985). The upper contact with the South Park Member is generally gradational (Miller 1985). Laminations are defined by alternations in calcite grain size and abundance of muscovite and quartz. It also contains finely disseminated graphite. Synsedimentary deformation, isolated clasts, and lenticular beds of clastic material have been reported (Miller 1985).

South Park Member (Wildrose exclusive)

Below the Wildrose Sub-member, the South Park Member is typically ~300 m thick and contains three lithologically distinct units that are mappable over the entire outcrop belt in the Panamint Range. They include 150 to 200 m of sandstone and pelite of the Middle Park Sub-member, 50 to 100 m of quartzite and conglomerate of the Mountain Girl Sub-member, and 50 to 200 m of limestone and dolostone of the Thorndike Sub-member (formerly referred to as the "un-named" Limestone (Prave 1999; Corsetti and Kaufman 2003)). The Mountain Girl Sub-member most likely records deposition in a fluvial braid plain (Swanson 1982; Miller 1985), which gives way upward to shallow marine platform conditions (oolitic shoals, domal stromatolites) during deposition of the Thorndike (see Chapter III). Due to the details of stratigraphic architecture both within and above these units, thickness variations and stratigraphic omissions of one or more units are common. For example, in the Wildrose Canyon area, an angular unconformity (~15°) at the base of the Mountain Girl variably places the unit on the Middle Park, Sourdough, and Surprise (Harding 1987; see Chapter III for further discussion). In the Telescope Peak area, an erosion surface at the base of the Wildrose Sub-member locally omits the entire lower portion of the South Park Member (Miller 1987), although as discussed below, this surface does not appear to be an angular unconformity.

Wildrose Sub-member of the South Park

The Wildrose Sub-member is variably preserved at the top of the South Park Member and below the Noonday Formation. Where present, it is a massive, unsorted, unbedded, matrix-supported diamictite. Its thickness varies from 0 to 190 m (Miller 1985), but is most often a few tens of meters thick. Although the unit is lithologically distinctive from the rest of the Kingston Peak Formation, there is significant internal variation in both clast and matrix compositions. It is distinct from lower diamictites in the section in that it typically contains abundant gneissic basement clasts. Clasts are primarily pebbles and cobbles. Boulders up to 0.5 m are common, and range up to 3 m in maximum dimension (Miller 1987). The matrix varies from dark grey to black argillite and immature fine sand where basement clasts predominate, to carbonate-cemented medium to coarse immature sand where carbonate clasts predominate.

Noonday Formation

In contrast to the predominately siliciclastic, diamictite-bearing Kingston Peak, the overlying Noonday Formation is predominately carbonate and diamictite-free. In the Panamint Range the Noonday Formation has traditionally be subdivided into three members, from oldest to youngest, the Sentinel Peak, Radcliff, and Redlands (Murphy 1932; Johnson 1957; Labotka *et al.* 1980; Albee *et al.* 1981). Work in progress by the authors has modified this nomenclature to include a fourth member, the Mahogany Flats Member, which lies between the Radcliff and strata equivalent to the type Redlands

(Petterson *et al.* 2006; Petterson *et al.* 2007). We herein describe only the lower three of these members, as it is these units that are most critical to the immediate post-glacial interval.

The Sentinel Peak Member is a readily identifiable carbonate marker horizon exposed throughout the Panamint Range. It ranges from <2 m thick in a basinal facies to as much as 70 m thick in a more platformal facies. We note that in earlier reports, in areas where the Wildrose Sub-member is not preserved between the Thorndike Sub-member and the Sentinel Peak, the two carbonate units were collectively mapped as Sentinel Peak, yielding much greater apparent thickness for the unit (e.g., the mapping of Albee *et al*, 1981 in the Telescope Peak area includes both units as Sentinel Peak).

In the Panamint Range, the more platformal facies of the Sentinel Peak Member consists of three parts. The lower and upper parts are both laminated dolostone approximately 1-2 m thick. The middle part is generally massive dolostone with irregular spar-filled vugs, but locally exhibits mound structures with carbonate intermound fills, and tube structures (Hunt and Mabey 1966; Cloud *et al.* 1974). In the more basinal facies, the middle part is absent and the upper and lower parts are apparently amalgamated into a single relatively thin carbonate marker horizon. At one locality in the basinal facies, a 10 cm-thick intraformational breccia occurs near the base of the unit.

The Radcliff Member is highly variable in both thickness and lithology. It ranges from 100 to 250 m in thickness, and includes limestone, dolostone, siltstone, sandstone, and breccia. Most commonly, it is laminated to thin bedded, with argillite in its lower part giving way upward to more abundant limestone with a distinctive pale yellowish orange color. Interbedded with the thin bedded limestones are meter-thick horizons of intraformational breccia. The top of the member includes quartz sandstones overlain by a distinctive siltstone unit containing coarse carbonate breccias. In areas where the Sentinel Peak is in its thin, basinal facies, the lower part of the Radcliff contains a few tens of meters of argillaceous arkose.

The Mahogany Flats Member is primarily stromalitic dolostone, about 200 m thick, with a gradually increasing component of quartz sand in the upper half of the unit. Stromatolites are ubiquitous, and include 1) meter-scale mound structures, 2) laterally linked heads, and 3) branching columns. Intermound fill includes both carbonate and quartz sandstone.

GLACIGENIC DEPOSITS AND ASSOCIATED STRATA

A glaciogenic origin has been suggested for three units within the Kingston Peak Formation in the Panamint Range, the Limekiln Spring Member, the Surprise Member, and the Wildrose Sub-member. Direct evidence for a glacial origin for the Kingston Peak Formation comes primarily from the eastern Death Valley sections, where striated and faceted lonestones have been reported (Troxel 1982, p. 62; Miller 1985; Miller *et al*. 1988, their Fig. 6). Evidence for glaciation within the Kingston Peak Formation in the Panamint Range is mostly circumstantial. Lonestones were reported from the Limekiln Spring Member in the Pleasant Canyon area (Miller 1985, her Fig. 9). In addition, striated clasts have recently been reported from the Surprise Member in the same area (Partin *et al.* 2007).

Diamictitic units of the Surprise Member and the Wildrose Sub-member are usually a few tens to a few hundred meters thick, and are traceable along the strike of the range for at least 50 to 100 km. Due to the difficulty of generating sediment gravity flows of these dimensions by non-glacial mechanisms (especially in what is otherwise a continental platform environment), deposition is presumably glacially influenced, either as glacimarine deposition off of an ice shelf, or in the case of the Wildrose, perhaps as lodgement till (Miller 1985).

BOUNDARY RELATIONS WITH OVERLYING AND UNDERLYING NON-GLACIAL UNITS

Boundary Relations of the Limekiln Spring/Surprise Members

In the Panamint Range, the Kingston Peak Formation is observed to overlie older units of the Pahrump Group and crystalline basement rock. In the southern part of the range, a non-conformity between the Limekiln Spring Member and crystalline basement is well exposed (Miller 1985). In the Telescope Peak area, where the base of the Kingston Peak is exposed, metamorphism and structural complexity complicate confident assessment of the nature of the contact. The youngest unit that underlies the Kingston Peak in this area is a dolomitic marble correlated with the Beck Spring Formation (Albee *et al.* 1981). The contact between this unit and the Limekiln Spring in Surprise Canyon may be locally conformable on the basis of interfingering lithologies of the two units (Labotka *et al.* 1980, their Fig. 2a). However, it is more commonly the case in this area that the contact is unconformable, including angular unconformity with underlying units of the Pahrump Group and non-comformity with the crystalline basement (Labotka *et al.*

1980). As noted above, the contact between the Surprise and the Sourdough Members, which defines the beginning of pre-Wildrose, non-glacial deposition, is generally sharp. However, in a number of places, the contact is marked by interbedded diamictite and limestone, and is therefore presumably conformable (Miller 1985; Partin *et al.* 2007).

Boundary Relations of the Wildrose Sub-member

The base of the Wildrose Sub-member in the Panamint Range is everywhere sharp and erosive. Its substrate ranges from the Thorndike Sub-member down to crystalline basement (Miller 1987, her Fig. 2). Even where it lies on the Thorndike, the contact locally truncates bedding. In the Telescope Peak area, the base of the Wildrose is observed to cut down section from west to east from the Thorndike down to the Surprise Member (Miller 1987). Similarly, in the southern part of the range, it cuts down section from west to east from the Middle Park Sub-member to crystalline basement (Prave 1999, his Fig. 2b). Despite the diversity of substrates along this contact, there does not appear to be a significant angular discordance between pre-Wildrose South Park units and the lower part of the Noonday Formation. Rather, as documented by Miller (1987, her Figs. 3 and 5), erosion of the pre-Wildrose South Park units is compensated by an increase in thickness of the Wildrose. The lateral replacement of the lower units with the Wildrose indicates that the Wildrose filled topographic lows with a minimum of 300 m of local relief that developed in post-Thorndike, pre-Wildrose time. The Thorndike-Wildrose contact is therefore a buttressed disconformity with a hiatus long enough to develop hundreds of meters of erosional relief.

The top of the Kingston Peak Formation in the Panamint Range is everywhere defined by the occurrence of the Sentinel Peak Member of the Noonday Formation. It is the oldest unit in Neoproterozoic succession that is never omitted by an unconformity or non-deposition (Petterson *et al.* 2006; Petterson *et al.* 2007). The contact is sharp, and its depositional substrate is typically either the Wildrose or Thorndike Sub-members.

CHEMOSTRATIGRAPHY

The Kingston Peak Formation in the Panamint Range contains two intervals of carbonate deposition, including limestone of the Sourdough Member and adjacent portions of the Surprise and South Park Members, and limestones and dolostones of the Thorndike Sub-member. In this discussion, we will also include carbonates of the overlying Sentinel Peak Member of the Noonday Formation. Carbon and oxygen isotopic data have been obtained from these intervals (Fig. 1; Prave 1999; Corsetti and Kaufman 2003). Additional data are presented in Chapter II and III (see below). Isotopic data has been also been obtained from the underlying Beck Spring Formation from the eastern Death Valley region, but not from proposed correlative carbonate strata in the Panamint Range.

The Sourdough Member in the Redlands Canyon area in the southern Panamint Range yields $\delta^{13}C$ values between -2.6‰ and -1.1‰, though a single +2.2‰ value is reported from the upper part of the unit (Prave 1999). Data from the Goler Wash and Pleasant Canyon areas reproduce the lower part of that trend, with $\delta^{13}C$ values ranging from -2.4‰ to -1.6‰ and -3.1‰ to -2.9‰ respectively (Corsetti and Kaufman 2003).

In contrast to the Sourdough, the carbon of the Thorndike Sub-member is generally isotopically heavy. $\delta^{13}C$ values from the Redlands Canyon area range from +6.3‰ to +5.7‰ (Prave 1999), and in the Tucki Mountain area they range from +4.7‰ to +5.3‰ (Corsetti and Kaufman 2003). Additional data from the Thorndike in the northern part of the range are consistent with these values (see Chapter III for discussion of Thorndike data).

There are currently no published data for the Sentinel Peak Member in the Panamint Range. The lower, tube-bearing dolostones in the eastern Death Valley region, generally believed to be correlative with the Sentinel Peak (e.g., Labotka *et al.* 1980; Miller 1987; Petterson *et al.* 2006; Petterson *et al.* 2007), consistently yield values near -3.0‰ (Prave 1999; Corsetti and Kaufman 2003). In the Panamint Range, isotopic profiles through six exposures of the Sentinel Peak consistently yield $\delta^{13}C$ values within 1.0‰ of -3.0‰ (Petterson *et al.* 2007, see Chapter II for further details), confirming correlation with the eastern Death Valley sections.

OTHER CHARACTERISTICS

A number of Neoproterozoic microfossil assemblages have been described from the Beck Spring and Kingston Peak Formations in the eastern Death Valley region (e.g., Pierce and Cloud 1978; Horodyski and Mankiewicz 1990; Awramik *et al.* 2000; Corsetti *et al.* 2003). No fossils have been reported from Pahrump Group strata in the Panamint Range, which is perhaps not surprising given both the degree of metamorphism and the general scarcity of fossils even in unmetamorphosed strata.

Marginally economic levels of U occur in a graphitic schist unit of the Limekiln Spring Member, mainly hosted by secondary brannerite (UTi_2O_6). In addition, sub-economic levels of U and Th are know from quartz pebble conglomerates in the lower part of the Mountain Girl Sub-member, hosted by unusually high levels of detrital monazite (Carlisle *et al.* 1980; Swanson 1982). Iron ore has been mined from the Kingston Peak Formation in eastern Death Valley, but no such deposits occur in the Panamint Range. Although many intrusion-related precious metal deposits are known from the Panamint Range, no other economically viable deposits directly related to depositional processes or diagenesis are known from the Kingston Peak Formation in the Panamint Range.

PALEOLATITUDE AND PALEOGEOGRAPHY

No paleolatitude estimates have been determined from any of these strata, either in the Panamint Range or in correlative strata from eastern Death Valley. Numerous attempts have been made to isolate primary magnetizations, but have all proved unsuccessful, mostly displaying Phanerozoic overprinting (J. Kirschvink, 2007, pers. comm.).

The paleogeographic setting of the Kingston Peak Formation is that of an episodically active cratonic rift basin. During Beck Spring time, the region was a marine cratonic platform. The pattern of unconformities within Kingston Peak strata in the Panamint Range demonstrates the development of kilometer-scale structural relief during deposition. For example in the Telescope Peak area stratigraphic relations within and below the Limekiln Spring Member were interpreted by Labotka *et al.* (1980) to reflect an island of subaerially exposed basement that supplied detritus to surrounding basins. The sub-Mountain Girl unconformity in the Wildrose Canyon area indicates gentle westward tilting during South Park time. By the end of Noonday time, the region returned to a tectonically quiescent, continental platform setting. The stratigraphic position of the Kingston Peak Formation below continental shelf deposits of the Cordilleran miogeocline has suggested to many workers that tectonism during Kingston Peak time represents the early stages of continental breakup and the development of an early Paleozoic passive margin (Burchfiel and Davis 1972; Stewart 1972; Wright *et al.* 1974; Levy and Christie-Blick 1991).

GEOCHRONOLOGICAL CONSTRAINTS

The geochronological constraints that exist for the Precambrian sedimentary succession in Death Valley are robust, but very sparse. The lower bound for the age of the section comes from diabase sills that intruded the Crystal Spring Formation (Fig. 1) and which appear as clasts in the Limekiln Spring Member. Samples of the sills from two locations in eastern Death Valley yield U-Pb baddeleyite ages of 1087 +/- 3 and 1069 +/- 3 (Heaman and Grotzinger 1992). The upper bound comes from identification of the pC-C boundary, nearly 5 km upsection from the Crystal Spring, within the lower member of the Wood Canyon Formation (Fig. 1, Corsetti and Hagadorn 2000). Chemostratigraphic correlations to well dated sections in Namibia (Hoffmann *et al.* 2004) may indicate an age of 635 Ma for the base of the Noonday Formation (Prave 1999; Petterson *et al.* 2007, and Chapter II below).

DISCUSSION

An important characteristic of the Kingston Peak Formation in the Panamint Range is the presence of the Sourdough Member and the three lower sub-members of the South Park throughout the range, which represent a significant interval of Neoproterozoic time without deposition of diamictite or other evidence of glacial activity. The presence of these strata therefore defines at least two distinct intervals of glacigenic sedimentation within the Kingston Peak, between which widespread deposition on a shallow marine carbonate platform occurred. In the eastern Death Valley sections, non-diamictic units, including a thin oncolitic limestone in the Kingston Range (Awramik *et al.* 2000; Corsetti *et al.* 2003), potentially represent interglacial deposition. However, unlike the South Park these units are not regionally mappable. Hence the questions of 1) whether or not a significant interglacial interval is preserved in the eastern sections, 2) how such intervals correlate from section to section, and 3) how they might correlate with the South Park Member, remain unresolved (Prave 1999).

Chemostratigraphic profiles through the Sourdough and Sentinel Peak Members suggest temporal correlation with the Rastof and Keilberg caps in Namibia, and presumably also the Sturtian and Marinoan cap carbonates in the Adelaidean section of South Australia, respectively (Prave 1999; Petterson *et al.* 2007). If correct, then the strongly positive $\delta^{13}C$ values recorded in the Thorndike Sub-member suggest temporal correlation with the lower part of the Trezona Formation in the Adelaidean section. However, alternative correlations have also been proposed. In one interpretation, the Beck Spring Formation is considered the Sturtian cap carbonate, suggesting the entire Kingston Peak is Marinoan (Halverson *et al.* 2005). In another, the Sentinel Peak Member is considered the Sturtian cap (Corsetti *et al.* 2007), making the entire Kingston Peak Sturtian. These hypotheses are further evaluated in Chapter II and III (see below).

REFERENCES

Albee, A.L., Labotka, T.C., Lanphere, M.A., and McDowell, S.D., 1981, Geologic map of the Telescope Peak Quadrangle, California.

Awramik, S.M., Corsetti, F.A., and Shapiro, R., 2000, Stromatolites and the pre-Phanerozoic to Cambrian history of the area south east of Death Valley: Bulletin of the San Bernardino County Museum, v. 47, p. 65-74.

Burchfiel, B.C., and Davis, G.A., 1972, Structural framework and evolution of the southern part of the Cordilleran orogen, western United States: American Journal of Science, v. 272, p. 97-118.

Carlisle, D., Kettler, R.M., and Swanson, S.C., 1980, Uranium- and thorium-bearing facies of the late Proterozoic Kingston Peak Formation, Death Valley region, California, *in* Fife, D.L., and Brown, A.R., eds.: Santa Ana, South Coast Geological Society.

Cloud, P., Wright, L.A., Williams, E.G., Diehl, P.E., and Walter, M.R., 1974, Giant Stromatolites and Associated Vertical Tubes from the Upper Proterozoic Noonday Dolomite, Death Valley Region, Eastern California: Geological Society of America Bulletin, v. 85, p. 1869-1882.

Corsetti, F.A., Awramik, S.M., and Pierce, D., 2003, A complex microbiota from snowball Earth times: Microfossils from the Neoproterozoic Kingston Peak Formation, Death Valley, USA: Proceedings of the National Academy of Sciences of the United States of America, v. 100, p. 4399-4404.

Corsetti, F.A., and Hagadorn, J.W., 2000, Precambrian-Cambrian transition: Death Valley, United States: Geology, v. 28, p. 299-302.

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.

Corsetti, F.A., Link, P.K., and Lorentz, N.J., 2007, $\delta^{13}C$ chemostratigraphy of the Neoproterozoic succession near Pocatello, Idaho, U. S. A.; implications for glacial chronology and regional correlations, *in* Link, P.K., and Lewis, R.S., eds., Special Publication - Society for Sedimentary Geology, v. 86, p. 193-205.

Halverson, G.P., Hoffman, P.F., Schrag, D.P., Maloof, A.C., and Rice, A.H.N., 2005, Toward a Neoproterozoic composite carbon-isotope record: Geological Society of America Bulletin, v. 117, p. 1181-1207.

Hammond, J.L.G., 1983, Late Precambrian diabase intrusions in the southern Death Valley region, California; their petrology, geochemistry, and tectonic significance [PHD thesis]: Los Angeles, CA, University of Southern California.

Harding, M.B., 1987, The geology of the Wildrose Peak area, Panamint Mountains, California [Map thesis]: Laramie, University of Wyoming.

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.

Hewett, D.F., 1940, New formation names to be used in the Kingston Range, Ivanpah Quadrangle, California: Journal of the Washington Academy of Sciences, v. 30, p. 239-240.

Hodges, K.V., McKenna, L.W., Stock, J., Knapp, J., Page, L., Sternlof, K., Silverberg, D., Wust, G., and Walker, J.D., 1989, Evolution of Extensional Basins and Basin and Range Topography West of Death-Valley, California: Tectonics, v. 8, p. 453.

Hoffmann, K.H., Condon, D.J., Bowring, S.A., and Crowley, J.L., 2004, U-Pb zircon date from the Neoproterozoic Ghaub Formation, Namibia: Constraints on Marinoan glaciation: Geology, v. 32, p. 817-820.

Horodyski, R.J., and Mankiewicz, C., 1990, Possible Late Proterozoic Skeletal Algae from the Pahrump-Group, Kingston Range, Southeastern California: American Journal of Science, v. 290A, p. 149-169.

Hunt, C.B., and Mabey, D.R., 1966, General geology of Death Valley, California; stratigraphy and structure, U. S. Geological Survey Professional Paper.

Johnson, B.K., 1957, Geology of a part of the Manly Peak Quadrangle, southern Panamini Range, California: University of California Publications in Geological Sciences, v. 30, p. 353-423.

Labotka, T.C., 1978, Geology of the Telescope Peak Quadrangle, California and late Mesozoic regional metamorphism, Death Valley area, California [Ph.D. thesis]: Pasadena, CA, United States (USA), California Institute of Technology.

Labotka, T.C., Albee, A.L., Lanphere, M.A., and Mcdowell, S.D., 1980, Stratigraphy, Structure, and Metamorphism in the Central Panamint Mountains (Telescope-Peak Quadrangle), Death-Valley Area, California - Summary: Geological Society of America Bulletin, v. 91, p. 125-129.

Labotka, T.C., Warasila, R.L., and Spangler, R.R., 1985, Polymetamorphism in the Panamint Mountains, California - a Ar-39-Ar-40 Study: Journal of Geophysical Research-Solid Earth and Planets, v. 90, p. 359-371.

Levy, M., and Christie-Blick, N., 1991, Tectonic subsidence of the early Paleozoic passive continental margin in eastern California and southern Nevada: Geological Society of America Bulletin, v. 103, p. 1590-1606.

Miller, J.M.G., 1985, Glacial and syntectonic sedimentation; the upper Proterozoic Kingston Peak Formation, southern Panamint Range, eastern California: Geological Society of America Bulletin, v. 96, p. 1537-1553.

Miller, J.M.G., 1987, Paleotectonic and stratigraphic implications of the Kingston Peak-Noonday contact in the Panamint Range, eastern California: Journal of Geology, v. 95, p. 75-85.

Miller, J.M.G., Troxel, B.W., and Wright, L.A., 1988, Stratigraphy and paleogeography of the Proterozoic Kingston Peak Formation, Death Valley region, eastern California, *in* Gregory, J.L., and Baldwin, E.J., eds., Geology of the Death Valley region: Santa Ana, South Coast Geol. Soc., p. 118-142.

Murphy, F.M., 1932, Geology of a part of the Panamint Range, California, Report XXVII of the State Mineralogist, Volume 28: San Francisco, California Department of Natural Resources, Division of Mines and Geology, p. 329-356.

Partin, C., Kennedy, M.J., and Mrofka, D.D., 2007, Interbedding of glacigenic rocks and cap carbonates in the Neoproterozoic Kingston Peak Formation, Panamint Range, Death Valley, CA (Abstract), Geological Society of America, Abstracts with Programs, Volume 39 (6), p. 144.

Petterson, R., Prave, A., and Wernicke, B., 2006, Architecture of Basal Ediacaran deposits (Noonday Group) in Southwest Laurentia: Abstracts with Programs - Geological Society of America, v. 38, p. 385.

Petterson, R., Prave, A., Wernicke, B., and Fallick, A.E., 2007, New Stratigraphic and Isotopic Constraints on the Cryogenian - Ediacaran Strata of Death Valley Region: Abstracts with Programs - Geological Society of America, v. 39, p. 222.

Pierce, D., and Cloud, P., 1978, New Microbial Fossils from - 1.3 Billion-Year-Old Rocks of Eastern California: Geomicrobiology Journal, v. 1, p. 295-309.

Prave, A.R., 1999, Two diamictites, two cap carbonates, two delta C-13 excursions, two rifts: The Neoproterozoic Kingston Peak Formation, Death Valley, California: Geology, v. 27, p. 339-342.

Stewart, J.H., 1970, Upper Precambrian and Lower Cambrian strata in the southern Great Basin, California and Nevada: U. S. Geological Survey Professional Paper, v. 620, 206 pp.

Stewart, J.H., 1972, Initial Deposits in Cordilleran Geosyncline - Evidence of a Late Precambrian (Less Than 850 My) Continental Separation: Geological Society of America Bulletin, v. 83, p. 1345.

Swanson, S.C., 1982, Sedimentology and provenance of the South Park Member of the Kingston Peak Formation, Panamint Range, California [Map thesis]: University of California, Los Angeles.

Wernicke, B., Snow, J.K., Hodges, K.V., and Walker, J.D., 1993, Structural constraints on Neogene tectonism in the southern Great Basin, *in* Lahren, M.M., Trexler, J.H., Jr., and Spinosa, C., eds.: Reno, University of Nevada.

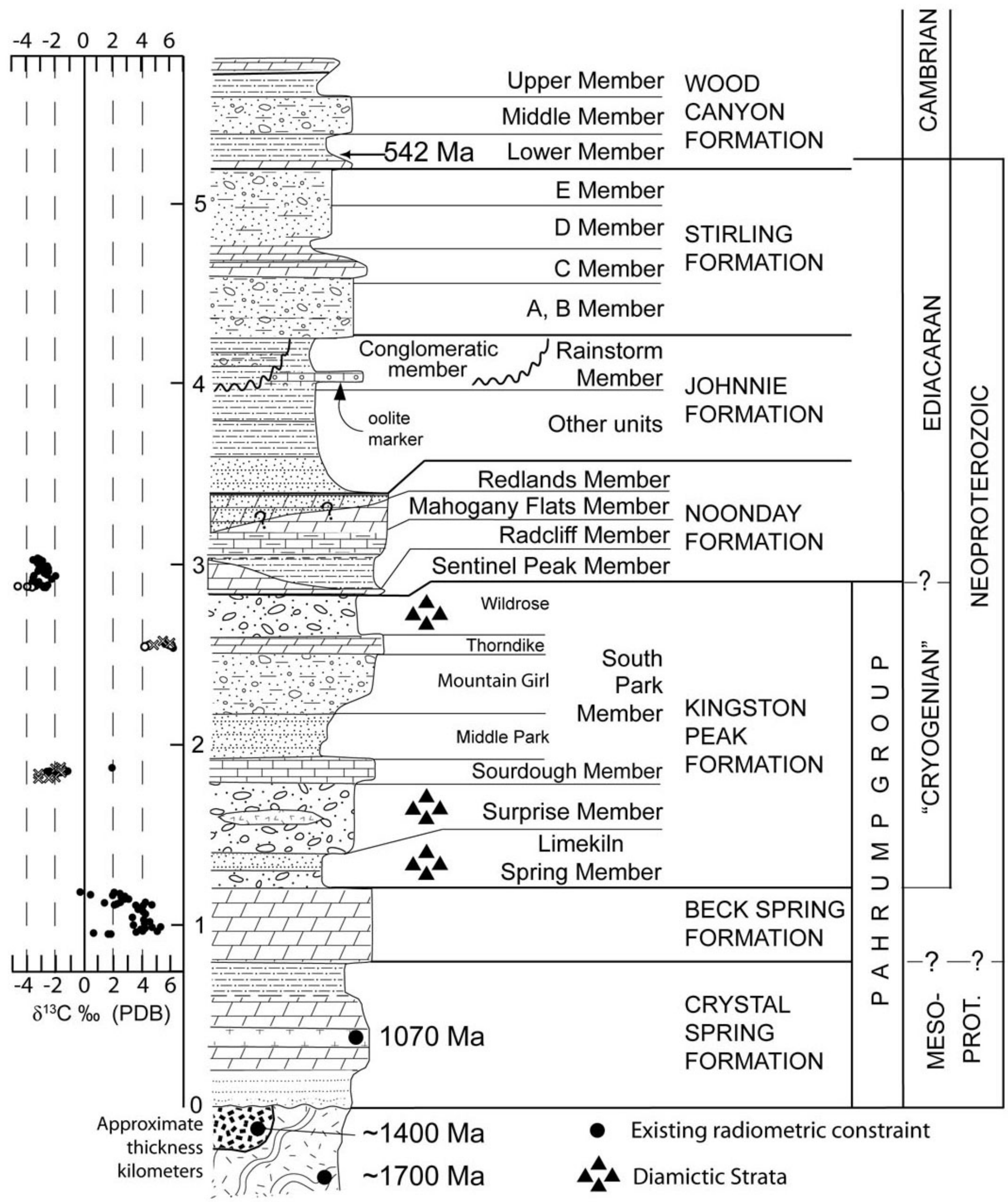
Wright, L.A., Troxel, B.W., Williams, E.G., Roberts, M.T., and Diehl, P.E., 1974, Precambrian Sedimentary Environments of the Death Valley Region, Eastern California, Guidebook; Death Valley Region, California and Nevada (see Geological Society of America): Shoshone, Death Valley Publication Company, p. 27-36.

FIGURES

Fig. 1. *Composite stratigraphic column of Neoproterozoic units in the Death Valley region (Stewart 1970; Wright et al. 1974; Labotka et al. 1980; Heaman and Grotzinger 1992), showing age constraints and key markers discussed in text. Lithologic symbols: Diagonal wavy lines, Early Proterozoic basement; plus symbols, diabase sills; v-pattern, mafic volcanics; cross-hatching, dolostone; brick pattern, limestone; stipple, sandstone; open circles, conglomerate (fine) or diamictite (bold); dash-dot lines, siltstone; dashed lines, shale. Left hand column shows a compilation of published carbon isotopic discussed in text.*

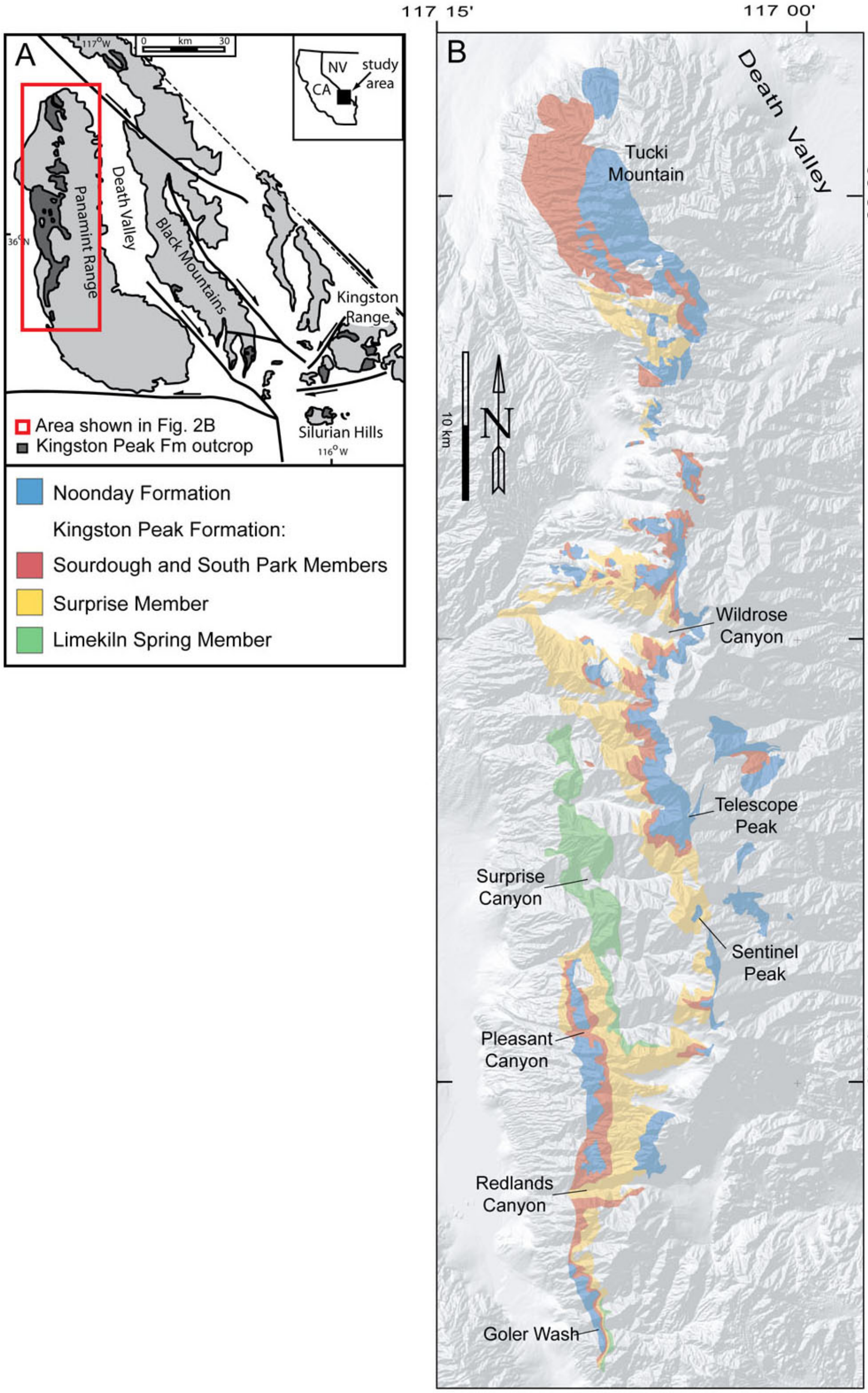
Fig. 2. ***A.*** *Map showing distribution of the Kingston Peak Formation in the Death Valley region.* ***B.*** *Map showing distribution of the four members of the Kingston Peak Formation and the Noonday Formation in the Panamint Range.*

Figure 1



-4 -2 0 2 4 6
δ13C ‰ (PDB)
Approximate thickness kilometers
0
1
2
3
4
5
Upper Member
Middle Member
Lower Member
542 Ma
WOOD CANYON FORMATION
E Member
D Member
C Member
A, B Member
STIRLING FORMATION
Conglomeratic member
Rainstorm Member
Other units
oolite marker
JOHNNIE FORMATION
Redlands Member
Mahogany Flats Member
Radcliff Member
Sentinel Peak Member
NOONDAY FORMATION
Wildrose
Thorndike
Mountain Girl
Middle Park
South Park Member
Sourdough Member
Surprise Member
Limekiln Spring Member
KINGSTON PEAK FORMATION
BECK SPRING FORMATION
CRYSTAL SPRING FORMATION
1070 Ma
~1400 Ma
~1700 Ma
PAHRUMP GROUP
CAMBRIAN
EDIACARAN
"CRYOGENIAN"
MESO-PROT.
NEOPROTEROZOIC
?
Existing radiometric constraint
Diamictic Strata

Figure 2


A
117°W
0 km 30
NV
CA
study area
Panamint Range
Death Valley
Black Mountains
Kingston Range
Silurian Hills
36°N
116°W
Area shown in Fig. 2B
Kingston Peak Fm outcrop
Noonday Formation
Kingston Peak Formation:
Sourdough and South Park Members
Surprise Member
Limekiln Spring Member
117 15'
117 00'
B
Death Valley
Tucki Mountain
36 30'
10 km
N
Wildrose Canyon
36 15'
Telescope Peak
Surprise Canyon
Sentinel Peak
Pleasant Canyon
36 00'
Redlands Canyon
Goler Wash

II. THE BASAL EDIACARAN NOONDAY FORMATION, EASTERN CALIFORNIA, AND IMPLICATIONS FOR LAURENTIAN EQUIVALENTS

ABSTRACT

The Neoproterozoic-Cambrian succession in the Death Valley region of SW Laurentia is among the best exposed and easily accessible in the world, and comprises one of the most complete sections in Laurentia. The largest single exposure of these strata occurs in the Panamint Range on the west flank of Death Valley, but this area has received little attention in comparison to numerous exposures to the east of Death Valley, primarily because of structural complexity and metamorphism. The eastern strata, although unmetamorphosed, occur in isolated fault-bounded exposures and are relatively thin and incomplete compared to the Panamint stratigraphy. These factors, combined with a lack of fossil or radiometric age control, has hindered confident regional correlation, as well as placement in the context of Neoproterozoic bio-geochemical and tectonic events observed in the South Australian, Namibian and other successions around the globe. New geological mapping, measured sections and high-resolution C-isotope data reported here from the Noonday Formation in the Panamint Range delineate its regional stratigraphic architecture and establish its age through correlation with section with radiometric age control. Carbon isotopic trends in the Panamint Range match to within 1-2‰ reproducibility previous results obtained for correlative

strata in the eastern sections, indicating that metamorphism did not significantly alter C isotopic ratios.

The combined lithostratigraphic and chemostratigraphic data form the basis for a revised, more complete stratigraphic framework for the Noonday Formation. A composite section shows that, where most complete, the Noonday consists of three members, from the base upward, the Sentinel Peak, Radcliff, and Mahogany Flats members. New mapping and chemostratigraphic data permit robust regional correlation of a thin dolostone marker horizon at the base of the Noonday in the Panamint Range as little as 2 m thick (Sentinel Peak Member) with a tube-bearing microbial dolostone in the eastern Death Valley region more than 200 m thick. The data also reveal that the Radcliff Member is bounded by disconformable surfaces and their correlative conformities. These surfaces are recognizable throughout the region and are used to construct a regionally unified stratigraphic nomenclature.

A key finding of this study is the construction of a chemostratigraphic profile spanning most of Noonday time. This was greatly aided by the discovery of carbonate-bearing strata in the lower part of the Radcliff Member in the Tucki Mountain area of the Panamints, and relating their stratigraphic position to upper Radcliff and younger Noonday strata in the Wildrose Canyon area. The chemostratigraphic profile of the Noonday strata is a remarkable match for the Maiberg cap carbonate sequence in Namibia, including the decline to a minimum at -5‰, a recovery to near 0‰, and then subsequent decline to -2‰. Globally, profiles through many post-Marinoan sequences are either too condensed or lack sufficient carbonate to record these features, including the sections in the eastern Death

Valley region (Halverson *et al.* 2005). As such, the Panamint profiles represent the first relatively complete post-Marinoan C-isotopic record outside of southern Africa. Correlation of these curves (1) firmly places the Noonday at the base of the Ediacaran Period, (2) indicates deposition of ~200 m of Sentinel Peak and Radcliff strata occurred between 635 and 632 Ma, (3) supports the hypothesis that the Wildrose Diamictite of the Kingston Peak Formation, which lies in sharp contact below the Sentinel Peak Member, represents at least part of the Marinoan glacial interval; (4) helps identify correlative cap carbonate sequences in key Laurentian sections, which include the Ravensthroat Formation in the MacKenzie Mountains, dolostones capping the upper diamictite of the Pocatello Formation in eastern Idaho, and the middle part of the Mina el Mezquite Formation in Sonora. The Noonday C-isotopic profile confirms that the details of relatively rapid, complex variations in ocean chemistry observed in basal Ediacaran strata in Namibia are globally reproducible.

INTRODUCTION

The Noonday Formation of southwest Laurentia is among the most intensively studied Neoproterozoic carbonate successions on Earth, comparing favorably in terms of thickness, accessibility, and quality of preservation to the best-known sections of similar character elsewhere (Cloud *et al.*, 1974; Williams *et al.*, 1974; Labotka *et al.*, 1980; Albee *et al.*, 1981; Wright and Troxel, 1984; Miller, 1985; Prave, 1999; Corsetti and Kaufman, 2003, 2005; Corsetti and Grotzinger, 2005; Halverson *et al.*, 2005).

Nonetheless, as described in detail below, its internal stratigraphic architecture and position relative to the Ediacaran GSSP in South Australia remain controversial. The most-studied sections of the Noonday Formation occur in relatively isolated exposures in numerous Basin and Range fault blocks in the eastern Death Valley region, including the Nopah Range, Kingston Range, Ibex Hills and numerous small fault blocks in the southern Black Mountains area (Figure 1).

The Noonday exhibits marked lateral variations from a carbonate-dominated "platform facies" to a predominantly siliciclastic "basin facies" as originally defined by Williams *et al.* (1974) and Wright and Troxel (1984). However, owing to the lack of continuity between exposures in various range blocks, correlation of depositional sequences and bounding surfaces from block to block has proved challenging (cf. Figures 3 and 5 in Williams *et al.*, 1974, and Figure 6 in Corsetti and Kaufman 2005), thus hindering development of a working chronostratigraphic framework. Unfortunately, carbon isotopic studies of the Noonday thus far have yielded relatively uniform values near -3‰ that permit multiple interpretations of the Noonday's position relative to the GSSP (Prave 1999; Corsetti and Kaufman 2003, 2005). Consequently, this non-uniqueness has resulted in its interpretation as either the cap carbonate related to the Sturtian (Corsetti *et al.*, 2007a) or Marinoan (Prave 1999; Halverson *et al.*, 2005) glaciations.

The most continuous outcrop belt of Noonday strata occurs to the west of Death Valley in the Panamint Range (Figure 1; Cloud *et al.* 1974; Labotka *et al.* 1980; Albee, 1981; Miller, 1985; Wernicke *et al.*, 1993). Although these strata are variably metamorphosed (up to amphibolite facies) and locally exhibit pronounced ductile strain

(Labotka *et al.*, 1980; Hodges *et al.*, 1987), primary sedimentary features are well preserved in a number of areas in the range and provide insight into depositional process and stratigraphic relationships. In this area, the same variations in facies (i.e., 'platform' versus 'basin') observed in the eastern sections are present, but the continuity of exposure allows for a more detailed assessment of the stratigraphic architecture. Further, in the northernmost part of the range (Tucki Mountain, Figure 1), a new facies similar to the siliclastic basinal sections has been discovered, but it is generally thicker, more complete and contains abundant limestone, permitting a unique opportunity to complete a densely sampled isotopic profile through a stratigraphically expanded basinal section.

In this paper, new geologic mapping and chemostratigraphic profiles through a series of measured sections in the central and northern parts of the Panamint Range are presented, as well as new observations from previously studied sections in the eastern Death Valley region.

Stratigraphic Setting and Previous Work

The Neoproterzoic section of the Death Valley region is some 5000 meters thick and is divisible into two main parts (Figure 2). The lower part includes the Pahrump Group, which contains a number of significant unconformities and abrupt changes in preserved thickness resulting primarily from pre-Noonday, rift-related tilting and erosion (Wright *et al.*, 1974). The upper part comprises a laterally persistent, generally concordant succession of the Noonday through Wood Canyon Formations (Wright *et al.*, 1974). The base of the Pahrump Group rests noncomformably on 1.7 Ga gneisses that are locally intruded by 1.4 Ga granites (Labotka *et al.*, 1980). The lowermost part of the Pahrump is intruded by 1.07 Ga diabase sills (Heaman and Grotzinger 1992). The oldest strata generally interpreted as glaciogenic occur in the lower part of the stratigraphically complex Kingston Peak Formation. In its most complete exposures in the Panamint Range, the Kingston Peak contains lower and upper parts characterized by glacial sedimentation (Limekiln Spring/Surprise Members, and Wildrose Diamictite, respectively), separated by an interval that includes shelf carbonate and siliclastic units as well as fluvial to shallow marine sandstone and conglomerate (Sourdough Limestone and South Park Member, exclusive of the Wildrose Diamictite, Figure 2) (Miller, 1985).

The upper part of the Neoproterozoic section begins with deposition of the Noonday Formation, followed by the Johnnie, Stirling, and Wood Canyon formations (Figure 2). Basal Cambrian trace fossils first occur in the lower part of the Wood Canyon Formation, just above Ediacaran fossils that occur in the upper part of the Stirling Formation and lowermost Wood Canyon strata (Corsetti and Hagadorn 2000). The Noonday was deposited on rocks ranging in age from 1.7 Ga gneisses to the Wildrose Diamictite (Wright *et al.*, 1974; Miller, 1985). In terms of direct radiometric and paleontological age control, the Noonday Formation is bracketed only between the occurrence of clasts of the 1.07 Ga diabase in the lower part of the Kingston Peak Formation, and the base of the Cambrian at 543 Ma, or about the length of the entire Phanerozoic Eon.

In the Panamint Range, the Kingston Peak, Noonday and Johnnie formations are continuously exposed for nearly the entire 100 km north-south length of the range (Figure 3). Most of the exposed Noonday strata belong to a structurally contiguous, east tilted basin-and-range fault block, and typically lies near the crest of the range. However, at the northernmost end of the range in the Tucki Mountain area (Figure 3), strata within the main fault block are thrust 10 to 15 km eastward over a contrasting facies of the Noonday Formation along the Cretaceous Panamint thrust fault (Figure 3; Wernicke *et al.*, 1988; 1993; Snow and Wernicke, 2000). The northernmost sections of Noonday lie in the footwall of the thrust, and at the time of deposition lay 10 to 15 km east of the northernmost exposures of Noonday preserved in the hanging wall of the thrust.

Definition

Strata that would later be assigned to the Noonday Formation were first described in a Caltech MS thesis (Murphy, 1929), followed by two publications based on that original work. The first was almost entirely concerned with the mineralization and economic potential in the central Panamint Range (Murphy, 1930), and the second dealt more generally with the geology of the area (Murphy, 1932). These reports focused on ore geology and contain only cursory stratigraphic descriptions, but nonetheless defined three units correlative with the type-Noonday later defined in the eastern Death Valley region. They included the Sentinel Dolomite, Radcliff Formation, and Redlands Dolomitic Limestone (Figure 4). He placed these formations in his Telescope Group, but this designation was abandoned by later workers.

Murphy (1929, 1932) described the Sentinel Dolomite as a white, slightly arenaceous dolostone, “characterized by irregular patches or segregations of moderately coarsely crystalline carbonates or more rarely chert”. The “patches” are most likely the well known Noonday “tubestones” (Figure 6e-h, see below for details), but he did not specifically describe such structures. Sentinel Dolomite was presumably named for exposures near Sentinel Peak, but no type or reference section was defined. The Radcliff Formation was defined as having variable lithologies, but primarily arenaceous limestone with distinctive "corrugated banding," and subordinate sandstones and shales. He also noted the widespread occurrence of pyrrhotite in the unit. It is presumably named for exposures near the Radcliff Mine in Pleasant Canyon (Figure 3), but no type or reference section was defined. Lastly, the Redlands Dolomitic Limestone was described as "white crystalline cherty limestone often containing blades of tremolite". Based on his mapping along the flanks of Sentinel and Telescope Peaks, Murphy believed it to be a lenticular body, but acknowledged that "mapping of the formation was largely a matter of conjecture." Albee *et al.* (1981) stated that the Redlands was named for exposures in Redlands Canyon but Murphy did not describe any geology south of South Park Canyon, leading to later confusion about the definition of the Redlands Member discussed further below.

Apparently unaware of Murphy's work in the Panamint Range, Hazzard (1937) defined the same interval of rocks in the eastern Death Valley region as the Noonday Dolomite, with a type locality near the Noonday Mine in the southern Nopah Range. He described the Noonday Dolomite as "light creamy-gray to cream-colored algal dolomite which weathers to a pale creamy-buff color," and noted that the upper portion is "sandy and at some places contains coarse grit and fine gravel" (Figure 4). Based on loose correlation of the sub-Noonday unconformity to the Great Unconformity of the Grand Canyon region, Hazzard placed the Noonday Dolomite in the Cambrian. His report stated that the stratigraphic details of the unit were to be presented in a forthcoming monograph on the geology of the Ivanpah Quadrangle by D. F. Hewett. Hewett (1956) provides only a brief discussion of the Noonday Dolomite. Following Hazzard (1937), he assigned a basal Cambrian age and described eastward thinning from as much as 600 m in the southern Nopah Range area to less than 70 m in the Winters Pass Hills (Figure 3). He described the formation only as "almost wholly pure, fine-grained dolomite." He did not describe any details regarding primary structures or variations in siliclastic components, and did not attempt to subdivide the unit.

In a report on the geology of the Manly Peak Quadrangle in the southern Panamint Range (including the exposures of Pahrump Group strata south of South Park Canyon, Figure 3), Johnson (1957) acknowledged the precedence of Murphy's (1930, 1932) nomenclature over Hazzard (1937) and Hewett (1956), but opted to use the latter for "consistency with stratigraphic terminology now used in the Death Valley region." He also noted that the regional relationships of Murphy's formations had been overlooked due to "inadequate descriptions, his different criteria in defining units, and his sketchy geologic map." Johnson was the first to place the Noonday in the Precambrian, on the basis of lowest occurrence of *Olenellus* in the Wood Canyon Formation. He subdivided the Noonday Formation into three units, from bottom to top 1) light gray to light-yellowish gray algal dolomite, 2) thinly bedded limestone and dolomitic limestone, 3) light gray to light-bluish gray dolomite and limey dolomite which lacks bedding (Figure 4). He described the "algal" structures in his unit 1 as "1/2 to 1 inch across and of more coarsely crystalline material than the matrix," similar to the descriptions in Murphy (1930). He suggested that his units 1, 2, and 3 correlated with Murphy's Sentinel Dolomite, Radcliff Formation, and Redlands Dolomitic Limestone respectively but chose to disregard the latter units rather than rename them as members of the Noonday Formation.

Subsequent to Johnson (1957), eight comparatively detailed studies bearing on definitional issues of the Noonday Formation and age-equivalent strata in the Death Valley region were published between 1970 and 1984, including the introduction of the "Ibex Formation" and associated members designated (from bottom to top) the Dolomite and Conglomerate, Arkose, Limestone and Shaley Limestone, and Dolomite-Quartz Sandstone members (Wright and Troxel, 1984). This nomenclature applied only to facies regarded as more basinal that the carbonate-dominated Noonday type section (Figure 4). Beginning with Stewart (1970) the more platformal sections in the eastern Death Valley region were informally subdivided into "upper" and "lower" members, but this nomenclature was not consistently applied throughout the region (Figure 4). In the Panamints, beginning with Labotka *et al.* (1980) and Albee *et al.* (1981), Murphy's three formations were mapped as members of the Noonday Formation.

Since 1984, the extensive literature on the Noonday has used some form of these designations, but a uniform nomenclature, in particular a nomenclature that rigorously ties the eastern sections to the Panamint Range has not been developed.

Chemostratigraphy

The first published chemostratigraphic study of Noonday strata (Prave, 1999) showed that values from the southern Nopah Range type section varied between -2 and -4 ‰, without systematic trends (Figure 5a). He suggested that these values (and associated facies) matched Varangian (Marinoan) cap carbonates elsewhere.

Abolins *et al.* (2000) independently sampled and measured a profile through the southern Nopah Range. The data show less scatter than that of Prave (1999), with a trend that is relatively invariant at around -3‰. They noted that the data were similar to the results of Hoffman *et al.* (1998) from the Maieberg and Elandshoek formations in Namibia.

In addition to summarizing much of the previous isotopic work in the region, Corsetti and Kaufman (2003) presented considerable new data for the Noonday Formation from the southern Nopah Range and the Winters Pass Hills (Figure 1). Their data for the "lower Noonday" (redefined below as Sentinel Peak member) is generally around -3‰. They also note a 1 to 2‰ positive step across a sequence boundary within in sandy dolostones of the upper Noonday. However, it is not clear from their descriptions where in the section their sequence boundary occurs. As discussed below, we regard it as the surface equivalent to the sequence boundary within the lower Johnnie Formation, denoted as J-SB1 by Summa (1993).

Corsetti and Kaufman (2005) subsequently presented data for the "Ibex Formation" in the Ibex Hills. There they sampled dolstones of the "Dolostone and Conglomerate Member" of Wright and Troxel (1984) for C isotopes. Their isotope data show a basal value of -4.4‰ followed by values between -2 and -3‰. They interpreted a conglomerate unit at the base of the sampled dolostone interval as evidence for a glacial interval within the Noonday, because the conglomerate interval is underlain by dolostones lithologically identical to those overlying the conglomerate.

Scope

To better understand these stratigraphic relations, chemostratigraphic data were obtained from three sections of Noonday strata in the Panamint Range (Fig. 5C, D, and E; Appendix E). In addition, chemostratigraphic data were obtained for a section in the Ibex Hills (Wright and Troxel, 1984) (Fig. 5B), and from a portion of the type section in the southern Nopah Range (Fig. 5A inset). These data are compared to an existing profile from the type section of the Noonday Formation in the southern Nopah Range (Fig. 5A). In addition to data from the five localities presented in Figure 5, chemostratigraphic profiles through the Sentinel Peak Member in the Panamint Range and its correlatives in the eastern Death Valley Region were obtained for nine additional sections (Appendix E; also see Fig. 11). The locations, geological maps and unit-by-unit lithologic descriptions for newly measured sections at Martin Cabin and eastern Wildrose Canyon (Fig. 5C, D), as well as representative sections of Noonday between these two localities (from north to south the Tucki Mine, Skidoo, and Wood Canyon areas; Fig. 3) are presented in Appendices A and F. The sections in Figure 5 use the base of the Noonday Formation as a datum, and show regionally correlative surfaces based on the stratigraphic framework proposed below.

It is apparent from the foregoing discussion and Figure 4 that existing nomenclature has been inconsistently applied (the same name assigned to different stratigraphic units, as well as different names applied to the same stratigraphic unit) to such an extent that using it to present the new data and synthesize it with previous work would be cumbersome. Instead, I will use informal names to summarize the generally acknowledged characteristics of three representative sections, including the platformal type section in the southern Nopah Range, the basinal “Ibex Formation” in the Ibex Hills, and a section in Wildrose Canyon in the central Panamint Range. I will then integrate the new results into this framework and propose a revised formal nomenclature.

REVISED GENERAL FRAMEWORK

Regional Correlations

The following general sequence has long been recognized at the Noonday’s type locality in the southern Nopah Range (Figure 1). From bottom to top it includes: 1) very finely crystalline dolospar and/or dolomicrite, usually laminated (Figure 6d) and locally exhibiting quartz or carbonate spar-filled structures termed “tubes” by previous workers (e.g., Cloud *et al.*, 1974; Corsetti and Grotzinger 2005; Figures 6f and 6h) and large mounds with at least tens of meters of synoptic relief; 2) siltstone and silty dolomite that fills the inter-mound hollows; and 3) pale gray dolostone in thin to medium beds that contain stromatolitic domes (Figure 7h) and laterally linked heads, capped by a karsted surface filled with coarse dolomitic sandstone (Williams *et al.*, 1974; Summa, 1993). These three units will be referred to as N1, N2, and N3, respectively (Figure 5A).

The Ibex Hills is the type locality of the Noonday-equivalent “Ibex Formation” (Figure 1; Troxel, 1982; Wright *et al.*, 1984). From bottom to top, three main units have been recognized: 1) well-laminated, grayish orange dolomite (similar to Figure 6B) with local meter-scale biohermal buildups and interbeds of coarse-grained sediment gravity flow deposits (Figures 6c and 10); 2) purple arkosic shale and fine sandstone, locally pebbly and in places comprised of decimeter-thick graded sandstone beds, followed by limestone and shaly limestone in thin- to medium-thick beds; and 3) massively bedded sandstone dolostone containing a 50/50 mixture of dispersed medium to coarse grains of dolomite and quartz and commonly containing clasts of laminated dolostone interpreted to be derived from N3 (Figure 5b; Wright and Troxel, 1982). These units will be referred to as I1, I2, and I3, respectively (Figure 5b).

In the eastern part of Wildrose Canyon in the Panamint Range (Figure 3), the following generalized sequence is recognized: 1) finely crystalline dolostone with spar-filled irregular segregations and isopachous cements (Figure 8a); 2) thin-bedded limestone, sandstone, and siltstone followed by arkosic sandstone, shale and sedimentary breccia; and 3) medium- to thick-bedded light gray dolostone containing stromatolitic domes and laterally linked heads. These three units will be referred to as W1, W2, and W3, respectively (Figure 5A, B, and D).

As stated above, N1 and I1 strata are have been assigned to, respectively, ‘platform’ and ‘basinal’ settings by Williams *et al.* (1974), who considered the two units to be temporally correlative (e.g., as implied in Figure 5 of Williams *et al.*, 1974). In many areas of discontinuous exposure, the transition from platform to basinal facies appears to be abrupt, occurring over less than one kilometer (Williams *et al.*, 1974; Wright and Troxel, 1984). Near the transition in the Ibex Hills, strata assigned to I1 consists of a breccia/conglomerate interval that contains clasts of the tube-bearing facies of N1, as well as clasts of pre-Noonday units (Williams *et al.*, 1974; Corsetti and Kaufman, 2005). There, the conglomerate is interstratified between thin-bedded dolomite units (see Figure 4 of Wright *et al.*, 1984). In contrast, as mentioned earlier, Corsetti and Kaufman (2005) interpreted this conglomerate as representing glaciogenic deposits wholly younger than N1. However, in a good exposure in the southern Black Mountains, a surface can be walked continuously such that over a lateral distance of 1 km, the thick, tube-bearing facies of N1(i.e., "platform facies") pass laterally into rocks identical to I1 (i.e., "basin facies"). I2 arkose blankets this surface, and there is no evidence for erosion (Figure 9A). These relations indicate that N1 and I1 are probably temporal equivalents and implies that where breccias are present they are intra-N1/I1. It also implies that the upper surface of I1/N1 is more-or-less isochronous, although with tens of meters of synoptic relief that was buried during aggradation of I2.

A similar transition from "basin" to "platform" facies is present in Wildrose Canyon in the Panamint Range (Figure 9B). There, as in the southern Black Mountains, thick W1 rocks can be traced laterally into a thinly laminated dolostone identical to I1, and from there to outcrops in the southern Panamint Range that have been previously correlated with N1 (Williams *et al.*, 1974). As such, N1, I1 and W1 are laterally equivalent, correlative units and as discussed below the breccias within I1/N1 in the Ibex Hills are best interpreted as olistostromes related to the development of relief in I1 time.

Williams *et al.* (1974) also recognized what they considered to be N3 in the southern Panamint Range. This unit is traceable along strike with exposures of W3 further to the north. As such, N3 and W3 are interpreted to be the same unit. The N2, I2, and W2 stratigraphy is rather complex and will be dealt with in detail below, but generally speaking can be considered as occupying the same stratigraphic interval.

Proposed Nomenclature

Given (1) the general understanding of Noonday strata described above, (2) the tendency toward stratigraphic incompleteness in the eastern sections, and (3) precedence (Murphy, 1932), a unified nomenclature for all exposures of the Noonday Formation and equivalent strata is proposed, based, to the extent possible, on the original nomenclature for the Panamints (Figure 4).

The threefold subdivision in the Panamints has included, in ascending order, the Sentinel Peak, Radcliff and Redlands members, corresponding to units W1, W2 and W3 in the descriptions and mapping of Labotka *et al.* (1980) and Albee *et al.* (1981). Correlations thus become straightforward. The lower part of the the Williams *et al.* (1974) platform facies (including N1 and W1) and the basal carbonate of their basinal facies (I1) are the Sentinel Peak Member. The heterolithic sequence above it (N2, I2 and by definition W2) is the Radcliff Member. This is consistent with previous usage in the Panamints.

The Redlands nomenclature is more problematic, having been inconsistently applied over the years to such an extent that a new name is warranted for the upper part of the Noonday to avoid confusion. It is proposed here that the light gray stromatolitic dolostones at the top of the Noonday, including N3 and W3, be designated the Mahogany Flats Member, after exposures in the upper Wildrose Canyon area documented below.

Whereas the lithologic characteristics of N3 and W3 strata strongly support correlation, the relationship between these units and I3, the massive, coarse dolomite-quartz sandstone that occurs at the top of the Ibex Hills section, is problematic. Some geologists have previously correlated I3 with rocks equivalent to Mahogany Flats

(Labotka *et al.*, 1980; Albee *et al.*, 1981; Troxel 1982). Those workers suggested that the change from laminated stromatolitic dolostone to massive dolomitic sandstone was gradational and represented a lateral facies change. An interpretation similar to that of Williams *et al.* (1974) in which I3 (the dolomitic sandstone in the Ibex Hills) is wholly younger than the Mahogany Flats member is preferred here. As elaborated below, I3 strata are hereby tentatively assigned to the Johnnie Formation, although additional fieldwork will be required to resolve this issue.

The proposed nomenclature provides a consistent set of Noonday members that are regionally mappable and robustly defined in type exposures. It requires abandonment of the complex, informal nomenclature based mainly on the eastern Death Valley exposures (Figure 4), including "lower algal dolomite member and upper sandy dolomite member" (Hazzard, 1937), "algal member, clastic wedge, and sandy dolomite" (Wright and Troxel, 1967), "upper dolomite, intermound fill and lower dolomite" (Williams *et al.*, 1974; Wright *et al.*, 1978), and "Noonday 1 and Noonday 2" (Wright, 1974). It also requires abandonment of the formally defined "Ibex Formation" (Troxel, 1982; Wright *et al.*, 1984), based on the equivalence of I1 and I2 strata with the Sentinel Peak and Radcliff, respectively, and as argued below the probable equivalence of I3 with the lower part of the Johnnie Formation. Lastly, it requires abandonment of the problematic "Redlands Member" (Murphy, 1932; Labotka *et al.*, 1980; Albee *et al.*, 1981; also see Appendix D). Throughout the remainder of the text the three member names will be abbreviated as SP (Sentinel Peak), RC (Radcliff) and MF (Mahogany Flats).

Platform Versus Basin Facies

In addition to the revised formal nomenclature discussed below, a more restricted definition is required of the designation of platform and basin facies in Williams *et al.* (1974). Traditionally the distinction between them is based on the presence or absence of the Ibex Formation (Wright *et al.*, 1984), wherein sections similar to the southern Nopah Range section would be considered platformal, and those similar to the Ibex Hills section would be considered basinal. This definition implies that N1 is always overlain by N2 and N3 and similarly that I1 is overlain by I2 and I3. However, in some areas the lower part of the Noonday may display characteristics similar to the southern Nopah section (for example, tube-bearing dolostone tens of meters thick, but not as much as 200) with the upper part being more similar to the Ibex Hills section, i.e., I2 resting on N1 (e.g., Wright *et al.*, 1978). The inverse is true as well, for example in the Martin Cabin section (Figure 5C) where a thin I1 dolostone appears at the base of the section and N3/W3 strata appear at the top. Thus, the many variations and gradations from "platform" to "basin" require a more refined definition.

In addition to sections that are not clearly one or the other, the genetic connotations of "platform" and "basin" are difficult to apply objectively. In the southern Black Mountains there is little to no antecedent topography on the underlying substrate, thus the base of the Sentinel Peak Member (SP) was deposited on a relatively flat surface. However, the upper surface of the SP shows significant synoptic relief due to the development of "mounds," the well-known large microbial bioherms of the Noonday (commonly many 10s of meters of relief). Where the SP is thick, Radcliff (RC) is much reduced or absent, and would be traditionally considered "platform." In contrast, localities where the SP is thin and the RC thick have been classified as "basin," despite the lack of depositional topography at the base of the Noonday. Thus the terms "platform" and "basin" are inappropriate in this context. In contrast, exposures in western Wildrose Canyon show significant topography on the pre-Noonday surface, but little or no thickness change in the SP. These two examples illustrate that there are significant thickness variations in Noonday units that are not always the result of water depth differences at the base of the Noonday. In addition, there are significant changes in topography at the base of the Noonday that do not always produce changes in the thickness of the SP.

Although the paleogeography of Noonday time likely had regions assignable to a "platform" or a "basin," without independent evidence (e.g., water depth indicators, paleoslope indicators, etc.) the practice of identifying sections as "platform" or "basin" based on basic lithostratigraphy alone should be discontinued. To minimize confusion non-genetic terms "Nopah facies" and "Ibex facies" rather than "platform" and "basin," respectively are used here. In most cases in this study, Nopah facies and Ibex facies may be distinguished on the basis of thin (2 m) versus thick (10 m+) SP only; those sections with a thin basal carbonate marker are considered the latter, and those with thick tube-bearing dolostone are considered the former. "Ibex Formation" nomenclature was originally defined to distinguish between two wholly distinct paleogeographic realms that existed during Noonday time. However, because these realms are not spatially distinct as once thought, use of "Ibex Formation" should be discontinued.

LITHOSTRATIGRAPHIC DATA

Noonday Formation

The systematic description of the Noonday Formation is based on new measured sections of SP, RC and part of MF in the Wildrose Canyon and Martin Cabin areas, and SP and part of RC in the Wood Canyon and Skidoo areas (Figure 3; Appendices A and E), as well as descriptions from previous studies in the eastern Death Valley region (e.g., Williams *et al.*, 1974; Wright *et al.*, 1984) and Panamint Range (e.g., Wright *et al.*, 1978; Labotka *et al.*, 1980; Harding, 1987). Detailed maps and unit descriptions of the new measured sections in the Panamint Range are in the Appendix and are summarized in the Martin Cabin and eastern Wildrose stratigraphic columns in Figure 5. Also included on Figure 5 is a representative section from the western Wildrose Canyon area (Harding, 1987). For comparison with the Panamint Range sections, two representative sections are included from the eastern Death Valley region, including the Nopah facies type section in the southern Nopah Range (Hazzard 1937; Wright *et al.*, 1978) and the type section of the Ibex facies from the eponymous range of hills (Wright *et al.*, 1984).

Sentinel Peak Member

In the Ibex Hills Facies, SP is primarily 2 to 10 m of laminated dolomicrite (Figures 6A and 6B). The one exception to this is the 15-km long exposure exposures of the Ibex facies in the Tucki Mountain area (Martin Cabin section, Figure 5), where the Sentinel Peak Member is calcmicrite rather than dolomicrite. Sedimentary breccia horizons occur in the Ibex facies, most commonly near transitions from Nopah to Ibex facies (Figure 6C). For example, in exposures in the Ibex Hills close to a transition, detailed sections measured along a 1 km strike length of SP (sections A though E, Figure 10) show that conglomerates and breccias (debrites) are (1) interstratified with laminated SP micrite along at least two horizons, (2) contain a mixture of intraformational and extraformational clasts, and (3) contrast both texturally and compositionally with underlying diamictites of the Kingston Peak Formation.

In Nopah facies exposures, SP comprises 100 to 200 m of laminated dolostone, commonly containing distinctive tubestone (Figures 6E through 6H; Cloud *et al.*, 1974) and sheet cracks filled with isopachous cements (Figure 6D). The tubestones contain vertical, typically spar-filled tubes several decimeters in length within laminated dolomicrite (Figures 6G and 6H). Tubes are ~1 cm in diameter and are fairly evenly spaced 2 to 3 cm apart on bedding surfaces (Figures 6E and 6F). They are especially well preserved in the eastern Death Valley sections (Figures 6F and 6H), but are also well preserved in many of the metamorphosed sections in the Panamints (Figures 6E and 6G). No consensus exists regarding the origin of the tubestone facies, but morphological and petrographic observations on the least altered examples from the eastern Death Valley region suggest the tubes may be vertically accreting, centimeter-scale depressions or "dimples" in microbial mats, a morphology perhaps promoted in some way by the rapid precipitation of carbonate (Corsetti and Grotzinger, 2005). Tubestone is not observed in the Ibex facies, except as clasts in the breccia horizons.

The breccias in SP Ibex facies generally contain clasts of pebble and cobble sizes (Figures 6C and 10), but also include clasts as large as 2 m in maximum dimension. Clasts include both tube-bearing dolostone of the Nopah facies and clasts from older units, such as diamictite of the Kingston Peak Formation and dolostones from the Beck Spring Formation. Clasts are dispersed in a silt-sized reddish-gray matrix with variable carbonate content, and inverse grading is observed locally (Figure 6C); some clasts project above the upper surface. Bases and tops are typically sharp and at outcrop scale bed bases are demonstrably erosive (Figure 10). These observations indicate: (1) significant depositional slope near Nopah-Ibex facies transition zones; (2) synchronism of deposition of the lower laminated dolostone of the Ibex facies (I1) with deposition of the tube-bearing Nopah facies (N1); (3) at least local gravitational instability of the Nopah facies and (4) exposure (probably subaqueously) and erosion of sub-Noonday bedrock in SP time.

The transitions from Nopah to Ibex facies observed in the southern Black Mountains (Figure 9A) and the Wildrose Peak area of the Panamint Range (Figure 9B) are both characterized by abrupt thinning of SP. These typically exhibit thinning (from a few tens of meters to a few meters) over distances of several hundreds of meters. Concomitant with the thinning of the SP dolostones, a complementary thickening of immature siliciclastic rocks of the lower RC occurs (mainly arkoses and siltstones). In these transitions, the upper laminated SP dolostones have a contiguous upper surface traceable from Nopah Facies to Ibex Facies, beneath thickening arkoses (Figure 9), suggesting this surface is a more-or-less isochronous horizon gently onlapped by the basal siliciclastics of the overlying lower RC. Abrupt changes in thickness of N2 siltstone and carbonate also occur within the Nopah facies, corresponding to local changes in the development of microbialite mounds having several tens of meters or more of relief. The N2 siltstone and carbonate were interpreted by Williams *et al.* (1974) to be intermound fill, an interpretation which the current study supports.

Nopah facies SP may be as thick as 200 m in the eastern Death Valley region, but equivalent strata near the transition to Ibex facies in the southern Black Mountains, and throughout the Panamint Range, are only a few tens of meters thick. These areas may be regarded as intermediate between the thickest Nopah facies sections and those of the Ibex facies. In these transitional locations, the arkose and siltstone at the base of the overlying RC is disconformably omitted at the SP-RC contact (Figures 5 and 9) as a result of progressive onlap against and burial of the paleotopographic relief marking the top of SP. Additionally, relatively thick (>100 m) sections of the upper part of the Radcliff can be developed, in marked contrast with the local preservation of relatively thin intermound fill in the fully developed Nopah facies sections.

Radcliff Member

The Radcliff Member (RC) is a heterolithic assemblage distinguished in the field by its well developed parallel stratification, whether in siliciclastic (Figure 7F), carbonate, or mixed carbonate-siliciclastic facies (Figures 7A-E). As previously interpreted, RC at least in part represents a “fill deposit” of the irregular paleorelief (synoptic relief) associated with SP bioherms. As such, the total thickness for this stratigraphic interval is roughly antithetic to that of the underlying SP. For example, in both the Nopah Range and eastern Wildrose Canyon sections, the base of the Mahogany Flats (MF) lies 215 and 200 m above the base of the SP, respectively, but the intervening strata in the Nopah Range is almost entirely SP and in the Panamints almost entirely RC

(Figure 5). The Martin Cabin section stratigraphic thicknesses are not reliable because of the potential for significant stratal omission by faults and ductile strain (Appendix A5), but the measured thickness between the bases of the SP and MF is also about 200 m. In the Ibex Hills, no MF strata are observed between RC and sandy dolostones that are herein interpreted to be younger than MF. In western Wildrose Canyon, there is at least 260 m of sub-MF Noonday, and in structurally complex areas near Skidoo, there may be even greater thicknesses of RC.

The RC can be subdivided into three informal sub-members: lower, middle, and upper (Figure 4). The lower sub-member is predominantly arkosic in composition, with lesser amounts of siltstone and carbonate. Bedding tends to be either laminated to thin bedded, but locally can be thick and massive. The former units range from siltstone to fine sandstone, and typically contain dispersed medium to coarse sand grains. The thick to massive units exhibit both grain-supported and matrix-supported textures. The base of this sub-member is typically gradational with the underlying Sentinel Peak at the scale of a few meters, and is therefore interpreted to be conformable (Figure 8B). On the steep sides of mounds developed in the SP, the contact is sharp and onlapping.

The middle Radcliff sub-member is dominantly thin-bedded limestone rhythmites (Figure 7A through 7D) with local intraformational breccias (Figure 7). Purely siliciclastic variants are common (Figure 7F). A transition from dominantly siliciclastic rocks in the lower part to dominantly carbonate rocks in the upper part is usually abrupt, with the exception of the Martin Cabin section where the transition is gradational. I interpret these strata as thin allodapic beds being sourced from shallow marine environments. The upper submember marks a return to coarser siliciclastic deposition characterized by more arenaceous sandstones than the lower part. The lowest part of the upper RC sub-member is a 5 to 10 m thick, relatively mature, feldspathic sandstone commonly dolomitic at its base. Above this, the sub-member is composed of a few tens of meters of siltstone and carbonate breccia beds, indicating that significant depositional slope existed near the end of RC deposition.

Regionally, the three RC sub-members are variably developed. In the central Panamint Range, as originally defined by Murphy (1932) and adopted by Labotka *et al.*, (1980), RC rests concordantly on the SP, but only the upper two sub-members are present. In Wildrose Canyon, Wood Canyon, and Tucki Mine (Figures 3 and 5), the lower siliciclastic sub-member is also absent even though the Sentinel Peak is a few tens of meters thick. In contrast, in the sections at Martin Cabin, Providence Ridge and the western part of Wildrose Canyon, all three lower sub-members are present. In general the lower sub-member is best developed when the SP is very thin (2 m), and tends to be less well developed or absent once SP becomes more than 10 to 20 m thick.

Mahogany Flats Member

Above RC is the dominantly stromatolitic dolostone of the newly defined Mahogany Flats Member (MF) (see Appendix 1 for detailed description of the type section). In both the Panamint southern Nopah ranges, this unit displays abundant meter-scale microbialite mounds and isolated laterally linked stromatolites. Where preserved in the Nopah Range, the MF is ordinarily 40-90 m thick. This thickness excludes the "intermound fill" that previous workers included in a single "upper Noonday" unit (e.g., Wright *et al.*, 1974), but which is here redefined as RC. As described above for the Ibex hills (Figure 5), in places the MF likely has been completely removed by the basal Johnnie unconformity. Commonly above that surface are massive dolomitic sandstones (I3) that previous work incorrectly placed within the upper Noonday.

Noonday-Johnnie Contact

In the southern Nopah Range, the contact between the Johnnie Formation and the MF is marked by a well-developed karst surface, denoted J-SB1 (Johnnie sequence boundary 1) by Summa (1993), a designation adopted here (Figure 5). The karst is filled in and overlain by coarse dolomitic sandstone (Figure 8C). This sandstone grades upward into interbedded sandstone and dolomitic sandstone with well developed cross stratification, designated the Transitional Member of the Johnnie Formation (Stewart, 1970).

In the Ibex Hills, as alluded to above, unit I3 or the "dolomitic quartz sandstone member" of Wright and Troxel (1984) is a coarse sandstone composed of quartz and dolomite grains in which cross-stratification is rare near the base of the unit but gradationally increases upward. In this area, karst breccias in underlying middle RC limestones has not been recognized, but the base of I3 is everywhere erosional and contains clasts of Mahogany Flats-type boundstones near its base (Wright and Troxel, 1984). This contact is interpreted to correlate with J-SB1.

In the central Panamint Range south of Wildrose Canyon, the lower Johnnie is also characterized by cross-bedded sandstone and dolomitic sandstone which appears to give way northward to carbonate and siltstone facies along the boundary (Labotka *et al.*, 1980; Verdel, 2008), but further work will be necessary to identify a precise boundary in the context of the associations in the Nopah Range and Ibex Hills.

Previous workers applied the name “Redlands Member” to describe any units between the Radcliff Member and the Johnnie Formation, but without distinguishing whether the unit was fundamentally a carbonate bioherm like MF, or arenaceous sandstone like I3, as is clearly distinguished in the Nopah Range. In some areas (e.g., the Wildrose Canyon area), “Redlands” has been used to describe MF, but in others (e.g., Redlands Canyon), it has been used to describe arenaceous strata similar to I3 (Albee *et al.*, 1981). McDowell (1967) observed that within this unit, predominantly carbonate and predominantly siliciclastic arenites are clearly gradational with one another. These gradations are interpreted as occurring between dolarenites with calcareous cements and quartz arenites with variable carbonate and silica cements, not between MF-type biohermal deposits and arenaceous basin-fill deposits. McDowell (1967) is followed in interpreting much of what was mapped as “Redlands” in the Panamints with I3 strata in the Ibex Hills. However, rather than assign these deposits to the Noonday, it is suggested that all massive sandy dolostones, cross-bedded sandstones and cross bedded dolomitic sandstones are correlative with the Transitional Member of the Johnnie Formation and lie above the J-SB1 unconformity defined in the Nopah Range.

Where this unit is well defined, its position relative to the base of SP in sections where both interfaces are present ranges from 150 to 380 m, and has a substrate ranging from relatively thin sections of middle RC to thick sections of MF, in contrast to the relatively consistent position of the base of MF relative to the base of SP (Figure 5). If these relationships have been interpreted correctly, use of the Redlands nomenclature should be discontinued, particularly to avoid confusing MF facies strata with what appears to be a wholly younger sequence of arenaceous dolostones and sandstones. Further, given the concordance in all sections between the Transitional Member and its substrate, there may have been as much as 200 m of (subaerial?) topographic relief at the onset of deposition of the Transitional Member, implying a significant hiatus across the unconformity (see appendix D).

CHEMOSTRATIGRAPHIC DATA

Methods

Sampling

$\delta^{13}C_{carbonate}$ measured from Neoproterozoic sedimentary carbonate rocks is commonly interpreted as a reliable measure of the variations in the $\delta^{13}C$ of contemporaneous seawater, assuming that $\delta^{13}C_{carbonate}$ and $\delta^{13}C_{seawater}$ are in isotopic equilibrium and, therefore, a reliable record of the secular change in the global carbon cycle; a large number of studies has established the veracity of these assumptions and overall utility of this approach (e.g., Halverson *et al*. 2005 and references therein). Because of the large buffering capacity of carbonates with respect to carbon, depositional C–isotopic signals can be preserved. This has been shown to be viable even under amphibolite facies conditions (Ghent & O'Neil 1985; Baker & Fallick 1989; Melezhik *et al.* 2001b, 2005, 2008). In part this is because, at elevated metamorphic grades, carbonate rocks can be relatively impermeable (the lack of an interconnected pore network), thus fluid infiltration, if any, often only results from shearing and hydrofracturing. Geochemical alteration processes and the resultant effects on C-isotopic compositions are largely limited to the meter-scale at most, more typically on mm- to cm-scales adjacent to fractures and/or lithological contacts (*op. cit*., also Holness & Graham 1995). Even in metacarbonate rocks that contain graphite, unless a fluid phase is present during metamorphism, there is little scope for solid-state isotope exchange between the relatively heavy carbon reservoir in the carbonate and the light carbon reservoir in the graphite, simply because kinetics of exchange are much too slow (>10^7 years) relative to the duration of metamorphism and high temperature states (usually $10^{5\text{-}6}$ years). Nevertheless, isotopic exchange between fluid and carbonate is usually incomplete and carbonate carbon is largely buffered by the composition of the carbonate given that metamorphic fluids are usually relatively poor in C-bearing phases (e.g., CO_2, CO, CH_4) (Baker *et al*., 1989; Banner & Hanson 1990; Bickle & Baker 1990; Graham *et al*., 1997; Lewis *et al*., 1998; Rye *et al*., 1976; Veizer 1992). Thus, it is critical to be extremely judicious in choosing samples to make certain that they are obtained from areas where C-isotopic alteration by post-depositional processes was unlikely.

Samples were chosen for analyses from outcrop areas free of visible alteration or discoloration and well away from zones of veining and fracturing. The samples were cut, cleaned and polished, and thin sections from representative samples were examined to confirm textural observations made in the field. All samples used in analyses exhibited micritic textures; recrystallized sparry areas were avoided wherever possible. Selected areas were then microdrilled using a Sherline 5100 drillpress and powders sent to SUERC.

C-O Isotope Analysis

Carbonate carbon and oxygen stable isotope analyses were done at the Scottish Universities Environmental Research Centre (SUERC) under the supervision of Prof A.E. Fallick. Analyses were performed with a continuous flow, triple collector mass spectrometer on pure carbon dioxide produced from carbonates by an automated, constant temperature reactor using phosphoric acid, a modification of the method of McCrea (1950). The mass spectrometer was an Analytical Precision 2003 coupled to an AP Carbonate Injector. This is an individual acid bath system. In detail, around 1 mg of carbonate was loaded into an Exetainer which was placed into a hotblock controlled to 70°C. The Exetainer was then flushed with GC grade He. Around 200 microlitres of 103% phosphoric acid was injected into each Exetainer by a triply concentric syringe and the reaction allowed to proceed overnight (see e.g., Rosenbaum & Sheppard, 1986). After reaction, each Exetainer was individually overpressured with He using a doubly concentric syringe, and the headspace gas sampled. With He as a carrier, the carbon dioxide was passed through a Nafion tube to remove water and then through a 120 microlitre sampling loop into the mass spectrometer carrier flow of He; a room temperature GC with Porapak separated any contaminant gases from the carbon dioxide, before it passed into the mass spectrometer ion source. Each pulse of sample carbon dioxide was bracketed by pulses of reference carbon dioxide of known isotopic composition. Each Exetainer was sampled four times, with isotopic composition calculated from the average of the last three injections (*i.e.*, the gas from the first injection was ignored to obviate, for example, memory effects). To correct for drift during a run, although little was observed over a typical tray of 44 carbonates, one laboratory standard carbonate (MAB, a marble from Carrara, Italy) was included with each 5 samples. Oxygen isotope fractionation factors between carbonate and carbon dioxide were taken from Rosenbaum & Sheppard (1986). The calibration to internationally accepted standards was achieved through analysis of NBS 19. Data are reported in the conventional delta per mil notation relative to V-PDB for carbon, and V-PDB and V-SMOW for oxygen. Precision at 1σ is better than 0.2‰ for both oxygen and carbon.

Results

As the $\delta^{13}C_{carbonate}$ profiles for the Noonday and associated lithologies show, there are systematic trends within given units and these are reproducible from area to area, *i.e*. the C-isotopic profiles from unmetamorphosed units in outcrop areas of eastern Death Valley are comparable to their equivalent units at amphibolite facies in the Panamint Range. For example, the $\delta^{13}C$ values in twelve profiles through different sections of SP from these two regions generally lie between -2 and -4 permil (Fig. 11A). Within this narrow range of variation, there is a tendency for the metamorphosed sections to be as much as 1 permil lighter than unmetamorphosed sections (Fig. 11B). However, exceptions to this pattern include the unmetamorphosed northern Saddle Peak Hills section, which yields values similar to metamorphosed sections, and the greenschist facies Tucki Mine section, which yields values similar to unmetamorphosed sections (Fig. 11A).

In contrast to the narrow range of the $\delta^{13}C$ data, $\delta^{18}O$ values range from -5 to -15 permil, with metamorphosed sections on average exhibiting a ~5 permil negative shift (Fig. 11B). The data, for both the Sentinel Peak alone as well as the complete data set, in general show no strong co-variance between carbon and oxygen (Fig. 11C). Thus, whereas $\delta^{18}O$ values are strongly affected by metamorphism, variations in $\delta^{13}C$ are primarily controlled by stratigraphic position, with lightening of perhaps 1 permil in some sections due to post-depositional alteration.

In terms of sedimentary facies, the data do not show a systematic pattern. For example, profiles for Ibex facies SP do not systematically differ from profiles for Nopah facies SP (Fig. 11D).

Sentinel Peak Member

Data from the SP usually cluster around -3‰. When they do show a trend it is generally declining to near -4‰ (Figure 5 and 11). In its thinnest occurrences, SP was sampled at decimeter-scale spacings with the aim of discerning differences, if any, in trends between Nopah facies Sentinel Peak and Ibex facies Sentinel Peak (Figure 11). No such pattern was discernable, such as that seen by Hoffman *et al.* (2007) in the Namibian cap dolostones in the Otavi Group, but still higher-resolution sampling may reveal if such patterns are present.

Radcliff Member

Where present, the lower RC sub-member records the lowest C-isotopic values in the Noonday (Figure 5). In most exposures of the lower Radcliff the lack of carbonate strata restricts sampling to the thin, gradational interval between carbonate and arkosic in the lowermost part of the Radcliff. The Martin Cabin section, however (Figure 5C), contains carbonate rocks throughout the Radcliff and affords documenting the C-isotopic trend from values near -4‰ at the top of the SP to a nadir around -6‰ in the lowermost rocks of the lower RC sub-member; this occurs over several meters. Values remain low for nearly 100 m before beginning a positive trend in the middle RC. This expanded negative interval relative to presumed equivalent sections in places elsewhere is interpreted to reflect relatively high sedimentation rates.

In many places (North Skidoo, Wood Canyon, Tucki Mine), the lower RC is absent and the middle RC sits directly on the SP. In this situation the isotopic curves fail to capture the nadir of the negative excursion, cutting off around -3‰ and placing the recovery, starting around -5‰, directly on top of it. This is similar to what we see in the curve for the Ibex Hills sections, but there it is due to a lack of carbonate in the lower Radcliff, not stratigraphic omission (Figure 5).

The carbonate rocks of the middle RC sub-member record a positive trend from the nadir in the lower Radcliff sub-member of near -6‰ to values near 0‰ at the top of the unit. This trend is observed in all sampled sections, including previous work by Corsetti and Kaufman (2005). The differences of curvature in this trend can be related to local variations in accommodation rates (sharper curve = faster accommodation, gentler curve = slower accommodation). It may be possible to further refine the sequence stratigraphic architecture of the Noonday by exploiting the differences in curve shape. For example, accommodation may have been slow during middle RC time near Martin Cabin (Figure 5C), while western Wildrose (Figure 5E) may have experienced rapid accommodation rates during the same interval.

Not all sections record values that approach 0‰. These curves are interpreted as being unconformably truncated, either as a result of erosion beneath J-SB1 (i.e., Ibex Hills localities) or as a result of non-deposition (i.e., parts of the southern Nopah Range that do not preserve RC beneath MF).

Carbonate data have been obtained from the siliciclastic upper Radcliff sub-member, which is exposed only in the Tucki Mine, North Skidoo, and eastern Wildrose Canyon sections. Presumably, if suitable carbonate lithologies existed in this interval, the C-isotopic profile would exhibit attain a maximum value ca. 0‰, which would mark the end of middle Radcliff sub-member deposition, before decreasing to the approximately -2‰ values at the base of the Mahogany Flats.

Mahogany Flats Member

The most complete isotopic data set for the Mahogany Flats Member (MF) was obtained from the eastern Wildrose section (Figure 5D). These data define a curve which begins around -2‰, increases to around +1‰, returns towards -2‰, then again changes direction and climbs steadily to +4‰. Even though this is the most complete Mahogany Flats section, the top is still truncated due to erosion at the base of the Johnnie Formation. The C-isotopic profiles of sections of the MF from elsewhere, although usually lacking the detailed structure present in the data from eastern Wildrose Canyon, similarly show an increasing trend from values around -2‰. However, in all cases, the top of the MF is truncated beneath the J-SB1, often well before the zero crossing (e.g., Martin Cabin section, southern Nopah sections) making the eastern Wildrose Canyon section particularly important for understanding upper Noonday deposition.

COMPOSITE CHEMOSTRATIGRAPHIC PROFILE

Due to the complex tectonic history of the Death Valley region, as well as the complex depositional framework of the Noonday Formation, complete individual sections are rare. In order to compare the Noonday Formation with more intact sections globally, a composite section has been constructed. Carbon-isotopic data were obtained for each of the individual sections, which are then consolidated to construct the composite curve. This allows a composite section to be constructed that contains the most complete available record of Noonday deposition and thus a means to obtain a more comprehensive understanding of its depositional history and C-isotopic record.

The composite section is derived primarily from the Martin Cabin and Wildrose Canyon sections (Figure 5), which are the most complete, based on both lithostratigraphy and chemostratigraphy. The Martin Cabin section is rare in that it contains carbonate rocks throughout the lower RC, as well as relatively thick occurrences of the RC in the Ibex facies and MF, which is otherwise only present in Nopah facies. It should be noted, however, that faulting of probable Cretaceous age in the Martin Cabin area disrupts the middle RC which may have removed a portion of the middle RC section. Because the middle RC is thin, most likely due to faulting (Appendix 1), the thickness of the middle RC from western Wildrose Canyon (Figure 5E) was used for that sub-member. Data from the Martin Cabin and other sections was then normalized to that thickness. At the top of the Martin Cabin section is ~20 m of MF that is truncated by karst of the J-SB1. This portion of the MF matches well with the lower 20 m of the MF from the eastern Wildrose Canyon section (Figure 5D), which has the most complete exposure of the MF, and therefore this section is used for the MF portion of the profile. MF data from the Ibex Hills (Ibex Formation Type locality, Figure 5B) was added directly to the profile because of comparable thicknesses at both locations.

The composite section and composite carbon isotopic profile for the Noonday Formation are presented in Figure 12A. Because it depicts the thickest sections of each member, the composite curve must take into account differences between the Nopah and Ibex facies. For example, the full thickness of the SP is shown, but this is only achieved in the Nopah facies. Likewise, the full thickness of the RC is used, but this is only present in the Ibex Hills Facies.

DISCUSSION

The new stratigraphic and isotopic framework presented above was dependent on clarification of relatively subtle field relations and their implications for the stratigraphic architecture of the Noonday Formation. Construction of the composite carbon isotopic curve depended on what units are included within the Noonday, and how these units correlate laterally. Even with good geochronological and chemostratigraphic control, differences in interpretation of field relations, if not resolved, may result in contrasting interpretations of whether the Noonday is the cap carbonate for Sturtian, Marinoan, or perhaps some other glacial event not recognized in the Ediacaran GSSP in South Australia.   To the extent that these issues were not resolved, any attempt to place the Noonday in the context of models for extreme climatic fluctuations such as the Snowball Earth hypothesis (e.g., Kirschvink, 1992; Hoffman *et al.*, 1998; Hoffman & Schrag, 2002), or models for the radiation of metazoans in latest Precambrian time, are compromised. Below we summarize how the new stratigraphic and isotopic framework requires modification or abandonment of previous models of Noonday deposition, and then address the problem of placing the composite carbon isotopic cure in a global context.

Previous Models of Noonday Deposition

The general stratigraphic framework presented here generally agrees with Williams *et al.* (1974). The essence of this model includes (1) period of microbial mound building and the creation of synoptic relief with unstable adjacent slopes (SP), (2) aggradation of intermound fill, including arkoses and variably siliceous detrital carbonates and intraformational breccia (RC), and (3) a subsequent period of relatively low-relief mound building (MF). This study builds on the framework of Williams *et al.* (1974) in documenting the scale and depositional architecture of the transitions between Nopah and Ibex facies successions (loosely, the platform and basin facies of Williams et al, 1974), but differs in suggesting I3 is wholly younger than MF and is part of the Johnnie Formation.

Williams *et al.* (1974) viewed the Noonday as either purely basinal or purely platformal throughout Noonday time, with relatively narrow facies transitions in between all three of their major units. The data presented above instead suggests broad areas of transition with intermediate thicknesses of tube-bearing SP occurring together with relatively incomplete sections of RC, typified by exposures in the central Panamint Range. Williams *et al.* (1974) did not comment on the architecture of the transition in facies of SP from platform to basin. Detailed examination of these transitions suggests that the top of SP is likely an isochronous surface gently onlapped by lower RC arkoses, and that Ibex facies SP sections contain debris flows cannibalized from both the growing tubestone-bearing mounds and their substrate. During SP deposition the tops of growing mounds were locally eroded and transported into more basinal sections, but the end of SP accumulation was synchronous throughout the basin. A key implication of this observation is that the growth rate of SP mounds in the Nopah facies was as much as two orders of magnitude higher than carbonate accumulation in the Ibex facies.

An important contrast in our depositional framework from the Williams *et al.* (1974) model is recognition that the variably carbonate-rich arenaceous rocks that overlie RC in Ibex facies sections (1) are equivalent to the Transitional Member of the Johnnie Formation, (2) are wholly younger than MP, and (3) lie above an unconformity with as much as 200 m of erosional—not synoptic— relief relative to underlying Noonday units.

The most recent model for a Noonday depositional framework included for the first time supporting chemostratigraphic data (Corsetti and Kaufman, 2005). This model represented a substantial departure from the framework of Williams *et al.* (1974), suggesting that a glacial event may have occurred during Noonday time. According to this interpretation, the base of the tubestone-bearing conglomerates described above in Ibex facies SP (Figure 10) represents a glacial event, or alternatively a tectonic event. The conglomerate is regarded by Corsetti and Kaufman (2005) to rest on a regional erosion surface which climbs rapidly upward onto thick SP in Nopah facies sections, such that supraconglomerate SP and younger Ibex facies strata postdate all Nopah facies SP. Two alternatives for the relationship between MF strata present in the Nopah Range, and the supraconglomerate SP and RC strata in the Ibex Hills were proposed (see Figure 7 in Corsetti and Kaufman, 2005). In their preferred model, MF strata in the Nopah Range are equivalent to middle RC strata in the Ibex Hills, so that supraconglomerate SP and lower RC arkoses pinch out beneath middle RC and are not present in the Nopah Range. In an alternative model, the supraconglomerate SP correlates with MF.

The Panamint stratigraphic data and the much-expanded temporal and spatial database of C isotopic data suggest the Sentinel Peak-Radcliff-Mahogony Flats subdivision of the Noonday is regionally mappable, and therefore precludes equating MF in the Nopah Range with either middle RC or upper SP in the Ibex Hills. Although parts of MF are isotopically similar to middle RC, where both units are exposed the contrast in lithofacies between parallel bedded, variably siliceous limestone and mound-forming dolomitic microbialite is consistent. Similarly, supraconglomerate SP in the Ibex facies is consistently parallel-bedded silty dolostone with a gradational upper boundary with lower RC sandstones (Figure 8B), and exhibits no tendency toward the formation of mounds or laterally linked heads. Ibex facies SP does not contain one conglomerate horizon, but rather contains lithologically identical parallel-laminated dolostones interstratified with multiple decimeter- to meter-scale debris-flow event horizons (Figures 8D and 10). The lack of a single identifiable break in rock type casts doubt on a major hiatus anywhere within the Ibex facies SP.

In support of eroding all of Nopah facies SP prior to deposition of the remaining Noonday, field mapping in the southern Black Mountains (Wright and Troxel, 1984) depicts a southward erosional pinchout of several tens of meters of Nopah-facies SP dolostones below RC, with local "patches" of SP preserved along the apparent incision surface (Corsetti and Kaufman, 2005). This is the same area where we have documented that laminated dolostones at the top of SP can be traced continuously southward as the SP thins (Figure 9A), and in all exposures it is in gradational contact with overlying lower RC arkoses (e.g., Figure 8B). We have also re-examined the erosional "patches" of SP located farther south, and determined that the mapping of Wright and Troxel (1984) simplifies a complex series of closely spaced normal faults, giving a superficial impression of isolated patches of SP strata along the purported erosional contact between the underlying Kingston Peak Formation and overlying lower RC arkose (Figure 13A). Inspection of each exposure of SP shows that bedding is oriented at a high angle to the trace of the contact and that the patchy outcrop results from closely spaced normal faulting (Figure 13B). In each of these blocks, the same gradational contacts between SP and lower RC arkoses observed farther north is preserved. Hence these outcrops do not provide support for erosive removal of SP beneath any younger elements of the Noonday Formation, and instead support the overall framework presented herein. A more detailed discussion of these field relations and their stratigraphic implications is included in Appendix F.

Stratigraphic Completeness

Since the work by Hazzard (1937), the southern Nopah Range has been one of the most examined exposures of Noonday strata. Access to those exposures is easy, there is very little structural complexity, and little or no metamorphism. In addition, the presence of very thick (~200 m) Sentinel Peak with well-developed tubes resting on basement and isolated lenses of glacigenic strata of the Kingston Peak Formation makes it a prime locality for study. As discussed in detail below, the Noonday is a striking match to Marinoan-age cap carbonates. In fact, it cannot be overlooked that the thickness of the Sentinel Peak in the southern Nopah Range is in fact the thickest development of a Marinoan-equivalent cap yet identified, by nearly an order of magnitude (Hoffman *et al.*, 2007). Why there is such a substantial development of this cap carbonate in the Death Valley Region is still an outstanding question.

The correlations presented in Figure 5 clearly demonstrate that the southern Nopah section is missing a great deal of Noonday "time." The interpretation implies that all of Radcliff "time" and the upper portion of Mahogany Flats "time" is unrecorded in this location. Although previous work had identified an unconformity at the contact between Sentinel Peak and Mahogany Flats, the unconformity is rather insidious, having no noticeable jump in the chemostratigraphic profile in that ~ -3‰ rocks are juxtaposed on ~ -3‰ rocks.

The Ibex Hills section has historically been an important section. Similar to the Nopah section it has been studied in significant detail and is the type-section for the "basin facies" (as well as our type-section for "Ibex Hills Facies"). It also contains well-developed sediment gravity flow deposits within the Sentinel Peak that are rare elsewhere. But this section is also relatively incomplete when it comes to Noonday strata in that, although Sentinel Peak and the lower two sub-members of Radcliff are present and well preserved, the upper Radcliff and the Mahogany Flats are absent. In addition the section does not have carbonate rocks in the lower portions of the Radcliff and as such fails to capture the complete negative excursion. Consequently, with C-isotopic data only from the Sentinel Peak and the middle Radcliff, correlations to the Nopah Range would be difficult (e.g., Corsetti and Kaufman 2005).

The Martin Cabin Section is perhaps the most important section presented here. While it is very structurally complex, the effort to decipher this paid off. Its completeness, both stratigraphically and chemostratigraphically, is what allows for making robust correlations that would otherwise be problematic. The lower portion of Noonday at Martin Cabin is very similar to the Ibex Hills, whereas the upper portion is easily correlated to the Eastern Wildrose Canyon section, which has the most complete record of Mahogany Flats.

It also provides a key opportunity to measure the carbon isotopic composition in the global ocean immediately following deposition of a cap dolostone in the Death Valley region due to the presence of carbonate units in the lower Radcliff. This is crucial since most sections that span this time interval globally are dominated by siliciclastic sedimentation immediately following the deposition of the cap dolostone (with the exception of Namibia) (Hoffman 2007).

The eastern Wildrose Canyon section is the thickest, possibly most complete, section of Noonday strata thus far recognized (Figure 5D). The thickness and chemostratigraphic data for the Mahogany Flats Member in this section clearly show that considerably more section (and, by inference, 'time') is preserved here than anywhere else in the Death Valley region (hence the designation as the Type Locality for the Mahogany Flats member). In the southern Nopah section (Figure 5A), Mahogany Flats is approximately 50 meters thick and the topmost strata show a rise in $\delta^{13}C$ values to -1‰ before being truncated by the J-SB1 surface. The Wildrose section contains that same lower 50 meters of Mahogany Flats having the same C-isotopic trend, but continues with another ~150 meters of stratigraphy through which $\delta^{13}C$ values rise to values near +4‰. This implies that the southern Nopah section (and Type Locality for the Noonday Dolomite in eastern Death Valley) is incomplete, either due to significant erosion or non-deposition during this interval. Considering that karsting is developed and that clasts derived from cannibalization of the MF are present, the former is the favored interpretation.

While excellent for exposures of the Mahogany Flats, the lower portions of the Noonday (Sentinel Peak and Radcliff) were not sampled in the eastern Wildrose Canyon section due to relatively poorer exposures and possible structural complications. In contrast, the western Wildrose section contains structurally coherent lower and middle Radcliff units (outcrop ends near the top of the middle Radcliff) and it was chosen as a complementary section to the eastern Wildrose section. Basic correlations between the two sections can easily be made, although minor differences (notably in the lower Radcliff) indicate that direct concatenation of the sections might be unwise. It is possible that several high-angle faults, which were certainly active pre-Noonday and reactivated during Tertiary extension, were also active during Noonday deposition (Harding, 1982). If so the correlations may not be as straight forward as they appear. With that in mind, the two sections were left as separate sections and obtaining a complete profile at the eastern Wildrose section remains a high priority target for further work.

Regional and Global Correlation

CCIP Definition

Carbon-isotopic profiles are widely used in correlation of Neoproterozoic strata, but there is as yet no standardized chemostratigraphic nomenclature. For example, the large negative excursion first characterized in the Shuram Formation in Oman may be variously referred to as the "Shuram excursion," "Wonoka anomaly," "Late Ediacaran negative" or any number of other synonymous descriptions. Although there is little confusion with regard to anomalies of this magnitude, more subtle variations may be clearly defined in only one or two sections, creating ambiguity as to whether the variations are intrabasinal or global in origin. Variations in deposition rates between sections can greatly alter the shape of the curves as well as changing the relative slopes of profile segments.

To simplify this discussion and to focus attention on relatively subtle but potentially correlative features in these curves, a convention that designates specific points on the composite carbon-isotope profile (CCIP) of Halverson *et al.* (2005) is informally proposed here (Figure 14). This convention is roughly analogous to the nomenclature in common use for stratigraphic sequence boundaries, but recognizing of course that the best characterization of chemostratigraphic anomalies would occur during conformable sedimentation, and hence I do not imply any relation between the two. The most reliable basis for correlating two profiles is the identification of maxima and minima, and the value of the carbon isotopic ratios where they occur. These parameters provide a strong basis for correlation, which becomes increasingly unambiguous as the sequence increases. For example, if we had data from an unknown section showing a minimum at -10‰, there is a strong basis for correlation with the Shuram negative, because it is the only known minimum that is that negative. A single minimum at -5‰ would be ambiguous in the absence of other information, because there are multiple examples of it on the CCIP. But as few as one or two additional maxima or minima can resolve the ambiguity. For example, a minimum at -5‰ followed by a maximum at 0‰ only occurs once on the post-Sturtian CCIP, and is diagnostic of basal Ediacaran strata (Figure 14). In addition to maxima and minima, ratios that can be accurately tied to a specific point in time can be used as distinct markers in the CCIP and provide the basis for age assignment of correlative strata that are not radiometrically dated. For example, basal Ediacaran strata in Namibia that are radiometrically constrained at 635 Ma and have an isotopic value of -3‰ is a key marker that provides a strong basis for many sections that have no direct radiometric control but do have the chemostratigraphic marker.

Thus although portions of the CCIP may lend themselves easily to this approach, the early Ediacaran is particularly well suited (Figure 14). I propose to designate key points with “CCIP,” followed by an abbreviation for the associated time period and a subscript. Numbered subscripts are for points that have good regional or global reproducibility. Lettered are applied to points that are either only locally observed or do not yet have an unambiguous match in the CCIP. As such lettered points are not intended as permanent designations. Points that occur at crossings of the 0‰ line are designated with a subscript of “ZX” (“zero-cross”).

CCIP-E_0 is defined as the carbon-isotope value at the base of the Ediacaran. For the CCIP used here, that $\delta^{13}C$ value is -3‰. CCIP-E_1 is the first minima at around -6‰. At CCIP-E_2 the curve nearly reaches 0‰ but begins decreasing just before crossing the zero line. After a small decrease to around -2‰ the curve changes direction once again at CCIP-E_3. After finally crossing the zero line at CCIP-E_{ZX1}, the data become diffuse but generally head toward CCIP-E_4 at a maximum value of around +10‰.

Global Context and Implications for other Laurentian Sections

Namibia and China. The most important outcome of the new composite curve for the Noonday is that it contains five point of correlation with the archetypal Marinoan-age cap carbonate sequence in Namibia (Figure 12). The CCIP-E0, -E1, -E2, -E3, and -EZX1 are well preserved in both sections, providing an unambiguous match on the basis of the isotopic data alone.

However, correspondence of both the lithological characteristics and deposition rates are also a remarkable match. In Namibia, the Keilberg cap carbonate consists of light grey to tan, well laminated dolomicrite with synsedimentary sheet cracks and soft-sediment deformation features developed locally. This is identical to the basal laminated dolomicrite of the Sentinel Peak Member. Tubestone dolomite is also present in both caps. In most sections in the Otavi fold belt sections in Namibia, tubestone dolomite is overlain by thin-bedded to laminated grey dolostone, locally displaying small-scale sedimentary structures such as ripple cross-lamination and rarely, purported giant wave ripples. Although the latter features have not been observed in the Panamint sections of the Sentinel Peak Member, laminated and thin-bedded dolostone identical to that of the upper Keilberg cap carbonate are common. Above this, in the Namibian sections, the thin-bedded dolostone passes gradationally into thin-bedded allodapic limestones and rhythmites of the Maieberg Formation, or a shaley interval typically no more than a few meters thickness that grade upward into limestones of the Maieberg Formation. This latter facies transition (fine siliciclastic rocks overlain by thin limestones) strongly resembles the lower to middle RC. In Death Valley, the lower RC is thicker and better developed than the siliciclastic interval in the basal Maieberg Formation in Namibia, but similarly thick sections of fine siliciclastic rocks intervening between the top of the Keilberg cap carbonate and the first limestones of the Maieberg Formation are known from sections outside of the Otavi fold belt (A. Prave, unpublished data, 2008). Above these siliciclastic rocks, the middle Radcliff thin-bedded allodapic limestones and rhythmites are identical to the Maieberg Formation, even matching in their overall pastel coloring.

It is in the overlying section where lithofacies differences occur between the Namibian and Death Valley sections. In the former, a sharp contact defines a change from thin-bedded limestones of the Maieberg Formation to thin-bedded dolostones and dolograinstones of the Elandshoek Formation. In Death Valley, feldspathic sandstones and shales of the upper RC rest with sharp contact on middle RC. This contact is likely a sequence boundary, although additional mapping is required to assess its overall stratigraphic character. Nevertheless, it is approaching this stratigraphic position in both the Namibian and Death Valley sections that the C-isotopic profile displays a trend towards the 0‰ values of CCIP-E_{ZX1} (Figure 12), lending further confidence to the correlations proposed herein. The overlying MF dolostones are marked by features indicative of deposition in relatively shallow water, such as well-developed stromatolites and microbial mats, cross-bedded and laminated grainstones and locally developed enterolithic bedding and small tepee structures. Similar shallow-water features are recorded in the uppermost parts of the Elandshoek Formation and the overlying Huttenberg Formation in Namibia. And, as shown on Figure 12, the C-isotopic trends between these upper units are comparable.

What is missing in the Death Valley sections is the trend in C-isotopes to strongly positive values of as heavy as +10‰ (e.g., Halverson *et al.*, 2005) defining CCIP-E4, recorded in dolostones of the Huttenberg Formation. Given that the lithofacies and C-isotopic trends between the Death Valley Noonday sections and the Keilberg-Maieberg cap sequence in the Otavi fold belt of Namibia can be matched unit-by-unit and the lower Ediacaran CCIP point-by-point, the absence of these strongly positive values in a suite of shallow-marine carbonate rocks provides further evidence that the basal surface of the

Johnnie Formation represents a disconformity of potentially significant hiatus in the Precambrian sedimentary succession of Death Valley. Above these basal Johnnie beds, the next point of correlation between the CCIP and the Death Valley sections occurs in the Rainstorm Member of the Johnnie, in which the values as low as -12‰ indicate correlation with the Shuram excursion (Corsetti and Kaufman, 2005; Verdel, 2008; Verdel and Wernicke, ms. in review). The age of the Shuram excursion is not known, but is regarded by some workers as about 560 Ma (e.g., Condon *et al.*, 2005; Fike and Grotzinger, 2007).

The base of the Sentinel Peak thereby represents the base of the Ediacaran Period in the Death Valley section. Because CCIP-EO is dated as 635 Ma (Hoffmann *et al.*, 2004), this is also the age of SP. Carbon isotopic data and zircon ages from basal Ediacaran strata in the lower Doushantuo Formation in China (Condon *et al.*, 2005) indicate that CCIP-E2 occurred at 632 Ma. This yields a second geochronological correlation point, indicating that upper RC deposition occurred at 632 Ma. Hence the accumulation rate from the base of SP to the top of middle RC was 150 m/3 Ma = 50 m/Myr, similar to rates in the Namibian cap carbonate sequence (Fig.12).

McKenzie Mountains Section, Canada. Considerable work has been done on the strata in the McKenzie Mountains, which has previously been correlated to Marinoan-aged glaciations (Narbonne *et al.*, 1994; Narbonne and Aitken, 1995; Kaufman *et al.*, 1997; James *et al.*, 2001; Pyle *et al.*, 2004). The new composite curve for the Noonday allows for a much more detailed stratigraphic and chemostratigraphic correlation (Figure 15). The new data reveal a clear correlation of SP with the Ravensthroat Formation. The Radcliff Member is therefore most likely correlative with the Hayhook and Sheepbed

Formations. The overlying Gametrail Formation is lithologically similar to MF, and occupies a similar sequence stratigraphic interval. However, its C isotopic profile suggests that it is younger than MF, because CCIP-E_{ZX1} occurs well within the Sheepbed Formation, whereas in the Noonday it does not occur until the middle of MF.

Pocatello Formation, Idaho. Neoproterozoic glacial and post-glacial strata have also been documented in the Pocatello area of Idaho (Link, 1983; Fanning and Link, 2004; Lorentz *et al.*, 2004; Link *et al.*, 2005; Corsetti *et al.*, 2007a). Correlation with the Noonday Formation is discussed in detail by Corsetti *et al.* (2007a), who concluded that the Noonday correlates with the cap on the “upper diamictite” of the Scout Mountain Member of the Pocatello Formation. This work agrees with that correlation, but disagrees with their interpretation that this cap correlates with the end of the Sturtian glacial period in the South Australian sections. The C-isotopic values and lithologic characteristics of the upper Pocatello cap strata are an excellent match for 635 Ma Marinoan-age cap sequences worldwide. This interpretation calls into question the 667 Ma age inferred for the upper cap dolostone by Fanning and Link (2004), based on a U/Pb zircon age. The accuracy of the U/Pb age is not in question. Rather, the age assignment for the cap, which is based on lithostratigraphic correlation of a geographically isolated, structurally complex exposure of Pocatello strata in the Oxford Mountain, Idaho area, where the age was obtained, with the more complete Pocatello Narrows section exposed more than 50 km to the NW, which contains the cap dolostone, is in question. Testing of this hypothesis will requires a re-examination of the structural and stratigraphic correlations between the incomplete sections yielding the 667 Ma age, and more complete sections of the Pocatello Formation.

Eastern Sonora, Mexico. A glaciogenic diamictite and cap carbonate succession was recently documented in eastern Sonora, Mexico (Corsetti *et al.*, 2007b). The diamictite-cap succession there was also interpreted to be Sturtian in age (ca. 750-700 Ma) based primarily on the chemostratigraphy, because lithologic criteria for discriminating between a Sturtian or Marinoan cap were considered to be equivocal. Highly positive $\delta^{13}C$ values (near +10‰) were measured in the overlying strata suggesting correlation with the 'Keele peak" in South Australia, which occurs between the type Sturtian and Marinoan glacials (Figure 12). However, these values are also characteristic of CCIP-E_4 (Figures 12 and 14, Halverson *et al.*, 2005), and therefore assignment of a pre-Marinoan age to these strata based on isotopes alone is ambiguous.

Based on comparison with the composite profile and lithostratigraphy from Noonday, a Marinoan age for this glaciation seems likely (Figure 16, modified from Figure 4 of Corsetti *et al.*, 2007). The lower portion of the Mina el Mezquite Formation appears similar to the Ibex Hills section (Figure 5B) and the lower portion of the Monteso Formation appears similar to MF in the eastern Wildrose Section (Figure 3D). In particular the succession of dolostone, sandy dolostone with stromatolites, and intraclastic dolostone (possibly karst related) is generally similar to the type MP. In this interpretation the overlying intraclastic dolostone is related to J-SB1.

The drop from -3‰ to -6‰ at the base of the Sonara section matches very well the drop between CCIP-E0 and CCIP-E1 in the SP and RC in the Martin Cabin section, although it is more abrupt than that seen in the lower RC, but CCIP-E1 is recognizable in the upper part of the Mina el Mezquite Formation and coincides nicely with the CCIP-E1 near the base of middle RC. The Sonoran data do not clearly indicate CCIP-E2 and -E3 but they are broadly compatible with these trends. If the placement of CCIP-E2 and E3 are correct it would most likely mean that the correlative base of the Mahogany Flats is older in the Sonora Region.

Shortly after CCIP-EZX1, the Sonoran curve is truncated by a disconformity that is lithostratigraphically and chemostratigraphically in a position similar to J-SB1. The remainder of the Monteso Formation is tentatively correlated with the Johnnie Formation. Carbon isotopic data for the lower portion of the Johnnie is sparse (Corsetti and Kaufman, 2003; Verdel 2008) and a replotted section modified slightly from these studies is shown in Figure 17. While CCIP-E4 is clearly present in the global composite (Figure 14), it is not present in Figure 17. Thus in this interpretation the upper Monteso Formation preserves strata that may not be present in the Death Valley region. Thus the placement of the surface equivalent to J-SB1 in Sonora is clearly equivocal, and it may be higher in the section.

CONCLUSIONS

New mapping and chemostratigraphic data in the northern Panamint Range and reappraisal of well studied sections in the eastern Death Valley region has provided the basis for constructing a relatively complete depositional record of the Noonday Formation. This unit defines a cap carbonate sequence and can now be viewed as among the most comprehensive archives on the globe of sedimentation and fluctuating oceanic C-isotopic composition in the wake of the Marinoan glaciation. These data demonstrate marked condensation of the Noonday in eastern Death Valley sections relative to those in the Panamints. In the latter region, a new stratigraphy has been constructed containing three regionally persistent members. From base to top, these are the Sentinel Peak (SP), Radcliff (RC, with three regionally developed sub-members lower, middle and upper) and Mahogany Flats (MP) members. SP ranges from a few meters to more than 200 m in thickness and consists of light grey to pale orange laminated dolomicrite with locally developed tubestone. RC typically ranges from 100 to 200 m thick and consists of a basal fine-grained arkosic facies with rare carbonate beds, a middle rhythmite and thin-bedded limestone facies and an upper siliciclastic interval with variably developed feldspathic sandstone. MF is a grey dolostone featuring stromatolitic boundstone and associated dolarenitic and quartz arenitic intermound fill. It is of variable thickness owing to erosional truncation beneath the basal sequence boundary of the overlying Johnnie Formation, but at its type locality in the Wildrose Canyon area it is more than 200 m thick. All or part of each of these three units can be recognized in eastern Death Valley sections. This revised nomenclature is thus applicable basin-wide and supersedes all formal and informal nomenclature in previous use. In particular, use of “Redlands Member” and “Ibex Formation” should be abandoned, and the dolomitic quartz sandstone unit previously referred to by many workers as the “upper Noonday” should be included as part of the lowermost Johnnie Formation.

The new composite C-isotopic profile constructed for the Noonday has been constructed and provides five points of correlation with the archetypal Marinoan-age cap carbonate sequence in Namibia. SP includes a basal Ediacaran value of -3‰ (CCIP-E0). Values decline upward through the lower RC, reaching a minimum of -6‰ at the base of middle RC (CCIP-E1). Values increase to a maximum near 0‰ at the top of middle RC

(CCIP-E2). A subsequent decline to a minimum at -2‰ (CCIP-E3) in lower MP is followed by a zero crossing about 1/3 of the way up in the thickest MP sections (CCIP-EZX1) and increasing further to values as high as +3 in youngest MP strata. These results (1) place SP at the base of the Ediacaran Period; (2) constrain deposition of SP through middle RC strata (inclusive) between 635 and 632 Ma; and (3) support the interpretation that the Wildrose Diamictite Submember of the Kingston Peak Formation represents at least part of the Marinoan glacial interval.

Comparison of other Laurentian sections to the Noonday strongly suggests that the Ravensthroat Formation in the MacKenzie Mountains, the cap dolostone above the 'upper diamictite' of the Pocatello Formation in Idaho, and the cap dolostone within the Mina el Mezquite Formation in Sonora are all basal Ediacaran in age.

REFERENCES

Abolins, M., Oskin, R., Prave, T., Summa, C., and Corsetti, F.A., 2000, Neoproterozoic glacial record in the Death Valley region, California and Nevada: GSA Field Guide, v. 2, p. 319-335.

Abolins, M.J., 1999, I, Stratigraphic constraints on the number of discrete Neoproterozoic glaciations and the relationship between glaciation and Ediacaran evolution; II, The Kwichup Spring Thrust in the northwestern Spring Mountains, Nevada; implications for large-magnitude extension and the structure of the Cordilleran thrust belt [Doctoral thesis]: Pasadena, California Institute of Technology.

Albee, A.L., Labotka, T.C., Lanphere, M.A., and McDowell, S.D., 1981, Geologic map of the Telescope Peak Quadrangle, California.

Cloud, P., Wright, L.A., Williams, E.G., Diehl, P.E., and Walter, M.R., 1974, Giant Stromatolites and Associated Vertical Tubes from the Upper Proterozoic Noonday Dolomite, Death Valley Region, Eastern California: Geological Society of America Bulletin, v. 85, p. 1869-1882.

Condon, D., Zhu, M.Y., Bowring, S., Wang, W., Yang, A.H., and Jin, Y.G., 2005, U-Pb ages from the neoproterozoic Doushantuo Formation, China: Science, v. 308, p. 95-98.

Corsetti, F.A., and Grotzinger, J.P., 2005, Origin and significance of tube structures in Neoproterozoic post-glacial cap carbonates: Example from Noonday Dolomite, Death Valley, United States: Palaios, v. 20, p. 348-362.

Corsetti, F.A., and Hagadorn, J.W., 2000, Precambrian-Cambrian transition: Death Valley, United States: Geology, v. 28, p. 299-302.

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.

Corsetti, F.A., 2005, The relationship between the Neoproterozoic Noonday Dolomite and the Ibex Formation: New observations and their bearing on 'snowball Earth': Earth-Science Reviews, v. 73, p. 63-78.

Corsetti, F.A., Link, P.K., and Lorentz, N.J., 2007, δ13C chemostratigraphy of the Neoproterozoic succession near Pocatello, Idaho, U. S. A.; implications for glacial chronology and regional correlations, in Link, P.K., and Lewis, R.S., eds., Special Publication - Society for Sedimentary Geology, vol. 86, p. 193-205.

Corsetti, F.A., Stewart, J.H., and Hagadorn, J.W., 2007, Neoproterozoic diamictite-cap carbonate succession and delta C-13 chemostratigraphy from eastern Sonora, Mexico: Chemical Geology, v. 237, p. 129-142.

DeYoung, D.P., 2005, The Neoproterozoic Ibex Formation, eastern California: Stratigraphic and Sedimentological Constraints on Ice Age and Carbonate Precipitation Events of Southern Death Valley, University of California, Riverside.

DeYoung, D.P., Kennedy, M.J., Wright, L.A., Troxel, B.W., and Anonymous, 2003, Slumping of large carbonate mounds into deep water; a record of rapid carbonate precipitation following a Neoproterozoic deglaciation: Abstracts with Programs - Geological Society of America, v. 35, p. 471.

Fanning, C.M., and Link, P.K., 2004, U-Pb SHRIMP ages of Neoproterozoic (Sturtian) glaciogenic Pocatello Formation, southeastern Idaho: Geology, v. 32, p. 881-884.

Halverson, G.P., Hoffman, P.F., Schrag, D.P., Maloof, A.C., and Rice, A.H.N., 2005, Toward a Neoproterozoic composite carbon-isotope record: Geological Society of America Bulletin, v. 117, p. 1181-1207.

Harding, M.B., 1987, The geology of the Wildrose Peak area, Panamint Mountains, California [Map thesis]: Laramie, University of Wyoming.

Hazzard, J.C., 1937, Paleozoic section in the Nopah and Resting Springs Mountains, Inyo County, California: California Journal of Mines and Geology, v. 33, p. 270-339.

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.

Hewett, D.F., 1956, Geology and mineral resources of the Ivanpah Quadrangle, California and Nevada, U. S. Geological Survey Professional Paper, p. 172.

Hoffman, P.F., Halverson, G.P., Domack, E.W., Husson, J.M., Higgins, J.A., and Schrag, D.P., 2007, Are basal Ediacaran (635 Ma) post-glacial "cap dolostones" diachronous?: Earth and Planetary Science Letters, v. 258, p. 114-131.

Hoffman, P.F., Kaufman, A.J., Halverson, G.P., and Schrag, D.P., 1998, A Neoproterozoic snowball earth: Science, v. 281, p. 1342-1346.

James, N.P., Narbonne, G.M., and Kyser, T.K., 2001, Late Neoproterozoic cap carbonates: Mackenzie Mountains, northwestern Canada: precipitation and global glacial meltdown: Canadian Journal of Earth Sciences, v. 38, p. 1229-1262.

Johnson, B.K., 1957, Geology of a part of the Manly Peak Quadrangle, southern Panamini Range, California: University of California Publications in Geological Sciences, v. 30, p. 353-423.

Labotka, T.C., Albee, A.L., Lanphere, M.A., and Mcdowell, S.D., 1980, Stratigraphy, Structure, and Metamorphism in the Central Panamint Mountains (Telescope-Peak Quadrangle), Death-Valley Area, California - Summary: Geological Society of America Bulletin, v. 91, p. 125-129.

Link, P.K., 1983, Glacial and Tectonically Influenced Sedimentation in the Upper Proterozoic Pocatello Formation, Southeastern Idaho: Geological Society of America Memoirs, v. 157, p. 165-181.

Link, P.K., Corsetti, F.A., and Lorentz, N.J., 2005, Pocatello Formation and overlying strata, southeastern Idaho; snowball Earth diamictites, cap carbonates, and Neoproterozoic isotopic profiles: GSA Field Guide, v. 6, p. 251-259.

Lund, K., Aleinikoff, J.N., Evans, K.V., and Fanning, C.M., 2003, SHRIMP U-Pb geochronology of neoproterozoic Windermere Supergroup, central Idaho: Implications for rifting of western Laurentia and synchroneity of Sturtian glacial deposits: Geological Society of America Bulletin, v. 115, p. 349-372.

Lorentz, N.J., Corsetti, F.A., and Link, P.K., 2004, Seafloor precipitates and C-isotope stratigraphy from the Neoproterozoic Scout Mountain Member of the Pocatello Formation, southeast Idaho: implications for Neoproterozoic earth system behavior: Precambrian Research, v. 130, p. 57-70.

McDowell, S.D., 1967, The intrusive history of the Little Chief Granite Porphyry Stock (Mesozoic), central Panamint Range, California; I, Structural relationships; II, Petrogenesis, based on electron microprobe analyses of the feldspars [Doctoral; Monographic thesis]: Pasadena, CA, United States (USA), California Institute of Technology.

Miller, J.M.G., 1985, Glacial and syntectonic sedimentation; the upper Proterozoic Kingston Peak Formation, southern Panamint Range, eastern California: Geological Society of America Bulletin, v. 96, p. 1537-1553.

Murphy, F.M., 1929, Geology and ore deposits of a part of the Panamint Range (California) [Master's thesis]: Pasadena, California Institute of Technology.

Murphy, F.M., 1930, Geology of the Panamint silver district, California: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 25, p. 305-325.

Murphy, F.M., 1932, Geology of a part of the Panamint Range, California, Report XXVII of the State Mineralogist, Volume 28: San Francisco, California Department of Natural Resources, Division of Mines and Geology, p. 329-356.

Narbonne, G.M., and Aitken, J.D., 1995, Neoproterozoic of the Mackenzie Mountains, Northwestern Canada: Precambrian Research, v. 73, p. 101-121.

Narbonne, G.M., Kaufman, A.J., and Knoll, A.H., 1994, Integrated Chemostratigraphy and Biostratigraphy of the Windermere Supergroup, Northwestern Canada - Implications for Neoproterozoic Correlations and the Early Evolution of Animals: Geological Society of America Bulletin, v. 106, p. 1281-1292.

Prave, A.R., 1999, Two diamictites, two cap carbonates, two delta C-13 excursions, two rifts: The Neoproterozoic Kingston Peak Formation, Death Valley, California: Geology, v. 27, p. 339-342.

Pyle, L.J., Narbonne, G.M., James, N.P., Dalrymple, R.W., and Kaufman, A.J., 2004, Integrated Ediacaran chronostratigraphy, Wernecke Mountains, northwestern Canada: Precambrian Research, v. 132, p. 1-27.

Snow, J.K., and Wernicke, B., 1993, Large-Magnitude Permian Shortening and Continental-Margin Tectonics in the Southern Cordillera - Reply: Geological Society of America Bulletin, v. 105, p. 280-283.

Stewart, J.H., 1970, Upper Precambrian and Lower Cambrian strata in the southern Great Basin, California and Nevada: U. S. Geological Survey Professional Paper, v. 620, 206 pp.

Summa, C.L., 1993, Sedimentologic, stratigraphic, and tectonic controls of a mixed carbonate-siliciclastic succession; Neoproterozoic Johnnie Formation, Southeast California [Doctoral thesis]: Cambridge, Massachusetts Institute of Technology.

Troxel, B.W., 1982, Basin facies (Ibex Formation) of the Noonday Dolomite, southern Saddle Peak Hills, southern Death Valley, California, in Cooper, J.D., Troxel, B.W., and Wright, L.A., eds., Geology of selected areas in the San Bernardino Mountains, western Mojave Desert, and southern Great Basin, California: Shohone, Death Valley Publ. Co., p. 43-48.

Verdel, C., 2008, I: Cenozoic geology of Iran: An integrated study of extentional tectonics and related volcanism; II: Ediacaran stratigraphy of the North American Cordilleran: New observations from eastern California and northern Utah [Doctoral thesis]: Pasadena, California Institute of Technology.

Wernicke, B., Axen, G.J., and Snow, J.K., 1988, Basin and Range Extensional Tectonics at the Latitude of Las-Vegas, Nevada: Geological Society of America Bulletin, v. 100, p. 1738-1757.

Wernicke, B., Snow, J.K., Hodges, K.V., and Walker, J.D., 1993, Structural constraints on Neogene tectonism in the southern Great Basin, in Lahren, M.M., Trexler, J.H., Jr., and Spinosa, C., eds.: Reno, University of Nevada.

Williams, E.G., Wright, L.A., and Troxel, B.W., 1974, The noonday dolomite and equivalent stratigraphic units, southern Death Valley region, California, Guidebook; Death Valley region, California and Nevada: Shoshone, Death Valley Publ. Co., p. 73-77.

Wright, L., Williams, E.G., and Cloud, P., 1978, Algal and cryptalgal structures and platform environments of the late pre-Phanerozoic Noonday Dolomite, eastern California: Geological Society of America Bulletin, v. 89, p. 321-333.

Wright, L.A., and Troxel, B.W., 1967, Limitations on Right-Lateral Strike-Slip Displacement Death Valley and Furnace Creek Fault Zones California: Geological Society of America Bulletin, v. 78, p. 933.

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, Guidebook; Death Valley Region, California and Nevada (see Geological Society of America): Shoshone, Death Valley Publication Company, p. 27-36.

Wright, L.A., Williams, E.G., and Troxel, B.W., 1984, Appendix II; Type section of the newly-named Proterozoic Ibex Formation, the basinal equivalent of the Noonday Dolomite, Death Valley region, California: Map Sheet - California Division of Mines and Geology, v. 34, p. 25-31.

FIGURES

Figure 1. *Map showing study areas and geographic names mentioned in text.*

Figure 2. *Composite stratigraphic column of Neoproterozoic strata in the Death Valley region (modified from Stewart 1970; Wright et al. 1974; Labotka et al. 1980; Heaman and Grotzinger 1992), showing age constraints and key markers discussed in text. Lithologic symbols: Diagonal wavy lines, Early Proterozoic basement; plus symbols, diabase sills; v-pattern, mafic volcanics; cross-hatching, dolostone; brick pattern, limestone; stipple, sandstone; open circles, conglomerate (fine) or diamictite (bold); dash-dot lines, siltstone; dashed lines, shale.*

Figure 3. *Map showing distribution of the four members of the Kingston Peak Formation and the Noonday Formation in the Panamint Range. Locations discussed in text are labeled.*

Figure 4. *History of nomenclature used to describe strata belonging to the Noonday Formation. The composite Noonday column at the left is a combination of both Nopah Range Facies and Ibex Hills Facies and is used for illustrative purposes only and is not meant to suggest the Noonday Formation exists in that completeness at any one locality. The new proposed nomenclature is shown on the right side of the figure.*

Figure 5. *New correlations of Noonday strata in the Death Valley Region. Locations of sections are shown in Figure 1 (for A and B) and Figure 3 (C-E). Carbon isotopic data is shown to the right of each section. Datum is the base of the Sentinel Peak Member of the*

Noonday. Tie lines connect contacts between members and sub-members of the Noonday Formation, as well as the Noonday-Johnnie Contact (J-SB1). ***A.*** *Southern Nopah Range.* ***B.*** *Ibex Hills (type locality of the "Ibex Formation").* ***C.*** *Martin Cabin, Panamint Range.* ***D.*** *Eastern Wildrose Canyon, Panamint Range.* ***E****. Western Wildrose Canyon, Panamint Range.*

Figure 6. *Photographs of the Sentinel Peak Member.* ***A.*** *Laminated to thin-bedded dolomicrite, Providence Ridge (younging is from left to right); base of member sits sharply on mixed-clast diamictite of Wildrose Member and top of member is itself sharply overlain by purplish fine-grained arkosic sandstones and shales of the lower Radcliff Member.* ***B.*** *Laminated to thin-bedded dolomicrite, Silurian Hills (younging is from left to right); base of Member rests with sharp contact on mixed-clast diamictite of the Wildrose Member whereas the top of the Sentinel Peak has, relative to the section at Providence Ridge, a more gradual transition into the overlying arkosic sandstone of the lower Radcliff Member (note the thin tan-colored dolostone beds weathering in positive relief in the middle-ground of the sunlit portion of photo).* ***C.*** *Thin 'event' beds, Ibex Hills. These beds are interpreted as thin, carbonate-clast-rich debrites (note inverse grading of clasts particularly in lower bed) with fine –grained tops likely representing hemipelagic rainout and settling. The topmost debrite is sharply overlain by platy yellow tan dolomicrites with shale partings of the Sentinel Peak Member.* ***D.*** *Isopachus cement filled sheet cracks in laminated dolomicrite, southern Nopah Range; this facies is typical of the lower portions of the Sentinel Peak Member.* ***E-H.*** *Examples of tubestone facies; representative examples of 'tubes' when viewed on bedding planes (E,F) and in cross-section (G,H) showing the typical plan-view circular and vertical tube-like*

characteristics (E,G – South Skidoo section; F,H – southern Nopah Range section). Tubes are commonly filled with coarse spar generally composed of quartz but locally calcite (although some examples contain dolomicritic infill).

Figure 7. *Photographs of Radcliff and Mahogany Flats Members.* **A-F.** *Examples of rhythmite and thin-bedded allodapic limestones typical of the middle Radcliff Member and showing variation in the carbonate to siliciclastic ratio ranging from 100:0 to 50:50, or less (A,C – East Wood Canyon; B,D – southern Black Mountains; E – Wire Peak, near Martin Cabin, northern Panamints; G – eastern Wildrose Canyon).* **G-H.** *Stromatolites in the Mahogany Flats Member (G – Type section, eastern Wildrose Canyon; H – southern Nopah Range).*

Figure 8. *Photographs of key textures and contacts discussed in text.* **A.** *Sentinel Peak Member displaying spar-filled vugs in light grey dolomicrite, Wood Canyon locality.* **B.** *Transitional contact from the platy dolostone rhythmites with thin shale partings typical of the upper Sentinel Peak Member into the basal purplish arkosic shales and fine-siliciclastics of the basal Radcliff Member; note the one thin, intraformational rhythmite breccia bed in the center of the photo; southern Black Mountains.* **C.** *Example of the sand-filled karst and karstic breccia developed along the sequence boundary (JSB-1) at the base the Johnnie Formation; southern Nopah Range.* **D.** *Sentinel Peak Member of the Ibex Hills Facies; this outcrop shows nicely the interlayered nature of tubestone-clast-bearing sediment gravity flow deposits and thin-bedded platy dolostones of the Sentinel Peak Member; two tubestone-breccia beds are present and marked by a concentration of brown silicified lenses and layers, a thicker one in then lower third of the outcrop*

(hammer head is resting on a large tubestone clast) and a thinner bed in the upper third of the outcrop, Saddle Peak Hills.

Figure 9. ***A.*** *This photo from the southern Black Mountains shows the lateral facies change that typifies the middle sub-member of the Radcliff Member (Znrm). Here, limestone rhythmite facies in the RHS of the outcrop laterally shale out into pastel and light-colored marls and shales in the LHS of the outcrop. Note that lower Radcliff Member rocks (Znrl) drape and bury the underlying Sentinel Peak Member (Znsp) which undergoes a depositional thinning from left to right. Yb – Beck Springs Dolomite; Zkw – Wildrose Member, Kingston Peak Formation; Znmf – Mahogany Flats Member.* ***B.*** *Onlap relationship of the lower Radcliff Member rocks(Znrl) onmmto a uniformly thick Sentinel Peak Member (Znsp), all depositionally overlain by the rhythmites and thin-bedded limestones of the middle Radcliff Member (Znrm); western Wildrose Canyon, Panamint Range.*

Figure 10. *North to South stratigraphic cross-section of the lower part of the Radcliff Member (formerly lower Ibex Formation of previous workers) in the southern Ibex Hills; section covers approximately 1.5 km of strike and individual measured sections are broadly evenly spaced. Section D is the same as the Type Locality of Wright et al. (1984) for their Ibex Formation. Note that debrite beds are intra-Sentinel-Peak deposits; their bases are sharp and commonly erosive, and bed geometries are lenticular across the length of the outcrop. Datum is the base of a thin, graded bed 'capping' one of the thick debrite units.*

Figure 11A. *Sentinel Peak C-isotopic data (plotted as $\delta^{13}C$‰ V-PDB) plotted to normalized thicknesses. The reproducibility of data are striking given that stratigraphic thicknesses vary over two orders of magnitude (215 m in the southern Nopah Range vs. 2 m in Staircase Canyon) and come from sections that range from unmetamorphosed to amphibolite facies.*

Figure 11B. *Sentinel Peak C and O-isotopic data plotted according to metamorphic grade. Metamorphosed sections are plotted with closed circles and unmetamorphosed sections are plotted with crosses. The right pane shows the $\delta^{13}C$ values and the left pane shows the $\delta^{18}O$ values. In contrast to the narrow range of the $\delta^{13}C$ data, $\delta^{18}O$ values range from -5 to -15 ‰, with metamorphosed sections on average exhibiting a ~5 ‰ negative shift.*

Figure 11C. *C-O cross plots for Sentinel Peak samples and for all Noonday Formation samples, demonstrating a lack of correlation and suggesting primary origin for the C-isotopic data.*

Figure 11D. *Sentinel Peak C-isotopic data plotted according to sedimentary facies. Nopah Range facies sections are plotted with red lines, Ibex Hills facies are plotted with blue lines. No systematic trends based on facies are evident.*

Figure 12. *Composite stratigraphic and chemostratigraphic section of the Noonday Formation (C-isotopic data plotted as $\delta^{13}C$‰ V-PDB, heights in meters). Data are compared to the archetypal Marinoan equivalent cap-carbonate sequence in Namibia (Keilberg-Maieberg succession). Tie points are denoted as CCIP points (see text for discussion).*

Figure 13. *Upper Kingston Peak Formation and Noonday Formation exposure in the southern Black Mountains.* ***A.*** *Interpretive contacts showing patchy preservation of erosional remnants of the Sentinel Peak Member below the basal surface of the Radcliff Member (e.g., Corsetti and Kaufman, 2005).* ***B.*** *Preferred interpretation, taking into account low-angle Tertiary normal faulting (see text for discussion).*

Figure 14. *The interpreted global composite C-isotopic profile (CCIP) of Cryogenian-Ediacaran time showing position of CCIP points discussed in text (modified from Halverson et al., 2005).*

Figure 15. *MacKenzie Mountains $\delta^{13}C$ profile showing positions of CCIP tie points (modified from James et al., 2001; inset from Hoffman and Schrag, 2002; see text for discussion).*

Figure 16. *Eastern Sonora, Mexico $\delta^{13}C$ profile showing positions of CCIP tie points (modified from Corsetti et al., 2007b; see text for discussion).*

Figure 17. *Composite section of Noonday and Johnnie Formations (modified from Corsetti et al., 2003) showing $\delta^{13}C$ profile. Note the absence of strongly positive values tipyfiying most post-Marinoan cap-carbonates world wide (CCIP-E4; e.g., Figures 14 and 16; see text for discussion).*

Figure 1

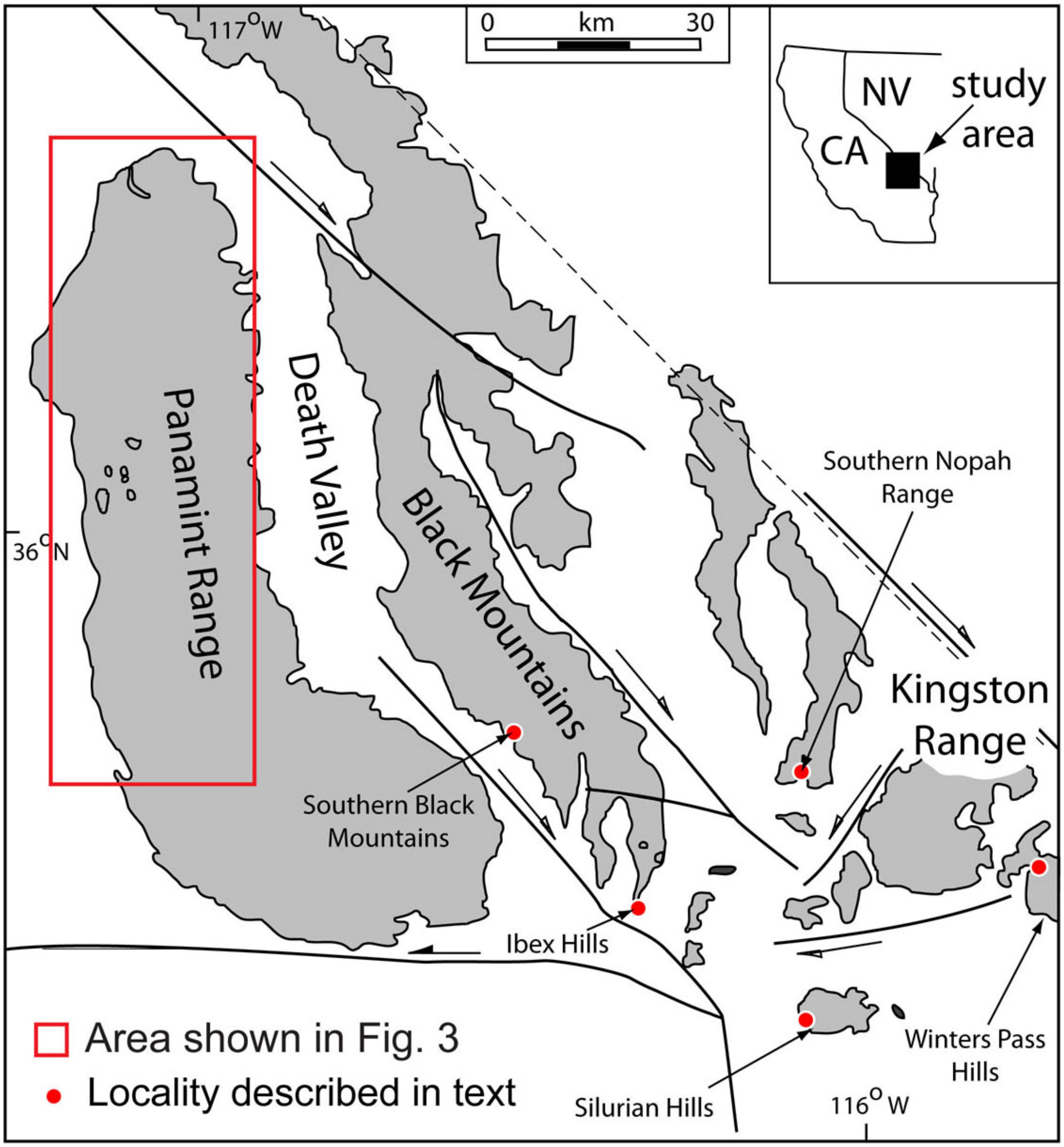
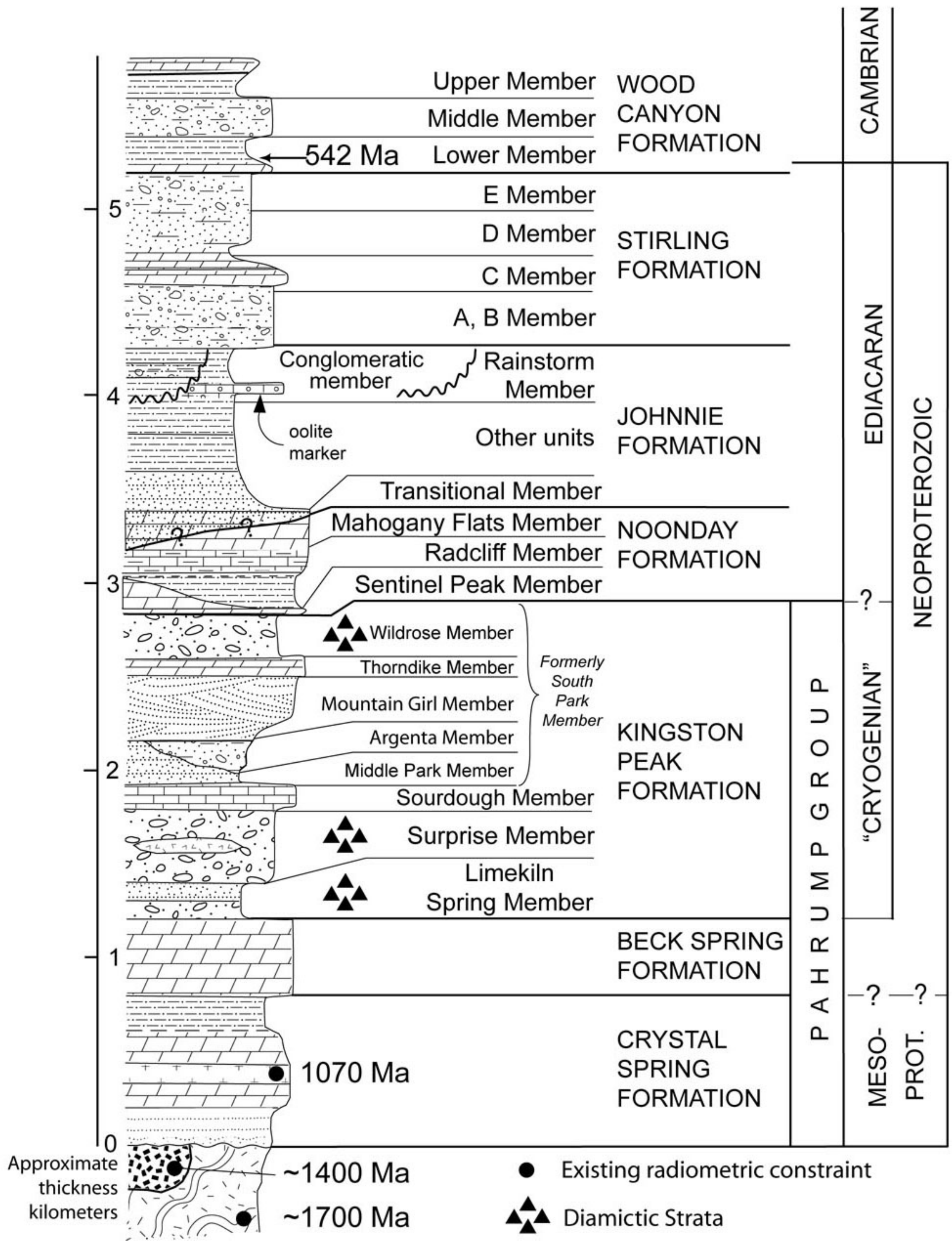

0
km
30
117° W
NV
study
area
CA
Panamint Range
Death Valley
Black Mountains
Southern Nopah
Range
36° N
Kingston
Range
Southern Black
Mountains
Ibex Hills
Winters Pass
Hills
Silurian Hills
116° W
Area shown in Fig. 3
Locality described in text

Figure 2



CAMBRIAN
EDIACARAN
NEOPROTEROZOIC
"CRYOGENIAN"
MESO-PROT.
PAHRUMP GROUP
Upper Member
Middle Member
Lower Member
542 Ma
WOOD CANYON FORMATION
E Member
D Member
C Member
A, B Member
STIRLING FORMATION
Conglomeratic member
Rainstorm Member
oolite marker
Other units
JOHNNIE FORMATION
Transitional Member
Mahogany Flats Member
Radcliff Member
Sentinel Peak Member
NOONDAY FORMATION
Wildrose Member
Thorndike Member
Mountain Girl Member
Argenta Member
Middle Park Member
Formerly South Park Member
Sourdough Member
Surprise Member
Limekiln Spring Member
KINGSTON PEAK FORMATION
BECK SPRING FORMATION
CRYSTAL SPRING FORMATION
1070 Ma
~1400 Ma
~1700 Ma
Approximate thickness kilometers
0
1
2
3
4
5
Existing radiometric constraint
Diamictic Strata

Figure 3

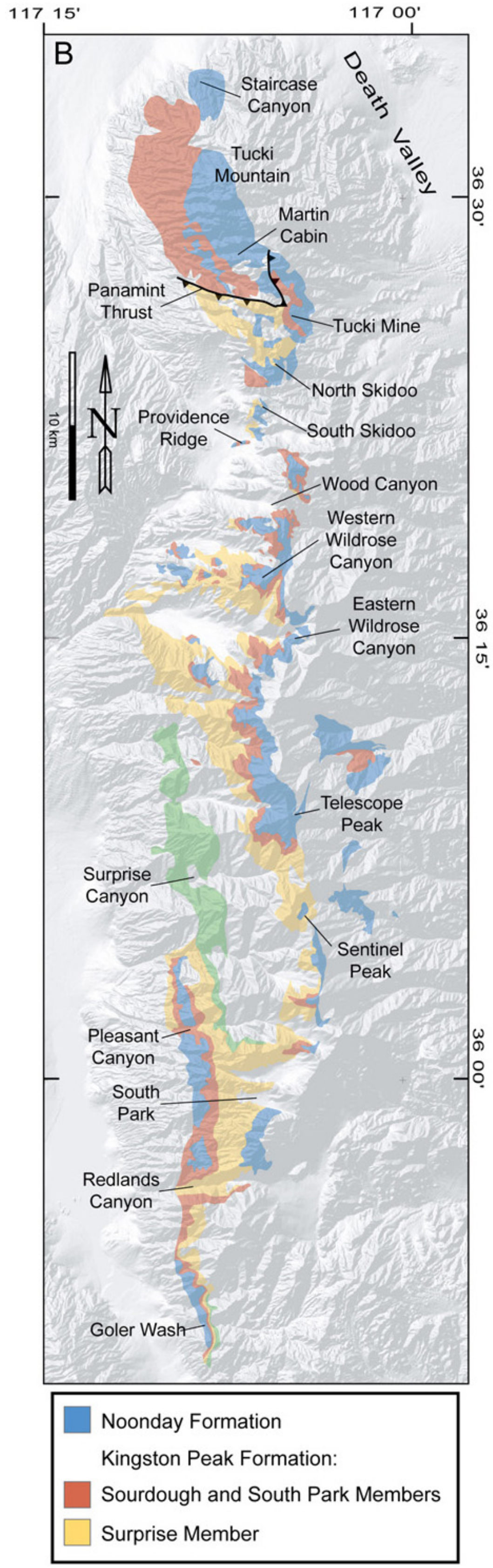

117 15'
117 00'
B
Death Valley
Staircase Canyon
Tucki Mountain
Martin Cabin
Panamint Thrust
Tucki Mine
North Skidoo
South Skidoo
Providence Ridge
10 km
N
Wood Canyon
Western Wildrose Canyon
Eastern Wildrose Canyon
36 30'
36 15'
36 00'
Telescope Peak
Surprise Canyon
Sentinel Peak
Pleasant Canyon
South Park
Redlands Canyon
Goler Wash
Noonday Formation
Kingston Peak Formation:
Sourdough and South Park Members
Surprise Member

Figure 4

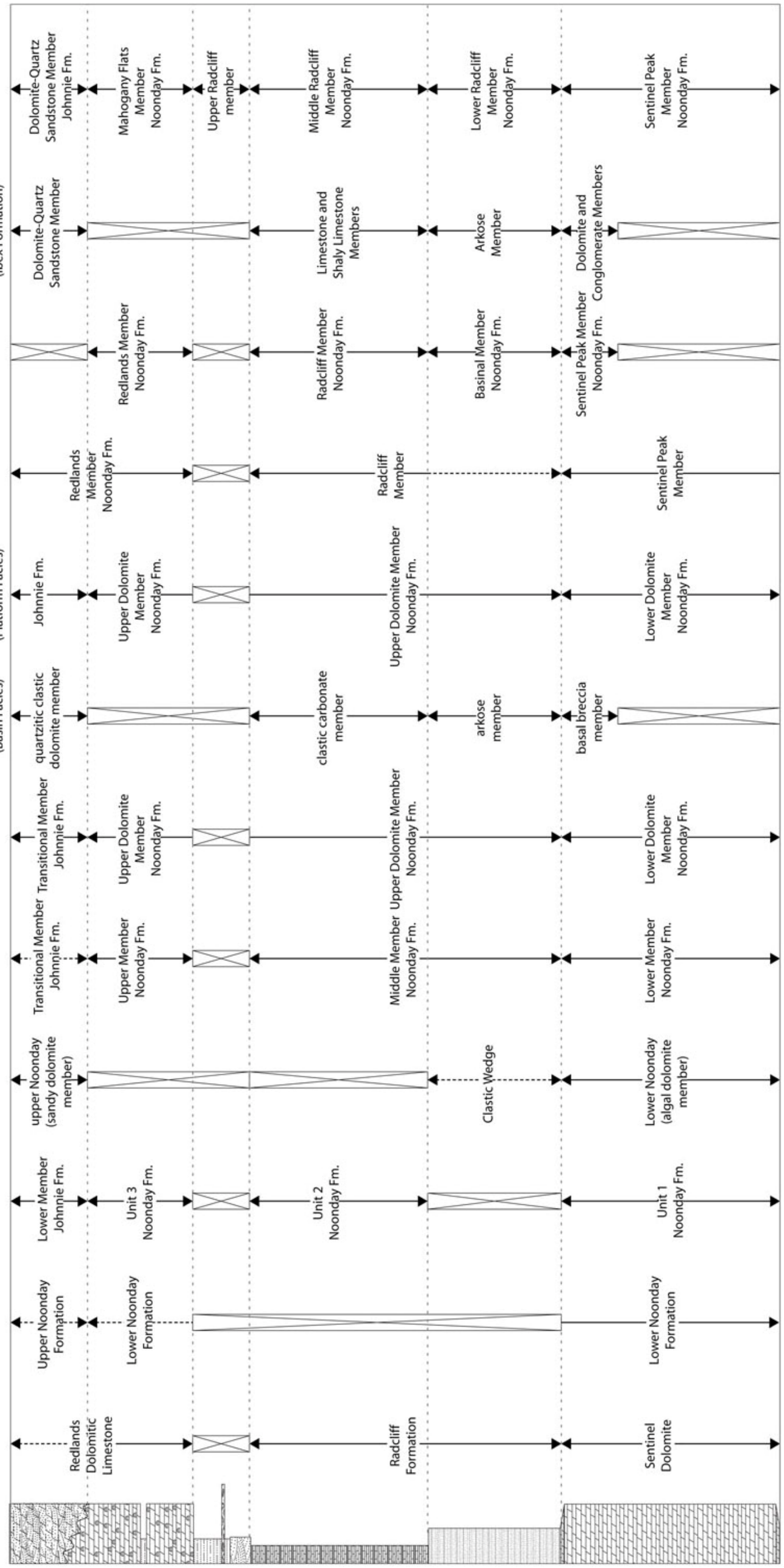

This Study
Dolomite-Quartz Sandstone Member Johnnie Fm.
Mahogany Flats Member Noonday Fm.
Upper Radcliff member
Middle Radcliff Member Noonday Fm.
Lower Radcliff Member Noonday Fm.
Sentinel Peak Member Noonday Fm.
Wright and Troxel (1984) (Ibex Formation)
Dolomite-Quartz Sandstone Member
Limestone and Shaly Limestone Members
Arkose Member
Dolomite and Conglomerate Members
Harding (1982)
Redlands Member Noonday Fm.
Radcliff Member Noonday Fm.
Basinal Member Noonday Fm.
Sentinel Peak Member Noonday Fm.
Albee et al (1981), Labotka et al (1980)
Redlands Member Noonday Fm.
Radcliff Member
Sentinel Peak Member
Williams et al (1974) (Platform Facies)
Johnnie Fm.
Upper Dolomite Member Noonday Fm.
Upper Dolomite Member Noonday Fm.
Lower Dolomite Member Noonday Fm.
Williams et al (1974) (Basin Facies)
quartzitic clastic dolomite member
clastic carbonate member
arkose member
basal breccia member
Wright et al (1978)
Transitional Member Johnnie Fm.
Upper Dolomite Member Noonday Fm.
Upper Dolomite Member Noonday Fm.
Lower Dolomite Member Noonday Fm.
Cloud et al (1974)
Transitional Member Johnnie Fm.
Upper Member Noonday Fm.
Middle Member Noonday Fm.
Lower Member Noonday Fm.
Stewart (1970)
upper Noonday (sandy dolomite member)
Clastic Wedge
Lower Noonday (algal dolomite member)
Johnson (1945)
Lower Member Johnnie Fm.
Unit 3 Noonday Fm.
Unit 2 Noonday Fm.
Unit 1 Noonday Fm.
Hazzard (1937)
Upper Noonday Formation
Lower Noonday Formation
Lower Noonday Formation
Murphy (1930)
Redlands Dolomitic Limestone
Radcliff Formation
Sentinel Dolomite

Figure 5

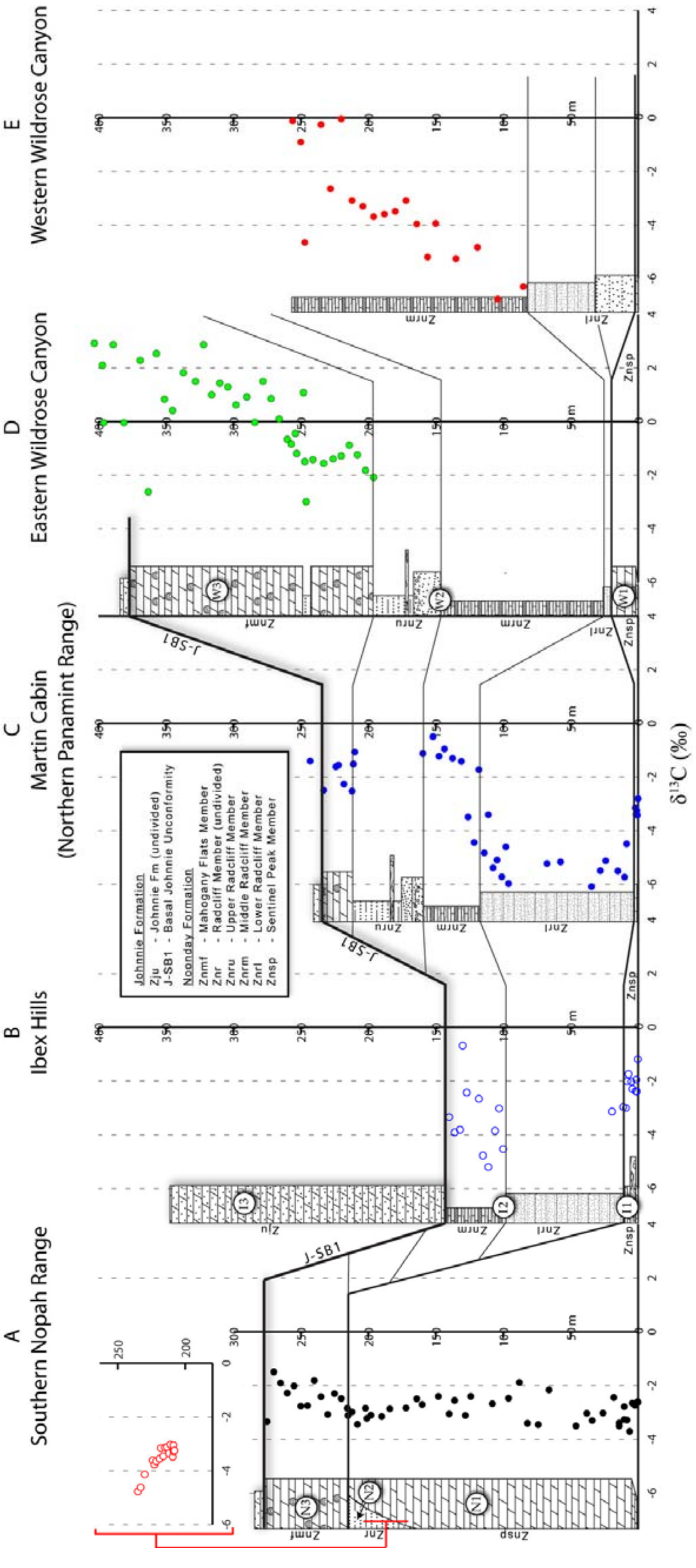

A
Southern Nopah Range
B
Ibex Hills
C
Martin Cabin
(Northern Panamint Range)
D
Eastern Wildrose Canyon
E
Western Wildrose Canyon
Johnnie Formation
Zju - Johnnie Fm (undivided)
J-SB1 - Basal Johnnie Unconformity
Noonday Formation
Znmf - Mahogany Flats Member
Znr - Radcliff Member (undivided)
Znru - Upper Radcliff Member
Znrm - Middle Radcliff Member
Znrl - Lower Radcliff Member
Znsp - Sentinel Peak Member
J-SB1
δ13C (‰)

Figure 6

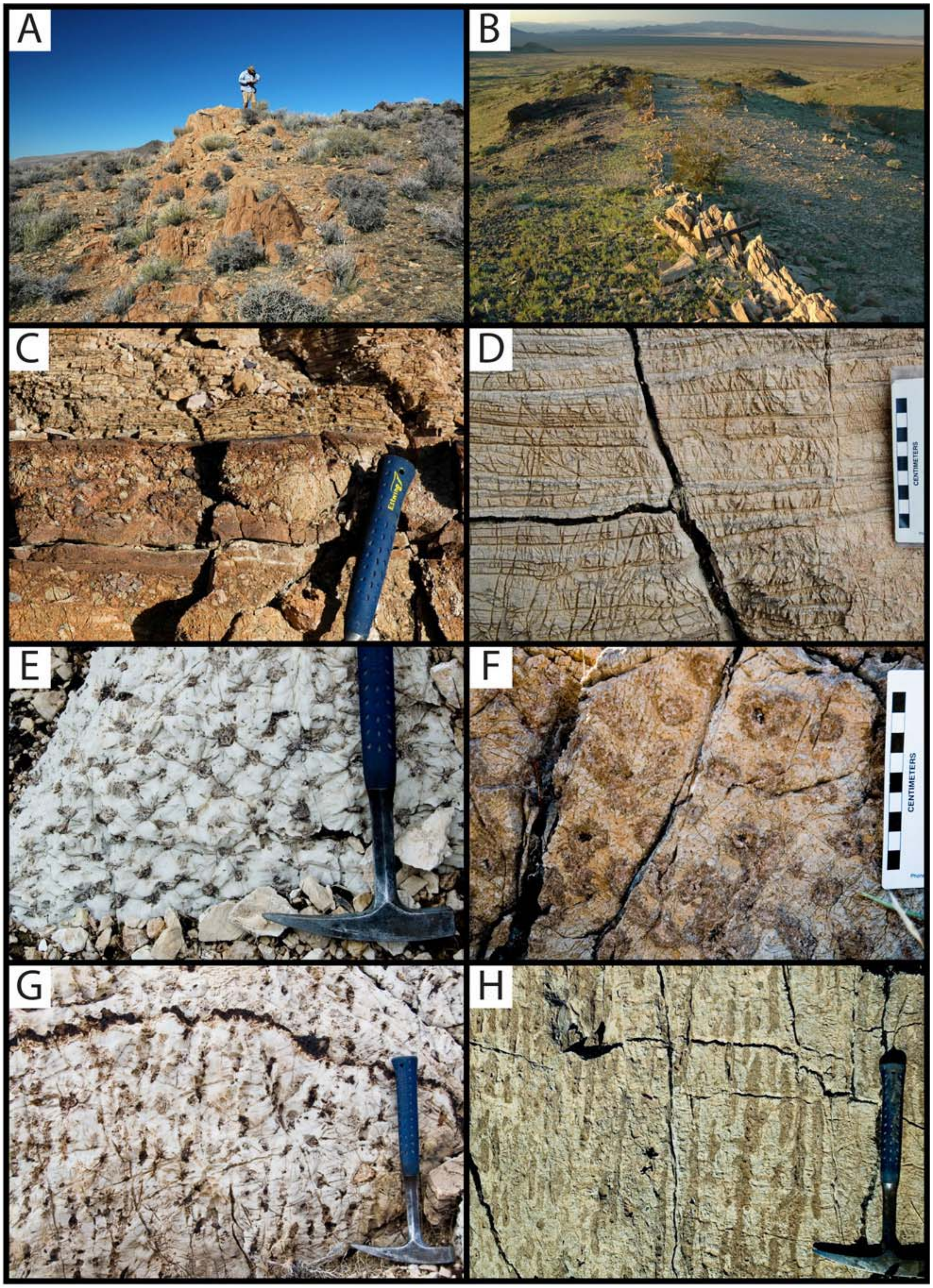


Figure 7

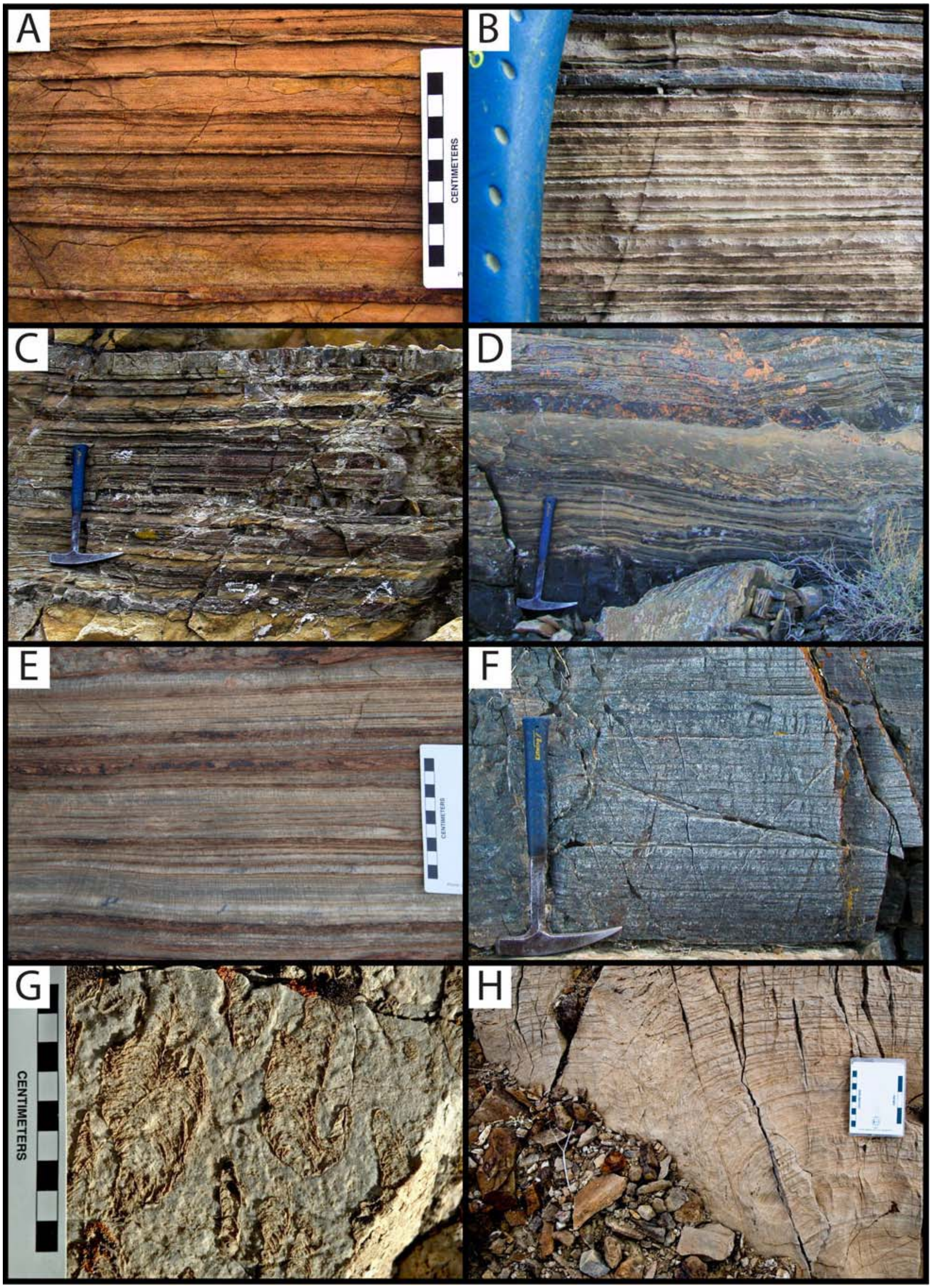


Figure 8

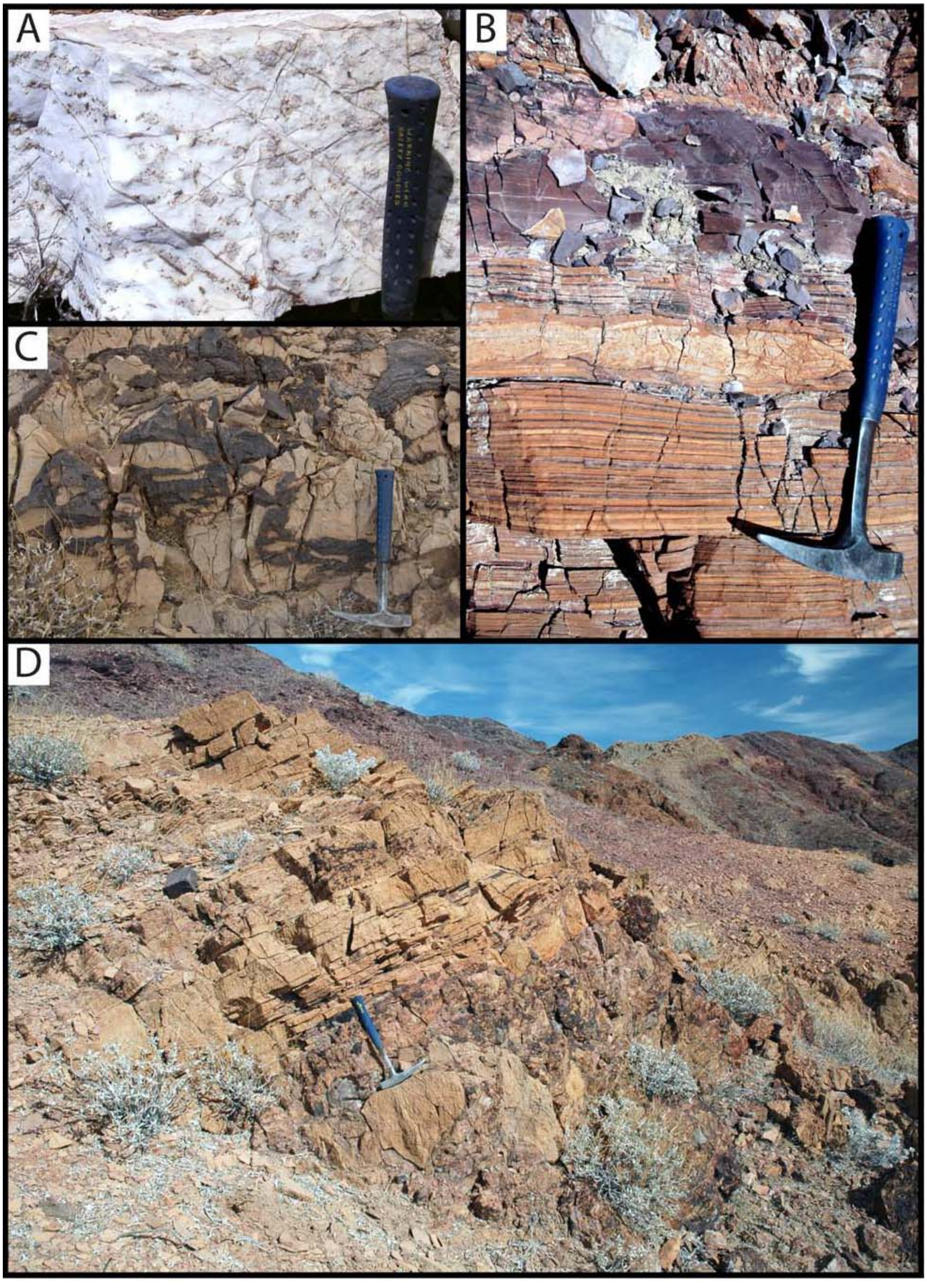


Figure 9

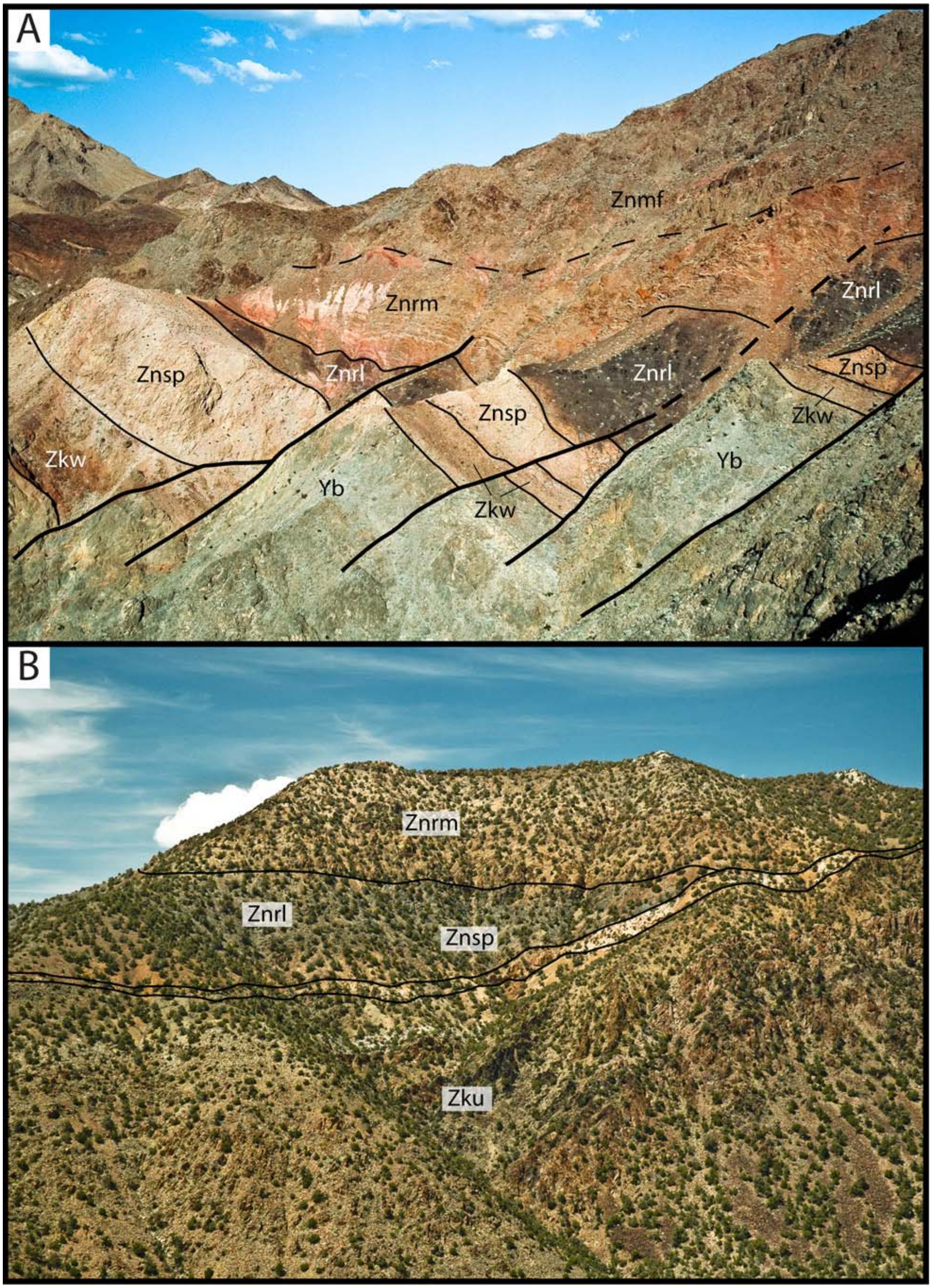

A
Znmf
Znrm
Znrl
Znsp
Znrl
Znrl
Znsp
Znsp
Zkw
Zkw
Zkw
Yb
Yb
B
Znrm
Znrl
Znsp
Zku

Figure 10

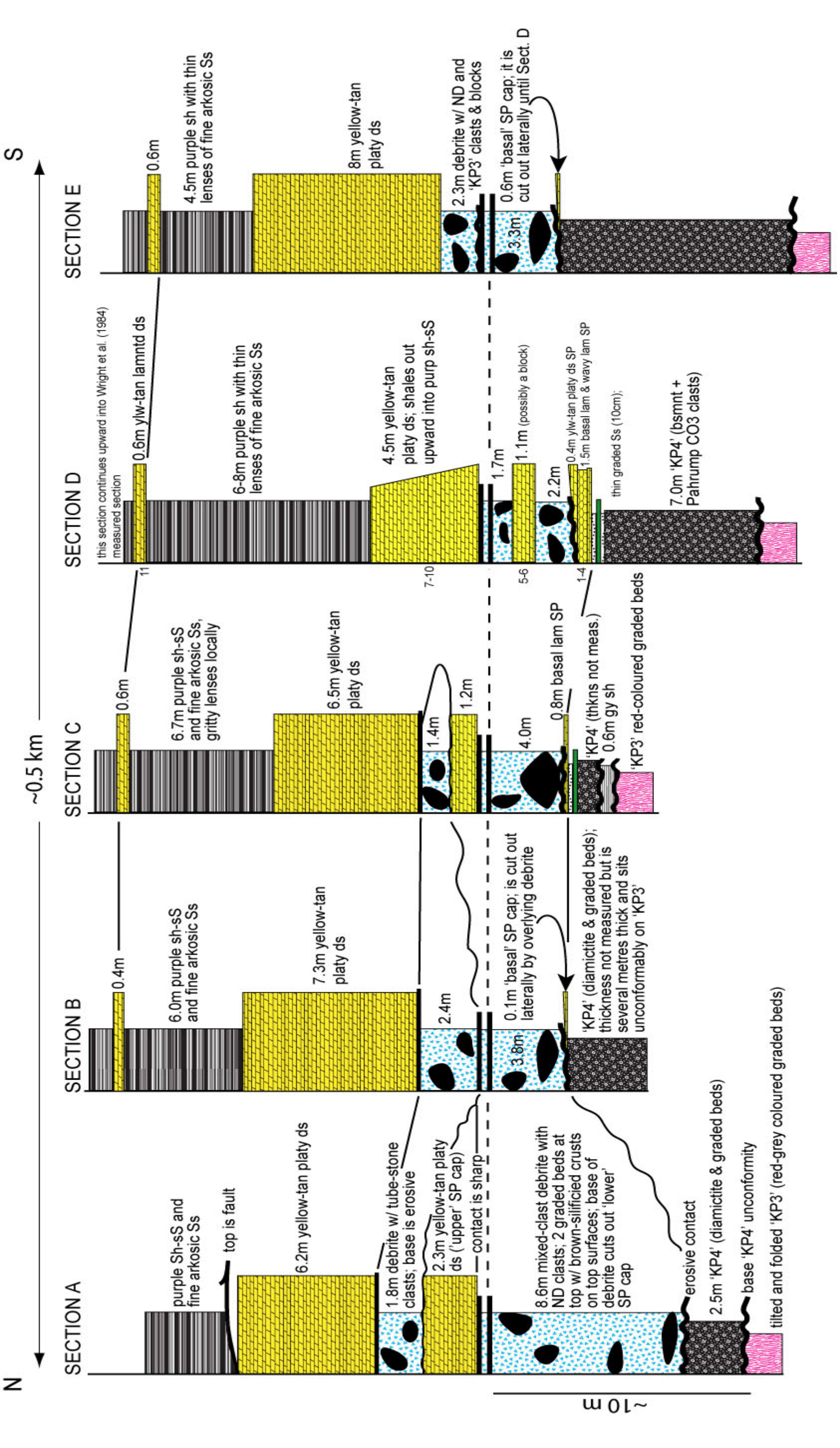

N
S
~0.5 km
~10 m
SECTION A
SECTION B
SECTION C
SECTION D
SECTION E
purple Sh-sS and fine arkosic Ss
top is fault
6.2m yellow-tan platy ds
1.8m debrite w/ tube-stone clasts; base is erosive
2.3m yellow-tan platy ds ('upper' SP cap)
contact is sharp
8.6m mixed-clast debrite with ND clasts; 2 graded beds at top w/ brown-silificied crusts on top surfaces; base of debrite cuts out 'lower' SP cap
erosive contact
2.5m 'KP4' (diamictite & graded beds)
base 'KP4' unconformity
tilted and folded 'KP3' (red-grey coloured graded beds)
0.4m
6.0m purple sh-sS and fine arkosic Ss
7.3m yellow-tan platy ds
2.4m
3.8m
0.1m 'basal' SP cap; is cut out laterally by overlying debrite
'KP4' (diamictite & graded beds); thickness not measured but is several metres thick and sits unconformably on 'KP3'
0.6m
6.7m purple sh-sS and fine arkosic Ss, gritty lenses locally
6.5m yellow-tan platy ds
1.4m
1.2m
4.0m
0.8m basal lam SP
'KP4' (thkns not meas.)
0.6m gy sh
'KP3' red-coloured graded beds
this section continues upward into Wright et al. (1984) measured section
0.6m ylw-tan lamntd ds
6-8m purple sh with thin lenses of fine arkosic Ss
4.5m yellow-tan platy ds; shales out upward into purp sh-sS
1.7m
1.1m (possibly a block)
2.2m
0.4m ylw-tan platy ds SP
1.5m basal lam & wavy lam SP
thin graded Ss (10cm);
7.0m 'KP4' (bsmnt + Pahrump CO3 clasts)
11
7-10
5-6
1-4
0.6m
4.5m purple sh with thin lenses of fine arkosic Ss
8m yellow-tan platy ds
2.3m debrite w/ ND and 'KP3' clasts & blocks
3.3m
0.6m 'basal' SP cap; it is cut out laterally until Sect. D

Figure 11A

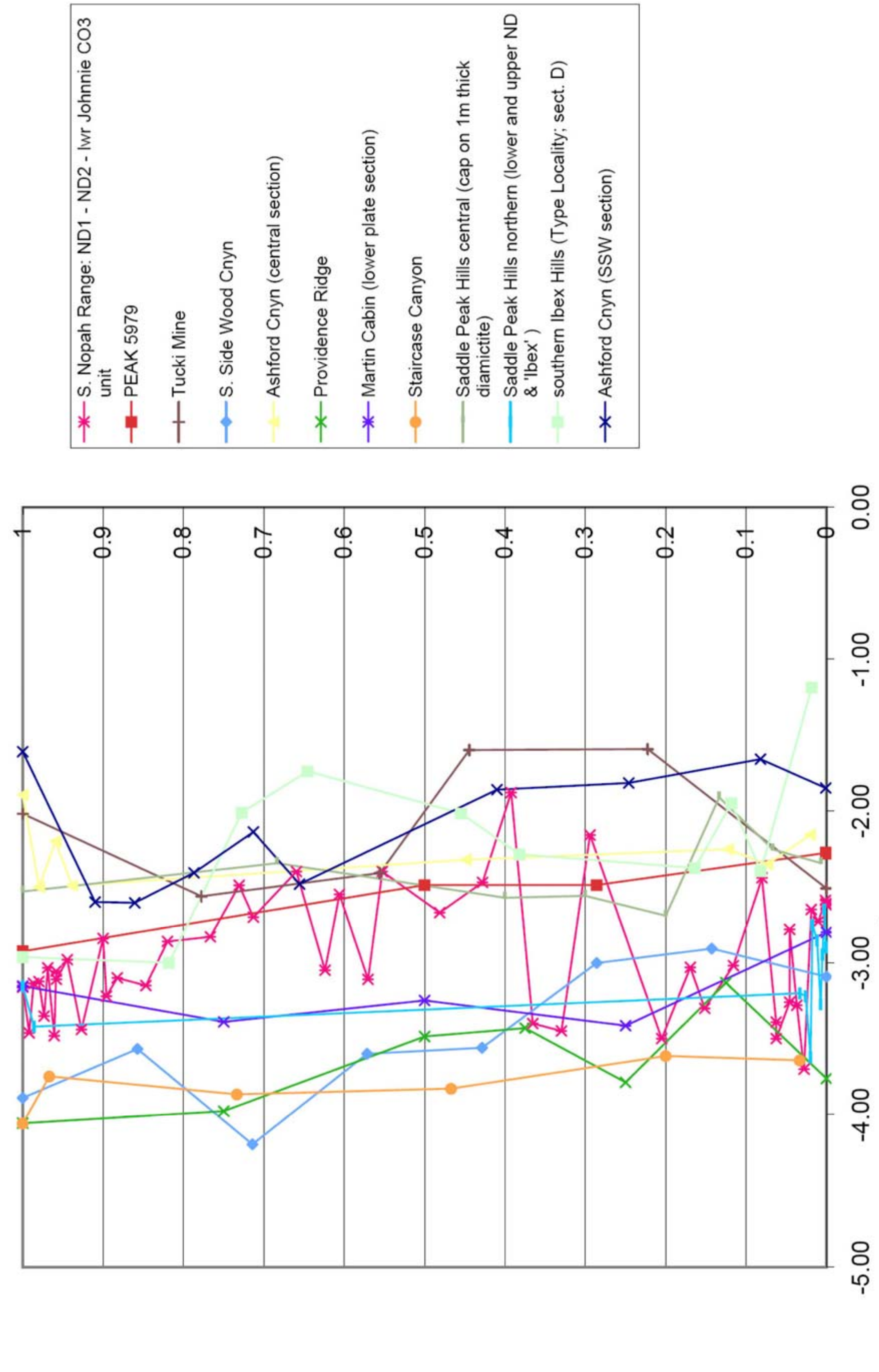

S. Nopah Range: ND1 - ND2 - lwr Johnnie CO3 unit
PEAK 5979
Tucki Mine
S. Side Wood Cnyn
Ashford Cnyn (central section)
Providence Ridge
Martin Cabin (lower plate section)
Staircase Canyon
Saddle Peak Hills central (cap on 1m thick diamictite)
Saddle Peak Hills northern (lower and upper ND & 'Ibex')
southern Ibex Hills (Type Locality; sect. D)
Ashford Cnyn (SSW section)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-5.00
-4.00
-3.00
-2.00
-1.00
0.00
δ13C (‰)

Figure 11B

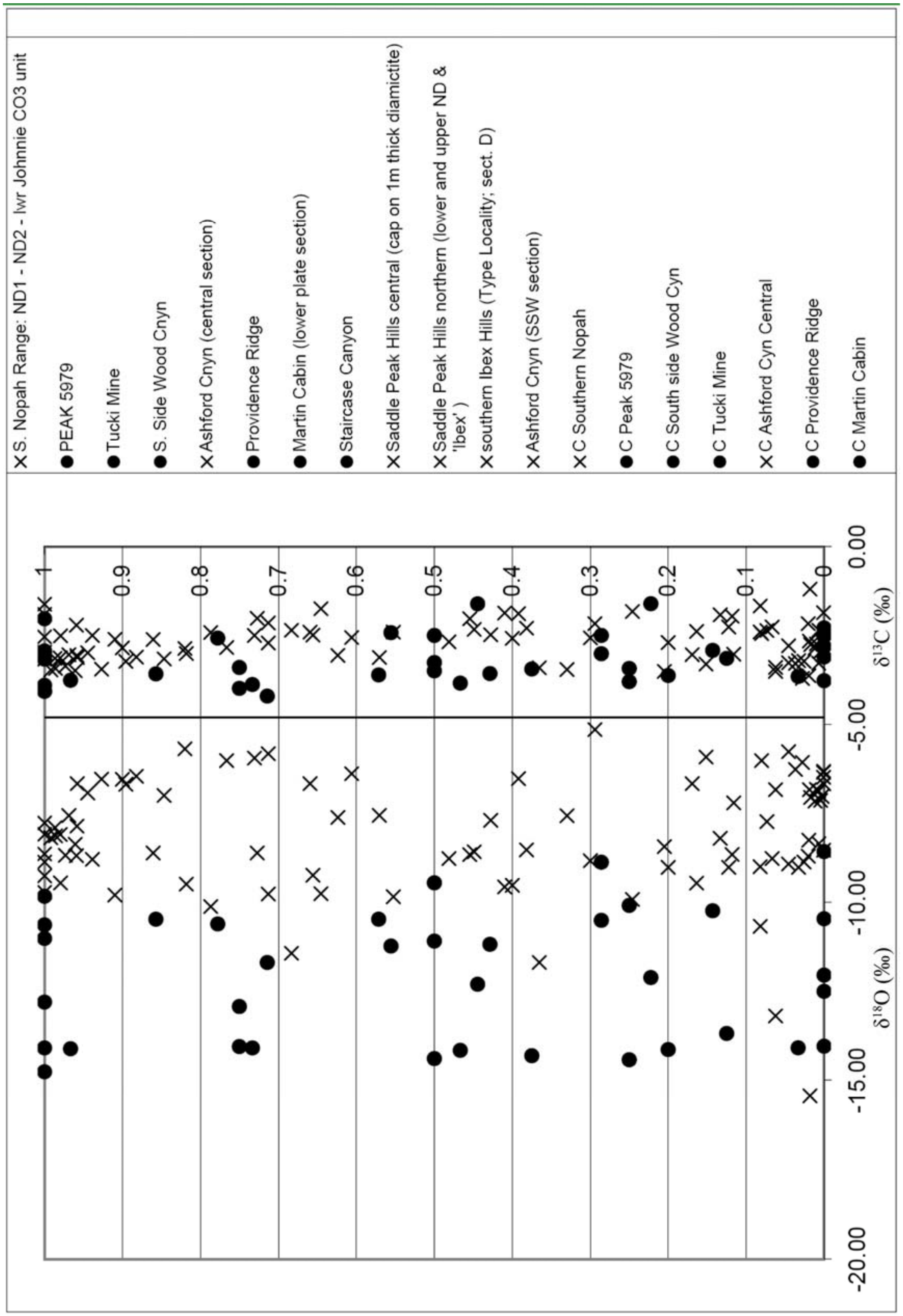
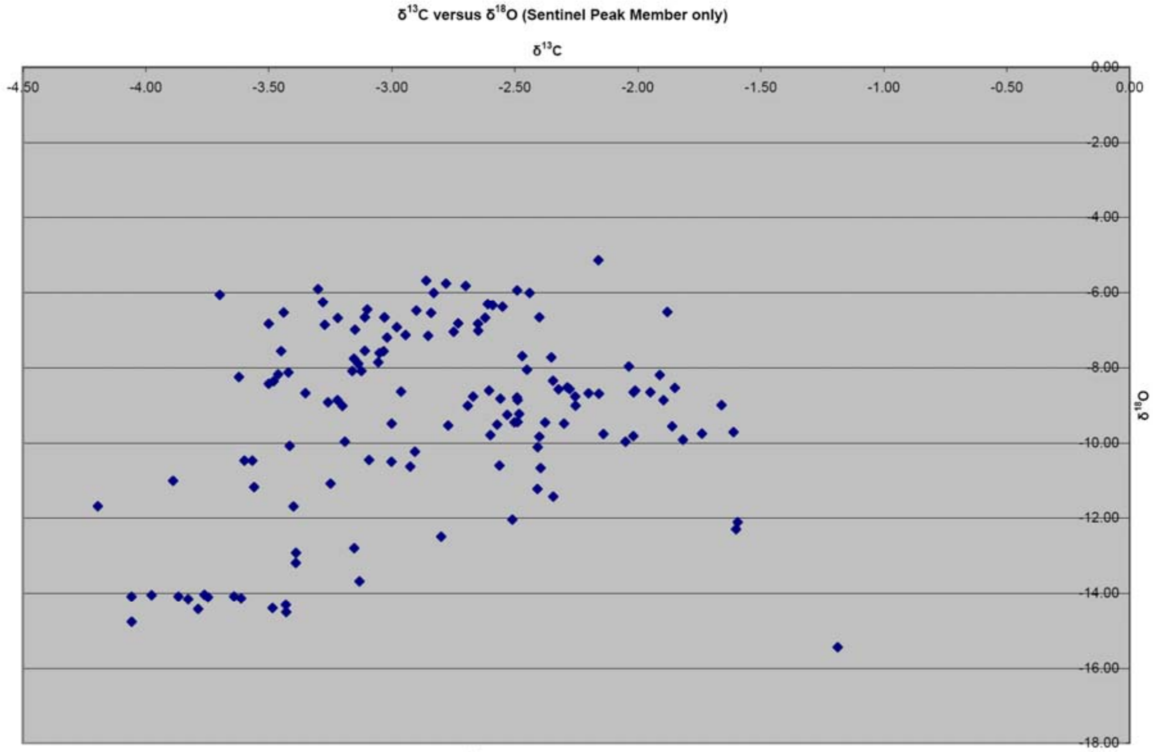
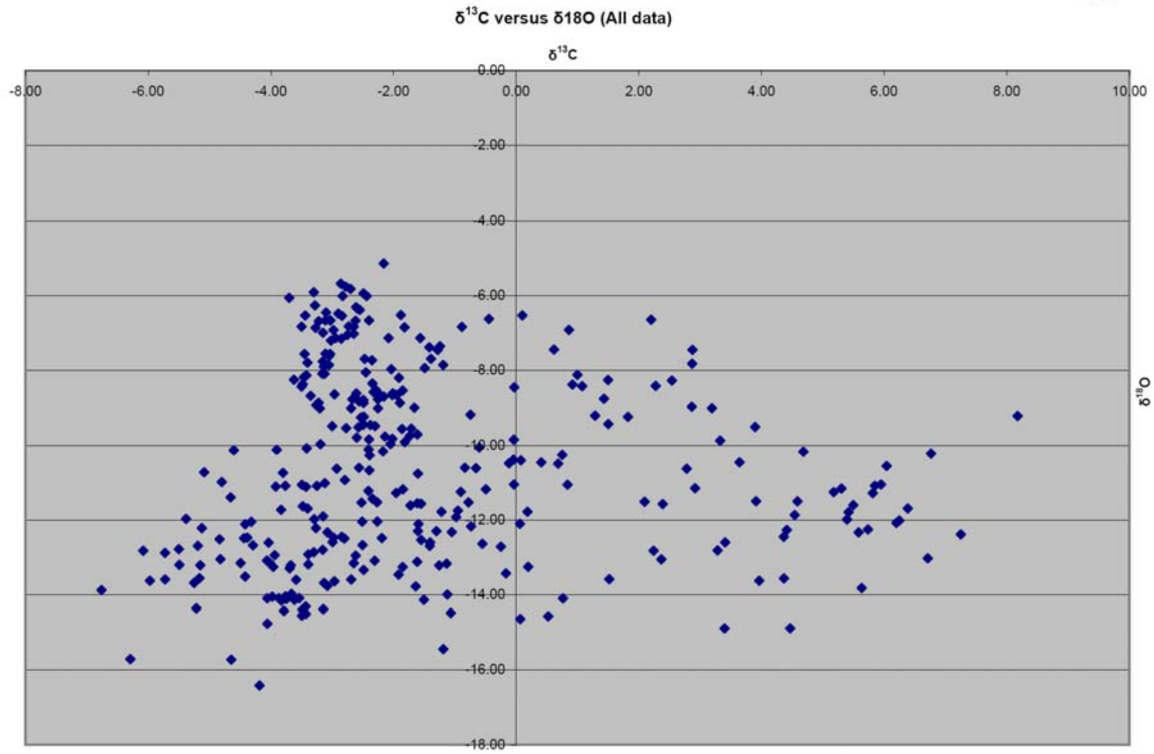

S. Nopah Range: ND1 - ND2 - lwr Johnnie CO3 unit
PEAK 5979
Tucki Mine
S. Side Wood Cnyn
Ashford Cnyn (central section)
Providence Ridge
Martin Cabin (lower plate section)
Staircase Canyon
Saddle Peak Hills central (cap on 1m thick diamictite)
Saddle Peak Hills northern (lower and upper ND & 'Ibex')
southern Ibex Hills (Type Locality; sect. D)
Ashford Cnyn (SSW section)
C Southern Nopah
C Peak 5979
C South side Wood Cyn
C Tucki Mine
C Ashford Cyn Central
C Providence Ridge
C Martin Cabin
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.00
-5.00
-10.00
-15.00
-20.00
δ13C (‰)
δ18O (‰)

Figure 11C



δ13C versus δ18O (Sentinel Peak Member only)
δ13C
-4.50
-4.00
-3.50
-3.00
-2.50
-2.00
-1.50
-1.00
-0.50
0.00
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
-12.00
-14.00
-16.00
-18.00
δ18O



δ13C versus δ18O (All data)
δ13C
-8.00
-6.00
-4.00
-2.00
0.00
2.00
4.00
6.00
8.00
10.00
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
-12.00
-14.00
-16.00
-18.00
δ18O

Figure 11D

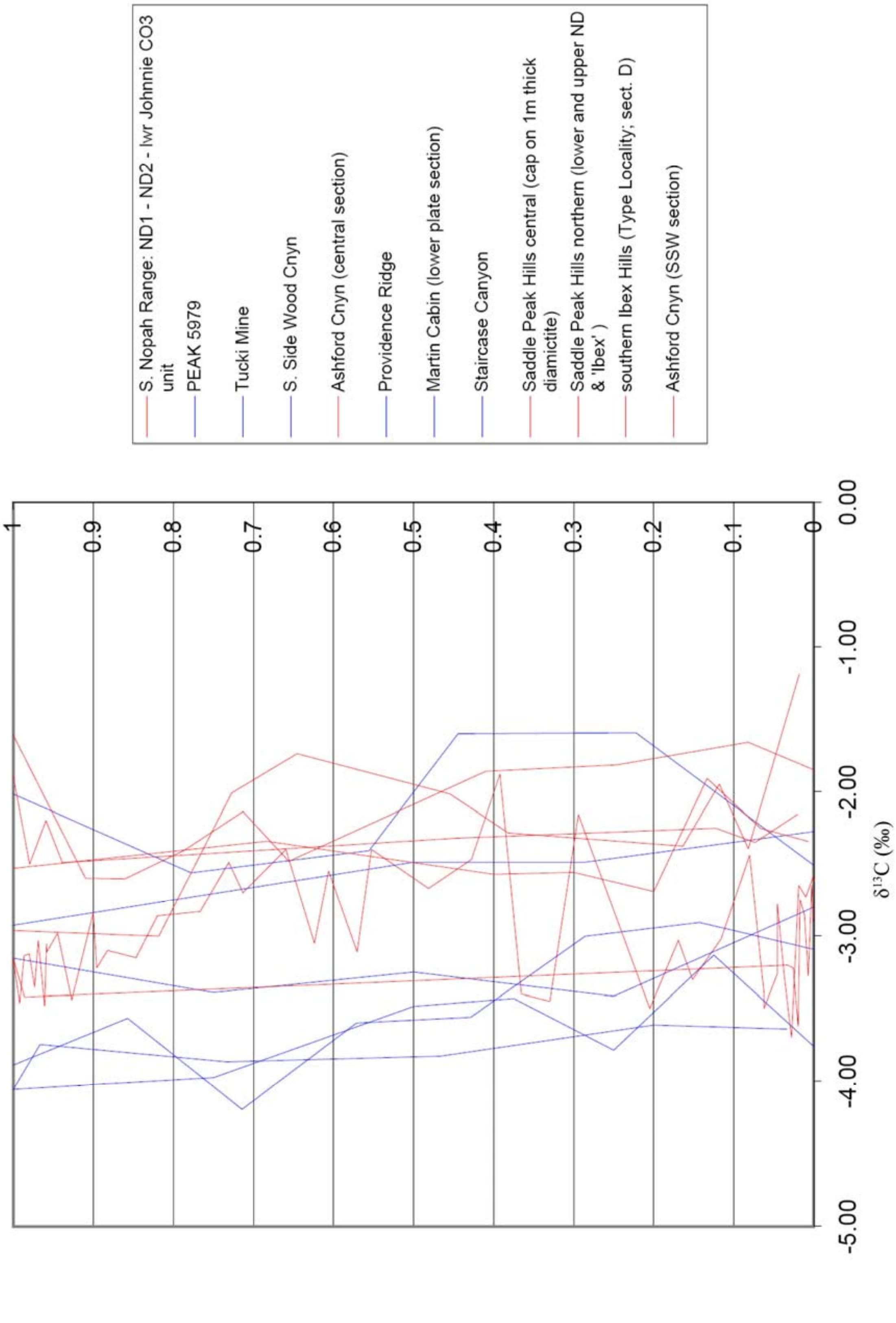

S. Nopah Range: ND1 - ND2 - lwr Johnnie CO3 unit
PEAK 5979
Tucki Mine
S. Side Wood Cnyn
Ashford Cnyn (central section)
Providence Ridge
Martin Cabin (lower plate section)
Staircase Canyon
Saddle Peak Hills central (cap on 1m thick diamictite)
Saddle Peak Hills northern (lower and upper ND & 'Ibex')
southern Ibex Hills (Type Locality; sect. D)
Ashford Cnyn (SSW section)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-5.00
-4.00
-3.00
-2.00
-1.00
0.00
δ13C (‰)

Figure 12

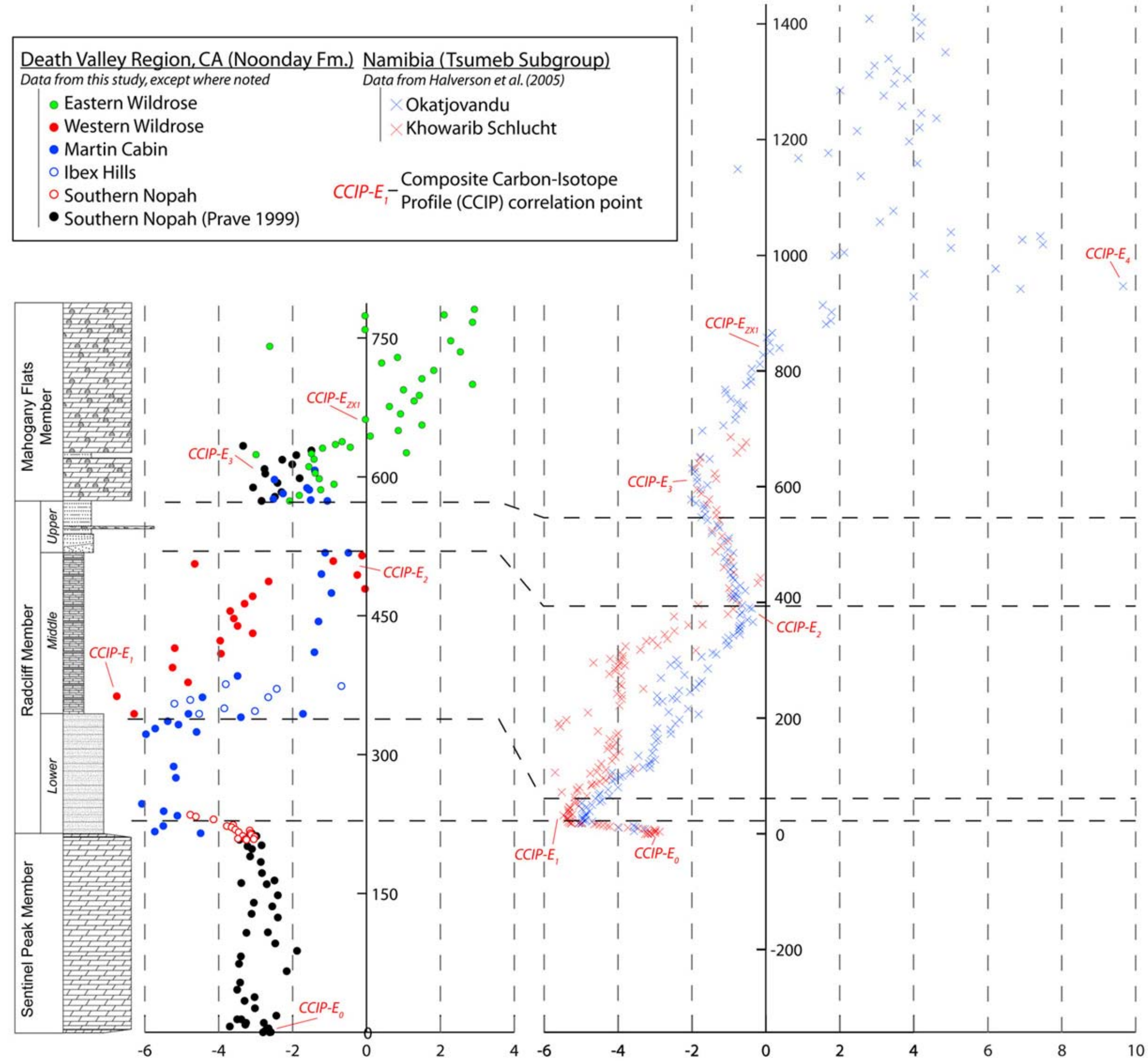

Death Valley Region, CA (Noonday Fm.)
Data from this study, except where noted
Eastern Wildrose
Western Wildrose
Martin Cabin
Ibex Hills
Southern Nopah
Southern Nopah (Prave 1999)
Namibia (Tsumeb Subgroup)
Data from Halverson et al. (2005)
Okatjovandu
Khowarib Schlucht
CCIP-E1 – Composite Carbon-Isotope Profile (CCIP) correlation point
Mahogany Flats Member
Radcliff Member
Upper
Middle
Lower
Sentinel Peak Member
CCIP-E0
CCIP-E1
CCIP-E2
CCIP-E3
CCIP-EZX1
CCIP-E4

Figure 13

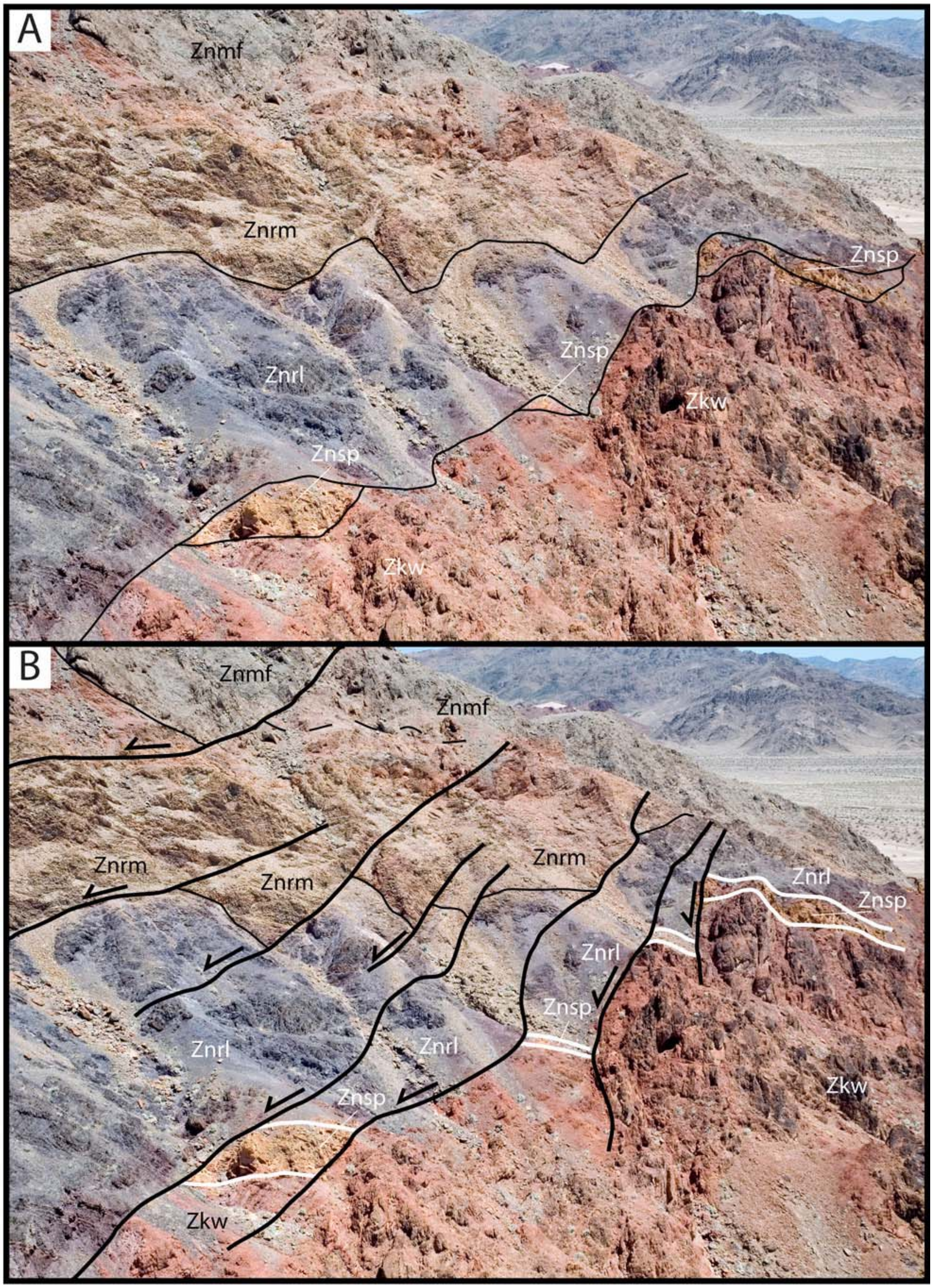

A
Znmf
Znrm
Znsp
Znsp
Znrl
Zkw
Znsp
Zkw
B
Znmf
Znmf
Znrm
Znrm
Znrm
Znrl
Znsp
Znrl
Znsp
Znrl
Znrl
Znsp
Zkw
Zkw

Figure 14

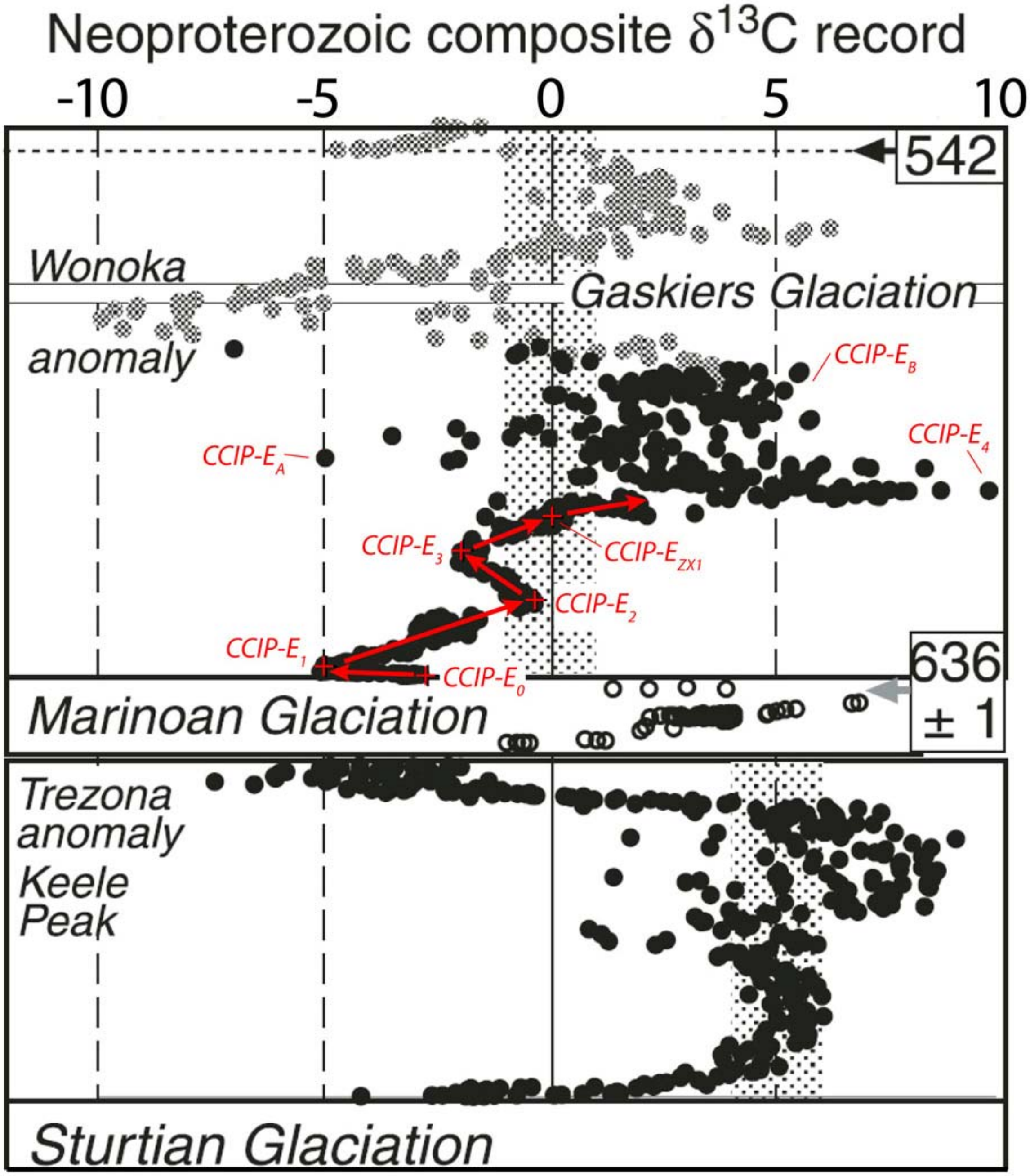
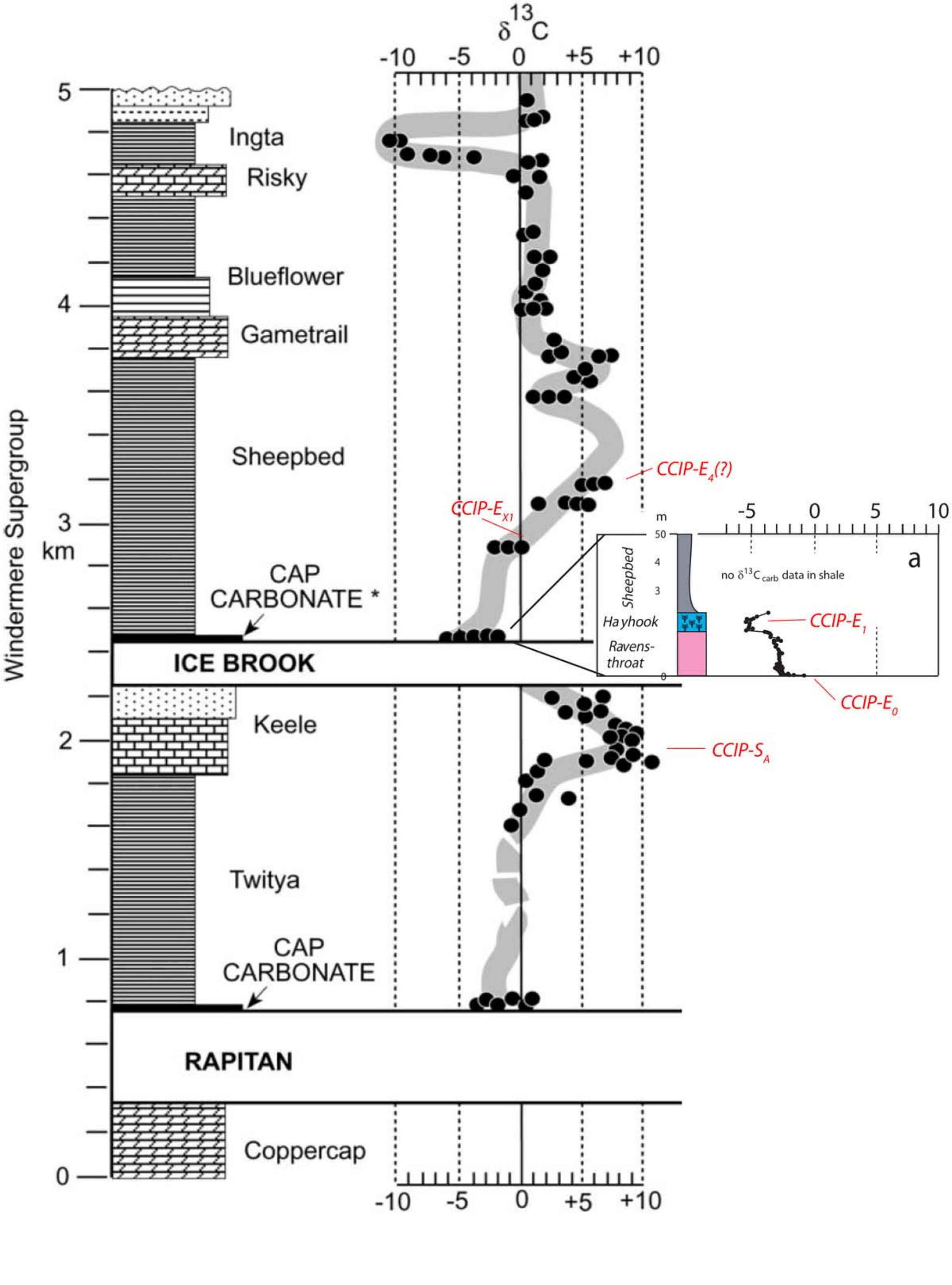

Neoproterozoic composite δ13C record
-10
-5
0
5
10
542
Wonoka
anomaly
Gaskiers Glaciation
CCIP-E_B
CCIP-E_4
CCIP-E_A
CCIP-E_ZX1
CCIP-E_3
CCIP-E_2
CCIP-E_1
CCIP-E_0
636
± 1
Marinoan Glaciation
Trezona
anomaly
Keele
Peak
Sturtian Glaciation

Figure 15



δ13C
-10 -5 0 +5 +10
Windermere Supergroup
km
Ingta
Risky
Blueflower
Gametrail
Sheepbed
CAP CARBONATE *
ICE BROOK
Keele
Twitya
CAP CARBONATE
RAPITAN
Coppercap
CCIP-E4(?)
CCIP-EX1
CCIP-SA
CCIP-E1
CCIP-E0
a
no δ13C carb data in shale
Sheepbed
Hayhook
Ravens-throat
m

Figure 16

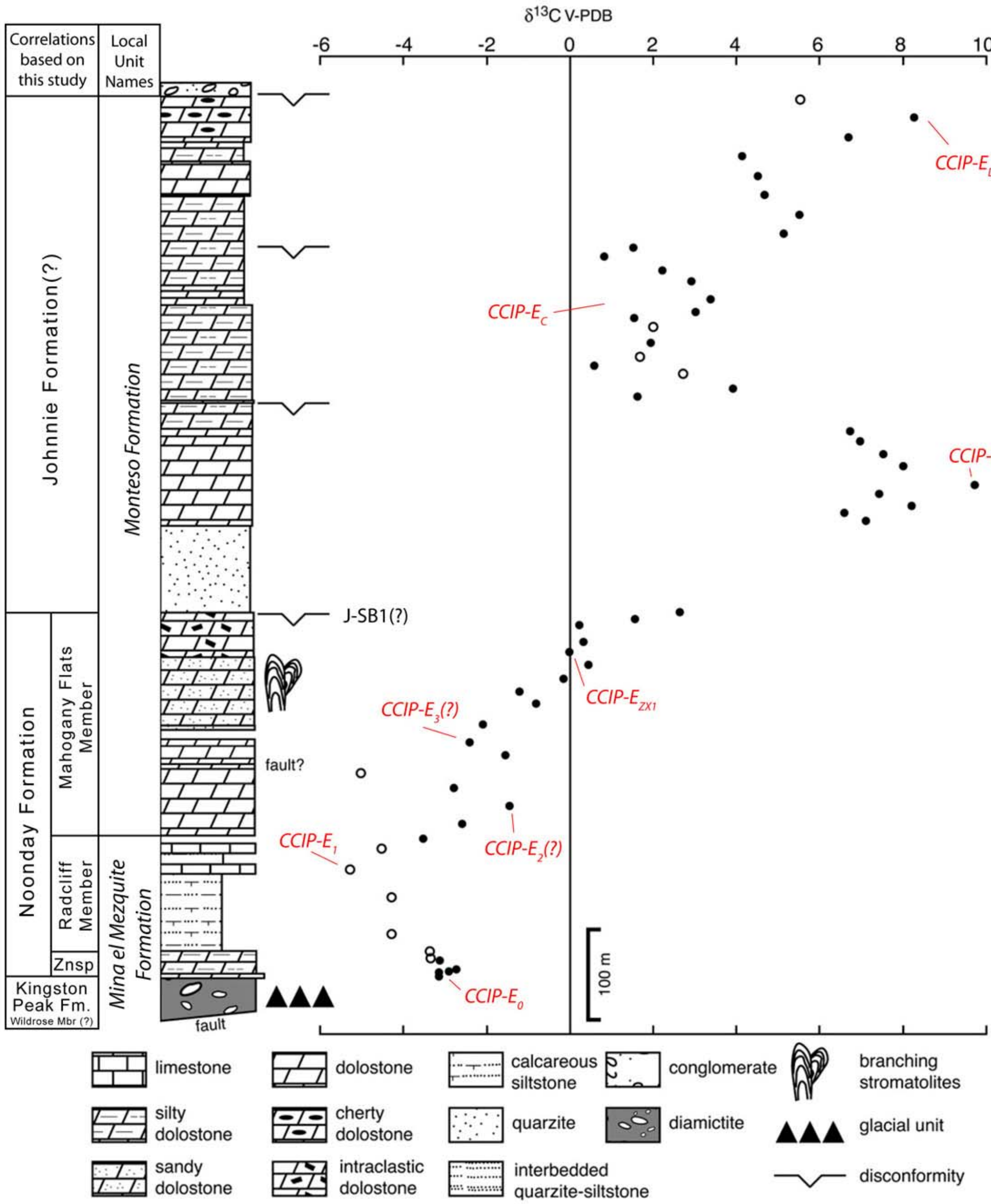
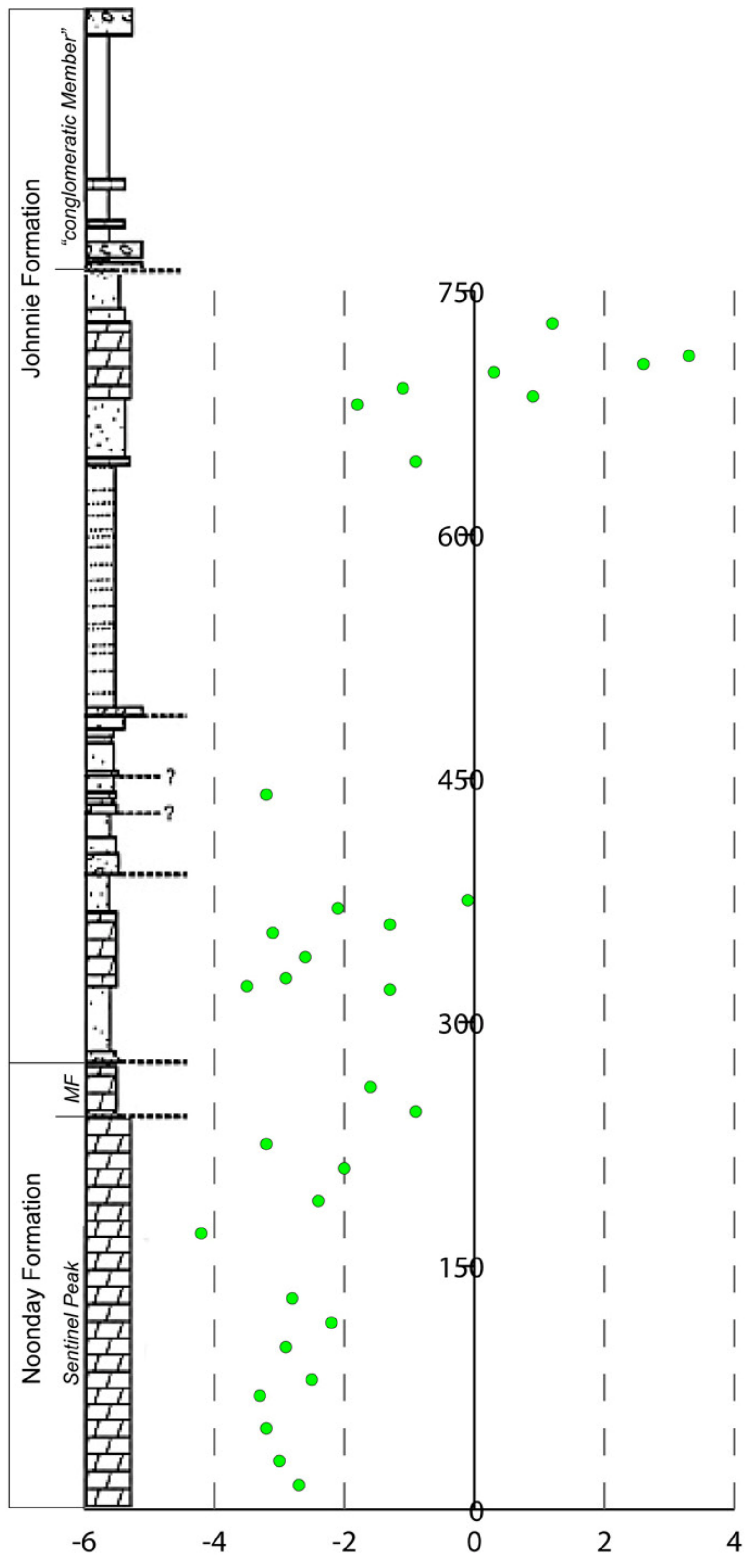

δ13C V-PDB
-6
-4
-2
0
2
4
6
8
10
Correlations based on this study
Local Unit Names
Johnnie Formation(?)
Monteso Formation
Noonday Formation
Mahogany Flats Member
Radcliff Member
Znsp
Mina el Mezquite Formation
Kingston Peak Fm.
Wildrose Mbr (?)
fault
fault?
J-SB1(?)
CCIP-E_D
CCIP-E_C
CCIP-E_4
CCIP-E_ZX1
CCIP-E_3(?)
CCIP-E_2(?)
CCIP-E_1
CCIP-E_0
100 m
limestone
dolostone
calcareous siltstone
conglomerate
branching stromatolites
silty dolostone
cherty dolostone
quarzite
diamictite
glacial unit
sandy dolostone
intraclastic dolostone
interbedded quarzite-siltstone
disconformity

Figure 17



Johnnie Formation
"conglomeratic Member"
MF
Noonday Formation
Sentinel Peak
?
?
750
600
450
300
150
0
-6
-4
-2
0
2
4

III. RIFTING OF SOUTHWEST LAURENTIA DURING THE STURTIAN-MARINOAN INTERGLACIAL: THE ARGENTA OROGENY

ABSTRACT

The Kingston Peak Formation in the Panamint Range represents the stratigraphically most complete section of Cryogenian strata along the SW margin of Laurentia. Two glacigenic diamictites and their associated cap carbonates, the older Surprise Member and Sourdough Member and the younger Wildrose Member and Noonday Formation (Sentinel Peak Member), provide timing constraints to bracket the inter-glacial succession to between *ca.* 713 Ma and 635 Ma, the ages of inferred correlative glacial-cap carbonate rocks dated elsewhere. This timing constraint is further strengthened by the presence of a sharp decline in C isotopes in the Thorndike Member, which occurs immediately beneath the Wildrose Member; this decline is readily correlated with the global Trezona anomaly.

Within the inter-glacial succession, new mapping in the northern Panamints has documented the presence of a previously unrecognized suite of coarse sedimentary rocks herein defined as the Argenta Member of the Kingston Peak Formation. The Argenta consists largely of poorly-sorted breccias and conglomerates containing an assemblage of gravel-sized clasts dominated by granitic gneiss, schist, feldspar augens, vein quartz and quartzite fragments, and locally carbonate rocks. These compositions indicate derivation from a basement

provenance and record deposition in alluvial-fan to coarse-braided fluvial settings; their textural and compositional immaturity implies relatively short distances of transport. Mapping shows that the Argenta defines wedge-shaped packages as much as 200 m thick and that the base of the Argenta is a significant angular unconformity. Combined, these features are evidence that deposition occurred during a phase of extensional tectonism interpreted as recording the initial dismemberment of the Rodinia supercontinent. Best estimates place the timing of this tectonism at *ca*. 650 – 700 Ma.

INTRODUCTION

The relationship between extensional disaasembly of the Rodinian supercontinent and the extreme glacial epochs of the Cryogenian has long been a central theme in Neoproterozoic Earth history. Over the last decade there has been growing consensus that Cryogenian glaciations may have involved freezing of most or all of the surface of Earth's oceans, primarily on the basis of paleomagnetic studies and geochemical proxies for oceanic isotopic compositions (e.g., Kirschvink, 1992; Hoffman and Schrag, 2002). Other workers have concluded, based on stratigraphic and sedimentological studies, that Cryogenian glacials were not exceptional and can be explained by processes similar to those active during the Quaternary or any other of the Phanerozoic glaciations (e.g., Allen and Etienne, 2008).

One of the key drivers of climate change is the feedback between tectonic uplift of continents, erosion of uplifted areas and atmospheric composition (Raymo and

Ruddiman, 1992; Molnar and England 1990). The Cryogenian glaciations occurred in the context of dismemberment of the Rodinian supercontinent, and hence the dominant tectonic style at the time was crustal extension (Powell *et al*., 1993; Dalziel, 1997; Hoffman, 1991; Li *et al*., 2008). This has led some workers to suggest a genetic link between the creation of extensional orogenic plateaus and the generation of continental and mountain glaciers during the Neoproterozoic (e.g., Crowell, 1999; Eyles and Januszczak, 2004; Donnadieu *et al*., 2004).

Well exposed Cryogenian-Ediacaran strata in the Death Valley region of southwest Laurentia lay within the core of the Rodinian supercontinent and are known to preserve a record of both glacial and extensional tectonic events (e.g., Wright *et al*., 1974; Miller, 1985; Prave, 1999). The aerially most significant and stratigraphically most complete Cryogenian section in this region is located in the Panamint Range. There, glaciogenic strata and syn-depositional rift-related structures of the Kingston Peak Formation are continuously exposed for nearly 100 km along the N-S strike of the range (Fig. 1). This outcrop belt is the largest single exposure of Cryogenian strata in the southwestern portion of Laurentia, providing an unusual opportunity to test the hypothesis that that the glacial events are linked to extensional tectonism.

Geologic Setting

Glacigenic strata in the Death Valley region of eastern California were first described by Murphy (1932), and included ≥1000 m of conglomeratic rocks exposed in the Telescope Peak area of the Panamint Range. Subsequently, Hewett (1940) documented equivalent rocks in the Kingston Range, about 50 km east of Death Valley, and named them the Kingston Peak Formation, the youngest of three formations he assigned to the newly defined Pahrump Group. This general nomenclature has since been adopted and used throughout the Death Valley region. However, in general, Kingston Peak strata are highly variable in thickness and sedimentary facies owing to syn-depositional tectonism. Therefore, regional correlation of units at the formational and member level has proved challenging (Miller *et al.,* 1988; Prave, 1999).

East of Death Valley, Kingston Peak strata are generally well exposed and have experienced only minor metamorphism. However, these sections are preserved in relatively small fault blocks isolated by large areas of alluvium. In addition, owing to stratigraphic variability and Tertiary structural deformation, it is difficult to follow any given section of these strata for more than a few kilometers along strike, which makes correlations between sections difficult. In contrast, Kingston Peak strata in the Panamint Range, although variably metamorphosed (up to amphibolite facies) and locally exhibiting pronounced ductile strain, are nearly continuously exposed along the length of the range with original sedimentary textures well preserved throughout.

The Panamint Range is a N-S trending, E-tilted range block within the Basin and Range extensional province. The main structural features affecting exposures of Kingston Peak strata include: (1) a NNW-trending anticline cored by 1.7 Ga gneissic basement locally intruded by a 1.4 Ga porphyritic quartz monzonite, exposed throughout the southern half of the range (Albee *et al*., 1981); and (2) an east-directed thrust fault and underlying recumbent fold in the Tucki Mountain area (Wernicke *et al.*, 1993). The basement rocks are non-conformably overlain by the Pahrump Group and younger strata (Labotka *et al.,* 1980).

Syn-depositional faulting and mafic magmatism have been identified within the Kingston Peak Formation and is generally interpreted to be a manifestation of continental rifting (e.g., Wright *et al.,* 1974; Prave, 1999). Regional contractile deformation affected the Panamint Range during Mesozoic time, accompanied by granitic magmatism and metamorphism in Jurassic and Cretaceous time (Labotka *et al.,* 1985). The final major deformation event was west-side-down normal faulting and accompanying eastward tilting in Late Tertiary time, accompanied by intrusion of granitic plutons and associated dikes (Labotka *et al.,* 1980; Hodges *et al.,* 1989).

Stratigraphy

In the Panamint Range, the Kingston Peak Formation has been subdivided into four units, from oldest to youngest, the Limekiln Spring, Surprise, Sourdough, and South Park Members (Labotka *et al.*, 1980; Miller, 1985). The South Park Member was originally defined by Murphy (1932), who further subdivided it into, from oldest to youngest, the Middle Park, Mountain Girl, Thorndike, and Wildrose Sub-members (Fig. 2).

Two stratigraphically distinct intervals of diamictic strata occur within the Kingston Peak Formation: a lower interval confined to the Limekiln Spring and Surprise units and an upper interval represented by the Wildrose (Fig. 2). The stratigraphy between these two intervals of diamictite is thick (as much as 700 m) and consists of a variety of siliciclastic rocks and two main limestone units, the Sourdough Member, which rests directly on Surprise diamictites, and the Thorndike, which occurs immediately below the Wildrose diamictites. These inter-glacial units are laterally persistent, with two or more of them present along the entire outcrop belt of the Panamint Range.

The Limekiln Spring and Surprise Members

The Limekiln Spring Member is the most stratigraphically complex unit of the Kingston Peak Formation in the Panamint Range, and despite continuity of exposure of the formation as a whole, mapped exposures of the Limekiln Spring are limited to two areas, a small one in the southern part of the range and a larger one to the north in the vicinity of Telescope Peak. Its stratigraphic architecture is accordingly not well understood. In the southern exposures, which are not strongly deformed or metamorphosed, it consists of laterally and vertically variable interbedded diamictite, sandstone and siltstone (Miller *et al.*, 1988). In the northern exposures, which are strongly deformed and metamorphosed, it is mostly immature sandstone, pelitic schist, amphibolite, minor dolomitic marble, and discontinuous lenses of metaconglomerate and breccia (Labotka *et al.*, 1980; Albee *et al.*, 1981; Miller, 1985). Thicknesses in both areas are highly variable, ranging from 0 to >1000 m. At large scale, the unit appears to thin eastward beneath the overlying Surprise Member, apparently filling lows around local topographic highs underlain by crystalline basement (Labotka, 1978; Labotka *et al.,* 1980; Miller, 1985).

The Surprise Member is poorly bedded to massive diamictite (Fig. 3A) in the southern Panamint Range but appears to pass northward into finer-grained facies consisting of argillite and immature sandstone (Labotka *et al.,* 1980; Miller, 1985). Locally, it contains a few tens of meters of tholeiitic pillow basalts (Hammond, 1983). The Surprise ranges from 35 m in thickness near Goler Wash in the southern Panamints (Miller, 1985) to locally as much as 1,300 m west of Telescope Peak, although this may be partly the result of structural thickening or duplication (Labotka *et al.,* 1980). The diamictic facies is dominated by quartzite and carbonate clasts supported by an argillaceous, sandy matrix. Clasts range from pebbles to boulders, with the quartzite clasts generally rounded to sub-rounded whereas the carbonate clasts are subangular (Miller, 1985).

North of the latitude of Telescope Peak, diamictite is uncommon and the dominant lithology is dark grey to black argillaceous siltstone and fine sandstone. Argillite is also present in minor amounts to the south, but unlike the southern sections the northern sections also contain a significant amount of interbedded laminated limestone and argillaceous limestone (Labotka *et al.,* 1980; Harding, 1987). The transition between these two facies occurs in a well exposed, but structurally complex area (Labotka, 1978; Labotka *et al.,* 1980), and thus it is uncertain whether the two facies are coeval. Assuming that they are coeval, the association implies a significant interval of simultaneous deposition of diamictite and carbonate.

The presence of lonestones in the Limekiln Spring Member in the Pleasant Canyon area (Miller, 1985; her Fig. 9) and the discovery of striated clasts in the Surprise Member in the same area (Partin *et al.,* 2007) are evidence used to infer that the laterally extensive diamictites and coarse-grained facies in the Surprise and Limekiln Spring units record glacigenic-influenced sedimentation (Miller, 1985). As such, this makes these units the oldest glacial-related deposits in the Death Valley area.

The Sourdough Member

The Sourdough Member overlies the Surprise Member with a conformable, sharp contact (Labotka, 1978; Miller, 1985), although locally diamictite and limestone are reportedly interbedded at the contact (Miller, 1985; Partin *et al.,* 2007). The Sourdough is a 0.5 to 45 meter-thick grey to dark grey laminated limestone (Fig. 3B), commonly highly internally deformed thus inhibiting confident identification of primary structures (Miller, 1985). The upper contact is generally gradational into overlying siliciclastic strata units. Laminations in the Sourdough are defined by alternations in calcite grain size and abundance of muscovite and quartz. It also contains finely disseminated graphite. Synsedimentary deformation, isolated clasts, and lenticular beds of clastic material have been reported (Miller, 1985).

South Park Member: redefinition and new stratigraphic terminology

The present clustering of Sub-members in the South Park Member tends to mask the significance of units that are important archives of the hallmark environmental and tectonic events of Neoproterozoic time. Consequently, a revised stratigraphy for this part of the Kingston Peak Formation is warranted. The new stratigraphy proposed herein abandons the term ‘South Park Member’ and elevates to Member status those units originally regarded as Sub-members, namely, the Middle Park, Mountain Girl, Thorndike and Wildrose (Fig. 1). Each of these newly defined Members is mappable over the entire outcrop belt in the Panamint Range.

The Middle Park Member is typically between 150 and 200 m thick and consists of pelite, shale and fine sandstone. This is overlain by the Mountain Girl Member that is 50 to 100 m thick and typically consists of a lower conglomeratic unit and an upper unit of cross-bedded quartzite (Fig. 3C, D). Above this are the light- to medium-grey banded limestones of the Thorndike Member (the term 'Thorndike' was first used by Harding, 1987; in certain previous literature these carbonate rocks are referred to as the "un-named" Limestone; e.g., Prave, 1999; Corsetti and Kaufman, 2003). Ooiltic lenses, hummocky-like cross stratification and rare stromatolites can be observed (Fig. 3E-G). In its most complete development, the Thorndike is as much as 200 m thick and can contain thin (10-20 m) siliciclastic-dominated intervals of shale and fine sandstone. The base of the Thorndike rests sharply on the quartzites of the underlying Mountain Girl Member and thus represents a marine flooding surface. The top of the Thorndike is truncated to variable depths by the erosive base of the overlying diamictic Wildrose Member (Fig. 3H). As Prave (1999) noted, in places where the Wildrose is not developed, the Thorndike was mistakenly placed into the Noonday (Miller, 1985).

Wildrose Member

The Wildrose Member is variably preserved below the Sentinel Peak Member of the Noonday Formation and varies in thickness from 0 to 190 m (Miller, 1985), but is most commonly a few tens of meters thick. Where present, it is a massive, unsorted, matrix-supported diamictite, displaying significant along-strike internal variation in both clast and matrix compositions. It is distinct from the mixed-clast diamictites typical of those lower in the Kingston Peak Formation (Surprise and Limekiln Spring Members) in that it contains abundant gneissic basement clasts of pebble and cobble sizes with boulders commonly having 0.5 m diameters (Fig. 4A), but ranging to as large as 3 m in maximum dimension (Miller, 1987). Locally it can be dominated by carbonate clasts (Fig. 4B), many derived from the subjacent Thorndike Member. The matrix varies from dark grey to black argillite and immature fine sandstone where basement clasts predominate (Fig. 4A), to carbonate-cemented medium to coarse immature sandstone where carbonate clasts predominate (Fig. 4B).

Unequivocal features of glacial deposition, such as dropstones or striated clasts, have been identified in the Wildrose Member. The diamictic texture need not be glacigenic in origin, and could instead be generated by sediment gravity flow processes. Such deposits, however, normally have dimensions of at most a few tens of kilometers and characteristically have lens-shaped geometries. The lateral continuity of the Wildrose, which can be traced for nearly 100 km along strike, combined with a lack of evidence for internal depositional surfaces, make it difficult to reconcile with a non-glacial mode of deposition. Accordingly, the Wildrose has been interpreted as a result of glacial processes, perhaps as a lodgement till (Miller, 1985). This makes the Wildrose the second glacial episode in the Kingston Peak Formation.

THE ARGENTA MEMBER AND EVIDENCE FOR TECTONISM DURING KINGSTON PEAK TIME

The above synopsis of the Kingston Peak Formation lithostratigraphy describes the stratigraphic framework used by geologists working in the Panamint Range for more than 75 years. As noted in Chapter I, the sections of the Kingston Peak Formation exposed in eastern Death Valley are less complete than those in the Panamints. The Sourdough through Wildrose Members are mappable for nearly 100 km along strike in the Panamint Range. In contrast, most if not all of the former "South Park Member" units (as well as other members) are missing in eastern Death Valley (e.g., Miller *et al*., 1988; Prave, 1999). Not surprisingly then, there is little consensus about the timing and number of glacial episodes and extensional tectonic events recorded by the Kingston Peak Formation (*e.g*., Miller, 1985; Prave, 1999; Abolins *et al.*, 2000; Corsetti and Kaufman, 2003, 2005).

In the Wildrose Canyon area, the Mountain Girl Member lies with ca. 20 degree angular discordance on the underlying Surprise Member (Harding, 1987). Locally, gravel lenses occur above this contact and beneath the Mountain Girl and were interpreted by Harding (1987) to be part of the Surprise Member, thus making the genesis of the angular unconformity an intra-Surprise event (Fig. 5A).

New geological mapping and stratigraphic analysis demonstrate that this unconformity and associated gravels persist as far north as the Tucki Mine area (Fig. 1B, 5B). The gravels form wedge-shaped bodies from 0 to 200 m in thickness and are herein named the Argenta Member, the type locality being Argenta Ridge (Fig. 1B and 6). The Argenta Member consists of poorly sorted, coarse-grained mostly arkosic breccias and conglomerates that display mixtures of rounded to angular boulders, cobbles, and pebbles of granitic gneiss, feldspar augen, schist, quartzite and vein quartz clasts in an overall arkosic sandy matrix (Fig. 7A-D). Locally, carbonate clasts dominate and are commonly flattened due to tectonic strain (Fig. 7C). In most instances, the coarse lithologies occur in meter- to many meter-thick beds that are massive, displaying little to no grading or stratification. Overall vertical trends, though, do exhibit both coarsening- and fining-upward sequences typically many tens of meters thick. In the relatively finer-grained portions of the Argenta, decimeter-thick beds of medium- to coarse-grained sandstone are present that exhibit slight grading, flat stratification (i.e., depositional layering, not tectonic flattening or cleavage) and/or cross-stratification (Fig. 7D). These occur between beds of poorly-sorted conglomerate and/or massive breccia and, where not eroded by the overlying bed, are laterally continuous at least at outcrop scale. Such sandstone beds display sharp bases marked by small-scale erosional scalloping and up to meter-scale channeled incisions; tops of beds are marked by erosional truncation by overlying units. Large angular schist and feldspar fragments occur among boulders of granitc gneisses and quartz, indicating minimal transport. These combined characteristics suggest the Argenta Member records deposition in an alluvial fan or coarse braided fluvial setting.

Six new stratigraphic sections were measured within the Surprise through Wildrose interval, from Wildrose Canyon in the south to the Tucki Mine area (Wire Peak) to the north (Fig. 1B and 8). These stratigraphic sections demonstrate that the Mountain Girl and Thorndike Members are continuously traceable across the northern Panamint Range. The substrate of the Mountain Girl, however, is complex. The sections show that highly variable thicknesses of the Argenta Member are found beneath the Mountain Girl, and that the substrate of the basal Argenta-Mountain Girl surface is diverse.

In Wildrose Canyon the base of the Argenta is observed to cut down section at an angle of about 20 degrees from east to west, from the Middle Park Member through the Sourdough to a position well within the Surprise. In the Skidoo-Tucki Mine area abrupt variations in the pre-Mountain Girl substrate are observed. In the south Skidoo section, a situation similar to that in Wildrose Canyon is observed. A relatively thick section of Mountain Girl rests directly on the Surprise Member with an angular discordance of ~10-20 degrees, and locally on a thin wedge of Argenta (Figure 5B). Within a kilometer to the north at the North Skidoo section, the Argenta is absent and Mountain Girl rests directly on Sourdough Member. An additional 2.5 km to the northwest at the Tucki Mine section, a 50 m-thick section of Argenta appears below the Mountain Girl, and ~300 m of Middle Park strata appear between the Sourdough and the Argenta. These two very different sections occur on either side of a flat-lying Tertiary normal fault, the Tucki Mine fault, which separates them by about 2 km (see Figure A3 of the Appendix, discussed in Chapter II). Restoring the base of the Mountain Girl Member on either side of the Tucki Mine fault juxtaposes the different sections, indicating that the fault had a period of pre-Mountain Girl, post Middle Park slip, presumably during Argenta time. This lowered the Tucki Mine section relative to the North Skidoo section by at least 350 m so as to allow the preservation of this thickness of Middle Park and Argenta Members between the Sourdough and Mountain Girl Members (Fig. 4). The Argenta Member is absent in the North Skidoo section, where Mountain Girl Member rest directly on

Sourdough Member. North of the Tucki Mine fault, the Argenta Member pinches in between the Middle Park and Mountain Girl Members, attaining a thickness of 140 m at the Wire Peak Section.

These relations demonstrate that faulting, tilting of up to 20 degrees, and the development of at least 350 m of structural relief in the northern Panamint Range occurred in post-Middle Park pre-Mountain Girl time. The total structural relief generated could be 1000 m or more based on the presence of abundant locally derived basement detritus, including a large rock avalanche deposit in exposures of the Argenta Member on Tucki Mountain, previously mapped as Wildrose Diamictite (Wernicke *et al.*, 1993). However, some of this relief may have been created during Limekiln Spring time based on relations Telescope Peak and Goler Wash areas (Labotka *et al.*, 1980; Miller, 1985). On the basis of these relations, we will refer to these two episodes of tectonism as the Limekiln Spring and Argenta events.

Timing of Tectonism

No direct radiometric age control exists for the Kingston Peak Formation and, hence, an absolute age for the Limekiln Spring and Argenta events remains unknown. However, correlating C-isotopic profiles for Kingston Peak carbonate rocks to global curves (e.g., Halverson *et al*., 2005, 20007) can provide a form of chronostratigraphy. It has been established that the Sentinel Peak Member of the Noonday Formation is correlative with the 635 Ma Marinoan cap carbonates dated elsewhere (see Chapter II). This defines the minimum age constraint for Kingston Peak deposition.

The two main carbonate units of the Kingston Peak Formation are the Sourdough and Thorndike Members. The Sourdough Member sits on the glacigenic diamictites of the Surprise Member and based on lithological characteristics and C-isotopes is considered by most workers to be a cap carbonate. Because the Noonday Formation is a Marinoan-age cap (see Chapter II), it is likely that the Surprise – Sourdough doublet is related to the older Sturtian glaciation (Prave, 1999). Of the numerous Sturtian-aged glacial – cap doublets known worldwide, the best documented is the Chuos – Rasthof sequence in Namibia for which there is strong C-isotopic evidence for correlation with the *ca*. 713 Ma Gubrah glacial in Oman (Halverson *et al*. 2005, 2007; Bowring *et al*., 2007).

To evaluate the potential correlations between Kingston Peak carbonates and global composite carbon isotopic profile (Halverson *et al.*, 2005), sections of Sourdough and Thorndike Members were sampled for C-isotopic analysis (Table 1, Chapter II). A composite C-isotopic curve for these two units is shown in Figure 9. Unfortunately, throughout much of the Panamint Range structural transposition precludes isotopic profiling through the interior portions of the Sourdough. However the bottommost and topmost beds in the sections measured, are structurally intact.

In the Sourdough basal values start around –5‰ and rise sharply to values as high as 5‰ and then show a more gradual decline back to values of -5‰ at the top. This C-isotopic trend matches well that for the Rasthof cap carbonate (Halverson *et al*. 2005, 2007). Thus, based on C-isotopic correlation and its position below the inferred Marinoan-equivalent Wildrose – Sentinel Peak glacial – cap carbonate sequence, the

Sourdough is correlative to the Rasthof cap carbonate, which suggests the Surprise is correlative with the Chuos and Gubrah diamictites and hence *ca*. 713 Ma in age.

The Thorndike Member occurs immediately subjacent to the glacigenic Wildrose Member, itself capped by the Marinoan-equivalent cap carbonate of the Noonday Formation; an age of 635 Ma has been established for these rocks (Hoffmann *et al*. 2004; Condon *et al.* 2005). What has been documented in numerous sections elsewhere is that the carbonate rocks underlying the Marinoan and equivalent glacial deposits exhibit a dramatic decline, from values of 6‰ to 8‰ to values as low as -8‰ or lower; this has been termed the Trezona anomaly (Halverson *et al*. 2005, 2007). Three sections of the Thorndike were sampled for C-isotopic analysis, South and North Skidoo and Wildrose Canyon. The composite data are shown on Figure 9. Although somewhat noisy, the features that stand out are the overall trend to positive values, as high as 8‰, followed by a terminal decline to values as low as –2‰ (one point shows a return to slightly positive values) before being erosionally truncated beneath the basal surface of the Wildrose Member. This 10‰ decline in C-isotopic values matches well the magnitude of decline of the Trezona anomaly and lends additional strong support for interpreting the Thorndike as recording the pre-Marinoan negative excursion in the global C profile.

The timing of extensional tectonism recorded by the Argenta Member can thus be broadly bracketed to between *ca*. 713 Ma and 635 Ma using C-isotope chemostratigraphy. An additional speculative constraint can be applied. The duration of the Marinoan glaciation is typically assumed to be between 5 and 30 Myr (Hoffman *et al.* 1998; Hoffman and Schrag, 2002). Given the correlation of the Sentinel Peak Member of the Noonday Formation to 635 Ma Marinoan-age cap carbonates (See Chapter II), pre-

Wildrose strata would be *ca*. >650 Ma. Thus, estimating the timing of the Argenta orogeny to be *ca*. 650 – 700 Ma is reasonable and likely records the initiation of break-up of the Rodinian supercontinent in this part of Laurentia. This is consistent with age constraints of 685 Ma for extensive bi-modal rift-related volcanism in Idaho (Lund *et al*., 2003).

DISCUSSION AND CONCLUSIONS

New mapping in the northern Panamint Range has documented the widespread occurrence of breccias and conglomerates between the Middle Park and Mountain Girl Members of the Kingston Peak Formation. The breccias and conglomerates are poorly-sorted and consist of granule to boulder-sized clasts of largely basement-derived detritus that record deposition in alluvial fan and coarse braided fluvial environments. Deposition occurred in wedge-shaped units as much as 200 m thick associated with tilting, faulting and development of several hundred meters of structural relief in post-Middle Park, pre-Mountain Girl time. I speculate that this event appears to be one of two events that created structural relief in Pahrump time throughout the Death Valley region.

It has been long noted by many that kilometer scale structural relief developed in post-Beck Spring pre-Noonday time resulting in abrupt southward pinch in of Pahrump Group units in eastern Death Valley (Wright *et al.*, 1974). The results presented above show that over a large area of exposure of the Kingston Peak Formation in the Panamint Range, evidence for tilting, faulting, and the generation of structural relief occurred just prior to and probably during Argenta time and hence this tectonism is referred to as the

Argenta event. This raises the possibility that the Argenta event is also responsible for most, if not all, of the pre-Noonday structural relief observed in the eastern Death Valley region. If correct, then evidence cited by Walker *et al.* (1986) in that region for intra-Kingston Peak tectonism, expressed as a significant angular unconformity the Kingston Peak section Range may provide an important link between these sections and the Panamints. I speculate that the Argenta and younger members of the Kingston Peak Formation in the Panamint Range correlate with the "Upper Kingston Peak Formation" of Walker et al (1986) and that the unconformity in the Panamint Range may be correlative with the surface interpreted by Walker et al (1986) to be an intra-Kingston Peak angular unconformity.

The Argenta and enveloping strata were assigned to a single previously defined member of the Kingston Peak Formation, the South Park Member. Documentation of a significant tectonic event within these strata warrants redefining the stratigraphic nomenclature for this part of the Kingston Peak Formation. The name Argenta Member is proposed for the coarse siliciclastic rocks and the South Park Member nomenclature is eliminated. Its constituent, formally named submembers are retained and elevated to member status, including the Middle Park, Mountain Girl, Thorndike and Wildrose members.

C-isotopic chemostratigraphy on the Sourdough and Thorndike members suggest age-equivalence with the Sturtian-age Rasthof cap carbonate in Namibia and the Trezona Formation of South Australia, respectively. These correlations, and establishment of the Sentinel Peak Member of the Noonday Formation as a Marinoan-aged cap carbonate (Chapter II) constrains the Argenta orogeny to between *ca*. 650 – 700 Ma. The Limekiln and Argenta events may represent the initiation of break-up of Rodinia in this part of Laurentia, but appears to be much older than the estimates of the age of rifting based on subsidence analysis of the Cordilleran miogeocline (e.g., Levy and Christie-Blick, 1992).

REFERENCES

Abolins, M., Oskin, R., Prave, T., Summa, C., and Corsetti, F.A., 2000, Neoproterozoic glacial record in the Death Valley region, California and Nevada: GSA Field Guide, v. 2, p. 319-335.

Abolins, M.J., 1999, I, Stratigraphic constraints on the number of discrete Neoproterozoic glaciations and the relationship between glaciation and Ediacaran evolution; II, The Kwichup Spring Thrust in the northwestern Spring Mountains, Nevada; implications for large-magnitude extension and the structure of the Cordilleran thrust belt [Doctoral thesis]: Pasadena, California Institute of Technology.

Albee, A.L., Labotka, T.C., Lanphere, M.A., and McDowell, S.D., 1981, Geologic map of the Telescope Peak Quadrangle, California.

Allen, P.A., and Etienne, J.L., 2008, Sedimentary challenge to Snowball Earth: Nature Geoscience, v. 1, p. 817-825.

Bowring, S.A., Grotzinger, J.P., Condon, D.J., Ramezani, J., Newall, M.J., and Allen, P.A., 2007, Geochronologic constraints on the chronostratigraphic framework of the neoproterozoic Huqf Supergroup, Sultanate of Oman: American Journal of Science, v. 307, p. 1097-1145.

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.

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': Earth-Science Reviews, v. 73, p. 63-78.

Crowell, J.C., 1999, Pre-Mesozoic ice ages; their bearing on understanding the climate system: Memoir - Geological Society of America, v. 192, p. 106.

Dalziel, I.W.D., 1997, Neoproterozoic-Paleozoic geography and tectonics: Review, hypothesis, environmental speculation: Geological Society of America Bulletin, v. 109, p. 16-42.

Donnadieu, Y., Godderis, Y., Ramstein, G., Nedelec, A., and Meert, J., 2004, A 'snowball Earth' climate triggered by continental break-up through changes in runoff: Nature, v. 428, p. 303-306.

Eyles, N., and Januszczak, N., 2004, 'Zipper-rift': a tectonic model for Neoproterozoic glaciations during the breakup of Rodinia after 750 Ma: Earth-Science Reviews, v. 65, p. 1-73.

Halverson, G.P., Dudas, F.O., Maloof, A.C., and Bowring, S.A., 2007, Evolution of the Sr-87/Sr-86 composition of Neoproterozoic seawater: Palaeogeography Palaeoclimatology Palaeoecology, v. 256, p. 103-129.

Halverson, G.P., Hoffman, P.F., Schrag, D.P., Maloof, A.C., and Rice, A.H.N., 2005, Toward a Neoproterozoic composite carbon-isotope record: Geological Society of America Bulletin, v. 117, p. 1181-1207.

Hammond, J.L.G., 1983, Late Precambrian diabase intrusions in the southern Death Valley region, California; their petrology, geochemistry, and tectonic significance [Ph.D. thesis]: Los Angeles, CA, University of Southern California.

Harding, M.B., 1987, The geology of the Wildrose Peak area, Panamint Mountains, California [Map thesis]: Laramie, University of Wyoming.

Hewett, D.F., 1940, New formation names to be used in the Kingston Range, Ivanpah Quadrangle, California: Journal of the Washington Academy of Sciences, v. 30, p. 239-240.

Hodges, K.V., McKenna, L.W., Stock, J., Knapp, J., Page, L., Sternlof, K., Silverberg, D., Wust, G., and Walker, J.D., 1989, Evolution of Extensional Basins and Basin and Range Topography West of Death-Valley, California: Tectonics, v. 8, p. 453.

Hoffman, P.F., 1991, Did the Breakout of Laurentia Turn Gondwanaland inside-Out: Science, v. 252, p. 1409-1412.

Hoffman, P.F., Kaufman, A.J., Halverson, G.P., and Schrag, D.P., 1998, A Neoproterozoic snowball earth: Science, v. 281, p. 1342-1346.

Hoffman, P.F., and Schrag, D.P., 2002, The snowball Earth hypothesis; testing the limits of global change: Terra Nova, v. 14, p. 129-155.

Hoffmann, K.H., Condon, D.J., Bowring, S.A., and Crowley, J.L., 2004, U-Pb zircon date from the Neoproterozoic Ghaub Formation, Namibia: Constraints on Marinoan glaciation: Geology, v. 32, p. 817-820.

Kirschvink, J.L., 1992, Late Proterozoic Low-Latitude Global Glaciation: The snowball Earth: The Proterozoic Biosphere.

Labotka, T.C., 1978, Geology of the Telescope Peak Quadrangle, California and late Mesozoic regional metamorphism, Death Valley area, California [Ph.D. thesis]: Pasadena, CA, United States (USA), California Institute of Technology.

Labotka, T.C., Albee, A.L., Lanphere, M.A., and Mcdowell, S.D., 1980, Stratigraphy, Structure, and Metamorphism in the Central Panamint Mountains (Telescope-

Peak Quadrangle), Death-Valley Area, California - Summary: Geological Society of America Bulletin, v. 91, p. 125-129.

Labotka, T.C., Warasila, R.L., and Spangler, R.R., 1985, Polymetamorphism in the Panamint Mountains, California - a Ar-39-Ar-40 Study: Journal of Geophysical Research-Solid Earth and Planets, v. 90, p. 359-371.

Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub, D.P., Jacobs, J., Karlstrom, K.E., Lu, S., Natapov, L.M., Pease, V., Pisarevsky, S.A., Thrane, K., and Vernikovsky, V., 2008, Assembly, configuration, and break-up history of Rodinia: A synthesis: Precambrian Research, v. 160, p. 179-210.

Lund, K., Aleinikoff, J.N., Evans, K.V., and Fanning, C.M., 2003, SHRIMP U-Pb geochronology of neoproterozoic Windermere Supergroup, central Idaho: Implications for rifting of western Laurentia and synchroneity of Sturtian glacial deposits: Geological Society of America Bulletin, v. 115, p. 349-372.

Miller, J.M.G., 1985, Glacial and syntectonic sedimentation; the upper Proterozoic Kingston Peak Formation, southern Panamint Range, eastern California: Geological Society of America Bulletin, v. 96, p. 1537-1553.

Miller, J.M.G., Troxel, B.W., and Wright, L.A., 1988, Stratigraphy and paleogeography of the Proterozoic Kingston Peak Formation, Death Valley region, eastern California, in Gregory, J.L., and Baldwin, E.J., eds., Geology of the Death Valley region: Santa Ana, South Coast Geol. Soc., p. 118-142.

Molnar, P., and England, P., 1990, Late Cenozoic Uplift of Mountain-Ranges and Global Climate Change - Chicken or Egg: Nature, v. 346, p. 29-34.

Murphy, F.M., 1932, Geology of a part of the Panamint Range, California, Report XXVII of the State Mineralogist, Volume 28: San Francisco, California Department of Natural Resources, Division of Mines and Geology, p. 329-356.

Partin, C., Kennedy, M.J., and Mrofka, D.D., 2007, Interbedding of glacigenic rocks and cap carbonates in the Neoproterozoic Kingston Peak Formation, Panamint Range, Death Valley, CA (Abstract), Geological Society of America, Abstracts with Programs, v. 39 (6), p. 144.

Powell, C.M., Li, Z.X., Mcelhinny, M.W., Meert, J.G., and Park, J.K., 1993, Paleomagnetic Constraints on Timing of the Neoproterozoic Breakup of Rodinia and the Cambrian Formation of Gondwana: Geology, v. 21, p. 889-892.

Prave, A.R., 1999, Two diamictites, two cap carbonates, two delta C-13 excursions, two rifts: The Neoproterozoic Kingston Peak Formation, Death Valley, California: Geology, v. 27, p. 339-342.

Raymo, M.E., and Ruddiman, W.F., 1992, Tectonic Forcing of Late Cenozoic Climate: Nature, v. 359, p. 117-122.

Walker, J.D., Klepacki, D.W., and Burchfiel, B.C., 1986, Late Precambrian Tectonism in the Kingston Range, Southern-California: Geology, v. 14, p. 15-18.

Wernicke, B., Snow, J.K., Hodges, K.V., and Walker, J.D., 1993, Structural constraints on Neogene tectonism in the southern Great Basin, in Lahren, M.M., Trexler, J.H., Jr., and Spinosa, C., eds.: Reno, University of Nevada.

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, Guidebook; Death Valley Region, California and Nevada (see Geological Society of America): Shoshone, Death Valley Publ. Co., p. 27-36.

FIGURES

Figure 1. ***A.*** *Generalized geological map of the Death Valley region.* **B.** *Map showing the distribution of Kingston Peak and Noonday strata in the Panamint Range and locations discussed in the text.*

Figure 2. *Generalized stratigraphic framework of the Kingston Peak Formation in the Panamint Range.*

Figure 3. ***A.*** *Diamictic facies of the Surprise Member, clasts include older Pahrump Group carbonate and basement rocks; Redlands Canyon, southern Panamint Range.* ***B****. Typical exposure of Sourdough Member, Wildrose Canyon.* **C.** *Clast-supported conglomerate of the lower Mountain Girl Member; clast compositions are typically quartzite and vein quartz, although rare basement and even rarer carbonate clasts are present locally. Although tectonic flattening compromises original clast-to-clast relationships, imbrication is apparent, lower left.* **D.** *Well-developed decimeter-scale co-sets of stacked trough cross-bedding characteristic of the upper parts of the Mountain Girl; photographs C and D from Wood Canyon.* ***E, F****. Oolitic (E) and hummocky cross-stratified (F) limestones of the Thorndike Member; South Skidoo.* **G.** *Stromatolite preserved in the Thorndike Member, Wildrose Canyon.* **H.** *Erosive base of Wildrose Member on Thorndike (light colored rocks below), with clasts of Thorndike in overlying diamictite.*

Figure 4. *Examples of the Wildrose Member lithologies.* **A.** *Basement-clast dominated diamictite, Martin Cabin.* **B.** *Carbonate-clast dominated diamictite, Argenta Ridge*.

Figure 5. *Angular unconformity at the base of the Argenta Member; fine lines indicate bedding in pre-unconformity units. Zks, Surprise Member; Zka, Argenta Member; Zkmg, Mountain Girl Member; Zkt, Thorndike Member.* **A.** *Photograph showing truncation of folded Surprise Member units, western Wildrose Canyon*. **B.** *Photograph showing angular truncation of Surprise Member, Bandit Bowl.*

Figure 6. *Photograph of Argenta Ridge, the designated Type Locality of the Argenta Member; note overall wedge-shaped geometry. Zks, Surprise Member; Zka, Argenta Member; Zkmgl, lower conglomeratic unit of Mountain Girl Member; Zkmgu, upper quartzite unit of Mountain Girl Member; Qa, Quaternary cover.*

Figure 7. **A.** *Argenta Member sedimentary breccias composed of clasts consisting mostly of granitic gneiss, feldspar augen and vein quartz fragments; Wood Canyon.* **B.** *Typical outcrop appearance of the Argenta Member; these rocks were commonly mistaken for Surprise Diamictite; Argenta Ridge.* **C.** *Carbonate-clast rich breccia; clasts flattened to aspect ratios typically exceeding 10:1 due to tectonic strain, Wire Peak.* **D.** *Medium- to coarse-grained sandstone bed exhibiting flat lamination and rare cross-stratification; Wire Peak. Sandstones such as this one are laterally continuous at least at outcrop scales and separate beds of the coarser breccia facies.*

Figure 8. *North-South stratigraphic cross-section showing the overall wedge-shaped nature of the Argenta Member. Stratigraphic relationships constrain extensional tectonism to post-Sourdough Member and pre-Mountain Girl Member deposition. All sections use the base of the Sentinel Peak Member of the Noonday Formation as a datum. See Fig. 1B for section locations.*

Figure 9. *Composite lithostratigraphic and C-isotope profile for the Kingston Peak Formation in the Panamint Range. Timing of Argenta extensional tectonics can be bracketed between the ca. 713 Ma and 635 Ma ages inferred for the Surprise Member and Marinoan. See text for discussion.*

Figure 1

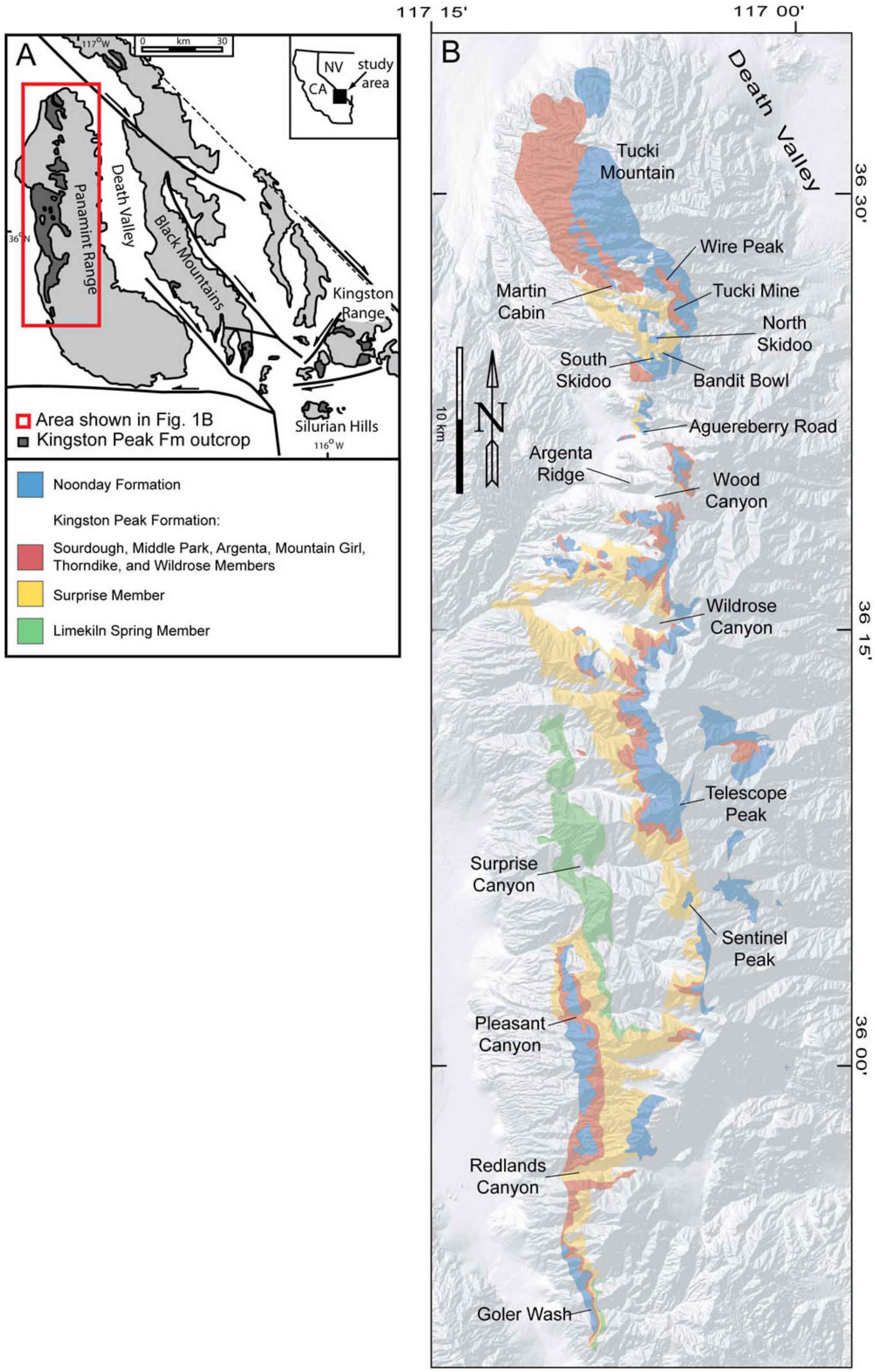
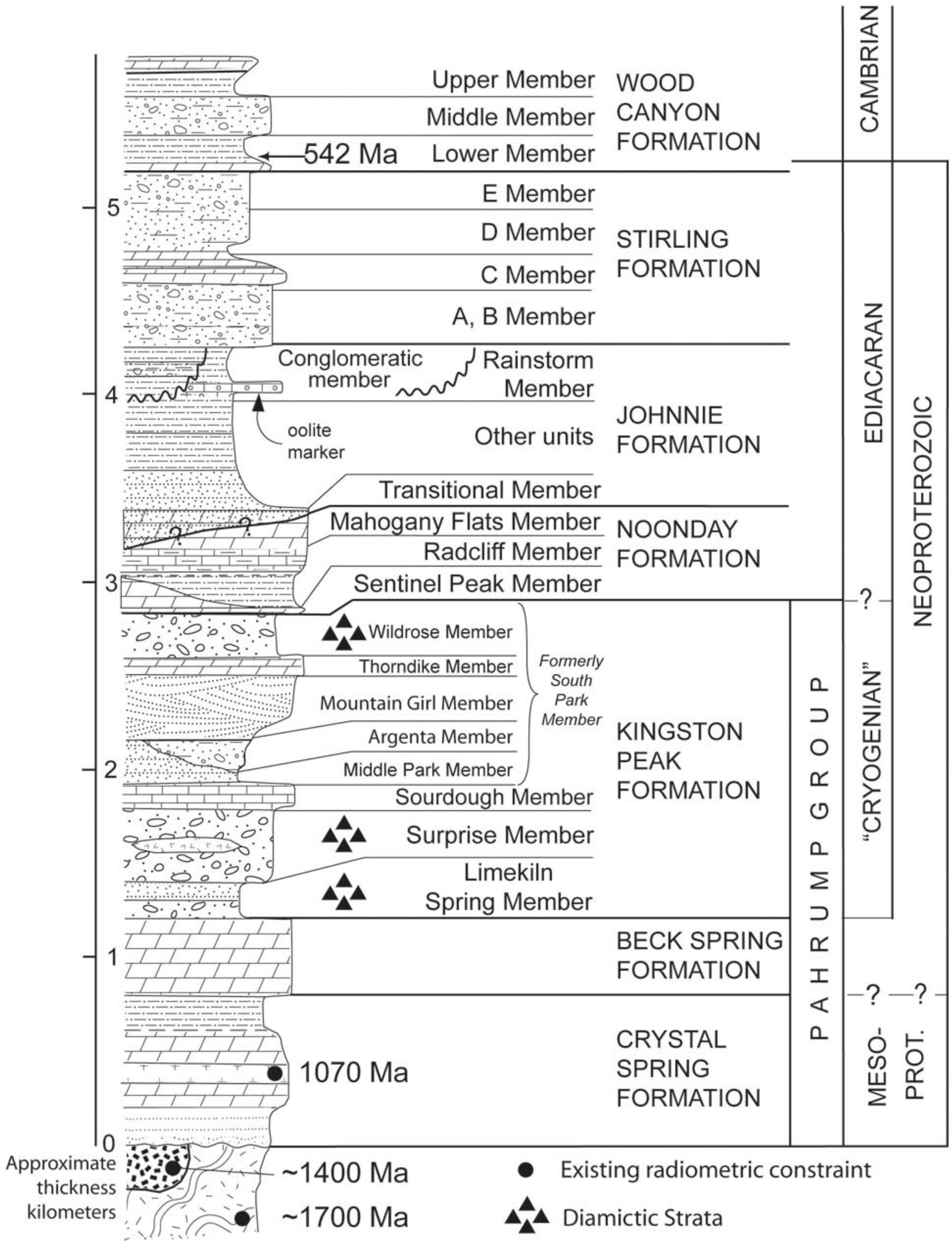

A
117°W
0 km 30
NV
CA
study area
Panamint Range
Death Valley
Black Mountains
Kingston Range
Silurian Hills
36°N
116°W
Area shown in Fig. 1B
Kingston Peak Fm outcrop
Noonday Formation
Kingston Peak Formation:
Sourdough, Middle Park, Argenta, Mountain Girl, Thorndike, and Wildrose Members
Surprise Member
Limekiln Spring Member
117 15'
117 00'
B
Death Valley
36 30'
36 15'
36 00'
Tucki Mountain
Wire Peak
Tucki Mine
Martin Cabin
North Skidoo
South Skidoo
Bandit Bowl
10 km
N
Aguereberry Road
Argenta Ridge
Wood Canyon
Wildrose Canyon
Telescope Peak
Surprise Canyon
Sentinel Peak
Pleasant Canyon
Redlands Canyon
Goler Wash

Figure 2



CAMBRIAN
EDIACARAN
"CRYOGENIAN"
MESO-
NEOPROTEROZOIC
PROT.
PAHRUMP GROUP
Upper Member
Middle Member
Lower Member
542 Ma
WOOD CANYON FORMATION
E Member
D Member
C Member
A, B Member
STIRLING FORMATION
Conglomeratic member
Rainstorm Member
oolite marker
Other units
JOHNNIE FORMATION
Transitional Member
Mahogany Flats Member
Radcliff Member
Sentinel Peak Member
NOONDAY FORMATION
Wildrose Member
Thorndike Member
Mountain Girl Member
Argenta Member
Middle Park Member
Formerly South Park Member
Sourdough Member
Surprise Member
Limekiln Spring Member
KINGSTON PEAK FORMATION
BECK SPRING FORMATION
1070 Ma
CRYSTAL SPRING FORMATION
~1400 Ma
~1700 Ma
0
1
2
3
4
5
Approximate thickness kilometers
Existing radiometric constraint
Diamictic Strata

Figure 3

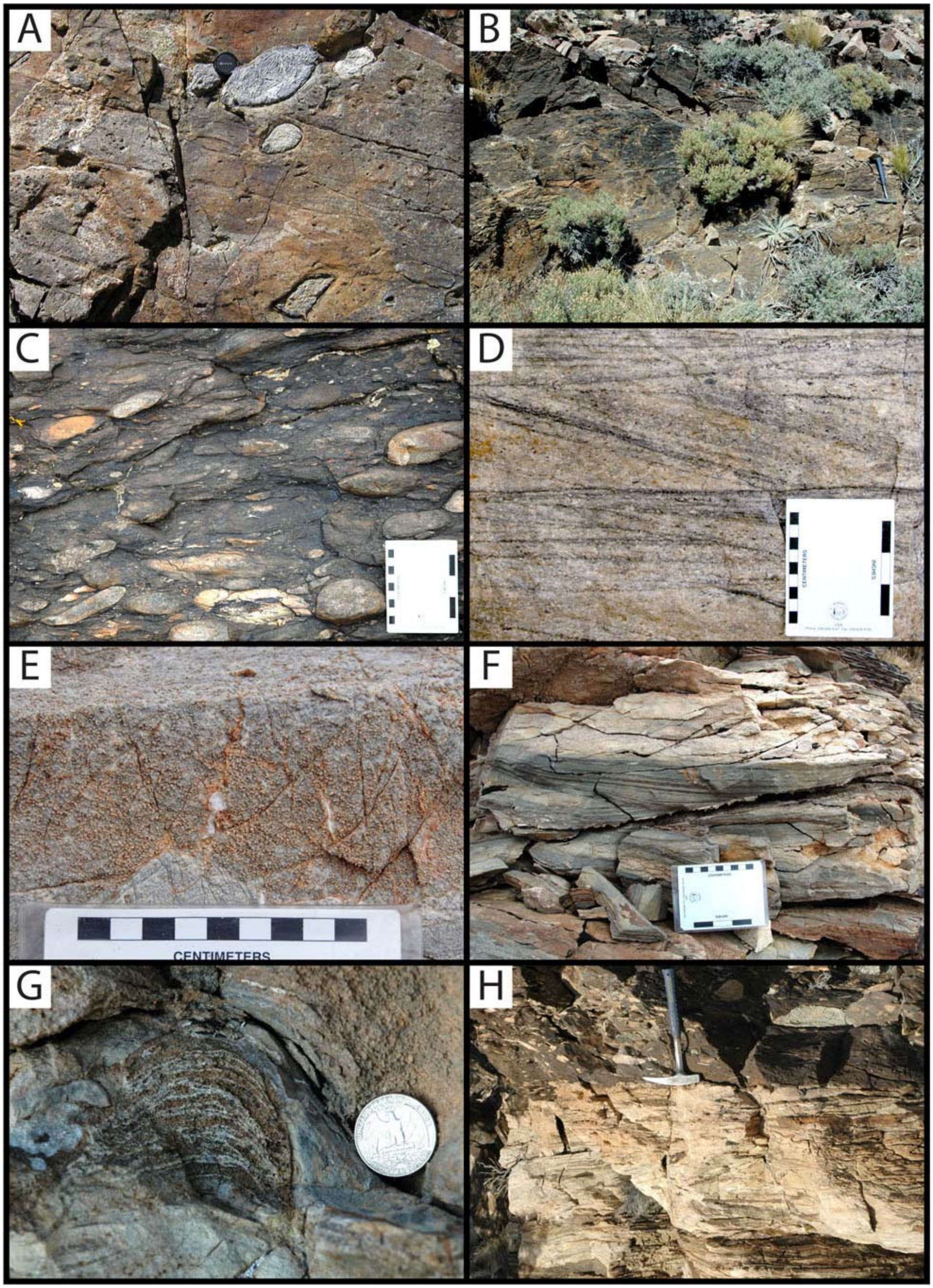


Figure 4

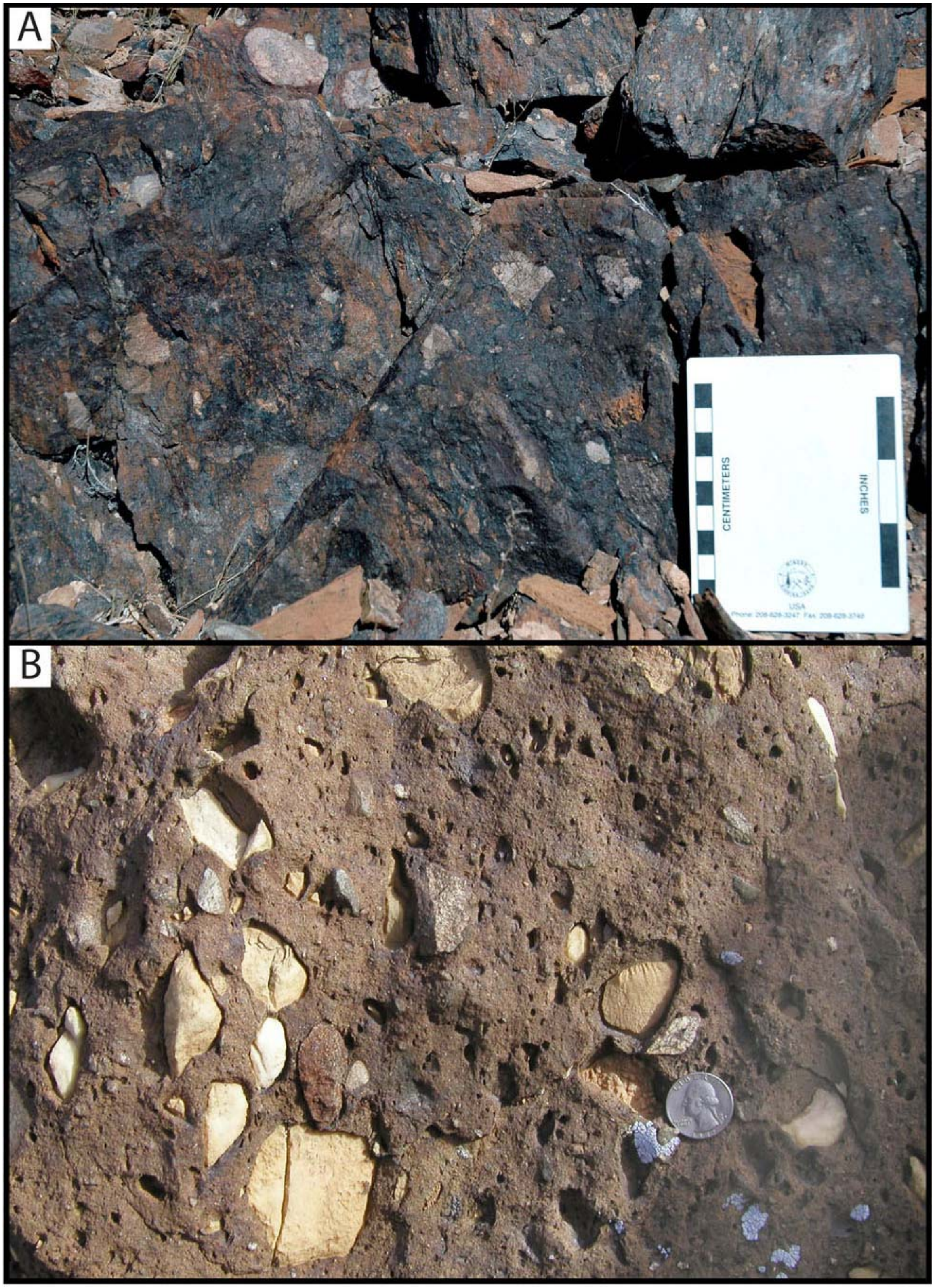


Figure 5

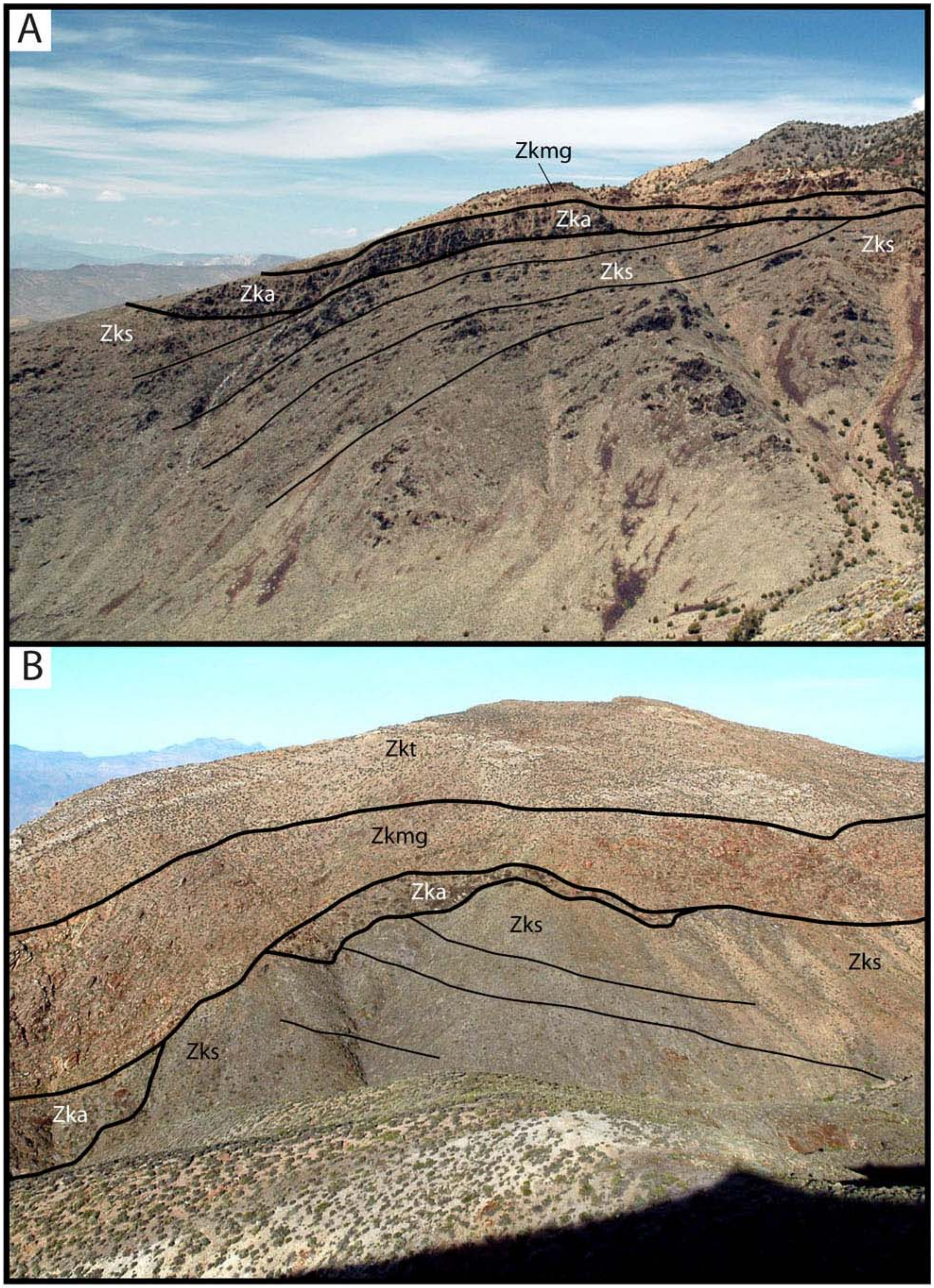


Figure 6

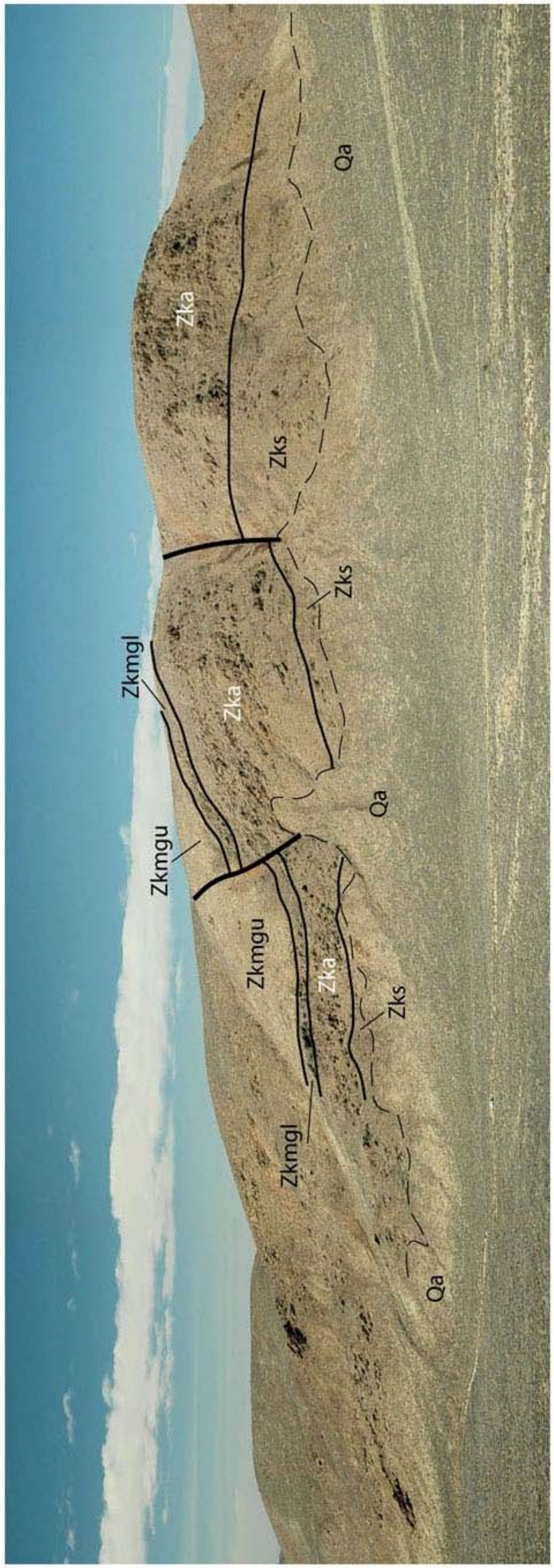


Figure 7

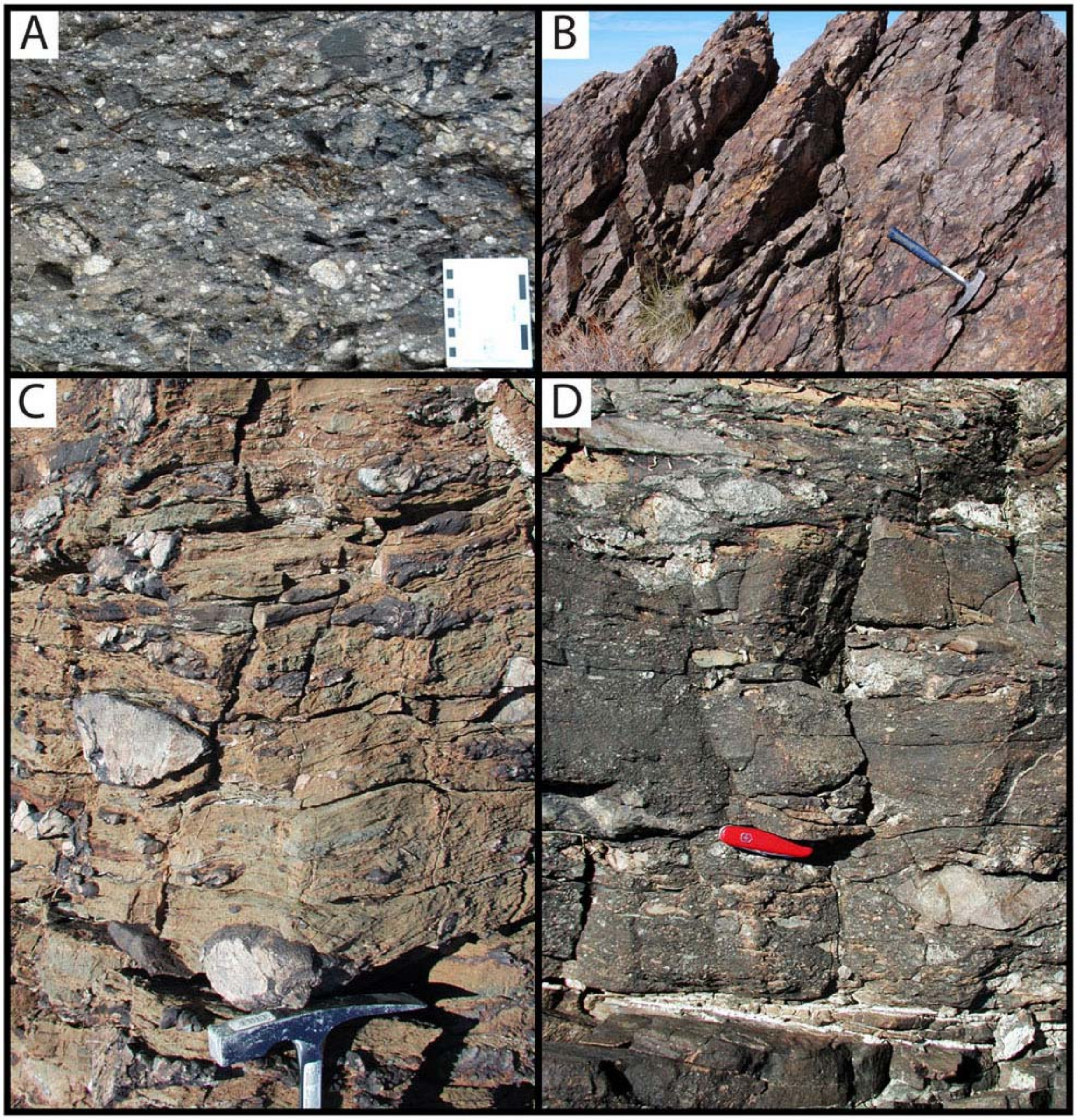


Figure 8

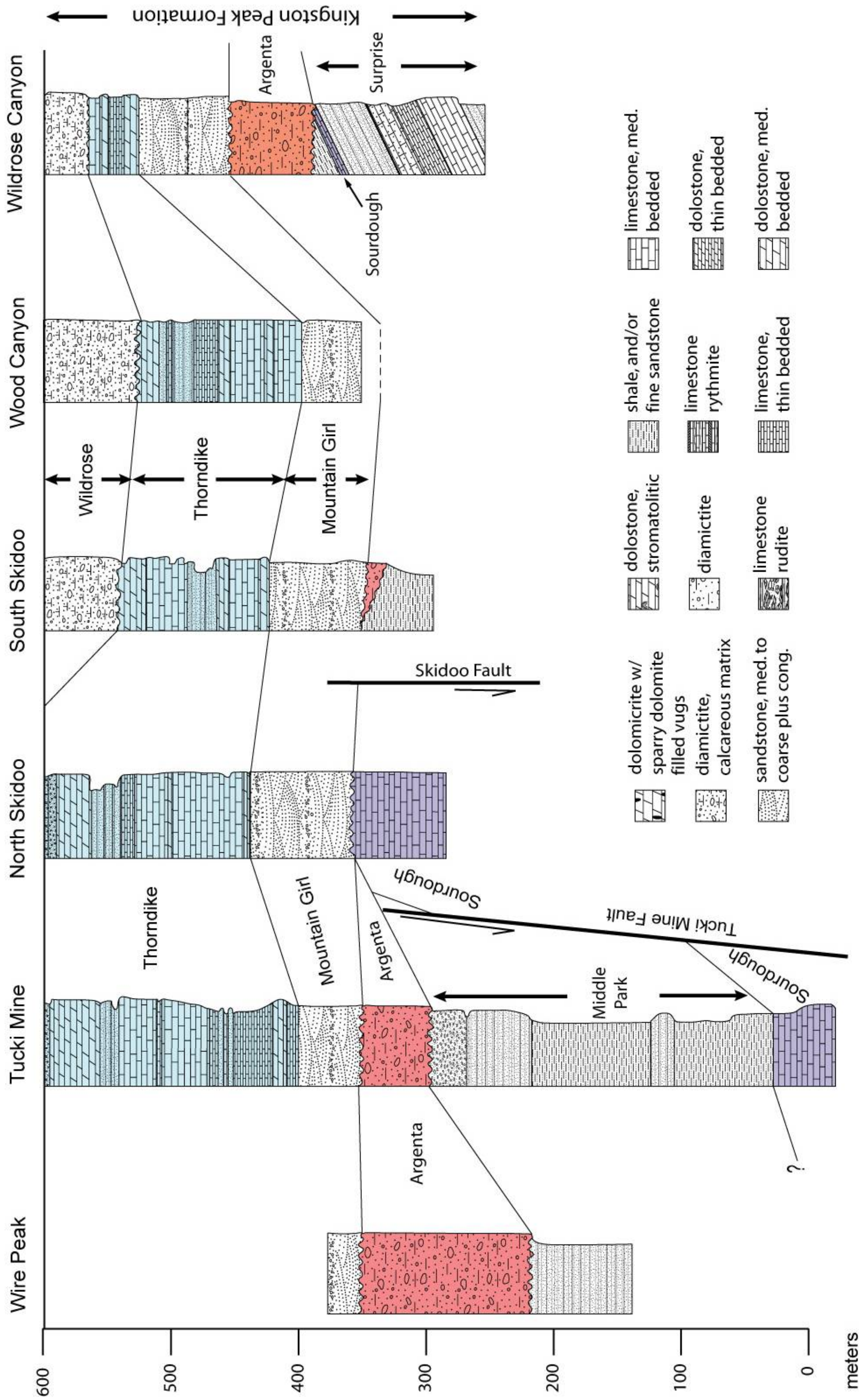
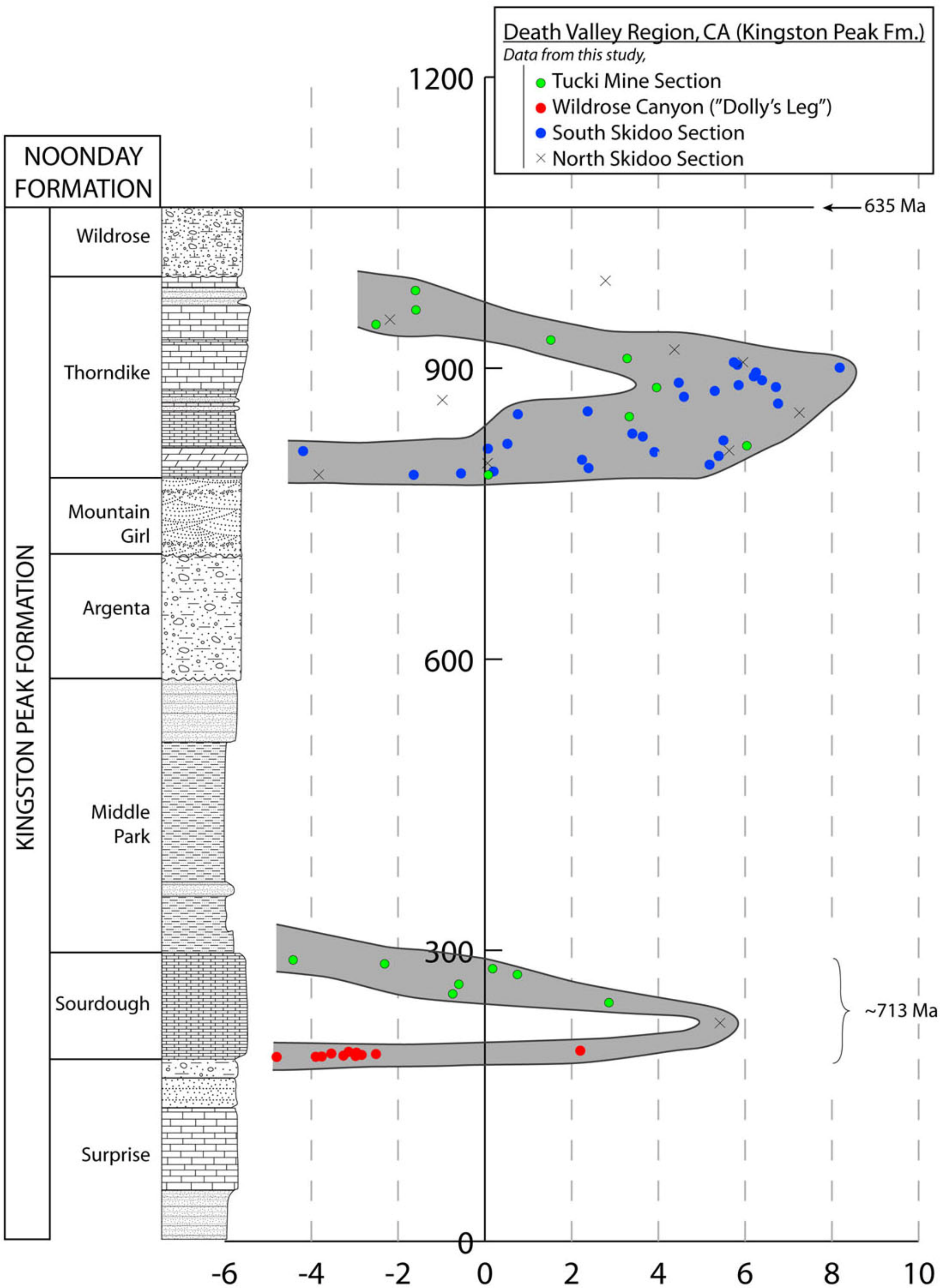

Wire Peak
Tucki Mine
North Skidoo
South Skidoo
Wood Canyon
Wildrose Canyon
Kingston Peak Formation
Argenta
Surprise
Sourdough
Wildrose
Thorndike
Mountain Girl
Skidoo Fault
Tucki Mine Fault
Middle Park
?
600
500
400
300
200
100
0
meters
dolomicrite w/ sparry dolomite filled vugs
diamictite, calcareous matrix
sandstone, med. to coarse plus cong.
dolostone, stromatolitic
diamictite
limestone rudite
shale, and/or fine sandstone
limestone rythmite
limestone, thin bedded
limestone, med. bedded
dolostone, thin bedded
dolostone, med. bedded

Figure 9



Death Valley Region, CA (Kingston Peak Fm.)
Data from this study,
Tucki Mine Section
Wildrose Canyon ("Dolly's Leg")
South Skidoo Section
North Skidoo Section
NOONDAY FORMATION
KINGSTON PEAK FORMATION
Wildrose
Thorndike
Mountain Girl
Argenta
Middle Park
Sourdough
Surprise
635 Ma
~713 Ma
1200
900
600
300
0
-6
-4
-2
0
2
4
6
8
10

IV. APPENDIX

A. MEASURED SECTIONS

Eastern Wildrose Canyon

Measured in two parts in the charcoal kilns area along the Wildrose Canyon Road, sec. 27 and western part of sec. 26, T19S, R45E. Section begins at 36°14'55.42"N, 117° 5'10.95"W and ends at 36°15'12.90"N, 117° 4'25.32"W (see Figure A1 for locations).

[Measured by R. Petterson, A. Prave, and B. Wernicke, 1/15/03]

Johnnie Formation (40+ m, incomplete)

18. Metasiltstone, medium bluish gray (5B5/1), greenish gray (5GY6/1) or, where carbonate cement present, yellowish gray (10YR7/6) weathering, laminated to thin bedded with normal grading.

Cataclastic zone observed between units 17 and 18, probable fault.

Noonday Formation (352 m):

Mahogany Flats Member (180 m):

17. Sandy dolostone marble (>90%) and metasandstone (<10%), both very light gray to white (N8 to N9), very pale orange (10YR8/2) to grayish orange (10YR7/4) weathering, sand is fine to medium grained; decimeter-scale microbial mounds separated by variably siliceous, cross-stratified intermound fill (80 m).

16. Dolostone marble, similar to unit 14, except lower 6 m exhibits parallel-laminated boundstone with laterally-linked heads (LLH); oolites observed in middle of unit; upper half of unit contains mound structures similar to unit 14, but in contrast to unit 14 also includes abundant parallel-laminated boundstone with sheet cracks filled with sparry dolomite (50 m).

15. Metasandstone and metasiltstone, moderate orange pink (10R7/4), moderate reddish orange weathering (10R6/6), or where carbonate cement is present very pale orange (10YR8/2), grayish orange (10YR7/4) weathering; thin bedded alternating fine sand and silt, hummocky cross-stratified; at km scale, unit pinches out to the north such that units 19 and 21 are in contact (5 m).

14. Dolostone marble, medium light gray (N6), light gray (N7) to very pale orange (10YR8/2) weathering, secondarily recrystallized, thick bedded (>1 m), unit composed almost entirely of algal boundstone exhibiting mound structure at meter scale, perhaps as large as 10 m; laminations typically at high angle (up to 90°) to bedding; abundant vugs and stringers of filled with sparry dolomite cement; basal contact abrupt, bedding parallel algal laminite not observed at contact or elsewhere in unit (45 m).

Radcliff Member (163 m):

Upper Sub-member (44 m):

13. Metasiltstone and fine-grained metasandstone, light olive gray (5Y6/1) to greenish gray (5YR6/1), moderate brown (5YR4/4) to grayish red (5R4/2) weathering; silt and sand generally interlaminated, but some sand beds are up to 10 cm; sand content increases toward top of unit; hummocky cross-stratified; limestone breccia horizon occurs 5 m below base of unit (30 m).

12. Feldspathic metasandstone, white (N9) to grayish pink (5R8/2), variably weathers pale red (10R6/2), pale yellowish brown (10YR6/2), or light gray (N8), granular to medium grained with overall upward fining, medium to thick bedded, low-angle trough cross stratified, 100-m scale channelization both within the unit and into underlying unit; capped by dark yellowish orange (10YR6/6) weathering, 10 to 20 cm thick transgressive lag, in turn overlain by white (N9), grayish orange (10YR7/4) weathering ash horizon 1 to 2 m thick (5 to 14 m)

Offset on unit 16 ~800 m N35W, so that overlying units, beginning at the base of unit 12, measured along the hiking trail from the charcoal kilns to Wildrose Peak, ~300 m N25W from the trailhead at the kilns (Figure A1).

Middle Sub-member (127 m):

11. Metasandstone and metasiltstone, brownish gray (5YR4/1), olive gray (5Y5/1) weathering, laminated to thin bedded (9 m).

10. Limestone marble, yellowish gray (5Y8/1) to light gray (N7), very pale orange (10YR8/2) weathering, thin to medium bedded with dispersed quartz and feldspar medium to coarse sand, low-angle cross stratification (8 m).

9. Limestone marble, similar to unit 12 (36 m).

8. Metasandstone and metasiltstone, medium gray (N5), light olive gray (5Y5/2) weathering, alternating laminations of fine sand and silt (4 m).

7. Limestone marble, similar to unit 11 but with only sparse siliceous partings (20 m).

6. Limestone marble, pinkish gray (5YR8/1), grayish orange (10YR7/4) to pale yellowish orange (10YR8/6) weathering, micritic, laminated, contains mm to cm thick siliceous horizons (38 m).

5. Limestone marble, rhythmically alternating medium gray (N5), weathering the same color, and light gray (N8), pinkish gray (5YR8/1) to light brown (5YR6/4) weatherning laminations and thin beds; contains decimeter-thick beds of intraclastic breccia with clasts up to 10 cm in maximum dimension (8 m).

4. Metasandstone and metasiltstone, pale yellowish brown (10YR6/2), light brown (5YR6/4) weathering, rhythmic, parallel thin beds of alternating sand and silt, calcareous matrix (5 m).

Lower Sub-member (disconformably omitted)

Sentinel Peak Member (9 m):

3. Dolostone marble, very pale orange (10YR8/2), weathers same color, micritic, largely massive with abundant spar-filled sheet cracks and vugs; base is faintly laminated; top meter displays low-angle cross lamination, with sharp, concordant contact with overlying unit (9 m).

Kingston Peak Formation (39+ m, incomplete):

South Park Member (39+ m, incomplete):

Wildrose Diamictite Submember (0 to 2 m)

2. Metadiamictite; matrix brownish gray (5YR4/1), dark yellowish brown (10YR/2) weathering, fine to coarse grained massive feldspathic sand with calcareous matrix; clasts predominantly 5 to 6 cm cobbles of grayish orange (10YR7/4) to pale yellowish orange (10YR8/6) weathering limestone; unit is discontinuously preserved below disconformity with overlying unit (0 to 2 m).

Thorndike Limestone Submember (37 m):

1. Limestone marble, alternating (1) yellowish gray (5Y7/2), grayish yellow (5Y8/4) weathering, contains dispersed medium to coarse detrital quartz and feldspar grains, thick bedded with 2-5 cm siliceous horizons parallel to bedding; and (2) medium gray (N5), alternating laminations to thin beds weather light gray (N7) to white (N9), thin siliceous horizons containing fine sand and silt parallel bedding; top of unit contains decimeter-scale cross stratification developed in sand-rich (up to 50%) horizons.

South Wood Canyon

Measured near the crest of the Panamint Range in a canyon on the east facing slope of Bald Peak, approximately 1 km NNE of the summit, near the head of Wood Canyon; section begins at 36°18'39.89"N, 117° 5'13.02"W and ends at 36°18'37.52"N, 117° 5'21.82"W.

[Measured by R. Petterson and B. Wernicke, 10/12/02]

Noonday Formation (136 m, incomplete)

Radcliff Member (125 m, incomplete)

Middle Submember (125 m, incomplete)

9. Limestone, similar to upper part of unit 7 (9 m).

8. Sandstone, pale red (10R6/2), weathers same, medium-grained to granular, massive (1 m).

7. Limestone, very pale orange (10YR8/2), micritic, medium bedded, upper 2 meters contains laminations with siliceous partings; intraformational breccia occurs 5 meters from base of unit (17 m).

6. Limestone, light to very light gray (N7 to N8.5), micritic, laminated (2 m).

5. Limestone (70%) and sandstone (30%), interstratified at cm-scale; Limestone very pale orange (10YR8/2), weathers pale yellowish orange (10YR8/6), generally micritic, mostly thin-bedded with some beds up to 50 cm; sandstone medium dark gray (N4), weathers same, fine-grained, thin-bedded, intraformational breccias similar to unit 4 occur at 10 m and 28 m above base of unit, proportion of limestone increases slightly upward; interstratification of limestone and sandstone is probably rhythmic; numerous ovoid alteration spots occur on bedding surfaces, ranging from 2 mm to 2 cm in maximum dimension (55 m).

4. Limestone, similar to limestone in unit 2, but 100% intraformational breccia (3 m).

3. Sandstone, medium gray (N5), weathers same to greenish gray (5GY6/1), fine grained, thin-bedded with clay-rich partings; bed internally laminated, but ripple marks occur on tops of some beds (5 m).

2. Sandstone and limestone; sandstone is dark greenish gray (5GY4/1), limestone is medium gray (N5), both weather grayish orange (10YR7/4) to pale yellowish orange (10YR8/6); weathering color is distinctive and dominates landscape; sandstone is fine grained, thin to medium beds are internally laminated; limestone medium to thick bedded, locally exhibiting intraformational breccias with clasts up to 10 cm. Lower part of unit largely obscured by talus (23 m).

Sentinel Peak Member (11 m)

1. Dolomicrite, white (N9), weathers same, or pale grayish orange (10YR7/2), very pale orange (10YR8/2) weathering, massive, locally laminated, lithographic; coarse sparry dolomite fills variably oriented, elongate vugs, locally defining crude cm-scale layering not necessarily parallel to bedding (11 m).

South Skidoo

Measured approximately 300 m west of Skidoo Road at 36°24'50.38"N, 117° 6'19.49"W (see Figure A2 for location).

[Measured by R. Petterson, A. Prave, and B. Wernicke 1/12/03]

Noonday Formation (7 m, incomplete)

Sentinel Peak Member (7 m, incomplete)

2. Dolostone, very pale orange (10YR8/2) to very light gray (N8), weathers same, micritic; lower 2 m strongly laminated with some low angle cross stratification; remainder of unit is medium to thick bedded and locally contains vertical tube structures, algal mounds and other algal features (7 m, incomplete).

Kingston Peak Formation

South Park Member

Wildrose Submember

1. Diamictite; matrix is micaceous sandstone, medium dark gray (N4) to dark gray (N3), weathers grayish brown (5YR4/2) to dark yellowish brown (10YR3/2), medium to coarse grained with carbonate cement, massive; clasts primarily include a distinctive pale yellowish orange (10YR8/6) to very pale orange (10YR8/2) limestone (approx. 50%), sandstone, gneiss, and granite. Clasts are primarily small pebbles to cobbles, but boulders with maximum dimension of a few decimeters are common; unit as a whole is massive and contains no trace of stratification (58 m).

North Skidoo

Measured on the crest of the Panamint Range, 4.2 km east of Skidoo town site, across peak 5979 on the Tucki Wash 1:24,000 quadrangle; section begins at 36°26'19.23"N, 117° 6'6.74"W *and ends at* 36°26'18.74"N, 117° 5'52.06"W *(see Figure A3 for locations).*

[Measured 5/12/01 by B. Wernicke, F. MacDonald, and K. Klein; and 1/13/03 by R. Petterson, A. Prave, and B. Wernicke]

Noonday Formation (266 m, incomplete)

Radcliff Member (211 m, incomplete)

Upper Submember (211 m, incomplete)

15. Limestone, as unit 10, except lower 10 m are very light gray (N8) to white (N9) on fresh and weathered surfaces (20 m).

14. Intraformational breccia, as unit 9 (0.5 m).

13. Limestone, as unit 10 (1 m).

12. Intraformational breccia, as unit 9 (13 m).

11. Siltstone, as unit 6 (1 m).

10. Limestone, medium gray (N5), medium light gray (N6) weathering, laminated, micritic, local siliceous partings (2 m).

9. Intraformational breccia, as unit 7, maximum clast dimensions <1 m (1 m).

8. Sandstone, grayish orange (10YR7/4), weathers same, coarse, well rounded, well sorted, dolomitic matrix, low-angle planar cross stratification (3 m).

7. Intraformational breccia, primarily limestone and dolostone intraclasts, varicolored gray and yellowish brown weathering, limestone clasts up to 2 m in maximum dimension; thickness in this unit and overlying units uncertain due possible tight folding (15 m).

6. Siltstone and conglomerate; siltstone, light brown (5YR5/6), weathers same to dark yellowish orange (10YR6/6), parallel laminated; conglomerate, clasts are dark gray (N3), yellowish orange (10YR7/6) to grayish orange (10YR7/4) weathering dolomicrite, poorly sorted pebbles to boulders, elongate, rounded, locally well imbricated; matrix similar to surrounding siltstone but may weather moderate pink (5R7/4); one bent conglomerate clast observed suggesting only partial lithification of dolostone at the time of deposition (40 m).

5. Dolostone, sandy dolostone, sandstone and siltstone; dolostone as unit 1; sandy dolostone similar to unit 2 but weathers yellowish brown (10YR5/2), recessive; sandstone is light gray (N7), weathers pale red (10R7/2), medium to coarse grained, medium to thick bedded; siltstone is very pale orange (10Y8/2), weathers pale reddish brown (10R5/4); intraformational conglomerates similar to that in unit 3 occur at 25 m and 95 m above base of unit; sandstone and siltstone interval is 5 m thick and occurs at 70 m above base of unit; thickness uncertain due to faulting within unit which may omit or duplicate section (115 m).

Sentinel Peak Member (55 m)

4. Dolostone; light orange pink (5YR7/6), weathers very pale yellowish brown (10YR7/2), thick bedded to massive, lower 2 meters is laminated; micritic; sparry dolomite fills variably oriented, elongate vugs up to 5 cm in length (55 m).

Kingston Peak Formation (38 m, incomplete)

South Park Member (38 m, incomplete)

<u>Thorndike Submember</u> (38 m, incomplete)

3. Dolostone, as unit 1; upper half meter is intraformational conglomerate, generally pebbles to small cobbles, matrix supported, includes clasts of unit 2 (15 m).

2. Sandy dolostone; white (N9), weathers pale yellowish brown (10YR7/2), arenaceous; sand fine to coarse; medium to low angle cross stratification; recrystallized ooids (~1 mm) (3 m).

1. Dolostone; light gray (N7), weathers pale orange (10YR7/2), sucrosic; thick bedded to massive, local faint lamination; secondary sparry dolomite in irregular segregations (20 m).

Martin Cabin

Measured near Martin Cabin, 3.4 km SSE of vertical-angle benchmark Tucki (6732) on Emigrant Canyon 1:24,000 quadrangle. Base of measured section located at 36°28'17.33"N, 117° 6'58.48"W, top of section located at 36°28'21.97"N, 117° 6'47.75"W (Figure A4).

[Measured by R. Petterson, A. Prave, and B. Wernicke 4/28/06]

Noonday Formation (164 m, incomplete)

Mahogany Flats Member (22 m, incomplete)

13. Karst breccia, clasts up to boulder size of unit 12 in a coarse sand matrix; lower contact is highly irregular with relief up to 12 m; uncertain whether unit represents karsting during Mahogany Flats time or at much later time (10 m, incomplete).

12. Dolostone, light gray (N7) to medium gray (N5), weathers same to light olive gray (5Y6/1), coarse sucrosic texture from secondary dolomitization, algal lamination locally preserved; top of unit is defined by karst breccia (12 m).

Radcliff Member (140 m)

Upper Submember (51 m)

11. Siltstone, sandstone and conglomerate; siltstones and sandstones are pale brown (5YR5/2), moderate brown (5YR4/4) weathering, thin to medium beds of fine grained sandstone interbedded with siltstone near base of unit; 1.5 m-thick conglomerate bed occurs approx 5 m from base of unit, clasts are predominately carbonate up to 1 m in maximum dimension (36 m).

10. Arkose, moderate reddish orange (10R6/6), very dusky red (10R2/2) weathering, coarse grained (up to small granules), medium to thick bedded, occasional low angle cross stratification; units 9 and 10 collectively form a resistant marker horizon (7 m).

9. Dolomitic sandstone, pale reddish brown (10R5/4), weathers dark yellowish orange (10YR6/6), arkosic, coarse grained, medium to thick bedded, arkosic, contains stringers of secondary silica parallel to bedding (8 m).

Middle Submember (42 m)

8. Limestone, very pale orange (10YR8/2), weathering to a variety of pastel hues (e.g., very pale orange (10YR8/2), moderate pink (5YR7/4), and pale yellowish orange (10YR8/6)), micritic, strongly laminated; approx. 10% of the unit includes medium to thick beds of unlaminated laminated limestone containing granular sand; uppermost and lowermost portions of unit contain thin interbeds of phyllitic siltstone similar to unit 6; intraformational breccia horizon occurs 12 m below the top of the unit; prominent fault disrupts section 14 m above base, potentially omitting a significant amount of section; pale yellowish orange (10YR8/6) weathering color is distinctive of this interval of the Radcliff Member and often dominates landscape (Figure A4) (42 m).

Lower Submember (47 m)

7. Phyllitic siltstone (80%) and limestone (20%); siltstone as in unit 6; limestone as in unit 3; measured thickness accounts for tight folding within unit that duplicates section (Figure A4) (22 m).

6. Phyllitic siltstone, greenish gray (5G6/1), light greenish gray (5G8/1) weathering; contains distinctive thin beds of moderate red (5R5/4), pale reddish brown (10R5/4) weathering limestone (10 m).

5. Phyllitic sandstone, very light gray (N8) to medium dark grey (N4), weathers same with patches of dusky red (5R3/4), fine grained; unit overall weathers a distinctive light gray color relative to surrounding units (15 m).

Line of section offset across minor fault, see Figure A4.

4. Sandstone, medium gray (N6), dusky yellowish brown (10YR3/2) weathering, poorly sorted with grain size ranging from silt up to small granules, massively bedded with decimeter- to meter-scale variations in grain size, arkosic; unit contains two pale yellowish brown (10YR6/2), dark yellowish orange (10YR6/6) weathering limestone beds 20 m above base; upper 7 m contains calcareous matrix similar to siltstone in unit 3; upper 3 meters forms a prominent light brown (5YR5/6) to pale yellowish brown (10YR6/2) dolostone marker horizon (33 m).

3. Calcareous siltstone (80%) and limestone (20%); calcareous siltstone is very pale green (10G8/2), weathers same, grayish orange pink (10R8/2) and pale reddish brown (10R5/4), contains dispersed sand grains; limestone similar to unit 2, in thin to medium beds concentrated near the base and the upper 10 m of the unit; lower contact is gradational with unit 2, upper contact sharp with unit 4 (30 m).

Sentinel Peak Member (2 m)

2. Limestone, pale yellowish brown (10YR6/2), very pale orange (10YR8/2) to grayish orange (10YR7/4) weathering, micritic, laminated at base with increasing frequency of thin beds (ca. 5 cm) toward top of unit.

Kingston Peak Formation (5 m, incomplete)

South Park Member (5 m, incomplete)

Wildrose Submember (5 m, incomplete)

1. Diamictite; dark gray (N3) to grayish blue (5PB5/2), weathers dark yellowish brown (10YR4/2); clasts primarily small pebbles to cobbles of gneiss, granite, quartzite, and carbonate, ranging from rounded to angular; matrix supported; matrix is massive and predominately siliceous, except in upper meter of unit where it is moderate olive brown (5Y4/4) weathering carbonate (5 m, incomplete).

B. DETAILED DISCUSSION OF PREVIOUS MODELS

Williams et al. (1974)

This work builds on that of Williams et al. (1974), clarifying details that were not deemed particularly significant, but in the context of global changes, such as those proposed by the Snowball Earth Hypothesis (e.g., Kirschvink, 1992; Hoffman *et al.*, 1998; Hoffman & Schrag, 2002), are of critical importance. For example, at the time, whether there were one, two or more thin intervals of conglomerate and dolostone seemed of minimal importance. However, if those conglomerates and dolostones each represent a global ice age, their exact number is important to document and the overall significance of a 2-meter carbonate bed is vastly disproportionate to its thickness. To that end, I consider the broad-scale correlations within Noonday strata described by Williams *et al.* (1974) to be generally correct (and admirably insightful considering the amount of data at hand), but not detailed enough to fully capture the necessary stratigraphic subtleties. For example, their model infers an abrupt change from Nopah Range Facies Noonday to Ibex Hills Facies Noonday. My work shows that this is not always the case. The transition is sometimes gradual, and commonly involves changes in one member of the Noonday but not another. They are also not clear on exactly how the lower Noonday on their "platform" transitions to the basal dolomite unit in their "basin." I also disagree on their placement of the Johnnie contact (see Noonday-Johnnie Transition section for further discussion.)

Corsetti and Kaufman (2005)

The lack of age control that haunts Neoproterozoic geology has made carbon isotopic profiles a widely used, and broadly accepted, proxy for age. In order to ascertain an age for a section, a curve for the rocks in question is constructed and compared with dated curves obtained elsewhere. However, the exact temporal framework of rocks needs to be known, otherwise one runs the risk of duplication or omission of parts of the profile. The Noonday has proved challenging in this regard (see Chapter II for previous chemostratigraphic work).

The most recent attempt at constructing a meaningful depositional sequence for Noonday strata is by Corsetti and Kaufman (2005). They conclude that at least three discrete glaciations (and associated C isotopic negative anomalies) are recorded in the Neoproterozoic rocks of the Death Valley Region. Their three glacial units and associated "caps" are as follows: 1) Surprise/Sourdough; 2) Wildrose/lower Noonday; and 3) Conglomerate/Dolostone Members of the Ibex Formation. I concur that the dolostone member (I1) of the "Ibex Formation" is a "cap" and most likely represents a deglaciation. However, my work shows that it is the same "cap" as the lower Noonday (SP).

Corsetti and Kaufman (2005) interpreted the Ibex Hills Facies of the Noonday Formation as wholly younger than that represented by the Nopah Range Facies of the Sentinel Peak Member, and thereby representing a third glacial event. This interpretation is based mainly on two observations: A) the erosion of "lower Noonday" under "lower Ibex" in the southern Black Mountains; and B) the presence of Noonday "tubestone" clasts in a diamictite below the dolostone member (Chapter II, Figure 8D).

In order to address and account for those observations, Corsetti and Kaufman (2005) propose two possible correlation schemes that both have the lower Noonday eroded beneath the “Ibex Formation”, but differ in how they correlate the upper Noonday to the Ibex Formation. In one of their scenarios, they correlate Upper Noonday (now recognized herein as MF) to the Limestone and Shaley Limestone members of the Ibex Formation (now recognized herein as the middle Radcliff sub-member). In the other, the Upper Noonday (i.e. the MF, but specifically the lower part) correlates to the Dolostone Member of the Ibex Formation (i.e. the SP). I will examine those correlations *assuming* the above observations A and B are true. Both schemes are immediately problematic based on a relationship that is illustrated in their own Figure 3. The map shows that “lower Ibex” (including the limestone members) is stratigraphically *below* the “upper Noonday” (i.e. MF); it would be exceedingly difficult (read impossible) for upper Noonday to be laterally equivalent to units that it clearly overlies. Furthermore, my work in the Panamint Mountains shows that numerous sections display a coherent, consistent, mappable stratigraphy in which the dolomite member (SP), the limestone units of the middle Radcliff, and the upper Noonday (MF; see the Martin Cabin section in the appendix for an example) are stratigraphically superposed, inconsistent with both of the correlation schemes suggested by Corsetti and Kaufman (2005).

Even though the suggested correlation schemes are incorrect, the observations require explanation. In reference to observation A, there is no evidence of the erosion of “lower Noonday” under “lower Ibex” in the southern Black Mountains. This conclusion appears to have inadvertently arisen by misidentifying depositional thinning of Sentinel Peak as erosion (see the interpretation of the relationships in the southern Black

Mountains as presented above). Early mapping in the area may have contributed to this mistake. As originally mapped by Wright and Troxel (1984) (and presented as modified in Corsetti and Kaufman 2005, their figure 3), the "lower Noonday" (i.e. SP) thins beneath a thickening "lower Ibex." However, the definition of the "Ibex Formation" at the type locality differs from what is being mapped in a subtle, but meaningful way. The type "Ibex Formation" (as defined in the appendix of the Wright and Troxel [1984] map) includes, from oldest to youngest, the conglomerate member, the dolomite member, the arkose member, the limestone and the shaly limestone members, and the dolomite-quartz sandstone member. However, on the map (and in the legend) the Ibex Formation is broken into "lower Ibex" (which contains the arkose member and the limestone and shaly limestone members) and "upper Ibex" (which contains the dolomite-quartz sandstone member). The conglomerate member and the dolomite member are conspicuously absent from the "Ibex Formation." A rather and straightforward solution to this is has been missed, namely, that the dolomite member is simply the lower Noonday (i.e. SP).

In addition to issues of definition, Tertiary faulting has played a part in the inferred cutout of the lower Noonday as suggested by Corsetti and Kaufman (2005). Pervasive imbricate normal faulting (Tertiary in age) is responsible for the apparent absence of the basal dolostone. This system of faults results in cutting the thin unit at a low angle, placing the overlying arkosic sandstones and shales of the Radcliff on the underlying diamictite. This relationship can be clearly seen when the bedding in the Sentinel Peak and Radcliff are visible (Figure 13A, mapped contacts of Wright *et al.*, 1974 used by Corsetti and Kaufman to show erosion, Figure 13B my contacts). This situation is a relatively common one in the Basin and Range. Corsetti and Kaufman (2005) also present photographs that reportedly show evidence of erosion (their figures 5a, b, and d). However, the photos are unconvincing and the authors were unable to provide locations for the photos that were detailed enough to allow further examination (Corsetti, pers. comm. 2006). My subsequent work in the same area found no evidence of erosion at the contact. In addition, here, as in all exposures of the laminated dolostone of the Ibex Facies of Sentinel Peak, it is interbedded upward with the purple arkosic shale of the lower Radcliff, i.e. the contact is gradational over approximately 2 m (Figure 8B).

In reference to observation B, the presence of "tubestone" clasts in the conglomerate member is cited as evidence that the "Ibex Formation" is wholly younger. This conclusion relies, explicitly, on the laminated dolostone being wholly younger than the conglomerate. However, detailed examination of the Ibex Formation type locality (and the original definition of Ibex Formation) shows that the "tubestone" containing conglomerate is interbedded with laminated dolostone. Wright *et al.*'s (1984) definition of the Ibex Formation clearly states that: (1) the "lower third [of the conglomerate member] consists of thinly and well-laminated dolomite, grayish yellow to grayish orange"; and (2) that the dolomite member "closely resembles lower part of the conglomerate member." Although a single bed at the type section, the conglomerate bed pinches out laterally, and in other outcrops in the same area there are multiple conglomerate beds interbedded with the dolostone instead of the single bed at the type section (Figure 10). Williams *et al.* (1974) even describe the dolostone as being *entirely* below the conglomerate (which he refers to as the breccia member). The conglomerate beds are usually graded, and range from a few centimeters to a few meters in thickness;

some display little to no erosion at their bases, others do eroded into underlying units. The grading, the lack of extensive basal erosion, and the interbedding with laminated dolostone, combined with the absence of striated clasts or convincing dropstones, or true diamictic textures make it improbable that these represent glacial activity, let alone another global glaciation. Instead, the objective and parsimonious interpretation is that the conglomeratic material represents slope instabilities and mass wasting along the growing Noonday biohermal mounds during deposition. This interpretation is consistent with previous studies (Williams *et al.*, 1974; DeYoung *et al.*, 2003; DeYoung, 2005).

Corsetti and Kaufman also specifically note that in the Black Mountains the stratigraphy is as follows, from oldest to youngest: lower Noonday (i.e. SP), pebble conglomerates of the Ibex Conglomerate Member, and Ibex Arkose Member. Though not noted therein, their model would then require that the dolostone member is inexplicably missing from this location. This presents both a local and global problem, the former because of the lack of evidence for erosion and the latter given that "cap carbonates" are almost universally preserved since they represent marine deposition during the demise of a global glaciation.

The only location where erosion of the SP is demonstrable is in the southern Nopah Range where the MF sits directly on the SP. The base of the lower Radcliff can be eliminated as a potential erosional surface because in all locations examined throughout the Death Valley region, that contact is gradational. Thus, the erosional surface must be higher. Unfortunately, the lack of laterally continuous, structurally coherent outcrop in the Southern Nopah range area does not permit ascertaining at which stratigraphic level that surface occurs. From my work in the Panamint Range, the most likely such surface appears to be the base of the upper Radcliff, which locally exhibits channelization of the sandstones into middle RC substrate. However, the distances and the complexity of the internal stratigraphy within the upper Radcliff render this correlation speculative; suffice to say there are options within the Radcliff. The other potential surface would be the base of the MF itself. However, nowhere else does the base of the MF show evidence of erosion, although hiatal surfaces can often be cryptic. It is entirely possible that the SP in southern Nopah Range, which is the thickest reported, was subaerially exposed prior to the initiation of MF deposition.

Corsetti and Kaufman (2005) also present several arguments for correlation based on their new chemostratigraphic data from the Ibex Hills locality. However, with data from only 2 incomplete sections (Ibex Hills and southern Nopah Range), they are forced to correlate based on only declining versus increasing trends instead of complete curves. For example, they prefer to interpret the dolomite member of the “Ibex Formation” as having a “declining $\delta^{13}C$ trend”, and therefore not the same as the N1 (i.e. SP), and suggest the Limestone members of “Ibex Formation” correlate with the “upper Noonday” (i.e. MF) because they both “record a positive $\delta^{13}C$ trend.” Although the *overall* trend in the dolomite member is “invariant” around -3‰, there are certainly parts that contain a declining “trend” very similar to their “trend” from I1, i.e. the SP. For example, data from Prave (1999) show a value of -1.88‰ at 88 m declining to a nadir of -3.44‰ at 208 m and Corsetti and Kaufman’s (2003) own data show a value of -2.7‰ at 15 m trending down to a nadir of -4.2‰ at 170 m. Furthermore, although both the I2 (i.e. middle Radcliff) and the N3 (i.e. MF) display increasing trends, they are at significantly different values. Corsetti and Kaufman’s I2 trend increases from -6‰ to 0‰ while my data for ‘N3’ (i.e. MF) starts at -2‰ and increases to +2‰; if not for the J-SB1 surface, this positive trend would likely continue to an apogee of around +8‰.

C. DETAILED DISCUSSION OF NOONDAY-JOHNNIE TRANSITION

Hazzard's (1937) very brief original definition of the Noonday Formation has been subtly and unintentionally modified over the years. This is particularly evident in attempting to follow discussion of the upper part of the Noonday Formation. Our work shows that, in all likelihood, his "lower portion" of the formation is in fact the entirety of what is now considered Noonday, and his "upper portion" is what a majority of workers would now consider the lower part of the Johnnie Formation. Hazzard (1937) describes the upper portion as "*sandy and at some places contains coarse grit and fine gravel composed of well-rounded to subangular fragments of white quartz and reddish jasper. The sandy and gritty portions usually weather to a rusty brown color and at many places show cross-bedding*." The quartz and jasper pebbles, as well as the cross-bedding, are often used as indicators of the base of the Johnnie Formation (i.e., Stewart, 1970; Williams *et al.*, 1974; Wright *et al.*, 1978). Hazzard (1937) describes the lower part of the unit as being "algal" but doesn't mention the abundant, and somewhat mysterious, "tube-structures" (despite having been incorrectly credited as having first described them by Corsetti and Grotzinger, 2005). Some have speculated on why this was (Cloud *et al.*, 1974), concluding that his estimation of the unit being "algal" comes from an unstated interpretation about the origin of the unmentioned, but likely observed, "tubes." However, it is possible that Hewett did not observe the tube structures and his description of the *lower* Noonday being "algal" may in fact come from the abundant stromatolites in what later workers have called *upper* Noonday.

Wright and Troxel (1967) and Stewart (1970) confused the issue in that they described the upper Noonday as a sandy detrital dolomite commonly cross-stratified.

It is likely that what they were describing was the lower Johnnie Formation, which erosionally truncates the Mahogany Flats member of the Noonday.

Two other issues also served to further confuse the issue. First, the Mahogany Flats in the southern Nopah Range is, in fact, coarser grained than the Sentinel Peak and has a minor detrital component (which the Sentinel Peak lacks), but is nonetheless distinctly different from the Johnnie. Second, deep karstification beneath the J-SB1 surface put clastic sandy dolostone well below the Noonday-Johnnie contact. As described by Wright *et al.* (1978), the lower portion of what is now recognized as MF in the southern Nopah Range is a laterally continuous, pale to medium brownish gray, wavy laminated dolostone that passes upward into massive, indistinctly laminated dolomite, which in turn grades into well-defined stromatolitic domes. They also report meter-wide columnar stromatolites up to 6 m high (op cit., their Figure 10E). However, these are most likely karst related erosional structures, not primary stromatolitic forms (Summa, 1993). The laminated stromatolitic silty dolomite at the top of MF is intimately associated with beautifully cross-bedded quartz-dolomite sandstone. Previous workers (e.g., Williams *et al.*, 1974; Wright *et al.*, 1978) interpreted this association as a gradational and interbedded contact with the overlying Johnnie Formation. However, work by Summa (1993) demonstrated that the surface is a mature karst surface, locally displaying grikes, karstic collapse breccias, and irregular fissures and cavities extending downward by as much as ~75 m below the contact. Mechanically stratified sandstone fills many of the karst cavities and this surface was designated by Summa (1993) as sequence boundary 1 of the Johnnie Formation (J-SB1). Similar karstic features are present at the top of nearly all the MF exposures studied, including those in the northern Panamint Range (see Martin Cabin and Wildrose sections).

However, the situation is somewhat different in the Ibex Hills further to the south. There, no Mahogany Flats member is present and the Noonday-Johnnie contact has been interpreted to be gradational between the dolomite-quartz sandstone member (I3) of the Noonday equivalent "Ibex Formation" and the transitional member of the Johnnie Formation. Williams *et al.* (1974) note that both the dolomite-quartz sandstone member (DQSM) and the transitional member are strikingly similar to each other at this location, the only difference being rare cross bedding in the lower unit and abundant cross-bedding in the upper unit. However, the base of the DQSM is everywhere erosional in the area, as evident by large clasts (many having dcm-scale diameters) of Mahogany Flats affinity in beds within a few meters of the base. I interpret the base of DQSM (i.e. base of I3) to be the J-SB1 surface, which makes DQSM (I3) part of the lowermost Johnnie Formation.

D. DATA TABLE

sample	height (m)	$\delta^{13}C$ V-PDB	$\delta^{18}O$ V-PDB	lithology/comments
Ashford Canyon (central section)				
Location:	***35°55'30.89"N, 116°38'50.11"W***			
AC-28	24.5	-1.90	-8.86	upper lam cap
AC-27	24	-2.50	-9.45	upper lam cap
AC-26	23.5	-2.20	-8.69	upper lam cap
AC-25	23	-2.49	-8.79	vuggy ND
AC-24	11	-2.32	-8.58	vuggy ND
AC-23	3	-2.25	-9.01	vuggy ND
AC-22	1.8	-2.35	-7.73	lower lam cap (sits on karsted? BS)
AC-21	0.5	-2.16	-8.70	lower lam cap (sits on karsted? BS)
Ashford Canyon (SSW section)				
Location:	***35°55'27.85"N, 116°38'52.42"W***			
AC-49	12.2	-1.61	-9.71	u. lam cap, pkrd ms prtngs; isolatd mounds
AC-48	11.1	-2.60	-9.79	u. lam cap, pkrd ms prtngs; isolatd mounds
AC-47	10.5	-2.60	-8.61	u. lam cap, pkrd ms prtngs; isolatd mounds
AC-46	9.6	-2.41	-10.11	u. lam cap, pkrd ms prtngs; isolatd mounds
AC-45	8.7	-2.14	-9.76	u. lam cap, pkrd ms prtngs; isolatd mounds
AC-44	8	-2.48	-9.23	lower lam cap (sits on 0-3m diamcte)
AC-43	5	-1.86	-9.56	lower lam cap (sits on 0-3m diamcte)
AC-42	3	-1.82	-9.92	lower lam cap (sits on 0-3m diamcte)
AC-41	1	-1.66	-8.99	lower lam cap (sits on 0-3m diamcte)
AC-40	0.01	-1.85	-8.53	lower lam cap (sits on 0-3m diamcte)
Eastern Wildrose Canyon - Mahogany Flats unit (m above Charcoal Kilns Ss)				
Location:	***See Appendix A***			
WR1-38	242	2.92	-11.15	sandy ds (ND2?)
WR1-37	236	2.10	-11.51	sandy ds (ND2?)
WR1-36	235	-0.04	-11.05	gy ds w/ qtz-grains, dolomcrts
WR1-35	228	2.87	-7.45	gy ds w/ qtz-grains, dolomcrts
WR1-34	220	-0.04	-10.39	gy ds w/ qtz-grains, dolomcrts
WR1-33	212			gy ds w/ qtz-grains, dolomcrts
WR1-32	208	2.28	-8.41	gy ds w/ qtz-grains, dolomcrts
WR1-31	202	-2.62	-12.95	gy ds w/ qtz-grains, dolomcrts
WR1-30	196	2.54	-8.27	gy ds w/ qtz-grains, dolomcrts

WR1-29	190	0.84	-11.05	gy ds w/ qtz-grains, dolomcrts
WR1-28	184	0.41	-10.46	gy ds w/ qtz-grains, dolomcrts
WR1-27	176	1.82	-9.24	gy ds w/ qtz-grains, dolomcrts
WR1-26	167	1.50	-9.43	gy ds w/ qtz-grains, dolomcrts
WR1-25	161	2.87	-7.82	gy ds w/ qtz-grains, dolomcrts
WR1-24	155	1.00	-8.12	gy ds w/ qtz-grains, dolomcrts
WR1-23	149	1.43	-8.75	karst; Ss lens; exposure intrvl.?
WR1-22	143	1.29	-9.21	karst; Ss lens; exposure intrvl.?
WR1-21	137	0.62	-7.44	gy ds; stroms and trctn bdg
WR1-20	129	0.92	-8.37	gy ds; stroms and trctn bdg
WR1-19	123	-0.03	-8.45	gy ds; stroms and trctn bdg
WR1-18	117	1.50	-8.25	gy ds; stroms and trctn bdg
WR1-17	111	0.86	-6.92	gy ds; stroms and trctn bdg
WR1-16	105	0.10	-6.53	gy ds; stroms and trctn bdg
WR1-15	99	-0.66	-10.61	gy ds; stroms and trctn bdg
WR1-11	96	-0.84	-10.60	ltgy ds; wavy-// and micrbl lams
WR1-14	93	-0.44	-6.62	gy ds; stroms and trctn bdg
WR1-10	92	-1.19	-7.85	ltgy ds; wavy-// and micrbl lams
WR1-13	87	1.08	-8.42	gy ds; stroms and trctn bdg
WR1-9	86	-1.49	-7.93	ltgy ds; wavy-// and micrbl lams
WR1-12	85	-2.99	-12.59	gy ds; stroms and trctn bdg
WR1-8	80	-1.42	-7.38	ltgy ds; wavy-// and micrbl lams
WR1-7	72	-1.56	-7.13	ltgy ds; wavy-// and micrbl lams
WR1-6	65	-1.39	-7.69	ltgy ds; wavy-// and micrbl lams
WR1-5	59	-1.28	-7.45	ltgy ds; wavy-// and micrbl lams
WR1-4	53	-0.88	-6.83	ltgy ds; wavy-// and micrbl lams
WR1-3	47	-1.24	-7.35	ltgy ds; wavy-// and micrbl lams
WR1-2	41	-1.82	-6.85	ltgy ds; wavy-// and micrbl lams
WR1-1	35	-2.08	-7.13	Base of Mahogany Flats Mbr

East Wood Canyon

Location: ***36°19'30.76"N, 117° 4'27.06"W***

EWD-10	127	-1.13	-13.16	Thorndike
EWD-9	121	-1.61	-11.55	Thorndike
EWD-8	110	-1.85	-13.26	Thorndike
EWD-7	81	5.58	-12.33	Thorndike
EWD-6	70	-0.17	-13.43	Thorndike
EWD-5	58	4.36	-12.45	Thorndike

EWD-4	45	4.68	-10.17	Thorndike
EWD-3	29	-1.25	-13.22	Thorndike
EWD-2	21	3.89	-9.51	Thorndike
EWD-1	8	4.41	-12.27	Thorndike

Martin Cabin (lower plate section)
Location: ***See Appendix A***

MC-1	-4	-4.38	-12.47	CO3-cmtd diamicte below SP
MC-2	0	-2.80	-12.50	Sentinel Peak micritic Ls
MC-3	0.5	-3.42	-10.08	Sentinel Peak micritic Ls
MC-4	1	-3.25	-11.09	Sentinel Peak micritic Ls
MC-5	1.5	-3.39	-12.92	Sentinel Peak micritic Ls
MC-6	2	-3.15	-12.80	Sentinel Peak micritic Ls
MC-7	8.5	-4.49	-13.15	thn ls intrbds in arkosic sh-sS
MC-8	10	-5.73	-12.88	thn ls intrbds in arkosic sh-sS
MC-9	15	-5.50	-12.78	thn ls intrbds in arkosic sh-sS
MC-10	24	-5.12	-12.22	thn ls intrbds in arkosic sh-sS
MC-11	28	-5.49	-13.20	thn ls intrbds in arkosic sh-sS
MC-12	34.5	-6.08	-12.82	thn ls intrbds in arkosic sh-sS
MC-13	57.5	-5.16	-13.56	thn ls intrbds in arkosic sh-sS
MC-14	67.5	-5.22	-14.35	ds (Unit 10)
MC-15	96	-5.97	-13.62	thn ls in grngy phyllite (Unit 13)
MC-16	98	-4.60	-10.13	thn ls in grngy phyllite (Unit 13)
MC-17	101	-5.72	-13.59	thn ls in grngy phyllite (Unit 13)
MC-18	104.5	-5.09	-10.72	thn ls in grngy phyllite (Unit 13)
MC-19	107.5	-5.38	-11.97	thn ls in grngy phyllite (Unit 13)
MC-20	111	-3.40	-7.79	thn ls in grngy phyllite (Unit 13)
MC-21	114	-4.82	-13.05	thn ls in grngy phyllite (Unit 13)
MC-22	118	-1.72	-11.61	ls lmnts, rare breccias (Unit 14)
MC-23	121.5	-4.44	-12.49	ls lmnts, rare breccias (Unit 14)
MC-24	126	-3.49	-11.06	ls lmnts, rare breccias (Unit 14)
MC-25	131	-1.41	-12.69	ls lmnts, rare breccias (Unit 14)
MC-26	137.5	-1.30	-12.30	ls lmnts, rare breccias (Unit 14)
MC-27	143.5	-0.95	-11.75	ls lmnts, rare breccias (Unit 14)
MC-28	147.5	-1.22	-11.78	ls lmnts, rare breccias (Unit 14)
MC-29	152	-0.49	-11.18	ls lmnts, rare breccias (Unit 14)

MC-30	159.5	-1.12	-13.99	sandy ds (Unit 16)
MC-31	210	-1.06	-14.48	ds, ds breccia ('Mahogany Flats'?)
MC-32	211	-1.51	-14.13	ds, ds breccia ('Mahogany Flats'?)
MC-33	212	-2.52	-11.53	ds, ds breccia ('Mahogany Flats'?)
MC-34	218	-2.26	-12.04	ds, ds breccia ('Mahogany Flats'?)
MC-35	222	-1.55	-11.56	ds, ds breccia ('Mahogany Flats'?)
MC-36	224	-1.61	-13.12	sandy Ds ('ND2')
MC-37	233	-2.49	-13.34	sandy Ds ('ND2')
MC-38	243	-1.40	-12.60	sandy Ds ('ND2')

North side of Aguereberry Rd (NSAR)- 'Mystery' black Ls

Location: ***36°22'3.75"N, 117° 5'39.39"W***

AR-1		-1.05	-12.32	ls beds in drk phyllite
AR-2		3.19	-9.01	ls beds in drk phyllite
AR-3		-3.29	-11.98	ls - blk phyllite intrbdd interval
AR-4		-3.48	-11.63	ls - blk phyllite intrbdd interval
AR-5		-4.04	-12.61	ls - blk phyllite intrbdd interval
AR-6		-3.12	-11.01	ls - blk phyllite intrbdd interval
AR-7		0.68	-10.49	dolostone bed
AR-8		-1.60	-10.76	ls bed
AR-9		-3.92	-11.11	drk banded grphtic ls
AR-10		-2.79	-10.93	drk banded grphtic ls
AR-11		-2.39	-10.27	drk banded grphtic ls
AR-12		-2.17	-10.16	drk banded grphtic ls
AR-13		-3.43	-11.11	drk banded grphtic ls
AR-14		-3.80	-10.74	thk CO3-clast cgr beds
AR-15		-1.85	-11.18	thk CO3-clast cgr beds
AR-16		-2.27	-11.52	thk CO3-clast cgr beds

North Skidoo

Location: ***See Appendix A***

RP03-60.20	500	-0.78	-11.53	CO3 breccias above arkose-sS unit
RP03-60.19	490	-1.55	-12.53	CO3 breccias above arkose-sS unit
RP03-60.18	480	-2.69	-13.59	CO3 breccias above arkose-sS unit
RP03-60.17	465	-1.96	-11.28	CO3 breccias above arkose-sS unit
RP03-60-16	455			no carbonate (qtz Ss)
RP03-60.15	325			no carbonate (qtz Ss)
RP03-60.14	300	-2.93	-10.63	top 'ND'
RP03-60.13	265	-2.49	-9.45	ND
RP03-60.12	250	-2.49	-8.87	ND

RP03-60.11	230	-2.28	-8.57	base 'ND'
RP03-60.10	220	2.78	-10.63	Thrndke top
RP03-60.09	200	-2.19	-12.48	Thorndike
RP03-60.08	165	4.37	-13.56	Thorndike
RP03-60.07	155	5.95	-11.05	Thorndike
RP03-60.06	125	-0.98	-11.92	Thorndike
RP03-60.05	115	7.25	-12.38	Thorndike
RP03-60.04	85	5.63	-13.82	Thorndike
RP03-60.03	75	0.06	-12.10	Thorndike
RP03-60.02	65	-3.83	-11.73	Thorndike base
RP03-60.01	0	5.42	-11.79	probably BS (not SD)

Providence Ridge

Location: ***36°21'43.97"N, 117° 6'42.61"W***

PR-1		-3.43	-14.50	Prov Rdge Ds (aka Sent Pk)
PR-1A	0	-3.76	-14.04	Prov Rdge Ds (aka Sent Pk)
PR-2	0.25	-3.13	-13.68	Prov Rdge Ds (aka Sent Pk)
PR-3	0.5	-3.79	-14.42	Prov Rdge Ds (aka Sent Pk)
PR-4	0.75	-3.43	-14.31	Prov Rdge Ds (aka Sent Pk)
PR-5	1	-3.49	-14.39	Prov Rdge Ds (aka Sent Pk)
P5-6	1.5	-3.98	-14.05	Prov Rdge Ds (aka Sent Pk)
PR-7	2	-4.06	-14.76	Prov Rdge Ds (aka Sent Pk)

Saddle Peak Hills, central (cap on 1m thick diamictite)

Location: ***35°43'18.97"N, 116°20'54.62"W***

SPC-8	3	-2.53	-9.26	up. cap lmnte w/ mm-tk rd sh
SPC-7	2.05	-2.34	-11.43	up. cap lmnte w/ mm-tk rd sh
SPC-6	1.2	-2.57	-9.52	up. part cap lmnt rd sh prtng
SPC-5	0.9	-2.56	-8.83	up. part cap lmnt rd sh prtng
SPC-4	0.6	-2.69	-9.01	up. part cap lmnt rd sh prtng
SPC-3	0.4	-1.91	-8.20	up. part cap lmnt rd sh prtng
SPC-2	0.2	-2.25	-8.77	up. part cap lmnt rd sh prtng
SPC-1	0.02	-2.34	-8.35	up. part cap lmnt rd sh prtng

Saddle Peak Hills, northern (lower and upper ND & 'Ibex')

Location: ***35°45'33.37"N, 116°21'39.31"W***

SPN-21	213	-3.15	-7.76	upper Nd tubes-lams (tubes +200m tk)
SPN-20	210	-3.42	-8.13	upper Nd tubes-lams (tubes +200m tk)
SPN-9	7	-3.20	-9.01	lower tubes
SPN-8	5.5	-3.22	-8.86	lower tubes
SPN-7	4.2	-3.62	-8.25	lower tubes
SPN-6	3.7	-2.75	-7.05	basal lam ND (on 'KP4'; CSl block)
SPN-5	2.5	-2.85	-7.15	basal lam ND (on 'KP4'; CSl block)
SPN-4	1.5	-3.27	-6.86	basal lam ND (on 'KP4'; CSl

				block)
SPN-3	1	-2.94	-7.13	basal lam ND (on 'KP4'; CSl block)
SPN-2	0.6	-2.65	-7.02	basal lam ND (on 'KP4'; CSl block)
SPN-1	0.15	-2.90	-6.48	basal lam ND (on 'KP4'; CSl block)

Southern Ibex Hills (Type Locality; sect. D on Figure 10, Chapter II)
Location: ***35°45'27.22"N, 116°25'56.19"W***

IH-10	11	-2.96	-8.64	yltn ds lmnts
IH-9	9	-3.00	-9.49	yltn ds lmnts
IH-8	8	-2.01	-8.61	yltn ds lmnts
IH-7	7.1	-1.74	-9.75	yltn ds lmnts
IH-6	5	-2.02	-8.66	yltn ds lmnts
IH-5	4.2	-2.29	-8.52	yltn ds lmnts (2.2m breccia below)
IH-4	1.8	-2.38	-9.46	yltngy lam to wavy-// ds
IH-3	1.3	-1.95	-8.65	yltngy lam to wavy-// ds
IH-2	0.9	-2.39	-10.67	yltngy lam to wavy-// ds
IH-1	0.2	-1.19	-15.44	yltngy lam to wavy-// ds

Southern Ibex Hills
Location: ***35°45'29.17"N, 116°25'58.64"W***

IH-A	0.01	-2.77	-9.54	lam upr cap on debrite
IH-B	0.5	-2.05	-9.97	lam upr cap on debrite
IH-C	1	-2.30	-9.49	lam upr cap on debrite
IH-A0	0.02	-2.04	-7.97	lam upr cap on debrite
IH-B0	0.5	-2.45	-8.05	lam upr cap on debrite
IH-C0	1	-3.19	-9.97	lam upr cap on debrite

Southern Nopah Range: ND1
Location: ***35°50'9.44"N, 116° 6'56.43"W***

SN-ND-1	0.05	-2.62	-6.67	ds lam = basal Noonday1 = SP
SN-ND-2	0.15	-2.61	-6.31	ds lam = basal Noonday1 = SP
SN-ND-3A	0.25	-2.59	-6.34	ds lam = basal Noonday1 = SP
SN-ND-4	2.25	-2.73	-6.82	ds 'tubers' = tubestone ND1
SN-ND-5	4.25	-2.65	-6.83	ds 'tubers' = tubestone ND1
SN-ND-6	6.25	-3.70	-6.06	ds 'tubers' = tubestone ND1
SN-ND-7	8.25	-3.28	-6.26	ds 'tubers' = tubestone ND1
SN-ND-8A	10.25	-2.78	-5.76	ds 'tubers' = tubestone ND1
SN-ND-8B	10.25	-3.26	-8.92	ds 'tubers' = tubestone ND1
SN-ND-9A	14	-3.50	-6.83	ds 'tubers' = tubestone ND1
SN-ND-9B	14	-3.39	-13.19	ds 'tubers' = tubestone ND1
SN-ND-10	18	-2.44	-6.01	ds 'tubers' = tubestone ND1
SN-ND-12	26	-3.02	-7.20	ds 'tubers' = tubestone ND1

SN-ND-14	34	-3.30	-5.91	ds 'tubers' = tubestone ND1
SN-ND-15	38	-3.03	-6.66	ds 'tubers' = tubestone ND1
SN-ND-15	38	-3.03	-6.66	ds 'tubers' = tubestone ND1
SN-ND-17	46	-3.50	-8.43	ds 'tubers' = tubestone ND1
SN-ND-22	66	-2.16	-5.14	ds 'tubers' = tubestone ND1
SN-ND-24	74	-3.45	-7.56	ds 'tubers' = tubestone ND1
SN-ND-26	82	-3.40	-11.69	ds 'tubers' = tubestone ND1
SN-ND-28	88	-1.88	-6.52	ds 'tubers' = tubestone ND1
SN-ND-30	96	-2.47	-7.69	ds 'tubers' = tubestone ND1
SN-ND-33	108	-2.67	-8.77	ds 'tubers' = tubestone ND1
SN-ND-37	124	-2.40	-9.84	ds 'tubers' = tubestone ND1
SN-ND-38	128	-3.11	-7.55	ds 'tubers' = tubestone ND1
SN-ND-40	136	-2.55	-6.38	ds 'tubers' = tubestone ND1
SN-ND-41	140	-3.05	-7.61	ds 'tubers' = tubestone ND1
SN-ND-43	148	-2.40	-6.66	ds 'tubers' = tubestone ND1
SN-ND-46	160	-2.70	-5.82	ds 'tubers' = tubestone ND1
SN-ND-47	164	-2.49	-5.94	ds 'tubers' = tubestone ND1
SN-ND-49	172	-2.83	-6.01	ds 'tubers' = tubestone ND1
SN-ND-52	184	-2.86	-5.68	ds 'tubers' = tubestone ND1
SN-ND-54	190	-3.15	-6.99	ds 'tubers' = tubestone ND1
SN-ND-56	198	-3.10	-6.45	ds 'tubers' = tubestone ND1
SN-ND-59	201	-3.22	-6.68	ds 'tubers' = tubestone ND1
SN-ND-60	202	-2.84	-6.54	ds 'tubers' = tubestone ND1
SN-ND-61	208	-3.44	-6.53	ds 'tubers' = tubestone ND1
SN-ND-62	212	-2.98	-6.92	ds 'tubers' = tubestone ND1
SN-ND-63	215	-3.11	-6.66	ds 'tubers' = tubestone ND1
Location:	***35°49'11.78"N, 116° 5'17.62"W***			
SNP-3	215.1	-3.05	-7.85	base upper cap lmnte
SNP-4	215.6	-3.48	-8.36	up. cap lmnte
SNP-5	217.4	-3.03	-7.56	up. cap lmnte
SNP-6	218.4	-3.35	-8.68	up. cap lmnte
SNP-7	219.9	-3.12	-8.09	up. cap lmnte
SNP-8	221.4	-3.14	-7.90	up. cap lmnte
SNP-9	222.6	-3.46	-8.18	wavy-prll lams, psuedo tepees
SNP-10	224.4	-3.16	-8.09	wavy-prll lams, psuedo tepees

South Skidoo section - Thorndike Ls

Location: ***See Appendix A***

SS-1	9.5	-1.64	-13.77	Unit 2 (sharp on 'Good Mtn Girl')
SS-2	11	-0.55	-12.64	Unit 2 (sharp on 'Good Mtn Girl')
SS-3	13	0.20	-13.25	Unit 2 (sharp on 'Good Mtn Girl')
SS-4	16.5	2.39	-11.57	Unit 3
SS-5	20	5.18	-11.25	Unit 3
SS-6	25	2.24	-12.82	Unit 3
SS-7	29	5.39	-11.99	Unit 3

SS-8	33	3.91	-11.50	Unit 3
SS-9	34	-4.19	-16.41	Unit 4
SS-10	36.5	0.07	-14.64	Unit 4
SS-11	41.5	0.52	-14.57	Unit 4
SS-12	45	5.50	-11.60	Unit 4
SS-13	49	3.64	-10.46	Unit 4
SS-14	52	3.40	-14.89	Unit 4
SS-15	72	0.76	-14.10	Unit 8
SS-16	75	2.37	-13.05	Unit 8
SS-17	83	6.76	-10.22	Unit 8
SS-18	90	4.59	-11.50	Unit 8
SS-19	96	5.30	-11.16	Unit 8
SS-20	100	6.71	-13.02	Unit 8
SS-21	102	5.85	-11.08	Unit 8
SS-22	104.5	4.47	-14.88	Unit 9
SS-23	107	6.39	-11.69	Unit 10
SS-24	111	6.20	-12.08	Unit 10
SS-25	115	6.25	-12.01	Unit 10
SS-26	120	8.18	-9.22	Unit 10
SS-27	123	5.82	-11.28	Unit 10
SS-28	125.5	5.74	-12.25	Unit 10

South Wood Canyon

Location: ***See Appendix A***

SWC-1	100	-1.71	-9.55	Radcliff Ls
SWC2	85	-3.15	-11.90	Radcliff Ls
SWC3	70	-4.29	-12.68	Radcliff Ls
SWC-4	55	-4.32	-12.05	Radcliff Ls
SWC-5	37	-4.66	-11.39	Radcliff Ls
SWC-6	17	-5.15	-13.21	Radcliff just above SP
RP02-29h	16	-3.89		Sent Pk top
RP02-29g	13.714286	-3.57		Sent Pk
RP02-29f	11.428571	-4.19		Sent Pk
RP02-29e	9.1428571	-3.60		Sent Pk
RP02-29d	6.8571429	-3.56		Sent Pk
RP02-29c	4.5714286	-3.00		Sent Pk
RP02-29b	2.2857143	-2.91		Sent Pk
RP02-29a	0	-3.09		Sent Pk base

Staircase Canyon

Location: ***36°33'51.99"N, 117° 9'31.35"W***

SCC-13	3	-1.92	-13.46	intbd ls-ms
SCC-12	2.5	-4.42	-13.51	intbd ls-ms
SCC-11	2	-3.66	-13.97	intbd ls-ms
SCC-10	1.5	-4.06	-14.09	Sent Pk (fine ls)
SCC-9	1.45	-3.75	-14.11	Sent Pk (fine ls)
SCC-8 (not				Sent Pk (fine ls)

sent)				
SCC-7	1.1	-3.87	-14.09	Sent Pk (fine ls)
SCC-6 (not sent)				Sent Pk (fine ls)
SCC-5	0.7	-3.83	-14.16	Sent Pk (fine ls)
SCC-4 (not sent)				Sent Pk (fine ls)
SCC-3	0.3	-3.61	-14.13	Sent Pk (fine ls)
SCC-2 (not sent)				Sent Pk (fine ls)
SCC-1	0.05	-3.64	-14.09	Sent Pk (fine ls)
Location:	***36°33'56.04"N, 117° 9'40.51"W***			
SCC-101	GRAB	-0.74	-12.17	probable TD (not SD) above thrust
SCC-102	GRAB	3.41	-12.60	probable TD (not SD) above thrust
SCC-103	GRAB	4.54	-11.87	probable TD (not SD) above thrust

Tucki Mine

Location: ***See Appendix A***

TM-22	700	-3.68	-13.21	Radcliff (ls)
TM-21	680	-4.02	-13.15	Radcliff (ls)
TM-20	660	-4.06	-13.08	Radcliff (ls)
TM-19	655	-2.02	-9.82	Sentinel Peak
TM-18	645	-2.56	-10.60	Sentinel Peak
TM-17	635	-2.41	-11.22	Sentinel Peak
TM-16	630	-1.60	-12.30	upr Thrndike; ds
TM-15	620	-1.59	-12.11	upr Thrndike; ds
TM-14	610	-2.51	-12.04	upr Thrndike; ds
TM-13	600	1.52	-13.59	Thorndike Ls
TM-12	580	3.28	-12.81	Thorndike Ls
TM-11	560	3.96	-13.62	Thorndike Ls
TM-10	540	3.33	-9.88	Thorndike Ls
TM-9	520	6.04	-10.55	Thorndike Ls
TM-8	500	0.08	-10.40	Thorndike Ls
TM-7	140	-4.42	-12.12	probable BS, but ls
TM-6	130	-2.31	-13.09	probable BS, but ls
TM-5	115	0.18	-11.78	probable BS, but ls
TM-4	95	0.75	-10.26	probable BS, but ls
TM-3	65	-0.60	-10.06	probable BS, but ls
TM-2	35	-0.74	-9.18	probable BS, but ls
TM-1	10	2.86	-8.97	probable BS, but ls

Western Wildrose (Dolly Parton Ridge) - Radcliff (SP-1m; lower Radcliff - 80m)

Location: ***36°16'35.28"N, 117° 6'16.23"W***

WR4-1	256	-0.12	-10.48	7m ltgy ds (lmnts and thkr beds)
WR4-2	250	-0.90	-11.25	7m ltgy ds (lmnts and thkr

				beds)
WR4-3	247	-4.65	-15.72	7m ltgy ds (lmnts and thkr beds)
WR4-4	235	-0.25	-12.72	ls lmnts, breccias
WR4-5	228	-2.65	-13.16	ls lmnts, breccias
WR4-6	220	-0.04	-9.85	ls lmnts, breccias
WR4-7	212	-3.08	-12.33	ls lmnts, breccias
WR4-8	204	-3.30	-12.86	ls lmnts, breccias
WR4-9	196	-3.69	-13.30	ls lmnts, breccias
WR4-10	188	-3.59	-13.60	ls lmnts, breccias
WR4-11	180	-3.49	-14.55	ls lmnts, breccias
WR4-12	172	-3.08	-13.76	ls lmnts, breccias
WR4-13	164	-3.96	-13.25	ls lmnts, breccias
WR4-14	156	-5.19	-12.69	ls lmnts, breccias
WR4-15	150	-3.94	-12.94	5m sandy ds
WR4-16	135	-5.25	-13.68	ls-gngy sS 'rhythmt'
WR4-17	119	-4.83	-12.52	ls-gngy sS 'rhythmt' (dip chnge)
WR4-18	104	-6.76	-13.87	CO3 breccia-lmnts in thn bd Ss
WR4-19	85	-6.29	-15.71	CO3 breccia-lmnts in thn bd Ss

Wildrose Canyon - Sourdough Limestone

Location: ***36°15'24.80"N, 117° 5'50.10"W***

WR3-11		2.20	-6.64	Sourdough Ls
WR3-10		-3.14	-14.38	Sourdough Ls
WR3-9		-2.96	-13.64	Sourdough Ls
WR3-8		-3.54	-14.09	Sourdough Ls
WR3-7		-2.51	-12.67	Sourdough Ls
WR3-6		-2.84	-12.45	Sourdough Ls
WR3-5		-3.26	-12.22	Sourdough Ls
WR3-4		-2.98	-12.47	Sourdough Ls
WR3-3		-3.76	-11.09	Sourdough Ls
WR3-2		-3.90	-10.12	Sourdough Ls
WR3-1		-4.80	-10.98	Sourdough Ls

Ashford Canyon (central section)

Location: ***35°55'30.89"N, 116°38'50.11"W***

sample	height (m)	δ^{13}C V-PDB	δ^{18}O V-PDB	lithology/comments
AC-28	24.5	-1.90	-8.86	upper lam cap
AC-27	24	-2.50	-9.45	upper lam cap
AC-26	23.5	-2.20	-8.69	upper lam cap
AC-25	23	-2.49	-8.79	vuggy ND
AC-24	11	-2.32	-8.58	vuggy ND
AC-23	3	-2.25	-9.01	vuggy ND

AC-22	1.8	-2.35	-7.73	lower lam cap (sits on karsted? BS)
AC-21	0.5	-2.16	-8.70	lower lam cap (sits on karsted? BS)

Ashford Canyon (SSW section)
Location: ***35°55'27.85"N, 116°38'52.42"W***

AC-49	12.2	-1.61	-9.71	u. lam cap, pkrd ms prtngs; isolatd mounds
AC-48	11.1	-2.60	-9.79	u. lam cap, pkrd ms prtngs; isolatd mounds
AC-47	10.5	-2.60	-8.61	u. lam cap, pkrd ms prtngs; isolatd mounds
AC-46	9.6	-2.41	-10.11	u. lam cap, pkrd ms prtngs; isolatd mounds
AC-45	8.7	-2.14	-9.76	u. lam cap, pkrd ms prtngs; isolatd mounds
AC-44	8	-2.48	-9.23	lower lam cap (sits on 0-3m diamcte)
AC-43	5	-1.86	-9.56	lower lam cap (sits on 0-3m diamcte)
AC-42	3	-1.82	-9.92	lower lam cap (sits on 0-3m diamcte)
AC-41	1	-1.66	-8.99	lower lam cap (sits on 0-3m diamcte)
AC-40	0.01	-1.85	-8.53	lower lam cap (sits on 0-3m diamcte)

Eastern Wildrose Canyon - Mahogany Flats unit (m above Charcoal Kilns Ss)
Location: ***See Appendix A***

WR1-38	242	2.92	-11.15	sandy ds (ND2?)
WR1-37	236	2.10	-11.51	sandy ds (ND2?)
WR1-36	235	-0.04	-11.05	gy ds w/ qtz-grains, dolomcrts
WR1-35	228	2.87	-7.45	gy ds w/ qtz-grains, dolomcrts
WR1-34	220	-0.04	-10.39	gy ds w/ qtz-grains, dolomcrts
WR1-33	212			gy ds w/ qtz-grains, dolomcrts
WR1-32	208	2.28	-8.41	gy ds w/ qtz-grains, dolomcrts
WR1-31	202	-2.62	-12.95	gy ds w/ qtz-grains, dolomcrts
WR1-30	196	2.54	-8.27	gy ds w/ qtz-grains, dolomcrts
WR1-29	190	0.84	-11.05	gy ds w/ qtz-grains, dolomcrts
WR1-28	184	0.41	-10.46	gy ds w/ qtz-grains, dolomcrts
WR1-27	176	1.82	-9.24	gy ds w/ qtz-grains, dolomcrts
WR1-26	167	1.50	-9.43	gy ds w/ qtz-grains, dolomcrts
WR1-25	161	2.87	-7.82	gy ds w/ qtz-grains, dolomcrts
WR1-24	155	1.00	-8.12	gy ds w/ qtz-grains, dolomcrts
WR1-23	149	1.43	-8.75	karst; Ss lens; exposure intrvl.?
WR1-22	143	1.29	-9.21	karst; Ss lens; exposure intrvl.?
WR1-21	137	0.62	-7.44	gy ds; stroms and trctn bdg
WR1-20	129	0.92	-8.37	gy ds; stroms and trctn bdg
WR1-19	123	-0.03	-8.45	gy ds; stroms and trctn bdg

WR1-18	117	1.50	-8.25	gy ds; stroms and trctn bdg
WR1-17	111	0.86	-6.92	gy ds; stroms and trctn bdg
WR1-16	105	0.10	-6.53	gy ds; stroms and trctn bdg
WR1-15	99	-0.66	-10.61	gy ds; stroms and trctn bdg
WR1-11	96	-0.84	-10.60	ltgy ds; wavy-// and micrbl lams
WR1-14	93	-0.44	-6.62	gy ds; stroms and trctn bdg
WR1-10	92	-1.19	-7.85	ltgy ds; wavy-// and micrbl lams
WR1-13	87	1.08	-8.42	gy ds; stroms and trctn bdg
WR1-9	86	-1.49	-7.93	ltgy ds; wavy-// and micrbl lams
WR1-12	85	-2.99	-12.59	gy ds; stroms and trctn bdg
WR1-8	80	-1.42	-7.38	ltgy ds; wavy-// and micrbl lams
WR1-7	72	-1.56	-7.13	ltgy ds; wavy-// and micrbl lams
WR1-6	65	-1.39	-7.69	ltgy ds; wavy-// and micrbl lams
WR1-5	59	-1.28	-7.45	ltgy ds; wavy-// and micrbl lams
WR1-4	53	-0.88	-6.83	ltgy ds; wavy-// and micrbl lams
WR1-3	47	-1.24	-7.35	ltgy ds; wavy-// and micrbl lams
WR1-2	41	-1.82	-6.85	ltgy ds; wavy-// and micrbl lams
WR1-1	35	-2.08	-7.13	Base of Mahogany Flats Mbr

East Wood Canyon

Location: ***36°19'30.76"N, 117° 4'27.06"W***

EWD-10	127	-1.13	-13.16	Thorndike
EWD-9	121	-1.61	-11.55	Thorndike
EWD-8	110	-1.85	-13.26	Thorndike
EWD-7	81	5.58	-12.33	Thorndike
EWD-6	70	-0.17	-13.43	Thorndike
EWD-5	58	4.36	-12.45	Thorndike
EWD-4	45	4.68	-10.17	Thorndike
EWD-3	29	-1.25	-13.22	Thorndike
EWD-2	21	3.89	-9.51	Thorndike
EWD-1	8	4.41	-12.27	Thorndike

Martin Cabin (lower plate section)

Location: ***See Appendix A***

MC-1	-4	-4.38	-12.47	CO3-cmtd diamicte below SP
MC-2	0	-2.80	-12.50	Sentinel Peak micritic Ls
MC-3	0.5	-3.42	-10.08	Sentinel Peak micritic Ls
MC-4	1	-3.25	-11.09	Sentinel Peak micritic Ls
MC-5	1.5	-3.39	-12.92	Sentinel Peak micritic Ls
MC-6	2	-3.15	-12.80	Sentinel Peak micritic Ls

MC-7	8.5	-4.49	-13.15	thn ls intrbds in arkosic sh-sS
MC-8	10	-5.73	-12.88	thn ls intrbds in arkosic sh-sS
MC-9	15	-5.50	-12.78	thn ls intrbds in arkosic sh-sS
MC-10	24	-5.12	-12.22	thn ls intrbds in arkosic sh-sS
MC-11	28	-5.49	-13.20	thn ls intrbds in arkosic sh-sS
MC-12	34.5	-6.08	-12.82	thn ls intrbds in arkosic sh-sS
MC-13	57.5	-5.16	-13.56	thn ls intrbds in arkosic sh-sS
MC-14	67.5	-5.22	-14.35	ds (Unit 10)
MC-15	96	-5.97	-13.62	thn ls in grngy phyllite (Unit 13)
MC-16	98	-4.60	-10.13	thn ls in grngy phyllite (Unit 13)
MC-17	101	-5.72	-13.59	thn ls in grngy phyllite (Unit 13)
MC-18	104.5	-5.09	-10.72	thn ls in grngy phyllite (Unit 13)
MC-19	107.5	-5.38	-11.97	thn ls in grngy phyllite (Unit 13)
MC-20	111	-3.40	-7.79	thn ls in grngy phyllite (Unit 13)
MC-21	114	-4.82	-13.05	thn ls in grngy phyllite (Unit 13)
MC-22	118	-1.72	-11.61	ls lmnts, rare breccias (Unit 14)
MC-23	121.5	-4.44	-12.49	ls lmnts, rare breccias (Unit 14)
MC-24	126	-3.49	-11.06	ls lmnts, rare breccias (Unit 14)
MC-25	131	-1.41	-12.69	ls lmnts, rare breccias (Unit 14)
MC-26	137.5	-1.30	-12.30	ls lmnts, rare breccias (Unit 14)
MC-27	143.5	-0.95	-11.75	ls lmnts, rare breccias (Unit 14)
MC-28	147.5	-1.22	-11.78	ls lmnts, rare breccias (Unit 14)
MC-29	152	-0.49	-11.18	ls lmnts, rare breccias (Unit 14)
MC-30	159.5	-1.12	-13.99	sandy ds (Unit 16)
MC-31	210	-1.06	-14.48	ds, ds breccia ('Mahogany Flats'?)
MC-32	211	-1.51	-14.13	ds, ds breccia ('Mahogany Flats'?)
MC-33	212	-2.52	-11.53	ds, ds breccia ('Mahogany Flats'?)
MC-34	218	-2.26	-12.04	ds, ds breccia ('Mahogany Flats'?)
MC-35	222	-1.55	-11.56	ds, ds breccia ('Mahogany Flats'?)
MC-36	224	-1.61	-13.12	sandy Ds ('ND2')
MC-37	233	-2.49	-13.34	sandy Ds ('ND2')
MC-38	243	-1.40	-12.60	sandy Ds ('ND2')

North side of Aguereberry Rd (NSAR)- 'Mystery' black Ls

Location: ***36°22'3.75"N, 117° 5'39.39"W***

AR-1		-1.05	-12.32	ls beds in drk phyllite
AR-2		3.19	-9.01	ls beds in drk phyllite
AR-3		-3.29	-11.98	ls - blk phyllite intrbdd interval
AR-4		-3.48	-11.63	ls - blk phyllite intrbdd interval
AR-5		-4.04	-12.61	ls - blk phyllite intrbdd interval
AR-6		-3.12	-11.01	ls - blk phyllite intrbdd interval
AR-7		0.68	-10.49	dolostone bed
AR-8		-1.60	-10.76	ls bed
AR-9		-3.92	-11.11	drk banded grphtic ls
AR-10		-2.79	-10.93	drk banded grphtic ls
AR-11		-2.39	-10.27	drk banded grphtic ls
AR-12		-2.17	-10.16	drk banded grphtic ls
AR-13		-3.43	-11.11	drk banded grphtic ls
AR-14		-3.80	-10.74	thk CO3-clast cgr beds
AR-15		-1.85	-11.18	thk CO3-clast cgr beds
AR-16		-2.27	-11.52	thk CO3-clast cgr beds

North Skidoo

Location: ***See Appendix A***

RP03-60.20	500	-0.78	-11.53	CO3 breccias above arkose-sS unit
RP03-60.19	490	-1.55	-12.53	CO3 breccias above arkose-sS unit
RP03-60.18	480	-2.69	-13.59	CO3 breccias above arkose-sS unit
RP03-60.17	465	-1.96	-11.28	CO3 breccias above arkose-sS unit
RP03-60-16	455			no carbonate (qtz Ss)
RP03-60.15	325			no carbonate (qtz Ss)
RP03-60.14	300	-2.93	-10.63	top 'ND'
RP03-60.13	265	-2.49	-9.45	ND
RP03-60.12	250	-2.49	-8.87	ND
RP03-60.11	230	-2.28	-8.57	base 'ND'
RP03-60.10	220	2.78	-10.63	Thrndke top
RP03-60.09	200	-2.19	-12.48	Thorndike
RP03-60.08	165	4.37	-13.56	Thorndike
RP03-60.07	155	5.95	-11.05	Thorndike
RP03-60.06	125	-0.98	-11.92	Thorndike
RP03-60.05	115	7.25	-12.38	Thorndike
RP03-60.04	85	5.63	-13.82	Thorndike
RP03-60.03	75	0.06	-12.10	Thorndike
RP03-60.02	65	-3.83	-11.73	Thorndike base
RP03-60.01	0	5.42	-11.79	probably BS (not SD)

Providence Ridge

Location: ***36°21'43.97"N, 117° 6'42.61"W***

PR-1		-3.43	-14.50	Prov Rdge Ds (aka Sent Pk)
PR-1A	0	-3.76	-14.04	Prov Rdge Ds (aka Sent Pk)
PR-2	0.25	-3.13	-13.68	Prov Rdge Ds (aka Sent Pk)
PR-3	0.5	-3.79	-14.42	Prov Rdge Ds (aka Sent Pk)
PR-4	0.75	-3.43	-14.31	Prov Rdge Ds (aka Sent Pk)
PR-5	1	-3.49	-14.39	Prov Rdge Ds (aka Sent Pk)
P5-6	1.5	-3.98	-14.05	Prov Rdge Ds (aka Sent Pk)
PR-7	2	-4.06	-14.76	Prov Rdge Ds (aka Sent Pk)

Saddle Peak Hills, central (cap on 1m thick diamictite)

Location: ***35°43'18.97"N, 116°20'54.62"W***

SPC-8	3	-2.53	-9.26	up. cap lmnte w/ mm-tk rd sh
SPC-7	2.05	-2.34	-11.43	up. cap lmnte w/ mm-tk rd sh
SPC-6	1.2	-2.57	-9.52	up. part cap lmnt rd sh prtng
SPC-5	0.9	-2.56	-8.83	up. part cap lmnt rd sh prtng
SPC-4	0.6	-2.69	-9.01	up. part cap lmnt rd sh prtng
SPC-3	0.4	-1.91	-8.20	up. part cap lmnt rd sh prtng
SPC-2	0.2	-2.25	-8.77	up. part cap lmnt rd sh prtng
SPC-1	0.02	-2.34	-8.35	up. part cap lmnt rd sh prtng

Saddle Peak Hills, northern (lower and upper ND & 'Ibex')

Location: ***35°45'33.37"N, 116°21'39.31"W***

SPN-21	213	-3.15	-7.76	upper Nd tubes-lams (tubes +200m tk)
SPN-20	210	-3.42	-8.13	upper Nd tubes-lams (tubes +200m tk)
SPN-9	7	-3.20	-9.01	lower tubes
SPN-8	5.5	-3.22	-8.86	lower tubes
SPN-7	4.2	-3.62	-8.25	lower tubes
SPN-6	3.7	-2.75	-7.05	basal lam ND (on 'KP4'; CSl block)
SPN-5	2.5	-2.85	-7.15	basal lam ND (on 'KP4'; CSl block)
SPN-4	1.5	-3.27	-6.86	basal lam ND (on 'KP4'; CSl block)
SPN-3	1	-2.94	-7.13	basal lam ND (on 'KP4'; CSl block)
SPN-2	0.6	-2.65	-7.02	basal lam ND (on 'KP4'; CSl block)
SPN-1	0.15	-2.90	-6.48	basal lam ND (on 'KP4'; CSl block)

Southern Ibex Hills (Type Locality; sect. D on Figure 10, Chapter II)

Location: ***35°45'27.22"N, 116°25'56.19"W***

IH-10	11	-2.96	-8.64	yltn ds lmnts
IH-9	9	-3.00	-9.49	yltn ds lmnts
IH-8	8	-2.01	-8.61	yltn ds lmnts
IH-7	7.1	-1.74	-9.75	yltn ds lmnts
IH-6	5	-2.02	-8.66	yltn ds lmnts

IH-5	4.2	-2.29	-8.52	yltn ds lmnts (2.2m breccia below)
IH-4	1.8	-2.38	-9.46	yltngy lam to wavy-// ds
IH-3	1.3	-1.95	-8.65	yltngy lam to wavy-// ds
IH-2	0.9	-2.39	-10.67	yltngy lam to wavy-// ds
IH-1	0.2	-1.19	-15.44	yltngy lam to wavy-// ds

Southern Ibex Hills

Location: ***35°45'29.17"N, 116°25'58.64"W***

IH-A	0.01	-2.77	-9.54	lam upr cap on debrite
IH-B	0.5	-2.05	-9.97	lam upr cap on debrite
IH-C	1	-2.30	-9.49	lam upr cap on debrite
IH-A0	0.02	-2.04	-7.97	lam upr cap on debrite
IH-B0	0.5	-2.45	-8.05	lam upr cap on debrite
IH-C0	1	-3.19	-9.97	lam upr cap on debrite

Southern Nopah Range: ND1

Location: ***35°50'9.44"N, 116° 6'56.43"W***

SN-ND-1	0.05	-2.62	-6.67	ds lam = basal Noonday1 = SP
SN-ND-2	0.15	-2.61	-6.31	ds lam = basal Noonday1 = SP
SN-ND-3A	0.25	-2.59	-6.34	ds lam = basal Noonday1 = SP
SN-ND-4	2.25	-2.73	-6.82	ds 'tubers' = tubestone ND1
SN-ND-5	4.25	-2.65	-6.83	ds 'tubers' = tubestone ND1
SN-ND-6	6.25	-3.70	-6.06	ds 'tubers' = tubestone ND1
SN-ND-7	8.25	-3.28	-6.26	ds 'tubers' = tubestone ND1
SN-ND-8A	10.25	-2.78	-5.76	ds 'tubers' = tubestone ND1
SN-ND-8B	10.25	-3.26	-8.92	ds 'tubers' = tubestone ND1
SN-ND-9A	14	-3.50	-6.83	ds 'tubers' = tubestone ND1
SN-ND-9B	14	-3.39	-13.19	ds 'tubers' = tubestone ND1
SN-ND-10	18	-2.44	-6.01	ds 'tubers' = tubestone ND1
SN-ND-12	26	-3.02	-7.20	ds 'tubers' = tubestone ND1
SN-ND-14	34	-3.30	-5.91	ds 'tubers' = tubestone ND1
SN-ND-15	38	-3.03	-6.66	ds 'tubers' = tubestone ND1
SN-ND-15	38	-3.03	-6.66	ds 'tubers' = tubestone ND1
SN-ND-17	46	-3.50	-8.43	ds 'tubers' = tubestone ND1
SN-ND-22	66	-2.16	-5.14	ds 'tubers' = tubestone ND1
SN-ND-24	74	-3.45	-7.56	ds 'tubers' = tubestone ND1
SN-ND-26	82	-3.40	-11.69	ds 'tubers' = tubestone ND1
SN-ND-28	88	-1.88	-6.52	ds 'tubers' = tubestone ND1
SN-ND-30	96	-2.47	-7.69	ds 'tubers' = tubestone ND1
SN-ND-33	108	-2.67	-8.77	ds 'tubers' = tubestone ND1
SN-ND-37	124	-2.40	-9.84	ds 'tubers' = tubestone ND1
SN-ND-38	128	-3.11	-7.55	ds 'tubers' = tubestone ND1
SN-ND-40	136	-2.55	-6.38	ds 'tubers' = tubestone ND1
SN-ND-41	140	-3.05	-7.61	ds 'tubers' = tubestone ND1

SN-ND-43	148	-2.40	-6.66	ds 'tubers' = tubestone ND1
SN-ND-46	160	-2.70	-5.82	ds 'tubers' = tubestone ND1
SN-ND-47	164	-2.49	-5.94	ds 'tubers' = tubestone ND1
SN-ND-49	172	-2.83	-6.01	ds 'tubers' = tubestone ND1
SN-ND-52	184	-2.86	-5.68	ds 'tubers' = tubestone ND1
SN-ND-54	190	-3.15	-6.99	ds 'tubers' = tubestone ND1
SN-ND-56	198	-3.10	-6.45	ds 'tubers' = tubestone ND1
SN-ND-59	201	-3.22	-6.68	ds 'tubers' = tubestone ND1
SN-ND-60	202	-2.84	-6.54	ds 'tubers' = tubestone ND1
SN-ND-61	208	-3.44	-6.53	ds 'tubers' = tubestone ND1
SN-ND-62	212	-2.98	-6.92	ds 'tubers' = tubestone ND1
SN-ND-63	215	-3.11	-6.66	ds 'tubers' = tubestone ND1
Location:	***35°49'11.78"N, 116° 5'17.62"W***			
SNP-3	215.1	-3.05	-7.85	base upper cap lmnte
SNP-4	215.6	-3.48	-8.36	up. cap lmnte
SNP-5	217.4	-3.03	-7.56	up. cap lmnte
SNP-6	218.4	-3.35	-8.68	up. cap lmnte
SNP-7	219.9	-3.12	-8.09	up. cap lmnte
SNP-8	221.4	-3.14	-7.90	up. cap lmnte
SNP-9	222.6	-3.46	-8.18	wavy-prll lams, psuedo tepees
SNP-10	224.4	-3.16	-8.09	wavy-prll lams, psuedo tepees

South Skidoo section - Thorndike Ls

Location: ***See Appendix A***

SS-1	9.5	-1.64	-13.77	Unit 2 (sharp on 'Good Mtn Girl')
SS-2	11	-0.55	-12.64	Unit 2 (sharp on 'Good Mtn Girl')
SS-3	13	0.20	-13.25	Unit 2 (sharp on 'Good Mtn Girl')
SS-4	16.5	2.39	-11.57	Unit 3
SS-5	20	5.18	-11.25	Unit 3
SS-6	25	2.24	-12.82	Unit 3
SS-7	29	5.39	-11.99	Unit 3
SS-8	33	3.91	-11.50	Unit 3
SS-9	34	-4.19	-16.41	Unit 4
SS-10	36.5	0.07	-14.64	Unit 4
SS-11	41.5	0.52	-14.57	Unit 4
SS-12	45	5.50	-11.60	Unit 4
SS-13	49	3.64	-10.46	Unit 4
SS-14	52	3.40	-14.89	Unit 4
SS-15	72	0.76	-14.10	Unit 8
SS-16	75	2.37	-13.05	Unit 8
SS-17	83	6.76	-10.22	Unit 8
SS-18	90	4.59	-11.50	Unit 8
SS-19	96	5.30	-11.16	Unit 8
SS-20	100	6.71	-13.02	Unit 8
SS-21	102	5.85	-11.08	Unit 8

SS-22	104.5	4.47	-14.88	Unit 9
SS-23	107	6.39	-11.69	Unit 10
SS-24	111	6.20	-12.08	Unit 10
SS-25	115	6.25	-12.01	Unit 10
SS-26	120	8.18	-9.22	Unit 10
SS-27	123	5.82	-11.28	Unit 10
SS-28	125.5	5.74	-12.25	Unit 10

South Wood Canyon

Location: ***See Appendix A***

SWC-1	100	-1.71	-9.55	Radcliff Ls
SWC2	85	-3.15	-11.90	Radcliff Ls
SWC3	70	-4.29	-12.68	Radcliff Ls
SWC-4	55	-4.32	-12.05	Radcliff Ls
SWC-5	37	-4.66	-11.39	Radcliff Ls
SWC-6	17	-5.15	-13.21	Radcliff just above SP
RP02-29h	16	-3.89		Sent Pk top
RP02-29g	13.714286	-3.57		Sent Pk
RP02-29f	11.428571	-4.19		Sent Pk
RP02-29e	9.1428571	-3.60		Sent Pk
RP02-29d	6.8571429	-3.56		Sent Pk
RP02-29c	4.5714286	-3.00		Sent Pk
RP02-29b	2.2857143	-2.91		Sent Pk
RP02-29a	0	-3.09		Sent Pk base

Staircase Canyon

Location: ***36°33'51.99"N, 117° 9'31.35"W***

SCC-13	3	-1.92	-13.46	intbd ls-ms
SCC-12	2.5	-4.42	-13.51	intbd ls-ms
SCC-11	2	-3.66	-13.97	intbd ls-ms
SCC-10	1.5	-4.06	-14.09	Sent Pk (fine ls)
SCC-9	1.45	-3.75	-14.11	Sent Pk (fine ls)
SCC-8 (not sent)				Sent Pk (fine ls)
SCC-7	1.1	-3.87	-14.09	Sent Pk (fine ls)
SCC-6 (not sent)				Sent Pk (fine ls)
SCC-5	0.7	-3.83	-14.16	Sent Pk (fine ls)
SCC-4 (not sent)				Sent Pk (fine ls)
SCC-3	0.3	-3.61	-14.13	Sent Pk (fine ls)
SCC-2 (not sent)				Sent Pk (fine ls)
SCC-1	0.05	-3.64	-14.09	Sent Pk (fine ls)
Location:	***36°33'56.04"N, 117° 9'40.51"W***			
SCC-101	GRAB	-0.74	-12.17	probable TD (not SD) above thrust
SCC-102	GRAB	3.41	-12.60	probable TD (not SD) above thrust

SCC-103	GRAB	4.54	-11.87	probable TD (not SD) above thrust

Tucki Mine
Location: ***See Appendix A***

TM-22	700	-3.68	-13.21	Radcliff (ls)
TM-21	680	-4.02	-13.15	Radcliff (ls)
TM-20	660	-4.06	-13.08	Radcliff (ls)
TM-19	655	-2.02	-9.82	Sentinel Peak
TM-18	645	-2.56	-10.60	Sentinel Peak
TM-17	635	-2.41	-11.22	Sentinel Peak
TM-16	630	-1.60	-12.30	upr Thrndike; ds
TM-15	620	-1.59	-12.11	upr Thrndike; ds
TM-14	610	-2.51	-12.04	upr Thrndike; ds
TM-13	600	1.52	-13.59	Thorndike Ls
TM-12	580	3.28	-12.81	Thorndike Ls
TM-11	560	3.96	-13.62	Thorndike Ls
TM-10	540	3.33	-9.88	Thorndike Ls
TM-9	520	6.04	-10.55	Thorndike Ls
TM-8	500	0.08	-10.40	Thorndike Ls
TM-7	140	-4.42	-12.12	probable BS, but ls
TM-6	130	-2.31	-13.09	probable BS, but ls
TM-5	115	0.18	-11.78	probable BS, but ls
TM-4	95	0.75	-10.26	probable BS, but ls
TM-3	65	-0.60	-10.06	probable BS, but ls
TM-2	35	-0.74	-9.18	probable BS, but ls
TM-1	10	2.86	-8.97	probable BS, but ls

Western Wildrose (Dolly Parton Ridge) - Radcliff (SP-1m; lower Radcliff - 80m)
Location: ***36°16'35.28"N, 117° 6'16.23"W***

WR4-1	256	-0.12	-10.48	7m ltgy ds (lmnts and thkr beds)
WR4-2	250	-0.90	-11.25	7m ltgy ds (lmnts and thkr beds)
WR4-3	247	-4.65	-15.72	7m ltgy ds (lmnts and thkr beds)
WR4-4	235	-0.25	-12.72	ls lmnts, breccias
WR4-5	228	-2.65	-13.16	ls lmnts, breccias
WR4-6	220	-0.04	-9.85	ls lmnts, breccias
WR4-7	212	-3.08	-12.33	ls lmnts, breccias
WR4-8	204	-3.30	-12.86	ls lmnts, breccias
WR4-9	196	-3.69	-13.30	ls lmnts, breccias
WR4-10	188	-3.59	-13.60	ls lmnts, breccias
WR4-11	180	-3.49	-14.55	ls lmnts, breccias
WR4-12	172	-3.08	-13.76	ls lmnts, breccias
WR4-13	164	-3.96	-13.25	ls lmnts, breccias
WR4-14	156	-5.19	-12.69	ls lmnts, breccias
WR4-15	150	-3.94	-12.94	5m sandy ds

WR4-16	135	-5.25	-13.68	ls-gngy sS 'rhythmt'
WR4-17	119	-4.83	-12.52	ls-gngy sS 'rhythmt' (dip chnge)
WR4-18	104	-6.76	-13.87	CO3 breccia-lmnts in thn bd Ss
WR4-19	85	-6.29	-15.71	CO3 breccia-lmnts in thn bd Ss

Wildrose Canyon - Sourdough Limestone

Location: ***36°15'24.80"N, 117° 5'50.10"W***

WR3-11		2.20	-6.64	Sourdough Ls
WR3-10		-3.14	-14.38	Sourdough Ls
WR3-9		-2.96	-13.64	Sourdough Ls
WR3-8		-3.54	-14.09	Sourdough Ls
WR3-7		-2.51	-12.67	Sourdough Ls
WR3-6		-2.84	-12.45	Sourdough Ls
WR3-5		-3.26	-12.22	Sourdough Ls
WR3-4		-2.98	-12.47	Sourdough Ls
WR3-3		-3.76	-11.09	Sourdough Ls
WR3-2		-3.90	-10.12	Sourdough Ls
WR3-1		-4.80	-10.98	Sourdough Ls

E. APPENDIX FIGURES

Figure A1. *Map of the Wildrose Canyon area. Solid red line—Section line; dashed red line—Section line offset. Kg, Skidoo Granite; Zks, Sourdough Member; Zkmg, Mountain Girl Member; Zkt, Thorndike Member; Zkw, Wildrose Member; Znsp, Sentinel Peak Member; Znra, Radcliff Member; Znre, Redlands Member (now Mahogany Flats Member); Zju, Johnnie Formation. Mapping modified from Harding (1987) and Albee et al. (1981).*

Figure A2. *(A) Map and (B) oblique aerial photograph of South Skidoo section, northern Panamint Range. Solid red line—Section line; dashed red line—Section line offset. Kg, Skidoo Granite; Zks, Sourdough Member; Zkmg, Mountain Girl Member; Zkt, Thorndike Member; Zkw, Wildrose Member; Znsp, Sentinel Peak Member; Znra, Radcliff Member.*

Figure A3. ***A.*** *Geologic map of the North Skidoo and Tucki Mine area. Note in particular the marked contrast in depositional substrate of unit Zkmg-t above and below the Tucki Mine fault.* ***B.*** *Photo (view to NE) of the Tucki Mine section.* ***C.*** *Photo (view to north) of the north Skidoo section. Zksd, Sourdough Member; Zkmp, Middle Park Member; Zka, Argenta Member; Zkmg-t, Mountain Girl and Thorndike Members; Zn, Noonday Formation. Solid red lines indicate measured section (dashing indicating offsets.)*

Figure A4. *Photograph of the Martin Cabin section, northern Panamint Range showing mapped contacts of sub-units of the Noonday Formation and section line. Solid red line—Section line; dashed red line—Section line offset. Numbers refer to unit numbers on Martin Cabin measured section (see Appendix A).*

Figure A5. *(A) Map and (B) photograph of the lower half of the Wood Canyon section, northern Panamint Range. Solid red line—Section line; dashed red line—Section line offset. Ksg, Skidoo Granite; Zks, Sourdough Member; Zkmg, Mountain Girl Member; Zkt, Thorndike Member; Zkw, Wildrose Member; Znsp, Sentinel Peak Member; Znb, Basinal Member (now Radcliff Member).*

Figure A1

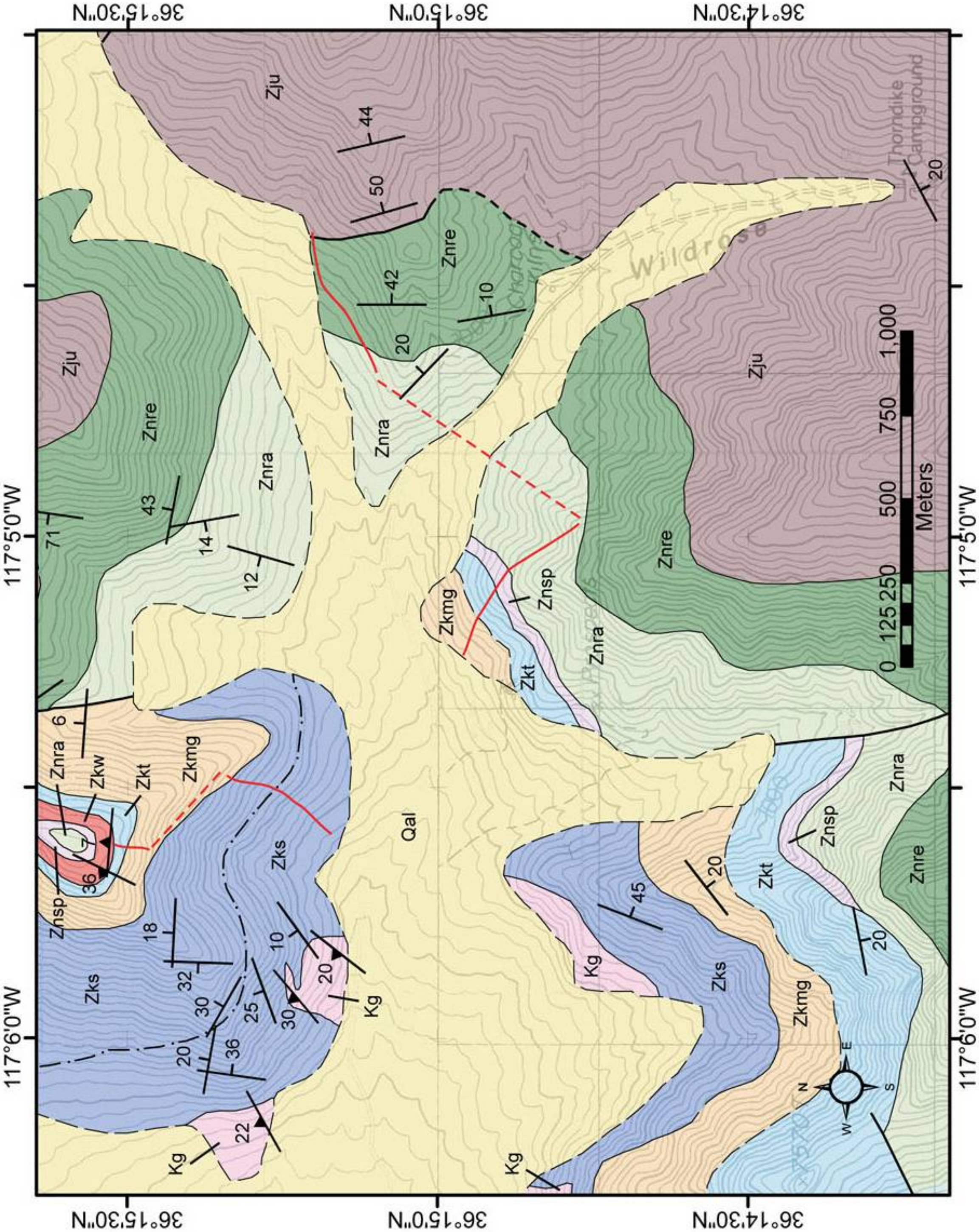

36°15'30"N
36°15'0"N
36°14'30"N
117°5'0"W
117°6'0"W
Meters
0 125 250 500 750 1,000
Thorndike Campground
Wildrose
Zju
Znre
Znra
Znsp
Zkt
Zkmg
Zkw
Zks
Kg
Qal

Figure A2

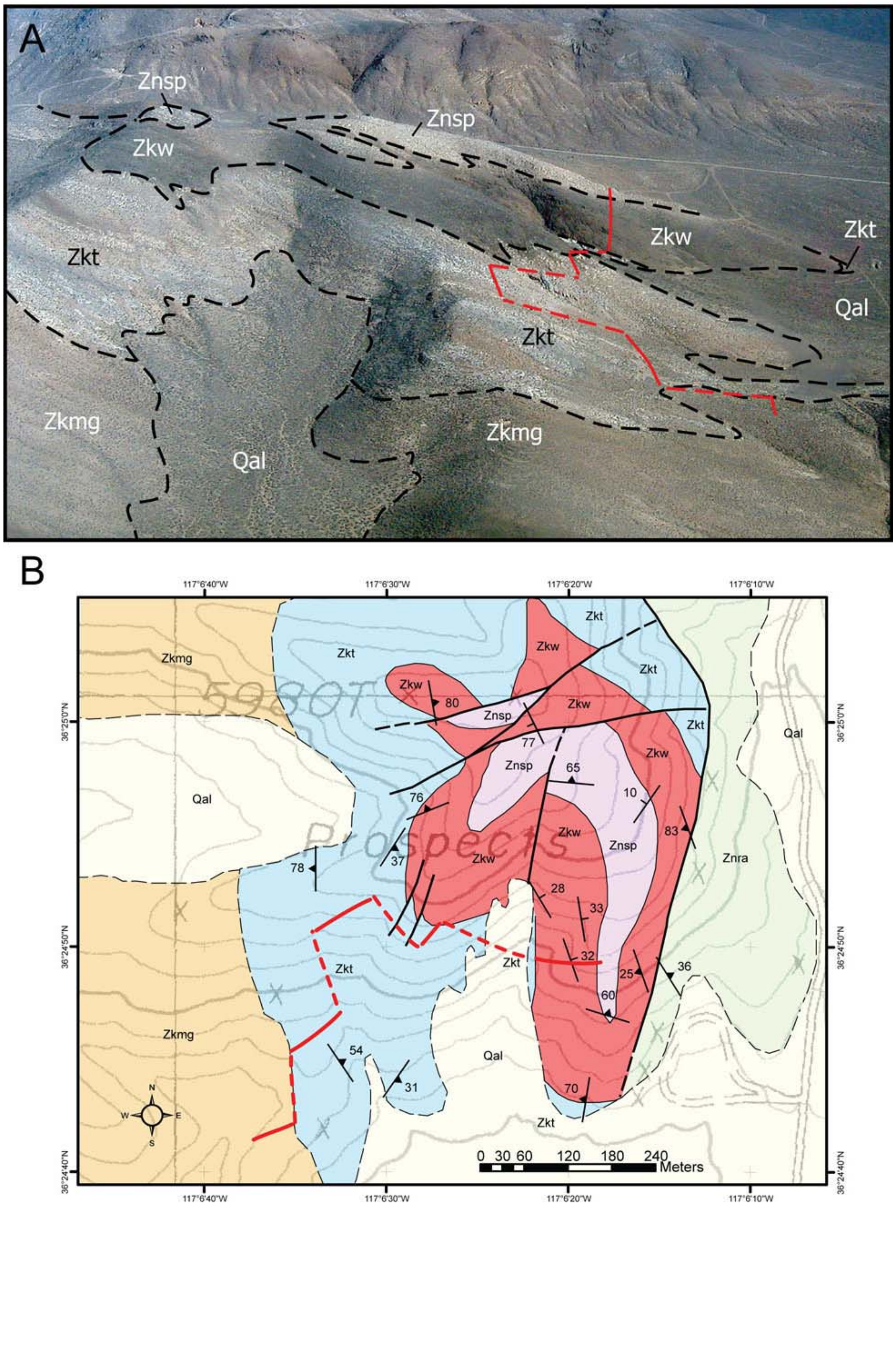

A
Znsp
Znsp
Zkw
Zkw
Zkt
Zkt
Zkt
Qal
Qal
Zkmg
Zkmg
B
117°6'40"W
117°6'30"W
117°6'20"W
117°6'10"W
36°25'0"N
36°24'50"N
36°24'40"N
Zkmg
Qal
Zkmg
Zkt
Zkt
Zkt
Zkt
Zkt
Zkw
Zkw
Zkw
Zkw
Zkw
Znsp
Znsp
Znsp
Qal
Qal
Znra
80
77
65
76
10
83
37
78
28
33
32
25
36
60
54
31
70
N
E
S
W
0 30 60 120 180 240
Meters

Figure A3

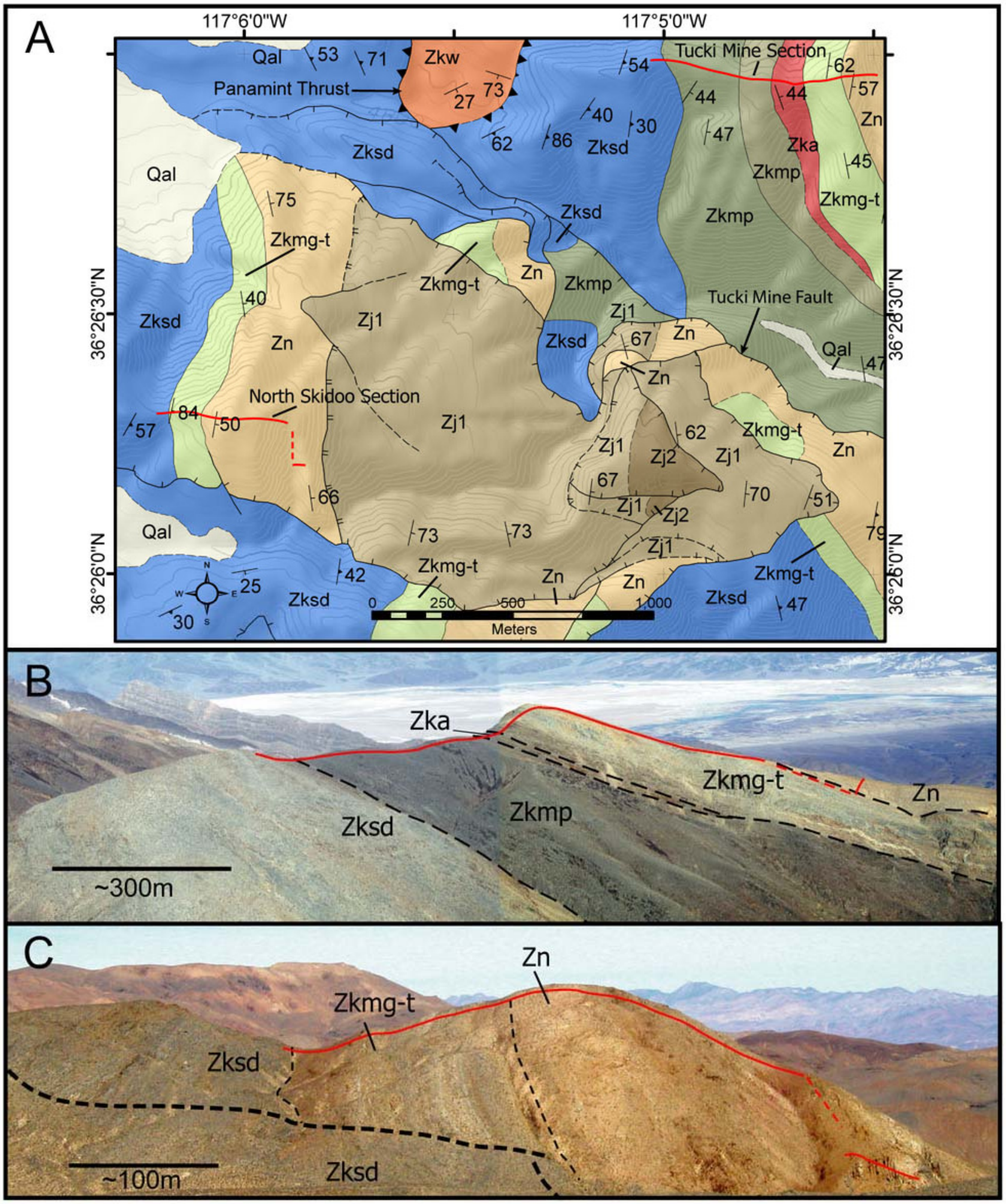

A
117°6'0"W
117°5'0"W
36°26'30"N
36°26'0"N
Qal
Zkw
Zksd
Zkmg-t
Zn
Zj1
Zj2
Zkmp
Zka
Panamint Thrust
Tucki Mine Section
Tucki Mine Fault
North Skidoo Section
0 250 500 1,000
Meters
B
Zka
Zkmg-t
Zn
Zksd
Zkmp
~300m
C
Zn
Zkmg-t
Zksd
Zksd
~100m

Figure A4

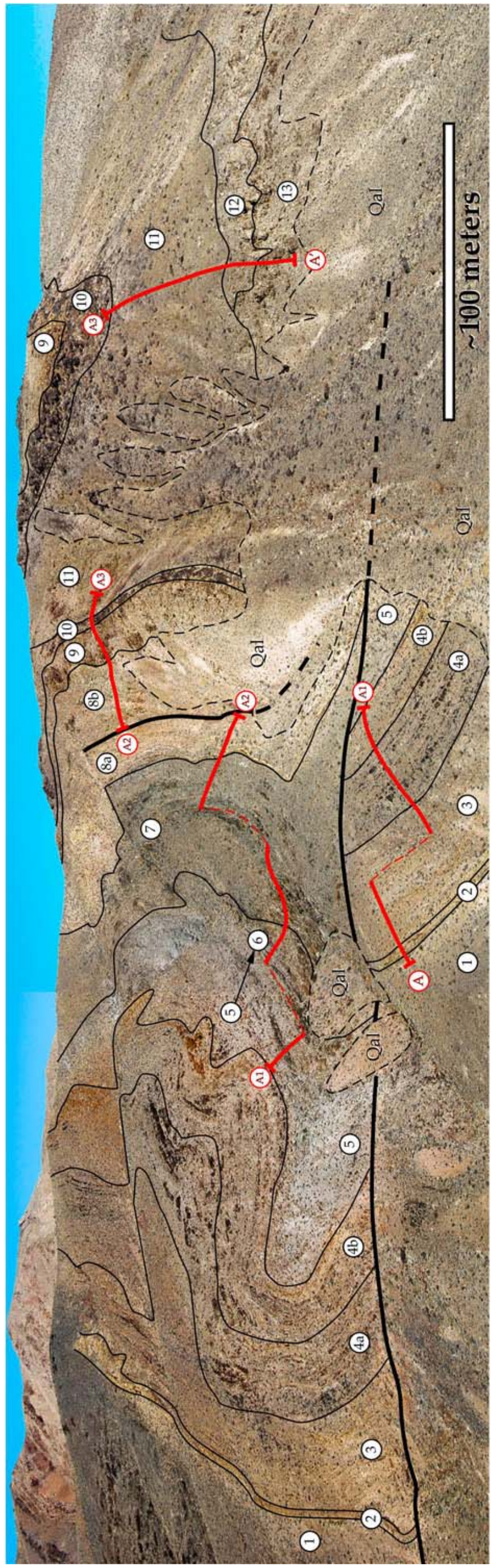
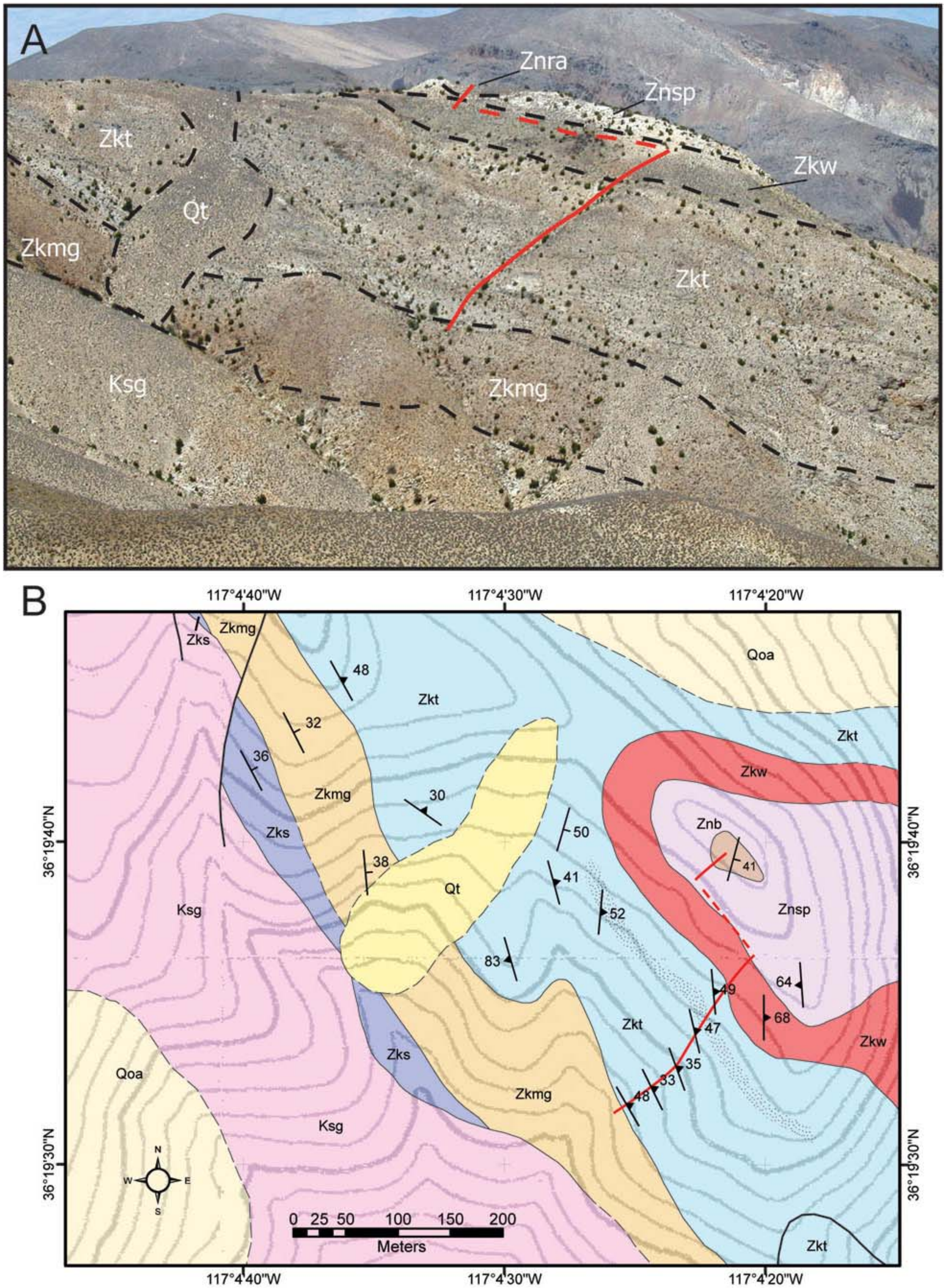


Figure A5


A
Znra
Znsp
Zkt
Qt
Zkw
Zkmg
Zkt
Ksg
Zkmg
B
117°4'40"W
117°4'30"W
117°4'20"W
36°19'40"N
36°19'30"N
Zks
Zkmg
Zkt
Qoa
Zkw
Znb
Znsp
Qt
Ksg
Zks
Zkmg
Zkt
Zkw
Qoa
Ksg
Zks
Zkt
0 25 50 100 150 200
Meters