TECTORIC DEFORMATION OF A LACUSTRINE MUDSTONE AT SODA LAKE GEOTHERMAL FIELD, WESTERN NEVADA, USA, FROM 3D SEISMIC INTERPRETATION

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ABSTRACT

The transition between the two structural and fault regimes of the right-lateral Walker Lane and the extensional Basin and Range, Nevada, allows for complex transtensional fault interactions. This study investigates this tectonic shift in the Carson Sink using the fault offsets of a paleo-planar lacustrine mudstone in a 3D seismic-reflection data volume at the Soda Lake Geothermal Field. The 3D and three-component reflection seismic survey covers an area of 34 sq km with 8374 source points and 3001 receivers. A Recent sandstone/mudstone package is a strong and the most expansive reflector in this survey, appearing from 0.2 to 0.3 seconds, at an approximate depth of 240 m. The interpreted mudstone reflectors illuminate a fault map of recent active tectonics in this basin. Fault offsets of this unit demonstrate post-depositional structural deformation of the Soda Lake geothermal field. Using OpendTect allowed multiple steps in specialized workflows to facilitate the interpretation of faults and horizons in this seismic-reflection data volume. A dip-steered, median-filtered, and diffusion-filtered volume gave sharper contrasts at the faults. Using this fault-enhanced data volume assisted the interpretation of the surface of the mudstone horizon and the faults that offset reflectors above and below the unit. The fault patterns show en echelon fault steps, large left bends and some antithetic-striking faults. Total horizontal offset across all the faults is 96 m across 5.4 km, yielding 1.8% as a value for recent extensional strain across the survey. The horizon map of the mudstone has a relative low point in the accommodation zone that accompanies a left bending fault and coincides with the most productive part of the geothermal field. A structural ramp between the major faults on the west side suggests a structural interpretation as a normal-fault step-over zone, suggesting a lack of strike-slip motion or pull-apart mechanics.

1. INTRODUCTION

1.1 Geologic and Tectonic Setting

The movement along the North American-Pacific plate boundary is unevenly distributed, with approximately half of the deformation being accommodated on the San Andreas fault, but variable depending on the latitude (e.g., greater percentage of motion is accommodated in northern California on the San Andreas fault than in southern California; Wensoulsky, 2005b). Dextral shear also occurs along the Walker Lane Deformation Belt and Eastern California Shear Zone (Wernicke, 1992; Atwater and Stock, 1998). This transition zone of the Walker Lane is allowing the northward movement of the Sierra Microplate (Figure 1) relative to the Basin and Range Province (Stewart, 1988). According to GPS geodetic studies 20-25% of the plate motion occurs along the Walker Lane in the form of transtensional deformation (Bennet et al., 1998; Faulds et al. 2005; Wensoulsky, 2005b; Hammond et al., 2011).

The Northern Walker Lane (NWL) accommodates transtension along the transition of the Basin and Range Province and the Sierra Nevada/Great Valley Microplate on overlapping, left-stepping dextral faults that are being modified due to a young dynamic change in the stress regime (Unruh et al., 2003). One of the sources of this change is from northward migration of the Mendocino triple junction (Faulds et al., 2005). These dextral faults tend to transition to more normal offset and northern strike as they exit the shear of the NWL and enter the extension of the Basin and Range (Faulds et al., 2005; Wensoulsky, 2005a; Wensoulsky et al., 2012). Left stepping dextral faults should enable clockwise rotations of fault blocks. But, the majority of fault block rotation in GPS is seen to be slightly counter-clockwise for the NWL (Hammond et al., 2011). Macroscopic Riedel shears are employed as a hypothesis that these stepping-faults are migrating toward the maximum extension in a counter-clockwise development that could account for the GPS block rotation observed (Faulds et al., 2005).

1.2 Carson Sink

The Carson Sink trends NE like much of the Basin and Range topography, although it has a more equant shape (Figure 1). The basin is overlain by Quaternary alluvium, sand dunes, silt and a large playa surface (McNitt, 1990). Like many of the basins in Western Nevada, the Carson Sink exhibits lacustrine deposits that can be attributed to Pleistocene Lake Lahontan (Adams and Wensoulsky, 1999; Benson et al., 2002). The NWL tectonic belt borders this area toward the west. Surface faulting indicates basin bounding normal faults (Bell, 1984) and some evidence of strike-slip faulting in the basin (dePolo, 1998; Caskey et al., 2004). The Carson Sink is the surface expression of a complex interaction of shear and extensional forces that cause crustal block rotation (Faulds and Perkins, 2007). It has been proposed that the transfer of NW-trending dextral shear in the Walker Lane to WNW extension in the northern Great Basin would allow for the formation of enhanced extension and pull-apart basins that bring about structural controls for geothermal systems (Faulds and Henry, 2008).
1.3 Soda Lake Geothermal Field

The Soda Lake geothermal field is located 10 km (6 mi) northwest of the town of Fallon in Churchill County, Nevada (Figure 1). It is in the south-central part of the Carson Sink, which is bordered by the <10,000 year-old Big Soda Lake volcanic explosion crater to the south, and the 25,000 year-old mafic Quaternary Upsal Hogback volcanic complex to the north (Hill et al., 1979; Sibbett, 1979; Cousens et al., 2012). There are multiple operating geothermal fields within 50 km (30 mi) of Soda Lake (McLachlan et al., 2011).

There are two current power plants, Soda Lake 1 (5.1 MW gross) and Soda Lake 2 (18 MW gross), although they have never reached maximum output. Twenty three large diameter wells and six re-drills have been completed, with five used for production and five for injection. This low success rate is due to an inadequate model of the resource, with drilling sites located near the central part of a shallow thermal anomaly (Echols et al., 2011).

The geothermal field was chosen for an American Recovery and Reinvestment Act (ARRA) award for the U.S. Dept. of Energy Validation of Innovative Exploration Technologies in the Geothermal Technologies Program. This provided the funding for the 3D seismic study (Gundy et al., 2010). While most geothermal lithologies in primarily volcanic regions are lacking in clean reflections, this site had a four-line seismic survey done by Chevron in the 1970’s that imaged coherent reflections (Echols et al., 2011). These horizontal and expansive reflections of thick sand and mudstone stratigraphy, relatively anomalous in Nevada geothermal systems, made this 3D survey viable at Soda Lake (Echols et al., 2011). At 34 sq km of seismic data, this is one of the largest seismic surveys of any geothermal field to date.

The seismic volume yielded a detailed map of the fault deformation of the same mudstone horizon found by Chevron, and also defined an inverted-cone-shaped basaltic unit at about 550 m depth (Echols et al., 2011). This extrusive basaltic unit has been dated to about 5.1 Ma (McLachlan and Faulds, 2012). The structural style of this...
field was interpreted by the operating company to be one of
nested pull-apart basins with the thickest sections of basalt
in the center of the production area (Echols et al., 2011).
Some of the larger fault picks lined up with higher thermal
anomalies in wireline data (J. Echols, pers. comm.).

1.4 Mudstone Reflector

A sandstone/mudstone package is the strongest reflector in
this survey, appearing from 0.2 to 0.3 seconds two-way
travel time, at an approximate depth of 240 m. The
interpreted mudstone reflectors illuminate a fault map of
recent active tectonics in this basin. This reflective unit
consists of shale, mudstone and fine sand that formed in a
deep lacustrine environment (Sibbett, 1979). Assuming an
environment of deep lake sediments, this unit was deposited
in a paleoplanar orientation. Therefore fault offsets of this
unit should demonstrate post-depositional structural
deformation of the Soda Lake geothermal field (Echols et
al., 2011).

The periodic presence of Lake Lahontan is common in
Western Nevada basins for the last 1 Ma, including Carson
Sink, Pyramid Lake to the northwest and Walker Lake to the
southwest (Reheis, 1999). Pyramid Lake shows Pleistocene
sedimentation rates from sediment cores, which indicate that
between 47.9 ka and 13.9 ka there was 17.32 m of sediment
deposition, giving a Pleistocene rate of 0.51 mm/yr (Eisses,
2012).

These Pyramid Lake sediment layers are continuous and
show consistent deposition of these reflective units for tens
of meters of thickness (on the order of >100 ka) past the
oldest dates in seismic CHIRP imagery (Eisses, 2012).
Walker Lake shows higher sedimentation, of 10 m from 13-
21 ka, yielding a rate of 1.25 mm/yr (Benson, 1988). These
rates are likely overestimations when applied to the more
cyclic nature of deposition in the Carson Sink, and are used
as minimums.

The Rattlesnake Hill basalt, at depth, is about 5 km
southeast of the 3D seismic survey (Figure 1). This volcanic
cone was likely erupted subaerially on the paleosurface of
the Carson Sink and ranges in age from 2.5 to 1.03 Ma
(Maurer and Welch, 2001). The closest basalt age to Soda
Lake that is on the lateral extent of the basalt flow is 1.5 Ma
and is 30 m below the shallowest indication of the mudstone
reflector. Assuming a simple layer cake model for lacustrine
sediments, this indicates a maximum age for the mudstone
around 1.5 Ma.

1.5 3D Seismic Survey

The 3D (and three-component) reflection seismic survey
occupies an area of 34 sq km with 8,374 source points and
3001 receivers. There are 52 paired source lines with a pair
separation of 33.5 m. Source interval is 33.5 m and the
paired, northeast-trending source lines are separated by 235 m.
Receivers are spaced at 67 m on 36 northwest-trending
lines separated by 168 m. This design provides 17 m
common midpoint (CMP) bins with high fold (40) in the 600
by 1200 meter-deep area of the geothermal reservoir. The
mudstone under investigation here is shallower and therefore
potentially has lower seismic fold. This geometry was
originally planned for just single component geophones, but
during project approval it was upgraded to include three-
component recording. Due to the long permitting process
already underway the geometry of the survey could not be
changed. The source is alternating sets of three 28,000 kg
vibrator trucks producing two sixteen-second-long, 8-72 Hz
sweps per source point.

This survey’s P-wave data were processed first with a field
static correction, and then a model-based noise attenuation
to eliminate low-velocity surface-wave noise. Two passes of
stacking velocity analysis with a 0.8 km interval and
surface-consistent residual statics were done. A curved-ray
3D Kirchhoff prestack time migration (PSTM) provided
velocity analysis. Another curved-ray 3D Kirchhoff PSTM
approach with sufficient half-aperture, 75-degree migration
dip, including P-wave VTI-anisotropy (if significant) and
PSTM residual velocity analysis, yielded the final image
Volume. The velocity model applied to convert the PSTM to
prestack depth migration (PSDM) is relatively simple and
horizontally continuous for the shallow section at and above
the mudstone, although it accounts for the faster velocities
and lateral heterogeneity at the basaltic unit (Echols et al.,
2011).

We interpreted the seismic volume in OpenTect®. Multiple
steps were taken according to specialized workflows to
facilitate the interpretation of faults and horizons in this
volume. First, a dip-steered volume was produced to allow
for the following processing of attributes to steer according
to the structural dip of the reflections. A median filter
applied to the volume reduced noise spikes and preserved
reflection trends. Similarity attributes calculated located
reflection offset in the volume to get a non-interpreted fault
map along the Z-plane (Chopra and Marflurt, 2007). To give
a sharper contrast at the faults, reflector amplitudes were
migrated toward areas of lower similarity using a diffusion
filter (Figure 2). Using this fault-enhanced volume assisted
the interpretation of the surface of the mudstone horizon and
the faults that offset reflectors above and below the unit.

2. DATA ANALYSIS

Faults and horizons picked in the 3d seismic provide
interpreted structural offsets of the paleo-planar mudstone in
the seismic volume. To facilitate the picking of faults the
“similarity” seismic attribute volume in horizontal, constant-
depth section recognizes the recent fault pattern cutting the
mudstone (figure 2). This map view shows the general strike
of the faults and the nature of their discontinuities.

The majority of picked fault planes strike between north and
northeast with some antithetic faults in the central part of
the survey (figure 3). The fault patterns show en-echelon fault
steps, large left bends and some antithetic-striking faults.

Fault picks were made on the inline vertical sections of the
fault-enhanced seismic volume because it is closer to
perpendicular to the general fault strike. The fault picks were
then checked on the crossline vertical sections. The faults
are assumed to be planar and have normal displacement. A
minimum of 6 m of vertical offset in the mudstone is
nominally required to delineate any fault because 6 m is a
quarter of the wavelength of the dominant frequency (~70
Hz) of the mudstone reflector. The best-picked faults cut
both deeper features, and the mudstone by more than 6 m
e.g., #1 in figure 4). Less well-observed faults cut the
The gamma ray logs in four wells also indicate the only high survey area. In some areas this maximum positive becomes from the overall coherence of that feature throughout the first maximum positive.

The mudstone unit is expressed as a source waveform of extensional strain of 1.

This is a paleoplanar lacustrine mudstone then we can use this as a value for extension. If the mudstone horizon is the lower ununit then we can use this to determine the horizontal offset of faults. The calculation of the extensional direction involves the assumption that all north to northeast striking faults have an eastern dip. This avoids the bimodal distribution of the same extension directions from horst and graben features that have parallel strikes but oppositely dipping fault planes. The rose diagram shows a mean fault dip trending 102°.

The vertical offset and dip of the faults are calculated along a cross section located perpendicular to faulting (Figure 4). There are 13 faults across this line with 8 dipping east and 5 dipping west. The average dip of these faults is 66° with a total length of the cross section being 5.4 km. If the horizontal offset of all the faults is individually totaled, the offset is calculated at 96 m across 5.4 km. Assuming that the mean depth yields a minimum age 1.5 Ma. This rate would be even higher if the age of 294 ka was used. Using the inferred maximum age (1.5 Ma) of the mudstone, the rate is 0.064 mm/yr. A rate of 0.19 mm/yr is almost a fifth of the rate of 0.5 to 1.5 Ma.

Topography of the mudstone unit shows a relative low near the bend of the faults that coincides with where peak geothermal production is located (Figure 3). Along the east side of the survey there is an interpreted horst or half-graben structural feature that creates a ridge in the mudstone horizon striking north-south.

To analyze the dip direction of the faults a simplified fault map is prepared, to estimate the strike of over one hundred faults. The calculation of the extensional direction involves the assumption that all north to northeast striking faults have an eastern dip. This avoids the bimodal distribution of the same extension directions from horst and graben features that have parallel strikes but oppositely dipping fault planes. The rose diagram shows a mean fault dip trending 102°.

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extension along a nearby GPS profile extending 250 km across the Basin and Range (Hammond et al., 2011), all in just 5.4 km. The minimum rate of 0.064/yr is still three times larger (for 5.4 km) than the average Basin and Range strain in the same GPS profile. This seems unreasonable; either this age is far too young or extension related to the NWL is enhancing this estimate near the Soda Lake 3D survey area.

The structural map from the depth of the mudstone horizon (Figure 3) shows a ramp leading to a relative low point. With no piercing point, there is no way to infer the amount of strike slip motion for these faults. The 3D seismic shows evidence for pure extension in the localized area of the geothermal field, and if the system was purely extensional, it would be interpreted as a step-over or relay ramp in a normal fault zone (Larsen, 1988; Faulds et al., 2005), although the 3D seismic survey lacks a major fault to carry the offset to the south (Figure 4).

A pull-apart basin is another interpretation that would allow for partitioning of normal and strike-slip motion (Wu et al., 2009; Brothers et al., 2009; Gürbüz, 2010; Mann et al., 1983). This model would account for the consistent east-dipping faults and the step-over with pure extensional displacement in the Soda Lake 3D. For this hypothesis to be valid there also needs to be dextral-slip motion oriented 120º from the extensional faults. This dextral motion would be striking 134º compared to the 14º strike of the mean fault direction in the study. This orientation coincides with NWL tectonics surficially shown by faults along the southern boundary of the Carson Sink and the Sagouse fault zone to the northeast of the seismic study (Figure 1). However there is no NWL-oriented fault to the northwest of the 3D seismic to connect possible strike-slip offset. Pull-apart basins also tend to focus extension (Wu et al., 2009), which could account for the specific points of recent volcanism expressed on the surface by Big Soda Lake and the Upsal Hogback.

4. CONCLUSION

Using 3D seismic we produce a representation of the deformation in the Carson Sink, Nevada that allows for multiple structural hypotheses to explain localized extension and crustal thinning. A fault and horizon map of the Soda Lake 3D is produced and quantified to indicate that this system is undergoing higher deformation than expected from the surrounding slow Basin and Range tectonics. The seismic volume demonstrates evidence for comparatively large amounts of offset, in comparison to Basin and Range expectations, indicating some influence from the Northern Walker Lane. The two interpretations of either a step-over or pull-apart system are presented and there is not yet slip evidence to disprove either.

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basaltic unit is indicated by the high amplitude and long wavelength reflections.

Figure 4: This fault-enhanced inline vertical section demonstrates the variety of the fault picks with host and graben features across the study. The 5.1 Ma basaltic unit is indicated by the high amplitude and long wavelength reflections.