Interpretations of a 3D Seismic Volume, Hawthorne Geothermal Field, Nevada

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by

Annie Kell-Hills

Dr. John N. Louie/ Thesis Advisor

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ANNA MARIE KELL

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John Louie, Advisor

Satish Pullammanappallil, Committee Member

Matt Reeves, Graduate School Representative

Marsha H. Read, Ph. D., Associate Dean, Graduate School

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Abstract

Hawthorne, Nevada is located in the Walker Lake Domain of the Great Basin, a region in the western United States known for extensional tectonics and the high temperature gradients necessary for geothermal power production. Geothermal heat sources include magmatic types and extensional. The extensional type is more common for Nevada, where near-surface thermal gradients come from a thinned crust instead of from volcanism. Extensional systems often do not exhibit surface indicators such as springs or fumaroles; rather, the thermal fluids remain capped below the surface in “blind” systems requiring the need for geophysical exploration. Heterogeneous compositions and seismic velocities common to geothermal systems create particular seismic imaging difficulties because simplifying assumptions about velocity gradients cannot be made. A 3d seismic volume collected by the Navy Geothermal Programs Office on the Hawthorne Ammunition Depot represents a rare opportunity to examine the range of geologic interpretations that can exist on seismic data in the Great Basin. Strong reflection events within the volume project to a ~20 degree dip, allowing the possibility of a low angle normal fault; while bedding offsets could be interpreted as a series of steep basinward step faults. Synclines in vertical sections correspond to concentric circles in horizontal sections, not only raising questions about the possibility of migration processing artifacts, but also present similarities to sill intrusions as seen in marine 3d data. This paper explores the seismic evidence for a range of structural interpretations.
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Introduction
This paper considers a 3d seismic volume from the western margin of the Great Basin and evaluates models for structural formations based on observations in the seismic reflection data. The geologic framework resolved from subsurface images is in great contrast to what is noted from surface observations. This data volume presents an exceptional opportunity to examine causes for and an understanding of structural formations under an extensional regime, within a seismically active and geothermal environment. This rare 3d volume was released for academic use by the U.S. Navy Geothermal Programs Office (GPO). It forms the basis for multiple working interpretation hypotheses, which are intended to examine geologic possibilities rather than determine drill targets for power production.

The Great Basin contains an estimated one-third of the world’s potential geothermal power production (Saunders, 2008) making research in Nevada essential in defining structural controls on geothermal systems. Geothermal sources are separated into two types of systems. One type is defined by magmatic systems in which the heat source comes from volcanic intrusions, and the other type are blind systems in which heat gradients are associated with rapid tectonic extension and crustal thinning (Coolbaugh et al., 2005). Nevada comprises a large portion of the Great Basin, a region in the western United States known for extension as well as high tectonic strain rates. This setting makes most of Nevada viable for geothermal power production through “blind” extensional systems (Blewitt et al., 2002). Thermal fluids are typically trapped below the surface in this setting and do not show surface springs or fumaroles; so these systems are identified by zones of active faulting, high temperature gradients and gravity anomalies.
(Coolbaugh et al., 2005; Blackwell et al., 1999) with recent exploration techniques expanding to include seismic reflection surveys.

Seismic exploration within the Great Basin and near geothermal zones presents challenges in imaging due to the heterogeneous composition of deposits surrounding the resource (Majer, 2003). Large lateral velocity gradients create a particular exploration challenge and require that seismic surveys be designed to suit the area to overcome the imaging difficulties. The causes of imaging difficulty include structures controlling blind systems often dip steeply and may not provide fault plane reflections, and that basin-fill materials in the Great Basin do not contain the laterally continuous stratigraphic layers needed to easily image fault offsets. Reflection surveys with petroleum-industry-standard parameters fail in such conditions. Research shows that imaging in geothermal environments is enhanced by using longer source offset distances in data collection and by processing with advanced techniques such as velocity optimization and pre-stack depth migration (Pullammanappallil et al., 2001).

Faults serve as the primary controls on fluid flow in extensional systems so locating and understanding the geometry of the fault systems becomes key in understanding geothermal systems. Steeply dipping faults enter the geothermal reservoir and allow for flow along and across the fault zones (Rawling et al., 2001; Hess et al., 2009). Fluid flow in and around fault zones varies depending on levels of fracturing, mineralization and the existence of low permeability clay zones. If high levels of fracturing dominate the fault zone, the damage zone along the fault path itself may serve as a conduit for fluid (Rawling et al., 2001). In other situations, the fault path may be clay-rich or become mineralized creating a zone of very low permeability. In these
situations the fault serves as a barrier to transverse fluid flow laterally but may still allow for fluid to migrate in high permeable zones parallel to the fault path (López and Smith, 1996).

Images observed within the seismic data collected in southern Walker Lake Valley provide insight to the geology and configuration of structures that could serve as fluid controls. Through examination of these data, understanding can be gained on types of controls on fluid flow that are not evident at the surface (Vice et al., 2007; Hess et al., 2009). Though the seismic volume allows a cross-sectional view of structures to depths greater than 1.5 km, it does not provide information regarding rock composition, fluid content, or permeability. Some interpretations of seismic data allow us to infer the presence of or characterize a reservoir based on amplitude and phase changes caused by fluid presence or high amplitude reflections caused by mineral alteration along a flow path (Brown, 2004). But, it must be noted that seismic data alone cannot allow a complete understanding of current fluid flow or reservoir presence.

Geologic Background of Western Nevada

Steep step-faults are common to geothermal systems as noted in the northern portion of Dixie Valley, Nevada where the range bounding fault dips at 54° to the east followed by the basinward faults which also dip at a high angles into the valley (Blackwell et al., 1999). Models for the Dixie Valley geothermal field are believed to be “typical” of extensional geothermal systems and show that several faults along the range front dip into the valley, creating multiple fault zones for possible fluid conduits. Cross sections show that multiple faults step into the valley dipping east and are intersected by an antithetic graben. Studies by Okaya and Thompson (1985) have also described steeply
dipping normal faults combined as the main feature defining basin and ranges.

Low angle detachment faults are observed in numerous geologic settings and have been extensively studied in the Great Basin by Wernicke (1988) and others since within the Great Basin. Current physical models for fault motion do not allow for the possibility that low angle faults could cause earthquakes (Anderson, 1942). However, observations of active low angle normal faults do exist. Models for low angle normal faulting describe that a fault may initiate at a high (~60°) angle but then rotate to 30° after rupture (Wernicke, 1995), or that an abandoned portion or “hinge” is inactive while the active portion remains at higher dip (Axen and Bartley, 1997). Models also suggest that there is simply a lack of observations of rupture on low angle systems because they are in seismically quiet regions (Wernicke, 1995). Locations of observed low angle normal faults include the southern portion of Dixie Valley, Nevada (Abbott et al., 2001), as well as numerous other locations in the Great Basin (Wernicke, 1995; Axen and Bartley, 1997). Despite observations of low angle faulting, research is ongoing as to the mechanics of seismicity and to describe the lack of low angle focal mechanisms from earthquakes on low angle faults (Chiaraluce et al., 2007).

Magmatic intrusions, specifically saucer-shaped sills have been extensively studied through seismic surveys in the North Sea by Thomson and Hutton (2003) and Hansen and Cartwright (2006), revealing lenticular shaped, highly reflective bands with lateral extents ranging from 1-10 km. Though sill intrusions are more typically circular in plan view, they have been observed at outcrop in the Karoo Basin, South Africa to show an elliptical saucer-shaped structure in aerial photographs. Saucer-shaped sills form in sedimentary environments, fed from vertical dikes below the sills. As magma intrudes
the subhorizontal inner sill is formed, pushing up the overburden and leaving a dome shape in the stratigraphy that is almost a mirror image of the sill below. Models show that when the thickness of the overburden is less than the width of the sill, the stress field becomes asymmetrical at the edges creating the upturned sill and thus the saucer shape (Polteau et al., 2008).

**Hawthorne Geologic Background**

Hawthorne, Nevada is located within Walker Lake domain of the Walker Lane, a belt of the Great Basin containing dextral and extensional faulting and an estimated 25% of the motion between the Pacific and North American plates (Surpless, 2008; Oldow, 2003). North-northwest-striking Basin and Range normal faulting dominates the western margin of the Walker Lake domain, where the eastern front of the Wassuk Range exhibits triangular facets indicative of active normal faulting (Wesnousky, 2005).

Studies by Bell (2007) show that stratigraphy in Walker Lake near to the 3d seismic volume contains Holocene tephra layers interlaid in cobble boulder debris flows. Basin composition in the nearby Queen Valley contains mostly Quaternary alluvial-fan deposits, which juxtapose Tertiary conglomerates and basaltic andesite (Lee et al., 2009). Basin composition of Queen Valley is assumed to be similar to compositions near Hawthorne.

Though there is little or no evidence for Quaternary volcanic activity in the Hawthorne basin east of the Wassuk range, nearby Long Valley southwest of Hawthorne reveals volcanic activity dated within 4000 ka (Bursik et al., 2003) and Queen Valley contains examples of Pliocene rhyolite. (Lee et al., 2009) Geological and drilling evidence suggests that Quaternary volcanic dikes intruded the Sierra Nevada rangefront
zone and migrated along weak fault zones (Bursik and Sieh, 1989).

**Methods**

The Navy Geothermal Projects Office (GPO) collected a 3 km by 10 km north-northwest-oriented 3D seismic reflection volume designed for exploration of the geothermal resource along the Wassuk Range front (Figure 1). Though many groups and individuals (i.e. Hinz, Shoffner and Faulds) have coordinated on structural models and well logs in development efforts for the geothermal resource, this paper considers structural interpretations and basic attribute analyses of the 3D seismic reflection volume. Structural indicators as revealed within the seismic data include possibilities of steep basinward step faults, low-angle detachment faults and sill intrusions within the fault zone. Major structures of interest within the seismic sections include strong easterly dipping and near horizontal reflections. We use two-way-travel time (TWT), the time it takes for the seismic wave to travel to a structural change and return to the receiver, to approximate the depth and geometries of the reflectors. By understanding the depth and orientation of reflections, they can be interpreted physically as geologic structures. Reflections are recorded by surface receivers and placed geometrically based on their TWT rather than their absolute amplitudes. Time locations of the received amplitudes along with a 3d velocity model provide information required of Pre Stack Time Migration (further details below).

Seismic reflection surveying uses land-based sensors to record wave changes caused by spatial variations in rock compositions in underground stratigraphy. The physical principles of Snell’s Law cause source waves put into the ground to refract and reflect at different angles and amplitudes based on the physical properties of the
structures and stratigraphy. Arrays of receivers record these waves and their variations. The structures are resolved spatially through post-survey processing, revealing cross-sectional images of the seismic reflectivity of the rocks. Seismic data record the changes in wave amplitudes caused by changes in underlying stratigraphy seen in numerous records. By analyzing seismic cross-sections for amplitude signatures and reflection orientations, a picture of the geologic framework can be created showing both tectonic and structural history, and possible controls on fluid flow.

Data discussed in this paper were collected using a vibrator source and perpendicular inline and crossline orientation of sources and receivers. The 3D seismic volume was collected in 2002 and processed by Dawson Geophysical using standard 3D techniques including 3D velocity modeling and prestack time migration (PSTM). When seismic data are collected, the records contain the spatial coordinates of latitude/longitude and the apparent time that the events occurred. Using a model for the seismic velocity property of rocks, the reflection events in shot gathers of seismic traces are moved from the apparent seismic travel time to their true location in time and space. PSTM properly places the time location of the reflections in areas with complex structures so long as the velocities do not vary greatly in the lateral direction. That is to say, if sharp changes in the seismic velocities above the structures occur, PSTM will not accurately construct an image of the structure.

Analyses of the 3d data begin with understanding the display of the inline/crossline sections. The ~10 km-long crosslines run roughly north-northwest along strike of the Wassuk Range and frontal faults. Inline sections are oriented roughly perpendicular to range front faults and run ~3 km east-west from the range base into the
Walker Lake Valley. These data have lower seismic fold in the northern portions due to limitations in receiver deployment as it is near to urbanized Hawthorne. Lower fold provides less resolution in data and causes an inability to image some structures.

An understanding of the time to depth conversion of the seismic data allow for the section views to be exaggerated to be ~1:1; meaning that the length horizontal is the same length in the vertical direction. Viewing the data in 1:1 sections allows assumptions that approximate dip angles in the image are the features’ true dips.

The phase of these data is used to understand the types of contacts that are encountered. These data are zero phase American polarity so acoustic impedance increases can be identified as a change from blue to blue (Brown, 2004). Being able to understand the impedance contrasts allows interpretation of the material. For example positive impedance contrasts result from both fluid layers and volcanic intrusions while gas filled sediments result in negative contrasts.

To gain an understanding of the geology that is represented within the seismic data, a succession of inline and crossline sections are examined in both vertical and lateral directions. Through the examination across a distance the information gained in one section can be extrapolated to show a representation of a structure in a physical sense and then hypotheses of the geology can be developed. The continuous events are followed using automated tracking features within OpendTect, the interpretation software. The tracked horizons are inspected to understand the underlying stratigraphy over the extent of the seismic volume. Manual picking of events on subsequent sections allows reconstruction and representation of events over a distance so that they can be recognized in ways that are not possible in just one seismic section.
Estimations of depths and dips of features are estimated by using a velocity-time-depth model. Well logs analyzed by Nick Hinz at the University of Nevada, Reno’s Bureau of Mines and Geology show changes from poorly consolidated sediments to meta-volcanics at 1500 m and from granite to chloritized meta-volcanics at 3400 m depth. By examining the seismic sections, the two-way-time location of these changes was identified and used to create a time to depth conversion of 2690 m/s. This simple conversion is essential in calculating the dip angles and depths and thus the geologic possibilities of reflection events.

Geothermal environments commonly have very complex structural frameworks and resultanty have complex velocity fields. The velocity model used in migration of the Hawthorne 3d data has seemingly overly smoothed velocity sections (Figure 2B), a result of industry standard processing techniques.

Some uncertainties in the geometric reconstruction of the reflections due to the smoothed velocity model guided an initial interpretation of range-front faults with regions of possible migration artifacts, where strong events show up-turned synclinal shape. Diffractions occur where there is an abrupt change in rock type and appear in prestack seismic sections as hyperbolic-shaped reflection events. Migration uses diffraction energy to position reflectors (Brown, 2004), but when seismic data are poorly migrated, those diffractions do not truncate suitably; rather they retain a hyperbolic appearance and can curve up or down (Yilmaz, 2001). Migration attempts to focus seismic energy, which is spread over the Fresnel zone. The accuracy of migration is dependent on the noise in the data and the accuracy of the velocity model so problems with these factors will result in problems in the resulting image (Brown, 2004; Yilmaz,
Though over and under-migration can often be recognized in seismic sections, it can create some confusion when interpreting the validity of a structure. Problems that migration artifacts cause in an image occur when there is a shortfall between seismic and geologic cross-sections (Yilmaz, 2001) so resolution characteristics must be analyzed to determine whether or not the event is real. Features can appear to be overlapping or to have a curved geometry due solely to effects of processing. For this reason, the curved appearance of migration artifacts required that we investigate them in horizontal sections of this 3d data set. By understanding how the curved features compare to the width of the uncertainty ranges we can assess the likeliness of a structure being a response to an actual geologic event. Extensive examples for migration artifacts can be viewed in texts by Brown (2004) and Yilmaz (2001).

Results

Initial indications of migration artifacts seen within these data were the upturned reflection events and circular “bullseye” features in horizontal sections (arrows in figure 3). Further analysis leads us to interpret the upturned reflections as geologic structures for two main reasons. The width of the circles formed by the upturned edges in the horizontal time sections (Figure 2 A; Figure 3) are twice as wide as the Fresnel radius (Table 1; Table 2), the horizontal uncertainty range at the depth of the dominant events. Because the events are much larger than the Fresnel radius, we have confidence interpreting them as response to structure rather than artifacts. Because frequency changes with depth, calculations of vertical resolution change with depth giving zones of resolution outlined
in Table 1. Higher confidence in the velocity model used to create a migrated image will result in higher confidence in the seismic resolution based on the Limit of Separability, which is maximum to one-quarter of the seismic wavelength. The Fresnel zone and limit of separability are important considerations when interpreting the dominant reflection events because they provide the minimum size that a feature must be in order to give a confident interpretation. Because circular features seen in time sections are larger than the Fresnel Zone, they are not interpreted as artifacts of processing (Table 2).

These data show regions of horizontal resolution outlined in Table 1, giving resolutions of less than 350 m at all depths while the circles are greater than 600 m. These data have uncertainties associated with the velocity model and noise in the data so confidence in the vertical resolution is estimated to be less than the limit of separability.

Information regarding the number of common midpoint bins and source offsets are not available. Inline sections within the volume run roughly perpendicular to the average Wassuk range-front strike. Other geophysical information available from within the survey area includes sonic logs and detailed lithologic logs from two wells located in the northern portion of the survey area. Well logs show fanglomerate to depths of ~1000 feet and then granite to depths of >3000 feet. The seismic data show dominant frequencies of ~20 hertz at depths greater than 500 ms.

Consistent subhorizontal reflections in the upper 200 ms are interpreted to be Tertiary volcanic flows that remain mostly horizontal and continuous throughout the extent of the volume as indicated by the purple line in Figure 2. The reflection volume clearly shows very strong east dipping reflectors at depths of ~ 1 km that intersect concave up reflection events. These reflectors have ten times higher amplitude than the
surrounding interfaces, causing them to stand out as dominant features within the volume. Inline sections reveal bright, high amplitude reflection events throughout the southern two-thirds of the survey that abruptly stop toward the northern portion of the survey area (Figure 4).

Events initially interpreted to be migration artifacts can be interpreted as structure because within the same inline section and within 100 ms of the upturned edges (e.g. near A in Figure 4) there are reflection terminations that do not indicate an over-migrated appearance (e.g. D in Figure 4). It is highly unlikely that the same seismic section would display reflections with proper terminations adjacent to over-migrated reflections (Brown, 2004). Structural interpretations based on the seismic data will follow an assumption that the synclinal features are geologically real. This assumption is based on calculations of imaging resolutions, and consistencies with the geologic models that are outlined in this paper.

Crossline sections show the strong reflection event that is dominant in the inline sections through the southern 2/3 of the survey area. Though in inline sections the reflection dips east and then changes into the strong synclinal events (e.g., A in Figure 2), in the crossline sections it grades gradually deeper toward the north as seen in Figures 2 (at B) and 3 (at B). The strong reflections can only be traced to within a region of 200 ms two-way travel time uncertainty in most areas because of the wide, multi-cyclic reflection band (e.g., C in Figure 2).

Geologic evidence and previous knowledge of the Wassuk Range reveal a series of east-dipping faults with NNW strike in near vicinity to the 3D survey (Oldow, 2003; Surpless, 2008). The strong, dipping reflectors (e.g., C in Figure 2) were initially
interpreted to be fault plane reflections and were followed using a fault-tracking feature within OpendTect as well as picksets that record locations in space and time.

Depth and dip projections have been created by correlating stratigraphic horizons as interpreted in well cuttings (Hinz, pers. comm. 2010) to reflections within the seismic data volume. The northern portion of the volume contains little to no indication of the strong reflections as seen in the southern portion of the data, making it difficult to tie seismic reflections to lithologic logs. Knowing the depth that sediment changes to metavolcanics within the well logs allows depth projections by associating the time of a reflection presumed to be caused by the lithology to its recorded depth. By assessing a set of possible relationships, a range of velocity models were created and used to calculate the dip on traced faults. This velocity model was also compared to average p-wave velocities as recorded in sonic logs, showing an average velocity range of 2500-3000 m/s. Figure 7 shows the well track within the 3d volume and the location of the reflection identified as the sediment to metavolcanic contact seen in the well log in pink.

Low Angle Fault Observations

Interpretations can be made of the dipping reflectors in the southern portion of the volume as fault plane reflections along a low-angle normal fault. The fault can be identified to a maximum range of uncertainty of 200 ms with some areas showing the fault zone collapsed into a narrower zone. More accurate processing could allow for some areas to have a more confident reconstruction of the fault location. Numerous places throughout the volume show strata that “rollover” into the fault plane, a feature that is common to low angle normal faulting. As motion occurs on a low angle, lystric normal fault, space is created between the hanging wall and footwall, leaving an open zone from
the hanging wall that collapses into the footwall. Sediments that collapse intersect the fault plane at a roughly perpendicular angle causing a rollover anticline (Koyi and Skelton, 2001). Figures 5 and 6 show rollovers, outlined in blue, that terminate into the 20 degree-dipping fault plane sketched in green.

The fault plane reflection (green) seen in figures 5 and 6 intersects a horizontal band of bright reflections (A in the Figures) at ~1000 ms or 1300 m depth. It is unclear as to whether the band is highly reflective sediment in the hanging wall or possibly volcanic flows, but it should be noted that it forms a syncline almost 1 km across. Interpretations of low angle faults on multiple inline sections are shown in Figures 5 and 6, revealing an average dip of ~20 degrees. Models for low angle normal faults suggest that the faults become horizontal at some depth but it is unclear whether the low angle structure soles into the horizontal reflection band or if it continues at 20 degree dip to greater depths as sketched in figure 6. It would be highly unusual for a lystric fault to go horizontal at 3 km depth, let alone the 1-km depth these sections seem to suggest.

**Basinward Step-fault Observations**

Our Hawthorne seismic sections can alternatively be interpreted as a range of structures, including a series of basinward step faults. Well-resolved reflections in the upper 500 m (400 ms) show a series of offset reflections stepping down away from the range front (purple lines cut by light blue faults in Figure 8). Tracing the truncations through depth indicates a series of faults with dips ranging from 40-55 degrees, normal-fault angles that are expected in areas of active tectonics and geothermal activity.

The bright dipping reflector, which could be volcanic flow across the valley, is tilted in the footwall (near A in Figure 8), and dipping at less than 20 degrees in the
headwall block of the clearest steep fault. An offset of ~150 m is observed and noted in figure 8, between the subhorizontal reflector in the hanging wall and the dipping reflector in the footwall. The lateral reflection bands could be a volcanic flow that is intersected by the fault zone, causing offset in the reflections as well as the reflector shape in the hanging wall and rotated section in the footwall. The strongest reflections bend up into the fault in a synformal shape.

Multiple inline sections show possible fault zones identified by truncations and offsets in reflections shown in purple in Figure 8. Inline 1216 shows a band of reflections dipping at less than 20 degrees that is offset from a near horizontal band. Strong reflections show a hanging wall syncline east of the interpreted range front fault, which could be caused by normal fault drag (Davis and Reynolds, 1996). Models show that as normal fault motion occurs on steeply dipping faults, layers in the hanging wall become up turned into synclinal structures while bedding in the footwall becomes convex down into anticlines. In Hawthorne, the synclines seen in the reflection volume are consistent with normal fault motion and are sketched in dark blue in Figure 8.

The width and reflectivity/energy of the 20 degree dipping reflector match that of the hanging wall syncline with thicknesses of ~100-150 m, allowing us to infer that they come from the same deposition. Figure 8 shows ~150 m of throw between the hanging wall syncline and the rotated reflections in the footwall outlined in pink.

Connecting truncations from the upper 200 ms to depths of over 1 second reveal the fault location and project a fault dip of ~55 degrees, sketched in light blue in Figure 8. Though multiple step-fault interpretations can be made on any given section (e.g., inline numbers 1203, 1217, 1177), they cannot be traced continuously throughout the volume.
The most continuous series of offsets occur on the range bounding fault with the interpretation becoming more difficult to keep consistent east of the range.

Faults east of the range front can be identified similarly to the range bounding fault, by connecting the offset reflections. Dip calculations of these basinward faults reveal steps dipping at ~60 degrees in the valley east of the Wassuk rangefront. The range front fault and three steeper basinward step faults can be identified over the 3 km wide section roughly parallel to the rangefront. Figure shows examples of steeply dipping basinward faults (blue) interpreted in the sections; however, other sections show more offset features that are not displayed in this section.

**Sill Observations**

Magmatic sills have been observed in 2-D and 3-D seismic surveys in rift margins and sedimentary basins including the Gulf of California (Kluesner, 2009), and in outcrop in southern Nevada (Valentine and Krogh, 2006). Seismic evidence of sills include strong saucer-shaped reflections, sediment cross-cutting, and uplifted sediments above the saucers. These Navy data from Hawthorne do show strikingly similar features to known sill intrusions, through a number of identifying factors. As seen in the North Sea (Thomson and Hutton, 2004), the Hawthorne volume shows concentric circular bands in horizontal time sections that are larger than the 300-m-wide Fresnel zone at that depth. Here we observe bowl-like bands with widths of 0.6-1.0 km in inline sections that continue ~5 km along crossline sections, with sizes that are analogous to other sill examples. Figure 9 (A) shows a vertical section with a number of upturned bands outlined in blue that are similar to sills observed in seismic sections from the North Sea (Thomson and Hutton, 2004). Studies by Hansen et al., 2006 show that winged sill edges
are expected to dip at angles between 15-40 degrees. The dips observed within this volume are outlined in Table 2.

An additional identifying factor for sills seen within this volume are the uplifted sediments above the down turned reflection bands. Throughout the entire volume, the upper 200-300 ms has continuous layered reflections interpreted to be tertiary volcanics or lacustrine sediments, which are interrupted above the areas of the saucer-shaped reflections. Figure 9 (a) shows the interrupted overburden as well as the continuous portion of the shallow structure.

Horizontal time sections in the central to southern portion of the volume show circular reflection trends initially thought to be migration artifacts (e.g. B in Figure 9). Further investigation shows the similarity to time sections in the North Sea, which reveal concentric circles caused by the uplifted edges of sills (Thomson and Hutton, 2004). In Figure 9, a time section and inset show the circular features that are similar to observations in 3d data in the Rockall Trough. Figure 9 also shows the extent of the high amplitude features. They are present in the central to southern portion but the events are not present in the northern half of time sections.

**Discussion**

**Phase and Impedance Changes**

Some of the high amplitude reflection sections exhibit shifts in phase within the high amplitude events. An example of this is seen in Figure 5 B beneath the green fault plane trace. The amplitude phase changes from a red center lobe to black center lobe. Phase changes can be induced by changes in the thickness of a structure and the interference that is caused by those changes (Hansen et al., 2008). Though gas and fluid
contacts can cause strong impedance contrasts (Brown, 2004), the noise level or quality of these data prevent definitive understanding of fluid presence possibilities. Impedance changes caused by granitic intrusions are the same changes caused by fluid presence (Brown, 2004) but fluid more commonly occurs as a flat reflector in seismic section to it is presumed that the changes are structural rather than fluid induced.

**Low Angle Fault**

Though there is little evidence for low angle faults as controls in geothermal environments or range-bounding fault zones (Blackwell et al, 1999), geological maps show inactive low angle normal faults in outcrop near the Hawthorne seismic volume (J. Oldow, personal communication, 2009). Some studies within the Great Basin indicate low angle faults in near proximity to active geothermal fields such as Abbott et al. (2001) and Lerch et al. (2009). Faults interpreted in the seismic volume roughly project in coincidence with exposed low angle fault scarps (J. Oldow, personal communication 2010) though it is not apparent whether the origins of the high amplitude reflections are in fact the exposed low-angle faults.

A subject of some debate is the reason that a strongly reflecting fault is seen in the southern portion of the data volume and not the northern. This could be due to the orientation of the volume; it runs very close to the range front in the south but the distance to the range increases in the north. The inline sections do not remain perpendicular to the range strike to the north. In the southern part, the inline sections run perpendicular to the range strike, but the range is oriented more westerly in the northern part of the volume. Fault images are most successful when the inline seismic sections run either parallel or perpendicular to the fault strike (Brown, 2004), for a narrow-azimuth 3d
dataset like this one. Increased distance to the range from the survey could mean that a fault could run deeper than can be imaged. However, because this structure is so low angle this effect is unlikely.

It is also possible that the dip of the fault steepens farther north, where limitations in fold and offset caused by the need for the survey to avoid an urbanized area would make imaging very difficult. Steeply dipping structures require very long source-to-receiver offsets that were not possible in the northern section of the volume given the limits in placing sources and receivers. It is expected that details of stratigraphic terminations should show the presence of a fault. However, given the heterogeneous nature of the terrigenous Tertiary to Quaternary Great Basin sediments, there are no well-resolved bedding layers that allow the recognition of terminations.

Though it is not considered impossible, it is unlikely that the fault dip would change significantly over such a small spatial range. The fact that the low-angle reflector ends abruptly, in 33-meters, the space between adjacent inline sections, suggests that some other effect may be causing the observed change of low angle structure to no resolved reflections. Models for low angle normal faults show that the faults sole out to horizontal, similar to what can be inferred in these data, though it is expected that the faults become listric at a much greater depth than the 1-km depths observed here.

**Basinward Step Fault**

The hypothesis that steeply dipping rangefront and basinward step faults exist within the volume is supported by the offsets observed in the Tertiary volcanic layers (purple line in Figure 8) in the upper 400 m, and that step faults are the common geologic control in Great Basin geothermal environments (Blackwell, 1999). However, some of
the seismic sections in our Hawthorne data set are inconsistent with this theory. Reflections are seen that are not offset by the proposed normal faults, suggesting that either the fault does not continue to depth or the vertical resolution does not image these offsets. Inline sections 1201 and 1218 (Figure 10) show clear offset of reflections at 350 ms, above strong reflectors at 700 and 1000 ms that are not offset, suggesting that the near-surface offsets project to any substantial depth. Figure 10 shows inline 1218 and one projection of a steep basinward normal fault. At ~700 ms there are a series of reflections dipping toward the west which are continuous despite the fact that the fault path goes through them. This inconstancy and thus the inability to trace a steep fault path throughout the volume creates doubt in this interpretation.

There are also regions as seen in inline 1215 (Figure 10) where the strong reflection band does not show offset, rather the reflections are continuous, shown in figure 6. A normal fault cannot exist without causing increasing offset along its path down. These reasons present limitation and holes in an interpretation of basinward step faulting.

**Low Angle Faults Intruded with Sills**

The brightness of some reflections in comparison to the surrounding rocks raises a question as to what causes the reflection. It is possible that it is a hard volcanic flow interbedded with soft sediments. On the other hand, it is plausible that it is from an intrusion similar to those studied by Valentine and Krogh (2006) in southern Nevada along Paiute Ridge, and by Bursik (2003) in Long Valley, California. At these locations research has revealed magmatic intrusions that progress up the planes of normal faults, the plane of greatest weakness (Valentine and Krogh, 2006; Bursik et al., 2003; Bursik
and Sieh, 1989). Geologic observations of Paiute Ridge, Nevada show fault zones that are intruded by magma, resulting in some areas where the intrusion spreads laterally and other areas where it migrates up the fault plane. The possibility of sills intruding the fault would require either that the fault is low angle because the reflection maintains an ~20-degree dip for its extent, or that the dipping reflector is from an interbedded sill itself, not because the magma followed a fault.

The up-turned edges on the observed sills dip within a range of 20-40 degrees (Polteau et al., 2008) consistent with the dips observed within these data. A sill working hypothesis explains the bowl-like features, and would explain why the reflector does not persist into the northern portion of the seismic volume; rather it abruptly stops. Current research on sills (Hansen et al., 2008; Valentine and Krogh, 2006) suggests that the lateral extent reaches from 1 to 10 km.

Identifying factors for sills not seen in these data are crosscut strata caused during the intrusion process, and feeder dikes. Valentine and Krogh (2006) note that the cross-cutting observed for sill intrusions in marine seismic data is not expected in Nevada due to the fluvial and alluvial composition of Great Basin sedimentary basins. A vertical dike structure would be difficult to image even if it was present because of the limitations of Hawthorne survey geometry. Vertical structures, even of high amplitude contrast, cannot be imaged without large source/receiver offsets. Unless a dike has become rotated, it would remain vertical and there is little chance that it would have been imaged by this survey. It is also likely that the dike width would be smaller than the seismic resolution.

Because the circular features observed in time sections are larger than the Fresnel radii, we have confidence in interpreting them as a structure rather than migration
artifacts. The widths of the circles are consistent with the size expected for saucer shaped sills. Seismic data are presently the only constraint on the sill hypothesis because no other surface evidence exists in the valley to verify it. Long Valley to the west, however, does contain magmatic intrusions (Bursik and Sieh, 1989; Bursik et al., 2003) so there is a possibility that they may exist without surface exposure. Igneous activity was pervasive throughout the Great Basin through out the later half of the Tertiary beginning ~40 m.y. (McKee, 1971) with a new insurgence beginning 16 m.y. through the present. Studies by McKee show the regional extent of magmatism across the western U.S.

Conclusions

These 3d seismic data provide a rare opportunity to examine multiple hypotheses for the structure of a Great Basin geothermal system. The data show evidence for basinward step faults as well as a low angle fault bounding the rangefront. Without a confident velocity model and longer source-receiver offsets, there is little chance to image multiple faults in a normal step-fault system. Though there is indication of stratigraphic offsets, some sections show continuous reflections below, discounting the interpretation. Low-angle dip on a range-bounding fault system seems unlikely, but a strong low angle reflector is present throughout majority of the volume. Though no Quaternary history or recent geologic evidence for sill like intrusions exist within this valley, the seismic signatures of sills are seen. So there is a possibility that Tertiary sills could exist within this region. Dip ranges seen on the strongest reflections are within ranges expected for a low angle fault or the upturned edges of sills.

The hypotheses could be better constrained if more geophysical data were collected within the Hawthorne area, or if seismic data is collected in regions such as
Paiute Ridge so that comparisons of seismic response to magmatic intrusions in the Great Basin could be made. If it ever became possible to analyze raw shot gathers for new velocities and a Pre-Stack Depth Migration (PSDM) rather than the current processing of PSTM, it may be possible to have better images that would allow assessment of contacts more clearly.

The wide range of geologic interpretations possible on these data clearly outline the necessity for seismic surveys to be designed for the specific region and composition of material within the survey area. By characterizing geologic hypotheses based on seismic data, it may be possible to more easily determine and locate geothermal controlling structures exploited for green energy development.
References


~1 km

A

B

Rollover

TWT (s)

0.5

1.0

1.5

2.0

Inline 1194
Resolved reflections without offset
Offset Volcanics
Continuous Reflections

~1 km

TWT (s)
0.5
1.0
1.5
0.5
1.0
1.5

Inline 1216
Inline 1218
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