GEOCHEMISTRY AND PETROGRAPHY OF THE JURASSIC METASEDIMENTARY AND METAVOLCANIC UNITS OF THE ALABAMA HILLS AND SOUTHERN INYO MOUNTAINS NEAR LONE PINE, CA

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ABSTRACT

Jurassic metavolcanic and metasedimentary rocks outcrop in the Alabama Hills and southern Inyo Mountains near Lone Pine, CA. The two outcrop areas lie approximately 10 kilometers apart on opposite sides of the right-slip Owens Valley fault system. This research examined geochemistry and petrology of the two areas.

The Alabama Hills and Inyo Mountains vary in major oxide geochemistry, the former enriched in silica and potassium and the latter alumina, calcium, iron and magnesium. Trace element content also varies, reflecting differences in source and depositional environment. Field observations, and thin section petrology mimic the geochemical patterns. Rocks from the Alabama Hills show restricted textures and mineralogy and are most likely the product of volcanic and volcaniclastic processes. In contrast, Inyo Mountain rocks are more diverse lithologically, often distinctly layered and in thin section have textures and mineralogy reminiscent of sedimentary rocks. Therefore, it appears the two rock units were deposited in differing environments, most likely separated geographically by 10's of kilometers. Comparisons of bulk rock chemistry and mineralogy utilizing ACF diagrams reveals that both areas did not experience regional metamorphism, but did experience similar degrees of contact metamorphism up to the albite-epidote hornfels facies.

There are two possible scenarios for the present geographic juxtaposition of the Alabama Hills and Inyo Mountains outcrops. Both involve significant transport prior to the onset of Basin and Range faulting. The first proposes that over 65 kilometers of late Cretaceous right-slip has occurred across the Owens Valley fault system. While this hypothesis does account for the significant lithologic differences in the two areas studied, and perhaps some of the geochemical trends, it does not explain the similarity of metamorphic overprint. The second theory envisions 20-30 kilometers of eastward transport of the Alabama Hills along a late Jurassic thrust fault. This hypothesis is preferred. It accounts for both the metamorphic overprint, as well as all observed major element trends.

Introduction

The Owens Valley and the Sierra Nevada of east-central California have been the focus of ongoing geologic research for over 75 years. Early work included the seminal paper on Sierra glaciations by Blackwelder (1931) and later Ph.D. dissertations by Curry (1968) and Gillespie (1982). In addition the valley has been a laboratory for the application of newly developed geochronolgoical techniques for K/Ar (Dalrymple, 1964), Ar/Ar (Gillespie, 1982) and exposure ages (Stone, 1993 and Bierman, 1995). The tectonic setting of the valley has been the subject of detailed research for over 50 years (see discussion in the following section) and continues to be a topic of intense debate. Despite the great volume of published literature, the Owens Valley continues to be a hotbed of geologic research with the pace of publication accelerating over the past decade.

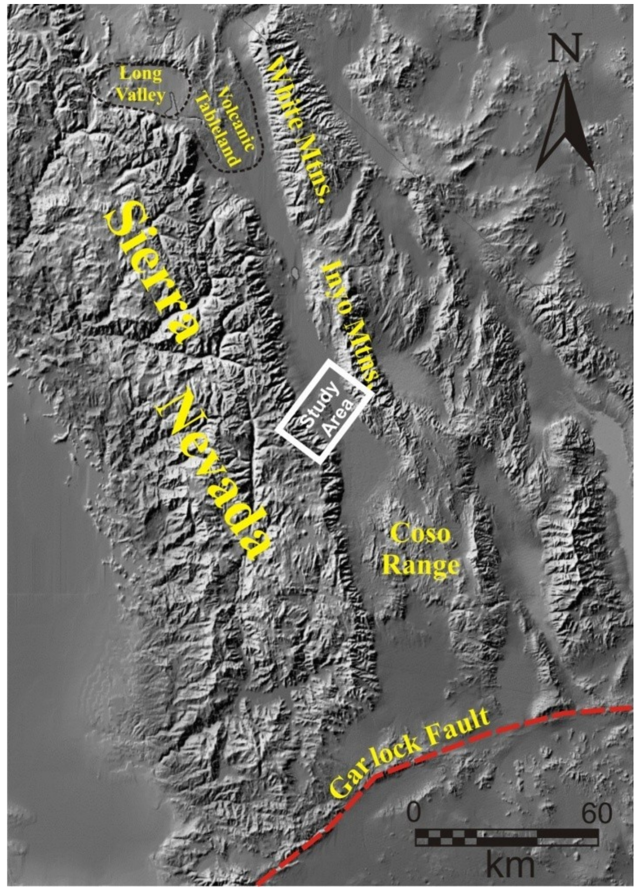

Figure 1. Shaded relief map showing the main physiographic features of the Owens Valley and location of the study area.

There are several factors that contribute to interest in the Owens Valley. One is its proximity to major research universities in both California and Nevada, making it an ideal day trip to test various hypotheses. The second is the relative accessibility of the outcrops in the valley. The valley is narrow, rarely more than 20 kilometers in width, bisected by U.S. Highway 395 with much of the land remaining in Federal and State ownership, thus facilitating access to outcrops. A third factor is the moderate climate. The Owens Valley rarely experiences the extreme summer heat that characterizes the Mojave

Desert to the south or the bitter cold of the Long Valley/Mono Basin to the north. Furthermore, the Sierra Nevada acts as an orographic buffer limiting precipitation. Finally, there is the tectonic setting and the fortuitous location at the western margin of the Basin and Range and the eastern edge of the Eastern California Shear Zone (ECSZ).

The Owens Valley trends nearly north-south for a distance of 200 kilometers. It ranges in width from less than 10 kilometers to a maximum of 35 kilometers and lies an average elevation of 1200 meters above MSL. Figure 1 depicts the main physiographic boundaries to the valley. To the north is the gently sloping volcanic tableland that rises to an elevation of more than 2000 meters. To the west is the nearly vertical escarpment of the Sierra Nevada with a crest more than 2 kilometers above the valley floor and to the east the White and Inyo Mountains which crest 1-1.5 kilometers above the valley. The southern boundary is less recognizable physiographically, but is marked by the left-lateral Garlock fault, a major crustal break separating the Owens Valley and Sierra Nevada Mountains to the north from the Mojave Desert to the south. Figure 1 also shows the location of the study area. The Alabama Hills lie 1-2 kilometers west of the town of Lone Pine, California. They form a prominent ridge of Cretaceous plutons and Jurassic metavolcanic and metasedimentary rocks separated from the main Sierra massif by a frontal fault. As such, they are only one of two areas of uplifted arc-related rocks within the valley; the other the Poverty Hills 50 kilometers to the north. Sampling for this study focused on the northern Alabama Hills as exposures of Jurassic rocks are more complete and access was via public land. The second area sampled lies approximately 10 kilometers to the west-northwest along the western flank of the Inyo Mountains. This area lies adjacent to the “famous” Union Wash ammonite locality and is geologically more complex. Outcrops range in age from Cretaceous granites through Jurassic metasediments with sparse metavolcanics. Older sedimentary units are present to the east. Samples were taken only from Jurassic age rocks. A second area of Jurassic rocks to the south was not sampled as much of the section has been truncated by a fault.

Tectonic Setting

The Owens Valley and southern Inyo Mountains lie near the western margin of the North American craton and at the center of the central Sierra Nevada segment of the Cordilleran arc (Sorensen et al, 1998). The emplacement of the Sierra Nevada batholith was a result of the oblique subduction of the Farallon oceanic plate beneath the North American continental plate from 210-80 Ma. The SN batholith youngs from west to east, a consequence of increasing rate of subduction (Harden, 1998). Thus, granitoids of the Owens Valley and White/Inyo Mountains are generally Late Cretaceous in age (Chen and Moore, 1979). Jurassic volcanism associated with early stages of arc formation produced the bulk of the metavolcanic units within the Owens Valley and southern Inyo mountains.

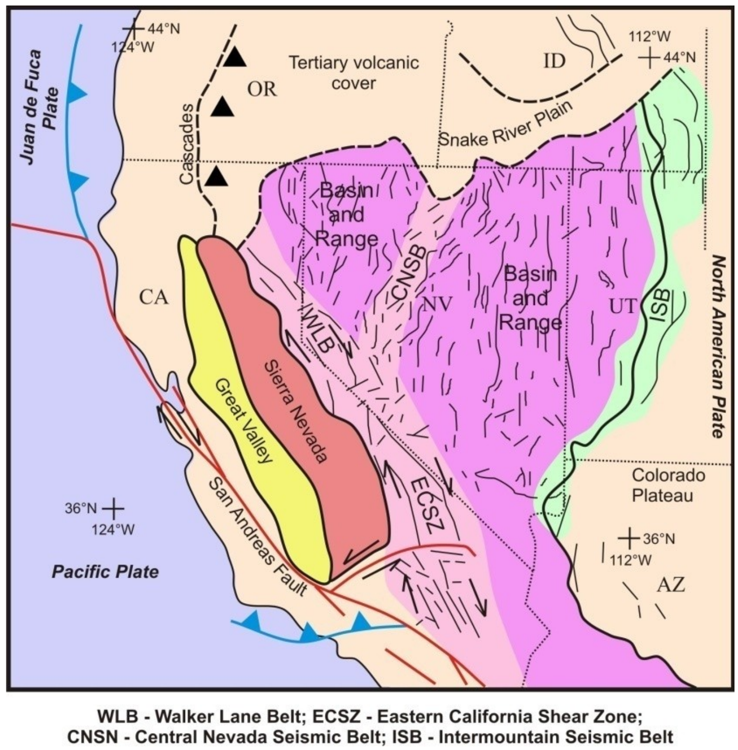

Figure 2. Tectonic map of the western Cordillera, after Lee, et.al, 2006

A more recent and better understanding of tectonics can be summed up in a single phrase: Eastern California Shear Zone (ECSZ) (Figure 2). This zone is an ever-changing element of the Pacific-North American plate boundary system. The ECSZ is the name for the southern segment of the larger Walker Lane belt, a zone of right-lateral strike-slip faults which relieve about twenty to twenty-five percent of the total relative motion of the plate boundary between the Pacific and North American plates (Gan, et. al., 2000). The Garlock fault forms the southern boundary of the ECSZ. The ECSZ is actually a 100 km wide zone comprised of four separate fault zones; from east to west the Death Valley-Furnace

Creek, Fish Lake Valley, Hunter Mountain-Panamint Valley, and Owens Valley (Frankel, 2008) (Figure 3). The Owens Valley fault is the only one of the four fault zones that has recorded a major seismic

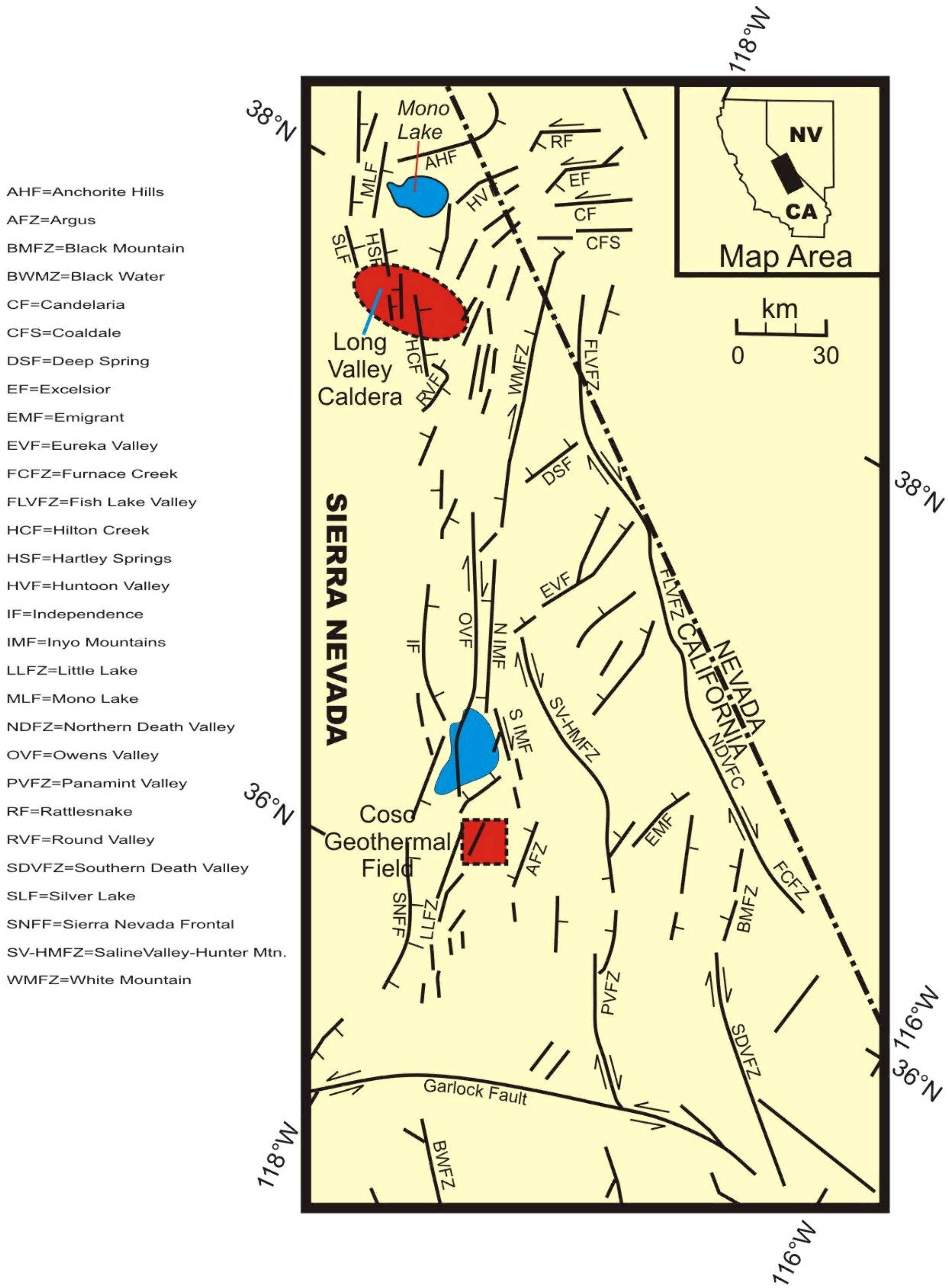

Figure 3. Quaternary faults of the ECSZ (after Bacon and Pezzopane, 2007).

event in the historic past (Bacon and Pezzopane, 2007). In 1872, the Owens Valley fault ruptured producing an estimated 8.0 M_w earthquake near Lone Pine (Southern California Earthquake Data Center, USGS). Slip rates for the Owens Valley fault are controversial, but estimates suggest 1-3mm/yr (Beanland and Clark, 1994, Lee et. al., 2001, Bacon et. at., 2002, Bacon and Pezzopane, 2007). This accounts for less than 25% of the total motion of approximately 15 mm/yr across the entire ECSZ and is at odds with geodetic measurements suggesting motion of 6-8 mm/yr (Peltzer, et. al., 2001). The discrepancy between satellite measurements (6-8 mm/yr) and paleoseismic studies (1-3 mm/yr) is difficult to reconcile. Suggestions include an elastic upper crust overlying a viscoelastic lower crust (Dixon, et. al., 2003) and a heretofore undiscovered component of oblique slip on many of the dip-slip faults. Beyond this, the picture gets more complicated. What is the relationship between transform faulting and high-angle range front faults and how is strain partitioned across the ECSZ? Finally, when did the current episode of dextral shear begin and what is the total amount of displacement across the ECSZ?

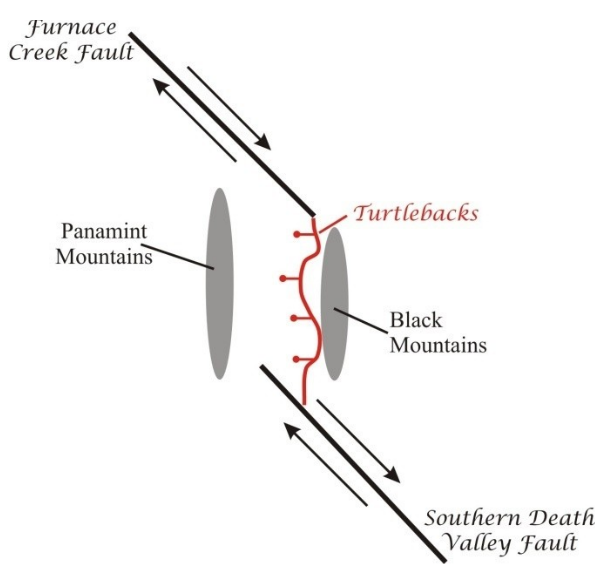

Figure 4. Simple model for transtensional extension across Death Valley, (after Tarman and Jessey, 2004).

Studies suggest that only some of the faults of the ECSZ are characterized by oblique slip; for example the Lone Pine fault (Lubetkin and Clark, 1988). Others, like the southern Death Valley fault zone are right-slip while still others such as the Sierra Nevada frontal faults are characterized by vertical motion (Le, 2004). This presents an enigma. If all of the motion is not accommodated by oblique slip how can dip-slip and strike-slip occur simultaneously? Stockli, et al., 2003 provide the simplest explanation. They suggest that vertical and horizontal motion do not occur simultaneously; the current regime of dextral shear began about 3 million years ago (Henry, 2007). Bellier (1995) suggests that the Owens Valley fault transitioned from dip-slip to dextral slip motion 0.288 Ma and that this transition may not have been the first. Prior to that, motion was largely dip-slip. In contrast Monastero, et. al., (2005) argue that the Coso Range represents an emerging core complex, unroofed by transtensional extension along the Owens Valley fault zone. Figure 4 provides a simple model for transtensional extension along the Furnace Creek-Sothern Death Valley fault zone. The current escarpment of the Black Mountains has been created by a detachment fault, a consequence of the right step in the dextral shear regime.

Over the last 3.5 million years, the rate of dextral shear on the southern end of the Eastern California Shear Zone is believed to be constant at about 10-15 mm/yr. How long the Eastern California Shear Zone has been active and the total displacement are still in debate. Most believe that ECSZ has been active only since Plio-Pleistocene time. Based upon measured rates of Holocene slip displacements on the order of 10 kilometers would be indicated (Frankel, 2008). Others, however, believe that at least the Owens Valley segment of the ECSZ may have been active since 83.5 Ma with displacements of about 65 kilometers in the Owens Valley (Carl, 2002, Kylander-Clark, et. al., 2005). If one assumes that the 50-60 kilometers of the displacement occurred before early Miocene and during the Laramide Orogeny (late Cretaceous to early Paleogene) and before formation of the Garlock fault, and that only ~5-10 kilometers has occurred since 3 Ma, them all of 65±5 kilometers of displacement is accounted for (Bartley et. al., 2007). Bartley et. al. (2007) even propose that 10-65 kilometers of additional offset occurred prior to 83.5 Ma, but this is speculative.

This research examines the premise that dextral shear across the ECSZ may exceed 65 kilometers. Conventional wisdom has been that net slip across the ECSZ rarely exceeds 20 kilometers and is less than 10 kilometers across the Owens Valley fault zone (Moore and Hopson, 1961, Lee et al., 2001, Manestero et al., 2002, Stockli et al., 2003). Glazner, et. al., (2005) provide several lines of evidence supporting 65 kilometers of slip, including offset dikes and plutons as well as displacement of the axis of dilation of dikes and an offset Devonian submarine drainage channel. While their arguments are compelling they, nonetheless, do not consider stratigraphic correlations across the Owens Valley. Near Lone Pine, CA rocks within the Alabama Hills and to the west of the Owens Valley fault have been correlated with outcrops on the east side of the fault in the southern Inyo Mountains, a distance of less than 10 kilometers. Certainly, if the fault has undergone 65+ kilometers of movement since the Jurassic there should be substantial geochemical and petrographic differences between those two outcrop areas. In the following section I will discuss both the geologic and structural framework of the central Owens Valley before presenting results of this research.

Stratigraphy and Structure

The focus of this research is the Jurassic age metavolcanic and metasedimentary rocks outcropping in the central Owens Valley of eastern California. These units, in the Alabama Hills and southern Inyo Mountains are part of a discontinuous, northwest-trending, belt of Jurassic rocks formed during the initial stages of emplacement of the Sierran magmatic arc (Figure 5).

Larie Richardson's (1975) Master's thesis from the University of Nevada, Reno, was the first and most inclusive publication on the geologic history of the Jurassic units of the northeastern Alabama Hills. The Jurassic sedimentary units are mostly nonmarine in origin, especially the younger units in the area (Sorensen et al, 1998). Geochemistry suggests the unmetamorphosed Jurassic volcanic units were continental arc rocks, a part of the calc-alkaline, basalt-andesite-dacite-rhyolite suite. These are the rocks that are exposed in the northeastern Alabama Hills. (They will be discussed in more detail below). Richardson postulates that the intrusion of rhyolitic to andesitic hypabyssal dikes and sills into the older volcanic and sedimentary units resulted in local alteration of the pre-existing rocks. This was followed by a second intrusive event consisting of a swarm of mafic dike. These were identified by Moore and Hopson (1961) as a part of the Independence dike swarm.

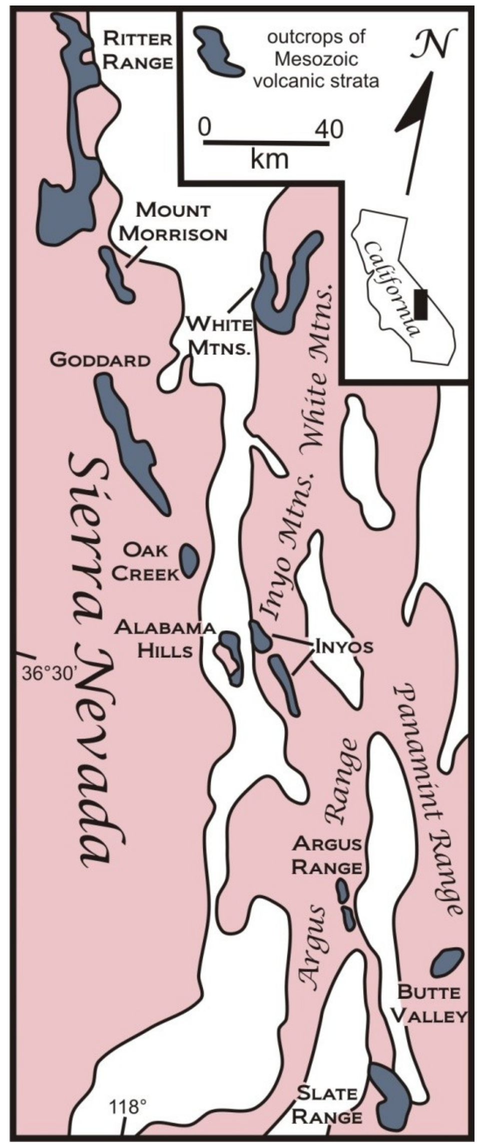

Figure 5. Major outcrops of Jurassic syn-arc strata in eastern California, (after Dunne and Walker, 1993).

A more recent paper by Dunne and Walker (1993) breaks down the lithostratigraphy of the Jurassic “volcanic and sedimentary units” of the Alabama Hills and includes descriptions of the southern Inyo Mountains as well (Figure 6). The authors subdivide the Alabama Hills into two intervals and divide the southern Inyos into three. The lower interval of the Alabama Hills makes up the majority of the outcrop of the Jurassic units. At about 2000m thick, this interval is comprised of moderately to

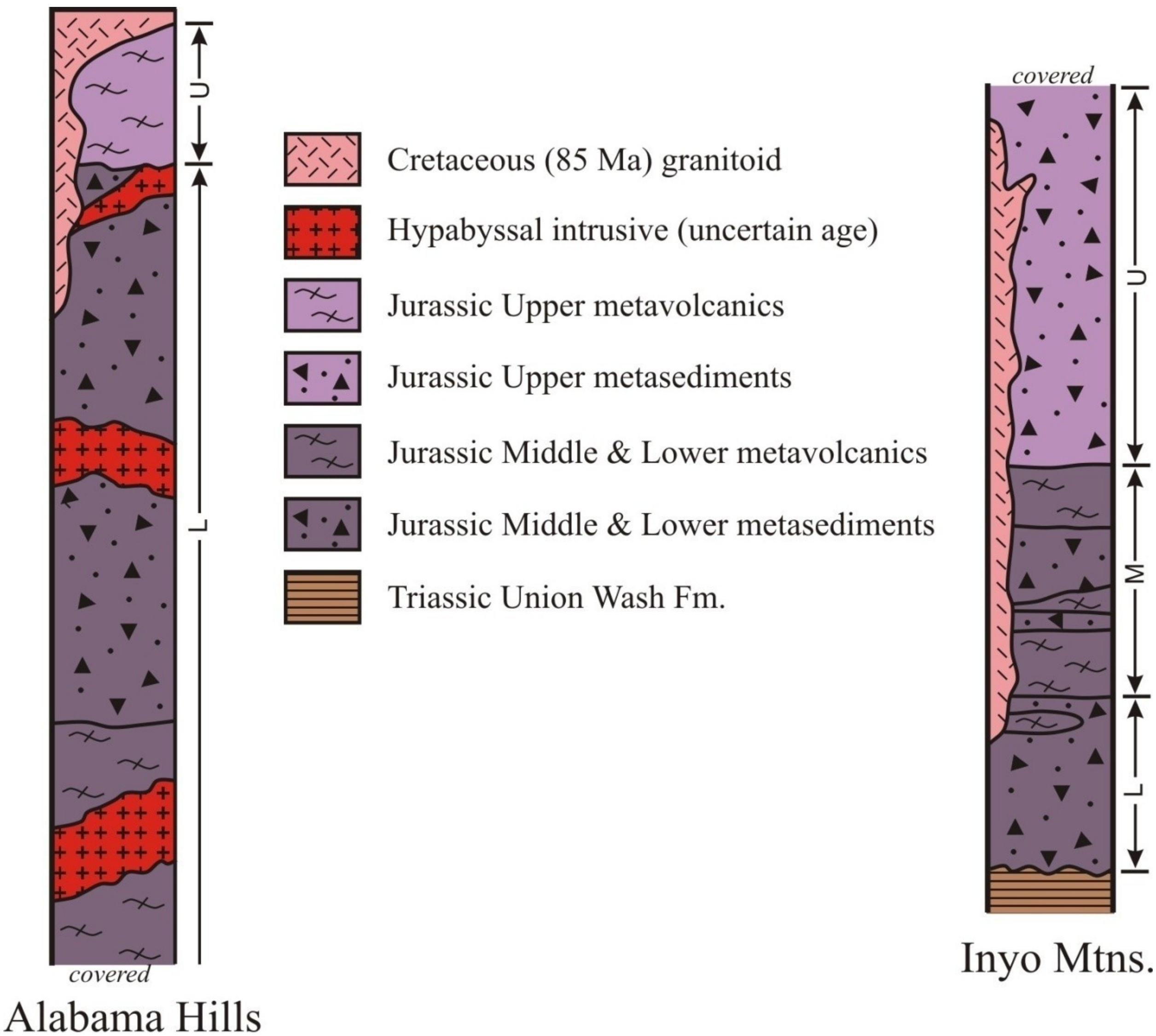

Figure 6. Stratigraphic column for Mesozoic syn-arc strata, Alabama Hills and southern Inyo Mountains (adapted from Dunne and Walker, 1993).

steeply southwest- dipping rhyolitic, ash-flow tuff and volcanogenic sedimentary strata in nearly equal amounts. This lower interval also contains two or more episodes of hypabyssal intrusions in the form of northwest-trending dikes and sills. The upper interval, as described by Dunne and Walker (1993), consists of a discontinuous basal segment, up to 10m thick, of lenses of recrystallized shale and minor quartz arenite and conglomerate. The majority of the upper Alabama Hills interval consists of at least 450m of rhyolitic, ash-flow tuff.

In the southern Inyo Mountains, the lower interval was measured at 200 to 400m thick. This interval is described as having a 2 to 5m thick basal conglomerate, overlain by volcanogenic conglomerate and breccia, sandstone and siltstone, and capped by a thin basalt lava flow. The middle interval, which on the general geologic map (Figure7) is lumped together with the lower interval, is about 300 to 800m thick. This interval is comprised of about 65% silicic tuff, 25% andesite and rhyolite, and 10% volcanogenic sedimentary units. The upper interval, of indeterminate thickness, is composed of roughly 95% volcanogenic conglomerate, sandstone, siltstone and about 5% welded and ash flow tuff. Dunne and Walker (1993) suggest that there is a geochronologic tie between the Alabama Hills upper interval rhyolite tuff and the Inyo middle interval rhyolite tuff at about 169 Ma. The authors also felt that the greater thickness of the rhyolite tuff in the Alabama Hills represents closer proximity to an undetermined "local volcanic feeder."

The volcanic and sedimentary units were then metamorphosed by a regional thermal event or thermal events, which more greatly affected the Alabama Hills due to closer proximity. The main, but not necessarily only, metamorphic event was the emplacement of the 85 Ma Alabama Hills granite (Chen and Moore, 1979). Sorensen et al (1998) found that the maximum temperature and pressure of metamorphism of the Alabama Hills were ~610°C and ~2 kBar, respectively. In contrast, temperatures in the southern Inyo Mountains probably did not exceed 400°C. Sorensen et al (1998) describe two additional stages of local alteration in the Alabama Hills. The first was minor potassic metasomatism and the second, overprinting the first, was Na and Na-Ca alteration. The former was induced by meteoric water and the latter related to contact metamorphism (Sorensen et al, 1998).

Plutonic rocks that border the Alabama Hills to the west and southwest are part of the Sierra Nevada batholith. They have unique compositions compared to the norm for the Sierra Nevada and it is suggested that they originated from a more highly differentiated magma. They were emplaced between the Alabama Hills metavolcanic and metasedimentary units to the east and Sierran granitoids of the main batholiths to the west.

Part of the Independence dike swarm crosscuts the metamorphosed volcanic and sedimentary units of the Owens Valley, and more specifically the northeastern Alabama Hills. This dike swarm has been extensively studied in recent years and sheds some light on post-metamorphism deformation. Firstly, the dike swarm in the Alabama hills has been dated at 148 Ma, thus the metamorphosed volcanic and sedimentary units are older than 148 Ma (Carl, et. al., 2002). Secondly, these Independence dikes in the Alabama Hills lack mylonitic fabric, which suggests a shallower level of intrusion for the dikes in this area (Carl, et. al., 1994). Finally, the dikes in the northern segment of the 600 km long Independence dike swarm, which includes those in the Alabama Hills, are generally west by northwest striking. This means the average strike of the Independence dikes in the Alabama Hills is about fifteen degrees counterclockwise to

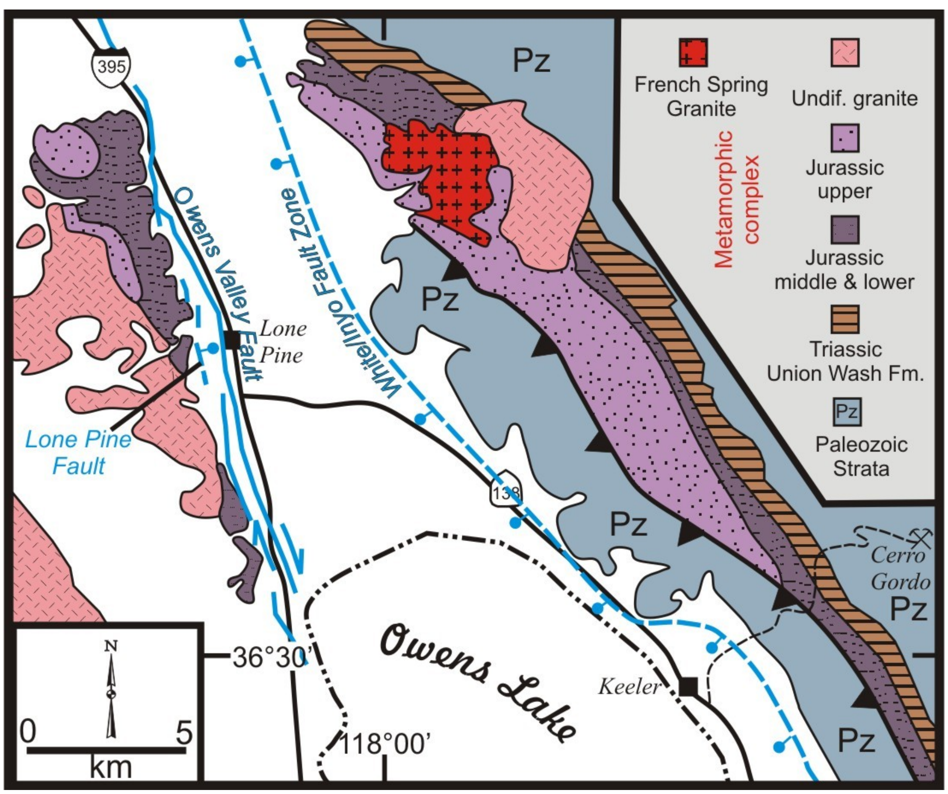

Figure 7. Geologic map of the central Owens Valley (modified from Dunne and Walker, 1993).

the strike of the northern segment. This may represent local counterclockwise block rotation. The dikes in the Alabama Hills and throughout California may represent extension perpendicular to their strike, possibly east-west back-arc extension related to the subduction zone to the west. The dike swarm may also represent rapid changes in plate motion, such as changes in the rate of subduction or direction of movement of the North American plate (Carl, et. al., 2002). What these dikes in the Alabama Hill represent for certain in unclear, but they do provide age constraints for the rocks they cross-cut and pose more questions about the tectonic history of the area.

Subsequent tectonic activity has significantly altered the Owens Valley. The post-Cretaceous tectonic history of this area, in particular, has been extensively researched and documented during the past decade. The Sierran Frontal fault forms the western boundary of the area, while the White Mountain-Inyo fault forms the eastern boundary. Other major faults include the Owens Valley, Lone Pine and Inyo Thrust (Figures 7 and 8). Minor east-west striking faults within the Alabama Hills may be left-lateral wrench faults associated with the dextral shear along the north-northwest-striking Owens Valley fault

Le, et. al., (2007) published a comprehensive study of Sierra Nevada frontal fault system including the Independence fault, lying 10 kilometers to the west of Lone Pine. Their study reported that movement along the Independence fault was dip-slip, east side down, at a rate of 0.2-0.3 mm/yr. This rate is about one-half to one-third that necessary to accommodate the 1500-2000 meters of vertical displacement between the Sierra Nevada crest and the Owens Valley. They suggested this discrepancy means the Sierra Nevada's are older than the generally agreed upon figure of 3-5 Ma (Wakabayashi and Sawyer, 2001), perhaps as old as 10 Ma, or that Quaternary slip rates are less than those of the Tertiary.

The Lone Pine fault lies immediately to the east of the Alabama Hills, as seen in Figure 7. The Lone Pine fault appears to be right, oblique-slip fault. Rates of vertical motion are estimated at 0.5

mm/yr (Le, et. al., 2007). Horizontal slip rates are less well constrained, but Lubetkin and Clark (1988) suggest rates <1 mm/yr. The relationship between the Lone Pine fault and the Owens Valley fault, a few hundred meters to the east, is enigmatic. Since both were offset by the 1872 Lone Pine earthquake they are clearly interrelated, however, Le, et. al, (2007) suggest that motion along the Owens Valley fault is almost pure dextral shear. Estimates of slip rate are variable from a high of 4.5 mm/yr (Kirby, et. al., 2008) to a low of 0.7 mm/yr (Lubetkin and Clark, 1988). No estimates are available for the vertical component of movement along the Owens Valley fault, which clearly manifests itself in the scarp created by the 1872 earthquake, but is undoubtedly small, perhaps 0.1-0.2 mm/yr.

The White-Inyo fault strikes along the east side of the Owens Valley, 6-8 kilometers east of Lone Pine. Its history is complex. Bacon, et. al., (2005) suggest that Holocene motion along this fault is predominantly right oblique-slip at a rate of 0.1-0.3 mm/yr. However, Beiller and Zoback, (1995) argue that motion along the White Mountains/Inyo Mountains fault system underwent a change from predominantly dip-slip (west side down) to oblique slip at 288 ka. This seems reasonable as the vertical component in an oblique-slip fault moving at a rate of 0.1-0.3 mm/yr would be insufficient to account for the relief between the White/Inyo crest and the valley floor.

The most controversial fault in the Owens Valley is labeled the Inyo thrust on the cross section (Figure 8). This fault was proposed by Stevens and Olsen (1972). Presumably, rocks were carried eastward along this fault a distance of approximately 20 kilometers. A major problem has been timing of the thrust. Stevens originally correlated the thrust with the Permo-Triassic Last Chance thrust. However, Dunne and Gulliver, (1978) questioned the existence of the thrust suggesting instead that the fault was a normal fault. Interestingly, in his 1993 article (Dunne and Walker, 1993) Dunne has shown the Inyo thrust on his geologic map (Figure 7). Apparently something happened to change his mind. something a normal fault would not allow. Dunne's more recent article left one controversy unresolved, the age of the thrust. Since he clearly established the age of the Alabama Hills and southern

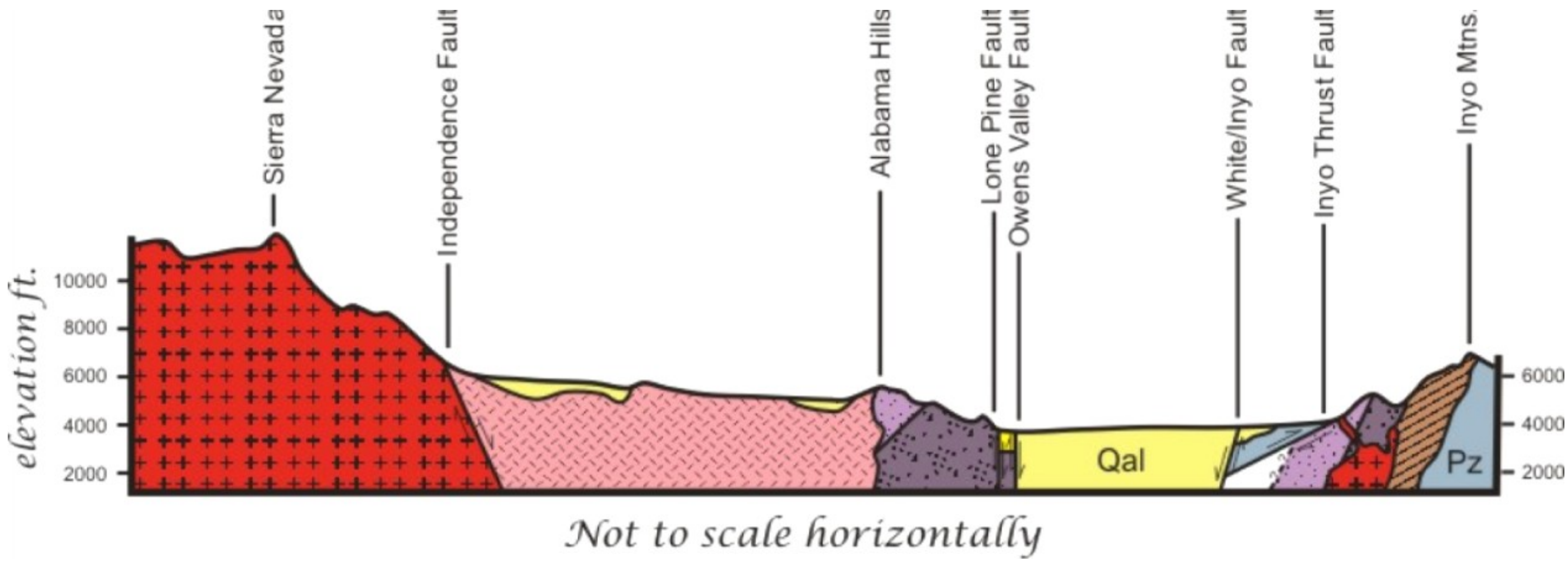

Figure 8. Generalized cross section of the central Owens Valley (modified from Stone, et. al., 2000).

Inyo metavolcanics at 160-170 Ma, and they lie in the footwall of the thrust, it cannot be Permo-Triassic in age, but must be younger than Middle Jurassic. Stone et. al., (2004) provide some resolution to this controversy. He renames the Inyo thrust of Stevens the Flagstaff thrust in the southern Inyo Mountains and suggests it is not correlative with the Inyo thrust, as mapped by Stevens along the base of the White Mountains. Stone believes the Flagstaff thrust is either late Jurassic or early Cretaceous in age. This controversy is important to this research as it places time/space constraints on the relationship of the Jurassic sections in the Alabama Hills and Inyo Mountains. This will be considered again during my discussion and conclusions section.

Sample Preparation for Geochemical Analysis and the Subsequent Quantitative Analysis

A total of 72 rock samples were collected from Jurassic outcrops in the central Owens Valley, specifically from the Alabama Hills and southern Inyo Mountains. Sample locations are given in Appendix A. Fresh, unweathered rock samples were collected using a 30 ounce rock hammer. All samples were removed from outcrops, none were float. After collection, the samples were taken to the Cal Poly Pomona Geochemical Lab for preparation and analysis. The preparation process has been described in detail by Anderson (2005) and will be briefly summarized below.

The first step in preparation was to cut each sample with a diamond hand saw to reduce volume to allow that sample to fit into a chipmunk jaw crusher and to halve the sample for possible thin section analysis.

The crusher pulverized the sample into pieces no greater than 1.5 cm in diameter. The pulverized sample was then placed into a steel ball mill. The sample was run in the ball mill for thirty minutes. Next, the sample is gently sieved through a 60 micron sieve. Six grams of the undersized (<60 micron) sample is measured out using an analytical balance to provide the necessary volume for XRF analysis.

The sample is then ready to be pressed into a pellet. Cellulose binder (1.2 gr) is added to the sample and the combined material is placed in the ball mill, without the steel ball, to mix for at least two minutes. The mixture of sample and cellulose is then placed inside a die and compressed into a circular pellet.

The pellets were analyzed in Cal Poly Pomona's Phillips PW 2400 x-ray fluoresence spectrometer (XRF). The samples were first analyzed for major elements, Si, Al, Ca, Mg, Fe, Mn, Na, K, P, and Ti, as weight percent oxides, utilizing standards provided by the United States Geological Survey. The results from major oxide analyses can be found in Appendix B. The samples were then analyzed for several trace elements, Ba, Ce, Cr, La, Nd, Sr, Sc, Y, Zr, and Sm, which are reported in parts per million. The trace element content was determined by a program designed by Dr. David Jessey of Cal Poly Pomona called basalt-trace. The results from trace element analyses can be found in Appendix C.

The major and trace element analyses were input into Excel and converted into .txt files for greater ease of presentation and interpretation. This data was then analyzed with IgPet 2006. This program enables easy creation of a myriad of petrographic diagrams. Only selected diagrams that provide insight into the Alabama Hills Jurassic metavolcanics and metasediments and comparisons with similar Inyo Mountains Jurassic units were utilized in this thesis.

Rock samples were examined with a binocular microscope in order to compare geochemical trends to petrographic (mineralogic) variations. Representative samples were selected and cut into billets for thin section preparation. Billets were sent to Arizona Quality Thin Sections, Tucson, Arizona for mounting and thin section preparation.

Geochemistry

Samples collected from the Alabama Hills represent the upper and lower units as mapped in the area. The upper unit is almost exclusively metavolcanic, while the lower is predominantly meta-sedimentary with a lesser volcanic component. Samples from the southern Inyo Mountains represent the upper metasedimentary unit, and lower and middle units comprised of both metasediments and metavolcanics. Again, samples were analyzed with a Philips PD2450 x-ray fluorescence spectrometer running analytical software routines designed by department faculty (USGS standards and basaltrace). The variations between the Alabama Hills and Inyo Mountains are depicted in geochemical charts and figures produced by IgPet 2006.

The Alabama Hills samples are significantly enriched in silica, (SiO_2), relative to the Inyo Mountains. If broken down into their respective intervals, the silica content varies further as seen graphically in Figure 9. The upper Alabama Hills interval of samples have an average of 75.7 percent silica while the lower Alabama Hills samples have an average of 70.1 percent silica. The difference in silica content between the upper and lower units most likely reflects original differences in silica content between sedimentary and volcanic protoliths. Alternatively, the upper Alabama Hills metavolcanics may have been more susceptible to metasomatism. The samples in the upper and middle Inyo Mountain intervals have an average of 61.6 percent silica and the samples in the lower Inyo Mountains interval have an average of 57.7 percent silica. The differences in silica content are less than those in the Alabama Hills and more difficult to explain. Perhaps they reflect differences in proto-

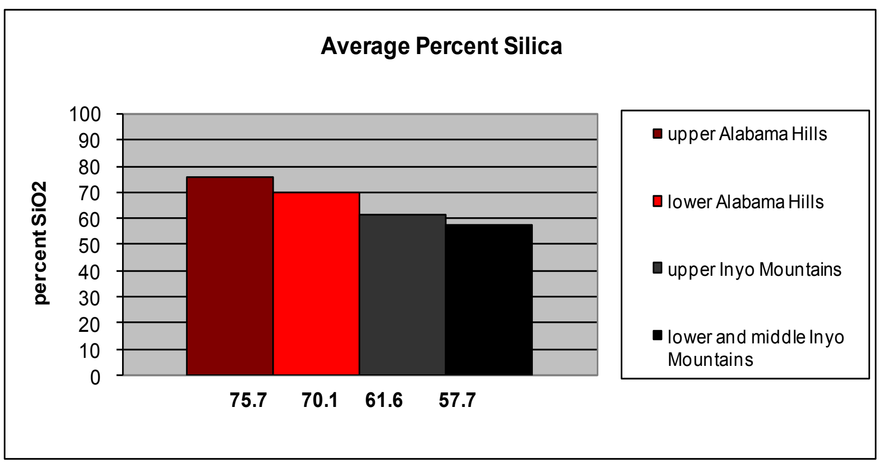

Figure 9. Average percent silica within the study area.

lith, but in this case the lower unit with the lower silica contains the volcanic rocks and hence the silica trend is inverted relative to the Alabama Hills. In either case (Alabama Hills or Inyo Mountains), the upper unit has the higher silica content.

Looking at overall silica content, we see that the Alabama Hills are about 12 percent higher. This variation seem to suggest silica flooding as an explanation. The Alabama Hills units are situated directly above the Cretaceous Alabama Hills Granite while the Inyo Mountains units are at some distance from an intrusive contact. Thus, the silica "flooded" the Alabama Hills.

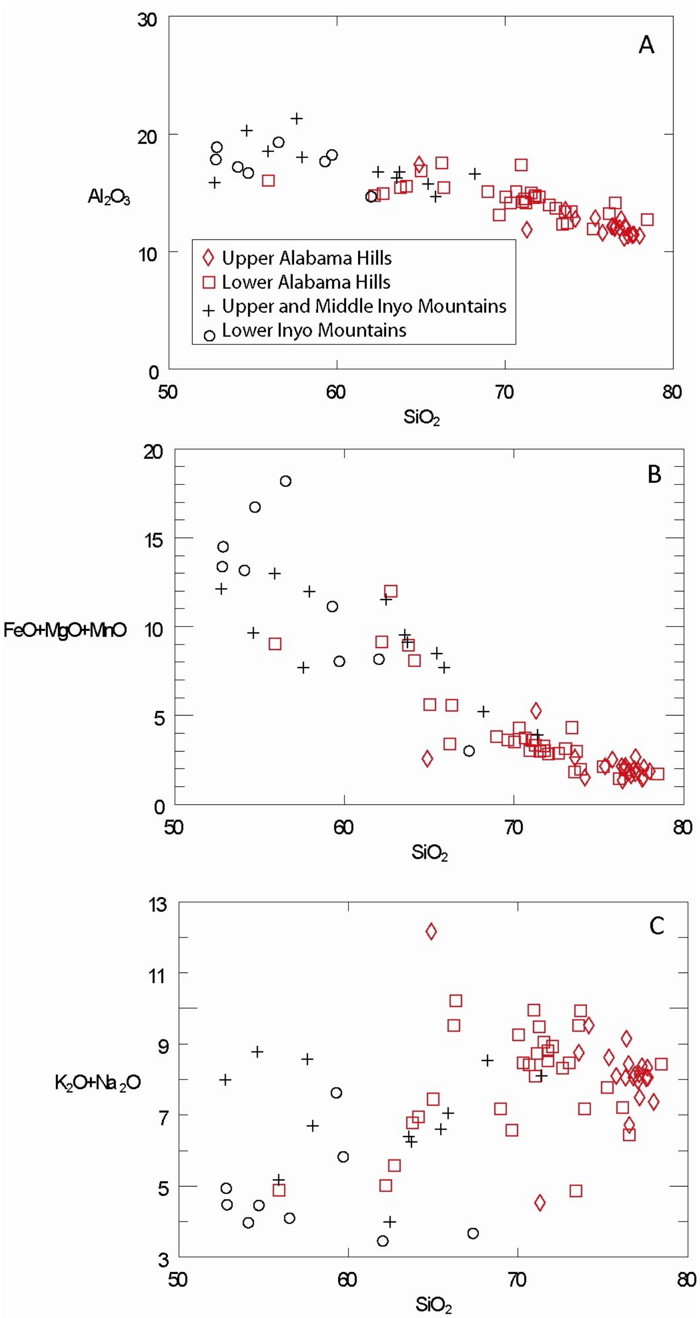

Figure 10. **A**- Alumina vs. silica, **B**- Mafics vs. silica, **C**- Alkalis vs. silica.

Using silica as a base, other geochemical trends can be observed. Plotting alumina versus silica on an x-y diagram reveals that the Inyo Mountains samples are more enriched in alumina than the Alabama Hills samples, as can be seen in Figure 10A. The average percent alumina in the Inyo Mountains samples is 16.9 percent while the average percent alumina in the Alabama Hills samples is 13.6. This is consistent with differences in protolith. The predominantly sedimentary protoliths of Inyos would be expected to have higher alumina concentrations. This supports the obvious stratigraphic differences between the two areas, and suggests they are products of distinctly different depositional environments..

A comparison of mafic oxides, FeO, MgO, and MnO, to silica, (Figure 10B) indicates the Inyo Mountains samples are considerably more enriched in mafics than the Alabama Hills. The average percent of mafic oxides in the Inyo Mountains samples is 10.3 percent and the average percent of mafic oxides in the Alabama Hills samples is 3.4 percent. In contrast, the Alabama Hills samples are enriched in alkalis compared to the Inyo Mountains samples, as seen in Figure 10C. The average percent alkalis in the Alabama hills samples is 8.0 percent and the average percent alkalis in the Inyo Mountains is 6.0 percent. These trends may represent differences in protolith, but are more likely explained by mobility of cations during metasomatism. Porphyry copper deposits are characterized by metasomatic alteration creating a zoning pattern with cores enriched in silica and potassium (potassic alteration) and peripheral zones characterized by increased iron and magnesium (propylitic alteration). Thus, the observed trends for the Alabama Hills and Inyo Mountains may simply reflect proximity to the intrusion and not be a function of original chemistry of the protoliths.

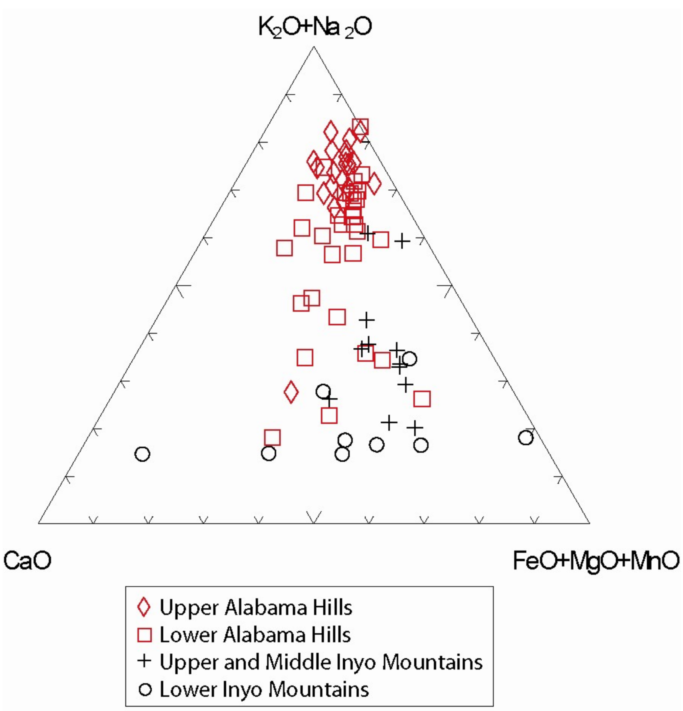

Figure 11. Ternary plot of CaO, alkalis, and mafics.

Why the upper Alabama Hills metavolcanics are more enriched in alkalis than the lower Alabama Hills metavolcanics is unclear. Differences in the Inyos may be explained by plagioclase-rich, alkali-poor andesites in the lower Inyo unit, in contrast to clay-rich sediments in the upper and middle units.

An alternative method of viewing geochemical trends is a ternary diagram that plots major cations (CaO-alkalis-mafics) (Figure 11). The Inyo Mountains are enriched in CaO relative to the Alabama Hills and the trends for alkalis and mafics are similar to those discussed above, i.e., the Alabama Hills are depleted in mafics and enriched in alkalis.

In summation, the Alabama Hills samples are enriched in silica and alkalis and deficient in alumina and mafics compared to the Inyo Mountains samples. The upper Alabama Hills samples are slightly more enriched in silica than their lower Alabama Hills counterparts. The upper and middle Inyo Mountain samples are also more enriched in silica than their lower Inyo Mountain counterparts. These trends show that the two sets of Jurassic metavolcanic and metasedimentary units differ chemically, possibly due to original lithology or metamorphic overprint.

Trace Element Geochemistry

Figure 12 plots the average trace element concentration on a logarithmic scale to enable the presentation of elements with less than ten and greater than 500 parts per million on a single diagram. When the averages of the trace element constituents are plotted the relationships between the trace element concentrations are more easily discernable (Figure 12).

The Alabama Hills samples and Inyo Mountain samples have similar amounts of Ba, Ce, and Zr.

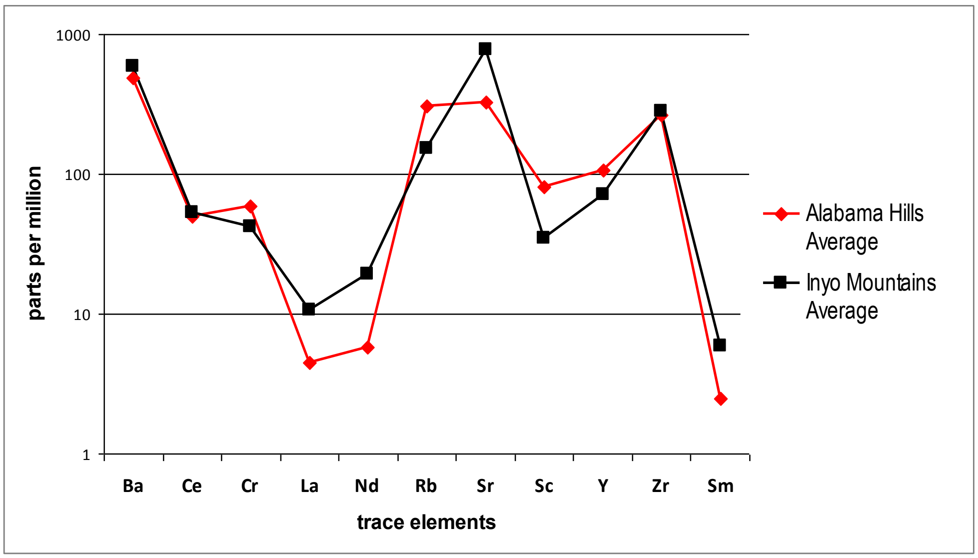

Figure 12. Trace element concentrations for the Alabama Hills and southern Inyos.

Ba is an incompatible element that substitutes for potassium in feldspar, micas, or hornblende and occurs in anomalous concentrations in samples taken throughout the California desert. It is not unusual for samples from different source rocks to have similar barium contents due to the Mojave "barium anomaly". Similarities in Ce and Zr content are more difficult to explain. In the case of Zr, it is a common constituent of granitic magmas and the similarity may reflect the extent to which the protolith has been overprinted by hydrothermal, metasomatic alteration.

The Alabama Hills samples are distinctly enriched in Rb, Sc, and Y while the Inyo Mountains samples are enriched in La, Nd, Sr, and Sm. These differences can most easily be explained by differences in source area. The two stratigraphic units were simply receiving sediments and volcanics from different sources. Another explanation is that the two areas may have shared the same source but were differing distances from the source resulting in differing depositional environments and filtering of the trace elements.

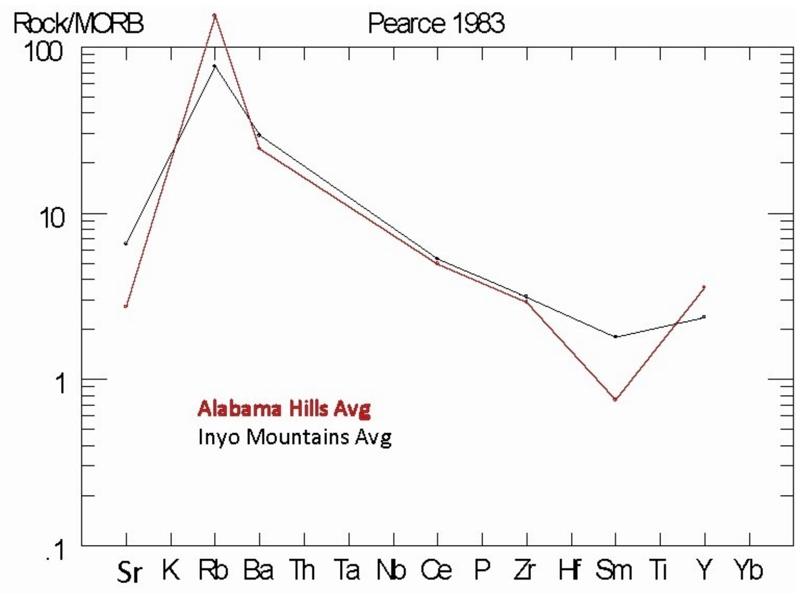

Figure 13. MORB normalized spider diagram.

When the average trace element concentrations are normalized to a mid-ocean ridge basalt, or MORB, as described by Pearce (1982), the same enrichments and deficiencies are seen (Figure 13). When compared to the data collected by Sorensen (1998), the concentration of Sm is considerably lower and Rb higher in the Alabama Hills. Overall, the two areas are enriched in LILs and incompatible elements, as seen in Figure 12 and Figure 13 and, in general, this spider diagram reveals a close correlation with the findings of Sorensen (1998).

Thin Section Analysis

For this thesis, fifteen petrographic thin sections were made from the 72 field samples; eleven from the Alabama Hills and four from the southern Inyo Mountains. The eleven thin sections from the Alabama Hills were samples: 1, 8, 15, 19, DJ16, DJ17, 53, 62, 76, 79, and 81. These eleven rocks were fairly similar to one other in thin section, but subtle differences were observed. In general, phenocrysts make up about twenty percent by volume. They are comprised predominantly of feldspars and quartz. The matrix is dominated by quartz, and other fine-grained mineral species that cannot be resolved with a petrographic microscope. Alteration was similar in all thin sections.

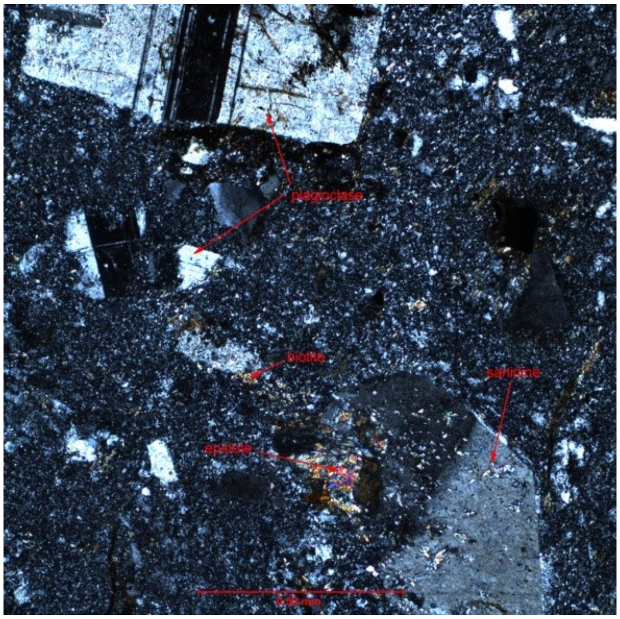

Figure 14. Sample 1, Upper Alabama Hills.

Rocks 1, 8, 15, DJ16, and DJ17 are quite similar and all are from the upper interval of the Alabama Hills. They have a pronounced porphyritic texture (Figures 14 and 15). Each has a heterogeneous matrix comprised of quartz, sanidine, sericite, and sometimes biotite. They originally were rich in glass because some retain their original devitrification textures. The phenocrysts, which make up between 15 and 30 by volume, are

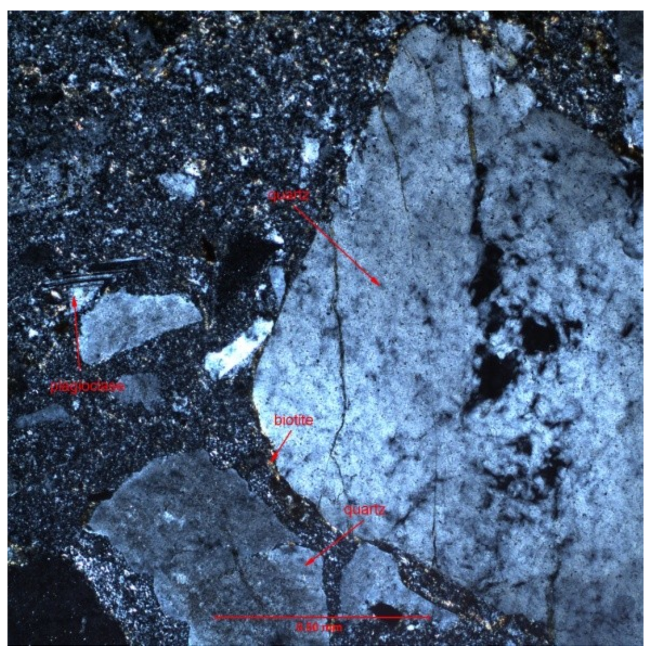

Figure 15. Sample 15, Upper Alabama Hills.

principally quartz, sanidine, and plagioclase with the majority quartz grains, (Figures 14 and 15). Some phenocrysts have been mildly to moderately fragmented during transport. None of the quartz phenocrysts have sutured grain boundaries and do not show evidence of having been recrystallized (Figure 15). Sanidine phenocrysts in these rocks are fragmented and show evidence of minor resorption. They are slightly clouded and show no exsolution textures. The plagioclase grains are also fragmented, they exhibit normal zoning, and have been moderately epidotized and sericitized, (Figure 14). Epidote, sericite, secondary biotite, and chloritized biotite are the principle metamorphic minerals and alteration products in these thin sections. Richardson (1975) terms these rocks meta-quartz porphyries. The nature of the fragmented phenocrysts and silica content suggest the rocks were originally volcanic (rhyolitic) debris flows and ash flows.

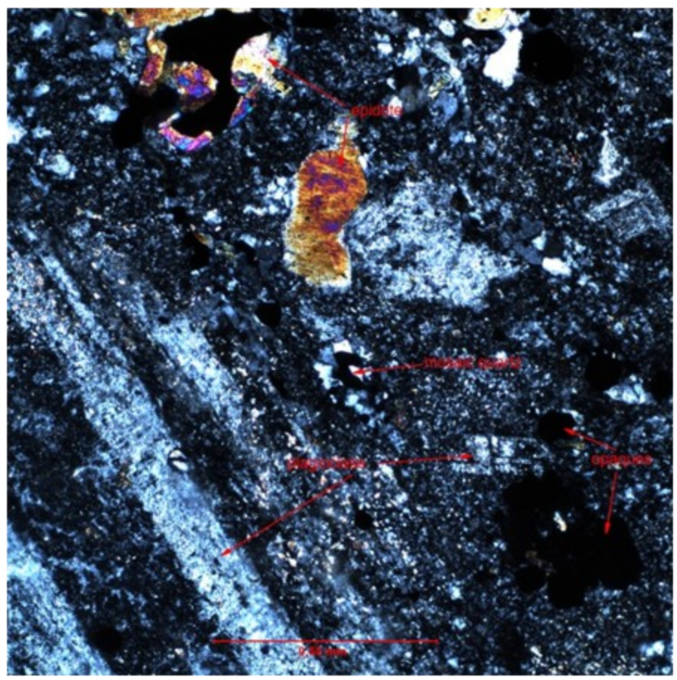

Figure 16. Sample 53, Lower Alabama Hills.

Samples 19, 53, and 76 are similar to those described above but are from the lower Alabama Hills which, according to Dunne and Walker (1998), are predominantly metasedimentary. These samples also have porphyritic texture and matrices of quartz, sanidine, sericite, and biotite. The phenocrysts, which make up about 20 percent of the total volume of each of the rocks, are principally quartz, sanidine, microcline, and plagioclase. Again, the majority of the phenocrysts are quartz and they exhibit sutured grain boundaries; only some are fragmented, and some have obviously been recrystallized into mosaic quartz. The sanidine grains also exhibit sutured grain boundaries, some are fragmented, and some have been mildly sericitized. Rocks 19 and 53 contained what appeared to be microcline phenocrysts with tartan twinning and sericitization. Plagioclase phenocrysts in these rocks show weak zoning, are fragmented, are clouded and have been sericitized, (Figure 16). Biotite, sericite, sometimes epidote, and sometimes chlorite are the metamorphic minerals and alteration products found in these samples, (Figures 16 and 17). Due to subtle differences from the previously described rocks, samples 19, 53, and 76 were termed meta-rhyolite tuffs by Richardson (1975). The limited fragmentation suggests shorter transport distance, or extrusion under less explosive conditions.

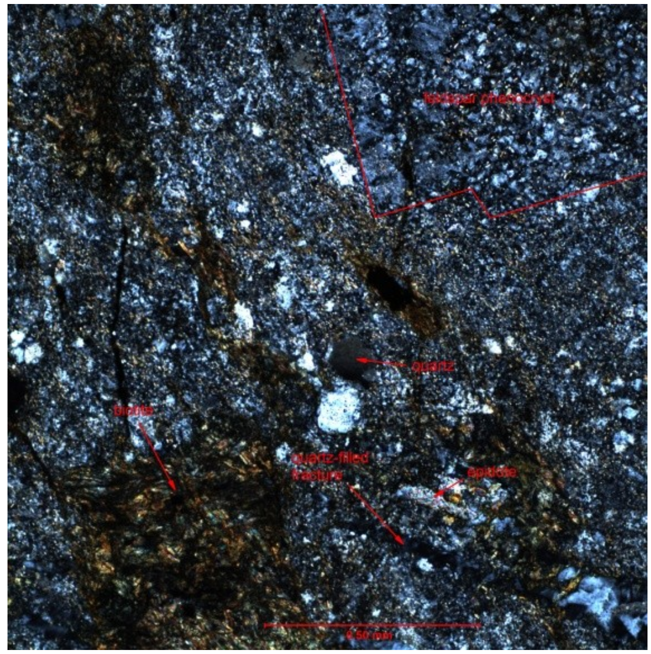

Figure 17. Sample 76, Lower Alabama Hills.

Sample 81, from the lower Alabama Hills, is unique. This specimen displays a devitrified matrix composed almost entirely of silica, (Figure 18). The phenocrysts in this sample are alkali feldspar, plagioclase, and to a lesser extent quartz. They make up only about 10 percent of the rock's total volume. Alkali feldspar phenocrysts, occur in glomeroporphyritic clusters, some showing perthitic texture, and exhibit sutured grain boundaries. The plagioclase phenocrysts are also glomeroporphyritic. They are zoned, often resorbed, mostly unbroken, sericitized and epidotized. The quartz phenocrysts are the least

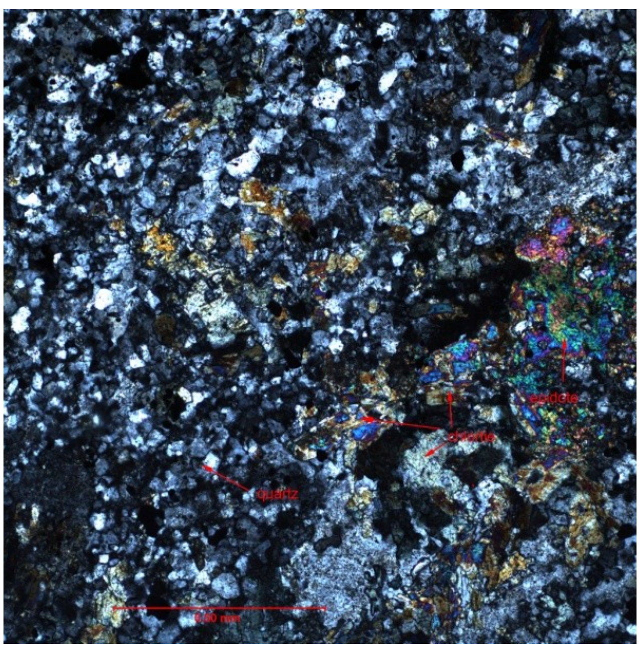

Figure 18. Sample 81, Lower Alabama Hills.

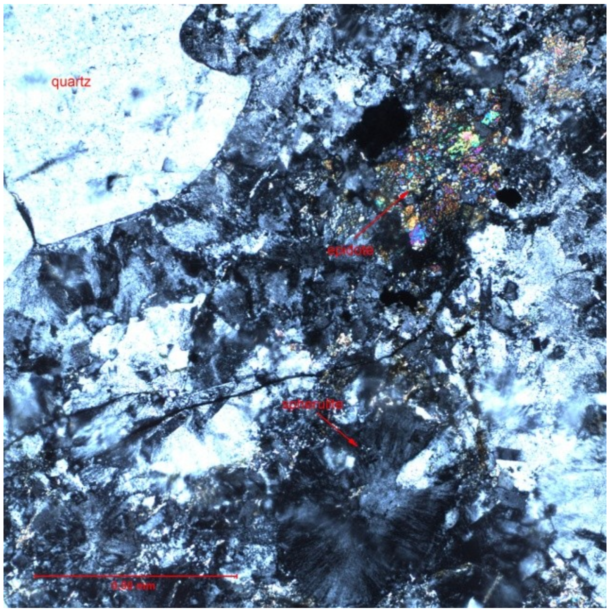

Figure 19. Sample 62, Lower Alabama Hills.

abundant. They are resorbed and their grain boundaries display suturing, (Figure 18). The metamorphic minerals are epidote, and secondary chlorite. This rock, is classified as a meta-alkali feldspar porphyry, by Richardson (1975).

Samples 62 and 79 are also unique and again from the lower Alabama Hills. The texture of these rocks is glomeroporphyritic. The matrix is heterogeneous and varies from a composition of plagioclase laths to devitrified glass that often has a spherulitic texture, especially apparent in rock 62, (Figure 19). The phenocrysts of plagioclase, quartz, and sanidine in these rocks make up about 10 percent of the total volume of the rock. Plagioclase is the most abundant phenocrystic phase; the grains are clouded, have sutured boundaries, and are sericitized and epidotized. The sanidine grains have similar characteristics. The quartz phenocrysts exhibit sutured grain boundaries and have obviously been recrystallized into mosaic quartz. Hornblende (?), has been completely replaced by a patchwork of biotite grains. The extent of alteration in these rocks makes distinguishing the type of phenocrysts challenging. Secondary biotite, chloritized biotite, epidote, and sericite are common metamorphic minerals and alteration products. Based on the unique groundmass texture and biotite-replacement in these samples, they are classified as meta plagioclase porphyry by Richardson (1975).

Note that Alabama Hills thin sections have not been described in stratigraphic succession. This is because the largely volcanic upper Alabama Hills and sedimentary lower Alabama Hills stratigraphic sections as described by Dunne and Walker (1998) cannot be differentiated in thin section. Both units appear to be comprised of volcanic ash flows and debris flows with minor interbedded rhyolites. There

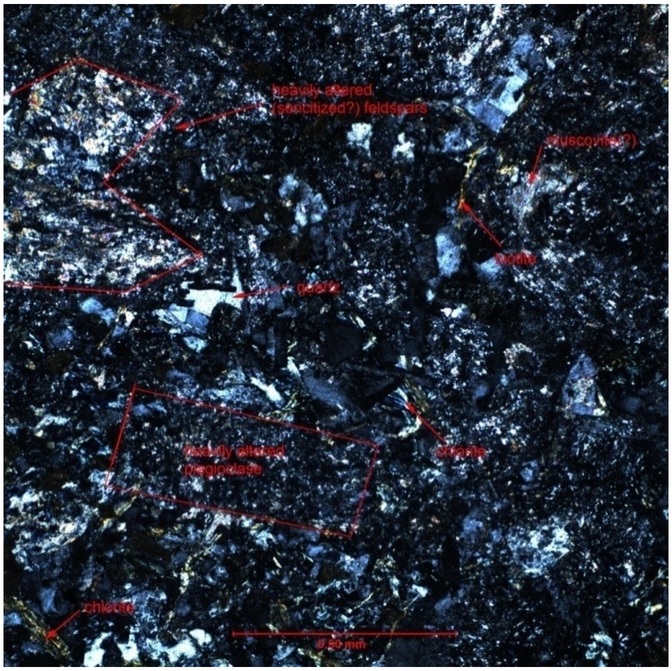

Figure 20. Sample 209, Lower Inyo Mountains.

does not appear to be the clear distinction in thin section between volcanic and sedimentary protoliths as they have proposed.

The Inyo Mountains samples that were made into thin sections were numbers 209, 215, 221, and 223. These thin sections are significantly different from the Alabama Hills. The Inyo Mountains samples have less silica-rich matrices, are highly altered, and have distinctive protoliths.

Rock 209, from the lower Inyo Mountains, is heavily altered. It appears to be metasedimentary, however this provisional classification is based largely upon its stratigraphic position (Dunne and Walker, 1998). This sample has biotite and chlorite in its matrix along with quartz, an altered clay, and in some areas tabular plagioclase grains, (Figure 20). Quartz and plagioclase make up the phenocrysts. The quartz grains are mildly fractured and anhedral in shape. Phenocrysts of plagioclase are often rounded and heavily sericitized and chloritized. The rounding of the phenocrysts, the fine-grained matrix, and the mineralogy suggest that this rock is a volcaniclastic sedimentary rock. This sample was collected from the lower inter-

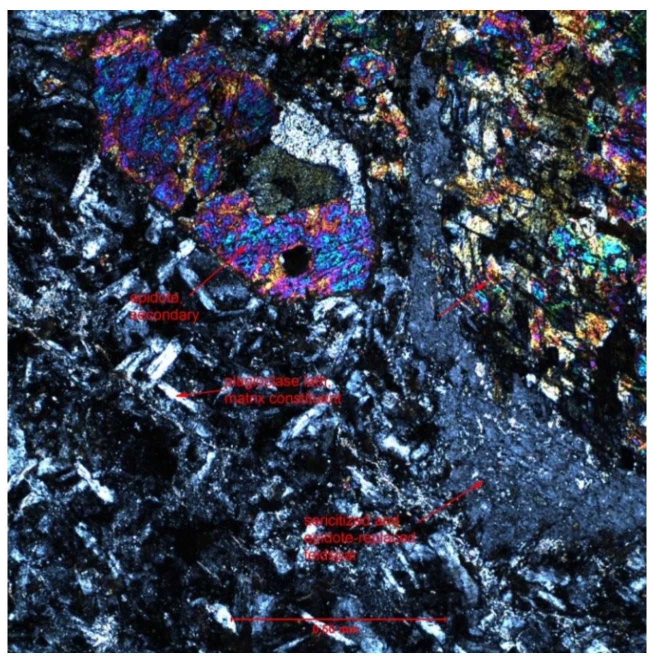

Figure 21. Sample 215, Middle Alabama Hills.

val of the Inyo Mountains complex. The stratigraphy of the lower interval is dominantly fluvial/alluvial debris flows and volcanogenic clast-brearing sediments (Dunne and Walker, 1998). Rock 209 is comparable to the volcaniclastic mudstone described in Dunne's 1998 publication.

Sample 215 is unique in that is rich in amphiboles with large epidote grains replacing both plagioclase and hornblende phenocrysts, (Figure 21). This rock is from the middle interval of the Inyo Mountains. The matrix is composed of small plagioclase laths, (Figure 21) with large subhedral phenocrysts of plagioclase. Another unique feature of this sample is the included rock fragments and opaques. The preponderance of plagioclase and amphibole phenocrysts and lack of quartz in the matrix lead to the belief that this rock is an andesite. This sample is therefore part of the 23-53% volcanics of the middle interval of the Inyo Mountains volcanic complex (Dunne, 1998).

Figure 22. Sample 221, Upper Inyo Mountains.

Rocks 221 and 223 are very similar. The both have a groundmass of very fine grained quartz and glass They have phenocrysts of quartz and heavily altered alkali feldspar, pieces of devitrified glass, rock fragments, and secondary chlorite and epidote, (Figure 22). They are most likely volcanic ash flows. They are part of the upper interval of the Inyo Mountains complex.

Thin section petrography and field observation suggest the Jurassic sections from the Alabama Hills and Inyo Mountains are significantly different. The Alabama Hills rocks show limited textural and mineralogic variation. The protolith is dominantly volcanic, and alteration, although mineralogically similar to that of the Inyo Mountains is less well developed, suggesting chemical differences to the Jurassic rocks of the Inyo Mountains. In addition, layering is apparent in the Inyo section, the rocks have an obvious sedimentary component and alteration is locally extensive. While the two stratigraphic sections may be time-correlative, it seems they were not deposited in close proximity to one another.

Metamorphism

To study metamorphism and metamorphic reactions in the Alabama Hills and Inyo Mountains field samples were examined in thin section and their bulk rock chemistry plotted on pertinent facies diagrams. The upper metavolcanic Alabama Hills interval is represented by samples 1, 8, 15, DJ16, and DJ17, and the lower metavolcanic Alabama Hills interval is represented by samples 19, 53, 62, 76, 79, and 81. The upper metasedimentary Inyo Mountains interval is represented by sample 209 and the middle and lower metasedimentary and metavolcanics Inyo Mountains intervals are represented by samples 215, 221, and 223.

Metamorphism within and adjacent to the Sierra Nevada batholith remains the subject of much controversy. Metamorphism most certainly occurred during Mesozoic plate convergence. Miyashiro (1961) pointed out the relationship of plate convergence to regional, polymetamorphic events and batholith emplacement. Specifically, arc volcanics could be expected to be subjected to repeated episodes of greenschist to amphibolites facies metamorphism as plutons were being emplaced (see Figure 23).

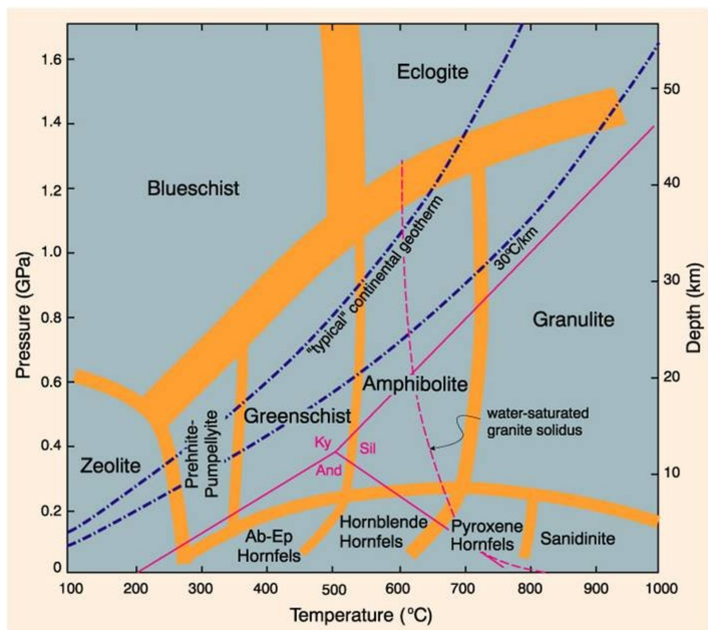

Figure 23. Metamorphic facies diagram (after Winter, 2001).

However, previous studies by Richardson (1973) and Sorensen, et. al., (1998) have suggested that plutons of the Alabama Hills are a product of contact metamorphism. To test this hypothesis, mineral assemblages from both the Alabama Hills and Inyo Mountains were plotted on, or compared to, relevant facies diagrams. Figure 24 is an ACF diagram for the greenschist facies. Reasons for utilization of ACF diagrams will be discussed below. Bulk rock chemistry results in all samples from both the Alabama Hills and Inyo Mountains plotting in the upper (gray) area of the greenschist facies diagrams.

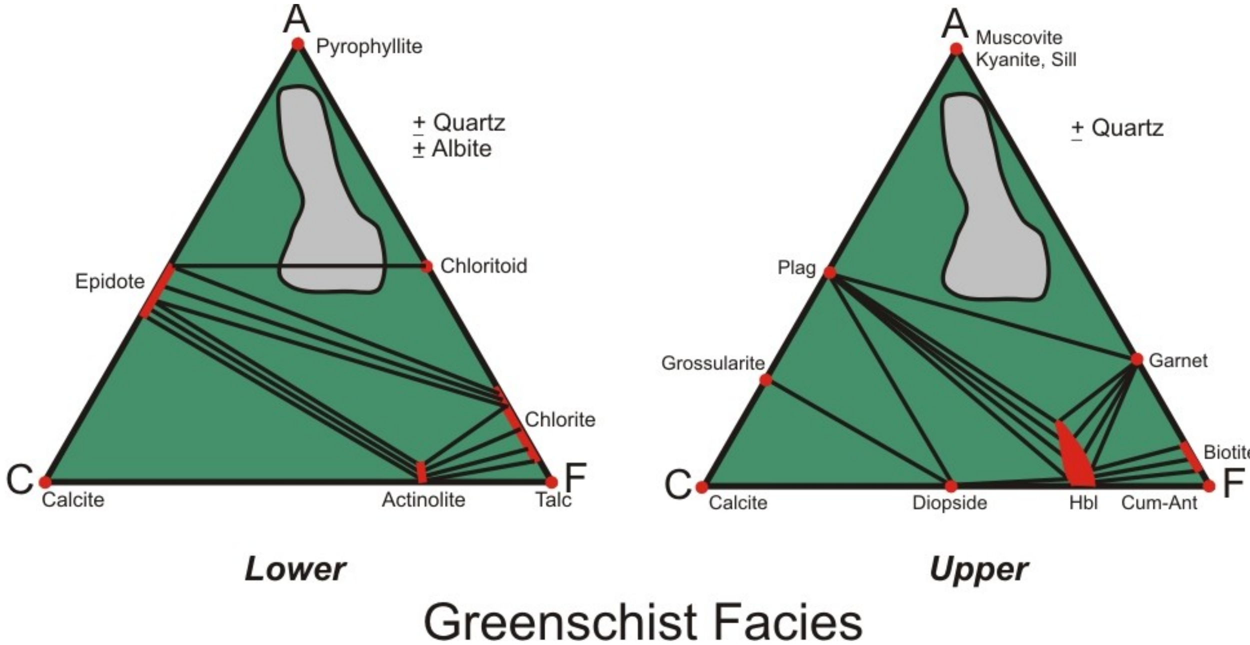

Figure 24. ACF diagram for greenschist facies regional metamorphism. Gray area represents the range of Alabama Hills and Inyo Mountains samples

Observed mineralogic associations argue strongly that greenschist facies metamorphism has not occurred. Specifically, garnet and kyanite are absent and any plagioclase that is present is often fractured or broken suggesting transport as primary phenocrystic phases in volcanic flows. Thus, upper greenschist facies P/T conditions were never reached. Epidote is an abundant phase, chlorite is common but pyrophyllite and chloritoid are absent. Therefore, lower greenschist facies conditions are problematic. In general, the observed mineral assemblages are a better fit for contact metamorphic facies (see below). This observation is in agreement with Sorensen, et. al, (1998) who suggested pressures at the time of metamorphism below the threshold commonly encountered in regional metamorphism.

To examine possible contact metamorphic facies relationships a series of ACF and AKF diagrams were prepared for the Alabama Hills and Inyo Mountains. Bulk rock chemistry was plotted using the method suggested by Spear (1993). Due to the high CaO content of most samples, AKF diagrams generally resulted in mineral assemblages that were incompatible with thin section observations, so these were not further utilized.

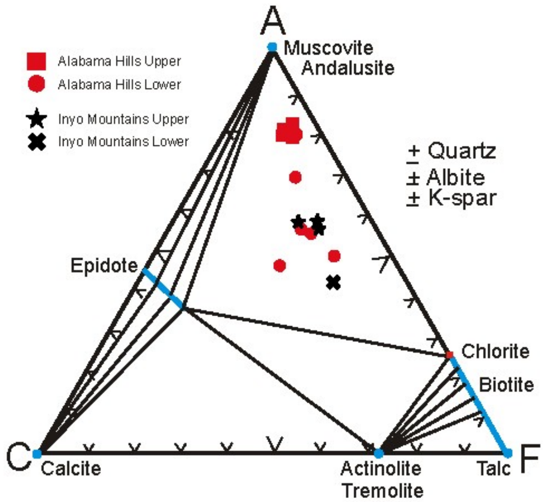

Figure 25. ACF diagram for the albite-epidote hornfels metamorphic facies.

All samples plot within the muscovite-epidote-chlorite triangle on the albite-epidote hornfels facies ACF diagram (Figure 25). This is consistent with thin section observation. Muscovite, in the form of fine-grained sericite, ubiquitous epidote, and chlorite, either as an alteration product of biotite or as a secondary mineral were common. All samples, therefore, appear to have been metamorphosed to the albite-epidote hornfels facies conditions (300-525°C).

When samples are plotted on a hornblende-hornfels facies diagram, (Figure 26), the samples do not fall within a single triangle but rather two triangles. A majority of the samples from both the Alabama Hills and Inyo Mountains fall within the plagioclase-muscovite-cordierite triangle. This creates a discrepancy between the thin section observations and this diagram because no cordierite was found in any of the thin sections and none was found by Richardson (1975). A minority of samples, those from the lower Alabama Hills and Inyo Mountains, lie in the plagioclase-cordierite-anthophyllite triangle. This creates an even greater discrepancy because not only was no cordierite found but no anthophyl-

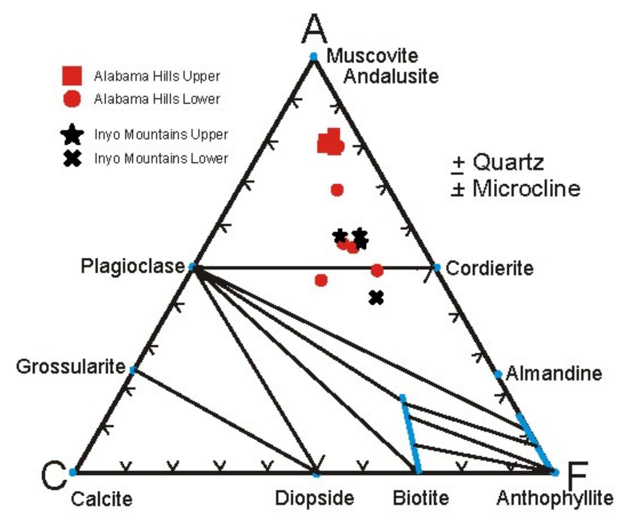

Figure 26. ACF diagram for the hornblende hornfels metamorphic facies.

lite was found in any samples from the Inyo Mountains or Alabama Hills. Thus, none of the thin section samples from this thesis represent the hornblende-hornfels metamorphic facies. Although Richardson (1975) also did not find any cordierite, he postulated that the western margin of the lower Alabama Hills metavolcanic rocks experienced hornblende-hornfels facies conditions. He offered no definitive evidence to support this statement.

Assuming the thin section samples are a representative sampling of the upper and lower intervals of the Alabama Hills and Inyo Mountains, it can be said that the Jurassic rocks experienced contact metamorphism up to the albite-epidote hornfels facies. This finding correlates with Dunne (1998) and Sorensen (1998) who stated that the Inyo Mountains experienced metamorphism up to the albite-epidote hornfels facies. This means that the sedimentary and volcanic rocks were metamorphosed at temperatures between 300˚C and 525˚C and pressures between 0 and 2 kilobars. These parameters are close to those described by Richardson (1975) who proposed the Alabama Hills units experienced metamorphism at temperatures between 400˚C and 640˚C and pressures between 0.5 and 2 kilobars.

Discussion and Conclusions

The relationship between the Jurassic sections in the Alabama Hills and southern Inyo Mountains is of significant geologic importance. The two areas are juxtaposed across the right-slip Eastern California Shear Zone. Various lines of evidence suggest that the ECSZ formed 3-5 million years ago. If so, given rates of motion on the order of 2-4 mm/yr, total offset across the Owens Valley fault should be no greater than 10 kilometers and perhaps significantly less. However, in 2005 Glazner et. al., suggested that total accumulated slip across the Owens Valley was at least 65 kilometer and possibly as much as 125 kilometers. Furthermore, they concluded that much of this slip occurred in the very late Cretaceous or early Cenozoic. This thesis tests that hypothesis by examining the two sections and their offset across the Owens Valley fault system.

Based on this research, several observations can be made. Geochemically, Alabama Hills samples are higher in silica and potassium; the Inyo Mountains are higher in alumina, mafics, and calcium. There are two possible explanations for these disparities. The simplest is that the two sections are lithologically distinct and represent differing source rocks and depositional environments. The second explanation invokes elemental migration during metamorphism. Studies of porphyry copper systems in the American southwest have shown a distinct zonation that forms during contact metasomatism by intrusion of granitic plutons. Characteristically, rocks adjacent to the pluton are flooded by silica and potassium yielding a zone of potassic alteration. Distally, host rocks are characterized by elevated concentrations of Ca, Mg and Fe comprising propylitic alteration. If the metamorphism in the Alabama Hills and Inyo Mountains is related to the intrusion of the 83 Ma Alabama Hills Granite, then the observed geochemical trends could be a function of contact metasomatism and not differences in original depositional environment.

Trace elements are generally better indicators of source and less sensitive to metamorphic overprint and migration. A spider diagram comparing the Alabama Hills and Inyo Mountains suggests differing hosts. Thus, geochemical data is inconclusive. The observed trends can be explained either by initial differences in lithology or metamorphic overprint. The trace element data appears to support the former possibility, as does the higher alumina content of the Inyo Mountains samples. In the case of alumina, a high concentration often is indicative of a crustal sedimentary environment. And contrary to other major elements it is relatively immobile during. In contrast, the major element zonation appears to favor a metasomatic overprint.

Petrographic analysis and outcrop sampling suggests the Alabama Hills samples represent poorly-layered, moderately-metamorphosed volcanic and volcaniclastic rocks. In contrast, Inyo Mountains rocks are predominantly sedimentary with minor interlayered volcanics. These units, while time-correlative do not appear to be stratigraphically equivalent. This leads to the conclusion that these two sections formed in two differing environments. Furthermore, the striking dissimilarities suggest the rocks were deposited in areas that were separated geographically, most likely by tens of kilometers.

Metamorphic facies relationships preclude regional metamorphism. Rather, ACF diagrams indicate all rocks in the Alabama Hills and Inyo Mountains underwent albite-epidote hornfels facies metamorphism. It should be noted that Richardson (1975) felt rocks in the Alabama Hills that were adjacent to the Alabama Hills granite were metamorphosed to hornblende hornfels facies conditions. During this research one thin section from the lower Alabama Hills Jurassic section contained a very fine-grained mineral that may be cordierite, as would be required by ACF diagram for the hornblende hornfels facies. Thus, there is some reason to believe that at least some of the rocks in the Alabama Hills did undergo a slightly higher grade of metamorphism.

Rationalizing the observed metamorphic relationships is difficult. Clearly, it appears as if the rocks from both areas were subjected to similar conditions during metamorphism. Furthermore, if one accepts the possibility of limited hornblende hornfels facies metamorphism in the Alabama Hills there appears to be a concentric pattern relative to the intrusion. This further implies the two areas, although separated geographically at the time of deposition, were already juxtaposed by the time of contact metamorphism. This would require the Alabama Hills section to be moved eastward during the late Jurassic with the upper block of the Inyo (renamed Flagstaff) thrust. Stone (2004) and Stevens (1972) suggest eastward transport on the order of 20-30 kilometers along this thrust, enough to juxtapose two very different lithologic sections.

The challenge of creating a timeline for this area is relating the deposition of the units, the various intrusive events, and the metamorphism temporally with the faulting events. We know that the deposition of the volcanic and sedimentary units occurred roughly 169 Ma (Sorensen, 1998). These are the future metasedimentary and metavolcanic units of the Alabama Hills and Inyo Mountains. The Independence Dike Swarm has been dated at 148 Ma (Glazner, et. al., 2005). The other major intrusive event was the emplacement of the Alabama Hills Granite at 83.5 Ma (Chen and Moore, 1979). The two faults in the area whose ages and relevant offset are in question are the right-lateral Owens Valley Fault and the Flagstaff thrust fault. With regard to the Owens Valley fault, Glazner et al. (2005) believe the right slip in this area and, contemporaneously, the dextral offset of the Owens Valley fault began around 83 Ma and is at least 65 kilometers. Their evidence for this is offset of the Independence Dike swarm, displacement of a Devonian submarine channel, and displacement of the 83 Ma Golden Bear dike. More conventional thinking, including Lee et al. (2001), Monastero et al. (2002), and Stockli et al. (2003) suggests that right slip of the Owens Valley fault, began in the Pliocene and does not exceed twenty kilometers. The second pertinent fault, the Flagstaff thrust fault, formerly the Inyo thrust fault (Stevens and Olsen, 1972), is now thought to be Jurassic (Stone, 2004) in age and to have accommodated 20-30 kilometers of eastward motion. The exact temporal relationships between these faulting events and the other events mentioned earlier are not certain and this discussion is an attempt to determine a possible timeline.

Let's start with the belief that the Owens Valley fault has experienced roughly 65 kilometers of offset since 83 Ma. If this is true, the timeline of major events in the study area is as follows. The Alabama Hills and Inyo Mountains volcanic and volcaniclastic sedimentary units were deposited as a direct result of the volcanic activity within the Jurassic Sierra arc. Geographically, the Alabama Hills units would need to roughly 65 kilometers south of and 30 kilometers east of the Inyo Mountains units to accommodate subsequent movement.

Deposition of the two sections occurs prior to 169 Ma. The Flagstaff thrust fault then moves the Alabama Hills units 30 kilometers east, relative to the Inyo Mountains between about 165 and 150 Ma. The Independence Dikes are intruded at 148 Ma. Next, two separate but equivalent metamorphic events cause contact metamorphism of the Alabama Hills and Inyo Mountains rocks to the albite-epidote metamorphic facies. Then, either before, during or just after, the previously described intrusive event, the Owens Valley fault becomes active and moves the Inyo Mountains south 65 kilometers. Finally, range front normal faulting, began between 10 and 5 Ma creating the graben that is the Owens Valley. The paradox with this theory is the contact metamorphism that occurred within both the Alabama Hills and Inyo Mountains. How likely it is that the Inyo Mountains units could be over 60 kilometers north of the Alabama Hills and still experience the same degree of contact metamorphism? Rocks within the Owens Valley have received widely differing degrees of contact metamorphism from albite–epidote to as high as pyroxene hornfels facies. This theory requires that right-slip has juxtaposed two stratigraphic sections that coincidentally were subjected to the same conditions of metamorphism and whose overprint pattern appears generally concentric relative to the Alabama Hills granite.

In contrast, if offset is roughly 10 kilometers across the Owens Valley fault, as proposed by Frankel (2008) the timeline of major events in the study area must differ from the one described above. The Alabama Hills and Inyo Mountains volcanic and volcaniclastic sedimentary units were deposited as a direct result of the volcanic activity of the Jurassic Sierra arc at about 169 Ma. The Alabama Hills units were about 10 kilometers south of and 30 kilometers east of the Inyo Mountains units. The Flagstaff thrust fault moved the Alabama Hills units 30 kilometers east, relative to the Inyo Mountains between 165 and 150 Ma. Then, the Independence Dikes intruded the Owens Valley at 148 Ma. Next, the Alabama Hills granite was intruded at 83 Ma. This caused contact metamorphism of the Alabama Hills and Inyo Mountains units to the albite-epidote and perhaps, hornblende hornfels facies. Range front normal faulting, began between 10 and 5 Ma, creating the Owens Valley. Finally, the Owens Valley fault became active in the early Pliocene and has subsequently moved the Inyo Mountains roughly 10 kilometers south, relative to the Alabama Hills.

To conclude:

- Alabama Hills and Inyo Mountains rock units are the products of differing depositional environments during the mid-Jurassic;
- mid-late Jurassic thrusting along the Flagstaff thrust juxtaposes the two stratigraphic sections;
- intrusion of Alabama Hills granite in late Cretaceous causes contact metamorphism;
- late Miocene-early Pliocene Basin and Range faulting downdrops Owens Valley;
- Pliocene-Recent dextral shear offsets the two sections a few kilometers across the Owens Valley fault.

Figure 27 is a cartoon style depiction of the events.

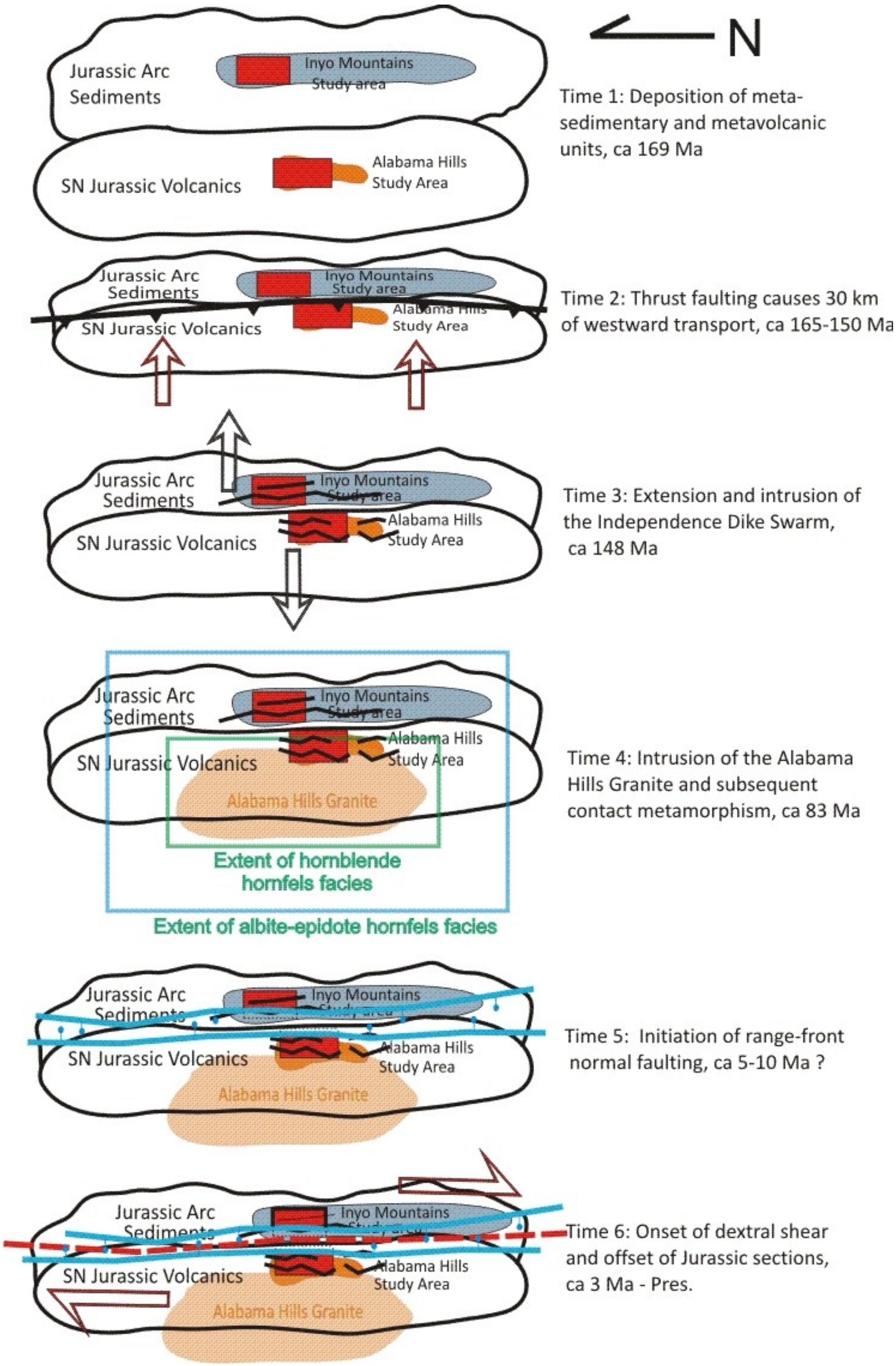

Figure 27. Timeline for the tectonic evolution of the central Owens Valley.

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Appendix A: Sample Locations

Alabama Hills			
SAMPLE	LATITUDE	LONGITUDE	INTERVAL
1	N36 39.39488	W118 7.86024	upper
2	N36 39.46688	W118 7.85363	upper
3	N36 39.54216	W118 7.80224	upper
4	N36 39.65016	W118 7.74236	upper
5	N36 39.67591	W118 7.57615	upper
6	N36 39.67673	W118 7.41717	upper
7	N36 39.60471	W118 7.30853	upper
8	N36 39.66057	W118 7.10275	upper
9	N36 39.67534	W118 6.67610	upper
10	N36 39.84278	W118 6.90796	lower
11	N36 39.81730	W118 7.09597	upper
12	N36 39.90941	W118 7.27316	upper
13	N36 39.88722	W118 7.42096	upper
14	N36 39.53912	W118 7.11511	upper
15	N36 39.48714	W118 7.06110	upper
16	N36 39.32173	W118 7.90316	lower
17	N36 39.23716	W118 7.81554	lower
18	N36 39.22786	W118 7.66996	lower
19	N36 39.16200	W118 7.83199	lower
DJ15	N36 39.73843	W118 7.16809	upper
DJ16	N36 39.77380	W118 7.30157	upper
DJ17	N36 39.77789	W118 7.39125	upper
DJ18	N36 39.70511	W118 7.56092	upper
DJ19	N36 39.68204	W118 7.75677	upper
DJ20	N36 39.48177	W118 7.90800	upper
DJ21	N36 39.31974	W118 8.02567	upper
DJ22	N36 39.06464	W118 7.92084	lower
53	N36 38.81481	W118 7.00244	lower
54	N36 38.74844	W118 6.79972	lower
55	N36 38.69717	W118 6.69920	lower
56	N36 38.62942	W118 6.48363	lower
57	N36 38.53050	W118 6.52423	lower
58	N36 38.43681	W118 6.61979	lower
59	N36 38.27713	W118 6.69949	lower
60	N36 38.71861	W118 6.38982	lower
62	N36 38.79984	W118 6.44458	lower
63	N36 38.88803	W118 6.51616	lower
67	N36 38.99613	W118 5.87253	lower
68	N36 38.90873	W118 5.87394	lower
69	N36 38.85910	W118 5.96360	lower

Alabama Hills			
SAMPLE	LATITUDE	LONGITUDE	INTERVAL
70	N36 38.74751	W118 6.05073	lower
71	N36 38.69353	W118 6.20979	lower
72	N36 38.62992	W118 6.36256	lower
73	N36 38.62888	W118 6.54685	lower
74	N36 38.57880	W118 6.74903	lower
75	N36 38.11877	W118 6.31918	lower
76	N36 38.22142	W118 6.16103	lower
77	N36 38.29582	W118 6.08755	lower
78	N36 38.17435	W118 5.97600	lower
79	N36 38.13469	W118 6.19944	lower
81	N36 38.13469	W118 6.19944	lower

Inyo Mountains			
SAMPLE	LATITUDE	LONGITUDE	INTERVAL
203	N36 42.37487	W118 1.85082	upper
204	N36 42.34875	W118 1.86861	upper
205	N36 42.30120	W118 1.83708	upper
206	N36 42.25281	W118 1.76724	upper
207	N36 42.18776	W118 1.65891	upper
208	N36 42.14734	W118 1.64225	upper
209	N36 42.09245	W118 1.67174	upper
210	N36 41.99117	W118 1.62472	upper
211	N36 41.90566	W118 1.69411	upper
212	N36 41.62628	W118 1.28742	lower and middle
213	N36 41.61912	W118 1.36523	lower and middle
214	N36 41.60891	W118 1.48330	lower and middle
215	N36 41.66737	W118 1.54116	lower and middle
216	N36 41.64304	W118 1.85314	lower and middle
217	N36 41.61889	W118 2.07140	lower and middle
218	N36 41.45336	W118 2.26900	lower and middle
221	N36 41.25786	W118 2.17236	lower and middle
222	N36 41.09711	W118 2.12252	lower and middle
223	N36 40.51895	W118 1.55546	lower and middle
224	N36 40.46090	W118 1.32438	lower and middle
225	N36 40.30065	W118 1.27862	lower and middle

Appendix B: Table of Major Oxides

SAMPLE	Al_2O_3	CaO	FeO	K_2O	MgO	MnO	Na_2O	P_2O_5	SiO_2	TiO_2
1	13.545	1.061	1.921	5.031	0.647	0.056	3.718	0.712	73.584	0.263
2	11.429	0.815	1.209	5.121	0.265	0.036	3.212	0.060	77.629	0.224
3	11.169	1.565	1.678	5.859	0.222	0.073	2.103	0.077	77.079	0.175
4	12.164	0.654	1.215	4.741	0.101	0.024	4.406	0.080	76.394	0.220
5	12.158	0.528	1.339	6.313	0.341	0.069	1.834	0.123	77.139	0.157
6	12.855	0.692	1.676	6.208	0.375	0.088	2.412	0.135	75.360	0.198
7	11.456	0.523	1.591	6.450	0.410	0.073	1.608	0.070	77.648	0.171
8	11.346	1.170	1.420	6.181	0.363	0.077	1.187	0.098	77.999	0.158
9	12.780	1.514	1.249	9.309	0.203	0.055	0.213	0.223	74.169	0.286
10	11.917	2.660	1.919	6.096	0.095	0.092	1.675	0.102	75.251	0.193
11	12.169	1.089	1.557	6.571	0.540	0.061	0.147	0.100	76.562	0.204
12	12.023	0.361	1.859	5.944	0.720	0.080	1.548	0.091	77.165	0.210
13	12.138	0.998	1.505	5.747	0.552	0.085	2.300	0.129	76.345	0.200
14	11.393	1.299	1.009	7.175	0.369	0.051	0.859	0.094	77.562	0.188
15	11.996	1.052	1.412	5.977	0.365	0.064	2.078	0.081	76.802	0.172
16	14.624	1.998	2.496	4.745	0.836	0.167	4.516	0.258	70.036	0.323
17	14.575	1.436	2.389	4.582	0.841	0.058	3.946	0.130	71.749	0.293
18	13.965	1.703	2.085	4.394	0.690	0.084	3.924	0.263	72.616	0.276
19	14.157	2.180	3.071	4.649	1.155	0.074	3.814	0.245	70.314	0.341
DJ15	11.613	1.609	1.850	6.560	0.619	0.046	1.535	0.169	75.788	0.212
DJ16	11.376	0.624	1.459	6.638	0.360	0.068	1.733	0.243	77.312	0.190
DJ17	12.005	0.729	1.506	6.191	0.462	0.048	2.243	0.105	76.520	0.192
DJ18	12.765	0.328	1.284	6.101	0.324	0.024	2.034	0.076	76.896	0.168
DJ19	17.416	0.068	1.720	7.297	0.755	0.092	4.865	0.087	64.881	0.202
DJ21	11.865	6.617	3.323	3.382	1.712	0.227	1.152	0.141	71.290	0.290
DJ21	13.423	1.383	1.367	5.363	0.430	0.041	4.154	0.100	73.550	0.188
DJ22	14.156	1.148	2.509	4.420	0.741	0.059	5.052	0.318	71.243	0.354
53	14.744	7.928	7.010	4.999	1.923	0.192	0.020	0.260	62.209	0.715
54	14.244	2.642	2.483	6.142	1.029	0.092	1.953	0.100	71.028	0.287
55	14.652	1.134	1.919	3.530	0.843	0.085	5.398	0.116	72.038	0.286
56	13.108	3.728	2.491	5.359	0.874	0.249	1.213	0.121	69.632	0.224
57	15.122	1.582	2.717	4.412	0.964	0.070	4.006	0.146	70.654	0.327
58	13.703	1.292	2.403	4.441	0.673	0.073	4.021	0.104	73.029	0.261
59	17.352	1.379	2.051	8.669	0.883	0.095	1.288	0.113	70.936	0.234
60	14.483	1.577	2.685	4.714	0.861	0.087	4.025	0.125	71.137	0.307
62	15.013	0.933	2.145	5.356	0.780	0.067	3.686	0.205	71.534	0.281
63	14.793	1.152	2.202	4.482	0.772	0.054	4.332	0.173	71.771	0.267
67	12.350	4.786	2.149	2.240	2.068	0.103	2.631	0.061	73.411	0.200
68	13.382	3.279	1.360	4.803	0.506	0.097	2.370	0.065	73.919	0.219
69	17.522	2.878	2.079	6.861	1.241	0.060	2.662	0.107	66.217	0.371

SAMPLE	Al[2]O[3]	CaO	FeO	K[2]O	MgO	MnO	Na[2]O	P[2]O[5]	SiO[2]	TiO[2]
70	14.162	0.610	1.176	6.388	0.733	0.008	0.048	0.076	76.551	0.248
71	12.739	0.001	1.366	7.661	0.332	0.007	0.772	0.041	78.458	0.183
72	15.444	1.394	3.420	6.807	2.092	0.055	3.405	0.302	66.341	0.739
73	12.429	0.649	1.765	8.102	1.132	0.097	1.824	0.104	73.689	0.209
75	16.044	13.099	4.811	0.330	3.837	0.395	4.552	0.360	55.902	0.671
74	13.239	1.743	0.820	6.331	0.613	0.009	0.881	0.044	76.180	0.140
76	15.463	4.029	6.086	4.657	2.676	0.176	2.113	0.366	63.769	0.665
77	16.887	4.152	3.907	3.800	1.608	0.097	3.645	0.318	65.007	0.579
78	15.128	4.531	2.270	5.426	1.418	0.126	1.751	0.105	68.971	0.275
79	14.915	3.661	7.382	3.383	4.453	0.163	2.187	0.341	62.725	0.790
81	15.554	4.432	5.484	5.215	2.443	0.158	1.724	0.296	64.129	0.567
203	19.250	0.566	9.524	2.481	8.580	0.042	1.599	0.289	56.553	1.117
204	14.638	11.922	4.270	2.999	3.718	0.140	0.437	0.227	62.058	0.466
205	18.179	7.233	6.102	3.274	1.733	0.168	2.530	0.287	59.726	0.767
206	17.789	10.065	8.794	3.874	4.306	0.232	1.046	0.364	52.823	0.706
207	8.718	18.579	1.863	2.747	0.989	0.117	0.906	0.159	67.381	0.354
208	17.152	10.248	9.727	3.158	3.162	0.242	0.795	0.254	54.134	0.678
209	16.639	6.069	10.118	2.391	6.371	0.197	2.049	0.492	54.749	0.898
210	18.836	8.209	9.588	2.784	4.656	0.212	1.674	0.236	52.875	0.930
211	17.631	3.388	6.142	1.257	4.801	0.150	6.346	0.523	59.312	0.450
212	18.019	4.323	6.714	2.906	5.075	0.176	3.791	0.294	57.904	0.797
213	21.303	3.834	6.039	6.208	1.531	0.113	2.371	0.482	57.587	0.531
214	15.870	10.382	5.933	5.373	5.664	0.528	2.613	0.396	52.719	0.522
215	20.321	5.514	6.692	5.924	2.761	0.195	2.858	0.502	54.636	0.597
216	16.622	0.624	3.902	6.807	1.288	0.042	1.719	0.237	68.207	0.552
217	14.728	1.303	2.768	6.916	0.941	0.201	1.195	0.200	71.385	0.363
218	14.698	4.002	5.705	2.760	1.881	0.123	4.299	0.210	65.871	0.461
221	16.282	3.494	6.710	3.455	2.662	0.164	2.944	0.190	63.555	0.509
222	15.784	3.039	5.921	3.279	2.441	0.138	3.322	0.184	65.430	0.461
223	16.801	3.295	6.128	3.278	2.831	0.160	2.973	0.243	63.719	0.570
224	16.808	4.282	7.766	2.186	3.580	0.181	1.798	0.205	62.433	0.761
225	18.543	6.297	8.348	1.460	4.468	0.152	3.722	0.265	55.882	0.864

Appendix C: Table of Trace Elements

SAMPLE	Ba	Ce	Cr	La	Nd	Rb	Sr	Sc	Y	Zr	Sm
1	575.846	52.081	46.793	1.168	2.180	272.982	518.154	81.865	104.823	304.495	2.819
2	413.420	46.500	78.815	2.879	7.838	255.165	449.551	89.221	106.275	246.135	2.142
3	77.111	38.004	86.045	7.156	10.059	330.555	221.994	86.517	114.541	185.358	3.111
4	529.009	49.972	55.161	0.857	3.117	232.969	266.069	97.875	100.677	262.307	1.976
5	11.572	36.053	45.626	6.651	10.337	457.154	216.775	91.493	134.133	185.938	2.194
6	81.969	38.380	60.740	8.284	7.942	412.614	234.306	90.086	121.042	191.918	2.215
7	61.253	37.336	55.332	4.046	8.428	459.176	206.386	91.925	130.236	184.306	3.309
8	175.190	40.673	50.294	10.811	12.801	379.519	180.414	99.281	116.973	186.503	4.298
9	453.477	49.387	80.096	7.503	6.554	460.498	187.963	86.949	129.932	236.660	4.913
10	174.731	40.264	62.875	0.582	9.816	305.061	173.796	85.110	107.667	182.059	3.736
11	172.165	40.231	63.701	8.906	5.721	399.107	206.939	89.545	119.857	193.563	2.944
12	165.290	39.675	49.440	2.801	8.740	440.345	128.239	84.245	125.583	188.044	2.278
13	125.875	39.621	54.222	6.417	7.630	374.914	271.071	91.601	121.515	210.344	4.434
14	411.129	45.995	82.572	12.095	12.628	410.545	201.003	98.199	121.174	184.243	6.079
15	34.488	36.108	50.180	1.168	7.456	406.582	198.076	87.815	127.357	185.353	2.632
16	904.640	60.911	65.892	2.759	0.479	224.909	627.696	76.997	95.899	343.515	0.997
17	623.878	53.272	66.234	0.779	4.727	259.220	530.696	84.029	102.827	327.017	0.184
18	566.039	51.839	66.433	4.703	2.145	256.945	459.006	85.651	102.689	313.252	0.774
19	870.817	61.287	54.222	5.287	6.324	219.322	524.685	78.728	89.894	353.624	0.445
DJ15	162.449	40.427	78.018	6.068	7.664	402.682	184.151	87.274	116.340	190.008	4.205
DJ16	359.523	45.481	56.044	5.679	11.205	386.622	199.310	92.899	116.905	202.852	2.976
DJ17	277.760	43.388	5.805	6.262	10.615	404.723	229.438	87.166	118.705	199.140	2.257
DJ18	59.878	37.758	73.151	4.279	6.727	406.003	196.735	96.036	129.637	193.757	2.069
DJ19	1512.913	77.666	81.576	2.876	6.519	285.267	565.693	83.163	107.349	241.092	3.038
DJ21	57.220	37.912	46.935	3.851	1.174	167.105	215.418	73.428	81.442	334.200	0.861
DJ21	653.485	52.566	49.551	4.551	8.046	277.837	478.701	80.134	101.284	277.708	3.465
DJ22	964.312	61.997	12.721	4.237	3.200	213.104	342.663	90.303	99.356	367.891	0.545
53	766.871	55.239	45.370	3.618	1.000	197.289	164.555	38.487	55.223	167.555	3.090
54	154.932	41.718	60.513	1.593	0.445	325.270	183.531	80.892	109.161	288.430	1.278
55	606.828	53.038	63.871	6.725	4.658	212.093	434.846	77.430	105.043	369.706	1.003
56	297.742	45.389	59.972	0.037	2.874	355.679	402.064	84.678	110.487	356.380	4.715
57	615.078	53.046	78.360	0.737	0.458	252.554	544.011	73.860	100.820	325.535	0.622
58	538.173	50.673	29.572	0.857	2.124	264.024	408.030	80.459	104.029	311.484	0.684
59	2185.349	95.920	99.622	5.795	2.388	506.541	209.403	81.108	132.417	184.395	4.621
60	750.464	56.789	36.432	0.154	1.568	266.639	588.935	77.755	101.329	336.905	1.101
62	773.838	58.017	64.782	3.109	0.319	297.880	378.677	85.435	107.801	302.286	0.111
63	500.408	49.650	48.216	1.865	0.666	252.813	391.105	76.673	102.459	317.884	0.549
67	1990.658	90.368	33.586	2.257	4.901	100.143	502.174	72.887	82.398	307.480	1.445
68	224.046	43.560	67.657	2.020	2.436	297.140	308.440	85.976	112.332	347.597	3.080
69	473.093	50.849	49.611	7.114	5.109	362.703	252.924	78.295	121.911	461.948	2.424

SAMPLE	Ba	Ce	Cr	La	Nd	Rb	Sr	Sc	Y	Zr	Sm
70	359.156	44.696	94.100	1.557	5.443	349.902	173.370	91.384	127.171	275.501	3.288
71	432.578	47.958	95.466	4.279	0.145	385.250	105.811	93.007	129.386	232.272	2.434
72	781.171	58.840	80.494	6.375	0.597	292.993	463.939	60.663	103.979	331.553	1.611
73	90.860	37.791	22.741	8.906	15.196	451.438	198.419	83.812	131.388	184.304	3.965
75	128.763	31.108	73.891	6.262	8.844	24.720	548.879	40.326	43.217	193.739	3.017
74	187.381	40.143	67.372	5.951	8.671	354.537	143.607	93.656	122.234	239.187	4.027
76	797.303	59.132	6.573	9.953	10.003	218.694	241.332	45.735	72.740	190.214	2.805
77	712.057	56.057	81.035	1.632	5.907	165.873	784.363	61.096	81.276	378.400	0.413
78	181.331	42.332	50.806	2.487	2.228	295.813	399.678	74.401	109.567	390.556	2.226
79	485.559	49.378	23.339	9.292	15.904	153.561	257.925	42.706	64.848	200.750	6.669
81	460.352	48.865	64.469	1.907	4.762	209.824	343.617	52.658	66.030	176.510	0.222
AH avg	487.815	49.320	58.359	4.454	5.818	307.731	326.364	80.410	106.693	261.605	2.476
203	1647.198	83.138	15.600	26.245	41.276	117.607	1721.688	17.222	58.260	345.858	14.115
204	611.320	51.997	17.703	1.437	0.618	158.724	1194.385	38.055	71.671	286.500	1.913
205	470.618	49.729	63.473	14.269	18.437	149.779	892.245	44.653	74.352	309.739	4.929
206	418.920	46.952	63.302	6.687	13.161	166.553	289.302	24.425	63.471	204.037	3.138
207	206.080	38.192	68.938	14.778	22.381	133.203	162.288	53.848	69.208	196.533	10.027
208	459.435	49.003	43.946	12.480	19.236	123.640	370.337	7.982	52.165	179.169	7.439
209	685.842	56.008	19.724	12.286	36.833	76.245	1096.282	11.597	48.503	243.469	10.043
210	472.726	48.952	23.367	12.169	18.333	108.156	481.342	17.114	51.376	137.230	6.617
211	1215.926	70.147	55.560	16.913	36.729	72.626	1778.620	35.999	67.649	328.321	9.731
212	655.410	55.648	48.529	16.835	29.787	147.677	525.496	33.511	70.957	254.998	7.731
213	494.084	51.033	64.014	1.320	8.129	207.073	1333.378	58.500	67.786	274.634	1.586
214	280.327	43.327	84.536	5.364	4.623	152.106	510.348	52.983	62.838	226.051	0.018
215	634.511	53.957	58.577	9.175	12.155	176.861	1551.679	54.605	60.461	295.604	1.711
216	655.776	57.724	64.953	14.658	21.700	349.138	332.379	62.935	119.848	403.204	4.107
217	475.659	50.506	71.727	1.632	4.102	355.073	162.945	75.916	111.817	242.455	0.253
218	523.416	51.183	11.985	11.897	15.244	119.597	739.320	25.831	80.859	400.610	5.367
221	437.711	49.374	25.388	7.853	23.505	145.044	474.943	25.398	79.156	356.321	6.679
222	429.553	49.069	31.280	10.303	20.763	155.324	460.876	33.620	85.148	372.404	7.252
223	666.409	55.849	23.595	12.441	16.841	136.272	609.773	26.480	81.058	391.498	5.992
224	673.284	56.805	11.924	9.681	23.019	84.294	691.913	18.367	57.221	261.749	7.294
225	197.830	41.521	7.403	4.237	18.958	66.271	992.196	4.349	51.446	198.105	8.325
IM avg	586.287	52.863	41.692	10.603	19.325	152.441	779.606	34.447	70.726	281.357	5.917