Geophys. J. R. astr. Soc. (1987), 89, 125-132

The nature of deep crustal structures in the Mojave Desert, California

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Summary. The character of multi-offset reflections from the deep crust in the Mojave Desert are examined to reveal the physical nature of the reflecting structures. We focus on distinguishing classical abrupt discontinuities, such as traditional models of the Conrad and Moho boundaries, from more unusual structures. Finite-difference modeling and simple interference relations show that pre-critical reflections exhibiting an increase in peak frequency with offset arise from thinly-layered horizontal structures, while reflections from step discontinuities show no change in frequency with offset. In the deep crust thin layers may result from sill intrusion or fault motion.

The sense of changes in Poisson's ratio and the relative strength of density changes determine whether reflection amplitudes will increase or decrease with offset. A simple linear regression on pre-critical reflection amplitudes against offset is adequate to separate reflections arising from increases in Poisson's ratio from those arising from decreases in Poisson's ratio and/or density changes. The latter condition may be the result of strong anisotropy or the presence of pore fluid. Comparisons of the properties of major deep reflectors across the Mojave Desert suggest that the effects of tectonic motion and fluid injection have penetrated all levels of the crust.

1. Introduction

Seismic reflection studies of deep-crustal structures have, to date, concentrated on imaging the geometry of the reflectors. While reflector geometry is useful in the geologic interpretation of these structures, many ambiguities regarding the physical nature or deep reflectors remain.

Reflections from deep crustal structures beneath the Mojave Desert of California were first recognized by Dix (1965) at Soggy Lake (Fig. 1). The more extensive COCORP survey across the western Mojave imaged the geometry of several deep-crustal reflectors over a wide area (Cheadle *et al.* 1985). With the exception of one reflection which they believe can be traced to surface exposures in the Rand Mountains (Fig. 1), their geologic interpretation of the mid- and deep-crustal reflections was guided by the geometry in stacked sections. They consider the major reflectors to be detachment fault structures. This interpretation ignores the possibility, proposed by Kosminskaya in 1964, that crustal velocity discontinuities may be due to the effect of physical conditions such as pressure or temperature. It is this possibility that motivated the CALCRUST consortium to add a secondary experiment to record reflections from the deep crust during their May-June 1985 seismic reflection survey in the eastern Mojave Desert.

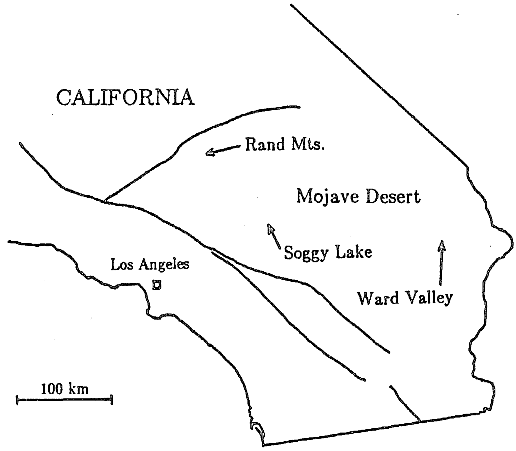

Figure 1. Map of southern California giving the locations of deep crustal reflection surveys in the Mojave Desert. Major faults are also shown.

2. Effects of deep crustal structures on reflection characteristics

We separate the problem of extracting the physical properties of the reflector from the seismograms into two parts. The first problem is to determine whether the reflector consists of an abrupt change in these properties (a step discontinuity), is a more gradual variation over some depth range (a gradient), or is composed of layers having thicknesses on the same scale as the seismic wavelength, the simplest case of which is an isolated thin layer. The ability to classify observed reflections into one of these three categories is crucial for deciding whether the structures represent broad-scale changes in composition or physical conditions, or are the result of more local processes such as sill intrusion or fault motion. The second problem is to use the variation of reflection amplitude with offset to yield information on the relative changes in the velocities and density. Such information is needed to decide whether the structures represent changes in mineralogy or are due to variations in physical properties such as porosity or anisotropy.

Our initial objective is to determine whether the deep reflectors in the Mojave Desert are classical discontinuities, similar to traditional models of the Conrad and Moho discontinuities. A classical discontinuity would be an abrupt increase in density and stiffness. We believe that any reflector which departs from the model of a classical discontinuity will produce distinctive effects on the variation of reflection frequency and amplitude with offset.

3. Frequency effects

The spectra of normal-incidence reflections have been used by many workers to support the concept of thin layering in the deep crust, most recently by Jones (1985). We investigated the reflection spectral response of the step discontinuity, gradient, and thin layer models through elastic finite-difference modeling in two dimensions. The finite-difference synthetic seismograms show that a thin layer produces a distinctive increase in the peak frequency of the reflection with offset. Simple acoustic interference relations give the pre-critical reflection peak frequency as $f_p = \dfrac{nv}{4d\cos\theta}$, where θ is the angle of incidence *within* a layer of velocity v and thickness d, for the overtone $n = 1, 2, 3, \ldots$. This relation allows the

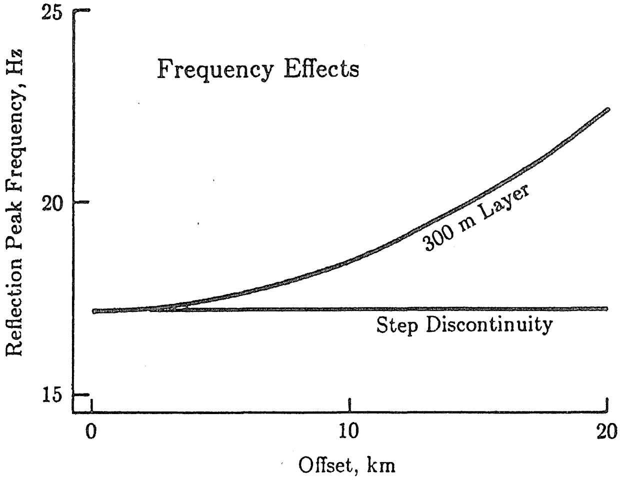

Figure 2. Comparison of the reflection peak frequency at different offsets from a thin layer and step discontinuity at 15 km depth.

thickness and velocity of the thin layer to be derived from the amount of dispersion. Fig. 2 compares the frequency response of a 300 m thick layer and a step discontinuity at a depth of 15 km.

4. Amplitude effects

The effects of different contrasts in physical properties on reflection amplitudes as a function of offset are calculated from the relations for plane waves incident on a plane reflector as given by Aki & Richards (1980, p. 150). The reflection power is a complicated function of several variables, even at pre-critical angles. However, as shown by Koefoed (1955) and Shuey (1985), under certain assumptions the sign of the contrast in Poisson's ratio at the reflector robustly predicts the sign of the amplitude variation with offset. These relations are

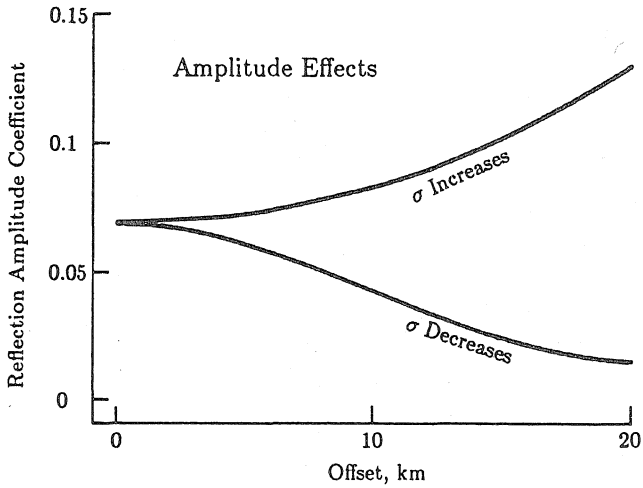

Figure 3. Comparison of reflection amplitudes at different offsets from an increase in Poisson's ratio from 0.347 to 0.392 and from a decrease from 0.347 to 0.292 at 12 km depth.

most simply demonstrated by Wu & Aki (1985) as resulting from the radiation patterns of equivalent point forces due to small relative variations in density, Lame's parameter, and rigidity. Where Poisson's ratio increases with depth more strongly than density varies, or the rigidity decreases, the reflection power will increase as offset lengthens. Conversely, where Poisson's ratio decreases or density changes drastically, the reflection power will decrease with offset. Fig. 3 shows this effect for strong changes in Poisson's ratio.

This study will not attempt to invert a measured relationship of reflection amplitude to offset for the exact physical property contrasts. The data from the Mojave Desert are contaminated with a variety of effects that preclude the measurement of the precise amplitude responses of the reflectors. Instead, we will look for unusual features of the deep crust, such as radical changes in anisotropy, or the presence of pore fluids, that should strongly attenuate their reflection power as offset increases.

5. The CALCRUST wide-angle survey

A total of 108 km of seismic reflection profiling were collected in May and June of 1985 by the CALCRUST consortium. The survey was located along five lines in the Ward, Rice, and Vidal Valleys of the eastern Mojave Desert (Fig. 1). While the main objective of the survey was to collect high-resolution seismic reflection data from the shallow part of the crust, the consortium was able to augment the main survey with a wide-angle experiment that resulted in reversed, long-offset, high fold common-midpoint records over a substantial portion of 3 lines. The line in the southern Ward Valley yielded 8.3 km of reversed common-midpoint gathers spaced at 75 m. Many gathers exceed 100 fold and include offsets beyond 155 km.

6. Analysis of reflection frequency at multi-offset

Hand-picked examples of deep-crustal reflections in the Ward Valley were examined for spectral dispersion. Reflections with and without dispersion were found from several areas providing the highest-quality data. A strong reflection at 6 s, about 15 km depth, can be identified as a thin layer at many midpoints. The amount of dispersion shows that the layer, a few hundred meters in thickness, must have a velocity of at least 10% higher than the velocity of the overlying medium. This is also true of many of the other very strong thin-layer reflectors observed. Such a velocity increase in a thin layer is most likely due to the presence of higher-grade metamorphic mineral phases, or to a more mafic composition. On the other hand, many strong reflections between 6.8 and 7.6 s do not show dispersion and are thought to result from broad-scale vertical velocity changes at step discontinuities. This suggests that the lower crust, at perhaps 18 km depth, undergoes a change in composition or physical state.

High-quality Moho-depth reflections could be picked on virtually every trace of the Ward Valley dataset. These events are grouped into two zones, arriving at about 8.4 and 9.4 s. The earlier reflection does not show dispersion, but the later arrival does. This, along with correlations with regional refraction profiles, suggests that the earlier reflection is due to a step increase in velocity at the top of a high-velocity basal-crustal zone. The later arrival is then from the Moho. The amount of frequency increase shows that it includes at least one layer a few hundred meters thick with a velocity exceeding that of the underlying mantle. This interpretation leads to speculation that such a layer could consist of the residual from partial melting and extrusion of mantle material, or be a zone of highly anisotropic mantle oriented by tectonic mobilization of the Moho.

7. Analysis of amplitude at multi-offset

To evaluate how the amplitudes of deep crustal reflections change with offset, the common-midpoint gathers from the Ward Valley were processed into a stack that reflects the true amplitudes of the arrivals. The gathers were stacked with two types of offset-dependent information being preserved. First, a measure of how well the velocity semblance focused the arrivals was calculated for each point of the stack in the manner of Harlan *et al.* (1984). This measure was multiplied by the stack to produce the section in Fig. 4, in which the deep reflections best imaged by the survey stand out as "bright spots." Second, at each point of the stack a linear regression was carried out on the amplitude of a small window of the traces at the normal moveout time against offset. The derived relations of amplitude to offset are plotted on Fig. 5. Both show several well-imaged reflections from the lower crust, as well as from the top of the basal-crustal zone at 8.5 s and the Moho below 9.5 s.

Fig. 5 shows that most of the well-imaged reflections result from classical discontinuities, since their amplitude increases with offset. Poisson's ratio probably increases at these reflectors, especially at the top of the basal zone. There are, however, a few structures which show a well-defined decrease in amplitude with offset. For these arrivals the semblance focusing and regression correlation are also high. We therefore interpret these arrivals, especially the one at 8.3 s which dips south into the top of the basal zone, as resulting from a decrease in Poisson's ratio or a strong density variation. In the deep crust, such a contrast is most likely to result from a radical change in the direction of anisotropy, or from the presence of pore fluid.

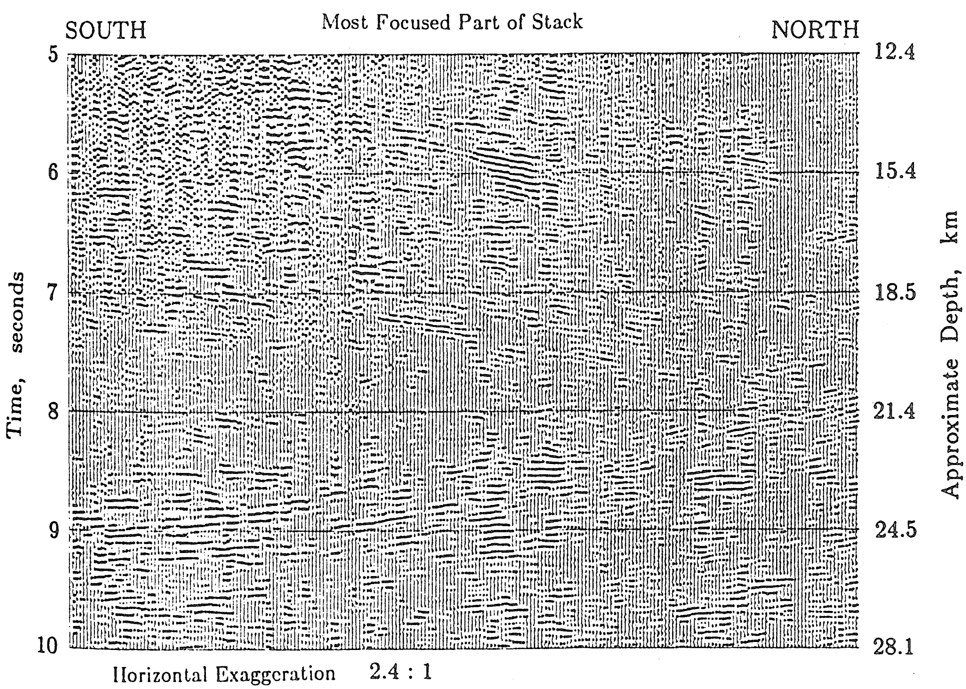

Figure 4. Stack of deep reflections from the CALCRUST Ward Valley wide-angle survey showing the true amplitude of the reflections multiplied by the semblance focusing of the stack, over 8.3 km of midpoints. The strongest reflections are from the top of the basal-crustal zone at 8.4 s and from the Moho at 9.5 s.

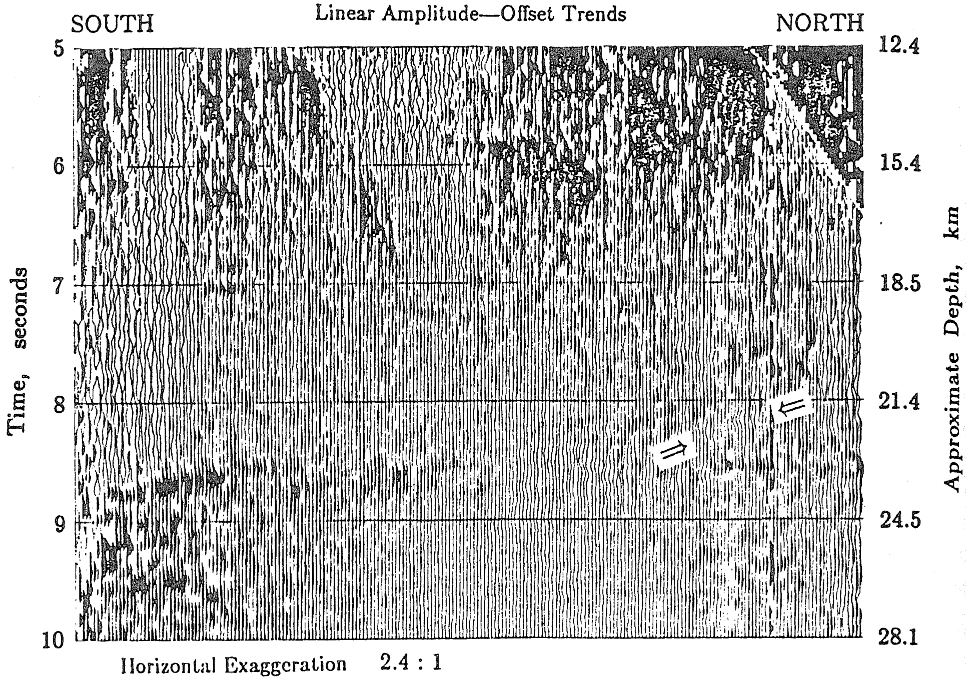

Figure 5. Image of the linear reflection amplitude dependence on offset for each point of the stack of Fig. 4. Dark areas indicate an increase in amplitude with offset. Most of the strong reflections result from classical discontinuities, but the south-dipping reflection on the lower right (between arrows) may be from a strong contrast in anisotropy, or an inclusion of pore fluid.

8. Conclusions

A comparison of generalized crustal columns in three areas of the Mojave Desert is made in Fig. 6. The depths of the throughgoing reflectors found in the Rand Mountains by the COCORP survey are shown on the left. Using the same methods as for the Ward Valley data, the major reflector at 16 km depth beneath the Rand Mountains was found to be an increase in Poisson's ratio with depth. Dix's survey at Soggy Lake (Dix 1965) produced essentially one high-fold shot gather with unusually good records of deep crustal reflections. These were similarly analyzed to derive the indications on the nature of the deep structures shown. The column for the Ward Valley generalizes the results discussed above. Note that even though the Moho is 5 km shallower in the eastern than in the central or western Mojave, the character of the Moho may be the same - it includes a thin, high-velocity layer yet is overall a classical increase in density and stiffness. The 22 km depth of the major reflectors above the Moho in all three columns suggests that thinning of a basal crustal zone may account for the thinning of the crust in the eastern Mojave, although the character of the top of the zone may change between the central and eastern Mojave.

In general, thin layers, decreases in Poisson's ratio, and strong density variations may be present at a large range of depths in both the central and eastern Mojave, although individual structures cannot be correlated between the two surveys. This suggests that the effects of tectonic movement and fluid injection have penetrated throughout the crust.

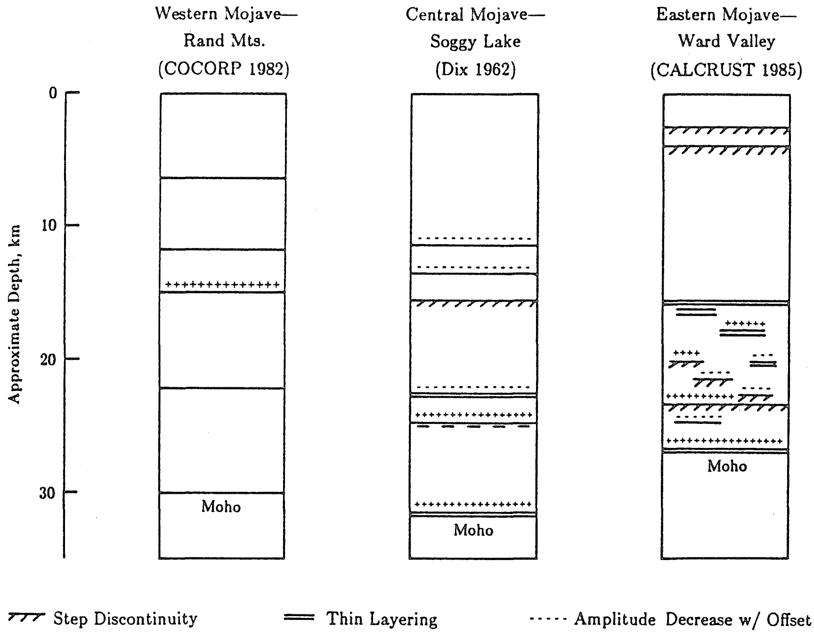

Figure 6. Generalized crustal columns showing the depths and character of major reflectors in 3 areas of the Mojave Desert. The physical nature of selected structures as derived from frequencies and amplitudes of multi-offset reflections are indicated. Increases or decreases of amplitude with offset are indicated by pluses or minuses above each reflector.

References

Aki, K., & Richards, P. G., 1980. *Quantitative Seismology, v. 1,* W. H. Freeman & Co., San Francisco.

Cheadle, M.J., Czuchra, B.L., Ando, C.J., Byrne, T., Brown, L.D., Oliver, J.E., Kaufman, S., 1985. Geometries of deep crustal faults: Evidence from the COCORP Mojave survey in *Reflection Seismology: The Continental Crust, Geodynamics series*, vol. 14, pp. 305-312, eds Barazangi, M. & Brown, L., American Geophysical Union, Washington, DC.

Dix, C.H., 1965. Reflection seismic crustal studies, *Geophysics*, **30**, 1068.

Harlan, W. S., Claerbout, J.F., & Rocca, F., 1984. Signal/noise separation and velocity estimation: *Geophysics*, **49**, 1869.

Jones, T. D., 1985. Nature of seismic reflections from the crystalline basement: COCORP Wind River line, Wyoming, *J. Geophys. Res.*, **90**, 6783.

Koefed, O., 1955. On the effect of Poisson's ratio of rock strata on the reflection coefficients of plane waves, *Geophys. Prosp.*, **3**, 381.

Kosminskaya, I.P., 1964. On layering of the earth's crust, *J. Geophys. Res.*, **69**, 802.

Shuey, R.T., 1985. A simplification of the Zoeppritz equations, *Geophysics*, **50**, 609.

Wu, R. & Aki. K., 1985. Scattering characteristics of elastic waves by an elastic heterogeneity, *Geophysics*, **50**, 582.