Constraints on Basin Formation and Deformation from Small Scale Geophysical Surveys in Eastern Death Valley Region, California

Gene A. Ichinose

Seismological Laboratory MS 174
University of Nevada
Reno, NV 89557-0141
phone (702) 784-4361
fax (702) 784-1766
email ichinose@seismo.unr.edu

Introduction

Geophysical surveys provide an important tool for the analysis of sedimentary basins, from defining broad basin geometry to identifying individual stratigraphic units which represent thousands of years of uninterrupted basin deposition [Christine-Blick and Biddle, 1985]. A 1996 University of Nevada Reno geophysics field course of ten graduate and undergraduate students provides a unique opportunity to investigate basin features using a multitude of geophysical techniques. The techniques included in this paper are potential field methods: magnetics and gravity, seismic imaging: shallow multichannel seismic reflection and refraction, and electromagnetic methods: shallow terrain conductivity and transient electromagnetics.

There is a poor consensus on the Cenozoic kinematics of the Death Valley Region and the Basin Range. This has lead to several conflicting tectonic theories based on various controversial observational constraints. The formation and deformation of basins during Cenozoic time provides constraints on the type and age of extension [e.g., Cemen et al., 1985; Link et al., 1985; Louie et al., 1996]

We investigate the Stewart, and Tecopa Valleys to delineate basin geometry and basin fill. The basin geometries can give insights into the age and type of extension. Shallow asymmetric basins are young and possibly formed by simple shear resulting in low angle detachments. Shallow to deep symmetrical basins are usually formed as grabens in a long term pure shear environment. Deep pull apart basins have a considerable amount of dextral shear like Death Valley but can form rather quickly. A correlation of geophysical signals to stratigraphic units could also help constrain the cessation of extension and the transition to quite deposition.

We also examine a range of possible slip rates along the State-line fault within the Pahrump Valley fault zone (PVFZ). This fault was originally found by *Ligget* and *Childs* [1973] and has been further examined by Schweickert [1989]. Schweickert claims that the State-line fault extends from Ivanpah Valley 50 km northward ending on the west side of Yucca Mountain, a proposed nuclear waste site. *Schweickert* [1989] and *Hoffard* [1991] both propose large displacements along the Pahrump Valley fault zone to be on the order of 20-25 km right lateral slip since late Miocene. This would suggest the existence of large lateral displacements east of the Furnace Creek-Death Valley fault zones which are considered the limit of Cenozoic strike slip faults. Recent Holocene to Pleistocene activity along the PVFZ poses a seismic risk to Yucca Mountain and Las Vegas, Nevada.

The survey areas in this study cover four sites near the California-Nevada border (Figure 1a and 2). We designate the Stewart Valley fault site as SVF in which shallow studies were done across geomorphic features identified as recent by *Hoffard* [1991]. The Stewart Valley playa site, designated as SVP involved a broad scale of north-south and east-west gravity and magnetic surveys. A same type survey was also conducted along the Old Spanish Trail highway (OSTH) just east of Tecopa, California. We finally revisit *Shields et al*., [1994] site designated as PVF and conduct electromagnetic soundings at the California-Nevada border in central Pahrump Valley.

Hoffard [1991] developed names for recent Cenozoic fault zones within the Stewart-Pahrump Valley region (Figure 1b). The Pahrump fault system (PFS) represents faults which bound a inferred pull apart basin in northern Pahrump Valley. The faults west of PFS are also involved in the pull-apart basin. PVFZ stretches from Ivanpah Valley to Yucca Mountain along the state line of California and Nevada. This fault system was previously referred to as the State-line Fault [*Schweickert*, 1989]. A high angle fault crossing Stewart Valley obliquely is considered to be involved in Mesozoic thrusts and has no evidence for recent movement [*Burchfiel et al*., 1983]. This fault is not considered in this study as belonging to PVFZ at our SVF site.

Regional Pre-Tertiary Geology

Details of per-Tertiary stratigraphy and structure of the Montgomery Mountains, Resting Spring, and Nopah Range are outlined by *Burchfiel et al*., [1983] and *Streitz et al*. [1991]. A thick miogeoclinal sedimentary wedge represents a Precambrian to Paleozoic passive continental margin which has been cut by several thrust faults from Mesozoic orogenies. This clastic wedge remains mysteriously unaltered thermally and increases dramatically in thickness from the Spring Mountains westward to a thickness of 5-10 km. The rocks exposed in the ranges includes Precambrian to Cambrian metamorphic gneisses, quartzites, and granites over lain by thrust sheets of Paleozoic sedimentary limestones and dolomites. These formations provide source regions for many Cenozoic sedimentary rocks within the mountain ranges and basins.

Geologic Setting and Local Stratigraphy

We provide a detailed summary of Tertiary to Quaternary units of the Pahrump, Stewart and Tecopa Valleys from *Malmberg* [1967], *Hillhouse* [1987] and *Hoffard* [1991] in order to gain an understanding of basin sedimentation.

Pahrump and Stewart Valley

Pahrump Valley is bordered on the east by the Spring Mountains, on the north and northeast by the Montgomery Mountains, and on the west by the east flanks of the Resting Spring and Nopah Range (Figure 2). The southern Valley extends into the Kingston Range and merges into Mesquite Valley. The Pahrump Valley Holocene-Pleistocene units include alluvial fan deposits occurring as lenses of boulders, gravels, sands, silts and clays thinning away from the range fronts. Unconsolidated and sorted gravels occur as channel deposits. Playa deposits include clay, silt, fine sand, and flocculated clay that are sometimes hard and compact. Sand dunes from lacustrine deposits are commonly stabilized by vegetation. Early Pleistocene to Pliocene deposits include fanglomerate to lacustrine deposits. Lacustrine deposits are characterized by Calcareous clays and silts to lesser amounts of find sands and muds. Pliocene debris flows derived from the Kingston Range are mainly found in the southern Pahrump Valley. Pliocene to Miocene tuffs and ash beds are exposed at the base of up thrown fault block along the PVFZ. These tuffs are white and light yellow to green beds of thinly laminated tuff which are extensively folded and faulted. These tuffs are highly consolidated and if saturated, will have low permeability but high conductivities.

Stewart Valley is bounded to the west by the Resting Spring Range, to the south by the Nopah Range and the east by the Montgomery Mountains. The northern end of Stewart Valley merges into Ash Meadows (Figure 2). The Quaternary stratigraphy of Stewart Valley is similar to Pahrump Valley such that both valleys probably shared the Pleistocene Lake Ash Meadows. A hiatus between the upper Pleistocene alluvial deposits and lower Pleistocene lacustrine deposits probably marks a time which the Lake drained through Stewart Valley into Amargosa Valley.

Tecopa Valley

Tecopa Valley is flanked to the east by the Resting Spring Range and to the west by Dublin Hills. The current drainage of Tecopa Valley extends northward through Greenwater, Amargosa and Chicago Valleys. When completely enclosed, Tecopa Valley filled to form a fairly deep lake since Neogene time. Overfilling or tectonic subsidence caused Lake Tecopa to drain through the south which resulted in deeply incised canyons in the Tertiary China Ranch Beds. Three exposed sections includes mudstone, claystone, and volcanic ash which become courser grain toward the edges of the basin near the tributaries. Three sharp and continuous ash falls within the lake sediments indicate direct air fall into the basin and date at 0.62, 0.73 and 1.6 Ma. Correlation of Lake Tecopa ash beds provides a total exposed thickness of 72 m [*Hillhouse*, 1987].

Regional Tectonics

Stewart, Pahrump, and Mesquite Valley straddle the California-Nevada border between the Spring Mountains and Death Valley. *Stewart*, [1987] recognized nine structural blocks within a northwest trending transition zone between the Sierra Nevada and Basin and Range Province. The Inyo-Mono and Spring Mountain structural blocks make up the southern Walker Lane belt and are separated by the Pahrump Valley and Stewart Valley fault zones.

Thick Versus Thin Skin Extension

Tectonic uplift and denundation coevolved with Cenozoic shearing to produce a complex formation of basins juxtaposed against high mountain ranges. Difficulty arises in trying to unravel extension from high angle normal and lateral slip faults from low angle detachment faults.

A controversy has evolved involving thick skin versus thin skin extension. Thin skin tectonics describes a mechanism of extension suggested by *Wernicke et al*. [1982] and *Wernicke et al*. [1988]. Wernicke and others reconstructed Mesozoic thrust faults across low-angle normal faults at the latitude of Las Vegas. His estimated amounts of extension range from 65 percent to over 100 percent west of the Spring Mountains since 20 Ma. Geologic features also suggest large scale thin skin extension. Detachment faults expose amphibolite facies metamorphic rocks and some case metamorphic core complexes [*Coney*, 1980] like the Amargosa Chaos which has been dated to be late Miocene event [*Topping*, 1993; *Fleck*, 1970]. *Stewart* [1983] suggests the Panimant Range block once sat 80 km southwest on top of the Black Mountains and was transported laterally during late Cenozoic extension to expose midcrustal rocks called turtleback surfaces.

Thick skin mechanisms proposed by *King* and *Ellis* [1990] involve high angle normal and lateral slip faults like the Furnace Creek and Death Valley faults which have many kilometers of offset [*Stewart*, 1967; *Stewart et al*., 1968; *Stewart et al*., 1970] although some dispute the validity of such displacements [*Wright* and *Troxel*, 1970; *Wright* and *Troxel*, 1976]. Stewart and others contend that large displacements have occurred along the Las Vegas shear zone, Furnace Creek and Death Valley fault zones. *Stewart* [1967] reconstructs thicknesses of quartzites to estimate displacements of over 30 miles along the Las Vegas shear zone caused by shearing and also by oroflexural bending. *Stewart* [1967], *Stewart* [1968] and *Christiansen* [1968; from *Stewart* 1968] suggests 10 to 12 miles of right lateral displacement along the Stewart Valley fault. Wright and Troxel disputes Stewart’s claims of structural offset and bending by limiting such offsets using linear geologic features in Death Valley to the Kingston Range. There is a building consensus from crustal studies using large scale COCORP seismic reflection lines that favors thin skin tectonics [*Serpa et al*., 1988].

Fluvial Lakes and Basin Deformation.

Wetter climates in the Pleistocene and closed drainage basins helped in the formation many of fluvial lakes. These lakes provide a record of deformation and also time constraints in basin formation [*Cemen et al*., 1985; *Link et al*., 1985; *Louie et al*., 1996]. Pleistocene Lake Tecopa filled from a drainage of 4080 sq mi to form a 98 sq mi lake surface [*Snyder et al*., 1964]. *Hillhouse* [1987] examined an exposed section of lacustrine deposits which includes mudstones, conglomerates, volcanic ash and tufa with an estimated total thickness of 72 m. Sediments show no evidence of tilting or deformation in what is believed to have been a fairly deep lake. Estimates from lacustrine thickness and average sedimentation rates would suggest a cessation of extension near 3 Ma but recent geophysical studies would place the thickness around 200 m. Other nearby Pleistocene lakes and their surface areas are mapped by *Snyder et al*. [1964]. They include Lake Pahrump (242 sq mi), Ash Meadows Lake (6 sq mi), Mesquite Lake (94 sq mi), Lake Manly (618 sq mi), and Ivanpah Lake (67 sq mi).

Previous Geophysical Studies

Recent small scale geophysical studies by Penn State, Massachusetts Institute of Technology and University Nevada Reno have help constrain cessation of active extension and displacements of the State-line fault. *Louie et al*. [1996] and *Shields et al*. [1994] have revised the thickness of the Lake Tecopa deposits to 200 m. This would suggest a cessation of active extension of at least 7 Ma, about 4 Ma earlier than suggested by *Hillhouse* [1987].

Basin models from gravity data suggests the center of the basin in Tecopa Valley to be 1 km deep and the basin edges to be 0.6 km deep [*Louie et al*., 1996]. Magnetics and gravity modeling has identified the Dublin Hills in the Tecopa Valley to be detached from the Resting Spring Range forming a half graben in northern Tecopa Valley near Shoshone, CA [*Gross et al*., 1992]. The maximum basin depths are generally smaller in Tecopa compared to 2-3 km basin depths for Pahrump and Mesquite Valley [*Shields et al*., 1994; *MIT Field Geophysics Course*, 1985].

Data Collection, Processing, Results and Interpretations From Modeling

Transient Electromagnetics

To supplement seismic reflection results we use transient electromagnetic (TEM) sounding and profiling. The TEM method is considered because of its sensitivity to saline pore fluids. TEM is also easy to employ and has good lateral and depth resolution unlike other electrical methods like DC resistivity. TEM is a recent and developing method in the field of geophysics. A rigorous explanation of this technique is lacking in textbooks but a paper by *Nabighian* and *Macnae* [1991] provides an introduction beyond the scope of this study. A small square receiver loop is place on the ground inside of a larger square transmitter loop. Current is passed through the transmitter loop as a boxcar function and induces a magnetic field in any subsurface conductors. The receiver loop measure the decay of the magnetic field when the AC current is shut off. Measuring only when the transmitter is off, gives TEM an advantage.

Early time sounding data are made using a Zonge GDP-16 multipurpose receiver and a ZT-20 3 amp transmitter. A square 40 x 40 m transmitter loop with 2 amps current is laid on the ground. The loops are positioned on the ground using a Brunton compass. We use a single turn 5 x 5 m square receiver loop in a receiver "in-loop" geometry which is centered on the ground within the transmitter loop. We record 31 gates from 1.222 us to 3.025 ms on a log time scale. The skin depth, δ, is used to estimate a depth of maximum sensitivity.

$$\delta = \sqrt{2/\sigma_0 \mu \omega} \tag{1}$$

where σ_0 is the half-space conductivity, μ is the magnetic permeability of free space and ω is the frequency. A δ of 70 to 200 m is estimated depending on σ_0 of 1 to 0.1 S/m (1 to 10 $\Omega\ m$). We stack of the transient response of several soundings to strengthen the signal to noise ratio and attain repeatability. The stack average transient response remained two to three orders of magnitude higher than the average deviation except for very late delay times where small responses fell below measurement deviations. Bad measurements at late delay times are usually susceptible to noise therefore are routinely edited out of the processing.

To construct a geoelectric image of the subsurface, the survey was conducted along a traverse using eight adjacent loops from approximately 100 to 420 meters across the SVF 200 line in figure 3. Our survey location was chosen across what appears as Holocene geomorphic feature seen in air photos as a vegetation lineaments [*Hoffard*, 1991]. The stacked soundings of apparent conductivity, σ_{app}, and delay time, t_i, are contoured in a psuedosection. TEM works best on the assumption of flat geoelectric layers. The complex response 320 meters along SVF 200 suggests some disruption possibly due to impedance of ground water flow from fault 1 (Figure 4).

We further investigate a conductivity anomaly in southern Pahrump valley found by *Shields et al.* [1994] who interprets the anomaly to be a major splay of the State-line fault. Three TEM soundings were placed relative to point 0.0 meters of Shields *et al.* traverse. We use the same loop geometry but spaced the loops about 630 meters apart.

We invert in-loop TEM soundings at the PVF site by using a time-domain deconvolution technique to produce 1D conductivity profiles. *Smith et al.* [1996] analytically outlines this technique and applies deconvolution to, "spike", σ_{app} psuedosections of a buried sulfide deposit. It is well known that σ_{app} psuedosections do not represent the true geoelectric structure therefore inversion schemes help in understanding the true structure [*Spies* and *Eggers*, 1986; *Taylor et al.*, 1992]. The TEM soundings are first converted to σ_{app} versus t_i, which was provided to us by the GDP-16 data logger. Delay times are converted to depths, z_i using the product of apparent resistivity and delay time over the loop radius squared

$$z_i = \frac{\rho_i t_i}{\mu_0 l^2} \tag{2}$$

where ρ_i is the apparent resistivity, t_i is the delay time, μ_0 is the magnetic permeability of free space, and l is the loop radius. The problem of this conversion is the occurrence of depth reversals. We assume depth reversal are caused by noise which are edited out before inversion. Further processing is needed to convert σ_{app} to real conductivity. A function with an amplitude decay of $w_i = z_{\max} / z_i$ is removed from the apparent conductivities by deconvolution which is similar to dividing the spectrum of the apparent conductivities by the spectrum ofw_i. A time domain inversion technique developed by *Claerbout* [1979] allows the use of smoothing constraints. A trade off exists between smooth models and model misfit. We make no analysis of model fit versus smoothness in this study but instead use existing data to search for realistic models. Right panels in figure 11 show inverted conductivities versus depth profiles. The conductivities increase instead of decrease as seen in the σ_{app} profile. This is an artifact of the inversion which tries to fit a model to where data is sparse.

Anomalous signatures from fault 1 shown in SVF site gravity and seismic reflection profiles are not seen in TEM psuedosections (Figure 4). The fault 1 trace indicates possible Holocene displacement and very little vertical offset. Fault 2 in figure 4 provides a very good signature in the TEM psuedosections. The high σ_{app} could be the result of disruption in the flat geoelectric structure from possible vertical displacements. Fault zones can act as ground water barriers leading to an increase in vegetation that allows the growth of sand dunes which mistakenly appear as fault scarps [*Hoffard*, 1991]. A high apparent resistivity of 0.1 to 10 Ωm at depth indicates very saline pore fluids. Previous electromagnetic studies in nearby basins indicates a highly conductive top layer over a layer that contains more fresh water [*MIT Geophysics Field Course*, 1985].

TEM inversion results at PVF site show a 5 m vertical offset of a 15 m thick (σ_{app} = 0.3 to 0.6 S/m) conductive layer across scarp 1 (west side down). Previous geophysical studies at this site indicate 3 scarps and an anomalous geophysical signature at scarp 1 (Figure 11). This is interpreted to be a more resistant ash bed displaced along the PVFZ with normal and possibly dextral shear. The ash beds and fault zone act as ground water barriers which unfortunately degrades the fault scarp. The sounding at PVF loop 11 shows another 5 m thick layer at 15 m depth with the same conductivity as the ash beds. This indicates several possible strands in the PVFZ accommodating dextral shear.

Shallow Terrain Conductivity

We initially investigate possible seismic reflection and TEM sites on the basis of air photos and shallow terrain conductivity measurements. The terrain conductivity works on the same basis as other controlled source inductive electromagnetic methods like TEM [*Telford et al*., 1990]. A transmitter coil induces magnetic fields in subsurface conductor which produces a measurable current in a receiver loop. The coupling of the transmitter, conductor, and receiver obeys a Maxwell‘s equation of electromagnetics called Faraday’s law of induction.

Three terrain conductivity traverses were made by a Geonics EM31 terrain conductivity meter. Station spacings were approximately 6 meters apart and locations of every fifth station was surveyed in by a theodolite to within 15 cm accuracy from a nearby benchmark. We made 185 in-line conductivity measurements at the SVF site along traverses labeled SVF100, SVF200 and SVF300 in figure 4. We profile in-line and transverse boom directions to see the response of parallel relative to perpendicular conductors across the traverses. Transverse measurements relative to in-line measurements differed by 1 mS/m on average but up to 10 mS/m at some locations. This small difference indicates the absence of nearby perpendicular conductors which could affect in-line measurements. The σ_{app} measurements only reflect the subsurface conductivity from 0 to 1.8 m depth (one-half the boom spacing). The measurements appear to be dominated by exposures of dry flocculated (popcorn texture) clays observed along the traverses. The average near surface conductivity $<\sigma_{app}>$ of 40 mS/m (25 Ωm) from the EM31 is within the measurements of the first few TEM gates.

Gravity

We use gravity geophysics to investigate the bedrock depth and basin geometry which would be assumed as the largest lateral density contrast in this survey. Previous gravity data shown by *Hoffard* [1991] and *Wright* [1989] indicates a 15 mGal difference within the Chicago and Stewart Valley basins. This magnitude is small compared to 50 mGal variation seen in the Pahrump Valley basin. Gravity data collected by *Shields et al*. [1994] also indicates large 50 mGal difference in the Tecopa Basin which translates into a 1 km basin depth using a $\Delta\rho = 0.6\ g/cc$. Gravity data from Pahrump Valley were inverted by *Shields et al.* [1994] and indicates a 2.5 to 3.0 km deep basin.

Gravity traverses were made at 3 sites OSTH, SVP and SVF (Figure 2). We made 60 gravity measurements using a La Coste Romberg gravimeter. A sensitivity of 0.01 mGal is usually reported for such instrument. A base station was set in Shoshone, CA and local benchmarks were tied to Shoshone. We returned to a base station every 2 hours to find variations in meter drift. Meter readings were reduced to complete Bouguer anomalies using standard methods [*Telford et al.*, 1990]. Terrain corrections were provided by a *Calif. Div. Mines Geol.* [1979] report. Terrain corrections to the I ring (approximately 3-4 km) were used from the report and nearby rings were done visually in the field. We survey station locations using Global Positioning System (GPS) and constrain elevations using total station to within 10 to 20 cm. Station spacing varied from 30 meters for SVF and 500 meters for SVP and OSTH.

Complete Bouguer anomalies were prepared for an inversion by removing regional trends. A linear trend removal was used to obtain residuals. Residual values were normalized and inverted for basin depth and geometry of the Stewart Valley and Tecopa basin. The Talwani inversion is based on columns with varying thickness and a single density contrast [*Talwani et al.*, 1959). A $\Delta\rho = 0.67 g/cc$ was used for a contrast between basin fill to bedrock.

Gravity modeling results from SVP, SVF and OSTH sites are shown in figure 15 as basin depth models. Model misfits range from 0 to 4 mGals which could translate to a several hundred meter misfit. The basin geometry in Stewart Valley (SVP) show a maximum 300 m thick asymmetrical basin (east side deeper). The OSTH modeling results show a complex basin basement interface which could instead represent lateral density contrasts rather than real subsurface topography. The average basin depth for OSTH is 175 m. Gravity measurements made at SVF are closely spaced and probably represent the response of lateral density variations in the basin sediments. Using a large density contrast of 0.67 g/cc gives a maximum sediment thickness of 50 m possibly overlying more compact sediments.

Magnetics

Magnetics provides additional constraints on subsurface anomalies inferred from gravity anomalies like intrusive dikes and faults. This technique can also indicate shallow features like buried basalt flows too small for large scale gravity surveys. We collect magnetic data using total field Geometrics 856 proton precession magnetometers which have a typical accuracy of 0.1 to 1 nT [*Breiner*, 1973]. A continuous running base station records time variations like micropulsations and diurnal variations. The background field is approximately 52500 nT at these latitudes. Station spacing varied from 6 m for SVF to 50 m for OSTH and SVP. Station locations were surveyed by GPS and total station. Raw data are reduced to 216 total-field measurements by removing time variations and instrument drifts. Magnetic data collected at SVF appears to be within the ±50 nT range of noise like typical micropulsations and magnetic storms. Previous studies in this area have found variations on the order of 100nT from known anomalies [*Shields et al.*, 1994] along the Pahrump Valley fault. *Louie et al.*, 1996 also found 700 nT magnetic anomaly along the east side of Tecopa basin from possible basalt sections.

A magnetic anomaly at the OSTH site shows a > 600 nT anomaly. The OSTH magnetic anomaly also exhibits an asymmetrical shape. The 3D magnetic response from buried prisms calculated for various sizes and depths can explain the OSTH anomaly. Using an inclination of 60 degrees and a declination of 14 degrees, we find best fit models for the OSTH anomaly with a elongated prism (x=100 y=∞ z=50 meters) cross-sectional area and depth less than 100 m. The susceptibility contrast range from 0.02 to 0.009, within the range of basalt. At this location, the flow direction appears to be north-south. The geometry, depth and susceptibility contrast indicate a possible buried Quaternary age olivine-rich basalt flow inbedded in lacustrine deposits from Pleistocene Lake Tecopa investigated by *Hillhouse* [1987] and *Chesterman* [1973]. Magnetic anomalies in SVP show 400 nT variations near the eastern side of Stewart Valley. If these variations are due to subsurface magnetic susceptibility contrasts then this possibly indicates a change from alluvial sediments to Tertiary volcanics eroded into buried alluvial fans.

Shallow Seismic Reflection

Seismic reflection provides the best resolutions out of all other geophysical methods. The basic technique of seismic reflection consists of generating seismic waves which reflect, diffract, and refract from vertical acoustical impedance contrasts (product of velocity and density). These waves returning from the subsurface are recorded at the surface with a series of geophones [*Telford et al*., 1990]. Erosional unconformities are easy to spot as reflectors and largest reflectors may occur as large variations in acoustical impedance like a basin-basement erosional surface.

We collect seismic reflection data with 10 parallel inverse spreads using a 32 bit 48 channel Bison data logger. The inverse spread is a lose term given to a stationary spread. The position of the geophones with respect to the source changes with each new shot point from zero offset to a maximum of 144 m in increments of the geophone spacing. This spread type is different from conventional end-on spread which has a constant shot-receiver offset after each shot point by moving the entire spread. Moving the entire spread after each shot is expensive and time consuming but necessary where good distance coverage and fold is needed. Each line covers 48 shot points trending approximately east-west direction at the SVF site. Single 100 Hz vertical component geophones were buried at 1.52 m intervals. We use a 12 lb sledge hammer source for approximately 4800 shots repeating 10 shots at each shot point. The record length was 0.25 s with a sampling rate of 0.125 ms.

The following data reductions have been made to separate the signal from noise and to obtain clear reflected signals. Bandpass filter corners were tested and picked at 50 to 500 Hz to optimize reflected signals. Constant velocity stacks (CVS) were made to find the best velocities for common midpoint stacks (CMP). CVS were visually checked for coherent reflections for 11 CVS at 200 m/s increments.

We measured the apparent dominant frequency of reflected signals around 0.103 ms two way travel time to get vertical and horizontal resolution. We estimate a vertical resolution of 1.6 m at 260 Hz around 87 m depth. The horizontal resolution is estimated at 17 meters using stacking velocity of 1700 m/s. A 200 m/s error in picking stacking velocities would translate to about ± 10 m error in depth accuracy.

A CMP time section for a single SVF line is shown in figure 4. The depths of late reflectors could be as deep as 256 meters using an average velocity of 1025 m/s. Reflectors are truncated at 250 meters offset from flag 183. This location correlates with a shallow gravity low and vegetation lineaments seen in low sun angle air photos. The inverse spread geometry results in a decrease of fold at the ends of the spread. This leads to distortion along the section edges due to surface waves which do not get stacked out of the time section. One prominent reflector at 0.125 seconds two way travel time is truncated and seems to reflect the most energy. This reflector could represent the transition from non-reflective lake bed sediments to alluvium or bedrock. A reflector at 0.03 s is possibly the transition of the saturated to unsaturated lake bed or alluvial sediments.

Pre-Stack Migration

We attempt a pseudo 3D inversion of reflection seismic data by using pre-stack migration. Pre-stack migration correctly positions dipping reflectors and also inverts time sections into geologic depth sections. Pre-stack migration is done after filtering from 200 to 1000 Hz and trace equalization. The migration is dependent on good velocity estimates. We use velocities from 2 layer refraction models (Figure 5). Pre-stack migration differs from post stack techniques because it improves events which do not stack well due to large dips but is usually slower and expensive.

Migration results are visualized using 3D volume rendering to enhance features which cannot be seen in opaque images. Real time rendering simplifies the search for buried stream offsets or facies changes in the data volume. Figure 6 shows a high resolution stack volume without migration constructed from collated CMP stacks. Figure 7 shows pre-stack migration results at 3 different horizontal depth slices 0 (surface slice), 24, and 48 meters. Half-ellipsoidal features are artifacts of the migration. The 24 m reflector could suggest a tuff fall or a transition to more consolidated sediments. The fault seen in CMP stacks can also be seen in the migration. The depth slice at 24 m depth indicates a possible right lateral offset of at least 18 m in the reflector on the east side of the fault. A sedimentation rate of 0.01 mm/yr would place the offset reflector around early Quaternary to Pliocene age.

Shallow Seismic Refraction

Seismic refraction is the analysis of first arrivals of refracted waves traveling along subsurface layer interfaces. This method assumes a positive velocity gradient which is one limiting factor of refraction surveys [*Burger*, 1992]. Refraction methods are usually employed along with reflection to constrain seismic velocities. While the refraction method gives good average velocities versus depth, it cannot give the image resolution provided by reflection.

The expected depth of exploration in refraction experiments is limited to the spread length. The depth of exploration is usually 1/3 to 1/4 times the cable spread length and in this case the first arrivals at the longest offsets could be from 42 m depth. We made first break picks from opposite end shots along the seismic reflection line to construct a reversed travel-time versus shot-receiver offset plot. Forward models using *Burger's* [1992] Refractmod fit a flat 2 layer model. An emergent 1620 m/s refractor seen at 10 meter depth could represent the transition from unsaturated to saturated sediments suggested from local residential wells. The surface velocity is around 350 m/s which is common for shallow depths in unconsolidated modern playa sediments.

Integration of Modeling Results

Basin Geometry of the Stewart Valley.

Gravity modeling along the north-south (N-S) and east-west (E-W) axis of SVP reveal an asymmetrical basin, 300 m deep along the N-S axis. The basin shallows along the N-S axis towards the north end of Stewart Valley. The asymmetry could suggest a tear-shape east-tilted half graben. Using dip measurements of the Cambrian Bonanza King Formation in the Resting Springs Range [*Burchfiel et al*., 1983], one can project the formation under the basin sediments of Stewart Valley. A dip of 30 degrees would place the axis of the basin near 1000 m depth, much deeper than SVP basin model. The misfits in the gravity modeling would make the basin deeper towards the east and possibly fitting the geologic model. If the basin fill is syndepositional, then the basin gravity model could reflect lateral density variations rather than basement topography. Further investigation into the depositional history of Stewart Valley could also reveal if it had a similar formation as Tecopa Valley. *Hoffard* [1991] indicates that Stewart Valley formed as a pull apart basin from CA Highway 178 into Ash Meadows and the Amargosa Desert using gravity data from *Mabey* [1963]. The basement appears to shallow towards the low hills separating Stewart Valley from Ash Meadows which conflicts with Hoffard's model. Although the Pahrump and Stewart Valleys might of shared a fluvial lake since Neogene time, their basin geometries are different (Figure 16).

The magnetic anomaly along the western side of the Montgomery Mountains coincides with the basin slope and continues into the range. The anomaly's high frequency content suggests a shallow source although there are no mapped extrusive volcanics in this range. This anomaly could be the result of Quaternary volcanic sediments in the Montgomery Mountains and in clastic wedges within the basin edges.

Stewart Valley Basin Fill And Deformation - Implications toward Seismic Hazards.

Seismic facies analysis of reflection data collected at SVF suggests a possible 24 m thick package of non-reflective sediments overlying more reflective sediments. The velocity of this layer appears to be 1620 to 1700 m/s from refraction modeling and velocity analysis. The geoelectric structure at SVF appears homogeneous with increasing conductivities versus depth toward 1 S/m. These sediments likely represent unconsolidated playa or lacustrine deposits saturated with saline fluids or consisting of large amounts of clay. A layer of non-reflective sediments also exists in Tecopa Valley bounded below by a prominent reflector at 25 m depth [*Louie et al*., 1996]. *MIT Geophysics Field Course* [1985] reports a 25 m layer with similar velocities between 1500 to 1600 m/s in Mesquite Valley. This reflector is possibly a regional depositional or erosional event rather than a lithologic variation because velocities do not change across this reflector down to 50 m depth. Considering a thickness of 25 m and the unconsolidated lithology, the age of this reflector could range from 0.1 to 1 Ma. One possible explanation for this sharp regional reflector is a air-fall tephra, a 0.5 to 4 m thick tuff with a K-Ar date of 0.62 Ma. *Hillhouse* [1987] called this the Lava Creek tuff which is underlain by 10 to 30 m of lacustrine sediments in Tecopa Valley.

The deformation in the SVF sediments appear to be right-oblique with a minimum displacement of 18 m. Early Pleistocene lacustrine deposit are also offset by 15 m along the main escarpment in the southern part of PVFZ [*Hoffard*, 1991]. We determine a slip rate by considering the age of the offset marker and the amount of displacement. A problem arises due to the portioning of slip along several fault splays and around extensional pull apart basins which can lead to an underestimate of slip. One can infer from a minimum 18 m of right lateral offset since 0.6 Ma that the slip rate along the State-line fault could on the order of 0.03 mm/yr. Long term average slip rate estimates from 19 km offset of Paleozoics reported from *Stewart* [1968] give slip rates of 0.8 mm/yr and offsets up to 25 km from *Schweickert* [1989] give 1 mm/yr since the early Miocene. We conclude that the resolution of slip along the northern portion of PVFZ is poorly constrained or that there is a lack of slip in Stewart Valley relative to Mesquite and Pahrump Valleys within the last 0.6 Ma.

Conclusions

A basin model for Stewart Valley is interpreted to contain mainly normal extension with little evidence for a pull apart basin. This does not rule out large possible displacements along the State-line fault which could of accommodated a phase of predominately normal extension prior to 11 Ma and a more recent overprint of dextral shear along preexisting normal faults.

We also check the timing and displacement along the PVFZ. We estimate slip rates from geological and geophysical constraints to be 0.03 to 1 mm/yr. With the slip rate and cessation of extension 11 Ma, the PVFZ could only attain 0.3 to 10 km of separate dextral displacement, only half the amount proposed by *Stewart* [1968] and *Schweickert* [1989]. This slip rate should be considered as a single minimum constraint. Further work should be done to refine the dates and displacements in order to obtain more reliable estimates. A motion of 0.03 mm/yr can be considered insignificant but slip rates approaching 1 mm/yr are active by California standards.

Acknowledgments. The gradate and undergraduate students who participated in 1996 University Nevada Reno geophysics field course were: Gene A. Ichinose, Mike Hasting, Zakir Kanbur, Shean-Der Ni, Gabriel Plank, Steve D. Bowman, David R. Aglietti, Andrew Hessel, and James Ollerton. The instructor, J. N. Louie is the principle investigator in this project.

References

Breiner, S., *Applications Manual For Portable Magnetometers*, Geometrics, Sunnyvale, CA, 1973.

Burchfiel, B. C., G. S. Hamill, and D. I. Wilhelms, Structural geology of the Montgomery Mountains and the northern half of the Nopah and Resting Springs Ranges, Nevada and California, *Geol. Soc. Am. Bull.*, 94, 1359-1376, 1983.

Burger, H. R., *Exploration of the Shallow Subsurface*, Prentice Hall, New Jersey, 1992.

California Division Mines and Geology, Principal Facts and Sources for 857 Gravity Stations on the Death Valley 1 by 2 deg. Quadrangle, California, *Calif. Div. Mines Geol.*, Open File Rep., 79-9, 1-42, 1979.

Cemen, I., L. A. Wright, R. E. Drake, and F. C. Johnson, Cenozoic sedimentation and sequence of deformation events at the southeastern end of the Furnace Creek strike-slip fault zone, Death Valley region, California, in *Strike – Slip Deformation*, *Basin Formation*, and *Sedimentation*, Edited by K. T. Biddle and N. Christie-Blick, pp. 127-141, Society of Economic Palentologists and Mineralogist Special Publication, 1985.

Chesterman, C. W., Geology of the northeast quarter of Shoshone quadrangle, Inyo County, California scale 1:24000, *Calif. Div. Mines Geol.*, Map Sheet, 18, 1973.

Christie-Blick, N. and K. T. Bibble, Deformation and basin formation along strike-slip faults, in *Strike – Slip Deformation*, *Basin Formation*, and *Sedimentation*, Edited by K. T. Biddle and N. Christie-Blick, pp. 1-34, Society of Economic Palentologists and Mineralogist Special Publication, 1985.

Claerbout, J. F., *Fundamentals of Geophysical Data Processing*, International Series in the Earth and Planetary Sciences, McGraw-Hill, New York, 1979.

Coney, P. J., Cordilleran metamorphic core complexes - An overview, in *Cordilleran Metamorphic Core Complexes*, Edited by Crittenden, M. D. Jr., P. J. Coney, and Davis, G. H., 153, pp. 7-31, Geol. Soc. Am. Mem., 1980.

Fleck, R. J., Age and tectonic significance of volcanic rocks, Death Valley area, California, *Geol. Soc. Am. Bull.*, 81, 2807-2816, 1970.

Gross, M., J. Louie, R. Laird, S. Nichols, D. Verdonck, N. Yonkers, and J. Zhang, M. Gross, and J. N. Louie, Geometry of normal faulting in Tecopa Valley, California from magnetic surveys, *California Geology*, 45, 110-117, 1992.

Hillhouse, J. W., Late Tertiary and Quaternary geology of the Tecopa basin, southeastern California scale 1:48000, *U.S. Geol. Surv. Invest. Map*, I-1728, 1-16, 1987.

Hoffard, J. L., Quaternary tectonics and basin history of Pahrump and Stewart Valleys, Nevada and California, Masters Thesis, Univ. Nevada Reno, Reno, NV, 1991.

King, G. and M. Ellis, Origin of large local uplift in extensional regions, *Nature*, 348, 689-693, 1990.

Ligget, M. A. and J. F. Childs, Evidence of a major fault zone along the California-Nevada state line, *NASA Rep. of Invest.*, CR-133140, E73-10773, 1-13, 1973.

Link, M. H., M. T. Roberts, and M. S. Newton, Walker Lake basin, Nevada: An example of late Tertiary to recent sedimentation in a basin adjacent to an active strike-slip fault, in *Strike – Slip Deformation, Basin Formation,* and *Sedimentation*, Edited by K. T. Biddle and N. Christie-Blick, pp. 105-125, Society of Economic Palentologists and Mineralogist Special Publication, 1985.

Louie, J. N., A. Cetintas, V. Chekuri, W. Corchuelo, Y. Lei, L. Li, G. Mekala, S. Ozalaybey, J. Raskulinecz, and R. B. Morrison, Geophysical constraints on the cessation of extension and thickness of basin fill in Tecopa Valley, California: for Geology of the Eastern Mojave Desert (in prep), *Geol. Soc. Am. Special Paper*, 1996.

Mabey, D. R., Complete Bouguer anomaly map of the Death Valley region California, scale 1:250000, *U.S. Geol. Surv. Invest. Map*, GP-305, 1963.

Malmberg, G. T., Hydrology of the valley-fill and carbonate rock reservoirs, Pahrump Valley, Nevada-California, *U.S. Geol. Surv. Water – Supply Paper*, 1832, 1-47, 1967.

MIT Field Geophysics Course, A geophysical study of Mesquite Valley: Nevada-California border, *J. Geophys. Res.*, 90, 8685-8689, 1985.

Nabighian, M. N. and J. C. Macnae, Time domain electromagnetic prospecting methods, in Electromagnetic Methods in Applied Geophysics, II, pp. 427-509, *Soc. Expl. Geophys.*, 1991.

Schweickert, R. A., Evidence for a concealed dextral strike-slip fault beneath Crater Flat, NV, *Geol. Soc. Am. Abs.* with Programs, 21, pp. 90, 1989.

Serpa, L., B. de Voogd, L. Wright, J. Willemin, J. Oliver, E. Hauser, and B. Troxel, Structure of the central Death Valley pull-apart basin and vicinity from COCORP profiles in the southern Great Basin, *Geol. Soc. Am. Bull.*, 1437-1450, 100.

Shields, G., M. Sleeman, J. N. Louie, K. Allander, R. Brigham, R. Crosbie, L. Trimble, R. Tucker, and H. Zhan, Magnetic and conductivity signature of an active fault: Results from geophysical surveys in southern Pahrump Valley, CA-NV border (abstract), *Eos Trans. AGU*, 75, 1994.

Smith, R., R. N. Edwards, and G. Buselli, An automatic technique for presentation of coincident-loop, impulse-response, transient, electromagnetic data, *Geophysics*, 59, 1542-1550, 1996.

Snyder, C. T., G. Hardman, and F. F. Zdenek, Pleistocene lakes in the Great Basin, *U.S. Geol. Surv. Misc. Geol. Invest. Map*, I-416, 1964.

Spies, B. R. and D. E. Eggers, The use and misuse of apparent resistivity in electromagnetic methods, *Geophysics*, 51, 1462-1471, 1986.

Stewart, J. H., Possible large right-lateral displacement along fault and shear zones in the Death Valley-

Las Vegas area, California and Nevada, *Geol. Soc. Am. Bull.*, 78, 131-142, 1967.

Stewart, J. H., J. P. Albers, and F. G. Poole, Summary of regional evidence for right-lateral displacement in the western Great Basin, *Geol. Soc. Am. Bull.*, 79, 1407-1414, 1968.

Stewart, J. H., J. P. Albers, and F. G. Poole, Summary of regional evidence for right-lateral displacement in the western Great Basin: Reply, *Geol. Soc. Am. Bull.*, 81, 2175-2180, 1970.

Stewart, J. H., Extensional tectonics in the Death Valley area, California: Transport of the Panamint Range structural block 80 km northwestward, *Geology*, 11, 153-157, 1983.

Stewart, J. H., Tectonics of the Walker Lane Belt, western Great Basin: Mesozoic and Cenozoic deformation in a zone of shear, in *Metamorphism* and *Crustal Evolution of the Western United States*, Edited by W. G. Ernst, Ruby Volume VII, pp. 684-713 , Prentice-Hall, New Jersey, 1987.

Streitz, R. and M. C. Stinson, Geologic map of California: Death Valley sheet scale 1:250000, *Calif. Div. Mines Geol.*, Sacramento, CA, 1991.

Talwani, M., J. L. Worzel, and M. Landisman, Rapid gravity computation for two-dimensional bodies with application to the Mendocino submarine fracture zone, *J. Geophys. Res.*, 64, 49-59, 1959.

Taylor, Ken, Mike Widmer, and M. Chesley, Use of transient electromagnetics to define local hydrology in an arid alluvial environment, *Geophysics*, 57, 343-352, 1992.

Telford, W. M., L. P. Geldard, and R. E. Sheriff, *Applied Geophysics*, Cambridge University Press, New York, 1990.

Topping, D. J., Paleogeographic reconstruction of the Death Valley extended terrain: Evidence from Miocene large rock avalanche deposits in the Amargosa Chaos basin, California, *Geol. Soc. Am. Bull.*, 105, 1190-1213, 1993.

Wernicke, B., Low-angle normal faults in the Basin and Range Province: nappe tectonics in an extending orogen, *Nature*, 291, 645-648, 1981.

Wernicke, B., J. E. Spencer, B. C. Burchfiel, and P. L. Guth, Magnitude of crustal extension in the southern Great Basin, *Geology*, 10, 499-502, 1982.

Wernicke, B., G. J. Axen, and J. K. Snow, Basin and Range extensional tectonics at the latitude of Las Vegas, Nevada, *Geol. Soc. Am. Bull.*, 100, 1738-1757, 1988.

Wright, L., Late Cenozoic fault patterns and stress fields in Great Basin and westward displacement of the Sierra Nevada block, *Geology*, 4, 489-494, 1976.

Wright, L. A. and B. W. Troxel, Limitations on right-lateral, strike-slip displacement, Death Valley and Furnace Creek fault zones, California, *Geol. Soc. Am. Bull.*, 78, 933-950, 1967.

Wright, L. A. and B. W. Troxel, Summary of regional evidence for right-lateral displacement in the Great Basin: Discussion, *Geol. Soc. Am. Bull.*, 81, 2167-2174, 1970.

Figure Captions

Figure 1a. A base map of showing the western extent of major strike slip faulting and the extensional extent of the Death Valley break away zone. The regional distribution of ranges and valleys are also referenced. (Modified from Wernicke et al., 1988 and Hoffard, 1991).

Figure 1b. A summary of the structures in Pahrump Valley. The Pahrump Valley fault zone (PVFZ) extends from Ivanpah Valley to the west side of Yucca Mountain, Nevada. (Modified from Hoffard, 1991).

Figure 2. A map showing the 4 sites in this study. Stewart Valley Fault (SVF), Pahrump Valley Fault (PVF), Old Spanish Trail Highway (OSTH), and Stewart Valley Playa (SVP).

Figure 3. A air photo of the SVF site where EM, gravity, magnetics and seismic reflection surveys were performed. Numbered dots represent flag locations. Flag spacing was approximately 6.1 meters but flags shown here were surveyed using total station. The road near flag 101 is Ash Meadows Road. Dashed lines perpendicular to the lines are the locations of State-line fault.

Figure 4. Multiple geophysical responses across the SVF site. Reduced magnetic anomaly across all three traverses indicate no variations. The complete Bouguer anomaly indicates a low density material at fault 1 location. Terrain conductivity from EM31 reflects strong surface conductivity variations. The dashed line represents SVF 200, dotted line represents SVF 300 and solid line represents SVF 100. Surface topography is plotted along with the location of fault traces from the air photo. Fault 1 indicates very little vertical topography compared to fault 2. TEM psuedosection image and contours are plotted using a log scale for conductivity (S/m). CMP stack is positioned below topography and TEM psuedosection for a comparison of fault anomalies.

Figure 5. Top panel shows the travel-time offset distance plot of first break picks at the SVF site. Two layer interpretation of refracted waves is shown below. The forward profile was shot from east to west.

Figure 6. 3D data volume constructed from 10 SVF seismic lines. The images of Pahrump Valley fault zone high resolution stack volume, with stacked positive reflectivies as darker, more opaque objects. The top image shows the volume face corresponding to the southeastern most stack. The bottom image shows a time slice at 103 ms two-way time.

Figure 7. Pre-stack migration results using the 3D data volume shown in figure 6. Images of Pahrump Valley fault zone high resolution 3D pre-stack migration volume, with migrated positive reflectivies as darker, more opaque objects. The left image shows the entire volume from a southerly, elevated viewpoint. The center and right images show depth slices at 24 and 48 m respectively. Slight warps or reflectivity changes in a layer truncated by the Stewart Valley fault at 24 m below the surface suggest a right lateral offset of more than 18 m.

Figure 8. SVP gravity flags for north-south and east-west lines. Magnetics was also done along both gravity lines.

Figure 9. SVP east-west reduced magnetics and gravity measurements. The Talwani inversion results are shown below as a basin depth model. Notice the asymmetry with a shallow sloping western basin edge. There is a 2:1 vertical exaggeration. Magnetics show a lateral change at the western edge of the Montgomery Mountains.

Figure 10. SVP north-south reduced magnetics and gravity measurements and basin model at 2:1 vertical exaggeration. The basin shallows toward the northern edge of the Valley. Magnetics shows very little interpretable response.

Figure 11. TEM soundings and modeling results at the PVF site. The position of loop 9 through 11 are shown over previous geophysical survey results from 1994. Ash beds are exposed in the PVFZ at scarp 1 and appear to be displaced in the TEM inversion results.

Figure 12. OSTH gravity and magnetic sites across the eastern side of Tecopa Valley.

Figure 13. OSTH reduced magnetic and gravity measurements. The magnetic anomaly at 7400 meters reflects a classic asymmetrical shape. Gravity results and modeling indicate either strong basement topography of strong lateral density variations.

Figure 15. A comparison of gravity traverses at SVP E-W, SVP N-S, OSTH, and SVF sites.

Figure 16. A geologic basin model for SVP which supports a tilted half graben.