Deformation in the Paleozoic Stratigraphy of the Piute Mountains in the Mojave Desert Region

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(Dated: 12 May 2014)

We present a geologic map of the Piute Mountains of the Mojave Desert Region and an accompanying structural interpretation. The region is part of a Precambrian metamorphic core complex, and has a predominantly overturned stratigraphy. Our investigation focused on a deformed sequence of Paleoizoic sediments within this complex. These sediments have a distinctive stratigraphy which reveals a series of distinct deformations. We found four distinct generations of ductile events, as well as recent extensional faulting. The timing of deformation events are constrained by two igneous units: the intrusive Lazy Daisy pluton (74Ma±3) and the late Tertiary Peach Springs Tuff (18.5Ma). Three ductile events date between the arrival of the pluton and the fall of the tuff, but at least one fold is younger than the tuff, implying that ductile deformation continued in the region for longer than was previously thought.

I. INTRODUCTION

We present a new map (see Fig. 5) of the Piute Mountains focused on a structural analysis of deformation in the Paleozoic sequence. The Piutes lie a few hundred miles south of the abrupt truncation of the North American Cordillera (see Fig. 1), which is discussed in detail in the next section. The region surrounding the Piute Mountains has a dominantly overturned stratigraphy, and the majority of the Piutes surface area consists of highly metamorphosed Precambrian units. This metamorphic complex is disrupted by the East Piute and Lazy Daisy plutons which were dated by Fletcher & Karlstrom (1990) at 85±7Ma and 74±3Ma respectively, and by a kilometre-wide band of highly deformed Paleozoic units. The structure of this band is the subject of our study. The Paleozoic units are less highly deformed than the basement and retain a distinctive stratigraphy which offers insight into the sequence of deformation events in the region. This stratigraphy has been correlated with the undeformed Grand Canyon Sequence of Arizona (Stone, Howard & Hamilton, 1983). The stratigraphy is also very similar to the Death Valley Sequence of California.

We found that the Piute Mountains have undergone multiple stages of both compression and extension. The most visible indicator of this is the highly deformed Paleozoic sequence within the Precambrian metamorphic core complex. There is evidence of several stages of folding, including east-west oriented isoclinal folds. This contrasts with the north-south trending folds and thrusts which are found in the bulk of the North American Cordillera and observed only a few hundred kilometres north. In addition, the Tertiary tuff layers show repeated west-dipping normal faults which appear to be part of a large-scale detachment fault.

Our mapping was done over the course of a month-long field course. Satellite imagery was used to confirm some contacts when the maps were digitalized. Outcrops in the region are well-exposed. The mapping area can be accessed by a jeep road running southeast-northwest down the main wash. Areas not immediately on the wash must be accessed by foot over rough terrain.

FIG. 1. Location of the Piute Mountains in the Mojave Desert Region. The rock units in the Piutes resemble the Paleozoic stratigraphy of Death Valley and the Grand Canyon, but are highly deformed.

II. REGIONAL GEOLOGIC SETTING: THE NORTH AMERICAN CORDILLERA

The North American Cordillera, which comprises the major mountain ranges of the United States including the Rocky Mountains, the Pacifc Coast Range and the Sierra Nevada, truncates abruptly a few hundred miles north of the Piute Mountains. The western coast of North America has been an active margin, contiguous with the circum-Pacifc orogenic belt, for the past 350 million years. During this time, a series of accretion and subduction events beginning in the Devonian and continuing into the early Mesozoic uplifted the Cordillera we see today. The geologic features of the Cordillera, including thick foredeep sediments and fold and thrust belts, generally strike north-south.

Rift sequence and formation of the Cordilleran miogeocline The eastern part of the Cordillera is underlain by the Laurentian craton, which rifted beginning in what is now Western Canada in the Neoproterozoic and continuing into the current western United States in the lower Paleozoic (Dickinson, 2004). The rift is clearly delineated by an elongate belt of marine sediments, the Cordilleran miogeocline, which run north-south from Southern California into Canada and truncates all pre-existing strata. These west-dipping sediments reach thicknesses of 8 km and were initially deposited in the rift basin in Rodinia, and then along the Laurentian passive margin after rifting was completed. The rift sequence is associated with thinning and extensional faulting of the underlying basement, as well as crustal flexure from the weight of deposited sediments

Accretionary and orogenic events from the Devonian through the Pennsylvanian From the late Devonian until the end of the Laramide thrust during the Eocene, the Laurentian western mar- gin was active and impacted by several major thrusts (Robert Mountains Thrust; Sonoma Orogeny; Laramide Thrust) and a series of accreted island arcs. The resulting strain raised the topography of the Cordillera in a north-south belt running from Canada to an abrupt truncation in southern California (Burchfiel, Cowen, & Davis). The eastern edge of the Cordillera contains the Colorado Plateau and the Basin and Range Province of Arizona. This region, including the Piute Mountains, is dominated by deformations most recently activated by E-W compression of the Laramide Thrust in the Eocene, which overprint the NE-SW strain created during the formation of the Ancestral Rocky Mountains in the Mississippian. The central Cordillera, covering modern Idaho and eastern Nevada and within our area of study including the Spring Mountains and the Keystone and Red Springs thrusts, contains repeated oceanic sequences due to overthrusting by oceanic crust after the Devonian. Finally, westwards from middle Nevada the Cordillera is composed of a series of largely volcanic island arcs of exotic origins, some of which traversed the ocean in its entirety and bear more resemblance geologically to what is now Asia than to Laurentia. The Laurentian margin activated in the late Devonian with the Roberts Mountain Thrust, which thrust the oceanic crust over existing passive-margin sediments. This event continued for 25Ma into the beginning of the Mississippian (Dickinson, 2004). The oceanic Antler allocthon was deformed by a series of shallow west-dipping thrust faults.

The weight of the allochthon flexed the underlying continental margin, creating a basin which filled with eroded sediments, and formed the Antler Foredeep. These sediments dip to the east and contain eroded basalts and cherts formed from the oceanic sediments of the Robert Mountains Thrust. The foredeep and allochthon cover much of modern Nevada (see p. 421 of Burchfiel, Cowen & Davis) but do not reach as far east as the Mojave region or our area of study. However the roughly east-west compressional stress from the thrust, however, was transmitted through the region, until the sequences truncation immediately north of the Piute Mountains. Within 110 million years of the deactivation of the subduction zone, a major tectonic event occurred to the southeast of the Cordillera: the creation of the Ancestral Rocky Mountains. This range runs NW-SE from Texas to Utah, with sediment now filling synclinal basins that trend in the same direction between Precambrian sediments which were folded to the surface. Although the formation of the Ancestral Rockies is contemporary with the Ouachita Orogen from the southeast, the trend of the folds indicates that the primary stress was in the NE-SW direction. This could have been caused by an accretionary event in what is now Mexico and southern California. If so, the truncation and deformation of the Cordillera during the Late Paleozoic left little evidence.

Late Paleozoic left little evidence. After the formation of Ancestral Rockies a deformational event lasting 25 million years occurred as the oceanic Sonoma allochthon was thrust over Laurentia from the west. This continental subductionand may be associated with a foredeep covering Nevada (Burchfiel, Cowen, & Davis) although Dickenson (2006) asserts that no foreland basin has been identified beyond the thrust front. During this period, the far western edge of Laurentia continued to accumulate marine sediments. These can be observed the in the Havallah basin in Nevada. Unconformities related to the Sonoma orogeny are found between the Silurian and the Triassic. After the Antler event, a series of island arcs containing Permian and Devonian volcanics and volcaniclastics (Dickinson, 2004) collided with the margin. During this period of subduction, the granitic inclusions which now make up the Klamath Mountains were formed. Dickenson (2006) proposes that these island arcs were responsible for slab rollback and the low angle over- thrusting of oceanic crust during the Antler and Sonoma orogenies.

The area of our detailed study is at the southern trun- cation of the Cordillera, just to the south of the region covered by the major fold-trust belt. We observe a sharp transition between the area of Nevada to the north of Las Vegas, which like much of the central Cordillera contains major west- and northwest-dipping thrust faults such as the Keystone and Red Springs Thrusts, and the generally north-dipping faults of the Maria Fold and Thrust Belt one hundred miles to the south (see Spencer & Reynolds, p. 542). The truncation is marked by the abrupt end of the miogeoclinal sediments, although its location is not well constrained as the full extent of these Paleozoic strata is uncertain, underneath the thrust belts and foredeeps.

Cenozoic subduction and magmatism in the southern Cordillera The eastern edge of the Cordillera was uplifted and deformed into the current Rocky Mountains in the Laramide Thrust, an orogeny lasting from the late Cretaceous to the Eocene. Additionally, igneous rocks, including the Sierra Nevada batholith, intruded the Cordillera and the region south of its truncation throughout the Mesozoic and Cenozoic. The Piutes were deformed by the arrival of the Lazy Daisy pluton at 743Ma, and the East Piute pluton at 857Ma (Fletcher & Karlstrom, 1990). In Canada and the northern United States, the Laramide thrust is associated with arc magmatism and deformation continuing until 45 Ma; however, in the southern United States, deformation continued for the same period with a magmatic lull from 75 Ma through the Eocene (Dickinson, 2004). The lack of magmatic activity despite continuing subduction, and the uplift of the Rocky Mountains hundreds of miles from the continental margin, are evidence for shallow-angle subduction of the Farallon Plate. In the northern United States subduction of the Juan de Fuca plate continues to this day, while in the southwest of the United States the orogeny terminated with the complete subduction of the Farallon plate at 45 Ma. As a consequence, magmatism in the Mojave and high-temperature ductile deformation in the Piute Mountains ceased with the crystallization of the Lazy Daisy pluton at 74 Ma. Fletcher & Karlstrom (1990) propose that this ended ductile deformation in Piutes.

III. MAJOR ROCK UNITS OF THE PIUTE MOUNTAINS

This section contains rock descriptions for the major units in the Piute Mountains. This will be followed in the next section by a stratigraphy for the Paleozoic sequence, which is placed in a regional context using the Grand Canyon and Death Valley sequences.

Precambrian basement Most of the outcrop of the Piute Mountains is a heterogeneous and highly deformed unit which we will refer to as the Precambrian basement. It is distinguished as the only unit in the area to contain igneous intrusions outside the borders of the East Piute and Lazy Daisy plutons or any metabasites. At the contacts with the other metamorphic units in the area, the basement typically consists of a banded orthogneiss, occasionally intruded by white metagranite dikes up to 5m wide. Elsewhere in the basement we observed a dark-red augen gneiss; a 30m wide metagabbro intrusion; a zebra basite gneiss; a fine-grained grey quartzite; and a series of paragneisses.

Cross-bedded quartzite The lowest layer in the Paleozoic sequence is quartzite. This layer is almost invariably cliff-forming, and its red-purple weathering to a dark-brown varnish makes it one of the darkest units in the area and easily distinguished. The quartzite grains are closely interlocked and smaller than 1mm. In direct contact with the basement is a layer of basal conglomerate, with rounded quartzite clasts between 0.5 and 10cm in size. The conglomerate forms beds up to 1m thick which grade into the bulk of the quartzite over a five to twenty meter section. This section is occasionally interbedded with a 0.5 to 5m section of biotite gneiss, which appears most regularly on the northeastern edge of the Paleozoic section. A second layer of basal conglomerate is observed above the gneissic layer. Finally, above the basal conglomerate, the quartzite commonly preserves cross-bedding from the original sandstone in beds 30 to 100cm thick. Both the basal conglomerate and the cross-bedding distinguish this unit from any quartzite found within the Precambrian basement. Additionally, they provide reliable paleo-up indicators.

Schist The second-lowest layer in the Paleozoic stratigraphy is a muscovite schist. This schist is usually dark blue or grey but highly lustrous, though green-grey and pale red colorings also appear. The constituent mineral grains are consistently between 0.2 and 0.5 mm in size. There is a clear foliation throughout the schist, though the direction of foliation varies in places on a scale of as little as half a metre in highly deformed areas. The schist's metamorphic grade also varies across the mapping area: muscovite is uniformly present, with staurolite, garnet, biotite and chloritoid appearing locally.

The schist is easily weathered and slope-forming. In the Piutes it commonly occurs in outcrops which protrude no more than two inches above the soil. The best outcrops are found in gullies or ridge tops. On steep slopes, the schist layer may be nearly masked by soil and colluvium from a more durable quartzite or marble layer above. In these places it may be identifed by its appearance in the colluvium, and a marked decrease in the slope steepness. Pelitic schist is also found in the Precambrian basement. These are generally of higher-grade than the Paleozoic schists and more durable, and unlike the Paleozoic layer they may contain biotite. However, both the Paleozoic and the Precambrian schists are of highly variable metamorphic grade, and in many instances they can only be distinguished within the context of the surrounding outcrops.

Laminate marble A layer of dark grey marble with thin laminations commonly appears in contact with the schist layer. These laminations are between 0.5 and 10 mm thick and differentially weathered. In the northernmost part of the mapped area this layer becomes grey-blue, with light and dark shades alternating across the laminated layers. Original bedding is not visible in this layer, but the laminations roughly parallel the nearby contacts. This marble is composed of interlocking ¡1 mm grains . They have no consistent cleavage, but the sides of individual crystals are subtly reflective on close inspection. Other minerals are almost non-existent, except for an isolated outcrop of wollastonite-bearing marble in D7. In this region the marble consists of nearly 5% modal wollastonite in parallel individual grains, 4 to 10 mm long, which are evenly distributed throughout the rock.

White marble A bright white marble, distinctive by both its color and the coarseness of its grains, is irregularly present between the laminate and massive gray marbles in the Paleozoic sequence. It is a very self-cohesive unit which forms very little colluvium. It is characterized by very large, coarse grains (varying from 1 mm to 5 mm in size). The unit is primarily white, although it does contain silicate nodules which are deformed into tightly folded layers no more than 5cm thick. Thin layers of a pale grey marble, of similar grain size, are occasionally observed and offer the most consistent attitudes in the unit. *Massive marble* laminated and

FIG. 2. White marble.

shows no differential wreathing, is found either directly in contact with the grey laminate marble or with the coarse-grained white marble. It is distinguished by color variation within the marble and by brown dolomitic boudins. The color variation is typically between regular alternating planes up to 50cm thick and does not appear to be associated with a change in grain size or composition. The boudins are a fine-grained dolomite ranging from regular ovals of 50cm diameter to large 10m blocks, and are found intruding into this marble within 20m of its contacts with the coarse-grained white marble. The grains of this marble are interlocked without regular cleavage, and less than one millimeter in size. Local post-metamorphosis uid deformation has left some regions laced with brown-varnished quartz.

This unit contains wide zones of breccia. The majority of breccia is angular, with homogeneous clasts varying in size from 0.5 to 20cm embedded in a fine-grained matrix. Its presence may imply that this unit was more resistant to deformation than the others, and failed with brittle fracture while the other layers folded. At the peak in D5 is an outcrop of rounded-clast breccia, picture in Fig. **??**. Whereas the other, angular breccias are likely related to local shear zones, rounded clasts imply that this area was subjected to physical wear by landslides or fluids. No convincing outcrops of rounded-clast breccia were found elsewhere in the mapping area.

Lazy Daisy Granite The pink granite Lazy Daisy pluton is found in the southeastern part of our mapping area. It was intruded in at least two phases: coherent units of both meta- and paraluminous granite are found within the pluton. The paraluminous granite is 25% quartz in 2-5mm grains interlocked with 50% potassium feldspar, 25% plagioclase and small quantities of 1mm muscovite. The granite weathers into smooth, rounded peaks which may form very steep slopes. It is periodically cut by straight pegmatite dikes, and by quartz veins 2 to 10cm thick. Granite dikes and sills extend in thin fingers from the pluton up to 100m into the surrounding units. This area is indicated by hatching on the map.

Tuff Lying atop the Paleozoic sequence is the Peach Springs Tuff. Across most of the region, the tuff is rhyolitic. It has with a reddish fine-grained groundmass and porphyritic crystals including 0.5 to 3mm grains of potassium feldspar, olivine and orthopyroxene. Elongate vesicles appeared locally. The most abundant inclusion is quartz, with crystals as large as 5mm making up 10% of the rock. This is tuff is often directly in contact with the older Paleozoic and Precambrian sequences, with a conglomerate holding 0.5 to 30cm clasts at its base. It is not a very competent layer. In many areas tuff remains only in isolated outcrops no more than 10m thick.

Tuff outcrop is widespread in the northwest part of the field area. These thick outcrops reveal multiple generations of ash flow. Below red tuff lies a black crystalline layer followed by a tan lithic layer. This layer is the least competent, and has substantial variation in grain size: the bulk of the rock is very fine-grained and weathers into smooth corners and hollows, but is interspersed with sandy beds with 1-3mm grains. One example of this is shown in Fig. **??**.

IV. STRATIGRAPHY OF THE PIUTE MOUNTAINS

Stratigraphy of the Mojave Desert Region The Precambrian basement in the Mojave Desert region is a remnant of the Laurentian craton. It consists of orthogneisses intruded by granitic dikes, which we observe in the basement in the Piutes. During the Paleozoic, sedimentary strata were deposited on top of this basement along the Laurentian passive margin. This sequence is revealed intact in both the Grand Canyon and Death Valley (see Fig 1 for geographic locations), and has been well-documented. One hundred miles further south, the Paleozoic sequences of the Mojave Desert region are the metamorphosed and deformed counterparts to this sequence. Stone et al. (1983) gives a detailed comparison between the Grand Canyon sequence and the metapelitic sequences which appear in various parts of the Mojave Desert region. We have chosen to compare our stratigraphy to the Death Valley sequence as it bears slightly closer resemblance to the Piutes.

Stratigraphy of the Piute Mountains Firstly, youngest rock units in the area are the two igneous units. The Peach Springs Tuff unconformably overlies the metamorphic units in the region, and the Lazy Daisy Pluton intrusively cuts through them. Although these two units are never in contact, radioactive dating has found the Lazy Daisy pluton to be older. The pluton intruded during the Cretaceous, while the Peach Springs Tuff is commonly dated at 18.5Ma (Fletcher & Karlstrom, 1990). However, ductile folding in parts of the tuff, which is discussed in detail in the Structures section, suggests that some tuff outcrops may be older than this.

The oldest unit in the region is the Precambrian Basement, which is highly deformed and unconformably overlain by the other rock units. The basement is inhomogenous, but some of its orthogneiss layers have been dated. One of these is the Fenner Gneiss which was found by Bender (2008) to be 1.6 billion years old. The basement's thickness is greater than that of any other units in the area. It extends out of our mapping area to the northeast and southwest ends of the Piute Mountains. The remaining metapelites were deposited conformably with one another. They have not been dated, but correlate with other Paleozoic units in southern California (Stone, Howard, & Hamilton, 1983). The stratigraphy is frequently incomplete due to the frequent deformations in the area, as units are frequently sheared out which causes them to vary in thickness by an order of magnitude. (See minimum and maximum thicknesses in attached stratigraphic columns; note the differences in scale.)

The next oldest unit is the quartzite, which is invariably found between the Precambrian basement and the schist layer. Paleo-up readings from the quartzites cross-bedding show that it is stratigraphically lower than the schist. This leaves the three marble units (laminate marble, white marble and massive marble) as the youngest They are not always clearly distinct. The white marble is frequently but not invariably found between the laminate marble and the massive marble. We are convinced that that the white marble was deposited between the other two marbles, as indicated by the stratigraphy in Fig. 3. This sequence is clearly displayed in the large syncline seen at F7, which has been illustrated in Fig. 4.

The white marble unit is unusual in the region: the cross-bedded quartzite, schist, and grey marble layers correlate fairly closely with both the Death Valley and Grand Canyon Paleozoic sequences, but neither of these contains anything which resembles the white marble of the Piutes. This observation was also made by Stone, Howard & Hamilton (1983). We assume that the carbonates which formed this marble were deposited less uniformly than those which formed the other marbles.

Using these rock units, we present our full geologic map in Fig. 5.

V. DESCRIPTIVE STRUCTURE

Deformation in the tuff The tuff is the youngest layer and has been subject to the fewest deformations. The northeast corner of the map- ping area is covered in tuff. The majority of the tuff dips 30-40 degrees west. It forms tilted plateaus on top of peaks at D5, C8) and D4. It is clear that at least one normal fault is necessary to explain its abrupt contact with the Paleozoic sequence along C4.

At the very western edge of the mapping area, the attitudes of the tuff become much less consistent, as shown by the stereonets in Fig. 6. The tuff is very thick here, covering a mountain with 113m relief. The two stereonets to the left were taken from the strikes and dips around A3 on the northwest and southeast sides of the mountain respectively. The fold axes calculated from the stereonets trend 164/30 and 265/41. This is clear evidence that ductile deformation has occurred in the Piutes since the tuff fell.

High temperature deformation in the Paleozoic sequence We can immediately observe that the rock units in this area have undergone high to medium grade metamorphosis. This is particularly striking when we compare them to the undeformed, low-grade rock units in the Grand Canyon. The degree of deformation varies throughout the mapping area. In many areas the sequence is relatively undisturbed - for example, in C4 and G7 we find that the quartzite shows intact cross-bedding and the schist has no higher-grade minerals than mica. In contrast, the quartzite in D5 is sheared to no more than a meter thin, and instead of schist running along it we find a banded pelitic gneiss. These units can be identified only by tracing them until they rejoin less-deformed sequences.

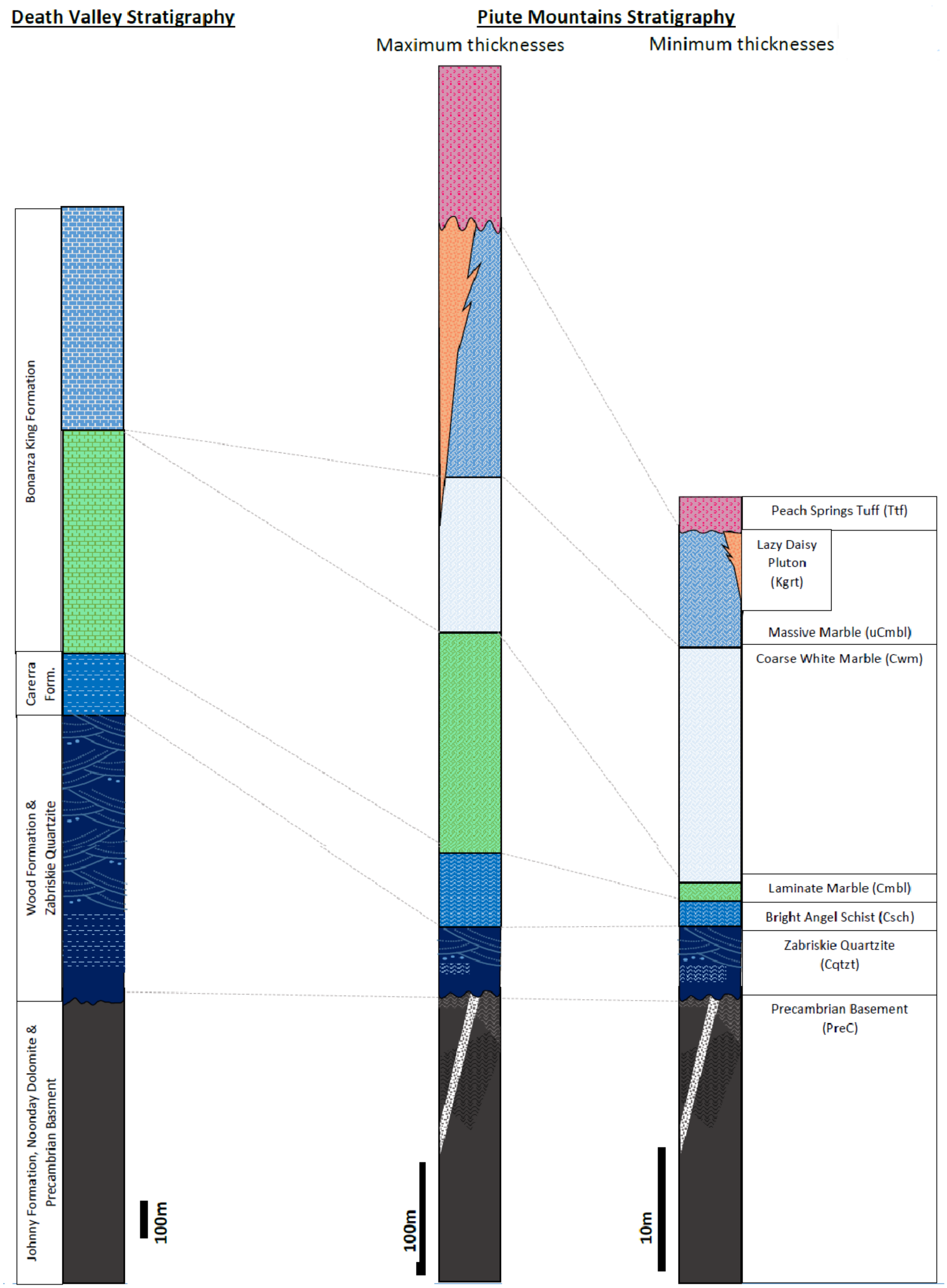

FIG. 3. Stratigraphy of the Piute Mountains. The Paleozoic sequence is highlighted and compared to the Death Valley Sequence (left-most column). Scale changes between columns.

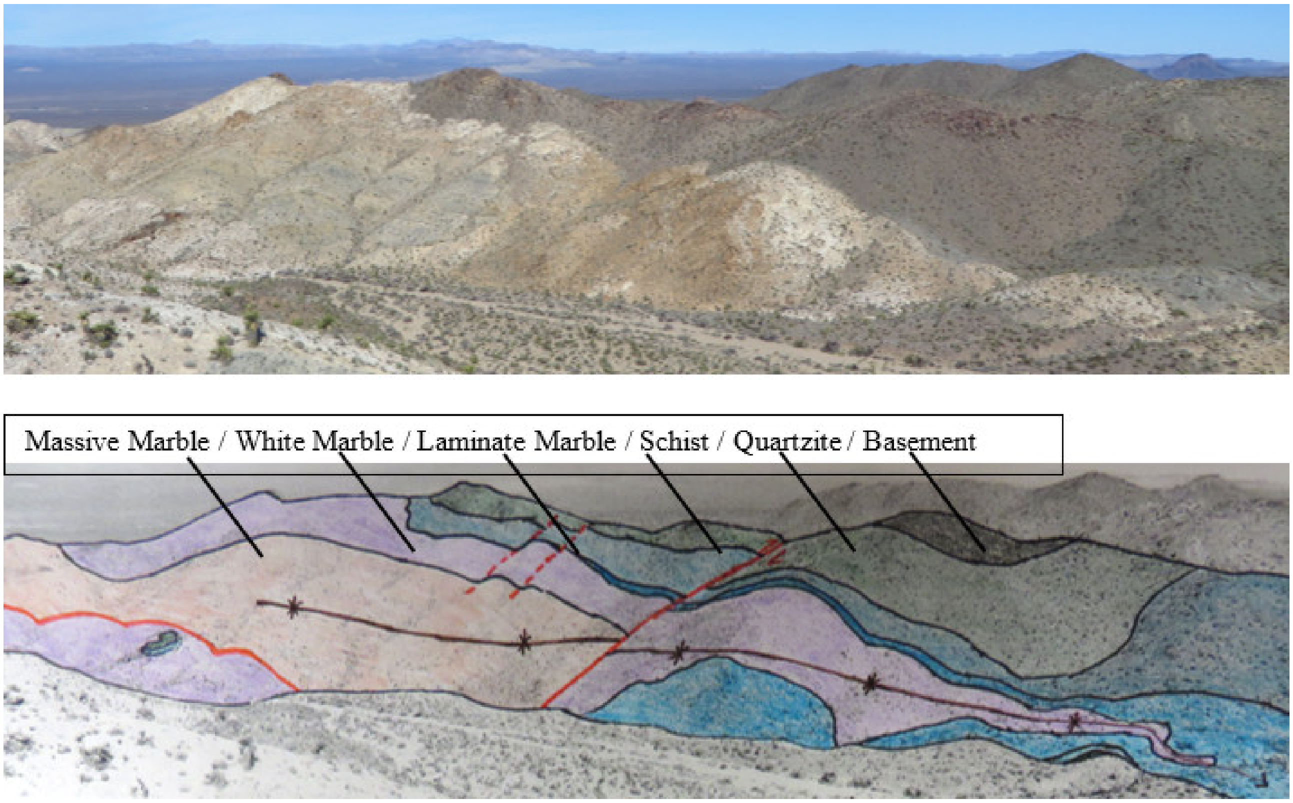

FIG. 4. Large syncline revealing the entire Paleozoic stratigraphy. Photo (top) was taken looking northwards across F7, and shows a 350m-long section of the ridge. The lower image is artificially colored to indicate rock units. The units on the ridgeline dip consistently north-northwest: the sequence is inverted, with the basement sitting on top. Rotation along the small fault cutting the ridge line is not completely constrained, but we estimate a displacement of 20m along the slope.

As additional evidence for high-temperature deformation, we found wollastonite grains at several locations in the Piutes. Wollastonite is formed from calcite and quartz, typically at temperatures above 500 °C (Ferry, Wing & Rumble, 2001). The largest crystals were found surrounding the tuff outcrops at D5. In this region wollastonite forms irregular splays of crystals up to 2cm long which cover the nearby marble. The mineral was not found more than 7m from the tuff outcrop and may have formed by contact metamorphism during the ash fall.

More dispersed wollastonite is found in the marble at D7. This area is also distinguished by an abrupt contact between laminate marble and the Precambrian basement. The laminate marble within 50m of the contact contains wollastonite, which occurs in individual 1cm-long grains dispersed at roughly 5cm intervals throughout the marble. These grains are parallel, trending 013/81. Because of their consistent alignment, this deposit must have been formed in the last stage of ductile deformation in the area. In turn, this requires that the last stage of deformation at D7 was accompanied by temperatures reaching 500 °C.

Ductile folding In the Piute Mountains, the Paleozoic sequence is folded tightly into a narrow band surrounded by Precambrian basement. The stratigraphy is overturned on a large scale, and shows many changes in orientation.

The largest fold which is visible on the ground is the dramatic syncline at F7 (see Fig. 4). The white marble layer is clearly pinched out in the nose of the plunging fold. The stratigraphy on top of the ridge is overturned, indicating that the fold is recumbent and that it is only a local feature within the large area of deformation which has pushed the basement up into a metamorphic core complex in the area.

The entire area is riddled with folds on every scale. A series of small folds may be observed across the wash from the large syncline, at F7. Mining in the area has obscured details in that area, but we can still see that the quartzite and schist layers rotate and move in and out of the hillside. Even within the white marble, which forms a cohesive block, we can observe isoclinal folds up to 1m in size. These are accompanied by 1m boudins of brown dolomitic marble, indicating large-scale folding throughout the block.

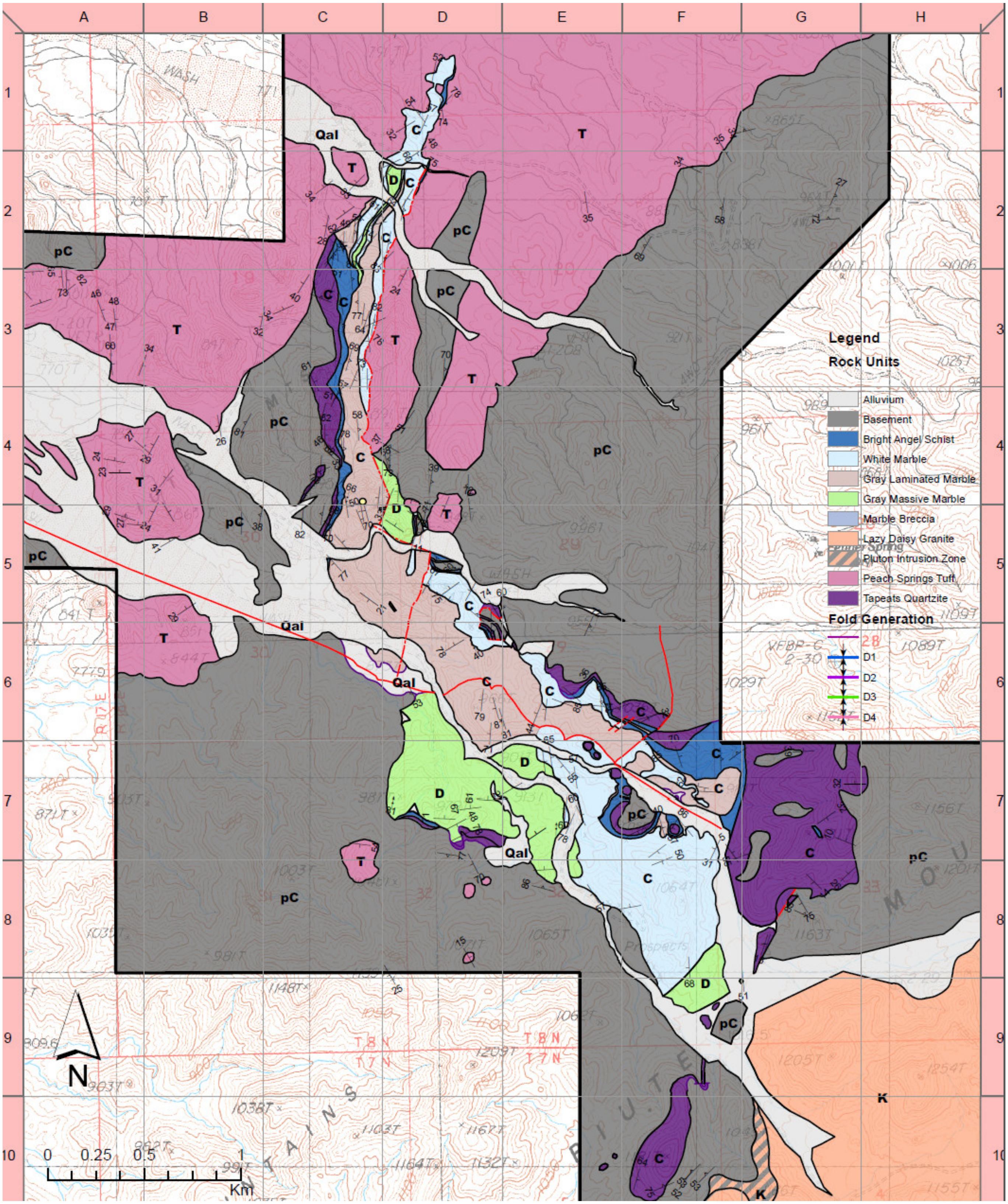

FIG. 5. Geologic map of the Piute mountains.

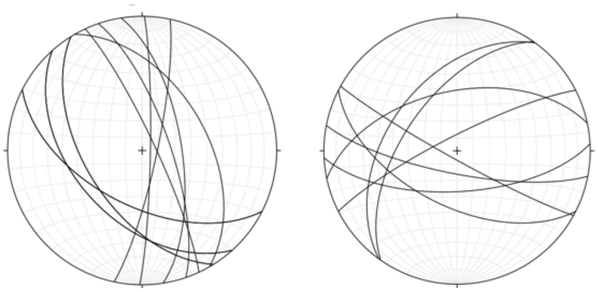

FIG. 6. Stereonets showing orientations measured in the tuff on the northwest (left) and east (right) side of the peak in A3.

Faulting in the Paleozoic sequence After the normal faults in the tuff, the region's clearest fault is found in E7. This fault is marked by an extremely visible fin of marble breccia. The fin, as well as the plane which describes its contact with the underlying marble unit, lie in a place along 120/51. We did not find any evidence to constrain horizontal motion along the fault. However, it has been identified as a normal fault by an outcrop of schist and quartzite at E7. This outcrop is small and badly weathered, leaving little but quartzite boulders and schist which outcrops mere centimetres above the marble, but the sequence here is overturned and its orientation parallels that found on top of the ridge to the north, implying that it was brought down by the fault.

Other faulting in the region is inferred by local brecciation and by offset bedding planes. We see clear offsets in the saddle of F6, which has clearly been shifted by a fault with right-handed transverse motion. The schist has been offset by 5m measured along the southern slope, and the quartzite by 10m measured along the north slope. South of the saddle, the fault appears to continue in a plane striking approximately 210/60 through a colluvium-filled gulley. We have inferred this fault plane north into the basement. Smaller offsets in the schist and laminate marble layers along the ridge indicate parallel faults.

The fault at D5) is also very visible in the field. We observe three distinct layers of quartzite here. The southernmost quartzite layer is 8m thick and cross-bedded, with a basal conglomerate at the north. It is in conformable contact with 17m of biotite gneiss, which we attribute to the slaty layers observed in the Zabriskie quartzite. This is followed by another 5m quartzite layer which sits conformably on a 20m layer of orthogneiss. All of these layers dip near-vertically, between 330/68 and 141/05, and truncate abruptly against white marble in gullies to both the west and southeast. Finally, we have highly brecciated zone of quartzite just south of the wash. This breccia, along with the unusual tripling of the quartzite, is strong evidence for a fault. The curve of the brecciated contact around the areas topography requires a normal fault with a plane striking roughly 140/30.

VI. INTERPRETATIVE STRUCTURE

In Fig. 9 we present a structural interpretation for the geology of the Piute Mountains. Our aim was to provide a coherent description of the deformation process which brought up the metamorphic core complex, the Precambrian basement, and folded it into the Paleozoic sequence. Where possible, we have indicated constraints on the timing of deformation events. Our interpretation requires four generations of folding - three of which pre-date the arrival of the tuff and the Lazy Daisy pluton, and one of which post-dates the tuff. This is followed by two normal faulting events: a large-scale detachment fault system which tilted the tuff, and a normal fault striking 120/51 which created the marble fin referred to above.

Stages of ductile deformation We begin by observing the previously described syncline (Fig. 4). This fold is isoclinal and overturned and has clearly been deformed by a series of later folds. We refer to this generation of folds as first generation, D1, and can trace it throughout the mapping area where it runs roughly from northwest to southeast. Secondly, we observe that the stratigraphy around this syncline is overturned, and that the entire formation is surrounded by Precambrian basement. We also observe the full Paleozoic sequence repeating no less than three times in C2 and again across F7-E8. To explain these features, we introduce a second fold generation, referred to as D2, which re-folded the syncline into an antiform. This structure is clearly visible in cross-section C. It runs the length of the mapping area (though the syncline shifts from the north to the south side of the antiform), reappearing at the north end of mapping area as shown on the left end of cross-section D.

Finally, we observe that the entire Paleozoic sequence, including fold generations D1 and D2, has been wrapped around so that it forms a crescent shape on the map. We call this generation D3. We calculated a fold axis of 040/32 using orientations taken from the laminate marble in D7, as shown in Fig. 10.

It is worth noting that this fold axis is 28° from the dominant trend of the wollastonite grains in the area, which does not support the hypothesis that the wollastonite grains were aligned by stresses during this fold. However, it is clear from the map that the scale of this fold is as large as the exposed Paleozoic sequence in the area. We cannot access the fold limbs to accurately constrain the fold angle.

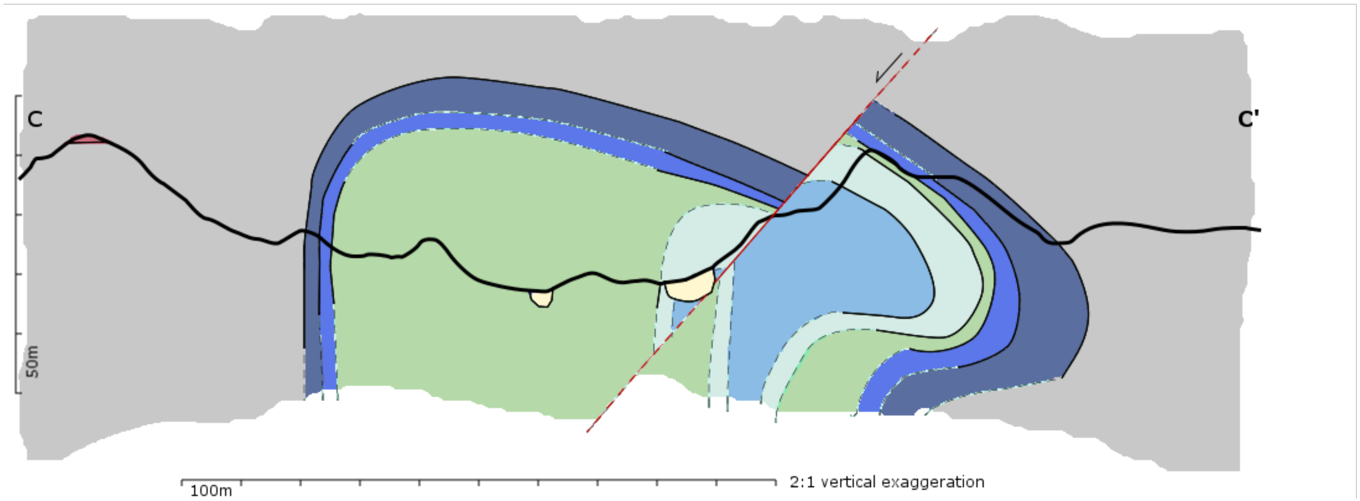

FIG. 7. Cross-section C, showing the antiform and syncline structure of fold generations D1 and D2. Heading 56 degrees.

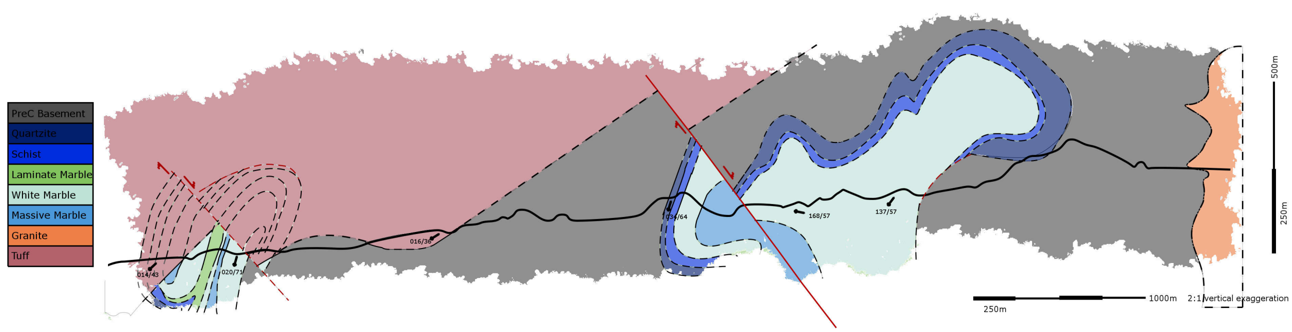

FIG. 8. Cross-section D. Thick black lines indicate apparent dips (heading 261 degrees). Detailed folding has been inferred from the geometry of the layers as they intersect the topography to the west.

We believe that folds in this generation lifted the Paleozoic sequence above the Precambrian basement in G7. This structure is indicated on the right-hand side of cross-section D. Smaller folds in this generation are found in F7, where the schist and quartzite layers weave in and out of the hillside on the south edge of the wash. Attitudes in this area were sparse due to mining, but the fold pattern was in general agreement with the axis calculated above. Unlike previous generations, this fold lies in a plane perpendicular to the boundary of the Lazy Daisy pluton. The folding is also concentrated near the pluton - we did not observe any folds of this generation northwest of D7. We therefore hypothesize that this stage of deformation was directly associated with the intrusion of the Lazy Daisy.

Ductile deformation in the tuff This leaves one later generation of folds, D4. This fold trends north-south through the tuff in the northwest area of the map (A3). As the Peach Springs tuff was found by Fletcher & Karlstrom (1990) to post-date the arrival of the Lazy Daisy by 55Ma, we are left with two hypotheses: either ductile deformation resumed over 55Ma after the Lazy Daisy cooled, or some of the tuff in the Piute Mountains was deposited long before the Peach Springs ash fall. Further work is required to date the tuff in the Piutes and resolve this question.

Detachment faulting in the Piutes As has been previously observed, there are two major directions of faulting in the Piutes: north-south faults running along the tuff, and a major northwest-southeast normal fault found in F7. We observe that the offset elevations of the tuff, as well as its tilt of 30 degrees east (except in the folded area described in the preceding paragraph), are consistent across the Piute Mountains and surrounding region. We therefore assume that these faults are part of a large detachment system. An instance of this fault system is presented on the left-hand side of cross-section C (Fig. 7).

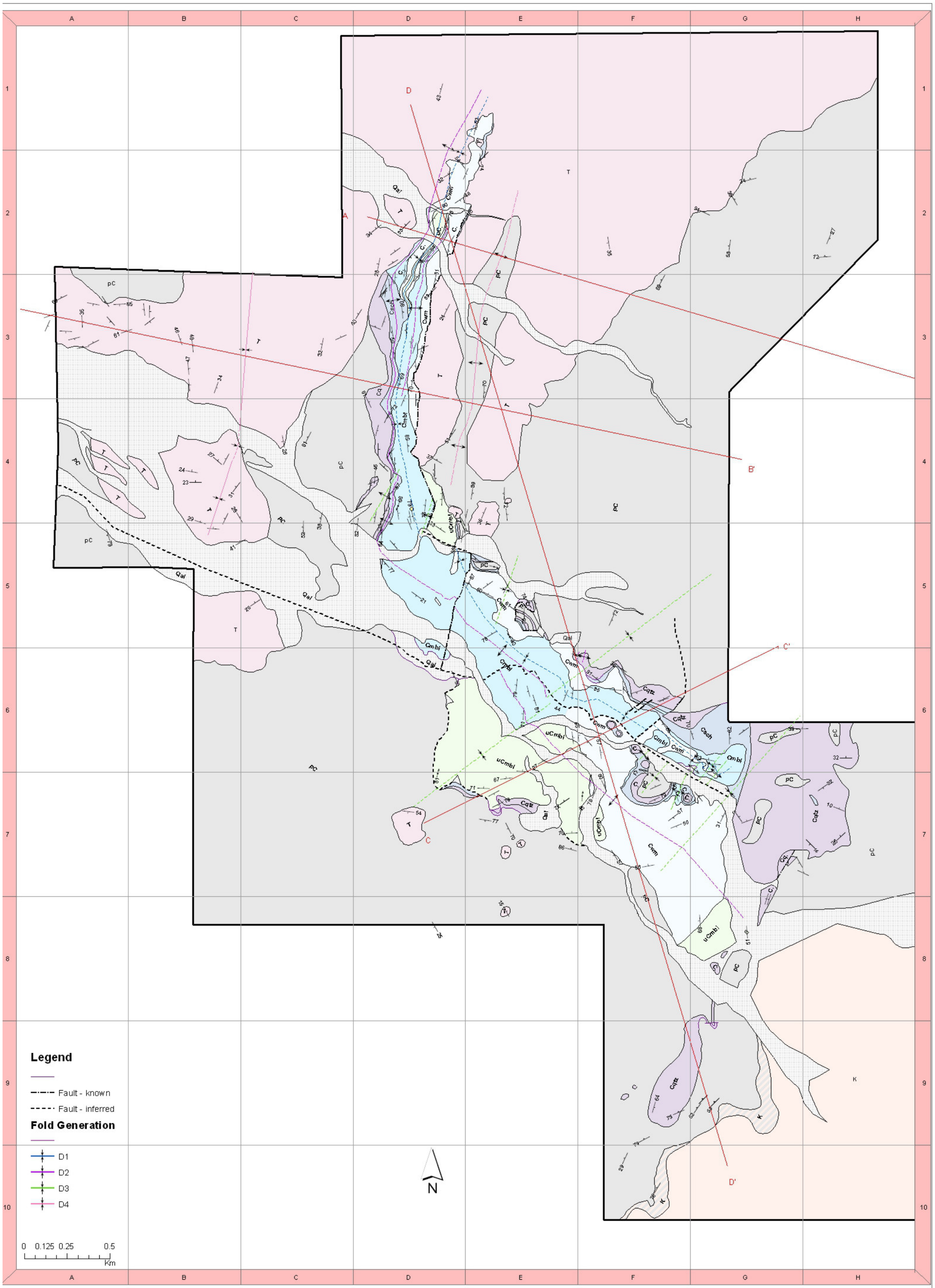

FIG. 9. Structural map of the Paleozoic sequence within the Piute Mountains. Straight lines ABCD indicate locations for cross-sections shown below. Four distinct generations of folds are labelled D1, D2, D3, and D4.

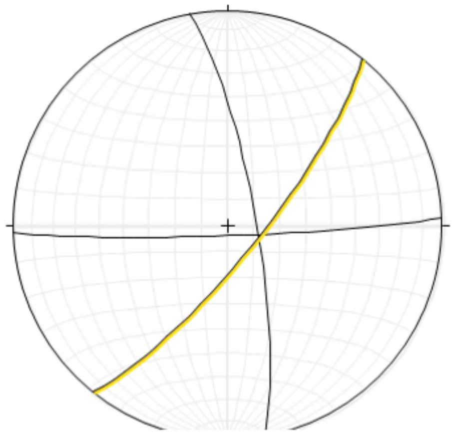

FIG. 10. Stereonet of orientations in laminate marble at D7. Yellow line indicates fold plane. Fold axis runs along 040/32.

VII. DISCUSSION

The stratigraphy of the Mojave is overturned on a regional scale. This must have occurred after the deposition of the Paleozoic sediments, but before the first deformations we observed. As can be seen in cross-section C (Fig. 7), fold generations D1 and D2 only push the Paleozoic sequence through the basement and do not seriously interrupt the overturned stratigraphy.

We found four distinct generations of folds within the Piutes. At least three generations pre-date the fall of the Peach Springs tuff which was dated by Bender (2008) at 18.5Ma. We contrast this hypothesis with previous work in the region by Fletcher & Karlstrom (1990), who explain the structure of the Piutes in terms of a single event during which deformation was concentrated in two major shear zones. We did find varying degrees of shearing and deformation within the Paleozoic, but we found clear evidence of multiple generations of folds.

Additionally, Fletcher and Karlstrom assert that ductile deformation in the Piutes ceased after the cooling of the Lazy Daisy pluton. Using apatite fissure track retention, they found that the pluton had cooled to 100 °C by 72Ma±3. We agree that three generations of folds appear to pre-date the arrival of the pluton, and that in particular generation D3 appears to have been influenced by its arrival. The presence of regularly lineated wollastonite around D7 also indicates hot temperatures in the region at the end of ductile deformation. All of this indicates that the Paleozoic sediments were buried within the basement, then rapidly uplifted and deformed before 72Ma.

Ductile deformation continued further south into the Little Maria Mountains, the Maria Fold and Thrust Belt, and the Clark Mountains, where zircon dating of the Ivanpah pluton placed an upper age limit of 147Ma on deformation of the Precambrian basement (Walker, Burchfiel & Davis, 1995). The Marias were studied by Spencer and Reynolds (1990) who concluded that the metamorphic core complex, the Precambrian basement, could have been rapidly uplifted by isostatic forces. The Maria Mountains were thickened by the Maria Fold and Thrust Belt. This abnormally thick region could have been eroded rapidly, creating isostatic uplift. It is possible that similar uplift in the Piutes occurred in response to thickening during the arrival of the Lazy Daisy.

However, we also found tight folds in the tuff in the Piute mountains. These were not recorded by Fletcher and Karlstrom, but they indicate that ductile deformation in the Piutes continued much longer than has been previously thought, or that some of the tuff is much older than the Peach Springs ash fall at 18.5Ma. Further work in the region with the objective of dating the oldest tuff could resolve this question, and leave us to explain this final stage of deformation in the context of the Mojave Desert Region.

ACKNOWLEDGMENTS

Oliver Jagoutz, Claire Bucholz and Clark Burchfiel for invaluable instruction both in the field and in the map-room. Allie Anderson and Emily Tencate for assistance in the field and for being photogenic scale indicators for many photos. Daniel Sheehan for ArcGIS lessons and troubleshooting.

[1] Bender, E.E. (2008) *Petrogenesis of the Fenner Gneiss, Piute and Old Woman Mountains, San Bernardino Country, California*, GSA Abstracts with Programs 40 (6): 240.

[2] Burchfiel, Cowen & Davis (n.d.) *Tectonic overview of the Cordilleran orogen in the western United States*, in Burchfiel, Lipman & Zoback *The Cordilleran Orogen: Conterminous U.S.* p.407-479. Geological Society of America, The Geology of North America.

[3] Davis, G. (1973) *Relation between the Keystone and Red Spring thrust faults, Eastern Spring Mountains, Nevada*, GSA Bulletin 84: 3709-3716.

[4] Dickenson, W. (2006) *Geotectonic evolution of the Great Basin*, Geosphere 2(7): 353-368.

[5] Dickenson, W. (2004) *Geotectonic evolution of the Great Basin*, Annual Review of Earth and Planetary Science, 13-45.

[6] Ferry, Wing, & Rumble III (2001) *Formation of Wollastonite by chemically reactive fluid flow during contact*

metamorphism, Mt. Morrison Pendant, Sierra Nevada, California USA, J. Petrology 42 (9): 1705-1728.

[7] Fletcher, J. & Karlstrom, K. (1990) *Late Cretaceous ductile deformation, metamorphism and plutonism in the Piute Mountains, eastern Mojave Desert*, J. Geophysical Research, 95: 487-500.

[8] Spencer & Reynolds (1990) *Relationship between Mesozoic and Cenozoic tectonic features in West Central Arizona and adjacent Southeastern California*, J. Geophysical Research, 95(B1): 539-555.

[9] Stone, P., Howard, K. & Hamilton, W. (1983) *Correlation of metamorphosed Paleozoic strata of the southeastern Mojave Desert region, California and Arizona*, GSA Bulletin, 94: 1135-1147.

[10] Dickenson, W. (1995) *New controls on initiation and timing of foreland belt thrusting in the Clark Mountains, southern California*, GSA Bulletin, 107: 742-750.