REGIONAL SETTING, GEOMETRY, AND STRUCTURE OF THE NORTHERN FISH LAKE VALLEY BASIN

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(view to south in northern Fish Lake Valley)

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SUMMARY

Northern Fish Lake Valley in west-central Nevada lies at the northern terminus of one of the most tectonically active structures in the western Great Basin, the Death Valley – Furnace Creek – Fish Lake Valley fault zone. The valley and adjacent mountain ranges expose a complex array of active faults that bound and internally dissect two deep structural basins lying below the valley floor. The valley and bounding faults form a west-facing arc with east-northeast structures changing to north-northeast from south to north over a distance of 30 km. The valley is internally dissected by a north-northeast fault system that relays displacement across the basin from the southeast to northwest bounding structures.

Through the integration of geologic mapping, stratigraphic and structural analysis, and the acquisition and modeling of gravity data, the geometry and internal stratigraphy of the basins underlying the valley have been estimated. Two basins are recognized in the north and south. They are separated by a topographic sill at a depth of about 2.2 km but linked at shallower levels. The southern basin has a total depth to basement of about 3.0 km and the northern basin has a depth of about 2.6 km. The basins are filled with Miocene to Quaternary volcanic and sedimentary rocks which were accumulated in a protracted history of basin formation during extensional faulting. The fault systems with prolonged displacement created topographic depressions that captured thick accumulations of sedimentary and volcanic rocks and also served as conduits for fluid migration that localized an active geothermal resource along the margins of the basin system.

The deep structural depressions beneath northern Fish Lake Valley reflect the intersection and superposition of two basin orientations. West-northwest trending basins formed during an early history of north-south crustal stretching starting at about 23 Ma and continuing to about 15 Ma, when a younger period of northwest-southeast stretching started. The younger period of stretching developed the north-northeast trending basins that are active today. The basin fill of both trends contribute to the negative gravity anomalies observed above the structural depressions. The combined gravity signal from these two superposed basin sources complicates analysis of the internal geometry of the basins. Deconvolution of the gravity signal was required to isolate the contributing geometry of the younger basin deposits, which represent the exploration targets in this study.

A grid of geologic sections, based on surface observations and well data, were constructed using three-dimensional gravity-depth inversion results as a preliminary constraint on the basin geometries. The internally consistent grid of geologic sections were modeled to produce a theoretical two-dimensional gravity response for comparison to observed gravity. Misfits between calculated and observed gravity values were reconciled by an interactive process of modifying the sections and comparing observed and calculated gravity. A best-fit solution for all geologic sections was used to estimate the internal distribution of stratigraphic units within each geologic section. Depth and thickness estimates of the upper basin deposits (exploration target) were extracted from the model grid and presented as structural contour map.
This analysis yields the spatial distribution and thickness of the primary reservoir target for lithium brine in the valley, the interbedded sandstone, mudstone, and conglomerate of the Fish Lake Valley assemblage. Based on our regional stratigraphic analysis, the Fish Lake Valley assemblage is exposed in several basins within west-central Nevada and correlates with the reservoir for active lithium-brine extraction in Clayton Valley 40 km to the east-southeast. The Fish Lake Valley assemblage in northern Fish Lake Valley achieves thicknesses of up to 1.2 km in the northern basin and nearly 1.8 km in the southern basin. The thickness of the Fish Lake Valley assemblage abruptly decreases along the western and northwestern margins of the basins, where older parts of the Cenozoic section are exposed at the surface. In contrast, thickness of the Fish Lake Valley assemblage decreases stepwise to the east and southeast as bedrock exposures in the adjacent ranges are approached across an array of down-to-the west faults.

INTRODUCTION

Fish Lake Valley in west-central Nevada and eastern California is underlain by a deep north-northwest trending basin containing mid-Miocene to Holocene volcanic and sedimentary rocks. The basin developed in response to displacement on the Fish Lake Valley fault system that bounds the valley to the west (Fig. 1). In the adjacent ranges, sedimentary and igneous rocks of Proterozoic through Paleozoic and Mesozoic ages, respectively, are overlain by volcanic and sedimentary rocks ranging in age from the late Oligocene through the Quaternary. A complete section of the rocks that composes the basin fill are exposed in the surrounding mountains and at the southern end of Fish Lake Valley. The basin is filled with a succession of late Oligocene to Pliocene basalt, ashflow tuff, andesite, and coarse sedimentary rocks. The deeper parts of the basin fill are overlain unconformably by a succession of Pliocene to Quaternary lacustrine sandstone, mudstone, and conglomerate, locally interleaved with basalt, that passes upward into a succession of interbedded sandstone and conglomerate. The basin fill varies in thickness along the valley axis from several hundred meters to over 3.0 km and formed through a complex history of displacement on the Fish Lake Valley fault system and a related array of faults that bound both sides of and internally dissect the valley.

The basin underlying Fish Lake Valley is a major hydrologic sink for the region and provides water resources for alfalfa production today and was the source of animal fodder since settlement in the 1860’s. In the northern part of the basin, a significant geothermal resource was developed through the stage of drilling deep-extraction wells in the 1990’s, but due to the inadequate capacity of existing transmission lines, was never completed. Borax was extracted from the northern part of the valley in the 1870’s and parts of the adjacent ranges to the east were extensively drilled during the 1980’s during borax exploration. A high concentration of boron and lithium was documented in Pliocene lake deposits exposed in the western Silver Peak Range. Ultimately the deposit was deemed to be noneconomic and all claims were vacated. Today, northern Fish Lake Valley is the focus of exploration for lithium brine.
Exploration for and development of lithium bine in Fish Lake Valley requires a comprehensive understanding of the geometry of the fault-bounded basins together with characterization of the lithology and spatial variability of the sedimentary-volcanic fill that form the reservoir. In this report, we present the results of nearly a decade of geologic and geophysical investigation of the geometry and kinematic evolution of the Fish Lake Valley basin and bounding fault systems. The report focuses on the three-dimensional geometry of the basins underlying northern Fish Lake Valley, the stratigraphy of the basin fill, and the geometry and history of displacement of the fault array that bounds and dissects the basin.

REGIONAL SETTING

The Fish Lake Valley basin is bounded on the west by and formed in response to displacement along the northern segment of the Death Valley – Furnace Creek – Fish Lake Valley (DV-FC-FLV) fault system (Fig. 1). The DV-FC-FLV fault system stretches northwesterly for over 300 km from the Mojave Desert at the southern end of Death Valley, California to Fish Lake Valley, Nevada. The fault is one of the most tectonically active structures in the western Great Basin (Rogers et al., 1991; Reheis and Dixon, 1996; Reheis and Sawyer, 1997; Shen-Tu et al., 1998; Frankel et al., 2007; Ganev et al., 2010; Foy et al., 2012) and records horizontal displacements, measured by GNSS (Global Navigation Satellite System) geodesy (Bennett et al., 1999; Oldow, 2003, Hammond and Thatcher, 2004, 2007) and the offset of geomorphic landforms (Frankel et al., 2007; Ganev et al., 2010; Foy et al., 2012), of between 4-6 mm/yr. Movement on the DV-FC-FLV fault system began in the mid-Miocene (Mueller et al., 2016) and the fault continues to move today. The fault system has a cumulative right-lateral displacement, determined from the offset of Proterozoic and Paleozoic lithologic facies, Mesozoic thrusts, Jurassic plutons, and Cenozoic volcanic rocks, of between 50 to 100 km (Stewart, 1967; McKee, 1968; Snow and Wernicke, 2000; Renik and Christie-Blick, 2013).

The DV-FC-FLV fault system terminates in northern Fish Lake Valley (Fig. 2). Displacement on the northern DV-FC-FLV fault system is transferred to a system of northwest striking transcurrent faults of Miocene to Holocene age in the central Walker Lane of west-central Nevada. The mechanism for displacement transfer from the FC-FLV segment of the fault system to structures in the central Walker Lane has changed through time (Oldow et al., 2008). Today, some of the displacement transfer is accomplished by structures at the northern end of the Fish Lake Valley (FLV) segment of the fault system and via faults intersecting the Furnace Creek (FC) and the FLV fault segments from the east. At the northern end of the valley, a fanned array of northwest, north-south, and north-northeast trending faults form a horse-tail array of structures, typical of the terminations of major transcurrent faults (Twiss and Moores, 2006). In addition to transfer at the end of the fault, a significant component of the displacement on the FLV fault system is transferred to west-northwest-striking transcurrent faults exposed in the ranges east of Fish Lake Valley. These left-lateral transcurrent faults carry displacement east for up to ~70 km and then north via a system of kinematically linked north-northeast extensional faults. During earlier stages of displacement transfer (mid-Miocene to Pliocene), motion on the FLV fault was accommodated...
by a structural stepover. The structural stepover connected the FLV fault to structures in the central Walker Lane via a low-angle detachment fault that underlies and is locally exposed in the ranges to the east of Fish Lake Valley.

Timing relations established by the regional stratigraphy indicate a major change in displacement transfer mechanism in the Pliocene. From about 12-15 Ma to 4-5 Ma, displacement from the FC-FLV fault was taken-up by northwesterly motion on the shallowly northwest-dipping detachment underlying the Silver Peak – Lone Mountain extensional complex (Fig. 3) east of Fish Lake Valley (Oldow et al., 1994; Oldow et al., 2008, 2009). From about 4-5 Ma to the Holocene, displacement has been accommodated by left-lateral motion on west-northwest transcurrent faults and kinematically related north-northeast extensional faults (Fig. 1) that underlie Clayton Valley and Jackson Valley to the east (Oldow and Geissman, 2013; Kerstetter et al., 2013; Katopody et al., 2013, 2016a, 2016b; Katopody and Oldow, 2015; Mueller et al., 2016) and by displacement on the horsetail array of structures underlying the northern end of Fish Lake Valley.

GEOLGY OF THE FISH LAKE VALLEY REGION

Fish Lake Valley is between 5 to 7 km wide in the south and stretches north for about 75 km where the northern end broadens to 20 km. In the north, the basin bifurcates into western and eastern arms separated by low hills (Volcanic Hills). The elevation of the narrow basin floor decreases from south to north from about 1580 to 1470 m, over a distance of about 50 km. In the north, where the basin is divided by the Volcanic Hills, which achieve elevations of around 1650 m, the western depression has elevations of about 1550 m whereas the eastern arm has elevations of around 1450 m.

Fish Lake Valley is surrounded by mountains. In the west, the valley is bounded by the Horse Thief Hills and the White Mountains (Fig. 2). The Horse Thief Hills form the southwestern flank of the valley and are a subdued ridge with an elevation of about 1700 m. In the White Mountains, elevations climb from about 2000 m in the south to as much as 4100 m in the north over a distance of 55 km. The elevation of the northern-most White Mountains abruptly decreases from 3900 to between 2500 m and 2200 m, where the physiography becomes subdued. The northern White Mountains merge with an east-west belt of hills about 40 km long that forms the northern part of the Volcanic Hills and northwestern part of the Silver Peak Range. These hills are the northern boundary of Fish Lake Valley and have a relatively constant elevation of 2000 m. The east-west trending hills are locally breached by narrow northerly-trending valleys with elevations of about 1440 m (Fig. 2). The eastern flank of Fish Lake Valley is made by the Silver Peak Range in the north and the Sylvania Mountains in the south. North to south, the Silver Peak Range rises from about 1900 m in 2800 m over a distance of 30 km and then decreases to 1800 m over a distance of 25 km. To the south, the Sylvania Mountains rise to 2400 m forming the southeastern flank of the valley.
Fault Geometry

An array of northwest-striking faults bound the eastern and western flanks of the southern and central parts of Fish Lake Valley and ramify into west-northwest, north-northwest, north-northeast, and east-northeast faults at the north end of the valley (Fig. 2). In the southern and central segments of the valley, the faults have a long continuous expression in the west but are discontinuous in the east. The western margin is characterized by the steep topography of the White Mountains, which contrasts dramatically with the relatively subdued physiography of the western Silver Peak Range and Sylvania Mountains in the east. In the north, the valley broadens with a prismatic morphology and is bounded on the west and east by west-northwest and north-northeast faults, respectively, and exposes north-south faults in the center of the depression..

The faults in the southern and central segments of the valley differ along the western and eastern margins of the topographic depression. The western flank is marked by a system of two parallel faults separated by about 1 km. The western fault strand separates bedrock from basin-fill units and has well developed triangular facets in Mesozoic granitoids and Proterozoic to Paleozoic clastic and carbonate rocks of the footwall. The eastern strand of the western fault system lies completely within basin-fill units and is characterized by profound fault-scarps, that reach heights of 120 m. The scarps are more-or-less continuously developed for the entire length of the Horse Thief Hills and White Mountains. The elevation of the scarps decrease in height from south to north. In the south and central parts of the valley, the faults show only minor decrease in height along strike with elevations diminishing to a maximum of 80 m in the north. The western fault array is stepped left (to the west) by 1 to 2 km at two locations 15 and 35 km north from the southern end of the basin. In contrast to the faults along the western margin of the valley, the morphology of the faults along the eastern flank of the valley vary substantially along strike. In the southern and central segments of the valley, the faults are often buried and scarps are poorly preserved and laterally discontinuous. With few exceptions, preserved scarps separate bedrock and basin-fill units and in a few instances occur as 1 to 2 m scarps in alluvium. For the most part, the eastern faults in this area are best expressed by splays within bedrock exposures and the morphology of the eastern valley margin is irregular and formed by a shallow westerly inclined ramp.

Surface expressions of faults that cross the southern and central segments of the valley are preserved two locations (Fig. 2). In the south, west-northwest to northwest trending scarps cross the valley from the Sylvania Mountains to the boundary between the Horse Thief Hills and southern White Mountains. A few isolated scarps in alluvium with north-northeast and east-northeast trends are exposed in the center and eastern sides of the valley about 3 km north of the west-northwest scarps. In northern the part of the central segment of Fish Lake Valley, north-northeast faults form a belt of anastomosing structures about 2 km wide (east-west) and 5 km long (north-south) just east of the central depression of the valley (Fig. 2).

The northern segment of Fish Lake Valley is underlain by a complex array of faults. For the sake of description, we divide the northern part of the valley into western and eastern domains, separated by a
north-northwest striking fault system stretching north from the axis of the central segment of the valley (Fig. 2). The north-northwest fault is well exposed in the northern Volcanic Hills, where it is marked by a Holocene scarp, and is approximately located along the western margin of the southeastern Volcanic Hills, where its trace is obscured by windblown sand. The southern segment of the fault is expressed by scarps in alluvium southwest of the Volcanic Hills and to the south the continuation of the structure is largely concealed by young alluvium and playa deposits. In the western domain, faults typically have west-northwest and east-northeast strikes and cut through bedrock exposures of Cenozoic and pre-Cenozoic rocks. In the eastern domain, faults strike east-northeast and north-northeast, forming long trace-length structures bordering and cross-cutting the lowest parts of the valley. A network of four major fault zones cut the basin and form the western range front of the Silver Peak Range and an anastomosing array of structures truncates the southern margin of the southeastern Volcanic Hills.

The prominent northwest-striking faults traced along the length of and forming the western margin of the Fish Lake Valley persist for about 15 km into the northern segment of the valley. In the northern segment of the valley, the surface expression of the northwest striking faults is progressively subdued along strike to the north. Fault-scarp heights decrease from a maximum of about 40 m in the south and become discontinuous scarps in alluvium 5 to 10 m high in the north. At the northern end of the western fault zone, the structure is characterized by a horsetail array of splays. Some of the structures pass into and cross the northern White Mountains as a zone of west-northwest trending faults that stretch along strike for 20 km, where they intersect east-northeast striking faults bounding Queen Valley (Fig. 2). A parallel system of west-northwest striking faults mark the transition between the White Mountains and the Volcanic Hills farther to the north. These faults are part of a network of structures up to 2 km wide that stretch about 20 km northwest from the northern part of Fish Lake Valley. The two west-northwest fault systems bound the topographically subdued part of the northern White Mountains and form a structural block about 10 km wide. The structural block is internally segmented by three east-northeast fault zones up to 1 to 3 km wide that connect the west-northwest fault systems (Fig. 2). To the east, north-northeast to east-northeast striking splays emanate from the northwest-trending western fault zone and make a conspicuous network of alluvial scarps discontinuously exposed across to the center of the valley (Fig. 2).

Faults along the eastern margin of northern Fish Lake Valley are much more prominent than those of the southern and central segments of the valley. The range-front topography of the adjacent mountains is abrupt and fault scarps between basin-fill units and bedrock and within the valley are prevalent. The topographic axis of northern Fish Lake valley has an arcuate trace that trends east-northeast in the south and changes orientation to north-northeast to the north (Fig. 2).

The eastern boundary of the valley is marked by a curvilinear fault zone along the western margin of the Silver Peak Range. The fault system is mapped for 30 km and trends east-northeast, north-northwest, and thence north-northeast from south to north. The fault separates basin fill deposits and bedrock in the south, where scarps are typically buried by canyon outwash. Along the central and
northern segments of the fault, which trends north-northeast, the structure is defined by a nearly continuous scarp up to 30 m high.

The boundary between the valley and the Volcanic Hills is formed by a physiographically subdued fault zone (Fig. 2). Both the southern and eastern flanks of the Volcanic Hills are underlain by a pediment of Cenozoic volcanic rocks covered by a thin veneer of alluvium. South of the Volcanic Hills, the valley is bounded by an east-northeast trending fault, which, to the north, shifts orientation to northeast and north-south.

The northern terminus of Fish Lake Valley is an east-west trending ridge of bedrock. The eastern 15 km of the ridge is composed of Paleozoic clastic and carbonate rocks overlain both unconformably and structurally by Oligocene ashflow tuff. The western 25 km of the topographic high does not expose Paleozoic strata and is underlain by Cenozoic volcanic and sedimentary rocks. The ridge is bounded and cut by an anastomosing belt of east-northeast striking faults between 2 and 4 km wide that composes the Coalville fault zone (Stewart, 1988).

A few faults are recognized within northern Fish Lake Valley. In the south, a fault cutting alluvial and playa deposits lies near the eastern flank of the depression and trends north-northeast for about 11 km. In the central part of the valley, the fault merges with the fault along the eastern flank of the Volcanic Hills. A curved fault bounds the eastern side of the playa underlying the northern part of northern Fish Lake Valley and merges with the western basin-bounding fault (Fig. 2).

The internal structure of the mountain ranges forming the eastern and western margins of Fish Lake Valley differ substantially. In the west, the Horse Thief Hills are cut by a bedrock fault that parallels the structural boundary with Fish Lake Valley. At the transition between the Horse Thief Hills and White Mountains, north-northeast faults that bound Deep Springs Valley merge with the northwest structures of the FLV fault zone. For most of the White Mountains, the footwall to the FLV fault system, is relatively intact. A major cross fault, striking west-northwest, cuts across the central White Mountains segmenting the range into two structural blocks. As outlined above, the northern White Mountains are separated from the higher parts of the range by a west-northwest striking fault zone that is part of the northern termination of the FLV fault. In contrast to the western ranges, the structure of the eastern margin of Fish Lake Valley is much more complex. Two major west-northwest fault zones, the Sylvania Mountain fault system and the Palmetto Mountain fault zone intersect southern and central Fish Lake Valley, respectively (Fig. 1). The west-northwest striking faults are major left-lateral structures that are traced for 60 to 70 km to the east. Cumulative sinistral displacement on the Palmetto Mountain fault is well constrained as 15 km (Oldow and Geissman, 2013; Katopody et al., 2013) with a comparable, but less reliable estimate of 16 km of sinistral displacement reported for the Sylvania Mountain fault zone (Oldow and Geissman, 2013). The Sylvania fault serves as a structural link between the southern FLV fault and extensional structures underlying Lida Valley to the east (Dunn et al., 2015). The Palmetto Mountain fault zone is a structural link between the central FLV fault zone (Mueller et al., 2013, 2014) and structures that occur within and along the flanks of Clayton Valley and Jackson Wash to the east (Katopody and Oldow, 2014; Katopody
The eastern boundary of the northern segment of Fish Lake Valley exposes the most complicated structure in the region. A series of west-northwest faults, many of which have contemporary activity, formed during Oligocene to Miocene north-south extension and accommodated the development of deep half-graben basin filled with tuff, andesite and volcaniclastic sedimentary rocks (Kerstetter et al., 2013, 2016). The structures were reactivated in the late Miocene to Pliocene and controlled deposition of sedimentary and volcanic rocks deposited in the upper-plate of the Silver Peak – Lone Mountain extensional complex (Oldow et al., 1994; 2003; 2009).

Lithologic Units

In this section, we summarize the stratigraphy and major lithologic units of the region (Figs. 3 and 4). In light of the emphasis of this study on lithium exploration, we focus our attention on the Cenozoic succession, which provides major source rocks and reservoirs for lithium brine. Although complicated by structures, the stratigraphy of all units is well established in excellent exposures found in the ranges and canyons in and around Fish Lake Valley. We divide the stratigraphy into pre-Cenozoic rocks, which constitute the basement complex for late Cenozoic deposition and deformation, and a Cenozoic succession that is divided into numerous units critical to assessing the history of basin evolution.

Pre-Cenozoic Rocks

Proterozoic to Jurassic layered and intrusive rocks dominate exposures of the ranges surrounding Fish Lake Valley (Fig. 3) and form the substratum on which Cenozoic volcanic and sedimentary rocks were deposited. Proterozoic and Paleozoic carbonate and siliciclastic rocks constitute part of the miogeoclinal succession of western North America (Bally, 1989; Oldow et al., 1989; Burchfiel et al., 1992) that records the history of continental break-up and development of a passive margin that initiated in the early pre-Cambrian. Deposition of shallow marine carbonate and clastic rocks continued through the Devonian and the stratigraphic succession reaches a thickness of 12 to 15 km. The miogeoclinal succession was deformed in the Devonian when deep water units of early Paleozoic age were thrust easterly over the western continental margin (Oldow, 1984; Oldow et al., 1989; Burchfiel et al., 1992). Minor exposures of Mesozoic clastic rocks are preserved along the western flank of the White Mountains and represent part of a marginal volcanic arc and back-arc basin that was constructed on Paleozoic units (Oldow et al., 1989; Burchfield et al., 1992). The Mesozoic layered rocks and pre-Mesozoic succession were intruded by Jurassic and Cretaceous plutons ranging in age from 175 to 85 Ma.

Cenozoic Rocks

We divide the Cenozoic section into three major sequences (unconformably bounded stratigraphic successions) in the north and two in the south (Fig. 3). Many of the units are lithologically heterogeneous and show significant lateral variations in composition, age, and thickness of constituent
rocks. The two sequences composing the stratigraphy in the southern part of the region are relatively simple and units can be traced laterally for 10’s of kilometers. In contrast, in the north, the succession is divided by three major unconformities representing the sequence boundaries. Additional unconformities are recognized within the individual sequences in the north (Oldow et al., 2009) but are of limited areal extent and omitted from our analysis. The complexity of the stratigraphy in the north is illustrated by the fact that virtually all of the lithologic units are observed to rest directly on the underlying pre-Cenozoic basement in some part of the region.

We summarize the regional stratigraphy in Figure 4, which illustrates the difference in Cenozoic deposition in the northern southern parts of the Fish Lake Valley region. In the north, stratigraphic complexity is a consequence of Oligocene to Miocene deposition during the formation of east-west trending extensional half-grabens (Kerstetter and Oldow, 2016; Kerstetter et al., 2016) and late Miocene to Quaternary deposition in basins controlled by kinematically linked west-northwest and north-northeast structures (Oldow et al., 2009). The early fault-bounded basins are exposed in many parts of the region and were wholly or partially reactivated during younger tectonism. In contrast, units in the south do not show abrupt changes in thickness or lithology and are laterally continuous for tens of kilometers. The continuity of the southern succession is indicative of deposition in a region of relatively subdued topography and tectonic quiescence.

In the descriptions below, we subdivide the units into time-slices for the northern and southern areas (Fig. 4). The oldest succession, composed of volcanic rocks and depicted as T1 on accompanying maps, is defined as the Ice House Canyon assemblage in the north and the Cucomungo Canyon assemblage in the south. The Ice House Canyon assemblage ranges in age between 23 to 15 Ma, whereas the Cucomungo Canyon assemblage is 16 to 11 Ma. These two successions are overlain by the Coyote Hole Group (T2) in the north. No comparable sequence of rocks exists in the south. The Coyote Hole Group is composed of sedimentary and volcanic rocks with ages from 13 to 6 Ma. The highest stratigraphic unit (T3) is the Fish Lake Valley assemblage, which is found both in the north and south areas and has an age range of 5 to 0.5 Ma.

Oligocene to Miocene (T1) The oldest succession (Fig. 3) consists of volcanic rocks that constitute the Ice House Canyon assemblage in the north, and the Cucomungo Canyon assemblage in the south (Fig. 4). The basal part of the Ice House Canyon assemblage is composed of crystal-rich ashflow tuff dated by K/Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ as 23 to 21 Ma (Oligocene). The tuff is overlain in angular unconformity by interbedded andesite flows and lahar, which are dated elsewhere by K/Ar at 19 to 15 Ma (Miocene). The thickness of the Oligocene tuff and Oligocene andesite varies dramatically over the northern part of the region. The thickness variations are, in many cases, due to deposition in east-west trending half-grabens active at that time (Kerstetter et al., 2013, 2016). The Oligocene tuff is not found in the southern part of the study region. Rocks of the same age as the andesite in the north are assigned to the Cucomungo Canyon assemblage in the south and consist of ashflow tuff with $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 16 to 14 Ma. The Cucomungo Canyon assemblage rests directly on pre-Cenozoic units. The ashflow tuff is
overlain by basalt flows and breccia dated by $^{40}\text{Ar}/^{39}\text{Ar}$ at 11.5 Ma. Units of the Cucomungo Canyon assemblage are exposed over a large region and are found on mountain tops and in valleys with elevations differing by over a kilometer. The lack of significant variation in the thickness of the basalt flows and breccias across the region indicates that little or no topography existed during deposition of basalt and possibly during deposition of the underlying ashflow tuff.

**Miocene (T2)** Late to mid-Miocene rocks, assigned to the Coyote Hole Group (Oldow et al., 2009), are exposed in the northern area but are absent in the south (Fig. 3). The rocks consist of a lower sedimentary succession consisting of interbedded shale, sandstone, and conglomerate (T2a), that passes upward into a vertical succession of air-fall tuff, volcaniclastic sediments, and ashflow tuff (T2b). The lower sedimentary rocks yield K/Ar ages from interbedded tuff of 11 to 13 Ma. The overlying tuff units yield K/Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 7 and 6 Ma. The units vary in thickness dramatically across the area and were deposited in fault-bounded basins formed during extension (Oldow et al., 2003, 2009).

**Pliocene to Pleistocene (T3)** The youngest stratigraphic sequence constitutes the Fish Lake Valley assemblage and is composed of interbedded sandstone, mudstone, and conglomerate that passes upward into medium- to coarse-grained sandstone and conglomerate. The unit is locally underlain by and interleaved with basalt that is widespread in the northern part of the study area. The lower age of the unit, based on K/Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ ages from air-fall tuff and basalt is between 5 and 4 Ma. The upper age determined in the southern part of the study area (Willow Wash in Cucomungo Canyon) is less than the youngest dated air-fall tuff (0.74 Ma) found a few hundred meters below the top of the unit and probably is about 0.5 Ma.

The Fish Lake Valley assemblage is of particular importance to this study because it represents the primary reservoir unit for lithium brine. Comparison of the stratigraphy observed in Fish Lake Valley to that reported for Clayton Valley indicates that the upper part of the Fish Lake Valley assemblage has the same lithology as the brine-rich reservoir (Zampirro, 2004). The lower part of the Fish Lake Valley assemblage is exposed in the low hills underlying the eastern part of Clayton Valley and is exposed in northern and southern Fish Lake Valley.

**Subsurface Basin Morphology**

Characterization of the subsurface morphology of the basin underlying Fish Lake Valley is based on the results of a regional gravity survey and lithologic logs from several boreholes. The boreholes are of limited areal extent and depth, but provide critical constraints on the internal structure of the basin and are used to calibrate a density structure for the basin used in our gravity depth modeling. The gravity data have good spatial coverage across the basin and are the primary observations used to determine the subsurface geometry of structures bounding and internally dissecting the basins.
**Borehole Data**

Borehole data provide critical constraints for the subsurface geology of the basin (Fig. 5). For the most part, the borehole information comes from water wells or shallow exploration wells that reach depths of a few hundred meters and which do not pass through the upper part of the Fish Lake Valley assemblage. Fortunately, several petroleum and geothermal wells in the northern part of the valley penetrate into the pre-Cenozoic basement and record the entire Cenozoic section.

Reheis et al., (1993) summarized well data for the central and southern segments of Fish Lake Valley that penetrated to depths up to 262 m. They recognized interbedded sandstone and gravel with horizons of lacustrine sandstone and shale to the bottom of their wells. Based on our understanding of the regional stratigraphy derived from exposures of the basin-fill along the periphery of the basin, the wells are restricted to the upper parts of the Fish Lake Valley assemblage.

In northern Fish Lake valley, eight wells within and adjacent to the southeastern Volcanic Hills and along the western range front of the Silver Peak Range (Fig. 6) have depths of up to 2.5 km and penetrate the pre-Cenozoic basement. These wells illuminate spatial variations in the distribution and thickness of Cenozoic volcanic and sedimentary units that make-up the basin fill (Fig. 7). Thirteen wells that do not penetrate basement are found in the northern Fish Lake Valley area and provide insight into the minimum depths and thicknesses of different parts of the Cenozoic section. In northern Fish Lake Valley, well logs show that rocks of the Ice House Canyon assemblage (T1) rest on Paleozoic basement in the Volcanic Hills and western Silver Peak Range. The units have thicknesses of 380 to 460 m in the southwestern part of the study area and thin dramatically to the east and northeast. Locally the units are absent. Rocks of the Coyote Hole Group show substantial differential thickness in the lower sedimentary section (T2a; Fig. 7) but relatively uniform thickness for the overlying tuff (T2b; Fig. 7). The sedimentary rocks at the base of the Coyote Hole Group range in thickness from at least 853 m to 30 m in the southwest and northeast, respectively. The overlying tuff succession (T2b) is exposed at the surface, and taken together with the lower contacts preserved in thirteen wells, indicates a relatively constant thickness of between 300 m to 350 m across the area.

**Observed Gravity**

The subsurface geometry of Fish Lake Valley was determined by analysis of gravity data. Both existing proprietary data (provided by Fish Lake Valley Power) and data freely available from the Pan American Center for Earth Studies (PACES) were combined with ~2500 measurements collected by faculty and graduate students from the University of Texas at Dallas to give a data coverage of ~3,500 stations. We carried out a series of gravity transects, where measurements were made at a nominal spacing of 300 m, (Fig. 8), using county roads and secondary dirt tracks across the study region. In most transects, data were collected using all-terrain vehicles, but for some transects, data were acquired on foot.
The data were collected using two Scintrex CG-5 gravimeters and positioning for the stations was determined using dual-frequency Leica GS 10 GNSS receivers. The gravity values for each station are the average of three series of 60 one-second measurements. All measurements are referenced to a common base station which was reoccupied both at the beginning and at the end of each field day. A secondary base station, located at the GNSS base station for each study area, was also measured twice a day. The gravity base station, located in Dyer, Nevada, was referenced to the National Geodetic Survey Gravity Reference Base Station 0455-1, located at the Tonopah airport 8 miles east of Tonopah, Nevada. GNSS data were collected in real time kinematic (RTK) mode and were post-processed in Leica GeoOffice. The station locations determined by GNSS have a relative uncertainty ranging between 0.017 and 0.011 m. All stations were located in an Earth Centered Earth Fixed (ECEF) frame controlled by the Continuous Observation Reference System (CORS) maintained by the National Geodetic Survey (NGS). The base station in Dyer, Nevada has a position of Latitude: 37° 52' 4.384698", Longitude: 117° 58' 6.337383" with a maximum uncertainty of 0.018 m (±0.011), and was used to transform all field observations into the ECEF frame.

The gravity data were used to compute a complete Bouguer anomaly (CBA) by combining our data with 72,645 regional stations downloaded from PACES (Fig. 9). We reduced all observed values using the standards established by the U.S. Geological Survey (Hildebrand et al., 2002) and the Standards/Format Working Group of the North American Gravity Database Committee (Hinze et al., 2003) for Bouguer computation using the spreadsheet by Holom and Oldow (2007). The computations are based on ellipsoidal heights, which were determined directly from the GNSS for our stations. For all other data sources (PACES and Fish Lake Valley Power) orthometric heights were transformed to ellipsoidal using the NGS National Oceanic and Atmospheric Administration program Geoid09. Consistency between our measurements and those of the other surveys was determined by reoccupying 26 pre-existing stations, which yielded a misfit of between -0.4 and 2.8 mGals. Gravity data were terrain corrected using an algorithm developed by Dr. John Ferguson at the University of Texas at Dallas. The Bouguer anomaly computation used a reduction density of 2.67 g/cm³.

We computed a residual Complete Bouguer anomaly (RCBA) for the region (Fig. 10). The irregularly spaced CBA values were gridded using a minimum curvature cubic spline algorithm with no tension; all points were honored. The Mickus et al. (1991) technique was used to remove the regional trends from the CBA by differencing the interpolated data produced both with and without the data from Fish Lake Valley and surrounding basins.

The regional RCBA was clipped to illustrate only negative values as an aid in characterizing the basins (Fig. 11) and clearly delineates deep basins underlying Fish Lake, Clayton, and Big Smoky Valleys and Columbus Salt Marsh. Maximum RCBA values for the basins range from -36 mGals in Columbus Salt Marsh, -28 mGals below northern Fish Lake Valley, -30 mGals in Big Smoky Valley, -21 mGals in northern Clayton Valley, and -14 mGals in southern Clayton Valley.
Depth Inversion

The RCBA was inverted to depth in 3-dimensions using the Geosoft Oasis Montaj GM-SYS 3D modeling software, which is based on the Parker-Oldenburg method (Oldenburg, 1974). Densities for the basin fill were established using borehole measurements in wells that penetrated Paleozoic rocks (basement) in northern Fish Lake Valley. We used the measurements from density logs and from measurements of gravity taken at wells that penetrated basement to establish an effective density of 2.4 g/cm³ for the undifferentiated basin-fill following the method of Litinsky (1989). The RCBA gravity values were upward continued to a common datum (Cordell, 1976) that corresponds to a maximum height of 460 m above the valley floor. Upward continuation resulted in a maximum loss to the RCBA signal of 3.5 mGal.

Not surprisingly, the depth model (Fig. 12) bears a strong resemblance to the RCBA (Fig. 11). Columbus Salt Marsh is about 4.0 km deep and forms a prismatic basin bound on all three sides by faults. The basin has a geometry similar to that underlying Rhodes Salt Marsh 30 km north, which we studied in detail (Ferranti et al., 2009) in previous investigations. Big Smoky Valley and northern Clayton Valley are underlain by a 3.0 km deep east-northeast and 2.6 km deep northwest trending basins, respectively. These two basins form on the flanks of the apex of a curved fault array that borders the northern and western margins of the Weepah Hills. The apex of the curved basin is underlain by an equant sub-basin 2.0 km deep. Southern Clayton Valley has a north-northeast axial basin 1.9 km deep that has two west-northwest basins branching west from the northern and southern ends. The southern and central segments of Fish Lake Valley have elongate northwest-trending deeps of 1.9 km and 1.7 km, respectively separated by a relative high with a depth of 1.3 km. The segmentation of this part of Fish Lake Valley basin coincides with the westerly projection of the Palmetto Mountain fault zone (Mueller et al., 2014). Northern Fish Lake Valley is separated from the northwest-trending part of the topographic low by a basement sill between 600-800 m deep (Fig. 12). Deep basins do not underlie alluvial deposits in the western part of northern Fish Lake Valley, but the eastern region is underlain by a 3.0 km and 2.6 km deep basement in the south and north, respectively. The northern basin extends west-northwest beneath the Volcanic Hills where depths of up to 2.5 km are recognized.

The depth inversion (Fig. 12) shows the subsurface distribution of the contact between Cenozoic rocks and the underlying pre-Cenozoic basement complex in the areas lying beneath the valley floors and the southeastern Volcanic Hills. The same contact is exposed in parts of the adjacent ranges and, for cases where only Cenozoic rocks are exposed, is buried beneath bedrock exposures. We do not illustrate the distribution of the depth to basement in the adjacent ranges but do show the depth to basement in the southeastern Volcanic Hills. We include the southeastern Volcanic Hills because it illustrates the impact of a thick sedimentary succession (T2a) on the gravity anomaly for the northern Fish Lake Valley. The pattern of negative gravity anomalies is created by the distribution of low-density rocks of the Fish Lake Valley assemblage (T3) and from the contribution of the anomaly by underlying
sedimentary rocks of the older sequence (T2a). Separation of the contributions of the two sequences is a critical concern of this project and will be outlined in detail in the following sections.

BASINS OF NORTHERN FISH LAKE VALLEY

Surface Geology and Structures

Of specific interest to this study is the geometry of structures that accommodate displacement transferred and partitioned from the northwest-striking Fish Lake Valley fault and how that displacement created the accommodation space for the accumulation of the Fish Lake Valley assemblage. As summarized above, the fault geometry changes systematically across the northern termination of Fish Lake Valley, with west-northwest and east-northeast striking faults underlying the western part of the valley and north-northeast and east-northeast striking faults dominating the structure of the eastern part of the valley. The two structural domains are separated by a through-going north-northwest trending fault that marks the western flank of the southeastern Volcanic Hills and which extends into and bifurcates the northern Volcanic Hills (Fig. 13).

The ranges bordering and lying within northern Fish Lake Valley expose rocks of the Cenozoic section, which locally are seen to rest both unconformably and nonconformably on Paleozoic carbonate and clastic rocks and Cretaceous granitoids. Units of the Ice House Canyon assemblage (T1) and the Coyote Hole Group (T2) are found throughout this area. In contrast, the Fish Lake Valley assemblage (T3) has a spatially restricted distribution. In the west, no sedimentary rocks of the Fish Lake Valley assemblage are exposed and the sequence is represented by basalt flows (Figs. 4 and 14). In the east, along the eastern flank of the southeastern Volcanic Hills and western flank of the Silver Peak Range, sedimentary rocks of the Fish Lake Valley assemblage are exposed on both flanks of the playa underlying northermost Fish Lake Valley.

In the western Silver Peak Range, rocks of the Fish Lake Valley assemblage consist of a lower succession of interbedded volcanogenic sandstone, mudstone, and minor conglomerate about 420 m thick. This section exposes thin basalt flows at the base (dated by $^{40}$Ar/$^{39}$Ar at 3.8 Ma) and passes upward into medium- to coarse-grained sandstone and pebble to boulder conglomerate with a thickness of about 250 m. The succession is faulted internally and separated from older Cenozoic rocks to the east by a north-northeast high-angle fault. The northern and southern boundaries of the Fish Lake Valley assemblage rocks are defined by two west-northwest striking faults. In the north, a buried west-northwest fault separates the Fish Lake Valley units from an ashflow tuff and andesite (T1) with a thickness of about 60 m. The older Cenozoic volcanic rocks rest unconformably on carbonate and clastic rocks of the Paleozoic basement. In the south, Fish Lake Valley is separated from uplands to the south by a west-northwest striking fault. In the uplands, tuff and andesite (T1) overlie Paleozoic carbonate and clastic rocks and are in turn overlain by sedimentary and volcanic units of the Coyote Hole Group (T2a and T2b, respectively). The western boundary of Fish Lake Valley assemblage outcrops is defined by a major down-to-the west normal fault (Emigrant Peak fault) which has a 30 m high scarp and is traced for about
15 km along strike. This fault separates the western margin of the Silver Peak Range from the playa and alluvial deposits of northern Fish Lake Valley.

In the southeastern Volcanic Hills, Fish Lake Valley assemblage rocks overlie tuff of the upper Coyote Hole Group (T2b). For the most part, the Fish Lake Valley assemblage is localized along the eastern flank of the hills and separated from Coyote Hole Group rocks farther west by a northerly striking fault with down-to-the east throw. The eastern boundary of the Fish Lake Valley assemblage exposures is marked by a north-northeast fault separating bedrock from the playa in northern Fish Lake Valley. In this area, Fish Lake Valley assemblage rocks consists of about 100 to 250 m of interbedded sandstone, mudstone, and conglomerate. To the west, the tuff of the Coyote Hole Group (T2b) has an exposed thickness of between 150 to 250 m and the stratigraphic bottom of the volcanic rocks is encountered in wells and exposed along the northwestern margin of the hills. In the northwestern Volcanic Hills, the tuff rests on volcaniclastic sedimentary rocks, dominated by fine- to medium-grained sandstone and conglomerate that constitue the lower part of the Coyote Hole Group (T2a). The sedimentary succession has an exposed thickness of at least 500 m, but no base to the lower part of the Coyote Hole Group (T2a) exists in the southeastern Volcanic Hills. The bottom of the unit is exposed in the northern Volcanic Hills, however, where it rests on andesite of the Ice House Canyon assemblage (T1a).

The northeastern part of northern Fish Lake Valley exposes a geometrically complicated array of faults. The faults are located along the eastern and western boundaries between the topographic depression and adjacent uplands. The faults separate playas and alluvial basins in the valley from bedrock exposures of Cenozoic rocks resting on Paleozoic units in the Silver Peak Range and Cenozoic rocks in the southeastern Volcanic Hills (Fig. 14). The eastern structural boundary is defined by a curvilinear range-front fault system that commonly exposes scarps in late Quaternary alluvium. The fault system stretches north from central Fish Lake Valley to the northern terminus of the valley. The eastern fault zone separates basin fill and bedrock and has well developed scarps for 30 km along strike. The fault changes orientation from east-northeast in the south (8 km) to north-northeast (22 km). In the north, the fault is truncated by east-west trending faults underlying the northwestern part of the Silver Peak Range. The western fault system separates the valley from the southeastern Volcanic Hills (Fig. 13) and changes orientation from east-northeast to north-northeast from south to north along strike.

The western Silver Peak Range is deformed in a broad zone (3 to 6 km wide) of faults that show down-to-the west displacement. In the southwestern exposures of the range, the faults strike east-northeast and are tracked along strike for 8 km to where they are truncated by a north-northwest fault zone. The north-northwest fault zone links the east-northeast faults to a system of north-northeast faults underlying the northern part of the range. The north-northeast faults are locally truncated by west-northwest structures, at the northern and southern boundaries of exposures of Fish Lake Valley assemblage rocks along the western part of the range. In general, the north-northeast faults step the Cenozoic section down to the west, with rocks stratigraphically underlying (T2) the Fish Lake Valley
assemblage exposed in the central part of the mountains. As outlined above, the Fish Lake Valley assemblage underlies the low hills forming the western part of the range.

The southeastern Volcanic Hills are deformed in a system of north-northeast and east-northeast faults. The hills are bounded on the east and west by north to north-northwest striking faults and on the south by east-northeast striking faults. The northern boundary relations are obscured by alluvial cover, but the juxtaposition of tuffs of the Coyote Hole Group (T2b) and Paleozoic rocks overlain by nearly 1 km of tuff of the Ice House Canyon assemblage (T1a) supports the interpretation of a major east-west trending fault forming the northern boundary. The fault forming the western boundary of the southeastern Volcanic Hills is obscured along much of the fault trace by windblown sand, but the fault is well located both at the north and southern ends (Fig. 13). The fault is part of a major right-lateral strike slip fault traced along strike for 30 km from central Fish Lake Valley into the northern Volcanic Hills, where it is truncated by the east-west trending Coaldale fault system (Fig. 13). The eastern flank of the southeastern Volcanic Hills gradually steps down to the east as a pediment, exposing Fish Lake Valley assemblage rocks, bound on the west and east by northerly-trending faults. The pediment is 1 km wide in the south and broadens to 3 km in the north, over a distance of 8 km. The eastern boundary fault separates the pediment from alluvial and playa deposits underling northern Fish Lake Valley. The southern boundary of the southeastern Volcanic Hills is also marked by a broad pediment 2.5 to 3 km wide that stretches east-northeast for about 11 km. The southern pediment is covered by a thin veneer of alluvium resting on rare outcrops of tuff of the upper Coyote Hole Group (T2b). The fault zone bordering the northern part of the pediment is discontinuously mapped for about 8 km and is commonly obscured by alluvium. The southern fault has local surface breaks in alluvium and playa deposits and coincides with the locus of springs along the eastern end of the structure.

Faults are not restricted to the margins of the valley. A north-northeast striking fault zone stretches along the axis of the valley for 23 km. In the south the fault forms the eastern margin of playa and fine-grained alluvial deposits and is traced south to north for 13 km where it forms the western margin of the northern playa. The fault does not extend north beyond the northern limit of the northern playa (Fig. 14) and is thought to be truncated by a west-northwest fault obscured by alluvial deposits washing south from the western arm of the Silver Peak Range.

Subsurface Basin Geometry

For the most part, the physiography of northern Fish Lake Valley reflects the geometry and distribution of deep basins (Figs. 15 and 16). Based on the depth inversion of the RCBA (Fig. 15), the topographic depression between the Silver Peak Range and Volcanic Hills is underlain by two deep basins of 3.0 and 2.6 km in the south and north, respectively (Fig. 16). The basins are separated by a subsurface ridge about 2.2 km deep that trends west-northwest. The basin in the south is prismatic in shape and is flanked by steep gradients in the gravity anomaly and depth inversion model on the northwest, southwest, and southeast sides of the central low. The gradients correspond to mapped faults
on the northwest and southeast margins, and are consistent with a southerly continuation of the north-northwest trending fault forming the western margin of the Volcanic Hills to the north. In contrast, the basin to the north has bounding gradients in the east and west that do not correspond to the orientation of north-northeast trending faults bounding the western Silver Peak Range and eastern Volcanic Hills (Figs. 15 and 16).

The basin beneath the northern part of the valley is part of a notable exception to the spatial correspondence between subsurface basins and physiography. The northern basin is part of a west-northwest gravity anomaly and depth inversion model low that underlies the Volcanic Hills (Figs. 15 and 16). The basin is up to 2.5 km deep in the west and is separated from the low beneath northern Fish Lake Valley by a minor north-northeast trending ridge. The axis of the deep depression does not correspond to the faults cutting the tuff of the upper part of the Coyote Hole Group (T2b) exposed at the surface. Rather, the basin was formed prior to the development of the structures that control the present-day morphology of the basin.

**BASIN MODEL**

Interpretation of the thickness of individual stratigraphic units contributing to the depressions in the underlying basement complex are based primarily on a grid of two-dimensional forward models. The models use a grid of geologic sections to predict gravity signatures compared to observed gravity in the region. We extract depth values for the basement and bottom of the Fish Lake Valley assemblage from the grid of sections. The data are hand-contoured to ensure consistency between isopachs and structural contours and geologic constraints.

**Cross Sections and Two-Dimensional Forward Gravity Models**

In this section, we present a grid of cross sections in northeastern Fish Lake Valley (Fig. 17). The geologic sections were constructed based on field relations and first-order depth determinations provided by the 3D inversion of the RCBA. The cross sections provide the means of deconvolving the contributions to the depth to basement models for each of the major lithologic successions constituting the Cenozoic section. In light of the fact that several units have similar or the same densities, it is critical to assess the contribution made by all the stratigraphic units to the negative RCBA (Fig. 15). The importance of this process is highlighted by the fact that a major west-northwest gravity negative predates deposition and subsequent deformation of the upper part of the Coyote Hole Group (T2b) in the Volcanic Hills. The eastern extent of this older basin coincides with the deep basement low beneath northern Fish Lake Valley, which contains both a thick succession of Fish Lake Valley assemblage rocks and older units of the underlying Coyote Hole Group (T2).

We use our regional synthesis of stratigraphic relations, well data, outcrop relations preserved in the surrounding hills and mountains, together with mapped faults to produce internally consistent geologic sections for northern Fish Lake Valley. By using a grid of cross sections, oriented west-northwest and
north-northeast, we insure internal consistency in the resulting three-dimensional model by requiring continuity of stratigraphic units and structures at the intersections of the lines.

The geologic cross-sections are tested against the smoothed gravity field interpolated from our irregularly spaced observations. Densities are assigned to the geologic units (Fig. 16) in the sections and a predicted gravity profile is produced from a forward modeling routine. Mismatches in the predicted and observed gravity for each section result in a revision of the geologic model to bring the section into conformity with the observed gravity. During successive iterations of the models, changes to one line requires revision and modification of all crossing lines; thus a single change in one line can impact the entire grid of lines, at least to some degree. We use two-dimensional models in the iterative process because they are fast and relatively easy to compute. A final step in the analysis would be to develop a three dimensional forward model, but this laborious and time-intensive process is beyond the scope of this project.

The gravity models are very sensitive to the densities assigned to specific stratigraphic units used in the sections. We established densities for each of the units by best fitting the gravity measured at boreholes that penetrated basement (Fig. 7). We computed the gravity signature for each borehole by using the depth and thickness of the stratigraphic units encountered in the wells. Down-hole estimates of density are provided for the wells and were used as initial values in the modeling. We modified the density of individual units to reproduce the observed gravity for each of the wells. Fortunately, the wells record different thicknesses of each of the stratigraphic units, and in some cases show omission of parts of the section. These lateral variations enhanced the capacity to establish individual densities for each of the stratigraphic units (Fig. 18).

The west-northwest sections (Sections A through E; Figs. 19 thru 23) illustrate the north to south changes in geology from the Volcanic Hills to the Silver Peak Range. In all sections, the western part is characterized by dramatic differences in the thickness of Fish Lake Valley assemblage. In Sections A, B, and C, the Fish Lake Valley assemblage achieves the greatest thickness beneath the valley floor (Figs. 19, 20, and 21). In Sections D and E (Figs. 22 and 23) the sedimentary rocks of the Fish Lake Valley assemblage are thin and rest on partially coeval basalt that increases in thickness to the west. The western parts of the sections are separated from areas to the east by a major north-northwest striking fault (Figs. 13 and 14) which has as much as 10 km of right-lateral displacement. East of the fault, the sedimentary rocks of the Fish Lake Valley assemblage are centered in the valley between the Volcanic Hills and Silver Peak Range. Thicknesses of Fish Lake Valley assemblage range from 250 m to 500 m on the western and eastern shoulders of the valley and thicken to 1,200 m in the north and to 1,800 m in the south. The underlying substratum varies in each of the sections. Volcanic rocks composing the upper unit of the Coyote Hole Group (T2b) have a relatively constant thickness of between 100 to 300 m across the area. In contrast, the sedimentary rocks of the Coyote Hole Group (T2a), which lie beneath the volcanic succession, show dramatic variations in thickness from about 2,000 m to 60 m. The lowest
Cenozoic unit in the area shows modest variations in thickness and typically is between 380 m and 460 m thick.

The north-northeast lines best illustrate the north to south variations in thickness of different parts of the Cenozoic section. In the western lines (Sections F and G, Figs. 24 and 25), the profound changes in thickness in the Coyote Hole Group sedimentary rocks (T2a) are well expressed and illustrate the steep bounding faults buried by the overlying volcanic tuff (T2b). Sections G and H (Figs. 25 and 26) show the abrupt variations in the thickness of the Fish Lake Valley assemblage, which range from 1,200 m and 1,400 m in the southern and northern basins, respectively. The easternmost north-northeast line (Section I; Fig. 27) illustrates the complex internal stratigraphy of the basin fill, with Fish Lake Valley assemblage resting on Ice House Canyon assemblage (T1) in the north, the upper part of the Coyote Hole Group (T2b) in the center and with a fault contact to the south, where the older stratigraphic units are exposed in the mountains.

Fish Lake Valley Assemblage Depth Model

The depth contour map for the Fish Lake Valley assemblage is presented in Figure 28. The map was derived from the geologic cross-sections and two-dimensional forward models of gravity, with depths to the base of the Fish Lake Valley assemblage determined at a spacing of 300 m along each section line. The depth determinations were contoured by hand to ensure that geologic constraints, such as lithologic boundaries and the location of faults, were honored. The zero edge of the Fish Lake Valley assemblage was located around the edges of the basin using geologic maps.

The Fish Lake Valley assemblage thicknesses show the general pattern reflected in the depth to basement (Fig. 16) determined in the three-dimensional gravity-depth inversion. The Fish Lake Valley assemblage has two major deeps of about 1.8 km in the south and about 1.2 km in the north. The southern basin is prismatic with the northern, southwestern, and southeastern boundaries marked by faults. The north and southeastern fault systems have surface expressions as small scarps in alluvium or long straight boundaries of playas. The fault boundary to the southwest, although well located by the gradient in thickness determined from our depth models, has no known surface expression, possibly due to the prevalence of windblown sand in this area. The northern basin is more rectangular in shape, with a 1.5 to 2.0 wide northern extremity that trends north-northeast broadening to nearly 3 km in the south. The basin is 8 km long and is segmented into a northern and southern sub-basins by a fault.

The two basins are separated by a topographic sill that has a depth of between 600 and 800 m. The sill, localized in the area known as “The Crossing” on topographic maps, stretches northwest-southeast from the Volcanic Hills to bedrock exposures in the western Silver Peak Range (Figs. 28A and 28B). The sill is about 1.7 km wide, along a north-northeast axis, and stretches northwest-southeast for nearly 4 km.

The deepest part of the southern basin lies near the northeast apex of the prism, where bounding faults converge. The subsurface deep corresponds with the surface gradient of topography, which is
lowest in the northeast (1430 m). No significant internal segmentation by internal faults is recognized in this basin. Based on the thickness distribution, the strata filling the southern basin probably have a shallow northeast dip.

The northern basin is internally segmented and flanked on all sides by faults. The northern sub-basin is bounded on the west and east by high-angle faults and the thickness of the Fish Lake Valley assemblage thickens from less than 200 m to nearly 1.2 km from north to south over a distance of 5 km. The southern sub-basin has thicknesses of Fish Lake Valley assemblage ranging from 950 m south of the basin segmenting fault and the eastern boundary and thickens to the southwest to 1.2 km (Figs. 28A and 28B). Unlike the basin in the south, the deepest parts of the northern basin lie beneath the southern end of the playa and farther south beneath windblown sand deposits with a surface elevation of about 1445 m. The thickness distribution in the northern basin suggests that strata within the basin will dip shallowly to the south.

SUPPLEMENTARY DATA

Included with this report are digital files, which are provided under separate cover. The files are Google Earth .kmz files depicting the depth contours of the Fish Lake Valley assemblage used to make Figs. 28A and 28B. Depth to basement and depth to the base of the Fish Lake Valley assemblage are also provided as XYZ files.

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Figure 1 Regional tectonic map showing major fault systems in the southwestern Great Basin. Complex array of faults in the Silver Peak – Lone Mountain region east of the northern end of the DVFLV fault zone from mapping during ongoing NSF funded research project (Oldow, unpublished). CVF, Clayton Valley fault; DVF, Death Valley fault; DSF, Deep Springs fault; DMF, Dry Mountain fault; EIF, Eastern Inyo fault; Fish Lake Valley fault; FCF, Furnace Creek fault; GF, Garlock fault; HMF, Hunter Mountain fault; MDF, Mount Dunfee fault; OVF, Oriental Wash fault; OVF, Owens Valley fault; PMF, Palmetto Mountain fault; PVF, Panamint Valley fault; PCF, Paymaster Canyon fault; SMF, Sylvania Mountain fault; SRV, Saline Range fault; SNF, Sierra Nevada fault; SLF, State Line fault; TPF, Towne Pass fault; WWF, Waucoba Wash fault; WMF, White Mountain fault. CCRB, Cucomungo Canyon Restraining Bend.
Figure 2  Shaded relief map of the Fish Lake Valley region illustrating major physiographic provinces and fault zones. BSV, Big Smokey Valley; CSM, Columbus Salt March; DSV, Deep Springs Valley; EV, Eureka Valley; HTH, Horse Thief Hills; FLV, Fish Lake Valley; LCR, Last Chance Range; NCV, Northern Clayton Valley; OV, Owens Valley; SM, Sylvania Mountains; SPR, Silver Peak Range; QV, Queen Valley; VH, Volcanic Hills; WM, White Mountains.
Figure 3 Geologic map of Fish Lake Valley region illustrating major lithologic units.
**Figure 4** Stratigraphic correlation diagram for the Fish Lake Valley region illustrating the timing relations, lithology, and north to south differences in the major rock units.

**Figure 5** Shaded relief map illustrating wells in the Fish Lake Valley region. Wells in southern and central Fish Lake Valley from Reheis et al. (1993).
Figure 6  Hillshade map of the northern Fish Lake Valley region illustrating well locations.

Figure 7  Interpreted and correlated stratigraphic sections of well logs in the northern Fish Lake Valley region.
Figure 8 Gravity station distribution in the Fish Lake Valley region. Detailed lines (300 m spacing) from the University of Texas at Dallas, gridded data in northern Fish Lake Valley is proprietary data provided by Fish Lake Valley Power, and the wide-spaced data from the Pan-American Center for Earth Studies (PACES).
Figure 9 Complete Bouguer anomaly map illustrating major gravity gradients in the Fish Lake Valley region. Reduction density used 2.67 g/cm$^3$. 
Figure 10  Residual complete Bouguer anomaly (RCBA) map of the Fish Lake Valley region showing positive and negative anomaly values. Residual computed using the Mickus et al. (1991) method, see text for discussion.
Figure 11  Residual complete Bouguer anomaly (RCBA) map of the Fish Lake Valley region showing only negative values to better illustrate the geometry of basins.
Figure 12 Depth-conversion calculated from RCBA using a constant basin-fill density of 2.4 g/m$^3$, illustrating the estimated depth to the pre-extensional basement of active basins.
Figure 13  Fault map of northern Fish Lake Valley region.
Figure 14  Geologic map of the northern Fish Lake Valley region.
Figure 15  Residual complete Bouguer anomaly (RCBA) for northern Fish Lake Valley.
Figure 16 Depth inversion from the RCBA showing the deep depressions of the pre-Cenozoic basement beneath northern Fish Lake Valley and the Volcanic Hills. The depth to basement below exposures of Cenozoic rocks in the adjacent mountain ranges is not shown.
Figure 17 Location of geologic cross sections in northern Fish Lake Valley.
Figure 18 Generalized stratigraphic section for the northern Fish Lake Valley area with brief lithologic descriptions and densities used in two-dimensional gravity models
**Figure 19** Section A crossing (Fig. 17) the northern Volcanic Hills, northern Fish Lake Valley, and western Silver Peak Range showing the correspondence between observed and calculated gravity.

**Figure 20** Section B crossing (Fig. 17) the central Volcanic Hills, northern basin in Fish Lake Valley, and the western Silver Peak Range showing the correspondence between observed and calculated gravity.
Figure 21  Section C crossing (Fig. 17) the southern Volcanic Hills, the central segment of northern Fish Lake Valley, and the western Silver Peak Range showing the correspondence between observed and calculated gravity.

Figure 22  Section D crossing (Fig. 17) the southern segment of northern Fish Lake Valley and the western Silver Peak Range showing correspondence between observed and calculated gravity.
Figure 23  Section E crossing (Fig. 17) the southern segment of northern Fish Lake Valley and the western Silver Peak Range showing correspondence between observed and calculated gravity.

Figure 24  Section F crossing (Fig. 17) the western Volcanic Hills and the southern segment of northern Fish Lake Valley showing correspondence between observed and calculated gravity.
Figure 25  Section G crossing the central Volcanic Hills and southern segment of the northern Fish Lake Valley showing the correspondence between observed and calculated gravity.

Figure 26  Section H crossing (Fig. 17) northern Fish Lake Valley and the western Silver Peak Range showing the correspondence between observed and calculated gravity.
Figure 27  Section I crossing (Fig. 17) through the western Silver Peak Range showing the correspondence between observed and calculated gravity.
Figure 28A  Google Earth image showing depth contours (200 m) to the base of the Fish Lake Valley assemblage and major faults. Source file included in attachments.
Figure 26B  Google Earth image showing depth contours (200 m) to the base of the Fish Lake Valley assemblage and American Lithium Corporation claim block. Source file included in attachments.