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Mantle Heterogeneity and Mislocation Patterns for Seismic Networks

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Abstract. Arrival time data from seismic networks in Fennoscandia and in Montana have been used to compute mislocations for events in three seismic source regions (China-Russia border, Central America, the island arcs around the Philippine Sea) where pronounced and rapidly varying slowness anomalies at the two large arrays NORSAR and LASA have been observed. Mislocations are related to, but for larger networks are more generally valid than, slowness anomalies. A comparison of array and network data does not confirm the array slowness anomalies. Network data from events in Central America (to Fennoscandia) and in the Northern part of the Bonin Arc (to Montana) do reveal $dT/d\Delta$ anomalies, but their source is unrelated to the slowness anomalies observed at NORSAR and LASA. The data suggest that most of the array anomalies are due to structure near the receivers, in particular NORSAR anomalies from the China-Russia border region, although some small scale features near the source region may not be resolved by the networks. The network anomalies point to lateral inhomogeneity in the deep mantle (from Central American events) and near the source region of the Northern Bonin Arc.

Key words: Mantle heterogeneity – Mislocations – Seismic networks – Arrays – Slowness anomalies.

1. Indroduction

Lateral variations of the seismic wave velocities in the deep mantle have been associated with observed travel time anomalies and with anomalies in the slowness vector at seismic arrays. Selected travel time data have been combined to infer inhomogeneities at great depths (e.g. Jordan and Lynn, 1974; Engdahl, 1975) and global data sets have been inverted to obtain a gross outline of the distribution of large scale inhomogeneities in the mantle (Sengupta, 1975;

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Dziewonski, 1975). While it is generally recognized that the slowness vector is sensitive to heterogeneity along the ray path, the interpretation of slowness anomalies has been the subject of some debate during the last few years. Heterogeneity in the upper mantle near an array tends to mask the effect of deeper structure; nevertheless, evidence has been presented to support the suggestion of structural anomalies in the lower mantle and near the source region. Davies and Sheppard (1972) and Sheppard (1973) pointed to rapidly changing features in the pattern of slowness vectors (the array diagram) at LASA and NORSAR, which in some cases appeared to correlate with surface tectonics in the source region, Kanasewich et al. (1973) and Powell (1975) observed consistency of certain slowness anomalies at several arrays in Western North America. On the other hand, conflicting observational evidence was presented by Okal and Kuster (1975), Wright (1975) and Berteussen (1975a). These authors, as well as Green (1975), argue that possibly small scale inhomogeneities in the upper mantle near the array could explain the observations.

Since the effect of small scale upper mantle inhomogeneities diminishes with increasing array aperture, it makes sense to compare conventional array data with data from an extended network of stations in the same region. Travel time and slowness anomalies are measured relative to theoretical data in a standard earth, with the assumption that the event location is unbiased. In the following the NOAA locations, using a global network of stations, are used as a reference. Using only a local network of station will result in a mislocation which, besides measurement errors, is due to earth heterogeneity. Mislocations may also be obtained from the slowness vectors at an array. Thus we will compare mislocations for NORSAR with those for the Fennoscandian network, and mislocations for LASA with those for a network centred in Montana. The geographical locations of the arrays and stations are shown in Figures 1 and 2.

In the next section we briefly review methods for obtaining mislocations and slowness vectors. These techniques have been applied to arrival time data reported to ISC from events in a number of source regions (China-Russia border, Central America, the island arcs around the Philippine Sea) where pronounced and rapidly varying slowness anomalies at LASA and NORSAR have been reported (Davies and Sheppard, 1972; Sheppard, 1973). The aim is to see whether the anomalies still persist at the "continental" networks (in Fennoscandia and Montana); we shall be concerned with the source of the anomalies. The increased network aperture of course diminishes the resolution in terms of earth structure, but this effect is most severe for structure near the receivers, and least near the source region, e.g. beneath subduction zones where significant lateral variations have been reported (Davies and Sheppard, 1972; Jordan, 1975; Engdahl, 1975).

It is realised that the ISC bulletins, while providing an easily accessible data base, suffer to some extent from the nonuniformity in interpretation and detection criteria. Suitable time corrections are also lacking for most stations. Another test for the presence of small scale inhomogeneities would involve the use of long period data from the LASA and NORSAR arrays. Our results with LASA LP data from one particular region (Bonin Arc) were inconclusive,

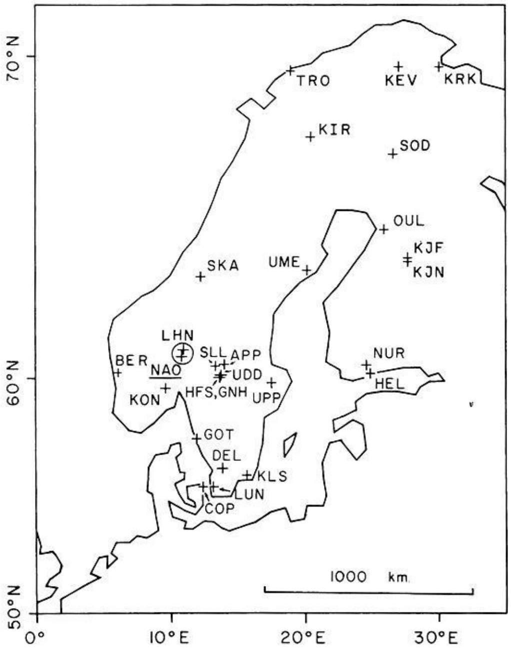

Fig. 1. The seismic network in Scandinavia and Finland, with the NORSAR array (NAO)

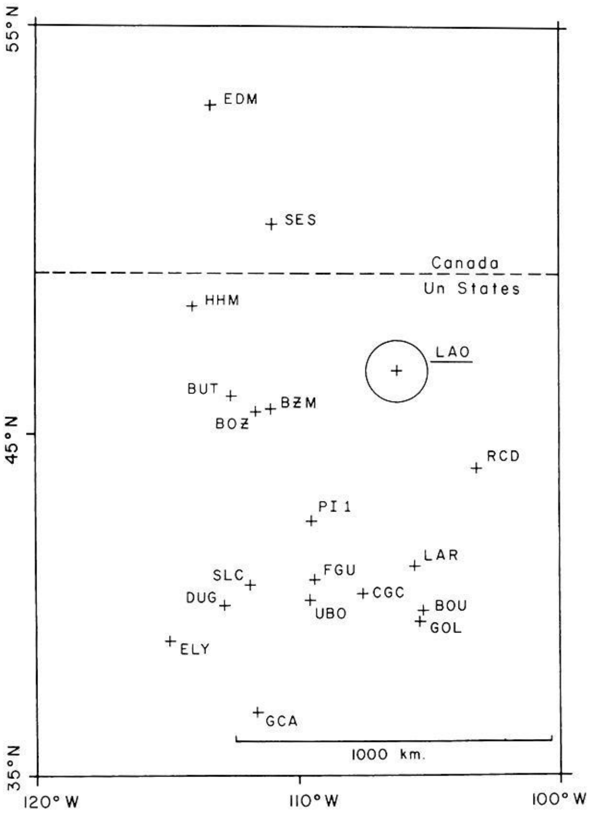

Fig. 2. The seismic network centred in Montana, with the LASA array (LAO)

since slowness estimates were obtainable only for a few large events in this region. In this paper we will not further explore this line of evidence.

2. Methods for Obtaining Mislocations

At seismic arrays like LASA and NORSAR the standard practice of locating events is to fit the best plane wave to the arrival times at the individual sensors (or subarrays). That is, given the arrival times t_j and coordinates $\mathbf{r}_j$ of stations $j = 1, \ldots, K$, the system of first order equations

$$t_j = \boldsymbol{\alpha} \cdot \mathbf{r}_j + c \qquad (c \text{ a constant})$$

is solved for the slowness vector $\boldsymbol{\alpha}$. In the standard earth the apparent event location is determined by the phase velocity $v = 1/|\boldsymbol{\alpha}|$ (ray parameter $\mathrm{dT}/\mathrm{d}\Delta = 1/v$, in s/deg) and azimuth of wave propagation $\phi = tg^{-1}(\alpha_1/\alpha_2)$.

With increasing aperture of the array or network, sphericity of the Earth's surface and curvature of the wave front may become important and the first order approximation should be modified. Assuming that the time-distance curve across the Earth's surface is smooth, Husebye et al. (1971) used a pseudo first order polynomial in spherical coordinates (θ, ϕ) to model the arrival times:

$$t_j = a\,\theta_j^{\alpha} + b\,\phi_j^{\beta} + c$$

where the constants α and β are iteratively adjusted. Compared to the more conventional second order approximation this procedure includes a gain in the degrees of freedom in the solution for a, b and c. Since deviations from the great circle plane are small we modify the procedure slightly by using epicentral coordinates (Δ, ϕ), the source at the pole and the array centre at $\phi = 0$, and modeling

$$t_j = a\,\Delta_j^{\alpha} + b\,\phi_j \sin \Delta_j + c$$

where α is iteratively adjusted. The apparent event location is again determined by the ray parameter

$$\mathrm{dT}/\mathrm{d}\Delta = (a^2 \alpha^2 \Delta_0^{2\alpha-2} + b^2)^{1/2}$$

and the azimuth deviation from the great circle

$$\gamma = tg^{-1}(b/a\,\alpha\,\Delta_0^{\alpha-1})$$

These two parameters are assumed to represent the wave at the centre of the network.

Parameterizing the travel time curve as above, then obtaining $\mathrm{dT}/\mathrm{d}\Delta$ to compare with values in the standard earth is a procedure that works well if the actual travel time varies smoothly across the network. In some distance ranges, in particular at short epicentral distances, this may not be the case and the results are in error. An alternative is to utilize directly the standard travel time curve in the location procedure. This is exactly the procedure of locating events by a global network: Using a local network we start from the reference location and relocate the event iteratively. Keeping the event depth fixed in accordance with the previous methods, the coordinate adjustments $d\theta$ and $d\phi$ are solved from the first order system

$$t_j=\tau_j+\frac{\delta\tau_j}{\delta\theta}\,d\theta+\frac{\delta\tau_j}{\delta\phi}\,d\phi+c$$

where τ_j is the standard travel time at station j.

The last two methods cannot be compared directly on the basis of confidence limits, since these are in ray parameter space and in geographic space, respectively. For the events and station configurations used in this paper it was found that, whereas stable solutions with the direct slowness method usually have somewhat smaller RMS time residue, the direct location procedure more often converged to a stable solution, provided a suitably damped iteration scheme is used. In one experiment both methods were applied to events in Central America and it was found that succesful solutions for the same event were not much different; if mislocations were transformed to slowness anomalies associated with the network centre, the relative difference was always within 0.05 s/deg. Of course, this comparison is restricted to events in the lit zone, events in the shadow zone can be characterized only by slowness (in the shadow zone the model $dT/d\Delta=$constant, hence there is no unique solution in the direct location procedure). With the exception of a few events with anomalous $dT/d\Delta$ near or below the core shadow boundary value, the data in this paper did not suffer from this restriction. A further remark in this context is that, whereas mislocation patterns are useful in revealing possible correlations with surface tectonics, in the interpretation one must take into account the flattening of the travel time curve near the shadow boundary. At the appropriate epicentral distances, this feature magnifies the mislocations due to inhomogeneities which are not related to the source region.

The criteria we have used in accepting solutions were: RMS time residual $\leqq$ 1.4 s, number of stations $\geqq$ 5, deleting stations reporting emergent onsets. Typically, the effective number of stations was 10 in Scandinavia, 7 in Montana. In the following, results from the direct location procedure will be presented and discussed.

3. Mislocations in Anomalous Regions

In this section we compare, in three seismic regions, mislocations for the NORSAR and LASA arrays with those using stations in Fennoscandia and Montana, respectively. One or more of these stations usually had to be excluded from the individual solutions, presumably due to gross errors in the bulletin data. The afore mentioned criteria serve to reduce the effect of arrival errors and retain solutions representing systematic changes in arrival time across the network. In our procedure station corrections have not been included. Station residuals have been published by various authors (e.g. Cleary and Hales, 1966; Enayatollah, 1972), but the possibly large variation with direction of approach of the waves (Lillwall and Douglas, 1970) degrades the practical use of the data. Using the Fennoscandian network, Husebye et al. (1971) obtained no significant change in dT/dΔ solutions by introducing constant correction terms. The relatively small impact of structure near individual receivers is suggested by the fact that azimuth deviations from the great circle plane are generally found to be small, the anomaly being mainly in dT/dΔ. The anomalies are obtained relative to the mantle model of Herrin et al. (1968). In some publications the Jeffreys-Bullen tables have been used in the data reduction process, but the resulting differences are unimportant for the present purpose.

A. China-Russia Border Region

Mislocations with the NORSAR array have been studied by Sheppard (1973). In most seismic regions of the world these data give a large mislocation which is generally attributed to near array structure. Noponen (1974) showed that part of the anomalies is also observable at the nearby Hagfors array in Sweden, which he interpreted as lateral velocity variation in the upper mantle beneath the Western part of Scandinavia. More difficult to explain are the rapid changes of mislocations in some regions. Sheppard gives two examples of these. One is the region in Central Asia near the borders of China, Russia and Afghanistan. From the Hindu Kush to the explosion site in Eastern Kazakh, about 1700 km to the North-East and corresponding to only a few degrees in azimuth from NORSAR, there is an almost complete reversal of the large NORSAR mislocations; the dT/dΔ anomaly changes from about $+0.3$ to -0.4 s/deg. The dotted arrows in Figure 3 illustrate the situation.

In this and the following figures the head and tail of the arrows represent the true (NOAA) locations and the observed, or network location, respectively. The anomalies in the Hindu Kush follow the trend of NORSAR mislocations throughout South-East Asia, but the difference between the explosion data and this trend is too large to be explained by inhomogeneity in the upper mantle under the source, or a system of dipping plane layers in the upper mantle under the receiver. Davies and Sheppard (1972) discuss these possibilities and place (roughly) an upper bound of 3% on the associated dT/dΔ anomalies. This is in accordance with some results from Berteussen (1975b), who concluded that relatively simple crust-upper mantle models under NORSAR can explain no more than about 20% of the variation in the observed anomalies.

Mislocations by the Fennoscandian network are displayed in Figure 3 and show no significant anomalies throughout the entire region considered. This remained true when we divided the network in a S.W. and a N.E. part and measured mislocations on both parts separately, although the scatter in the data was somewhat increased. The fact that the inhomogeneity responsible for the NORSAR pattern has not been sampled on the entire S.W. part of the Fennoscandian network, constrains its dimensions; these would be progressively less restricted with increasing distance from the source. A small inhomogeneity near the source may satisfy these restrictions, however the NORSAR dT/dΔ anomalies require one which should be quite large near the source region, but may be small under the array. Moreover an extensive inhomogeneity near the explosion site would produce observable travel time anomalies; there are,

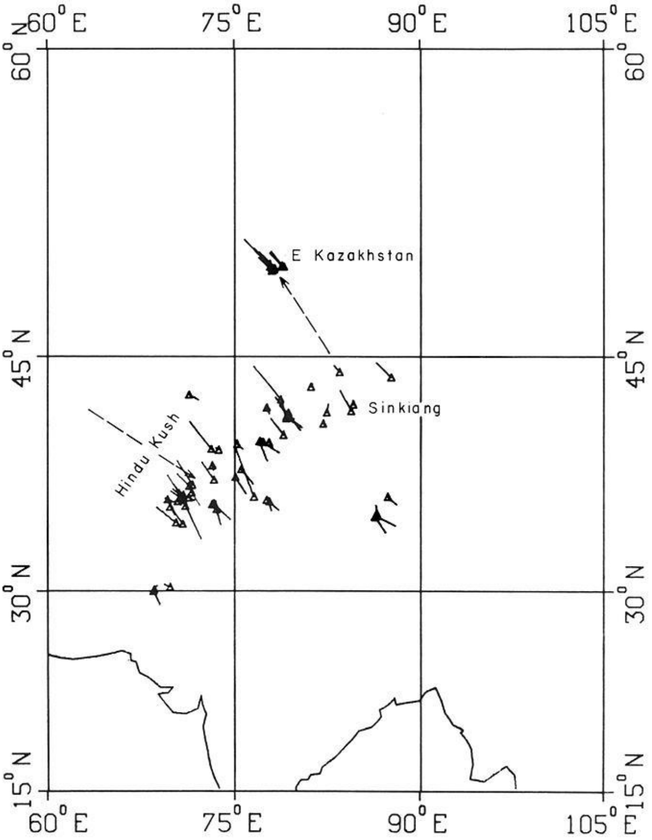

Fig. 3. Fennoscandian network mislocations of events in Central Asia. The dashed arrows represent NORSAR mislocations in Hindu Kush and in E Kazakhstan (Sheppard, 1973)

however, no significant time differences at NORSAR between both regions. Similar arguments apply to a hypothetical deep mantle anomaly. Although in the latter case the arguments are less restrictive, an additional constraint is supplied by the fact that in this part of the deep mantle two "normally behaving" ray tubes intersect: one connecting a source in E. Kazakh with S.W. Scandinavia, the other connecting a source in Hindu Kush with N.E. Fennoscandia. On the basis of these considerations near array structure would be the most likely source of the NORSAR slowness anomalies, although recent models of the structure under NORSAR, deterministic (Aki et al., 1976) or stochastic (Dahle, 1975), may need some modification to explain the type of anomaly mentioned here.

B. Central America

The second example given by Sheppard concerns the Central America region; throughout this region NORSAR mislocations vary significantly with geographic

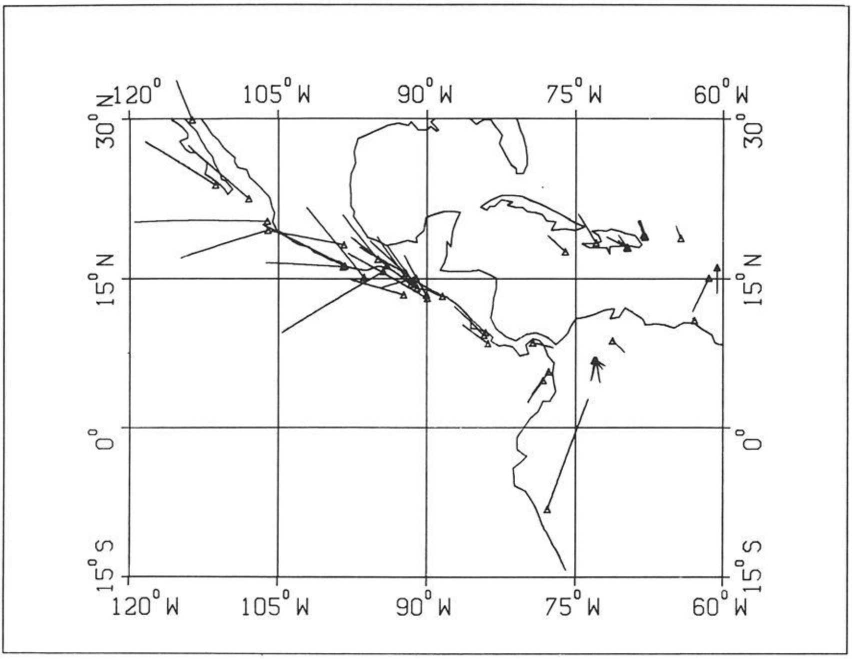

Fig. 4. NORSAR mislocations of events in Central America

location; in particular, a pronounced splitting in location occurs for events from Oaxaca to Guatamala (around 15° N, 95° W): a number of events with NOAA locations within 100 km from each other, are located by NORSAR as much as 700 km apart. This feature has also been cited by Jordan (1975) as corroborating evidence for the existence of a deep seated anomaly under the Caribbean.

We have processed an independent sample of NORSAR data and the results in Figure 4 show this splitting phenomenon, though slightly less pronounced than in the data from Sheppard. In Figure 5 we show mislocations in the same region obtained with the Fennoscandian network. This figure shows significant anomalies, but the pattern is clearly different from the NORSAR data, for example the splitting phenomenon is not reproduced. We may relate mislocations to slowness anomalies (referred to the network centre) and Figures 6 a and b give the $dT/d\Delta$ anomalies in the Central America region, (between 105° and 90° W), for the NORSAR and Fennoscandian data, respectively.

Plotting the data versus event depth again brings out the splitting of events observed at NORSAR. The most conspicious feature in the Fennoscandian data is the avaraged large negative $dT/d\Delta$ anomaly (about -0.2 s/deg). Besides, the scatter in these solutions is larger than expected from computed confidence limits, and is also larger than the scatter in some other regions like Central Asia; this may be caused by relatively fine structure near the source region. Any way of plotting $dT/d\Delta$ anomalies will bring out these points. We have

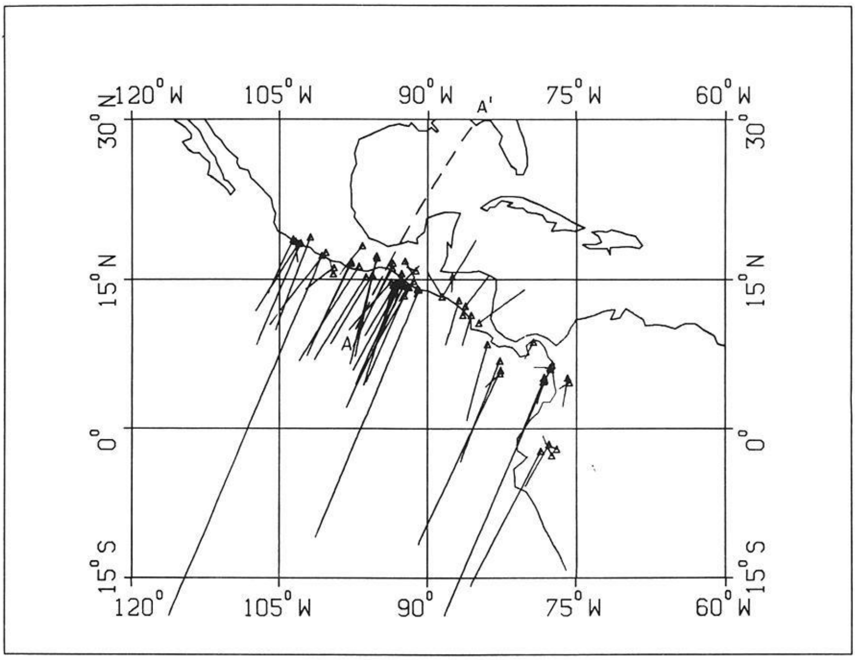

Fig. 5. Fennoscandian network mislocations of events in Central America. AA' is a part of the great-circle through 15° N, 95° W and the network

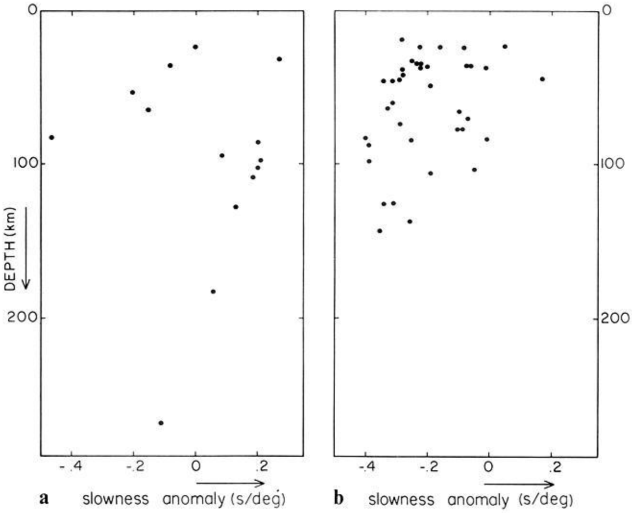

Fig. 6 a and b. Slowness anomalies vs. event-depth for Central American events between 105° and 90° W as observed at NORSAR (**a**) and at the Fennoscandian network (**b**)

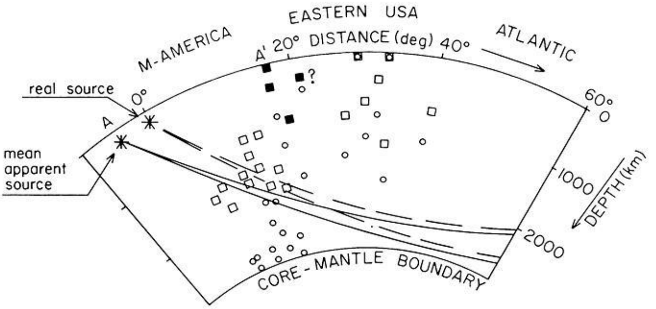

Fig. 7. Part of the great-circle plane through a source at 15° N, 95° W and the Fennoscandian network. AA' is also indicated in Figure 5. Dashed lines: raytube connecting network with real source. Solid lines: apparent raytube connecting network with mislocated source. Intersecting points of early P phases (■) other P (□) and PcP (○) from Jordan and Lynn (1974) are also indicated

plotted the data versus depth; in this way the splitting phenomenon in Figure 4 seems to be partly reflected in Figure 6a, as an averaged $dT/d\Delta$ difference ($\simeq 0.06$ s/deg) between relatively deep and shallow events. It may be caused by the fact that these two groups are also geographically separated due to the dip of the Benioff zone. Finally, for the Fennoscandian data we note a lateral variation in $dT/d\Delta$ anomalies from Mexico (-0.2 s/deg) to South America (-0.1 s/deg), although it may be somewhat difficult to observe this feature in a plot like Figure 5, due to the afore mentioned magnification of mislocations for events near the shadow boundary.

Seismic waves from Central America to Scandinavia pass through several regions in the Earth which have been suggested to be anomalous: the mantle under the Caribbean (Jordan and Lynn, 1974), the lower mantle under the North Atlantic (Phinney and Alexander, 1966), the upper mantle under Scandinavia (Noponen, 1974) and its ocean-continent boundary (Sipkin and Jordan, 1975). One or more of these regions may contribute to the broad-scale negative $dT/d\Delta$ anomaly, while the lateral variation in $dT/d\Delta$ requires the inhomogeneity to be laterally bounded.

From P, PcP, S, ScS arrival times from 2 South American events with practically identical location, measured at standard stations in the United States and Canada, Jordan and Lynn (1974) reported anomalously early P and S at 3 of 4 stations lying near to each other. This configuration of sources and receivers defines a narrow section through the Earth which is intersected at approximately right angles by the great circle plane through a hypothetic source in Mexico and receiver in Scandinavia.

Figure 7 schematically illustrates the situation. The apparent ray tube in this figure connects the network with a mislocated source. The inhomogeneity which causes the mislocation must bend the rays in such a way that they connect the network with the real source. The figure shows that this inhomogeneity cannot be related to the "Caribbean anomaly": the apparent ray tube passes underneath the anomalous section in Figure 7, and is in or below the depth range sampled by the PcP and ScS data from Jordan and Lynn, which

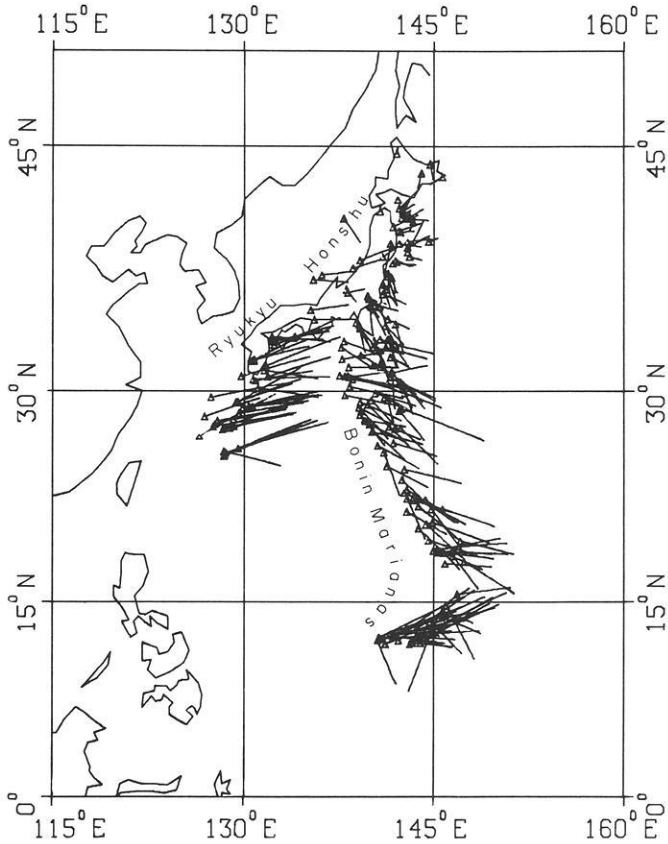

Fig. 8. LASA mislocations around the Philippine Sea

were shown to behave normally. The source of the negative dT/dΔ anomaly is probably located deeper in the mantle, or in the mantle under Scandinavia. Dividing the network in a N.E. and a S.W. part as before, the negative dT/dΔ anomaly appeared to persist at both subnetworks separately. It is to be expected that the NORSAR data also suffer from this anomaly. It must then be compensated locally, since the averaged NORSAR dT/dΔ anomaly in this region is near zero (Fig. 6a). Finally, although we have not confirmed the splitting of NORSAR mislocations, we cannot exclude from the foregoing that the Caribbean anomaly is responsible for it. Of course, the fact that it is not resolved by the network further constrains its location and linear dimensions. Through ray tracing we are now modeling the various possibilities.

C. Bonin, Ryukyu, Mariana Islands

In a study of mislocations with the LASA array, Davies and Sheppard (1972) point to a rapidly varying feature in the source regions surrounding the Philippine Sea. We have reprocessed the LASA slowness data with the Herrin Mantle

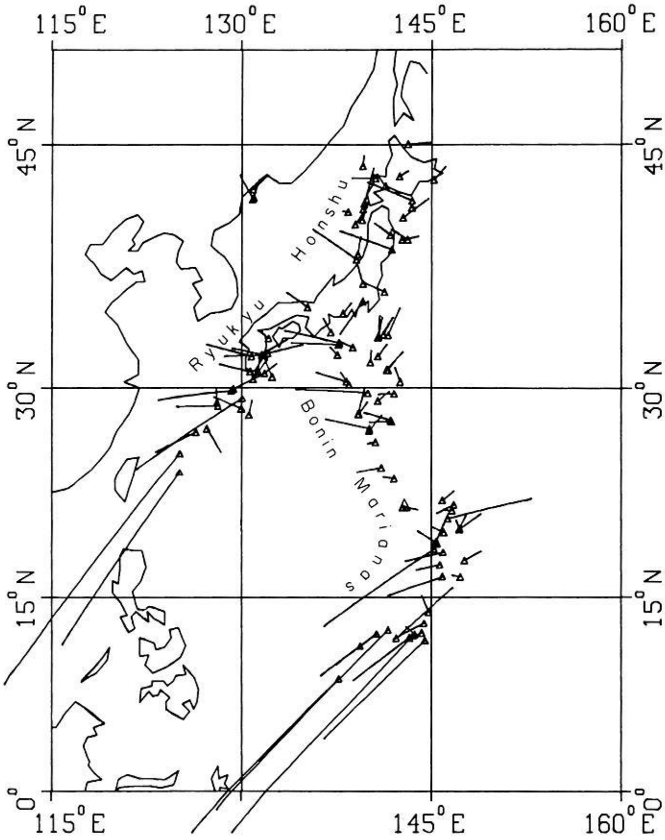

Fig. 9. Montana network mislocations around the Philippine Sea

model, and the resulting mislocations in Figure 8 are very similar to the original figure of Davies and Sheppard (using the J.B. model).

The figure suggests that Bonin events are anomalous in the sense that, relative to events in Ryukyu and Mariana Islands (south of 20° N), dT/dΔ in the bonin Arc is relatively low, the azimuth term remaining approximately constant. It is difficult to place the source of the relative dT/dΔ anomaly (about 0.1 s/deg) in the upper mantle, the descending slab beneath the event, but the apparent correlation with surface tectonics has led to propose a lateral heterogeneity in the deeper mantle beneath the source. In view of the fact that the anomaly is maintained across a major part of the arc, a source related inhomogeneity might be sufficiently extensive to be detectable in a larger part of the United States, including Montana.

Mislocations by the Montana network (Fig. 9) do not reflect the proposed Bonin anomaly in the form of Figure 8, although there is evidence of an anomaly for events in the Northern part of the Bonin Arc (30°–35° N). A plot of dT/dΔ versus geographic latitude (Fig. 10a, b) brings out the anomalies in LASA and Montana more clearly. We may note several trends in the LASA dT/dΔ

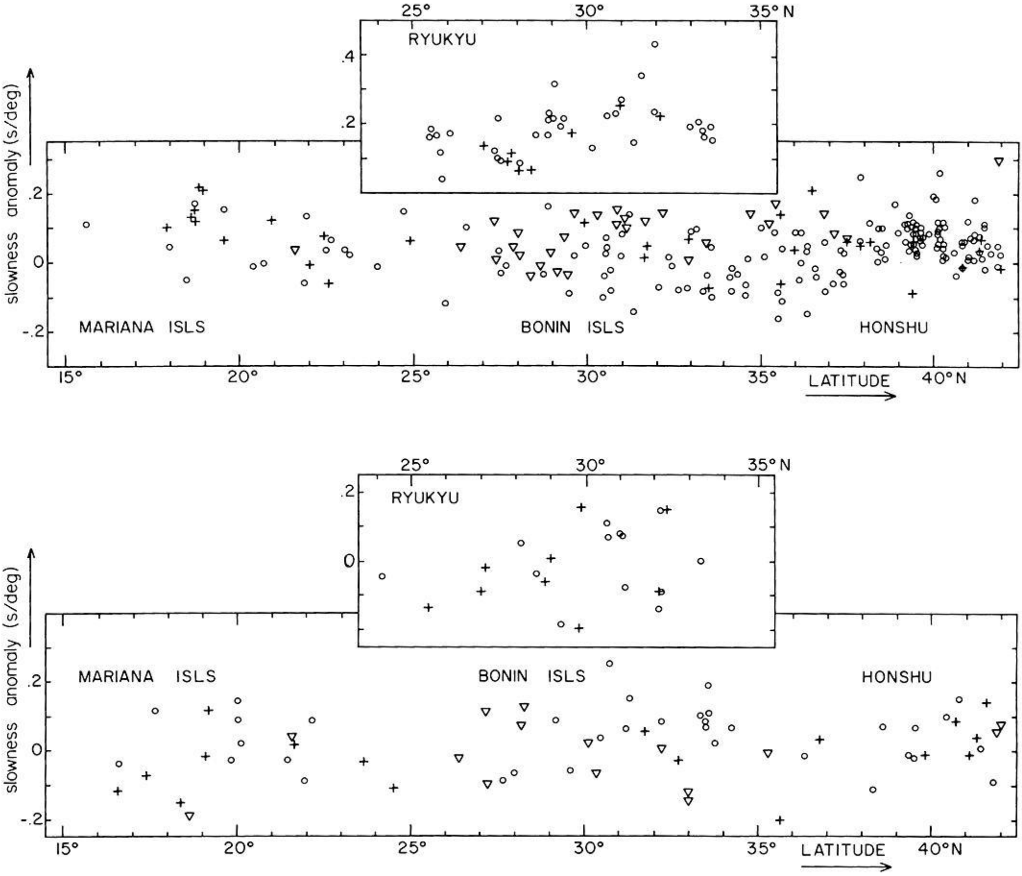

Fig. 10. Slowness anomalies vs. latitude for Ryukyu, Honshu, Bonin and N Marianas as observed at LASA (a) and at the Montana network (b). ○ = shallow (0–70 km), + = intermediate (71–300 km) ▽ = deep events (> 300 km)

values in Figure 10a: anomalies in the Honshu region (35°–42° N) are intermediate between those in Ryukyu and in the Northern part of the Bonin Arc. In the latter part the anomalies for deep and shallower events are clearly separated; anomalies for the deep events trend to the data in Ryukyu and in Honshu. Note that the deep events here are also geographically on the Ryukyu side, even more after correction for focal depth. The Montana data (Fig. 10b) do not reproduce the trends in the LASA data. However, in this case deep and shallow events also separate in 30°–35° N. The dT/dΔ anomaly, to be associated with the shallow events, is here about 0.1 s/deg positive, contrary to the trend in the LASA data. If more data and improved measurement precision prove this feature to be real, it is indicative of a source related inhomogeneity near the triple junction off the coast of Honshu. As in Central America, we cannot completely exclude the possiblity that the negative Bonin anomaly in the LASA data is related to structure near the source region, but the trends noted in Figure 10 suggest that near array structure may also be responsible for it.

4. Concluding Remarks

Systematic changes in the travel time anomaly across a seismic network can be parameterized by an event mislocation. This representation is related to, but for larger networks is more generally valid than, the representation as a slowness vector anomaly. A comparison of array and network data confirms that near array structure may cause a significant bias in the measured slowness vector that is not always smoothly varying, even at large arrays like LASA and NORSAR. Specifically, the NORSAR anomalies from the China-Russia border region have been argued to be due to near array structure. The array evidence for lateral inhomogeneity near the source regions of both Central America (observed at NORSAR) and the Bonin Arc (observed at LASA) has not been confirmed by the network data, although dT/dΔ anomalies were measured in both cases. The source of the network anomalies is here, however, unrelated to the anomalies in the array data. In one case considered, the northern part of the Bonin arc, the dT/dΔ anomalies at the Montana network are indicative of a lateral inhomogeneity near the source region. Improvements in this experiment are possible by obtaining better control on the following factors: scatter in the bulletin data, variability in effective number of stations and lack of suitable station corrections. It is to be expected that more interesting features emerge from other suitably selected source-receiver combinations.

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