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GEOLOGIC STUDY OF THE COSO FORMATION

FINAL REPORT
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Final Report on Geologic Study of the Coso Formation

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PROJECT BACKGROUND

There have been great advances in the last 20 years in understanding the volcanic, structural, geophysical, and petrologic development of the Coso Range and Coso geothermal field (Figure 1). These studies have provided a wealth of knowledge concerning the geology of the area, including general structural characteristics and kinematic history. One element missing from this dataset was an understanding of the sedimentology and stratigraphy of well-exposed Cenozoic sedimentary strata - the Coso Formation.

The Coso Formation is loosely defined to include all sedimentary and pyroclastic rocks between pre-Tertiary basement and the voluminous late Pliocene to recent volcanic rocks (Schultz, 1937). Sedimentary facies include lacustrine, fanglomerate, volcanoclastic and, locally, volcanic tuffs. The history of the Coso Formation has received limited treatment in the geologic literature (e.g., Bacon et al., 1982; Grant, 1986; Stinson, 1964; Duffield et al., 1986). The study of the Coso Formation is important for the following reasons: 1) it provides a look at events older than most of the volcanic rocks in the area, and 2) it can give detailed insights into paleogeographic and structural development on the local and regional scale.

At the time this study began, the relation between exposures of Coso Formation in the northern Coso Range and those in the southern part of the range was somewhat uncertain. For example, correlation of rocks exposed in the northern Coso Range adjacent to Owens Lake with those in the western part of the range was problematic. Northern exposures of the Coso Formation were reported as Mio-Pliocene in age (Bacon et al., 1982) whereas the bulk of the formation adjacent to Rose Valley was reported as either middle to late Pliocene (Bacon et al., 1982) or early Pliocene (Grant, 1986) in age. In addition, whether these areas are related sedimentologically or structurally was unclear. We believed that understanding the connection between these exposures

Figure 1. Map of the physiographic provinces of southern California and the location of the Coso Range shown with the letter X.

allowed for significant new insights into the paleogeographic and structural development of the Coso Range and surrounding areas.

Geologic background

Panamint Valley started opening during the late Miocene because of motion on west-dipping normal faults on the western part of the Panamint Mountains. The timing and mechanisms of formation for Rose Valley and Indian Wells Valley were less well known: the information from this study of the stratigraphy and sedimentology of the Coso Formation was proposed to add new data concerning the development of these valleys and to improve our understanding of the timing of these events. These bear directly on understanding the uplift of the Sierra Nevada Range, a topic of current concern.

The Coso Formation owes its present structural configuration to the tectonics of Rose and Owens valleys. Numerous folds and faults had been mapped within the Coso Formation in its various exposures (Stinson, 1977a, 1977b; Duffield and Bacon, 1981). At the start of this study the age of these faults was unknown. Our premise was that some of these faults were syndepositional, controlling stratigraphic patterns, while other faults were wholly post-Coso in age. We proposed a study of these structures to provide greater insight into the relative roles of strike-slip and normal faulting in the development of the Rose-Owens Valley system, and for new knowledge about the late Miocene to present structural development of the area.

The study was initiated in cooperation with CalEnergy Company, Inc., the U.S. Navy Geothermal Program Office and DOE to better understand the geologic development of Basin and Range structure around the Coso geothermal field. An understanding of Coso and Basin and Range structure and kinematics was deemed useful in developing exploration models for the Coso region and Basin and Range.

RESEARCH RESULTS

Summary

A detailed sedimentation and tectonics study of the Coso Formation was undertaken to provide a more complete picture of the development of the Basin and Range province in this area. The Coso Formation is a Mio-Pliocene stratal succession which was deposited in a small

extensional basin from approximately 6 and 3 Ma. Detailed mapping and depositional analysis distinguishes separate northern and southern depocenters, each with its own accommodation and depositional history. The southern depocenter is dominated by lacustrine facies and ash-rich intervals. A number of distinct ash beds also occur and are mapped and correlated throughout the depocenter to define structural features. The northern exposures are dominated by extensive sand flat and eolian strata. Here the volcanic influence is limited to discrete intervals. While strata in both depocenters is disrupted by faults, these faults show modest displacement, and the intensity and magnitude of faulting does not record significant extension. For this reason, the extension between the Sierran and Coso blocks is interpreted as minor in comparison to range bounding faults in adjacent areas of the Basin and Range.

Stratigraphic studies - southern sections

Four locations were selected for detailed facies analysis and described in detail: Haiwee Ridge; north of Haiwee Ridge; Vermillion Canyon; and west of Sugarloaf (Figure 2). The vertical successions at Haiwee Ridge, the section north of Haiwee Ridge, and the section west of Sugarloaf are similar. At Haiwee Ridge, four distinct stratigraphic intervals have been identified: basal conglomerate, arkosic sandstones, interbedded volcanic ashes and lacustrine deposits, overlying conglomerate (Figure 3). These are described in detail below. The outcrop exposure does not reveal a continuous vertical sequence, but a complete section is seen across a 3 km transect. At the eastern extent of exposure, the Coso Formation onlaps basement rock and consists of conglomeratic alluvial fan deposits. This conglomerate consists of granitic, subangular to subrounded clasts, although many clasts are flat or elongate (Figure 4). Clasts are up to 70 cm in length, with an average clast size of 20 cm. This coarser conglomerate alternates with a finer grained conglomerate, where clast size averages 1 cm in diameter. The conglomerates are matrix supported, where the matrix is predominantly very coarse sandstone. The conglomerate is composed of a series of beds 1.5 - 7 m in thickness. Beds are sharp based, with crudely defined graded bedding, and occasional large scale planar cross stratification. Strata are interpreted to represent a series of bars migrating through a braided stream system in an alluvial fan complex.

Figure 2. Geologic map of the Coso Range showing the extent of the Coso Formation outcrops. The dark yellow and tan colors show Coso Formation, the pink colored outcrops are Mesozoic basement, and the light pink are Tertiary volcanics. Haiwee Reservoir is shown in blue. The location of the measured sections are shown as follows: 1 - Haiwee Ridge; 2 - north of Haiwee Ridge; 3 - Vermillion Canyon; 4 - west of Sugarloaf.

10 Kilometers

Taken from California Division
of Mines and Geology
1:250,000 Series

Figure 3. A schematic composite section of the strata in the southern exposures of the Coso Formation, measured near Haiwee Rldge.

Haiwee Ridge Section

Section about 100 m thick

Figure 4a. The basal conglomerate containing subangular to subrounded granitic clasts.

4b. Beds within the basal conglomerate onlapping the Mesozoic basement. Beds average 1.5 - 7 m in thickness.

The conglomerates interfinger with and are replaced laterally by a pebble-rich, arkosic sandstone of fluvial origin. This facies consists of poorly sorted, orange-stained, ferruginous/uranium-bearing pebbly arkosic sandstone-to-sandy pebble conglomerate (maximum clast size of .5 - 1 cm) and contains compound, complex cross sets and planar tabular bedding punctuated by low angle scour surfaces. Upsection, this unit is predominantly an arkosic sandstone, characterized by 5-20 cm thick sandstone beds, occasionally alternating with thin beds of conglomeratic sandstone. Bedding here is crudely developed. Scour surfaces and planar bedding also occur. These sandstones and pebbly sandstones are interpreted to represent fluvial deposits at the distal end of a braid plain. Caliche beds are interbedded with the orange-stained sandstone and may represent lacustrine influence. Proximal to Haiwee Ridge, the arkoses are seen onlapping red-stained granitic protrusions which helps show the original topographic expression of the basin near the uplift (Figure 5).

The arkosic sandstone is overlain by a thick interval of volcanic ashes interbedded with lacustrine deposits (Figure 6). The ashes consist of distinct beds of tuffaceous volcanic ash, ranging from a few meters to 30 m in thickness. The lacustrine beds consist predominantly of reworked volcanic ash and sand. Based on field evaluation, each ash bed within a measured section is mineralogically distinct, but not distinct enough for confident correlation of ash beds between measured sections. Individual ash beds exhibit a great deal of lateral variability. For example, the 30 m ash ranges from a bomb-dominated tuff, to a well bedded volcanic deposit exhibiting inversely graded beds, to a fine grained, bedded unit with well-developed large scale foresets (Figure 7). This lateral variability reflects the different modes of deposition for this ash, ranging from proximal ash fall deposits to more distal surges. The upper most ash shows marked lateral changes in thickness from 12 m to less than 7 m. It is dominated by the presence of bombs, and internal stratification or bedding is absent.

Interbedded with the distinct ash beds are lacustrine units composed of reworked ash. The thickest section of lacustrine deposits shows a marked, vertical zonation (Figure 6). The lower half of the thickest section is a well bedded, somewhat resistant unit, while the upper lacustrine deposits are more of a slope former. The lower lacustrine deposits are composed of well-developed upward-shallowing packages, averaging 4 to 7 m in thickness, interpreted as parasequences (Figure 8). Parasequences are repetitive, hemi-cyclic deposits and display a predictable succession of sedimentary

Figure 5. The original topographic expression of the basin near the uplift is seen by arkosic sandstones of unit 2 onlapping red-stained granitic protrusions.

Figure 6. View looking west from Haiwee Ridge showing unit 3 (volcanic ashes interbedded with lacustrine strata). A 30 meter thick ash is seen near the base of the photo. This ash is overlain by a thick lacustrine suite, which is then overlain by additional ash. The lacustrine suite shows a marked vertical zonation. The lower half is well bedded and is seen as the orange-stained interval immediately above the 30 m ash. The upper half of the lacustrine suite lacks well defined bedding and is more of a slope former. The resistant orange-stained ledge near the top of the outcrop is the uppermost conglomerate of unit 4.

Figure 7. Lateral variability in the 30 m ash, Haiwee Ridge area. This ash ranges from a bomb-dominated tuff (Figure 7a - hammer for scale in lower left of photograph); to a well bedded volcanic deposit exhibiting inversely graded beds (Figure 7b), to a fine grained, bedded unit with well-developed large scale foresets (figure 7c), reflecting the different modes of deposition for this ash, ranging from proximal ash fall deposits to more distal surges.

Figure 8. Distinct parasequences seen in the lacustrine suite. Large forsets are seen in the left half of the third parasequence (counting from the bottom). Geologist for scale, lower right of photograph.

structures. Seven parasequences are recognized at Haiwee Ridge. Each parasequence consists either of basinward inclined foresets of small, prograding deltas, or thin beds of wave-rippled volcanic sands and reworked ash (Figure 9). Each parasequence is capped by a bioturbated bed, overlain by a clean, coarser-grained, well-cemented sandstone. Laterally, these parasequences can show significant soft sediment deformation characterized by chaotically arranged elongate "clasts" of brecciated volcanic sands greater than 0.5 m in length (Figure 10). Each well-developed parasequence is terminated by a rapid flooding event, indicating a sudden deepening event in the basin. These sudden deepening events could represent cyclic climatic change, but we think they more likely represent episodic faulting within the basin. In foreland basins, parasequence architecture has been suggested to record the history of thrust sheet movement in the corresponding fold and thrust belt. In the Coso Formation, parasequence development is postulated to reflect the fault history associated with the opening of the Indian Wells/Rose Valley. The 4 to 7 m thickness of each of the parasequences is consistent with possible magnitudes of throws on faults bounding and within the basin. The presence of significant soft-sediment deformation supports the interpretation of a tectonic driving force for the development of the parasequences.

Upsection in the lacustrine suite, parasequences are not well developed, but the lacustrine section still consists of thin bedded, wave-rippled volcanic sands and reworked ash (Figure 11). This interval is over 30 meters thick and represents nearly continuous deposition in a shallow lake environment. The absence of parasequences in this upper interval is significant with respect to basin evolution and the development of accommodation space available for lacustrine deposition. We interpret subsidence events associated with the upper lacustrine interval to reflect a more gradual subsidence history, as opposed to the more rapid and episodic events which produced the well developed parasequences in the lower lacustrine interval. We interpret this change in subsidence history to reflect a change in faulting style within the basin.

The ash/lacustrine suite is overlain by an interval of interbedded conglomerate and sandstone. The conglomerate contains both reworked clasts of basement rocks and reworked volcanics and contains numerous scour surfaces and planar bedding. The sandstone is texturally and compositionally more mature than the underlying volcanic sands. It also contains numerous scour surfaces and large scale planar tabular cross bedding and trough cross bedding. This interval is interpreted as a fluvial in origin. The reintroduction of

Figure 9. Wave ripples within the lacustrine deposits.

Figure 10. Chaotically arranged elongate "clasts" of brecciated volcanic sands, some greater than 0.5 m in length, as seen within the parasequences in the lower half of the lacustrine succession.

Figure 11. Lacustrine deposits in the upper half of the lacustrine suite.
These deposits contain abundant beds of wave rippled structures, but do not consist of well-developed parasequences.

basement clasts in this fluvial unit indicates renewed uplift and displacement of the lacustrine environment by a high-energy fluvial system following fill of the depositional basin. The remainder of this section, due to structural dip, is buried beneath Haiwee reservoir and Highway 395.

Stratigraphic studies - northern sections

The Sugarloaf section, at the northern end of the Coso Range, shows a different vertical succession than the southern Coso exposures (Figure 12). The main difference is the absence of thick lacustrine deposits which dominate much of the sections to the south, and the presence of a thick sheet sand/sand flat interval. This section also begins with a conglomerate/sandstone interval, however, unlike the conglomerate to the south, this unit contains a significant amount of reworked volcanic ash. Individual beds of conglomerate are thin (averaging less than 0.5 m) and interbedded with thicker beds of sandstone. Sharp-based beds, crudely defined graded bedding and occasional large scale planar cross stratification occur, along with thick intervals of structureless (volcanic) sandstone. The presence of localized scouring and graded bedding is interpreted to indicate deposition by fluvial systems. The conglomerate/sandstone interval is abruptly overlain by an eolian sandstone containing cross beds which average 2 m in thickness. This eolian unit is overlain by a thick succession (~ 180 m) of sand sheet/sand flat deposits consisting of horizontally laminated sandstone and low angle, inclined foresets. These are interpreted to represent a transitional facies between dune, interdune and non-eolian deposits. Small cut and fill structures and low angle inclined foresets suggest this interval was subjected to both fluvial transport and wind reworking. Proximal to the basement uplift, small growth faults occur in this interval, with syndepositional displacement averaging 2 m. The sand sheet/sand flat deposits are overlain by an ash-rich horizon. Much of the ash-rich bedding shows evidence of water reworking, preserved either as fluvial or lacustrine (?) deposits. In places, the ash appears clean (i.e., not reworked). This interval is overlain by a thin coarse grained deposit of fluvial origin, indicating renewed uplift.

Figure 12. Schematic of vertical section through the northern depocenter.

Sugarloaf Section

Geologic Mapping and Structural Studies

In the southern outcrops of the Coso Formation, five mappable units are identified based on the stratigraphic studies, and are listed from oldest to youngest: (1) basal conglomerate, (2) arkosic sandstone, (3) volcanic ash/lacustrine suite, (4) upper ash, (5) upper sandstone/conglomerate (Figure 13). In the northern outcrops, three mappable units are identified: (1) basal conglomerate, (2) eolian and sand flat/sand sheet sandstones, and (3) upper ash-bearing interval. Previous geologic maps (i.e. Stinson, 1977a, 1977b; Duffield and Bacon, 1981) which include the Coso Formation are not based on an established stratigraphic framework of mappable units, but rather map lithofacies which are not defined or placed in stratigraphic hierarchy. These previous attempts often map the same stratigraphic unit as multiple units, and sometimes combined different aged stratigraphic units as the same mappable unit. Outcrops of the Coso Formation have been mapped using the mappable units listed above. This mapping shows that the stratigraphic framework established can be carried regionally across this area. Detailed mapping of the Coso Formation outcrops distinguishes separate northern and southern depocenters. These depocenters are separated by a large, east-west trending monocline with a gently-dipping limb angle.

Structural features

Mapped structural features include a series of north-south trending faults with normal separation (Figure 14). Offset along these faults is limited to 30 meters, with many of the smaller faults displaying offsets of only 5 meters or less (Figure 15). These smaller faults, however, are often within a fault series, which collectively show offsets of around 20-30 meters. Although sparsely distributed, grooves and ornamentation on fault surfaces are consistent with down-dip movement. A number of east-west trending, broad open folds were identified and mapped (Figure 16).

One large fault zone has been identified that runs from east of Haiwee Ridge through the Vermillion Canyon area. This fault zone is generally high-angle, and is has dominantly down-to-the-east separation in its southern portion. In addition, it appears to have served as a conduit for some of the later volcanic flows – the fault zone hosts dikes that feed some of the mid-Pliocene basalts. About 3 km south of Vermillion Canyon, however, the fault takes on a more complex character. It hosts a large anticline/syncline pair that has amplitude of at least 500 m. The fault zone itself widens and contains several

Figure 13. View looking west from Haiwee Ridge, showing 4 of the 5 mappable units. Photograph was taken while standing on unit 1 (basal conglomerate). Unit 2 is the yellow stained sandstone interval in the foreground. Unit 3 is the interval consisting of the white colored ash in center of the photograph, and the overlying orange stained (lacustrine) strata within the distant cliff. Unit 4 is the thin white-colored near the top of the cliff, above the orange-stained strata. Unit 5 is the resistant, orange stained ledge-former, seen to the left of the photograph near the top of the succession.

Figure 14. Structural map near the area north of Haiwee Ridge, showing typical style of faulting in the area. Faults have modest separation.

Map of North Haiwee Area

Figure 15. Small fault in area north of Haiwee Ridge showing modest separation.

Figure 16. View looking west/southwest from Vermillion Canyon area, showing a number of broad, open folds within the lacustrine interval.

large panels of breccia and gouge developed in vertically dipping strata. We interpret these features as part of a negative flower structure along a strike-slip fault. Unfortunately, slip on the fault zone is uncertain, but is probably at least 1 km or larger in a right-lateral sense based on regional considerations and the width of the zone.

Overall, the Coso Formation is cut by few faults or folds. Faults are either of strike-slip or normal character, and folds are mostly related to the faults. The amount of extension during and after deposition of the Coso Formation appears to be relatively minor. This indicates to us that the unit was deposited in a simple half graben developed off of the Sierran front. Uplift along the east-dipping Sierran frontal fault, therefore, began about about 6 Ma (the approximate age of the oldest part of the Coso Formation). This is consistent with initiation of extension in the Nova Basin to the east (Coleman and Walker, 1990; Hodges et al., 1989).

Approximately 13 relict springs were mapped in the area north of Haiwee Ridge. The relict springs occur along north-south trending faults, either as isolated units, or in a linear arrangement of three or more small spring deposits. Individual relict springs range from a few meters to more than 5 meters in diameter (Figure 17). The exact nature of fluids emanating from these springs is uncertain, but may represent relatively hot ground water fluxing into the fluvio-lacustrine setting of the Coso Formation. The springs are significant because they suggest geothermal activity may have been present in the latest Miocene to earliest Pliocene time in the Coso Range.

With one exception, the relict springs are mineralized surficial features which are characterized by a mound-shape geometry. Because they are surficial features, their age cannot be determined based on stratigraphic relationships. One spring, however, occurs within the stratigraphic section thus constraining the time of its formation as coeval with deposition of the arkosic sandstone interval (Figure 18). Lateral to the base of this spring are well preserved rhizoliths. This relict spring is not mineralized, but is immediately overlain by an interval characterized by extensive silicification.

AGE OF THE COSO FORMATION

The age of the Coso Formation previously has presented problems in correlation of the unit. Bacon et al. (1982) reported an age of 3.1 Ma for pyroclastic rocks interbedded with the Coso Formation at Haiwee

Figure 17. Relict spring deposit showing mound-like geometry, Cactus Flat road area.

Figure 18. Relict spring occurring within the arkosic sandstone interval (unit 2).

Ridge. The bulk of the Formation in the Sugar Loaf area, on the other hand, was well dated at somewhat older than 6 Ma to as young as 5.5 Ma (Bacon et al., 1982).

Our work modifies this chronology somewhat. At the Vermilion Canyon section, we obtained an age of 5.94 ± 0.03 Ma (Ar/Ar biotite) for a tuff near the top of the lacustrine section. This is consistent with the results of Bacon et al. (1982). Results for the Haiwee section were less successful. We were unable to repeat the results of Bacon et al. (1982) for their unit interbedded with the Coso Formation. Despite ten attempts at getting an age on this unit (including biotite, pumice, and whole rock separates), we did not get a reliable age: Our ages varied from 1.7 to 6 Ma. Bacon et al. (1982) got two different ages as well (based on biotite and sanadine). Hence we do not consider the Bacon et al. age on this sample to be reliable. We did, however, get an age of 4.05 ± 0.06 Ma on a tuff at the top of the lacustrine section in the Haiwee Ridge location. This is consistent with the age of overlying units.

Hence, the inconsistency of ages between northern and southern sections does not seem to present a problem - this difference is probably not real. For this reason we consider the bulk of the exposed Coso Formation to be latest Miocene (~6.0 Ma) to middle Pliocene (~4.0 Ma) in age.

PALEOGEOGRAPHIC RECONSTRUCTION/IMPLICATIONS

Based on the structural and sedimentologic analysis, the following paleogeographic reconstruction is proposed for the southern depocenter (Figure 19). Following uplift of the Coso Range, erosion of the Mesozoic basement resulted in deposition of coarse conglomerates proximal to the uplift, and deposition of braided stream deposits further west into the basin. This was followed by a period of intense volcanic activity and deposition of a number of discrete ash beds. Many of these ash beds were reworked into lacustrine deposits. Deposition of lacustrine strata corresponds to a period of active basin subsidence which is coincident with volcanic activity. Initially, basin subsidence was episodic, as interpreted through the deposition of well-developed parasequences. This period of active, episodic subsidence was followed by a period of slower, more gradual subsidence. This change in subsidence history could reflect a change in the location of faulting either away from this depocenter, or possibly away from a sill which controlled fresh water input into the basin. Following basin fill by lacustrine and ash deposits, renewed

Figure 19. Paleogeography of the southern depocenter. Time 1 - erosion of the Mesozoic basement and deposition of coarse conglomerate proximal to the uplift, and deposition of braided stream deposits further west into the basin. Time 2 - volcanic activity and deposition of discrete ash beds. Many ash beds were later reworked into lacustrine deposits. Time 3 - deposition of lacustrine strata corresponding to a period of active basin subsidence, coincident with volcanic activity. Time 4 - renewed uplift occurred in the source area following basin fill by lacustrine and ash deposits. Deposition of conglomerate and sandstone from braided streams.

Paleogeography of Southern Coso Formation Sections

Haiwee Ridge

Conglomerate
(alluvial fans)

Braided streams
(arkosic unit)

Time 1

Haiwee Ridge

Volcanic input

Time 2

Paleogeography of Southern Coso Formation Sections

Lacustrine
environments

Time 3

Renewed uplift

Arkosic
deposits

Braided
stream system

Time 4

uplift occurred in the source area resulting in deposition from braided streams across the basin and deposition of the overlying conglomerate interval.

In the northern depocenter, deposition of a coarse conglomerate also occurred following uplift of the Mesozoic basement (Figure 20). The interfingering of this conglomerate with thick beds of sandstone suggests the presence of areally restricted alluvial fans which quickly passed down dip into a braided stream complex. Following deposition of the braided stream/alluvial fan facies, a migrating dune field produced large-scale cross bedded sandstones. The eolian deposits indicate an arid climatic setting, and are overlain by a thick succession of sand flat deposits. These are interbedded locally with thin eolian deposits. The thickness of these deposits, with minimal facies variation is interpreted to indicate deposition in a gradually subsiding basin. The sand flat succession was followed by a period of volcanic activity, seen by the presence of a water-reworked ash. The water reworked ash is the first depositional indicator of lacustrine influence in this depocenter. The lack of thick lacustrine deposits, so voluminous in the southern depocenter is interpreted to support the existence of a structural divide between the two depocenters. Both depocenters underwent significant subsidence, as interpreted by the thick stratal succession seen in both basins.

Figure 20. Paleogeography of the northern depocenter. Time 1 - erosion of Mesozoic basement and deposition from alluvial fans and braided streams. Time 2 - infill of gradually subsiding basin from migrating dune fields and vertically accreting sand flat facies. Time 3 - volcanic activity and introduction of volcanic ash into the basin, which is later water-reworked.

Paleogeography of Northern Coso Formation Sections

Braided system/
alluvial fans

Time 1

Dune fields/
sandsheets

Arid setting

Time 2

Time 3

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