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COCORP DEEP REFLECTIONS: MOHO AT 50 KM (16 S) BENEATH THE COLORADO PLATEAU

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Abstract. COCORP deep reflection data on the Colorado Plateau reveal complex reflections to about 16 s two-way travel time (50+ km), beyond which there is an abrupt decrease of reflectivity. This boundary is interpreted to represent the Moho, an inference consistent with the existing but limited refraction data sets when they are reconciled with the recent independent determination of an 8.10-8.15 km/s Pn velocity beneath the Colorado Plateau. This ~50 km depth to Moho and 8.10-8.15 km/s Pn velocity for the Colorado Plateau closely resembles that of the High Plains just east of the Rocky Mountains. The absence of continuous strong reflections at the Moho suggests that the Moho beneath the Colorado Plateau is a transition, not a velocity step function on the scale of the reflection experiment. The reflection boundary may represent the base of complex and discontinuous reflectors of the crust and crust/mantle transition, below which the mantle may be largely peridotite with a velocity of 8.1 km/s. These results strongly reinforce the suggestion that the Moho on deep reflection data in relatively stable continental regions is represented by an abrupt decrease in reflectivity, below which the mantle is relatively seismically transparent.

Introduction

The Moho, long defined as where the P wave velocity increases relatively abruptly from nearly 7 km/s to about 8 km/s [Mohorovicic, 1910], has been mapped in a general way by various seismic refraction experiments so as to suggest a distinct boundary of uniform character. However, the growing body of deep seismic reflection data in recent years has revealed important regional variations in the character of the Moho which bear upon its local nature and evolution [Allmendinger et al., 1987]. The Moho as determined on the basis of reflection data is mainly manifest either as a strong reflector [e.g., Klemperer et al., 1986] or as an abrupt decrease in reflections [e.g., Brown et al., 1983] at the base of the reflective crust; in either case, however, the mantle appears relatively nonreflective. The correlation of the reflection-defined Moho and that inferred from refraction experiments is supported in the few places where refraction and deep reflection profiles are nearly coincident [Barton et al., 1984; Barton, 1986; Braile and Chaing, 1986; Mooney and Brocher, 1987]. Clear reflections from within the mantle below the Moho are rare, the principal exception being the Flannan fault on British Institutes Reflection Profiling Syndicate (BIRPS) profiles [Smythe et al., 1982; Brewer et al., 1983; McGeary and Warner, 1985].

Consortium for Continental Reflection Profiling (COCORP) data from the Colorado Plateau reveal reflections to about 16 s two-way travel time (about 50 km) where they abruptly cease. However, the depth of this distinct reflection boundary is clearly greater than the 40-43 km depth previously suggested for Moho from limited existing refraction data [Roller, 1965; Warren, 1969; Prodehl, 1979]. Furthermore, the existing refraction data on the Colorado Plateau have been interpreted to suggest an anomalously low sub-Moho (Pn) velocity of 7.8 km/s [Roller, 1965; Warren, 1969; Prodehl, 1979]; whereas a recent "two-station" analysis independent of the previous refraction data sets has determined a remarkably consistent Pn velocity of 8.10-8.15 km/s beneath the Colorado Plateau [Beghoul and Barazangi, 1987, 1989]. These clear discrepancies between previous interpretations of the limited refraction data and the new observations require a reevaluation of the existing refraction data and interpretations. Might these new observations indicate a Moho deeper than previously thought below the Colorado Plateau, with a normal subMoho velocity of about 8.1 km/s?

In this paper, we discuss the limitations of the existing refraction data and show how they can be reconciled with both the new independent observations of an 8.1 km/s Pn velocity beneath the Colorado Plateau and a Moho at a depth of about 50 km, corresponding to the 16-s reflection boundary on the COCORP data.

COCORP Deep Reflection Data on Colorado Plateau

COCORP has collected six deep reflection lines on the Colorado Plateau (Figure 1). Where the data are of high quality, such as along Arizona line 6 (Figure 2), reflections are imaged to about 16-s two-way travel time (TWTT), below which there is a marked absence of reflected energy. The two-way travel time of this boundary is consistently about 15-17 s on this and other lines on the Colorado Plateau, at least where the data quality is good, suggesting that this change in reflectivity probably represents a geologically significant boundary. The continued decay of source-generated signal to travel times greater than this boundary suggests that a threshold of ambient noise has not been reached. On one of these COCORP profiles a distinct zone of reflections is locally observed at this boundary (~15 s on the east end of UT-4) [Allmendinger et al., 1986]; however, the general lack of zones of laterally persistent reflections at this boundary suggests a transition rather than a discrete boundary with sharp velocity contrast.

This reflection boundary at about 16 s in the COCORP data is clearly deeper than the 40-43 km depth previously inferred for Moho beneath the Colorado Plateau [Roller, 1965]; furthermore, there are no apparent zones of reflections or change in reflectivity at travel times (~13-14 s) corresponding to the depth previously suggested for Moho [Roller, 1965]. To further demonstrate this discrepancy, the assumption that the 16-s boundary lies at 40 km would require an unreasonably low, vertical average crustal velocity of 5 km/s. A minimum depth of at least 50 km to this reflection boundary can be calculated by using a mean crustal velocity of 6.2 km/s, the velocity of the shallow basement rocks indicated by the refraction data [Roller, 1965], and by sonic logs from basement-penetrating wells on the Colorado Plateau. However, in a more realistic case wherein crustal velocity increases with depth the reflection boundary would lie even deeper.

Refraction Data on the Colorado Plateau

In the early 1960s Nevada Test Site (NTS) explosions were recorded along a profile (unreversed) across the Colorado Plateau to Ordway, Colorado (Figure 1) [Ryall and Stuart, 1963]; receiver stations were widely spaced (31 seismometers over 1108.4 km, i.e., average station spacing of nearly 37 km), and the profile was unreversed. Data on crustal velocity variation along this line are lacking because of the absence of in-line shots. However, first arrivals across the Colorado Plateau suggested a Pn velocity of 8.0 km/s [Ryall and Stuart, 1963]. Although a crustal thickness of 42 km was suggested for the Colorado Plateau, it was "based on differences in arrival time of the phase Pn and a phase tentatively identified as SPS" [Ryall and Stuart, 1963, p. 5827]. The uncertain identity of this second arrival and its undoubtedly complex ray path from within the Basin and Range and into the Colorado Plateau make an inference of crustal thickness from this refraction data set suspect.

Most discussions of Colorado Plateau crustal thickness and Pn velocity reference the refraction experiment conducted between Chinle, Arizona, and Hanksville, Utah (Figure 1) [Roller, 1965] (also reinterpreted with a similar result by Prodehl [1979]). This refraction profile (Figure 4), presently the only reversed one on the Colorado Plateau, is of 1963 vintage and recorded on analog instruments. The large station spacing, averaging 7.8 km, makes it

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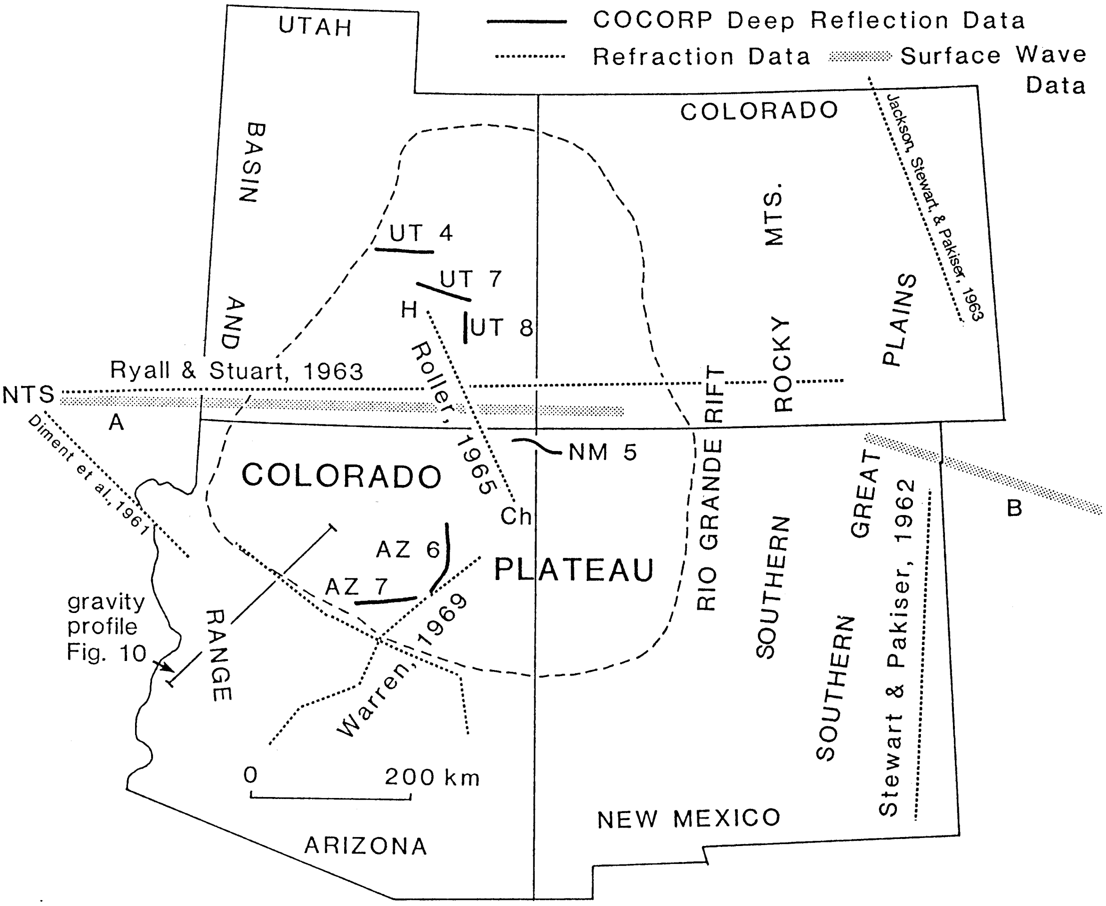


Fig. 1. Location map of COCORP deep reflection lines on the Colorado Plateau. The only reversed refraction profile on the Colorado Plateau [Roller, 1965] is between Hanksville (H), Utah, and Chinle (Ch), Arizona. Other refraction profiles of region are labeled with publication reference. A, surface wave profile [Keller et al., 1979a]; C, surface wave profile [Keller et al., 1979b].

difficult to identify and correlate phases, especially second arrivals, and emergent Pn first arrivals at far offsets are additionally difficult to identify above the noise level.

In general, the depth to Moho is difficult to determine with great precision, even from modern refraction data, unless both Pn and PmP arrivals are clearly identified and correlated in the data and traceable across many adjacent records. The wide station spacing and low data quality of the currently available refraction data on the Colorado Plateau (Figures 1 and 4a) make this phase identification and correlation difficult.

The original layered crustal model interpreted from the Chinle-Hanksville refraction data [Roller, 1965] (Figure 3) suggests a Moho at about 40-43 km having an anomalously low Pn velocity of 7.8 km/s; the 6.8 km/s velocity of the lower crust was interpreted entirely from second arrivals. The Moho in this model would correspond to a vertical two-way travel time of about 14 s; however, as noted above, there is no apparent boundary or structure in the COCORP reflection data at about 14 s (40-43 km) which might potentially correspond to such an important boundary (Figure 2).

The contention that the Pn velocity beneath the Colorado Plateau is about 7.8 km/s is placed in doubt, however, by the recent two-station analysis of hundreds of earthquakes received at pairs of stations on the Colorado Plateau [Beghoul and Barazangi, 1987, 1989]. This two-station analysis indicates a remarkably consistent Pn velocity of 8.10-8.15 km/s, a result foreshadowed by the early work of Ryall and Stuart [1963] mentioned above. The depth to this 8.15 km/s layer, however, is not constrained by the two-station analysis alone [Beghoul and Barazangi, 1987, 1989].

Alternative Refraction Models

The new information indicating a Pn velocity of 8.15 km/s beneath the Colorado Plateau, together with the reflection boundary observed at about 16 s on the COCORP data, require a critical reconsideration of the refraction data between Hanksville and Chinle.

The Hanksville-Chinle refraction profile [Roller, 1965] (Figures 1 and 4a) is reversed; however, for the Hanksville shots there are only four stations beyond 200 km (maximum offset of 293 km), and the records at these stations (Figure 5) are particularly noisy and first arrivals cannot be accurately picked. As a result, in an attempt to identify Pn arrivals, the profile from the Chinle shot point is effectively unreversed. In addition, large nonlinear variation (0.65-0.90 s) in the first arrivals (Pg, basement surface refraction) for stations at ranges up to 150+ km was recognized by Roller [1965] and is particularly significant near Hanksville on the profile from the Hanksville shot point (Figure 4a; also see Figures 2 and 3 of Roller [1965]). The variation in these Pg arrivals indicates a laterally varying upper crustal velocity structure in the vicinity of Hanksville which is particularly important since it occurs where the arrivals from the Chinle shot at ranges of 250-350 km would also be affected. As a result, even if weak emergent Pn first arrivals could be accurately picked in the 250-350 km range from the Chinle shot point, variations of crustal velocity near Hanksville would result in local shifts in arrival times and uncertainties in any calculated Pn velocity. This is an effect not considered in the existing interpretations [Roller, 1965; Prodehl, 1979].

Not only are Pn first arrivals obscure on the these refraction data (Figure 4a), but also PmP reflections are unclear and can not be picked and traced unambiguously across adjacent stations. This may explain why Roller [1965] and Prodehl [1979] interpret and pick a PmP reflection and critical point at quite different times and ranges. Also, without in-line shot points one can also not preclude shallow crustal velocity variations, like that observed near Hanksville, which could affect arrival times in the central part of the profile.

Given the clear evidence of laterally varying upper crustal

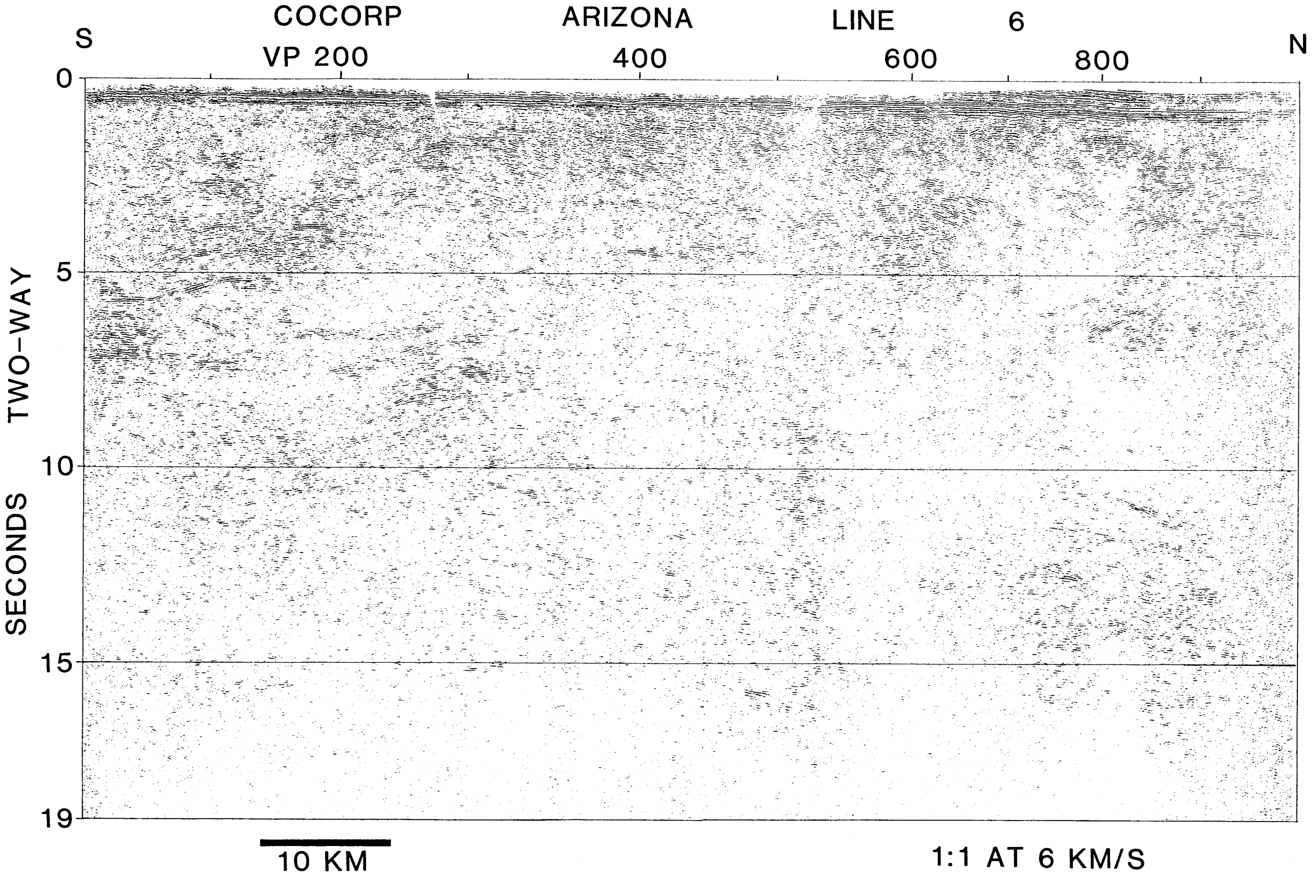


Fig. 2. COCORP line 6 from the Colorado Plateau north of Winslow; for location see Figure 1. Note the abundance of coherent reflections to about 16 s, below which there is a relative absence of reflections. Coherency filtered after stack for photographic enhancement. Time section in seconds two-way travel time, datum at t=0 is 1600 m, display scale is 1:1 at 6 km/s.

velocity, at least near Hanksville, together with the difficulty in precisely identifying the weak Pn arrivals, an interpretation of a Pn velocity and Moho depth from the Chinle-Hanksville refraction data is nonunique, and different Pn velocities and Moho depths are allowable. To demonstrate this point, for an independently determined Pn velocity of about 8.1 km/s [Beghoul and Barazangi, 1989], a simple single-layer model (Figure 6b) with an average crustal velocity of 6.3-6.4 km/s and a Moho at about 50-51 km can fit within ±0.1 s of the Pn first arrivals picked by Roller [1965] and Prodehl [1979]. Although second arrivals were interpreted by Roller [1965] to indicate a 6.8 km/s lower crust, they are not reevaluated here. However, the Pn arrivals of the single-layer model in Figure 6b can also be achieved by modifying the Roller [1965] model by thickening the 6.8 km/s lower crust to a depth of 51-52 km with a mantle velocity of 8.1 km/s (Figure 7). This misfit (Figure 6b) is slight considering the apparent lateral velocity variation in the upper crust along this part of the profile, as discussed above. Furthermore, the vertical two-way travel time for a Moho at 51-52 km with a vertical average crustal velocity of about 6.3-6.4 km/s is about 16 s, corresponding to the boundary observed on the COCORP data.

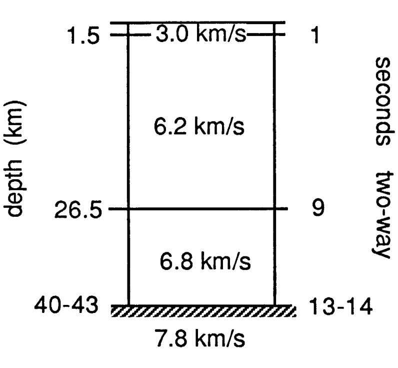


Fig. 3. Velocity depth model of Roller [1965], equivalent two-way travel times added.

One might attempt to rotely reconcile the earlier refraction interpretation [Roller, 1965; Prodehl, 1979] with the new observations of an 8.15 km/s Pn velocity [Beghoul and Barazangi, 1987, 1989] by suggesting that a layer of 7.8 km/s lies at about 40-43 km with the 8.1 km/s observation representing a deeper boundary which is unrecognized on the existing refraction data. Such a model might suggest an uppermost mantle layer which has an anomalously low velocity and abundant reflections. However, as discussed above, 7.8 km/s arrivals can not be unambiguously identified on the Chinle-Hanksville data. Furthermore, so far there is no evidence of an important boundary at 40-43 km (~14 s) on the COCORP data and no evidence of anomalously low Pn velocities from the two-station analysis, even at shorter offsets [Beghoul and Barazangi, 1987, 1989]. Therefore, unless such a 7.8 km/s layer is a "hidden layer" and not represented by unambiguous arrivals, this more complicated model seems presently unwarranted. However, such a model would indicate a reflective upper mantle, a unique observation in deep reflection data sets, and would represent a significant counterexample to the available worldwide observations that suggest that the upper mantle is relatively nonreflective. Perhaps only a new refraction experiment having closer station spacing and in-line shots can explore the need for more complicated alternatives. However, as discussed in the next section, by considering a Pn velocity of 8.10-8.15 km/s, the other main refraction data set on the Colorado Plateau [Warren, 1969] also indicates a Moho deeper than the 40-43 km previously suggested.

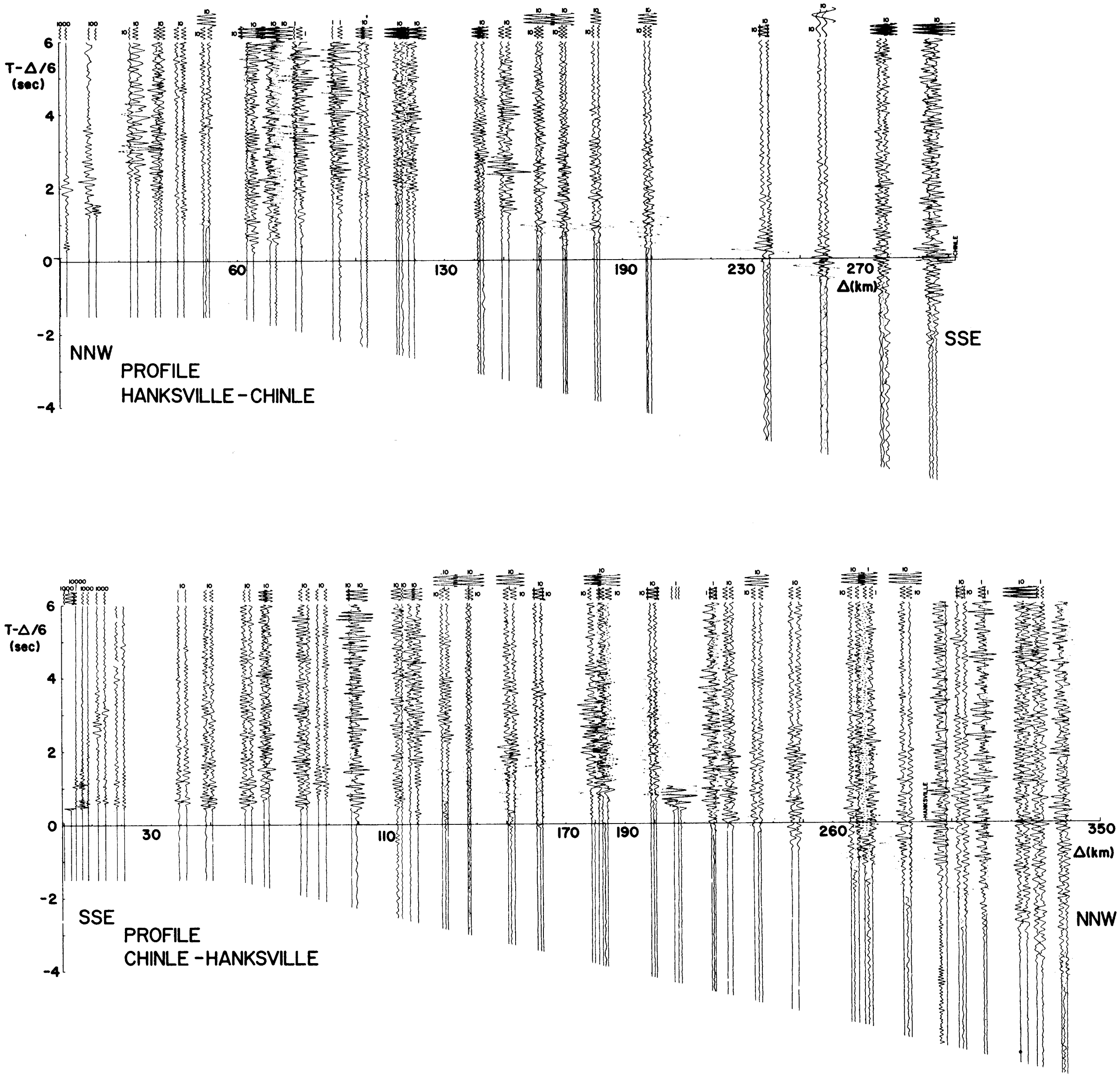


Fig. 4a. Unannotated refraction data, reduction velocity of 6 km/s, used by Roller [1965] and Prodehl [1979] to interpret a 7.8 km/s Pn velocity and a 40-43 km crustal thickness for the Colorado Plateau. Note the wide station spacing and the difficulty correlating phases. The Pn first arrivals at ranges greater than 200 km are obscure. Pg arrivals from the Hanksville shot point are significantly nonlinear.

Modification of the Warren [1969] Delay Time Analysis

Refraction data on the southwest Colorado Plateau (Figure 1) [Warren, 1969] have also been commonly referenced as supporting a Moho at about 40 km beneath the Colorado Plateau having a Pn velocity of about 7.8 km/s. These refraction data were collected in 1964 [Warren, 1969] along two main traverses (Figure 1), one NW-SE along the margin of the Colorado Plateau in the transition zone with the Basin and Range Province, and another SW-NE from the Basin and Range and onto the Colorado Plateau. Although Pn first arrivals were identified and picked, a conventional refraction interpretation was not attempted. Instead a delay time or time term method was used (Figure 8a, and equation (1) below) [Warren, 1969] that assumes a uniform Pn velocity V_n, with the total travel time T at a receiver of offset X partitioned between a source time term (τ_a in equation (2)), a receiver time term (τ_b in equation (2)), and a horizontal term.

$$T = \frac{h_a}{V_n \tan\theta} + \frac{h_b}{V_n \tan\theta} + \frac{X}{V_n} \qquad (1)$$

or

$$T = \tau_a + \tau_b + \frac{X}{V_n} \qquad (2)$$

The time term τ_a, or depth h_a, at each source location was initially assumed by Warren [1969], and a Moho depth at a source

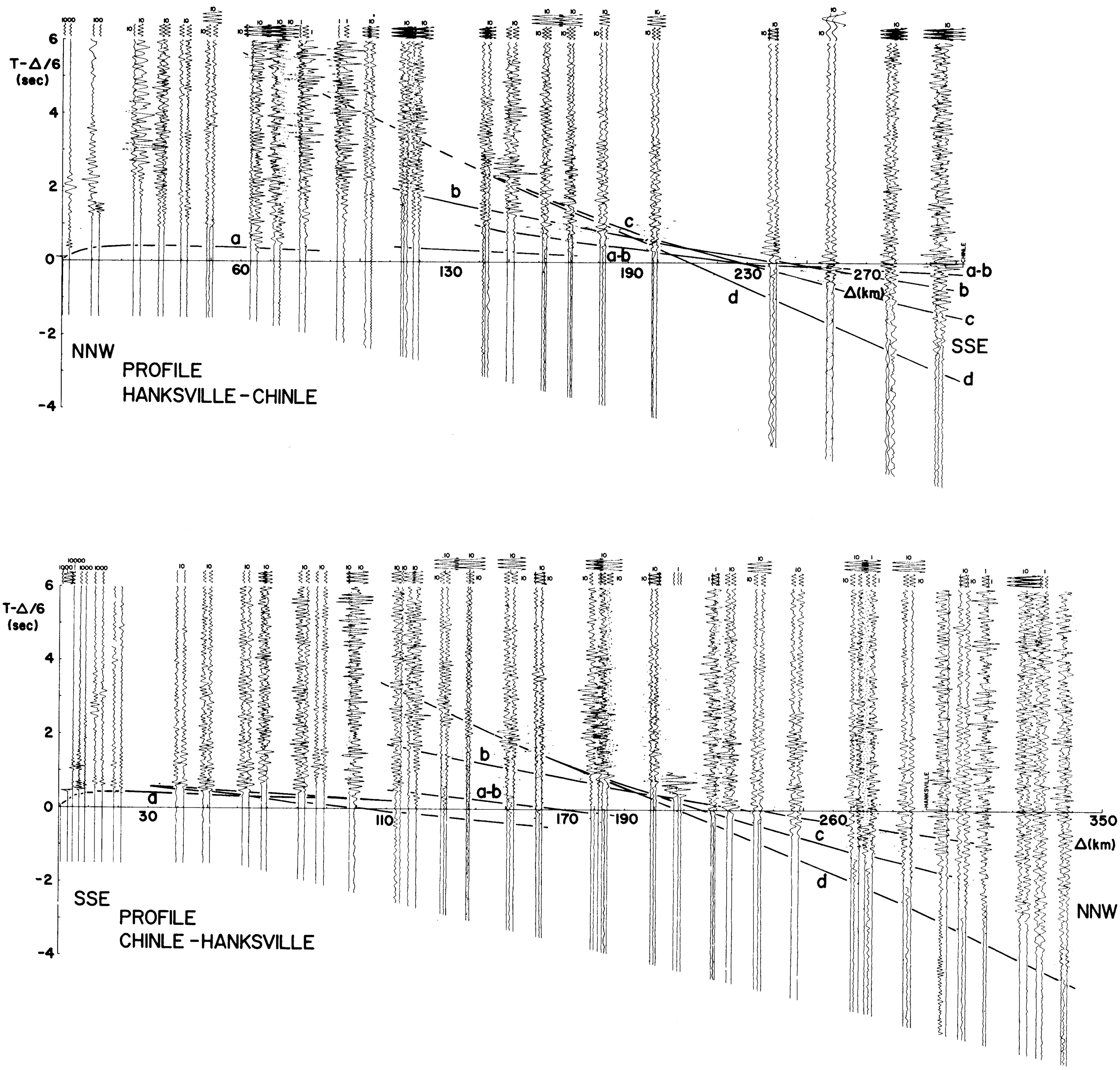


Fig. 4b. Refraction data between Hanksville and Chinle with the Prodehl [1979] phase interpretation, reduction velocity of 6 km/s.

or reciever location was calculated. The various site-specific time terms and their resulting thicknesses were then adjusted to make the depth values consistent at a particular location [Warren, 1969].

The time terms determined by Warren [1969] may be internally consistent despite limited redundancy; however, the Moho depth beneath the Colorado Plateau was interpreted not by measuring but by assuming a 7.8 km/s Pn velocity beneath the Colorado Plateau [Warren, 1969, p. 275]. This assumption was based on (1) the velocity which resulted when the Pn arrivals on the NW-SE profile (Figure 1) were "forced into a reversed pair;" and (2) the velocity "consistent with nearby crustal-refraction surveys" by Roller [1965] and Diment et al. [1961].

The NW-SE profile of Warren [1969] (Figure 1) might indicate a velocity near 7.8-7.9 km/s for the Transition Zone; however, the profile described by Diment et al. [1961] (Figure 1) is unreversed and lies entirely in the Basin and Range Province, therefore not constraining the Pn velocity beneath the Colorado Plateau. Such relatively low Pn velocities are generally characteristic of the Basin and Range Province with its high heat flow and thinned and extended crust [Eaton, 1963; Prodehl, 1979]. The Roller [1965] data are from a profile located in the central Colorado Plateau, but as discussed above, the Pn velocity there is ambiguous. Not only was a faster (8.0 km/s) Pn velocity beneath the Colorado Plateau foreshadowed by the results of Ryall and Stuart [1963] (Figure 1), but they also suggested that a transition in Moho velocity in southernmost Utah occurs at or near the boundary between the Basin and Range and the Colorado Plateau provinces. Consequently, it is necessary to reevaluate the time term analysis as applied by Warren [1969] for the case where the Pn velocity changes laterally from 7.8-7.9 km/s beneath the Basin and Range Province and Transition Zone to 8.1-8.15 km/s beneath the Colorado Plateau [Beghoul and Barazangi, 1987, 1989].

In Figure 8b and equation (3), the delay time analysis as applied by Warren [1969] is modified for a case where the Pn velocity varies laterally:

$$T = \frac{X - x}{V_1} + \tau_a + \frac{x}{V_2} + \tau_b^* \qquad (3)$$

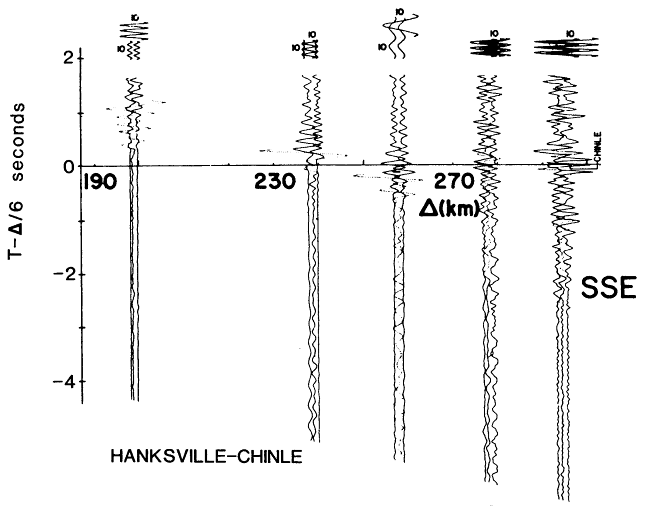


Fig. 5. Enlargement of part of Roller [1965] data (Figure 4) from Hanksville shot point, reduction velocity of 6 km/s. Pn first arrivals can not be precisely picked on the noisy, widely spaced data beyond 230 km.

where

$$\tau_b^* = \frac{(h_b + z)\cos\theta^*}{V_c}$$

In equation (3), V_1 and V_2 are the different Moho velocities (e.g., 7.85 km/s and 8.15 km/s, for the Basin and Range and the Colorado Plateau, respectively), and x is that part of the total range (Figure 8b) where the Moho velocity is V_2.

Since the total travel time T remains unchanged by definition, combining equations (2) and (3) results in equation (4), which represents the trade-off of depth and Moho velocity necessary to keep the Colorado Plateau time term unchanged:

$$\tau_b = \frac{x}{V_2} - \frac{x}{V_1} + \tau_b^* \tag{4}$$

Replacing for τ_b and τ_b^* in (4) results in

$$\frac{z\,[1-(V_c/V_2)^2]^{1/2}}{V_c} = x\left(\frac{1}{V_1} - \frac{1}{V_2}\right) + \frac{h_b}{V_c}\left([1-(V_c/V_1)^2]^{1/2} - [1-(V_c/V_2)^2]^{1/2}\right) \tag{5}$$

Expression (5) shows that for a Moho refraction arrival at a location x km from where the Moho velocity changes to V_2 (Figure 8b), the Moho would lie z km deeper than that previously suggested (h_b) at the refracting point without affecting the total travel time or the Colorado Plateau time term as determined by Warren [1969]. An example calculation is instructive. For a Moho refraction arrival recorded 200 km east of where the Moho velocity changes to 8.15 km/s (instead of remaining 7.85 km/s) and for an average crustal velocity (V_c) of about 6.2 km/s (minimum), the Moho could be about 7 km deeper at the refracting point than the 40 km previously suggested by the Warren [1969] time term analysis without affecting the total travel time. Using a higher average crustal velocity of 6.5 km/s in this modified time term calculation has only a minor effect, increasing the depth by less than 1 km. A minor correction for the additional ray path distance to this deeper Moho (Figure 8c) results in a time correction of less than 0.2 s, a value which if applied entirely to the Colorado Plateau time term would reduce the Moho depth there by less than 1 km. Consequently, a modification of the delay time technique applied by Warren [1969] in order to consider a lateral change to a sub-Moho velocity results in a Moho beneath the Colorado Plateau that is deeper than previously suggested.

Alternative Refraction Model to Fit Warren [1969] Data

A ray-traced refraction model (Figure 9) further demonstrates how the Warren [1969] data are consistent with a deeper Moho beneath the Colorado Plateau having a Pn velocity of 8.1-8.15 km/s. The model of Warren [1969] (Figure 9a) was modified and then ray traced iteratively to fit the Moho first arrivals picked and published by Warren [1969] (Figures 9b, 9c, and 9d). West of the edge of the Colorado Plateau the velocity-depth structure used in this alternative model closely resembles that of Warren [1969]; in particular, a 7.85 km/s Pn velocity is used for the Basin and Range Province and the Transition Zone. The main difference in this alternative model (Figures 9b, 9c, and 9d) is that the Moho velocity changes at the

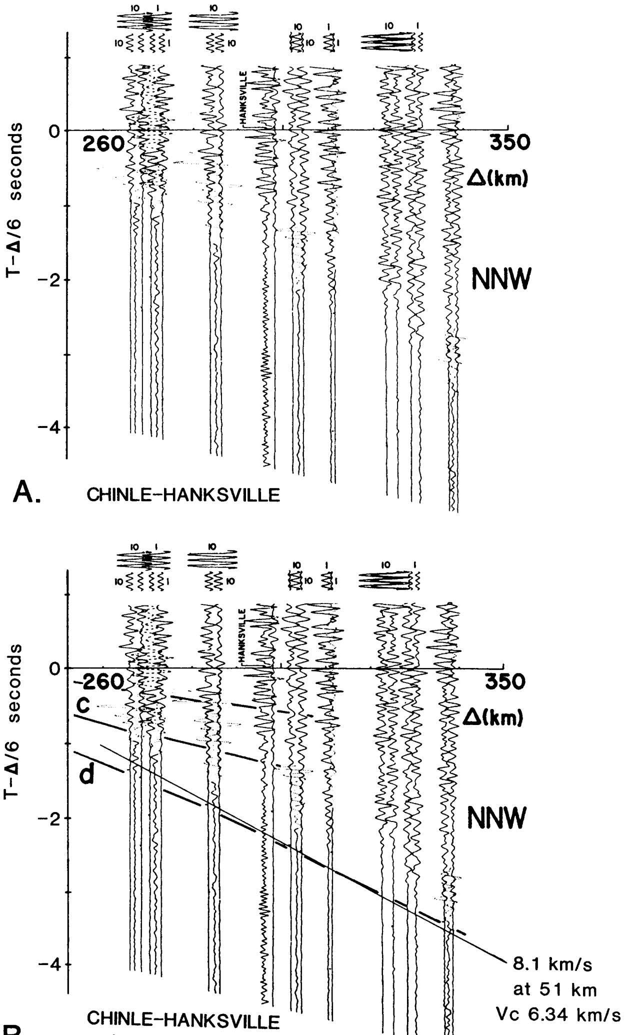


Fig. 6. Enlargement of part of Roller [1965] data at far ranges from Hanksville shot point (from Figure 4), reduction velocity of 6 km/s. (a) Unannotated data. (b) Bold lines denote the previous phase interpretation and correlation by Prodehl [1979], "d" is the previously interpreted Pn. For comparison, the fine line represents the arrival times for a Pn of 8.1 km/s at ~51 km depth with an average crustal velocity of about 6.34 km/s. Such an alternative interpretation is allowed by the refraction data, given the uncertainty in precisely picking the Pn first arrivals together with the evidence for significant lateral variation in upper crustal velocity in this region.

Moho step or "fault" suggested by Warren [1969], east of which the lower crustal layer is thickened so that the Moho is nearly level at about 50 km with a sub-Moho velocity of 8.1 km/s. In this model there is a significant lateral velocity gradient in the upper mantle where the Moho velocity changes, rather than an abrupt boundary. As can be seen in Figures 9b and 9c, the Pn first arrivals published by Warren [1969] can be reasonably matched by this model. Interestingly, a Moho step or "fault," suggested by Warren [1969] from abrupt changes in Pn arrival time from the Gila Bend shot (Figure 9b), may be 10 km or greater rather than the 4 km previously suggested.

Despite its simplicity, this alternative refraction model notably reconciles (1) the apparent Pn first arrivals of the old refraction data set [Warren, 1969], (2) the independently determined Pn velocity of 8.10-8.15 km/s [Beghoul and Barazangi, 1987, 1989], and (3) a Moho at about 50 km, corresponding to the abrupt decrease in reflections at 16 s on the COCORP data.

Other Geophysical Data

This alternative model is also consistent with other geophysical data sets on the Colorado Plateau. Surface wave dispersion results from the Colorado Plateau (A on Figure 1) [Keller et al., 1979a] were originally interpreted as consistent with the 7.8 km/s Pn velocity of the former refraction models by assuming a Poisson's ratio of 0.25. However, those results are equally consistent with an 8.1 km/s Pn velocity for a Poisson's ratio of 0.27-0.28. Poisson's ratio for the upper mantle below the Colorado Plateau is not known; however, a Poisson's ratio of 0.27-0.28 is within the range of values for upper mantle in various continental regions where Pn and Sn have simultaneously been observed (summarized in Figure 14 of Ukawa and Fukao [1981]). Therefore, even ignoring uncertainty in the modeled Sn velocity from surface wave analysis, by assuming a different yet reasonable Poisson's ratio the surface wave results appear equally consistent with a Pn velocity of 8.1 km/s beneath the Colorado Plateau. It is perhaps also significant that the surface wave modeling suggested a somewhat thicker crust [Keller et al., 1979a].

The alternative model can also be reconciled with gravity observations. Bouguer gravity values in Figure 10a are taken from the regional Bouguer gravity map [Lyons et al., 1982] along a line across the SW margin of the Colorado Plateau and parallel to the Warren [1969] refraction profile (Figure 1). The values range from about -200 mGal on the Colorado Plateau to about -50 mGal near the Colorado River in western Arizona.

One might debate details or construct more complex models; however, by using the Moho depth from the alternative seismic model discussed above together with reasonable density contrasts, the principal variation of Bouguer gravity across the SW margin of the Colorado Plateau can be modeled as a simple combination of crustal thickness change and a lateral change of mantle density (Figure 10b). A relatively more dense mantle lithosphere (i.e., +0.1 g/cm^3) beneath the Colorado Plateau is suggested by the lateral change in Pn velocity from 7.8 km/s in the Basin and Range Province to 8.1 km/s beneath the Colorado Plateau.

With the exception of the major Moho step beneath the margin of the Colorado Plateau (Figures 9b and 10), the nature of the change in Moho depth is generalized in the gravity model (Figure 10) as a smooth incline beneath the Transition Zone between the Colorado Plateau and the Southern Basin and Range Province. However, COCORP profiling across the Transition Zone indicates that one or more Moho steps of as much as 3 km may occur there [Hauser et al., 1987]. The presence of small steps in place of a smooth incline, although important in a structural or tectonic sense, has little effect on the calculated gravity anomaly and has been ignored in this simple model.

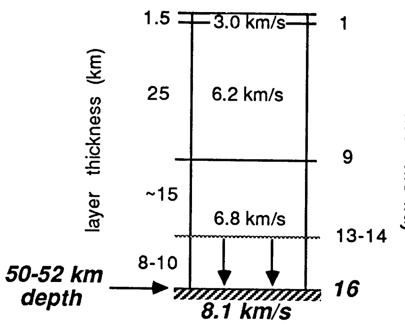


Fig. 7. Roller [1965] model modified by thickening the lower crustal layer and changing the sub-Moho velocity to 8.1 km/s, also resulting in the alternative Pn model of Figure 6b.

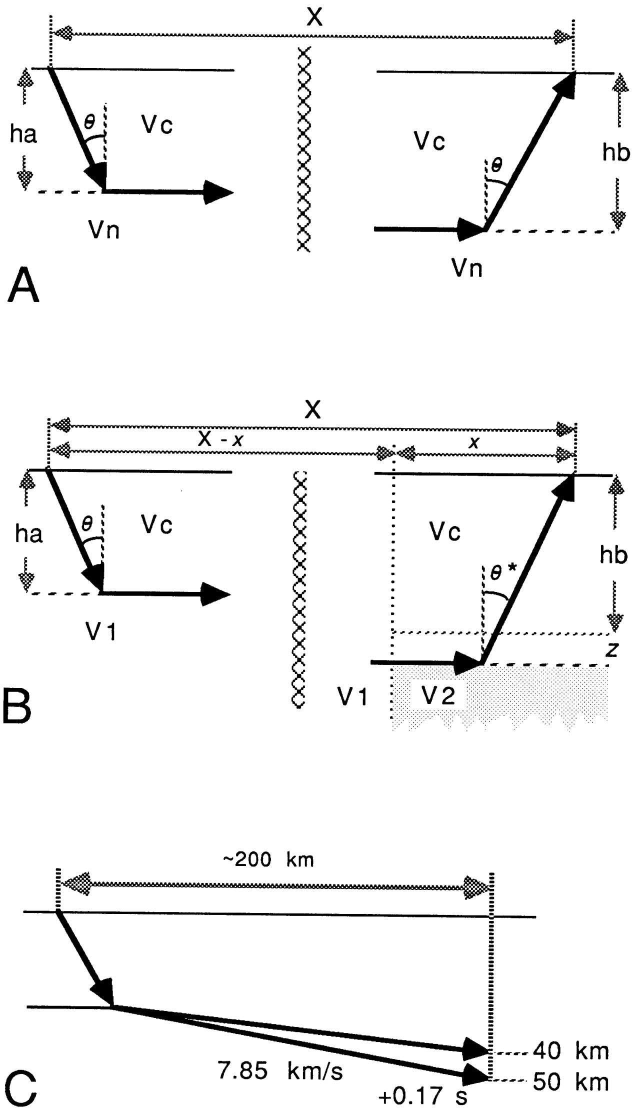


Fig. 8. (a) Geometric basis for the Warren [1969] time term analysis wherein a uniform Pn velocity is assumed. (b) Geometric basis for a modification of the time term analysis of Warren [1969], wherein a lateral change in Pn velocity is allowed. (c) Approximate calculation of the additional time taken to reach a deeper Moho in methods in Figure 8b versus Figure 8a.

Discussion

Perhaps it should not be surprising that the Moho beneath the Colorado Plateau may lie at a depth of 50 km or more and have a normal Pn velocity of 8.1 km/s. A Moho at about 50 km with a Pn velocity of about 8.2 km/s beneath the High Plains east of the Rocky Mountains has been interpreted from refraction and surface wave profiles (Figures 1 and 11) [Stewart and Pakiser, 1962; Jackson et al., 1963; Keller et al., 1979b]. Therefore this new interpretation results in a Colorado Plateau which more closely fits in the general

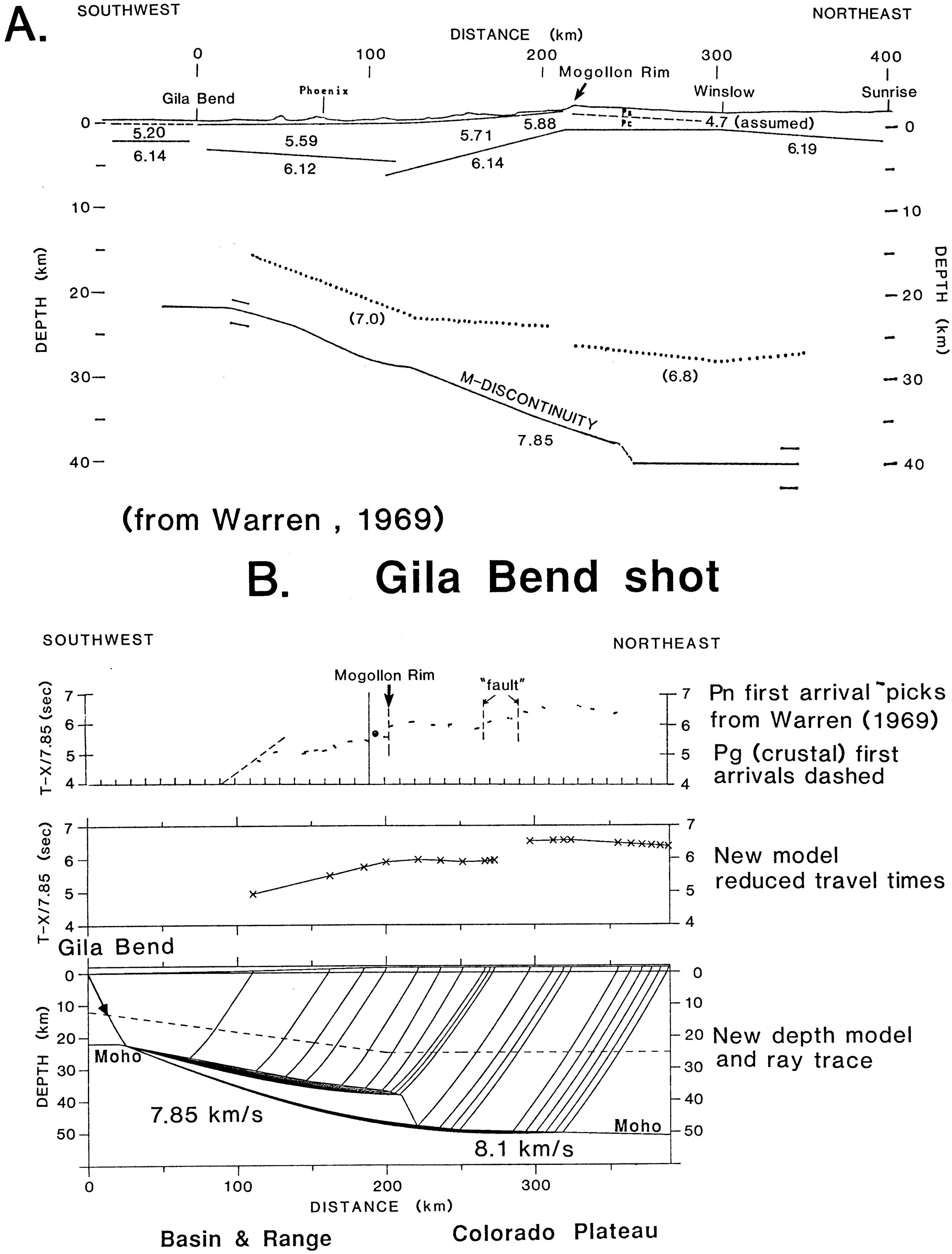
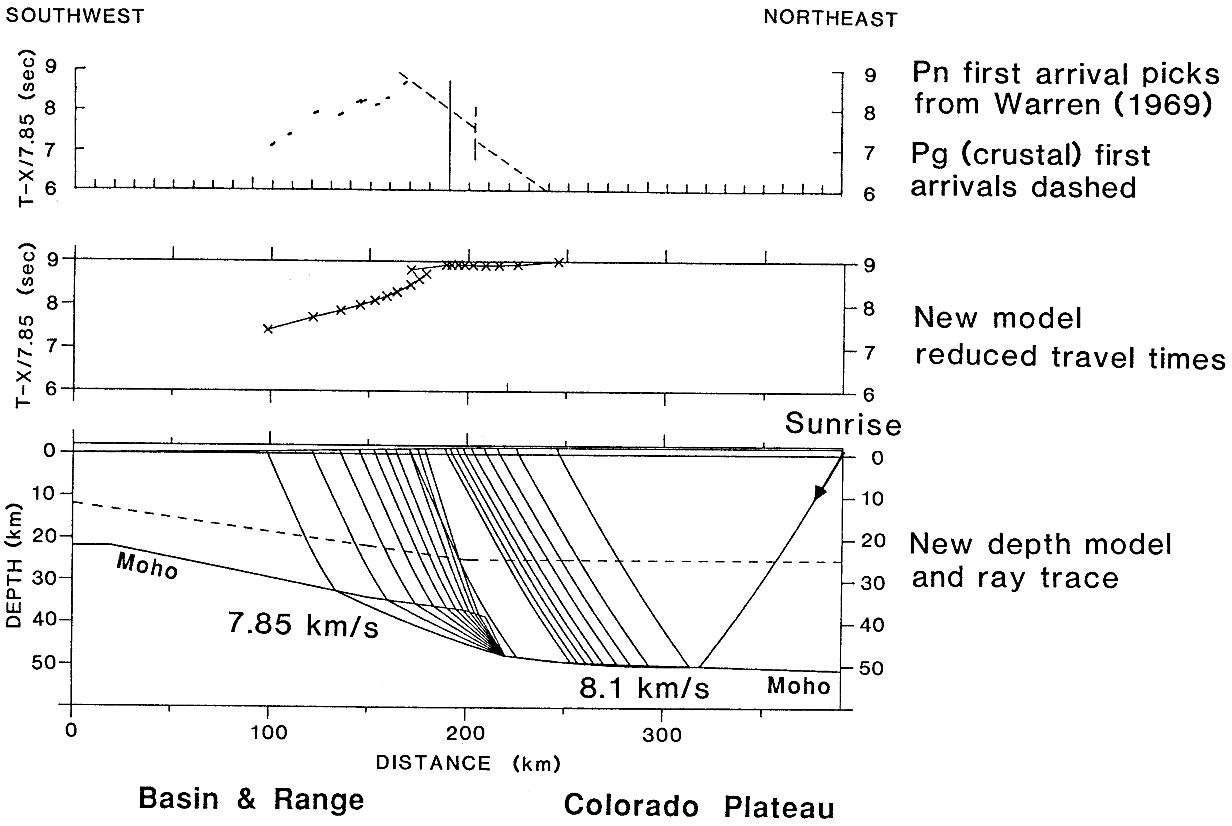


Fig. 9. Ray trace modeling to fit the published Warren [1969] Pn picks. (a) original model interpreted by Warren [1969] using a time term method. Uniform 7.85 km/s Pn velocity assumed; Moho interpreted at about 40 km beneath Colorado Plateau. (b,c,d) Ray-traced models for different shots on the NE-SW profile in Arizona (see Figure 1). Velocity model resembles previous model (Figure 9a) except that the Colorado Plateau Moho lies at about 50 km with a Pn velocity of 8.1 km/s. The Pn first arrivals reported west of the Colorado Plateau from the Sunrise shot (Figure 8c) are modeled as diffractions from the bottom corner of this Moho step.

C. Sunrise shot



D. Strawberry shot

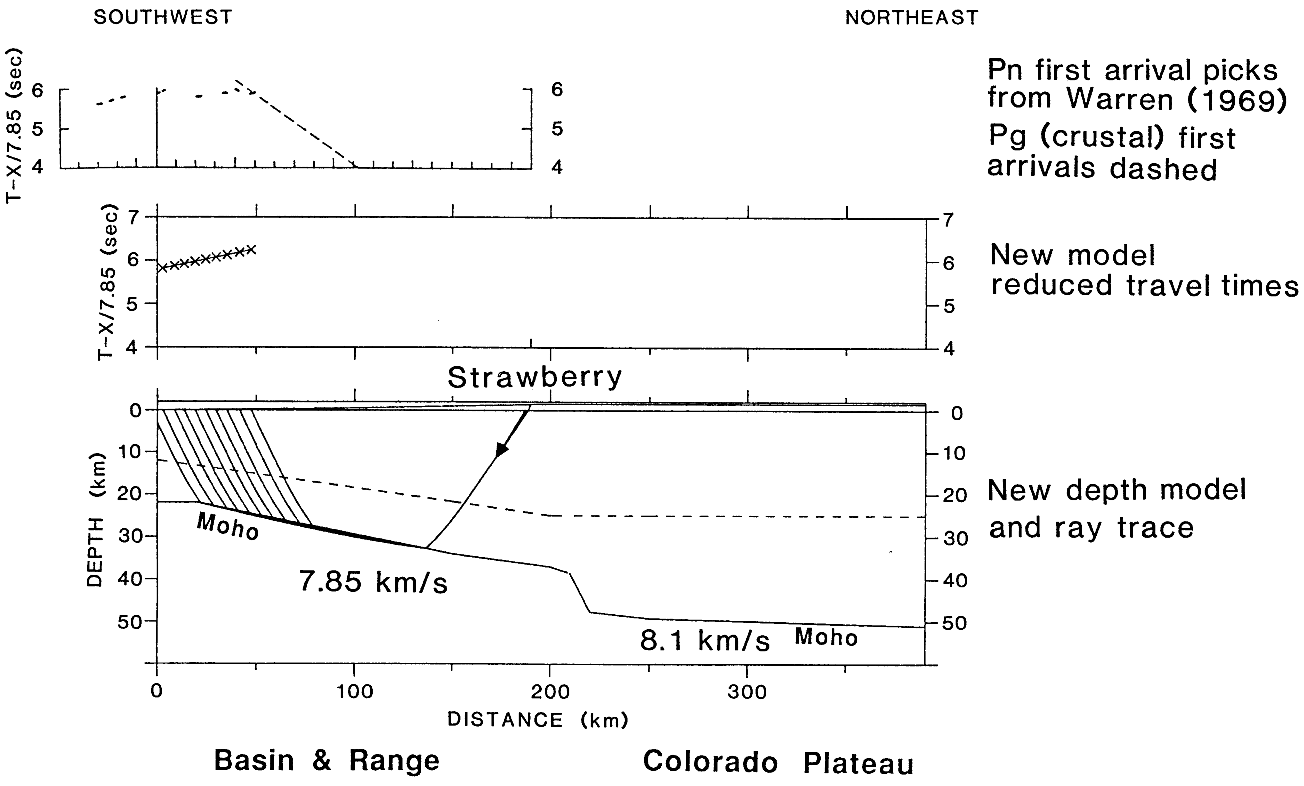


Fig. 9. (continued)

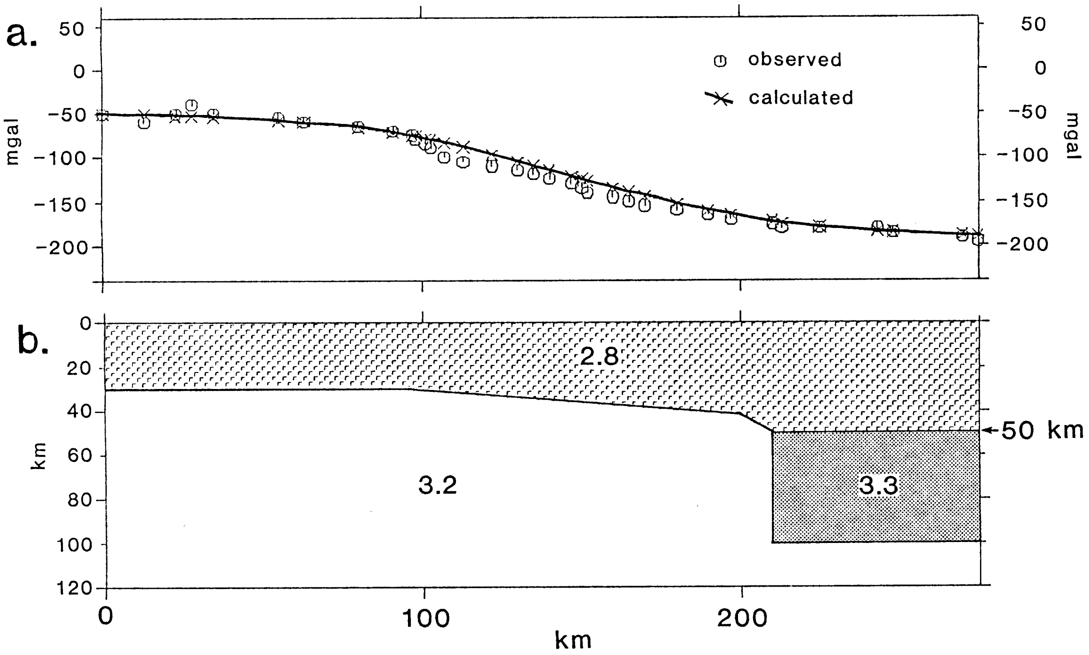


Fig. 10. (a) Circles denote Bouguer gravity values from contours of regional gravity map [Lyons et al., 1982]; for profile location see Figure 1. Crosses and solid line denote the calculated curve from the density model below. (b) Generalized gravity model based upon the alternative seismic model discussed in this paper, especially a Colorado Plateau crustal thickness of about 50 km with a normal 8.1 km/s upper mantle. Since gravity modeling uses density contrasts, the average density values shown for the crust, asthenosphere (or hot lithosphere), and mantle lithosphere could instead be 2.9, 3.3, and 3.4 g/cm^3, respectively. In this simple model, both the Southern Basin and Range Province at low elevation near the Colorado River and the Colorado Plateau with its ~2 km elevation are in approximate isostatic equilibrium above a compensation depth at the base of the Colorado Plateau lithosphere in the model. In this simple model, the depth of compensation or the base of the mantle lithosphere beneath the Colorado Plateau is a simple trade-off between mantle lid thickness and density; a mantle lithosphere density of about ~3.3 g/cm^3 beneath the Colorado Plateau is consistent with a compensation depth of about 100 km, within the broad range of previously suggested depths [e.g., Archambeau et al., 1969; Biswas and Knopoff, 1974].

pattern of crustal thickening westward across the Great Plains and Rocky Mountains. As a result, the Colorado Plateau may be less of a lithospheric pariah than previously thought and may more easily fit into geodynamic models which attempt to explain the origin of the regional crustal thickening [e.g., Bird, 1984]. Also, geodynamic modeling of mechanisms of Colorado Plateau uplift would seem to need reevaluation since much of the nearly 2 km elevation of the Colorado Plateau may be due to a greater crustal thickness. However, the extent and timing of uplift of the Colorado Plateau may still be governed by mantle processes which reduce the mass surplus at the base of the mantle lid, thereby "allowing" the thick crust to rise.

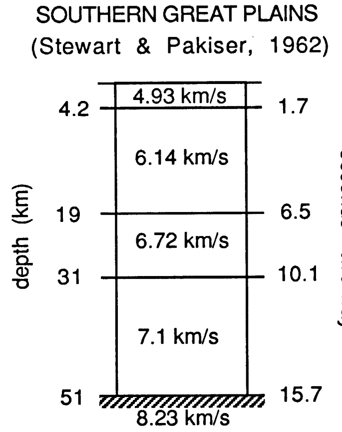


Fig. 11. The velocity model of Stewart and Pakiser [1962] inferred from nuclear source refraction data from eastern New Mexico (for location see Figure 1).

Summary

Here we have discussed and evaluated the previous refraction data sets and interpretations in light of recent observations of a normal 8.10-8.15 km/s Pn velocity and presented an alternative model for the Colorado Plateau lithosphere wherein the Moho lies at a depth of about 51-52 km, about 8-10 km deeper than that previously interpreted. The appeal of this new model is its ability to reconcile the independently determined 8.10-8.15 km/s Pn velocity beneath the Colorado Plateau [Beghoul and Barazangi, 1987, 1989] with the existing refraction data [Roller, 1965; Warren, 1969] and with a Moho at a 16-s boundary on the COCORP data. The indication that this abrupt decrease in reflectivity at 16 s on the COCORP data represents Moho beneath the Colorado Plateau strengthens the generalization that such a boundary represents the Moho on deep reflection data in relativley stable continental regions.

The lack of prominent, laterally extensive reflections at or near the Moho on the COCORP data is inconsistent with a simple velocity step function at the Moho. Instead, the boundary of reflections at 16 s may represent the base of a transition from complex and discontinuous crustal reflectors to a mantle which may be dominantly peridotite and relatively nonreflective.

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