THE SEISMOLOGY OF EXTENSIONAL HYDROTHERMAL SYSTEMS

Peter E. Malin (1)

(1) Department of Geology, Duke University, Box 90235, Durham, NC 27708-0235

INTRODUCTION

It has long been recognized that extensional crustal regimes have unique structural and petrologic features. Imbricated detachment faults develop in response to the extension, dividing the crust into vertically and horizontally stacked blocks. Continued extension exposes ever deepening crustal levels, bringing to the surface deep seated rocks such as mylonites. Hydrothermal fluids play an important role in the development of these features. Further, they have their own unique seismological signatures, including extensional earthquake focal mechanisms along reflective fault surfaces and shallow brittle-ductile transitions with correspondingly thin seismogenic layers. This paper reviews some of what is known about the seismology of extensional hydrothermal systems, with examples drawn from the Mojave Desert and Owens-Death Valley regions of California, including their metamorphic core complexes and the Coso-Indian Wells Valley geothermal areas.

REFLECTION/REFRACTION STRUCTURE

On regional scales, extended crust appears to present a volumetric paradox: in reflection and refraction data, the bottom of the crust appears unexpectedly flat across zones of significant displacement. In the Owens-Death Valley region extension of several hundred percent has produced crustal thinning of less than a quarter of its likely original thickness (Figure 1; Shalev and Malin, in prep.).

More locally, the deep crust can appear domed, as for example in the case of the Rand Mts., the Whipple Mts. core complex, and the Coso-Indian Wells Valley areas (Figure 1.). In the upper half of the crust, parts of the reflection structure correlate with known surface geology, as in the exposure of Rand Schist in the Rand Mts., the mylonite front in the Whipple Mts., and active listric faults in the southern Owens Valley (Figure 2; modified from Caruso et al, in prep.; Monastero et al; unpublished data; Malin et al., in press; Malin et al. in prep.).

Preliminary Moho Depth Map

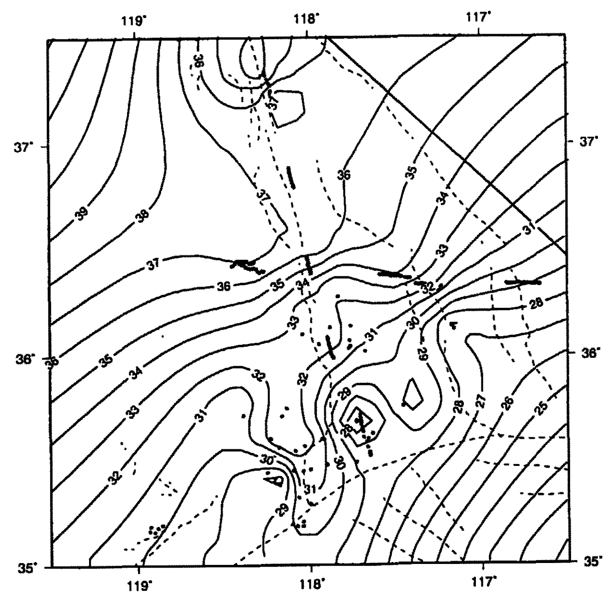

Fig. 1. A preliminary Moho depth contour map of eastern central California, from the San Joaquin Valley on the west to Death Valley on the east, and from Mammoth Lakes area on the north to the Mojave Desert on the south. The central north-south strip is along the Owens Valley. The closed-in contours in the southern Owens Valley lie beneath the Coso-Indian Wells Valley area. The map is based on forward modeling of PmP travel times from both explosions and earthquake data, with the subsurface reflection point indicated with black dots. (Fig. from Shalev and Malin, in prep.; Data are from the Southern Sierras Continental Dynamics Project.)

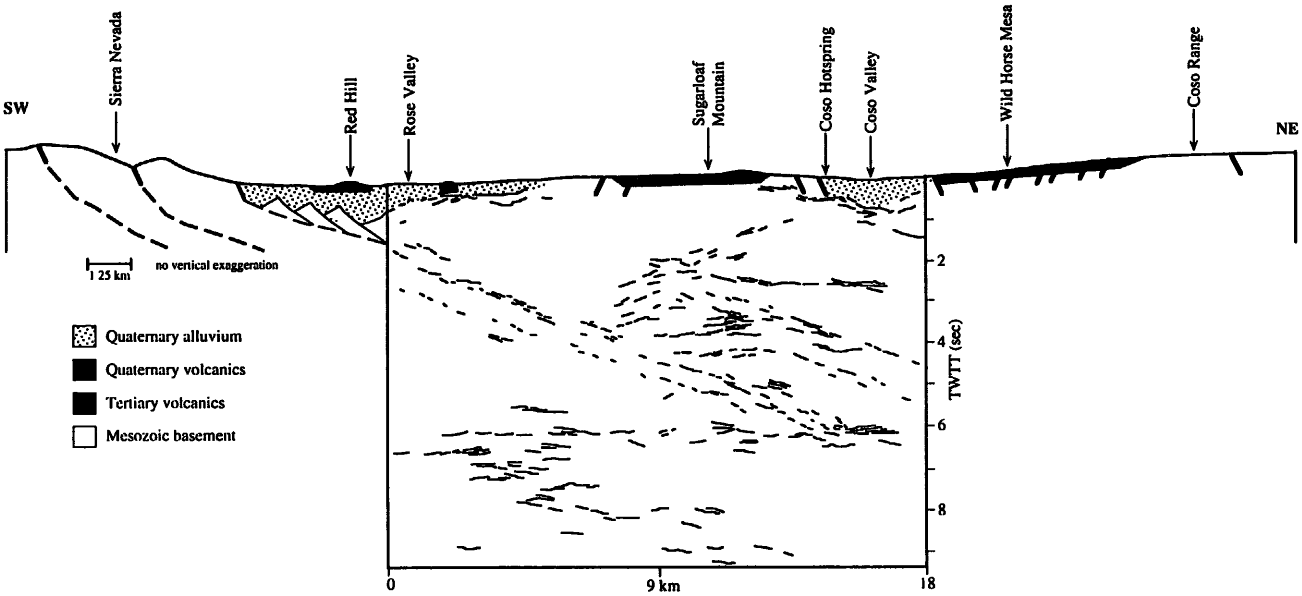

Fig. 2 Generalized cross section of the southern Owens Valley in the area of the Coso Range. The cross section is based on the geology of Duffield et al., (1980) and interpreted seismic reflection section of Caruso et al. (in prep.). The strong band of east-dipping reflections underneath Rose Valley is thought to represent a major, listric fault zone which soles into a shallow brittle-ductile transition.

3-D VELOCITY STRUCTURE

In the case of the Coso geothermal area, earthquake tomography and forward modeling of refraction data reveal a heterogeneous velocity structure in the otherwise petrologically uniform basement above 5 km (Figures 3 and 4; modified from Shalev and Malin in prep., and Caruso and Malin, in prep.). High velocity regions may correlate to relatively unfractured, mineralized, or low porosity rocks.

Further, the velocity structure at Coso appears anisotropic. This anisotropy is readily apparent in S-wave observations, which show azimuthally dependent particle motions and arrival times (Figure 5; modified from Lou and Rial, 1994).

SEISMOTECTONICS

Microearthquakes in the southern Owens Valley occur in spatially restricted clusters that group together along a northwest ward trend (Figure 6). A possible interpretation of this clustering is that the events are taking place mainly at the intersections of fault segments. Less frequent, larger earthquakes perhaps jump between segments, as in the case of the 1992 Landers M=7+ earthquake. The shallow seismogenic cut off reflects the local high heat flow, lying well above 10 km in the case of the Coso Geothermal area.

In the Coso-Rose Valley areas, earthquake activity often appears in the form of swarms whose spatial extents expand with time (Figure 7; Malin et al., unpublished data). While the time-distance characteristics of these swarms suggest the involvement of flowing fluids, simple models assuming Coulomb failure of a poroelastic medium fail to account for the spatial distribution of events (Lakings, unpublished ms).

Preliminary composite focal mechanisms from the Coso Geothermal area indicate that the local state of stress there is consistent with the regional stress (Figure 8; Lakings, unpublished ms). However, a full account of the interaction of the regional stress with the range of normal and strike slip faults observed at this site has not yet been given.

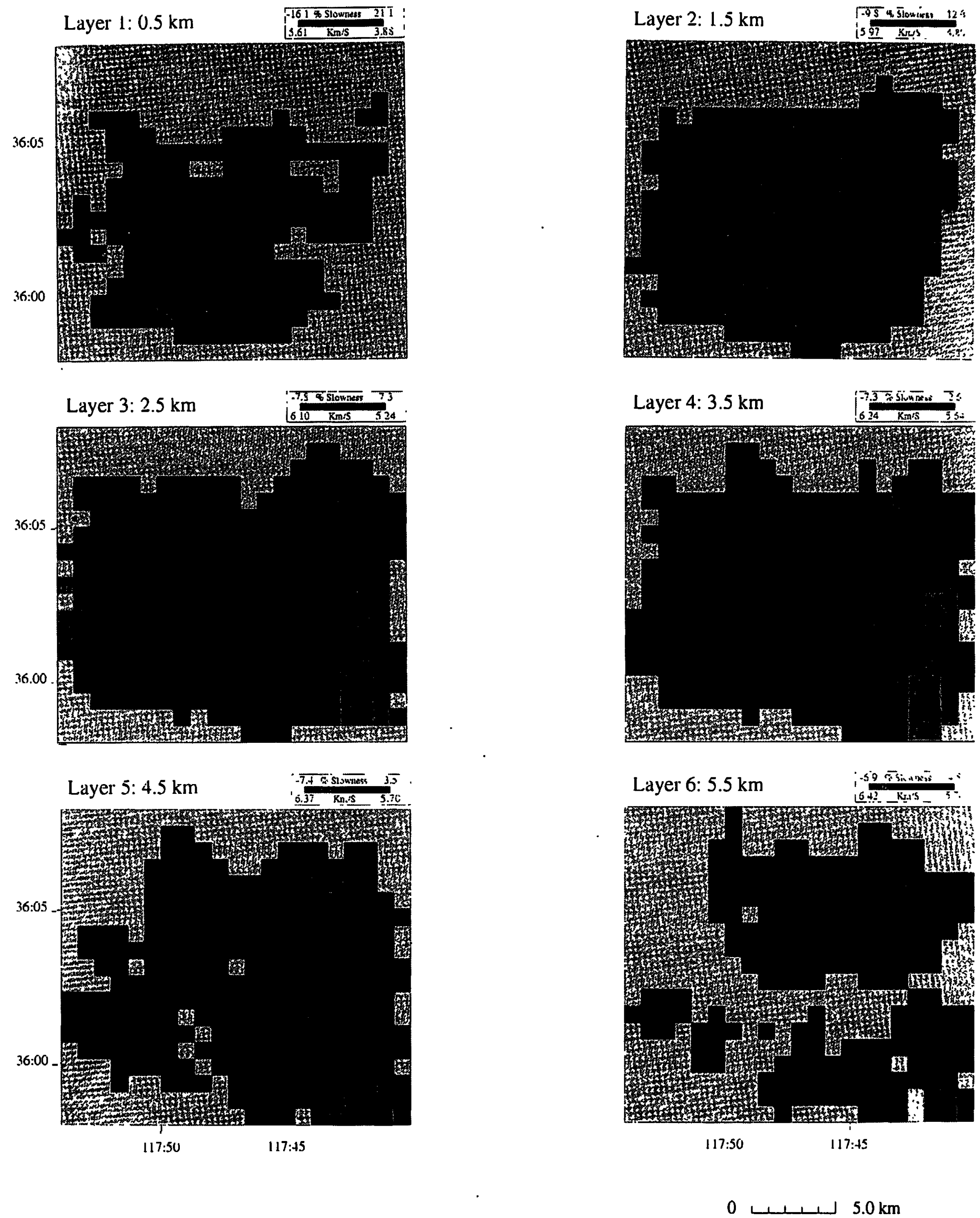

Fig. 3. Earthquake P-wave tomography of the Coso area showing high velocity regions in the upper 1.5 km of the crust. One possible interpretation of these zones is in terms of regions of either low fracture density or secondary mineralization. (Fig. modified from Shalev and Malin, in prep.).

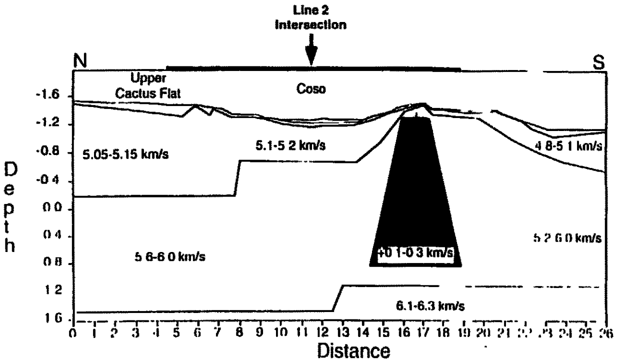

Fig. 4 Results of forward modeling of explosion source refraction data from the Coso area (Caruso and Malin, in prep.). The high velocity feature south of the line crossing coincides with the one seen in the earthquake P-wave tomography.

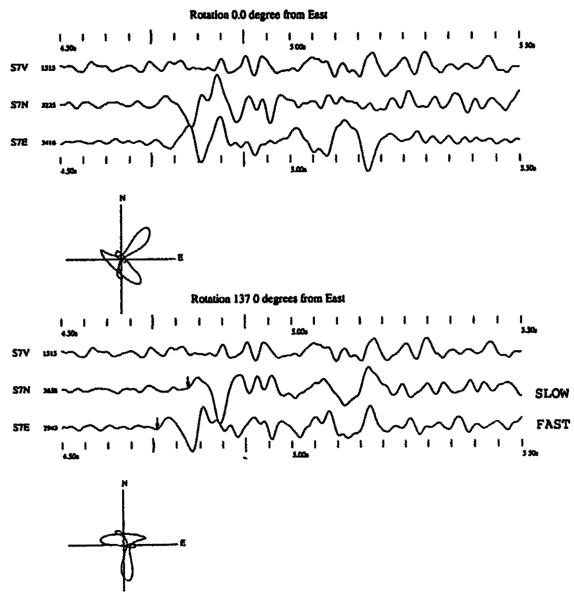

Fig. 5 An observation of shear wave splitting from the Coso area. The top 3 traces and associated polarization diagram show vertical, north, and east motions in a time window centered on the S-wave. The polarization diagram shows that the S-wave is split into 2 orthogonal motions, a typical indicator of S-wave significant S-wave anisotropy. The lower traces and polarization diagram show the motion after rotation into fast and slow directions of S-wave propagation. Figure from Lou and Rial (1994).

DISCUSSION

The surface geology and seismic reflection/refraction structure of the Rand and Whipple Mts., for example, show that regional extension of the crust results in local tilting and doming. This process exposes deep seated rocks along low angle faults, which are themselves associated with significant amounts of hydrothermal flow. The end member of these processes is the development of metamorphic core complexes. In the Rand and Whipple Mts, the times of active extension are long gone. Moreover, the immediate effects of shallow hydrothermal activity have been removed by weathering. Aside from geometric arguments, their seismotectonic evolutions are unknown.

In the case of the southern Owens Valley, however, both the extensional and hydrothemal processes are active and can be recognized in their unique seismology. Reflection profiles from this region contain the same type of listric faults seen in the Tertiary extended terrains of the Mojave — in the Whipple Mts. and Waterman Hills core complexes. The localization of seismicity on fault intersections and the space-time development of earthquake swarms maybe related to concentrations of hydrothermal activity. Locally high heat flows account for thin seismogenic layers. The 3-D velocity structure suggests the presence of shallow low porosity or unfractured zones, as well as areas of anisotropy.

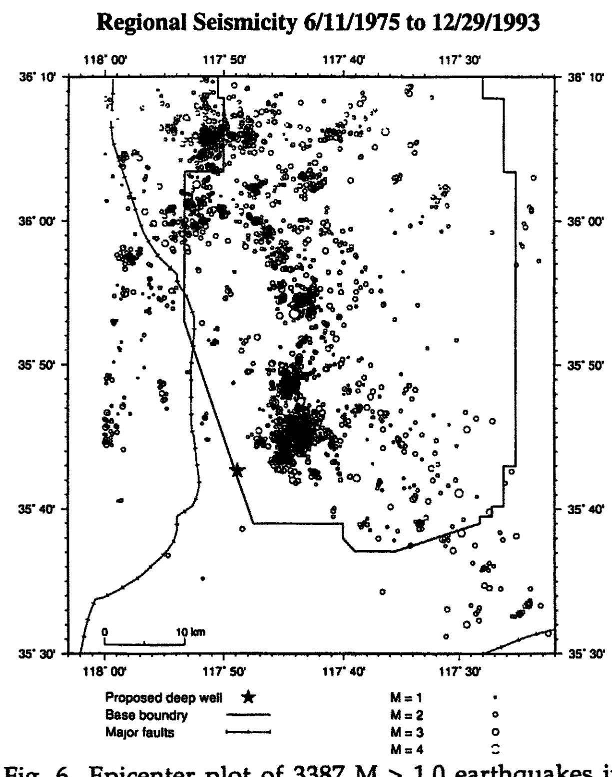

Fig. 6 Epicenter plot of 3387 M > 1.0 earthquakes in the southern Owens Valley, centered on the Coso-Indian Wells Valley region. The events were detected and located by the seismic network operated by the USGS-CIT in the southern California region. The earthquakes appear in clusters, groups of which define

a trend to the northwest. The clusters are interpreted as being located at the intersections of faults and associated with hydrothermal systems of this region. The base boundary is that of the China Lake Naval Air Weapons Station.

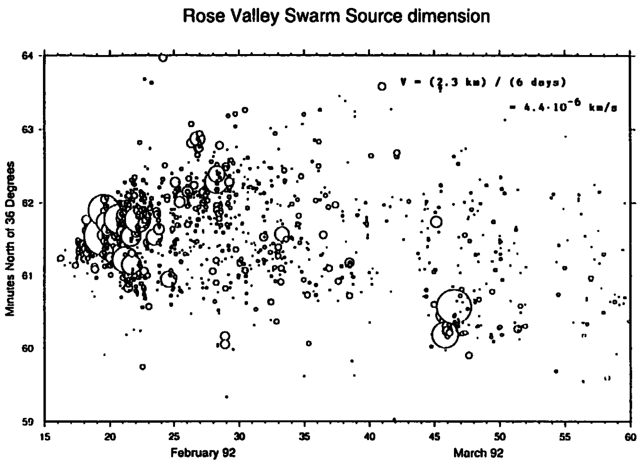

Fig. 7 This figure shows the space-time evolution of the Rose Valley, CA, earthquake swarm in the first month. The circles shown have radii equal to the rupture lengths of the microearthquakes that took place at the time and latitude shown. The radii were determined using the moment-stress drop relations of Abercrombie and Leary (1993). Important features are the build up and decay of the sequence, including the larger events south of the initial swarm and almost 1 month later. It should be noted that another part of this swarm took place 7 mo. later.

Many of these seismic characteristics contrast with those of volcanic hydrothermal systems, such as Hawaii, Iceland, or Yellowstone. While highly seismically active, the extensional systems appears to lack seismic tremors. Further, in the case of the southern Owens Valley, the mechanics of local earthquakes conform to the regional structure and crustal-dynamics, as do the reflection and refraction observations. The recognition of these unique signatures should aid in the exploration of extensional hydrothermal systems. The significance of the clustered earthquakes and spreading swarms needs to be studied further, as these they may hold the keys to the local crustal fluid system. Finally, both earthquake and reflection exploration needs to be done in a regional context in order to avoid missing the central characteristics of this system.

Eigenvalues and eigenvectors of summed moment tensor

Eigenvalues	Eigenvectors
4.33	(.928, .370, -.039)
-.717	(-.013, .137, .990)
-3.62	(.372, -.919, .132)

Components of eigenvectors are (east, south down)

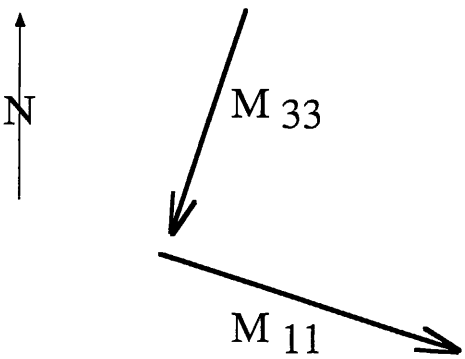

Fig. 8 Eigenvalues and eigenvectors of a moment tensor analysis of composite microearthquake focal mechanisms from the Coso geothermal area. The values and directions are consistent with the regional state of stress inferred from larger earthquakes and geological relationships. (Fig. from Lakings, unpublished ms).

ACKNOWLEDGEMENTS

A number of individuals and institutions have contributed to this paper. In no special order, the individuals include Mr. John Copp, Mr. Jess McCullouch, Dr. Frank Monastero, Mr. Alan Katzenstein, Mr. Mike Hasting, Ms. Carolyn Shepard, Dr. Min Lou, Dr. Jose Rial, Dr. Jeff Karson, Dr. Eylon Shalev, Dr. Cary Caruso, Mr. James Lakings, Mr. William Andrews, Ms. Jaana Browoski, Mr. Don Lippert, and Mr. Ramsey Haught, amoung many others. The institutions include California Energy Company Inc., Geothermal Program Office NAWSCL, Lawrence Berkeley Laboratory, and Duke University. This list is by no means complete and all these other individuals are thanked for their contributions as well

REFERENCES CITED

Abercrombie, R.E., and P. Leary, Source parameters of small earthquakes recorded at 2.5 km depth, Cajon Pass, southern California; implications for earthqkuake scaling, Geophys. Res. Letts., 20, 1511-1514, 1993.

Duffield, W.A., C. Bacon, and G. Dalrymple, Late Cenozoic volcanism, geochronology, and structure of the Coso Range, Inyo County, California, J. Geophysical Res. 85, 2381-2404, 1980.

Lou, M., and J. Rial, Characterization of the crack geometry at the Coso, California geothermal reservoir by analyzing shear-wave splitting from microearthquakes, Proceedings of the Nineteenth Workshop n Geothermal Reservoir Engineering, Stanford University, January 18-20, 1994.

Malin, P.E., E.D. Goodman, T.L. Henyey, Y.G. Li, D.A. Okaya, and J.B. Saleeby, Significance of seiesmici reflections beneath a tilted exposure of deep continental crust, Tehachapi Mountains, California, J. Geophysical Res., In Press.