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Upper mantle models and the thickness of the continental lithosphere

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SUMMARY

Analysis of the Early Rise traveltimes in the United States shows that on several of the profiles there are features which can be interpreted as indicating a low-velocity zone above 200 km, i.e. that the continental lithosphere thickness is less than 200 km. The explosion data from the Nevada Test Site, GNOME and Early Rise are all consistent with Lehmann's suggestion that there is a discontinuity at a depth of about 200 km. Comparison of the observed data between 15° and 23° with model calculations shows that the major differences between the western and central–eastern United States upper mantles occur above 200 km. It appears that the only reasonable explanation for the 200 km discontinuity is that it represents the termination of a zone of partial melting.

Key words: lithosphere thickness, traveltimes, upper mantle.

INTRODUCTION

In the 1950s the two best known models of the seismic velocities in the Earth were those of Jeffreys and Gutenberg. The Gutenberg model had a low-velocity zone in the upper mantle, but the Jeffreys model did not. The Jeffreys model had a fairly steep increase in velocity at a depth of about 400 km corresponding to the '20° discontinuity' in traveltimes. The Gutenberg model did not have this feature.

Haskell's development of the 'propagator matrix' in (Haskell 1953) made possible the calculation of surface wave velocities for realistic earth models for the first time. The development at Lamont of long-period seismometers provided good surface wave velocity data as a function of period. Comparison of computed and observed surface wave velocities showed that these were consistent with the Gutenberg model, but not with the Jeffreys model.

The introduction of transverse anisotropy in the uppermost mantle in the PREM model (Dziewonski & Anderson 1981) makes it possible to dispense with a low-velocity layer. Although there is undoubtedly some anisotropy in the upper mantle, the fact that low surface wave velocities and late teleseismic arrivals are always associated with regions of orogenic uplift and high heat flow suggests that the low-velocity layer solution should be preferred.

The existence of a low-velocity layer above a depth of 200 km is also more consistent with determinations of the effective elastic thickness of the lithosphere. For example see Bechtel *et al.* (1990). There is broad similarity between fig. 3 of Bechtel *et al.* and the traveltime delays for *P* and *S* shown in figs 20(a) and (b) of Hales & Herrin (1972).

The '20° discontinuity' in traveltimes and the associated sharp increase in the seismic velocities at a depth of about 400 km of the Jeffreys model is now generally accepted and occurs in all current models of upper mantle structure.

Short-period body waves provide information of greater depth resolution than is possible with long-period body waves or surface waves. Explosion data has the great advantage that the locations and origin times of the events are known. It is the purpose of this paper to discuss the large volume of explosion data available from the continental United States and its interpretation in terms of upper mantle structure.

NUCLEAR EXPLOSION TRAVELTIMES

Since 1957 the hypocentral parameters of all United States nuclear explosions have been published. The traveltimes of these explosions provide an invaluable databank of traveltimes to 20° arc distance in a continental region. There have been a large number of explosions at the Nevada Test Site (NTS), but this discussion begins with the times from the nuclear explosion GNOME fired close to the New Mexico–Texas border in 1961. Observations were made along a profile extending to about 400 km north of the hypocentre to determine crustal structure at the site, along a profile WNW from GNOME site to NTS and along a profile ENE across the central and eastern United States as well as

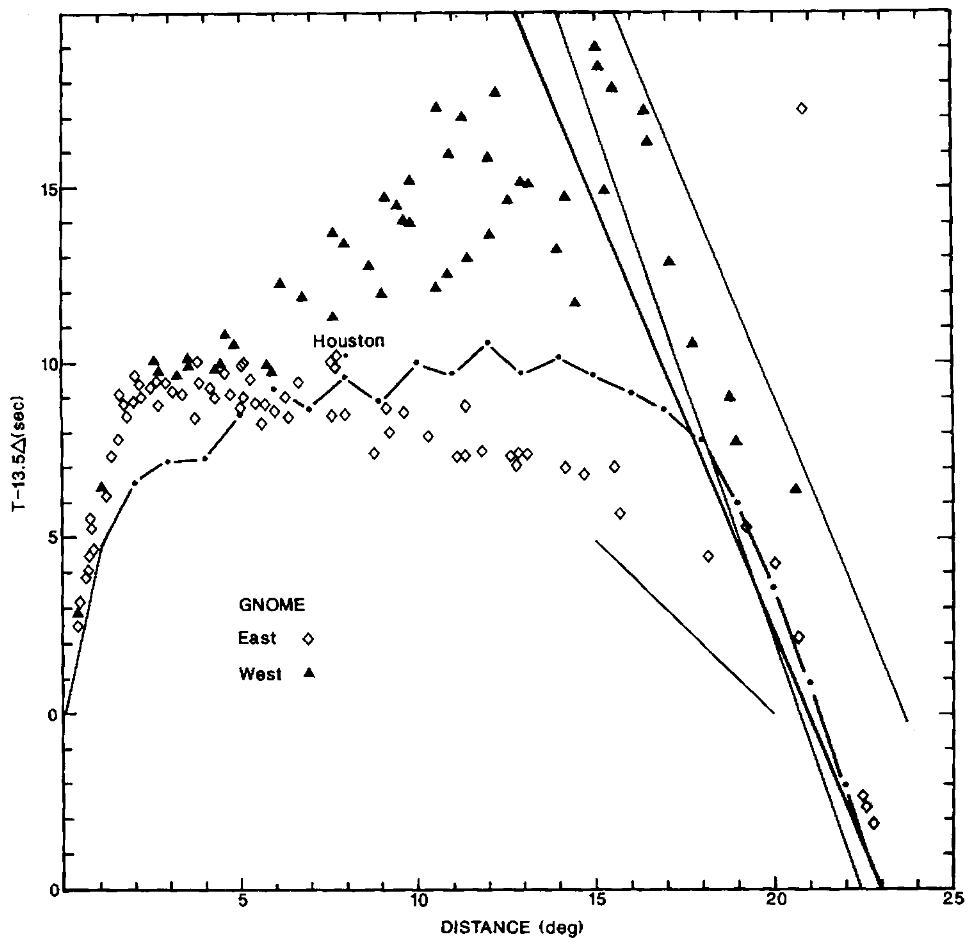

Figure 1. Reduced traveltimes from the GNOME explosion in the eastern and western United States. The two steep thin lines on the right of the figure enclose the observations interpreted as refracted below the 400 km discontinuity. The heavy line shows the traveltimes for this refraction for the British Columbia Early Rise profile (equation 2). The dash–dot line shows the average global traveltimes of Dziewonski & Anderson (1983) as quoted by Kennett (1989, personal communication).

at permanent and temporary stations more widely distributed across the United States and Canada (Romney *et al.* 1962).

The observations were analysed by Herrin & Taggart (1962) and by Romney *et al.* (1962). Fig. 3 of Herrin & Taggart showing traveltime residuals from the HARDTACK traveltimes and fig. 4 of Romney *et al.* showing residuals from the Jeffreys–Bullen traveltimes established unequivocally that the traveltimes in the western United States were later than those in the central and eastern United States at corresponding distances. The differences reach as much as 10 s at 12°–15° as is illustrated in Fig. 1. Herrin & Taggart also showed that amplitudes and interval velocities were lower in the west than in the east. Herrin & Taggart remarked that the 'difference was too great to be explained by variations in crustal thickness and must be attributed to systematic variations in the seismic velocity of the upper mantle'. They concluded also that low P_n velocity is associated with high attenuation of the P_n signal.

Also plotted in Fig. 1 are the average global times of Dziewonski & Anderson (1983) used by Kennett (1989, personal communication) in constructing his interim upper mantle model. The average times lie between the times for the western and central–eastern United States.

Figure 2 shows the averaged reduced station traveltimes for eight events at NTS. In this case the traveltimes are all slower than the average global traveltimes. Beyond about 6° there is considerable scatter as was the case for the GNOME traveltimes. The nuclear explosion traveltimes were discussed by Lehmann (1964) who attributed the scatter to different physiographic provinces. Lehmann's interpretation of traveltimes in the western United States was in terms of a low-velocity layer beginning at a depth of 70 km and terminating in a discontinuous increase in velocity at a depth of 215 km. The Lehmann model of the upper mantle is shown in Fig. 3 together with the Gutenberg model. The models differ in that Lehmann (1964) did not think that the low velocity extended up to the M discontinuity as it does in the Gutenberg model. Lehmann remarks that on the Gutenberg model 'there will be no P_n (in the usual sense) emerging at any distance'.

Lehmann's model derived from the eastern United States GNOME observations is also shown in Fig. 3. It includes a low-velocity layer beginning at a depth of 150 km and terminating as in the western US at a depth of 215 km. In this paper Lehmann remarks after a discussion of earthquake traveltimes in southeastern Canada, and the

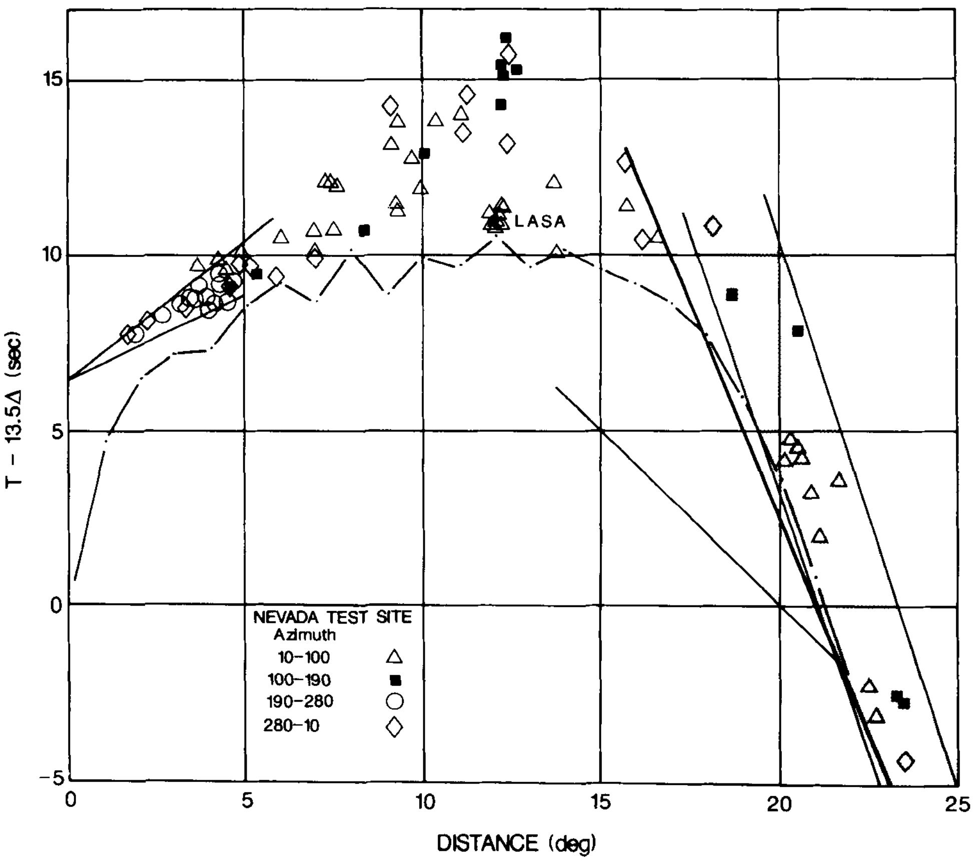

Figure 2. Reduced average station traveltimes for eight NTS explosions. The two steep thin lines on the right of the figure enclose the observations interpreted as refracted below the 400 km discontinuity. The heavy line shows the traveltimes for this refraction for the British Columbia Early Rise profile (equation 2). The dash–dot line shows the average global traveltimes of Dziewonski & Anderson (1983) as quoted by Kennett (1989, personal communication). Also shown is the traveltime line for refractions from below the 200 km discontinuity for the Yellowknife Early Rise profile (equation 1).

northeastern US extending to Missouri: 'It appears, therefore, that there is no low velocity layer at small depths in these regions. If there is a low velocity layer at all it is at considerable depth with its upper boundary probably well below 100 km'.

The Lehmann interpretation of the NTS traveltimes as

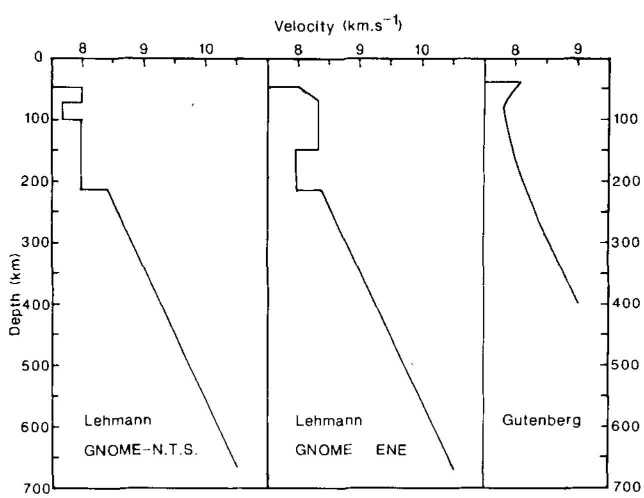

Figure 3. Upper mantle *P* velocity models of Lehmann for the eastern and western United States and the Gutenberg model.

showing an increase in velocity beyond 16° was confirmed by Green & Hales (1968), who made observations of a nuclear explosion GREELEY at a number of stations from Oklahoma to the Smoky Mountains. At a distance of 10° the arrivals were 6 or 7 s later than the Early Rise arrivals at the same distance. From this distance to about 18° the apparent velocity was about 8.9 km s^{-1}. There was a break in the traveltimes to a velocity of 10.2 km s^{-1} at about 20° followed by a break to an apparent velocity of 12.2 km s^{-1} at about 23.5°.

THE EARLY RISE TRAVELTIMES

During the Early Rise Experiment, organized by the US Geological Survey, a long series of 5 ton shots was fired in Lake Superior and observed along profiles in several azimuths by the participating United States and Canadian institutions. The full set of Early Rise data was analysed by Iyer *et al.* (1969), the Texas and Arkansas profiles by Green & Hales (1968) and the Washington profile by Lewis & Meyer (1968).

Means calculated over 1° cells along many of the profiles (some are composite) are shown in Fig. 4. The Early Rise traveltimes are in general earlier than the average global traveltimes of Dziewonski & Anderson (1983), except that at distances less than 4° the average global traveltimes are earlier. The earlier average global traveltimes at distances

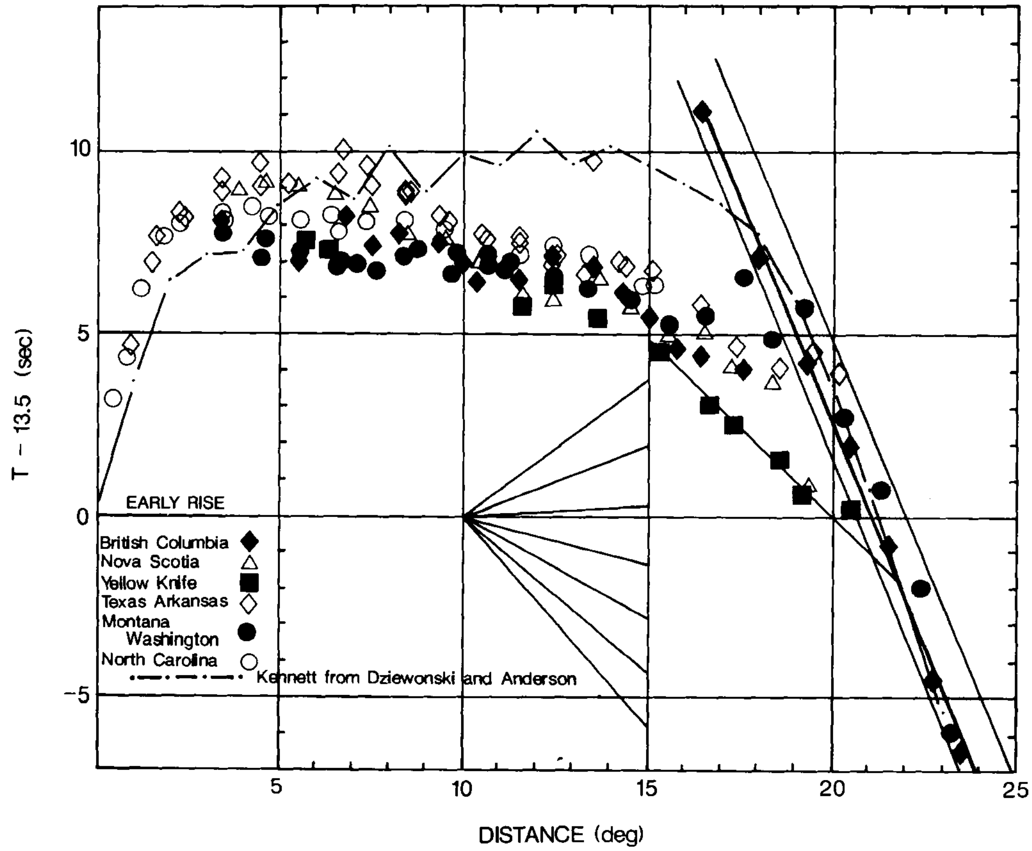

Figure 4. 1° cell reduced traveltimes along several Early Rise profiles. Other features as for the NTS times in Fig. 2. The rose shows velocites from 7.8 to 9.0 km s^{-1} by steps of 0.2 km s^{-1}.

less than 4° must mean that the hypocentral parameters used in calculating the average traveltimes are systematically incorrect. It is probable that the errors arise from errors in depth of focus and the associated errors in time of origin.

From 2° to 5° or 6° the velocities lie between 8.0 and 8.2 km s^{-1}. From 6° to about 13° the velocities are of order 8.4 km s^{-1}. The increase on some profiles is fairly sharp and is more likely to be caused by a first- or second-order discontinuity in the upper mantle velocities than by a smooth continuous increase in velocity from the M discontinuity to some depth of the order of 150 km.

Beyond 14° the velocities are greater as is shown most clearly on the Yellowknife profile. A linear fit by least squares to these Yellowknife observations yields

$$t = (12.514 \pm 0.044)\,\Delta + 19.701, \qquad \text{velocity} = 8.886 \pm 0.031\ \text{km s}^{-1}. \tag{1}$$

On the other profiles the velocities beyond 13° are similar at first, but then the observations scatter and are in general later.

The apparent velocity of 8.886 km s^{-1} is greater than would be inferred from Lehmann's model for the refraction from below 215 km, but is comparable with the 8.9 km s^{-1} estimated by Green & Hales (1968) from the GREELEY observations, with that inferred from the CAP8 model of Hales, Muirhead & Rynn (1980) for the refraction from below 200 km in northern Australia and the velocity of 8.8 km s^{-1} found by Hales, Helsley & Nation (1970) in the Gulf of Mexico at a similar distance.

The observations related to refractions from below the 400 km discontinuity are enclosed by the two steep thin lines on Fig. 4, the most complete set being from the British Columbia profile. A linear least-squares fit to the British Columbia observations yields

$$t = (11.051 \pm 0.063)\,\Delta + 51.43, \qquad \text{velocity} = 10.062 \pm 0.058\ \text{km s}^{-1}, \tag{2}$$

the sum of the squares of the residuals being 0.762 s^2. This line is plotted on Fig. 4 and it is clear that the observations would be better fit by a quadratic. The quadratic fitted by least squares corresponds to a value of 0.09 s deg^{-2} for $d^2t/d\Delta^2$. This is a greater value than the average $d^2t/d\Delta^2$ for the lower mantle. There are observations also for the Texas profile and for the Washington line lying within the area on Fig. 4 indicating the observations interpreted as refractions from below the 400 km discontinuity.

Both Iyer *et al.* (1969) and Green & Hales (1968) discussed models with a low-velocity layer, but concentrated the analysis on the models without low-velocity layers. When the 1° cell means were plotted it was noticed that there were offsets on several of the profiles of the kind described by Dowling & Nuttli (1964) as typical of the effect of a low-velocity layer. The 1° cell means have been replotted on Fig. 5 to show this effect more clearly,

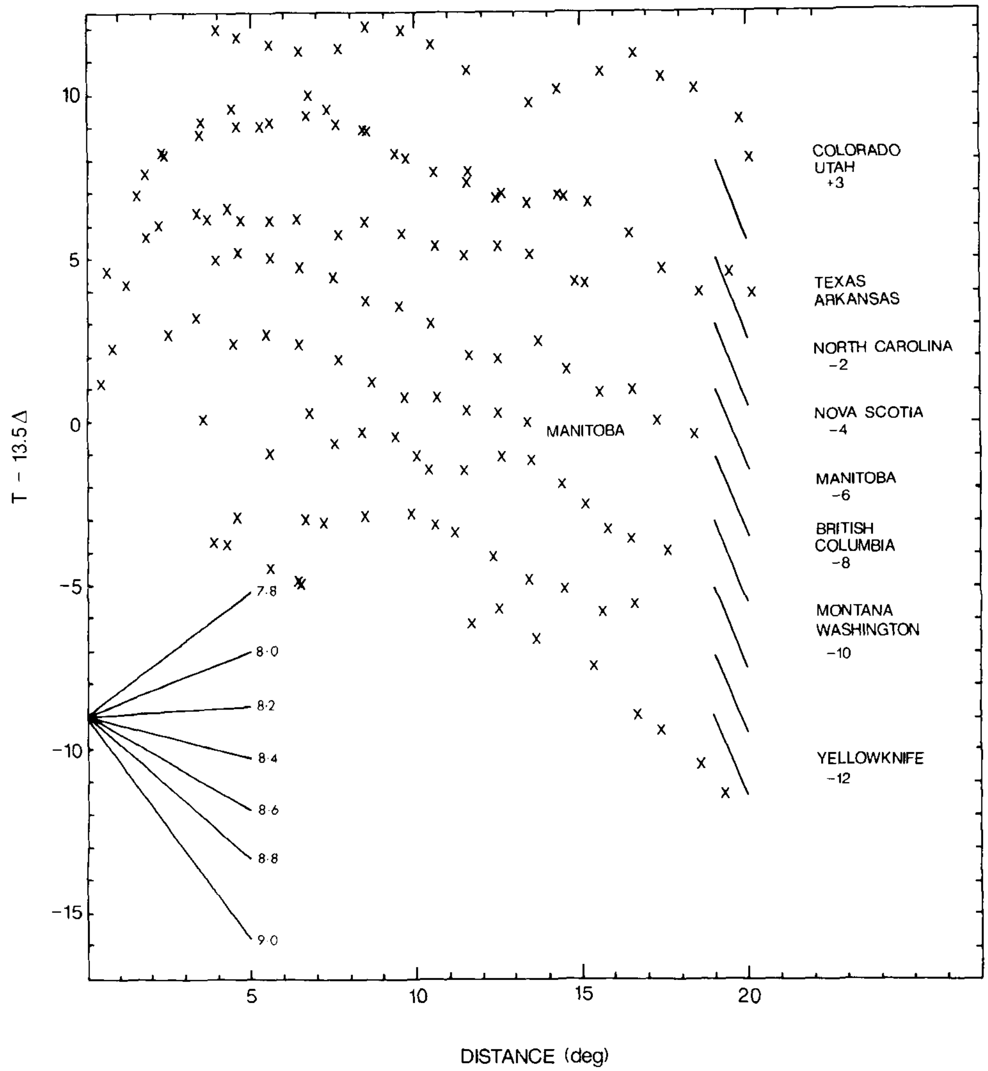

Figure 5. 1° cell reduced traveltimes along Early Rise profiles replotted to show the times more clearly. The Colorado–Utah profile not shown in Fig. 4 shows the low-velocity zone offset most clearly.

especially on the Colorado–Utah profile for which region there is other evidence of a low-velocity layer. On the other profiles the offset is smaller. In all cases it is followed by a sharp increase in apparent velocity which has been associated with refraction from below the 200 km discontinuity.

DISCUSSION

The determination of the velocities in a low-velocity zone is always difficult because there are no arrivals at the surface from rays bottoming in the zone. Gerver & Markushevich (1966) proved a series of theorems which they summarize as follows: 'The ambiguity arising from wave-guides is reduced by a joint analysis of travel time curves from surface and deep sources [and it is proved that] if the travel-times for a source between any adjacent waveguides as well as for a surface source are known, then the velocity between these waveguides can be determined uniquely'. As pointed out by Hales *et al.* (1980) the traveltimes not only for the first arrival segments, but also for other arrivals, must be known for the application of this theorem. Gutenberg (1953, 1959) had earlier remarked on the usefulness of deep focus observations. Gutenberg pointed out that the apparent velocity at the surface was a minimum for the waves leaving the focus horizontally and that the velocity at the depth of the earthquake could be determined from this apparent velocity. The effect is illustrated in fig. 2 of Hales *et al.* (1980), and was used by them as the starting point for the analysis which led to the CAP8 model.

In this discussion we are dealing with surface sources. Lehmann (1964) remarks that 'It may seem as if the assumption of the presence of a low velocity zone in other regions where the traveltimes from a certain distance onwards are found to scatter in a similar way should not too readily be discarded'. Lehmann pointed out that on the profile from NTS to GNOME the phases became delayed and uncertain beyond 700 km and used this as a basis for the introduction of a low-velocity layer at a depth of 70 km.

Assuming a constant velocity in the upper mantle from the M discontinuity to the top of the low-velocity layer the distance travelled in the upper mantle, Δ, and the distance

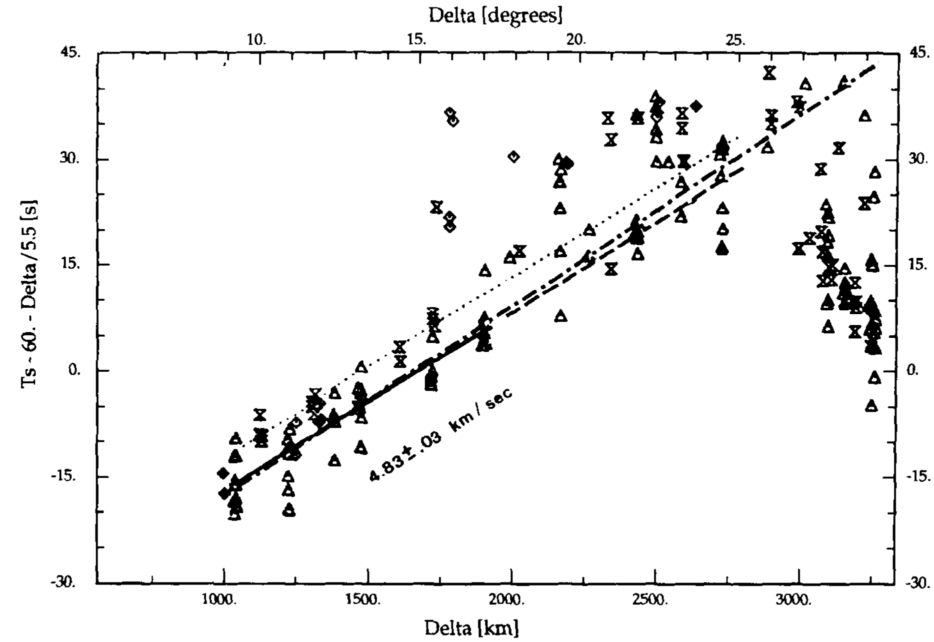

Figure 6. S traveltimes for explosions at Novaya Zembya from Maki-Lopez (1983).

between the M discontinuity and the bottoming depth are related by

$$d = r_m(1 - \cos 0.5\Delta)$$

where r_m is the radius of the M discontinuity. Values of d for values of Δ are given below:

Δ(°)	4	5	6	7	8	9	10	11	12	13	14	15
d (km)	4	6	9	12	15	19	24	29	35	41	47	54

If the velocity increases with depth, either continuously or discontinuously, the values of d for any Δ will be greater.

For the western US the assumption of a constant velocity upper mantle down to the low-velocity layer may be a reasonable approximation. In that case the depth from the surface to the low-velocity layer would be only 54 km allowing 1° for the paths in a 48 km thick crust. For the central and eastern US the assumption of a constant velocity upper mantle is not valid.

S traveltimes for nuclear explosions at Novaya Zemlya start to scatter at 16° as shown in Fig. 6 from Maki-Lopez (1983). The traveltimes for S suggest that the assumption of a more or less constant velocity upper mantle S velocity is reasonable. Allowing as before 1° for the paths in a 48 km thick crust the minimum depth to the onset of the low-velocity layer is 102 km.

In the Lehmann (1964) analysis the low-velocity layer was terminated by a sharp increase in the P velocity from 7.97 to 8.37 km s^{-1} at a depth of 215 km. Thereafter the velocity increased continuously to a depth of 650 km, i.e. there was no 400 km discontinuity. In the Gutenberg (1959) model the low-velocity layer ended gradually and again there was no 400 km discontinuity. The US data all require the 400 km discontinuity.

Green & Hales (1968) considered three Nevada models. Model N_1 has a 7.0 km s^{-1} low-velocity layer from a depth of 104 to 156 km, N_2 a 7.5 km s^{-1} layer from 104 to 171 km and N_3 an 8.00 km s^{-1} layer from 104 to 216 km. Two other zones of rapid increase of velocity were modelled; the first an increase of 0.67 km s^{-1} between depths of 362 and 382 km and the second an increase of 0.95 km s^{-1} between depths of 623 and 645 km corresponding to the traveltime discontinuities shown on the record section of fig. 12 of Green & Hales (1968).

Hales *et al.* (1980) modelled the velocity in Northern Australia as showing a decrease of velocity from 8.28 km s^{-1} at a depth of 75 km to 8.24 km s^{-1} at a depth of 200 km, followed by a step increase of 0.48 km s^{-1} at 200 km. This estimate of the depth of the discontinuity was based on observations of an earthquake at a depth of 176 km (ISC) or 167 km (PDE). The record sections showed that the focus was certainly above the discontinuity. There was a further step increase of 0.42 km s^{-1} at a depth of 411 km and other step increases at 610 and 630 km. The traveltimes from the GNOME, NTS and Early Rise explosions shown in Figs 1, 2 and 4, leave no doubt that there is a traveltime discontinuity at about 20° and that the apparent velocity thereafter is greater than 10 km s^{-1}.

The traveltimes for models N_1, N_2 and N_3 are shown in fig. 11 of Green & Hales (1968) and are compared with the times for model ER1 for the central US in Fig. 7 of this paper. All three models have the same delay time relative to ER1 for the refractions from below 200 km between 15° and 18°, namely 7.5 s. Between 18° and 23° the refractions from below the '400 km discontinuity' branches of N_1, N_2 and N_3 are delayed with respect to the refractions of ER1 from below the same discontinuity by 4.4 to 4.1, 3.8 to 3.6 and 2.8 to 2.6 s respectively. The refractions from below the '650 km discontinuity' show smaller delays of the N_1, N_2 and N_3 models with respect to ER1.

The NTS times in Fig. 2 and the Early Rise Colorado–Utah profile times show delays of 10 to 8 s with respect to the Yellowknife profile (equation 1) between 15° and 18°. For the '400 km' refraction branch the delays for

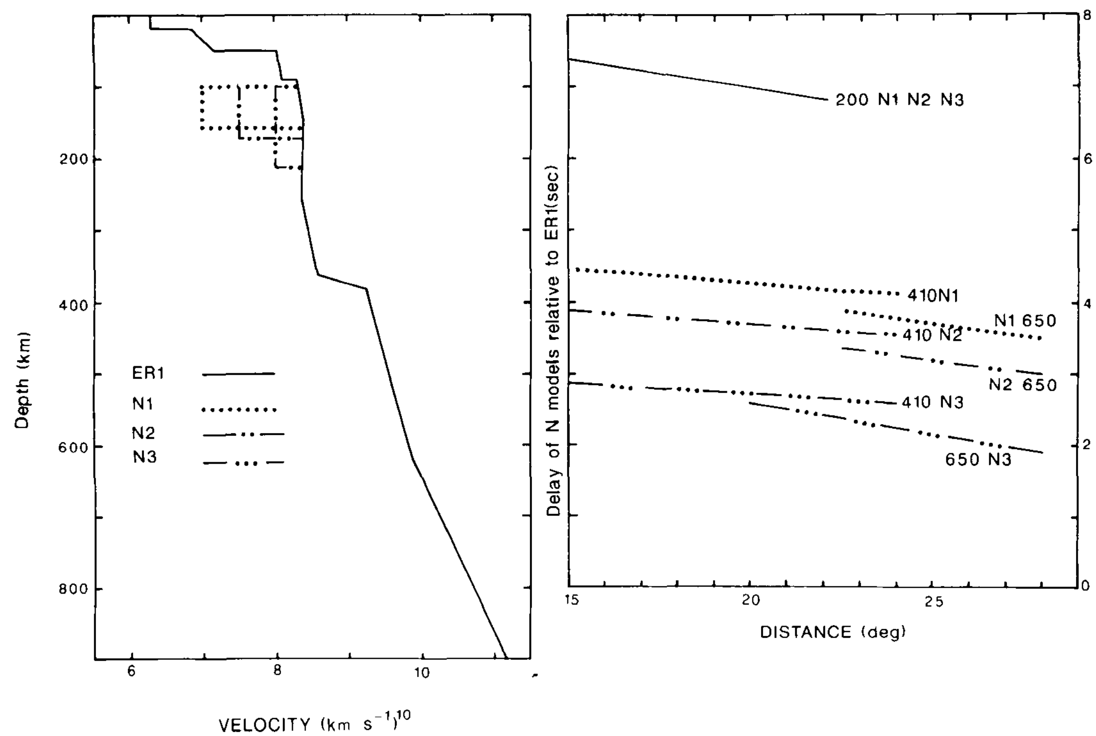

Figure 7. Differences between the reduced traveltimes of Green & Hales models N_1, N_2 and N_3 and the ER1 model of Green & Hales (1968).

the NTS times (azimuths from 280° to 10° and 10° to 100°) relative to the British Columbia line (equation 2) range from 3 s at 18° to about 1.5 s at 22.5°.

These delays follow the pattern of the calculated delays shown in Fig. 7 for the models with low-velocity layers above 200 km. In fact the N_3 model which shows the most rapid decrease in the delays fits the data best. This means that a very thick low-contrast low-velocity layer is required in the western US. It should also be noted that the apparent velocity of the NTS refraction times identified as coming from below the '400 km discontinuity' is slightly greater than that for the British Columbia profile showing that the delays of the western US times are still decreasing slightly as the ray paths steepen. It is suggested that this means that the major difference between the western and central US upper mantles lies above 200 km.

For the Early Rise observations the Texas data from 15° to 18° are late with respect to the Yellowknife times by 2.5 s, but beyond 20° they are less than 1 s late with respect to the British Columbia times (equation 2). For the other Early Rise profiles the differences are smaller and also decrease beyond 20° thus reinforcing the conclusion that the major differences in the upper mantles of the various regions of North America lie above a depth of about 200 km.

INTERPRETATION

There is no difficulty in accounting for an increase of velocity in the lithosphere at a depth of about 90 km for Ringwood (1975; see fig. 6-4 of that reference) shows the change from pyroxene pyrolite to garnet pyrolite as occurring at about that depth. However, if the similar increase shown in the velocities in the Gulf of Mexico by Hales *et al.* (1970) is due to the same cause then the slope of the boundary between pyroxene pyrolite and garnet pyrolite is of opposite sign to that shown in Ringwood's figure.

The interpretation of the 200 km discontinuity presents more difficulty for Ringwood (1975, p. 488) remarks that 'the region between 180 and 330 km is essentially homogeneous and no further phase transformations which might cause velocity anomalies [in this region] have been discovered despite intensive search'. In so far as the oceans are concerned Green (1973), Ringwood (1975) and Green & Liebermann (1976) have shown that the low velocity and low Q of the suboceanic asthenosphere are well accounted for in terms of partial melting of pyrolite with less than 0.4 per cent H_2O. Shown in Fig. 8 are temperature distributions from Clark & Ringwood (1964) and the 0.1 per cent H_2O pyrolite solidus (Green 1973; Ringwood 1975). It would appear from this figure that the low-velocity zone should terminate at about a depth of 150 km instead of 200 km and that beneath the Precambrian shields partial melting should not occur. For this reason Hales *et al.* (1980) ascribed the 200 km discontinuity to solution of pyroxene in the garnet structure. However Akaogi & Akimoto (1977) showed that although pyroxenes begin to transform to garnet structure at a depth of about 150 km the transition to garnet solid solution is most effective at depths of 450–540 km. Thus Hales (1981) returned to partial melting followed by a reversion to solid as the explanation for the 200 km discontinuity.

Neither the petrology nor the temperature distributions are well-constrained between depths of 120 and 400 km. Ringwood (1975) remarked that at pressures greater than 40 kbar the 'solidus is based upon estimates which have a wide range of uncertainty, particularly above 50 kbars'. If the pyrolite solidus were modified as shown by the dotted curve in Fig. 8 the discontinuity would occur at about

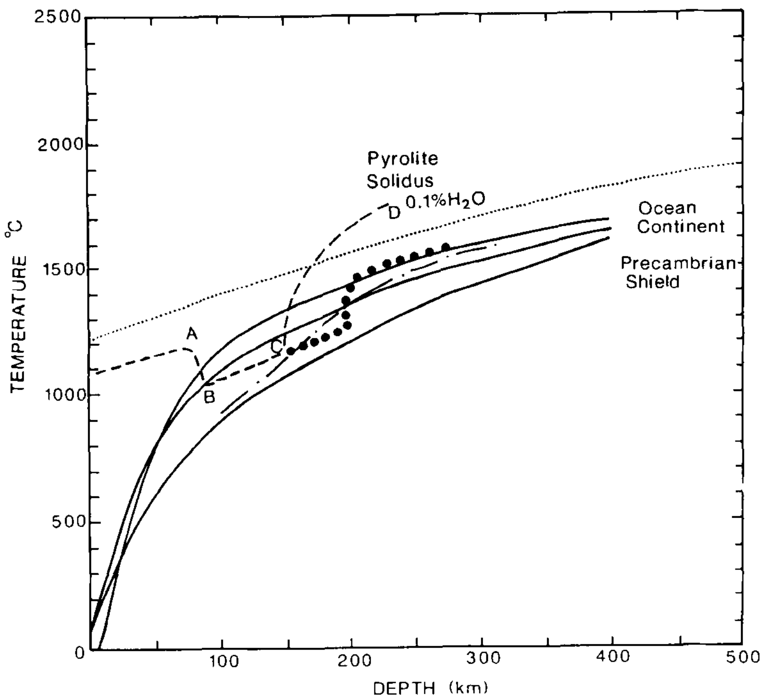

Figure 8. Temperature distributions from Clark & Ringwood (1964) and the 0.1 per cent H_2O pyrolite solidus (Green 1973; Ringwood 1975). The dotted curve shows the modification to this solidus suggested in this paper. The dash–dot curve shows the suggested modification of Clark & Ringwood's Precambrian shield temperatures.

200 km. Some modification of the temperature distribution is also necessary if there is to be a low-velocity layer beneath Precambrian shields. The suggested change of the Precambrian shield temperature is shown by the dot–dash curve in Fig. 8. The continent temperature–depth curve should also be modified to lie much closer to the suggested Precambrian shield temperature distribution.

The refractions from below the 200 km discontinuity observed in Australia were strong at first, but at a distance of about 14° the amplitude fell sharply. The fall in amplitude was interpreted by Hales *et al.* (1980) as being caused by a low-velocity zone below 230 km. If the temperatures at these depths are close to the pyrolite solidus then low velocities and low Q would be expected.

Temperatures close to the solidus would also explain the lack of good observations of short-period S from 15° to 24°.

CONCLUSIONS

The principal conclusion of this analysis is that the differences between the upper mantle velocity distribution in the various regions of continental North America arise above a depth of 200 km and are associated with differences in the temperature distribution in those regions.

The S velocity distribution is not well determined below about 100 km and will not be until studies such as that of Grand (1987) have been extended to shorter periods, say down to 3 s. Such data when combined with the interval times between discontinuities for near-vertical ray paths obtained from the *ScS* reverberation studies of Revenaugh & Jordan (Jordan, J. N., personal communication 1989) will lead a better understanding of the S velocities in the upper mantle.

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