MULTICOMPONENT GEOPHYSICAL ANALYSIS IN DRILLING TARGET DEFINITION IN AN EXTENDED TERRANE

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ABSTRACT

In the process of selecting a site for **a** deep test hole, the Geothermal Program Office used a hroad range of geophysical tools to optimize data recovery for funds expended. The area, known as the Indian Wells Valley, is a poorly-explored region of suspected significant crustal extension located approximately 50 km south of the Coso Geothermal development area in eastern California, U.S.A. Recent studies in the area have produced encouraging prospects of a resource in the valley itself which is filled with up to 2.5 km of sedimentary rocks thereby masking the geothermal signature. One hundred twenty kilometers of high-quality reflection seismic data were interpreted along with an analysis of seismicity and gravity data in an effort to select a location for a deep test well. Geophysical data indicate that the crust in this area is approximately 15% thinner than other Basin & Range locations.

INTRODUCTION

The Basin and Range Province of the western United States is one of the most widely studied extensional regions in the world. It is also one of the more heavily developed areas for geothermal resources. Geothermal power facilities ranging From a few megawatts to as much as 250 MW are in operation and there are numerous sites which have electrical power generating potential, hut await a positive change in market conditions before development proceeds.

The United States Department of Defense, Geothermal Program Office has becn conducting an active exploration program in the western U.S. for more than ten years with a focus on location of exploitahle resources beneath lands under their control. The Coso power generation project located in the Coso Mts. (see Figure 1) is at present the only site that has heen developed. Intensive geological and geophysical investigation has been ongoing for the past three years in the Indian Wells Valley (IWV) which lies immediately south of the Coso Mountains in an attempt to define a resource that is helicved to he thereunder (Figure 1). A key part of that exploration strategy has heen the siting and drilling of a second deep (3048 m) test hole (SNORT #2) in the western part of the IWV. The location of that test hole was based on shallow temperature gradient drilling, results from the SNORT #1 deep test hole, seismicity information (hypocenters and focal plane mechanisms), and analysis of more than 120 km of reflection seismic data. The working hypothesis is that the location is coincident with the area of maximum extension in the upper crust. The resource if it exists, is "blind", which is to say that there are no surface manifestations of hydrothermal activity. This is one of the few cases where an attempt has heen made to locate a blind resource.

GEOLOGIC SETTING

The IWV is located in the western portion of what is referred to as the Basin and Range of the United States. This area has heen the site of crustal extension for at least the last 17 million years (Zohack and Thompson, 1978) with the most active sites moving from east to west. Wernicke (1992) suggests that at the present time, the Owens Valley located immediately adjacent to the eastern boundary of the Sierra Nevada is the locus of extension along a N 60° W trajectory. This is consistent with independent findings of Argus and Gordon (1991) that the Sierra Nevada microplate is moving on a N 36° W trajectory at a rate of 11 ±1 mm yr^{-1} relative to the stable North American craton. In a recent update of that model, Argus (personal communication) has found that the Owens Valley sites are moving southeast at a rate of 1.5 to 2.0 mm yr^{-1} relative to the Sierra

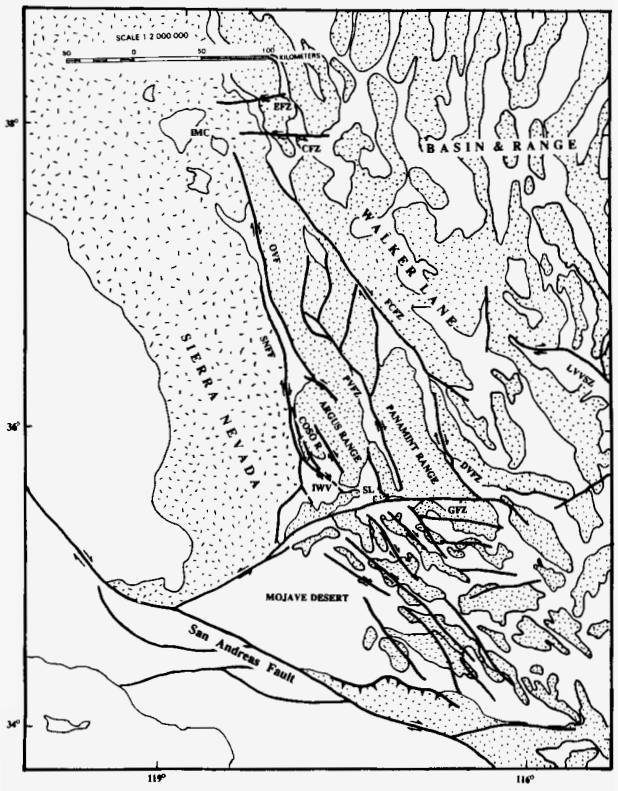


Figure 1. Physiographic map of the western Basin and Range, U.S.A. Significant features discussed in the text include: DVFZ-Death Valley Fault Zone. GFZ-Garlock Fault Zone, IWV-Indian Wells Valley, PVFZ-Panamint Valley Fault Zone (from Monastero, 1992). The Panamint Valley proper lies immediately west of the PVFZ.

Nevada which means that only 15-20% of the extension hetween the North American and the Pacific plates is being accommodated in the Owens Valley. Presumahly the remainder is distrihuted across the Eastern California Shear Zone in a manner similar to that suggested by Dokka & Travis (1990).

The total amount of extension over the Basin and Range has heen estimated as high as 250 km over the distance from the western boundary of the Colorado Plateau to the castern front of the Sierra Nevada (Wernickc, et al, 1988) with the extension being partitioned between strongly extended domains (upwards of 350%) and intervening areas of virtually no extension (Wernicke, 1992).

The westward progression of extension in the Basin and Range is demonstrated in the independent work of numerous investigators. Extensional activity in the eastern portion of the B & R began approximately 30 Ma (Gans, et al. 1985) while extension in the central Basin and Range did not start until 17 Ma (Zohack and Thompson, 1978). Extension in Death Valley, the most studied of all of the extensional terrains, commenced approximately 12 Ma (Stewart, 1983) and continues to the present: the total amount of

extension is estimated at 80 km with a net transport direction of N 60° W. Schweig (1989) found that extension in the Coso Mountains and the Saline Range west of Death Valley commenced approximately 4 Ma while Hodges, et al (1989) and Zhang, et al (1991) place the initiation of opening of the Panamint Valley at 3.6 Ma. Duffield, et al (1980) show that the opening of the Coso Wash. immediately east of the Coso Mountains, and initiation of "step faulting" in that area began in the period of 3-2 Ma based on radiometric dating of basalts.

The IWV itself was first considered as a locus of extension hy Monastero (1992) on the hasis of stratigraphic information obtained during the drilling of a 2375 m deep test hole (see Figure 2) designated SNORT #1. Examination of the stratigraphy of that hole indicated that the majority of the sediments in the hasin were derived from the nearhy Sierra Nevada which was initially uplifted 9 Ma (Jones, 1987; Huber, 1981) and most recently underwent an episode of uplift as late as 2 Ma (Jones, 1987). Analysis of the well cuttings showed that much of the sequence was poorly-consolidated, angular to sub-angular quartz grains with traces of Fe-Mg minerals and some feldspar. The suite was typical of a proximal hasin fill facies with a granitic source. prohahly in the form of coalescing alluvial fans.

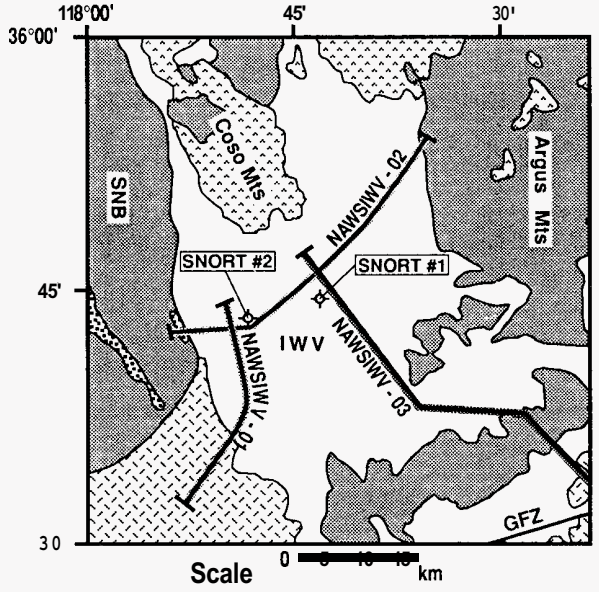


Figure 2. Map showing Indian Wells Valley and surrounding area. Also shown are the locations of the SNORT #1, SNORT #2, and reflection seismic lines designated NAWSIWV-92-01. 02, or 03.

Three temperature gradient holes drilled in the eastern part of the IWV showed gradients in the range of 46 to 66°C km^{-1} and quartz conductive geothermometer calculations on lluid samples yielded values of 100 to 140°C for original fluids. The maximum bottom hole temperature at SNORT #1 was 122°C with a gradient of 42°C km^{-1} for the entire hole. However, there was substantial hydrothermal alteration of the basement and evidence of pervasive fracturing with chloritically-altered fault gouge throughout.

On the hasis of these data, the GPO moved ahead with plans to acquire reflection seismic data in the IWV in hopes of better understanding: the nature of hasement fracturing, the depth to crystalline hasement, and the nature of the crustal thickness. Ultimately, the goal was to drill a deep test holc for geothermal resources in the valley.

METHODS

Geophysical evaluation involved three types of data: reflection and refraction seismic, seismicity, and gravity. The first was acquired hy the GPO in the summer of 1992. The seismicity data are recorded on a continuous hasis hy means of the Cal Tech/U.S. Geological Survey seismometer network. The gravity data are a compilation of diverse sets of data acquired ovcr a twenty year period from approximately 1965 to 1985.

Reflection seismic data were acquired using a 360-channel recording system and four 20,000 kg vihrators as a sound source. Geophone group spacing was SO m with 18 phones per group. Vihrator points were on every group which made the multiplicity of the data 180 fold giving a very high signal-to-noise ratio. The maximum offset in a split-spread configuration was nearly 10 km. Data were recorded at 2 ms sampling rate with a record length of 8 seconds. Sweep frequency was 12 to 72 Hz. In all, 122 km of data were acquired over three lines (Figure 2). The layout of which was hased on known geologic structure from surface mapping and was intended to he reconnaissance in nature. One of the principal criteria for line location was to ensure the broadest possihle coverage in the hasin while crossing what were helicved to he hasin-hounding structures.

As noted ahovc, seismicity data were ohtained through the Cal Tech/U.S. Geological Survey seismometer network which in the IWV area consists of 18 permanent locations. Geophones have a peak response of 1 Hz or 2 Hz. Data are transmitted to the Cal Tech processing center in Pasadena, CA, and are rebroadcast hy means of satellite link to end-users such as GPO. The system has heen in continuous operation since 1981 during which time nearly 10,000 events with magnitude M≥1.0 have heen recorded. Focal plane mechanism solutions were hased on a minimum of sixteen station responses and are considered A-quality data.

Refraction data were provided by the southern Sierra Crustal Dynamics (SSCD) project, a multi-university consortium funded principally hy the National Science Foundation with assistance from the Department of Energy and the GPO. Data were acquired in the fall of 1993 hy means of two long (325 and 400 km) lines of self-contained recorders laid out in a crossing pattern oriented NS/EW. The energy source was a series of high explosive charges ranging in size from 1,500 kg to 5,000 kg.

Gravity data (Figure 3) show a deep negative anomaly heneath the IWV. The location of this feature is centered just to the north of seismic line #2. It has heen viewed as resulting from a thick pile of unconsolidated detrital material produced hy erosion of the Sierra Nevada. Modelling has shown that it would take a wedge of sediment nearly 3,000 m thick to produce this type of anomaly. This has not heen borne out by drilling at SNORT #1 nor hy the reflection seismic data.

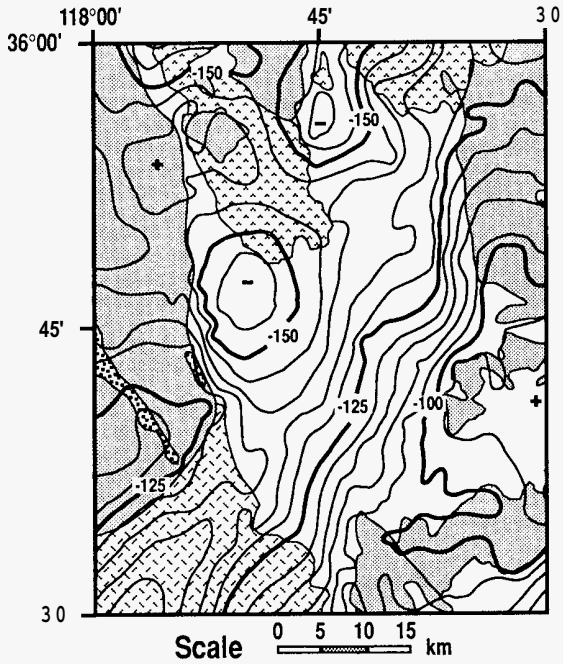


Figure 3. Gravity data for the Indian Wells Valley. Contour interval is 5 milligals. The deep gravity low is located directly heneath the western IWV. Adapted from Nilsen and Chapman, 1971.

RESULTS

Of the three types of geophysical data used in this effort, the most informative and most heavily relied upon was the reflection seismic. Figure 4 shows a portion of seismic line #2 in which several key

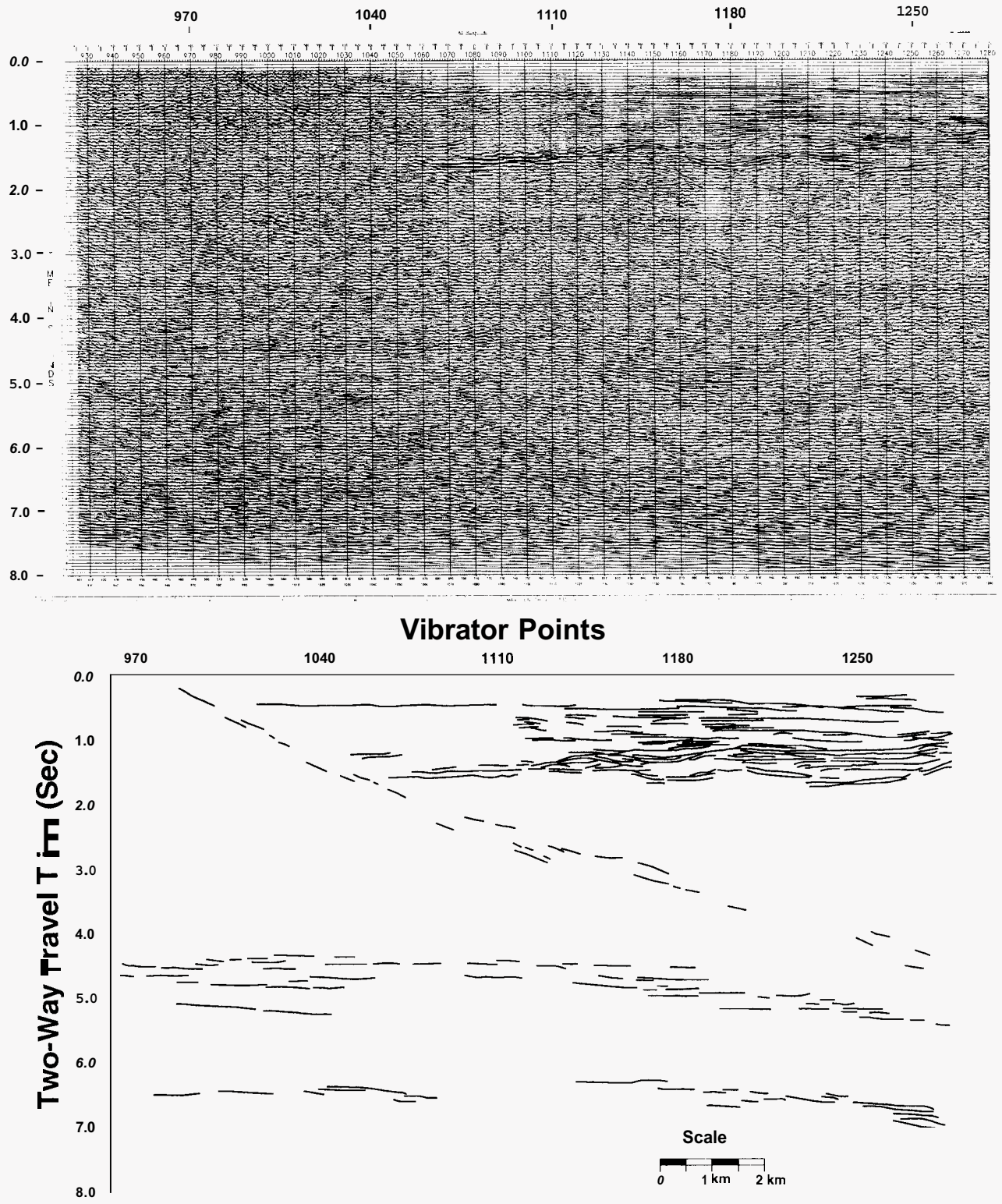


Figure **4.** A portion of the western end of NAWSIWV-92-02 reflection seismic line with a line drawing of major reflectors. Vibrator points (V.P.) are 50 meters apart. See text for discussions.

horizons can be clearly seen. The line originates in the Sierra Nevada, extends due east for 9.3 km and then turns northeast. The well-developed doublet found at 1.5 s two-way travel time (TWTT) heneath vihrator point (V.P.) 1100 is correlated with the top of the granitic basement found in the SNORT #1 drill hole. It is continuous over most of the IWV becoming shallower as one approaches the eastern edge of the hasin where it emerges in the Argus Mountains as a classic granite, similar in composition to rocks found in the southern Sierra Nevada.

Lying immediately above the hasement are one of two types of reflectors: those that are clearly layered with a characteristic frequency of 22 to 26 Hz, and those that arc weakly- to non-layered. The former can best be seen heneath V.P. 1180 whereas the latter are best seen near the western end of the line (V.P. 1100). Near the top of the section, the rocks become more or less transparent to acoustic energy showing only weakly-reflective horizons where they do exist.

The upper part of the section has anacoustic velocity in the 2200-2560 m sec^{-1} range indicative of poorly consolidated sedimentary rocks. Below 0.8 s TWTT, the velocity increases continuously from **3.000** m sec^{-1} to 3650 m sec^{-1} immediately ahove the hasement. The top of the hasement is marked hy a substantial increase in acoustic velocity to nearly 4,900 m sec^{-1} consistent with the change to granitic rock.

There is a well-developed set of discontinuous reflectors at 4.5 s TWTT which spans more than 0.5 s TWTT. The top of the hand corresponds to a depth of approximately 11 km. These are concave downward across most of the section and drop to a depth of 8 sec TWTT (21 km) on the eastern end of the line.

Also prominent on the section is a reflector which dips approximately 45" east. It originates in the Sierra Nevada extending out beneath the IWV where it becomes morc diffuse, hut still recognizable. It appears to merge with the 4.5 s reflector package *30* km to the east heneath the Argus Mountains.

Refraction data show that the top of the Moho heneath the IWV (Malin and Shalev, in prep) is significantly shallower than in the surrounding areas. It forms a definite high (Figure 5) which is more than 5 km nearer the surface than the average of 32 km for the southern Sierra Nevada.

In Figure *6,* seismicity data for the IWV have hcen plottcd in cross section along an east-west line extending from 117° to 118° W longitude. What is most notable from this plot is the ahsence of events heneath the IWV. There is clearly an aseismic shadow reaching up to a depth of approximately 7 km. On either side of this shadow, the seismically active zone lies at a depth of 12 to 15 kin.

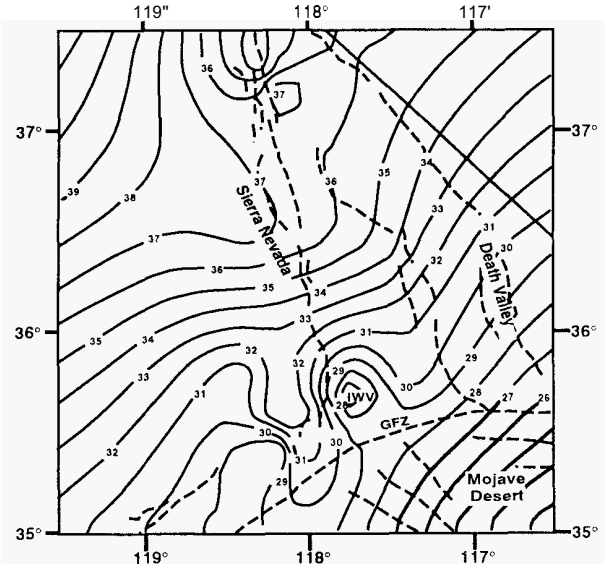


Figure 5. A preliminary Moho depth (km) contour map of east-central California hased on forward modeling of PmP travel times from hoth explosions and earthquake data. The center of the Indian Wells Valley is located heneath 117° 45' W and 35" 45' N (from Malin and Shalev. in prep., data are from the Southern Sierra Crustal Dynamics Project). The outline of the Sierra Nevada and other key physiographic features are shown hy the dashed lines; refer to Figure 1 for specific locations. GFZ = Garlock Fault Zone, IWV = Indian Wells Valley.

Focal plane mechanism solutions for most of these events show a dominant right lateral or right oblique movement with down to the east. This pattern is consistent with the regional tectonics which places the Mojave Desert and the area immediately north of the Garlock Fault in a dextral strike-slip fault regime.

DISCUSSION

Crustal extension in the southwestern U.S. has hecn widely recognized and reported hy numerous authors. The most notable, and most thoroughly studied, of the extensional features are the

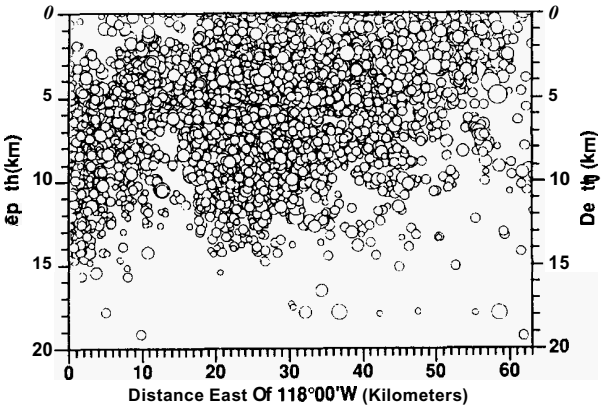


Figure 6. East-west cross section from 117° 19' W to 188° W longitude of nearly 10,000 seismic events M ≥ 1.0 during the period 1-1-81 to 3-17-94. These events occurred between 35° 36' N and 35° 54' N latitude. See text for discussion.

metamorphic core complexes (MCC). Davis & Coney (1979), Spencer (1984), Wernicke and Axen (1988). and Block & Royden (1990) deal in various ways with the crustal dynamics of these Cenozoic features. The most comprehensive summary of all work done on MCC's is found in Davis and Lister (1988). It is generally concluded that there is some degree of flow in the lower crust in order to compensate for the extension and thinning in the upper crust

Wernickc (1983, 1985) proposed and then subsequently developed more fully a model of lower crustal llow which is shown in summary form in Figure 7. This model shows that in areas of highly extended upper crust, the lower quartzose "lluid" crustal layer has flowed laterally to compensate for the diminished lithostatic load. This flow causes the mid-crustal reflectors representing the transition from the brittle upper crust to the more plastic lower crust to how upward heneath the most highly extended portion **of** the crust.

This appears to he the case in the IWV where the 4.5 s TWTT reflector represents that transition houndary. The non-reflective, low-velocity sequence of sediments over the western portion of the IWV is interpreted as loosely-consolidated hasin fill whereas the more stratified sediments found to the east arc interpreted to he lacustrine deposits associated with the ancient IWV hasin. The higher velocity sequence found immediately ahove the hasement is likely Miocene and perhaps even Eocene rocks that were deposited in a shallow **lake** (Loomis & Burhank, 1988).

There is also a coincidence of the non-reflective sequence of rocks, the upward bulge in the mid-crustal reflectors, and the significant 5 km positive relief on the Moho (Malin & Shalev, in preparation). Likewise the ahsence of seismicity heneath 10 km indicates that the rocks are incapable of supporting brittle fracture, which leads us to helieve that the package of rcllectors at 4.5 s TWTT represents the top of the brittle-plastic transition. We believe the non-reflective sediments on the western end of the seismic line immediately east of the Sierra Nevada front arc alluvial tan-type deposits derived from that mountain range since it's uplift over the last two million years (Jones, 1987).

These data fit Wernicke's model (1983) for lower crustal flow and are consistent with what is known ahout extension in the western Basin and Range. The system appears to be extending in response to right-oblique separation along low-angle, east-dipping faults. The reflector discussed in the previous section **is** an example of such a feature. Independent work done hy Sanders, et al (1988) on a tomographic inversion for V_s/V_p using teleseismic arrival times indicated that there was a significant slowness in the V_p as well as a very low V_s/V_p ratio which the authors attrihuted to the presence of a magma chamber at depths as shallow as 5 to 7 km.

The gravity data are interpreted to he a response to the less dense quartzose layer than they are to a thick pile of sediments as was previously believed. The comhination of 2,000 m of unconsolidated material as determined from the reflection data. with a less-dense quartzose layer closer to the surface, provides a reasonable crustal model the densities of which would approximate the measured gravity.

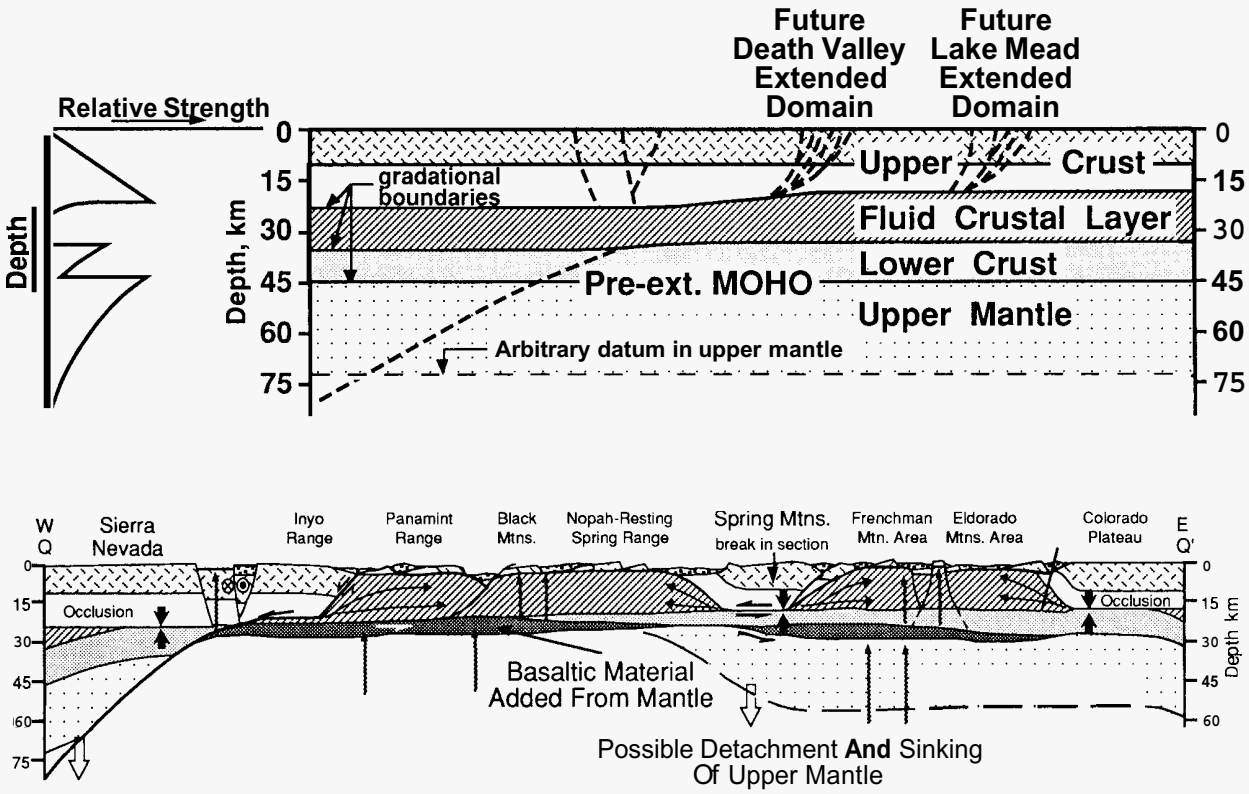


Figure 7. Fluid layer model of Wernicke (1992) as applied to the southwest basin and range. Diagram is an east-west section at approximately 36°N latitude. The model shows flow from within the fluid layer located between the upper and lower crust. Note that flow is predicted from beneath the Sierra Nevada eastward under the mountains to the east with heat passing upward along the strike slip faults. The equivalent position of Coso, if this section were to the south of this location, would be where the Inyo Range is. The datum in the upper mantle is not intended to be either a thermal or mechanical boundary.

This same type of crustal structure has heen reported on the basis of interpretation of reflection seismic profiles in the Death Valley region (Serpa, et al, 1988). The significance of this similarity is that Death Valley is a well-documented right-oblique extensional system with as much as 80 km of separation over the last 10 to 12 Ma (Stewart, 1983). The Death Valley and IWV may, in fact, be structurally linked through a master decollement at a depth of 12 to 15 km where the base of the zone of seismicity occurs. Surfaces such as this have been proposed for the northeastern Mojave Desert hased on tomographic studies of P_n arrival times and V_p slowness (Hearn and Clayton. 1986).

CONCLUSIONS

Based on data from SNORT #1 and the geophysical evidence gathered to date hy the GPO, a second deep (3048 m) test hole, SNORT #2, was sited at V.P. 1100 (see Figure 2). Drilling on this hole was begun in June and is currently underway. The objective is to test for geothermal resource over what appears to he an area of maximum extension in the IWV. Integration of several types of gcophysical information was invaluable in the interpretation of crustal structure and in selection of the drill sitc. Use of a regional geologic model as a context for data interpretation also was extremely valuable in site selection. The use of multicomponent seismology in exploration for petroleum resources is a well-known and widely-accepted practice. Its place in geothermal exploration has yet to be firmly established, hut is long overdue.

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