Superposed deformed beds produced by single earthquakes (Tecopa Basin, California): Insights into paleoseismology

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Abstract

Well-exposed soft-sediment deformation (SSD) structures occur in Tecopa paleolake beds largely composed of ash from the Bishop (760 kyr) and the Lava Creek (640 kyr) ultraplinian eruptions. In both cases the SSD structures affected volcaniclastic deposits concentrated by overland flow from the surrounding topography into the lower slope and lake environments. Re-sedimentation of ash produced alternations of volcaniclastic layers with different grain sizes and ash content that allowed for reverse density gradients, which favoured liquefaction and deformation. In the Tecopa Basin, extensive outcrops show these deformed strata continuing laterally for hundreds of metres, along with three-dimensional exposures. This study illustrates the 3-D complexity of soft-sediment deformation including some novel morphologic features. Of particular interest were examples of superposed deformed beds that laterally change into one single deformed horizon. Heterogeneities in ash concentration, grain-size, and water content produced contrasting permeabilities that were barriers to liquefaction and soft-sediment deformation. The probable causes for liquefaction were Middle Pleistocene paleo-earthquakes. There are several active faults in the region with enough seismic potential to produce moderate to large earthquakes. The fact that a single deformed deposit laterally merges into multiple superposed deformed beds indicates that multilayer liquefaction could be produced by a single shaking event. In these cases, SSD layers are insufficient and unreliable indicators of paleo-seismic recurrence intervals.

1. Introduction

The particular geological history of the Tecopa basin, located in the Amargosa Desert in SE California (Fig. 1), has favoured the presence of well-exposed load-type soft-sediment deformation structures. The Tecopa lake beds show >70 m of outcropping deposits that record the geological history of the region between ~2 Ma and ~0.2 Ma (Hillhouse, 1987; Morrison, 1999). This enclosed basin acted as a trap for Plio-Pleistocene ash eruptions in the Western United States. Many of these ash-rich deposits show soft-sediment deformation (SSD) structures, and can be used as key marker beds for correlation around the Tecopa Basin.

Soft-sediment deformation structures in lacustrine deposits have been widely described in the geological record (Sims, 1973; Hempton and Dewey, 1983; Alfaro et al., 1997; Rodríguez-Pascua et al., 2000; Moretti and Sabato, 2007; among others). Deformation structures generated during liquefaction by shaking from earthquakes are referred to as seismites (Seilacher, 1969). Lacustrine sedimentary environments have been noted as excellent recorders of earthquake events, owing to the presence of water-saturated sediment with high susceptibility to liquefaction (Sims, 1973, 1975).

Here we report a study on soft-sediment deformation structures that occur in the ash-rich Pleistocene deposits associated with the Bishop and the Lava Creek eruptions. These two tuffs outcrop extensively in the Tecopa Basin. The kilometric continuity and three-dimensional exposures of these deformed beds permit detailed observations of novel morphologic features developed during liquefaction. The most interesting observation is the presence of complex deformation where superposed deformed beds laterally evolve into one single deformed horizon. We discuss the seismic origin of these SSD features and if these superposed deformed beds are the result of single or successive events.

2. Geological setting

The Tecopa Basin is located in the Basin and Range physiographic province, 50 km SE of Death Valley, in what is now the Amargosa River valley. The basin is approximately 500 km², limited by the Dublin and Ibex Hills in the west, the Resting Springs and Nopah Ranges to the east and the Sperry Hills to the south. These surrounding mountains
basement in Fig. 2) are composed of Precambrian gneisses and metasediments, Early Paleozoic marine rocks and mid-Cenozoic volcanics. During the Late Pliocene and much of the Pleistocene, the Tecopa Basin was the site of an ephemeral shallow lake system. Toward the end of the Middle Pleistocene (~0.2 Ma) the Amargosa River breached the southern margin of the Basin and integrated with Death Valley (Morrison, 1999), thus initiating arroyo cutting that exposed >70 m of Pleistocene sedimentary deposits. Beds are sub-horizontal with a general dip of ~1° basinward. This geometry has been interpreted as the result of differential compaction on a slight depositional dip (Sheppard and Gudde, 1968; Hillhouse, 1987).

Numerous rhyolitic vitric ash layers are intercalated within the Tecopa beds. Two of them are chemically correlated with ultra-plinian eruptions from the western US: the Bishop (760 kyr) and Lava Creek (640 kyr) Tuffs (Izett et al., 1970; Izett, 1981). Detailed paleomagnetic studies have been carried out immediately below the Bishop Tuff, showing the Matuyama to Brunhes polarity change (Hillhouse and Cox, 1976; Hillhouse, 1987; Valet et al., 1988; Larson and Patterson, 1993). Both the Bishop and Lava Creek tuffs are key lithologic marker beds that can be identified at many outcrops along the basin.

Infilling of the Tecopa Basin was dominated by mud and silt in the central part and sand to clay around the margins, along with isolated carbonate beds and paleosols (Hillhouse, 1987). Paleoflow directions and fluvial facies distribution show an axial fluvial system coming from the north (ancient Amargosa river). Transverse channels drain into the basin through the Chicago (east) and Greenwater (west) Valleys. Around the margins of the basin occasional reports of ostracods, diatoms, vertebrate fauna, and footprints have been made, along with the more common paleosols, and wave and current ripples (Hillhouse, 1987). The central facies shows mudstones with calcite-filled casts of gaylussite (Larson, 2008), a salt found in alkaline and saline lakes from California, usually associated with halite and trona. Sheppard and Gudde (1968) described the occurrence of thin beds of finely crystalline dolomite, which could be related to periods of higher lake level in an alternating wet/dry environment. Morrison (1999) reported halite in some mudstones below the Bishop Tuff and Starkey and Blackmon (1979) reported sepiolite as the dominant authigenic clay-type mineral in the basin. Sepiolite is found mainly near ash beds, probably being precipitated when silica became abundant, through dissolution of volcanic ash in the Mg-bearing lake waters. Sepiolite occurs in modern desert lakes with high salinity (Hardie, 1968; Parry and Reeves, 1968).

Diagenetic processes affected the ash beds as well as most fine-grained sediments over large parts of the central Basin. Sheppard and Gudde (1968) describe three concentric zones with increasing alteration toward the center of the Basin: the fresh-glass, zeolite, and K-feldspar diagenetic facies. This diagenesis reflects chemically zoned pore waters, which were fresher near the margins and increasingly alkaline and saline basinward. According to Sheppard and Gudde (1968), this zonation was probably inherited from a depositional environment where the groundwater of paleo-Lake Tecopa was moderately-to-highly saline with a pH  9, except around the margins. All SSD structures developed before early diagenetic cement and lithification of the sediments. Deformation structures are ubiquitous in
the central K-feldspar facies, common in ash-rich beds of the zeolite facies, and only locally seen in some ash beds of the fresh-glass facies.

We interpret the paleogeography of the Tecopa Basin as an ephemeral saline lake surrounded by local freshwater ponds near springs and fluvial inlets. Paleo-Lake Tecopa probably experienced large fluctuations in water level, chemical composition, and salinity reflecting the climate-driven hydrologic budget (see other examples in Rosen, 1994). During dry periods, paleosols would develop in marginal areas while sediments accumulated in a central playa by groundwater-fed discharge or occasional floods. During wet periods, a shallow lake would be temporarily established (Fig. 3). For example, the present interglacial climate does not allow the occurrence of a persistent lake in Tecopa owing to evaporation greatly exceeding precipitation (Hillhouse, 1987).

3. Stratigraphy of the deformed beds

Eight stratigraphic sections have been studied, five on the west side (Greenwater Valley), two on the north (near Shoshone) and one more central (Amargosa River) (Figs. 2, 4 and 5). Sections near Shoshone and in Greenwater Valley include the Bishop Tuff and some of them also the Lava Creek Tuff, which are distinctive beds with SSD structures. The central deposits represented by section 7 (Amargosa river) are correlated with section 1 in Greenwater Valley using a basal biotite-rich tuff (Tuff C of Hillhouse, 1987) (Fig. 4). The composite section from both the Amargosa and Greenwater areas indicates the existence of several other tuffs and deformed beds.

The sections in the Greenwater area are dominated by fine-grained deposits, largely mudstones and siltstones, unconformably covered by post-Lake Tecopa alluvial gravels. These sections are included within the zeolite diagenetic facies (Sheppard and Gudde, 1968), showing strong SiO₂ cementation, nodules and phillipsite neoformation. The correlation between sections uses the Bishop Tuff as a stratigraphic marker (Fig. 4). Among the different SSD structures that have been identified, the most spectacular examples occur in the volcaniclastic deposits of the Bishop and Lava Creek Tuffs, which were selected for this study. Average sediment accumulation rates of ~10 cm/kyr can be calculated for section 3 using the 11.6 m separating the Bishop Tuff (760 kyr sensu Sarna-Wojcicki et al., 2000) and Lava Creek Tuff (640 kyr sensu Lanphere et al., 2002) (Fig. 4).

The two sections near Shoshone (8 and 9) are in the fresh-glass diagenetic facies (Figs. 2 and 5). In section 8, deposits below the pumiceite
quarry consist mainly of alluvial sandstones covered by palustrine carbonates that include gastropods and paleosol development and volcaniclastic deposits related to the Bishop Tuff. The Lava Creek Tuff in this area is a 2.5 m thick deposit, apparently concentrated by re-deposition and overland flow from the surrounding uplands. Wave ripples are common, indicating shallow water in a pond environment. SSD processes variably affect these multiple beds of ash. In this quarry, Lava Creek Tuff is covered by coarser-grained alluvial deposits.

In section 9, the Bishop Tuff was affected by deformation and SiO2 replacement during diagenesis. A fine-grained detrital succession, representing distal fluvial deposits, lay below this ash. Immediately on top of the Bishop Tuff are palustrine carbonates. An average sediment accumulation rate of ~7 cm/kyr has been calculated for deposits lying between the Bishop and Lava Creek Tuff. Here the Lava Creek Tuff occurs within fine-grained fluvial deposits (Fig. 4).

4. Study of soft-sediment deformation outcrops of the Tecopa Basin

Deformed beds are common across large parts of the Tecopa Basin. We chose to study the soft-sediment deformation structures in two prominent ash beds, the Bishop and Lava Creek tuffs. These two deformed key beds, characterized by inter-layered sandy and silty sediments, have a regional kilometric extension. Two high-quality outcrops were selected: along an arroyo in the Greenwater Valley; and in an abandoned quarry near Shoshone (Figs. 2, 4 and 5).

4.1. Soft-sediment deformation structures in Bishop Tuff (Greenwater Valley)

Well-exposed deformed beds <2 m thick are composed of two lithological units. The overlying unit consists of silt and fine sand, rich in volcanic shards; the underlying unit is made of fine-grained ash and mud. This deformed horizon is continuous and extends laterally for hundreds of metres (Fig. 6), allowing the observation of structures in both cross-section and plan view (Fig. 7).

The deformed beds can morphologically be described as pillows and sagging load structures (sensu Anketell et al., 1970; Alfaro et al., 1997). In vertical section, these load-type structures show curved and concentric laminae, which are slightly curved or planar at the base and highly dipping or vertical along the edges (Fig. 8). The thickness of these load-type structures varies between 0.5 and 1.5 m. Narrow fluidization channels, <1 m wide, separate individual load-type structures. In plan view they show an elliptical shape with the major axis ranging from 0.7 m to 3 m. The direction of the major axis has been measured in several outcrops separated by hundreds of metres and shows no preferred orientation (Fig. 7; see Alfaro et al., 2010). A revealing morphological feature of this deformed bed is the presence of local lateral changes, from simple large load-type structures, into more complex structures involving two deformed beds with smaller load structures separated by less deformed (or undeformed) thin layers (Fig. 9). The transition to more complex deformation occurs within a few metres, and appears related to local facies changes. The simple reverse density gradient systems change to multilayered systems characterized by an alternation of sands with thin layers of fine-grained ash and mud. Some of these thin layers separate two deformed horizons or act as detachment layers generating unconformable surfaces (Figs. 8 and 9).

In the Greenwater the size of SSD structures in the Bishop Tuff decreases north-eastward (towards the margin) (Fig. 4). The deformation appears again farther north near Shoshone. These changes appear to correlate with areas less susceptible to liquefaction, probably without groundwater saturation or less appropriate density gradients, although an early diagenetic cementation could also be responsible.

4.2. Soft-sediment deformation structures in Lava Creek Tuff (Shoshone Quarry)

Excellent outcrops of deformed Lava Creek Tuff are located in the pumicite quarry near Shoshone. For 100 m along the quarry walls, several load-type and fluid-escape structures are exposed. Morphologically they are mainly sagging load structures, drop structures and pillows (sensu Owen, 2003) varying from centimetres to several tens of centimetres in size (Figs. 10, 11, 12 and 13).

The soft-sediment deformation that involves the Lava Creek Tuff is characterized by a main horizon ~1 m thick composed of sandy sediments with several intercalations of thin laminae of silt. Locally, this horizon shows complex internal deformation involving different deformed sandy layers separated by undeformed silty laminae (Fig. 13). Therefore, the main deformed horizon has a variable number of superposed beds involved in deformation. The most relevant feature is that these superposed deformed layers merge laterally into a single deformed layer as the smaller load structures pass into a single bigger load structure (Figs. 11 and 13). In the larger load structures, the silty laminae are cut by large fluid-escape structures, which extend from the bottom to the top of the deformed unit. The maximum thickness of the fluid-escape structures is ~1 m, through the total thickness of the Lava Creek Tuff (Figs. 11 and 13).

In one of the studied outcrops (Fig. 11) an apparently undeformed internal layer from the main horizon laterally evolves into an intensely deformed unit. Probably, local sedimentary conditions (degree of water saturation, depositional packing, etc.) were responsible for these local variations in style and magnitude of deformation.

5. Discussion of soft-sediment deformation

5.1. Trigger mechanisms

Various natural processes can trigger soft-sediment deformation in lakes, such as: overloading (Allen, 1982; Owen, 1987), wave-induced cyclical and/or impulsive stresses (Molina et al., 1998; Alfaro et al., 1997). In section 9, the Bishop Tuff was affected by deformation and SiO2 replacement during diagenesis.
Fig. 4. Greenwater stratigraphic sections showing the location of Bishop and Lava Creek ash beds. The figure shows 9 superposed SSD beds which can be correlated locally. S7 and S9 occur immediately above the Bishop and Lava Creek tuffs in deposits originated after ash in the surrounding area was redeposited in the basin. This figure shows also a correlation with deposits outcropping in the Basin in the central facies near the Amargosa River. Both sections occur in different diagenetic zones (Sheppard and Gudde, 1968). Each section shows the UTM coordinates.
sudden changes in groundwater level (Owen, 1987), and earthquakes (Seilacher, 1969; Obermeier, 1996).

After a facies analysis we can discount overloading since overlying units do not appear related to rapid sedimentation, being typically composed of thin laminae from several millimetres to tens of centimetres in thickness. We also discount the effect of water waves, given the low wave-energy conditions of the Tecopa paleolake with its small areal extent. Finally, these soft-sediment deformation structures are morphologically very different from those produced by groundwater movements (Obermeier, 1996).
We interpret the soft-sediment deformation structures described in the Bishop and Lava Creek Tuffs (Tecopa Basin) as seismites (sensu Seilacher, 1969). A seismic origin is also favoured because: (1) deformation structures continue laterally for hundreds of metres, occurring in the central and marginal facies and being overlain and underlain by planar units not involved in soft-sediment-deformation, and (2) the study area is in a region subjected to moderate to large earthquake shaking events.

The Tecopa region was tectonically active during the Plio-Pleistocene. Nearby faults are responsible for historical earthquakes in the vicinity (Jennings, 1994). In the Tecopa Basin, several local faults have potentially generated earthquakes during Pleistocene. Additionally, other large faults in Death Valley and Panamint Valley, as well as the Garlock Fault zone (Jennings 1994), could be important. Most of these faults are large and have the seismic potential to generate earthquakes with magnitudes >7.0. These high-magnitude earthquakes could produce liquefaction at distances from the epicentre of between 100 and 200 km, as can be deduced from empirical relationship between magnitude and maximum epicentre distance for liquefaction sites proposed by Ambraseys (1988).

5.2. Significance of superposed deformed beds

A common morphological feature of both the Bishop and Lava Creek Tuff-rich deposits is that the main deformed beds are divided, at least locally, into several superposed deformed layers separated by thin laminae of fine-grained sediment. These minor deformed units, with smaller load-type structures, can be seen to merge laterally into a single deformed bed, apparently where more favourable conditions existed for the formation of large load-type and fluid-escape structures.

The following field observations indicate that a single shaking event or closely spaced shaking events caused liquefaction that produced superposed deformed structures.

- Large fluid-escape structures usually cut through the entire thickness of the deformed bed. Fluidized sediment flowed from the
lower layers, past the overlying beds, until reaching and flowing onto the surface existing at that time. These large fluid-escape structures were formed after the uppermost involved layer was initially deposited. Deformation is also constrained to have terminated just after the accumulation of the horizontal layer of sediment transported by fluidization, and the next bed being deposited on top of the deformation package.

• Thin superposed layers showing deformation are separated by undeformed laminae of silty sediment in some areas. However, laterally these same laminae were cut by fluid-escape structures. Silty laminae that separate ash-rich layers acted as local barriers to permeability during liquefaction (sensu Moretti et al., 1999).

These specific internal structures in the main deformed beds, composed of several superposed thinner deformed units, are interpreted as the product of earthquake shaking. The internal laminae of fine-grained sediments acted as permeability barriers to produce detached load-type structures. According to experimental results, load-type structures begin as detachments from an upper layer, collapse and move down into the underlying layer with a lesser bulk density (Kuenen, 1958). The style of deformation described in our study area is similar, showing pillows and drop structures. Our observations support a model where several superposed load-type structures were detached simultaneously during a major earthquake, with the lateral formation of larger, unified load and fluid-escape
structures. The examination of the SSD structures in the Tecopa outcrops indicates that the original internal layering of a deposit can control the final morphology of the soft-sediment deformation structures produced. Within each ash-rich deposit, the number of superposed deformed layers containing detached structures depends on the number of heterogeneities. However, these thin layers can be completely engulfed and deformed if large parts of the lower deposit become liquefied and move upward. Lateral changes from simple to multilayered reverse density gradient systems could be responsible for these local variations in the number of superposed deformed beds (Fig. 14).

Lacustrine paleo-environments appear to be ideal places to record past seismic events. However, we would caution again a direct calculation of recurrence intervals using only a sequence of seismites.

Fig. 10. Several examples of centimetric soft-sediment deformation structures in Lava Creek ash bed. A. Vertical section of a thin deformed layer (less than 10 cm in thickness, see coin for scale), with pillow load structures. A narrow fluidization channel is observed to the right. B. Plan view of a deformed layer where is possible to recognize the circular to elliptical morphology of the fluid-escape structures (indicated by black arrows).

Fig. 11. Complex deformation of the Lava Creek ash bed (east wall of the quarry next to Shoshone with a N–S trend). Observe superposed load structures to the left with several non-deformed layers and fluid-escape structures which cut all the deformed bed to the right.
Firstly, seismites can only develop under conditions adequate for liquefaction in saturated sediments. In shallow lakes, temporarily non-saturated areas are common during dry seasons and this would allow many shaking events to go unnoticed. A second difficulty in calculating recurrence intervals is revealed in this report only because of the extensive exposures. We have shown that lateral changes in the internal layering of a single ash-rich deposit will produce lateral changes in the number of deformed beds.

A shaking event can produce a single deformed bed characterized by large soft-sediment deformation structures in simple reverse density gradient systems but, a few metres away, if the sedimentary column passes to a multilayered reverse density gradient system, this deformed bed is divided into two (Bishop Tuff outcrop) or more (Lava Creek Tuff) superposed deformed beds. This difficulty would be pronounced in studies with limited exposures (such as in drill cores) and could cause confusion in counting liquefaction events.

6. Conclusions

The Pleistocene sedimentary record of the Tecopa Basin is characterized by several ash-rich beds and other deposits showing pervasive soft-sediment deformation. Two deformed levels were examined in detail: those related to the Bishop and the Lava Creek Tuffs. These beds could be studied around and across the basin, where they were deposited in different paleo-environments, and subjected to different diagenetic processes. Where deformed, the Bishop Tuff is characterized by load-type structures up to 1.5 m thick. Similarly, the Lava Creek Tuff is characterized by load-type structures with local fluid-escape structures up to 1 m high.

We interpret these soft-sediment deformation structures as seismites, formed during seismic shaking events. Specific conditions favoured their widespread development in the Tecopa Basin: (1) the accumulation of ash and silts provided unconsolidated sediments with reverse density gradients; (2) the more central parts of paleo-Lake Tecopa provided a saturated groundwater environment necessary for liquefaction; and (3) the region had numerous fault zones that were active during the time of deposition.

Both ash-rich beds were traced laterally, where we observed changes in the extent of soft-sediment-deformation. A single deformed deposit merged laterally into multiple superposed deformed beds, before then merging into an undeformed deposit. A morphological and structural examination suggests that this lateral variation in deformation style was the result of a single shaking event (probably from a major earthquake, plus aftershocks). The presence of heterogeneities in the deformed ash-rich sedimentary deposit, especially thin layers of finer sediment (barriers to liquefaction), acted as partitions between deforming horizons. Laterally, where more extensive deformation occurs, large fluid-escape structures cut and fold these thin layers which act as passive beds.

Fig. 12. Several superposed deformed layers with centimetric to decimetric load structures. Observe the horizontal thin layer approximately at the center of the picture which separates two main deformed beds. Laterally (see Fig. 12), this horizontal thin layer is cut by a large fluid-escape structure.

Fig. 13. A. Complex deformation of the Lava Creek ash bed (west wall of the quarry next to Shoshone), where small superposed deformed beds (B) pass to an area with large load and fluid-escape structures (C).
Fig. 14. Simple genetic sketch showing an initial sedimentary column with reverse density gradient systems separated by thin laminas of fine sediment. A single earthquake produces superposed deformed beds of load and fluid-escape structures. The thin layers of fine sediment favour the detachment of underlying load structures (load casts, pillows and drop structures).

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