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A Study of Short Period *P*-wave Signals from Longshot

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Summary

Well documented short period seismic observations from the nuclear explosion Longshot provide an unusual opportunity to study seismic wave propagation in the mantle beneath an island arc. Ray calculations for a model containing a descending lithospheric slab predict an extensive *P*-wave shadow zone covering much of Canada and Europe and this is in close agreement with the pattern of reported magnitudes. Other features of the short period waveform which occur on some seismograms also seem amenable to explanation in terms of the complications that a slab introduces into seismic wave propagation in the vicinity of an island arc. Many examples are cited, including instances where a slab beneath the observing station also modifies the waveform.

1. Introduction

The underground nuclear explosion Longshot (80 kT) was fired 1965 October 29 on Amchitka Island in the Aleutians and is one of the most widely documented seismic events ever to have occurred. An extensive compilation and discussion of near-field and far-field data and statistics has been made by Lambert *et al.* (1970) (referred to in this paper as LVAG). Using the data in that report it is possible to make an extensive study of short period waveforms. It is the purpose of this paper to attempt to draw together some of the generalizations that can be made from such an analysis. Longshot affords us an unrivalled opportunity for studying seismic waves from an isotropic radiator of relatively well known pulse shape in the vicinity of strong lateral heterogeneities in the Earth's crust and upper mantle. Since Longshot, Milrow (about a megaton) and Cannikin (about 5 megatons) have been fired in almost the same location. We have deliberately restricted our discussion to Longshot, however. Conclusions from Milrow follow a similar pattern, but at many short period seismometers, Milrow gave too large a signal to permit clear writing on photographic paper whereas the quality of recording of Longshot's signals was reasonably good. A global study of long period body waves from Milrow and Cannikin would form an interesting next step.

Island arcs are associated with the most pronounced known lateral variations in the physical properties of the upper mantle. These heterogeneities in seismic wave velocity and attenuation are in fact the primary evidence that lithospheric slabs descend into the mantle as the ocean floor is consumed in oceanic trenches. (We use the word 'slab' to describe lithospheric material after it is no longer at the Earth's surface.) The main cause of lateral variation in properties is probably the thermal anomaly associated with a descending slab. In most cases the rate of plate consumption is between 2 and 10 cm/yr, and since the thermal relaxation time of the lithosphere is on the order of 5 or 10 My, the slab remains hundreds of degrees cooler than its surroundings to depths of several hundred kilometres. In addition, the lithosphere may be chemically different from the rest of the upper mantle, since it was formed by a process of chemical differentiation at oceanic ridges, and thus a slab may maintain its identity even after reaching thermal equilibrium.

The expected (and observed) effect of slabs being cold is that they have higher seismic velocities and lower seismic attenuation than has the surrounding mantle (Utsu 1967; Oliver & Isacks 1967; Davies & McKenzie 1969, hereafter called DM). On the basis of travel-time anomalies, various workers have concluded that the velocity contrast between slab and surrounding mantle amounts to about 5 to 10 per cent (for instance Mitronovas 1969). Theoretical calculation of the temperature field in and near a slab is subject to a variety of uncertainties (Toksöz, Minear & Julian 1971; McKenzie 1971; Hanks & Whitcomb 1971) but nevertheless it seems, on the basis of such calculations, that the observed seismic velocity contrast in at least the upper 200 km is greater than would be expected on the basis of the effect of temperature on a mantle of uniform composition and phase. The explanation of this discrepancy probably lies in the fact that at an early stage in its descent the slab passes through the low-velocity zone, thought to be the site of partial melting. Since seismic velocities are quite sensitive to the presence of small amounts of a fluid phase, the low-velocity zone probably enhances considerably the velocity contrast associated with a descending slab.

If the velocity contrast is indeed as large as 5 to 10 per cent, certain gross effects upon the amplitudes and waveforms of seismic waves ought to be apparent. The paths of rays emerging from a source in or near a slab should be strongly distorted, producing shadows in some regions while others are more strongly insonified than calculations for a spherically symmetric earth would indicate. The existence of many paths from source to receiver owing to multiple reflections and refractions is also a strong possibility. The purpose of this paper is to try and identify some of these phenomena for Longshot, first by three-dimensional ray tracing in a model of the Aleutian region, then by studying signal waveforms, drawing together qualitative observations and noting their distribution over the Earth. Our discussion is limited to the effects of lateral heterogeneities in velocity. Attenuation heterogeneities also undoubtedly exist in the vicinity of the Aleutian slab, but we expect a less drastic effect on signal amplitudes from such regions than from velocity heterogeneities. Attenuation heterogeneities should produce broad regions of low amplitudes without sharp boundaries. They should not lead to multipathing. We shall show in this paper evidence both of sharp shadows, especially in western Canada, and of multipathing, and therefore believe velocity heterogeneities to be the dominant effect. Douglas, Marshall & Corbishley (1971) recently proposed that Longshot signal amplitude anomalies be explained in terms of differential attenuation at depth for different ray paths. Numerical calculations performed by us indicate that the effect of a geometrical shadow upon the spectrum of a signal should be nearly identical to the effect which would be produced by attenuation. Thus it is to be expected that it should be difficult to distinguish between the two phenomena experimentally. We believe, however, that the velocity structure gives us a model already having a degree of acceptability from which to work and against which data may be tested. A differential Q explanation of the anomalies would in our opinion be an *ad hoc* solution to be considered only if the velocity structure predictions turned out to be hopelessly incorrect. A fully quantitative discussion is at present impossible. We lack adequate solutions to the wave equations even for relatively simple models of slabs, let alone the complications introduced by the curvature of actual slabs such as that beneath the Aleutian arc. Ray tracing techniques are the first step in this direction and are invaluable for obtaining an understanding of the complexities of propagation in the neighbourhood of slabs. Whether finite difference techniques, WKB methods, the

Cagniard technique or any as yet untried method will yield more useful results in terms of waveforms that can be compared with the observations remains an open question.

2. Seismic velocity model

The detailed shape, location, orientation and thickness of the sub-Aleutian slab are difficult to determine, as are the details of the seismic velocity field in and near the slab. Fig. 1 is a section through the Aleutian arc showing the seismicity in the vicinity of Amchitka projected on to a plane perpendicular to the trench axis (Engdahl 1971). It suggests that the slab dips at an angle of about 60° beneath Amchitka and that the Amchitka test site is about 30–40 km above the thrust boundary between the Pacific and Bering Sea plates. Stauder (1968) has reported focal mechanisms for many earthquakes in this region which imply that it is overthrusting activity which generates at least the larger shallow earthquakes. No focal mechanism solutions are possible for these smaller events, so we do not know whether they too are dominantly overthrust or associated with internal fracturing of the plate, as is observed further out to sea in normal faulting earthquakes. Thus it is not clear whether the seismicity maps the total extent of the elastic slab or only its top surface. We have made the latter assumption and as will be seen obtain good agreement between the observed and predicted location of the seismic shadow cast by the slab. We have adopted a thickness for it of 75 km, in keeping with the inference that the lithosphere (at least at seismic wave frequencies) and the ‘ lid ’ above the low-velocity zone are equivalent (Kanamori & Press 1970).

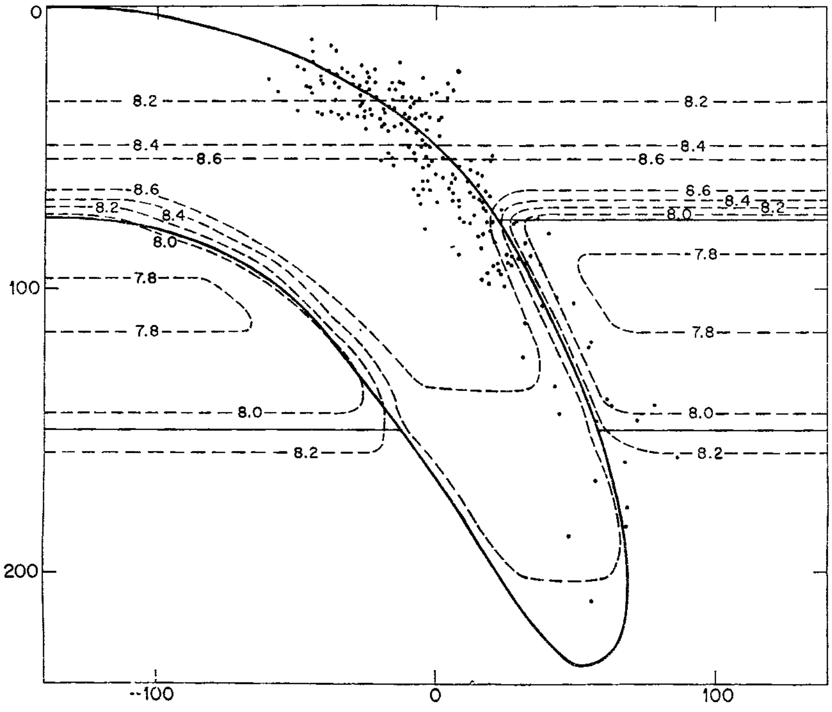

Fig. 1. Cross-section perpendicular to the Aleutian arc in the vicinity of Amchitka Island showing projected earthquake locations of Engdahl (1971) (dots), and velocity contours for the model proposed here (dashed lines). Heavy lines indicate the assumed boundaries of the lithosphere and the low-velocity zone. Longshot is at point (0,0).

The velocity contrast between slab and surrounding mantle has been chosen to satisfy 1·5–2·0 s negative travel-time anomalies observed from Longshot. Residuals of higher value have been reported but it is difficult to isolate source, station and deep mantle anomalies, so we take conservative values. The required velocity contrast averaged over the assumed 230 km vertical extent of the slab is about 5–7 per cent. Since the contrast must be small near the surface and in the deepest part of the slab, the maximum velocity contrast at intermediate depths must reach about 10 per cent. In the model used here, contoured in Fig. 1, the velocity inside the slab reaches values between 8·6 and 8·7 $\mathrm{km\,s^{-1}}$ between depths of 60 and 150 km, while the velocity outside the slab at these depths is 7·8 $\mathrm{km\,s^{-1}}$. Velocities this high at such shallow depths are surprising, but interestingly Hales, Helsley & Nation (1970) have, in an explosion seismology experiment in the Gulf of Mexico, observed velocities of about 8·6 $\mathrm{km\,s^{-1}}$ at 60 km depth. More such studies to increase our knowledge of upper mantle structure in oceanic areas would be invaluable.

We cannot emphasize too strongly that the model in Fig. 1 is not to be considered as more than a structure which, through a process of refinement, fits most of the seismic observations well. It, no more than the quite similar models of Sorrells, Crowley & Veith (1971) and Jacob (1972), is not necessarily close to reality—the models are devised to fit a very restricted data set and might be extensively modified if, for instance, Russian seismic recordings of Longshot were released.

3. Ray tracing

A computer program (Julian 1970) is used to calculate ray paths through the structure shown in Fig. 1. We have assumed the structure to be two dimensional, with the dip being constant along the arc. Of course, if we were modelling a large section of the arc we would have to include variable dip of the slab (seismicity indicates the dip to be as shallow as 40° in Alaska, and probably near 90° at the western end of the arc). However, in the immediate vicinity of Amchitka we have assumed the dip to be uniform. This aids computation considerably as we can construct a spherical co-ordinate system in which the centre of curvature of the island arc is at the pole and the trace of the slab is bounded by two small circles about the pole. In this co-ordinate system the elastic properties are a function of r (distance from the centre of the Earth) and θ (polar angle) only. We have used a radius of curvature of 10 degrees for the Aleutians in the vicinity of Amchitka.

Eliseevin's (1965) formulation of the ray problem is used. A set of five simultaneous differential equations is derived from the eikonal equation in spherical polar co-ordinates, and the ray tracing reduces to simultaneous integration of these equations for position on the ray and direction of the ray. The program follows individual rays through any structure, defined either numerically or in terms of analytical functions, and will produce standard seismological parameters such as T, Δ, $dT/d\Delta$, and azimuth for the emergence point of each ray.

In the presence of heterogeneities, neither $dT/d\Delta$ nor azimuth are generally preserved along a seismic ray, and although this does not lead to any difficulties in ray tracing, it does make visual representation a problem. Rays leaving the source perpendicular to the strike of the plate, however, are easily represented, as shown in Fig. 2. They remain within the plane of the diagram. A ‘shadow’ zone can be seen very clearly—it is not actually a completely dark shadow but only a region of greatly reduced amplitudes. Also obvious is the region of triplication that occurs on the topside of the shadow. Any station at a distance of more than 67° should record anomalously low amplitudes, and a station at a distance of less than 67° should record a strong signal consisting of three pulses, one of which would be a precursor of small amplitude. There is the slightest indication of a complication in the ray pattern for very steep angles also.

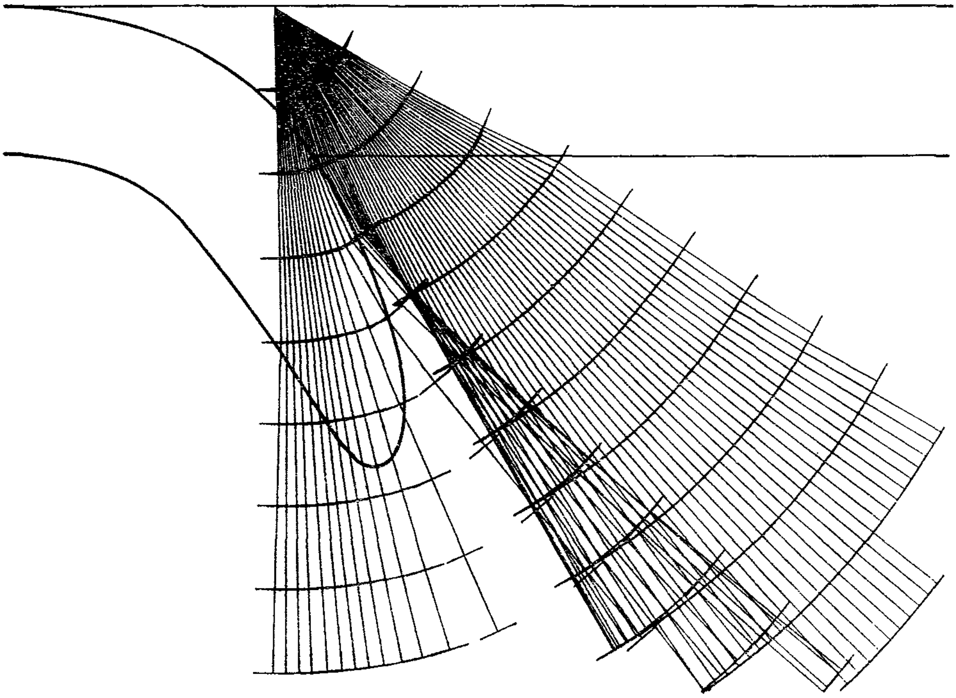

FIG. 2. Ray paths of *P* waves calculated for the model illustrated in Fig. 1. Rays are spaced 1° apart and lie in the plane normal to the island arc. Wavefronts indicated are 5 s apart. The lithospheric slabs are outlined.

Fig. 3 shows rays emerging from the source at an azimuth of 30°. To assist in visualization of individual rays a small circle is drawn on the wavefront every 5 s so that the ray vector is perpendicular to the plane of the circle. In Fig. 2 these circles are perpendicular to the plane of the figure and thus appear as straight line segments. We can now see quite strong azimuth shifts along the rays, and the same shadow phenomenon persists. The projection cannot show which direction the rays are turned; in all the cases shown here, however, rays that travel through the slab—regardless of where they emerge—are deflected ultimately towards the inside of the island arc. Three distinct pulses should arrive at many points of the Earth's surface—they will however not have emerged from the source with exactly the same azimuth. The shadow zone for rays emerging with an azimuth of 30° is at a smaller distance than that for the zero azimuth example, because the apparent dip of the plate is less steep at 30° azimuth.

The 45° launch azimuth diagram (Fig. 4) shows the phenomena described above in an even more marked way.

It will be clear from these figures that the apparent location of the seismic source based only on the ray parameter (such as a seismic array can obtain) can easily be in error by 200 km because of slab structure. A preliminary report on observations of this phenomenon was given by Sheppard (1970).

We attempt in Fig. 5 to draw together the rather complex results available from this program. Rays were traced at 1° dip angle spacings for emergent azimuths at source of 0°, ±20°, ±40°, ±60° ±70°, ±80°, ±100°, and ±120°. The ultimate location of the ray when it reached the surface is plotted on an equal area projection centred on the location of Longshot. The density of emerging rays indicates in a qualitative way the amplitude of the signal.

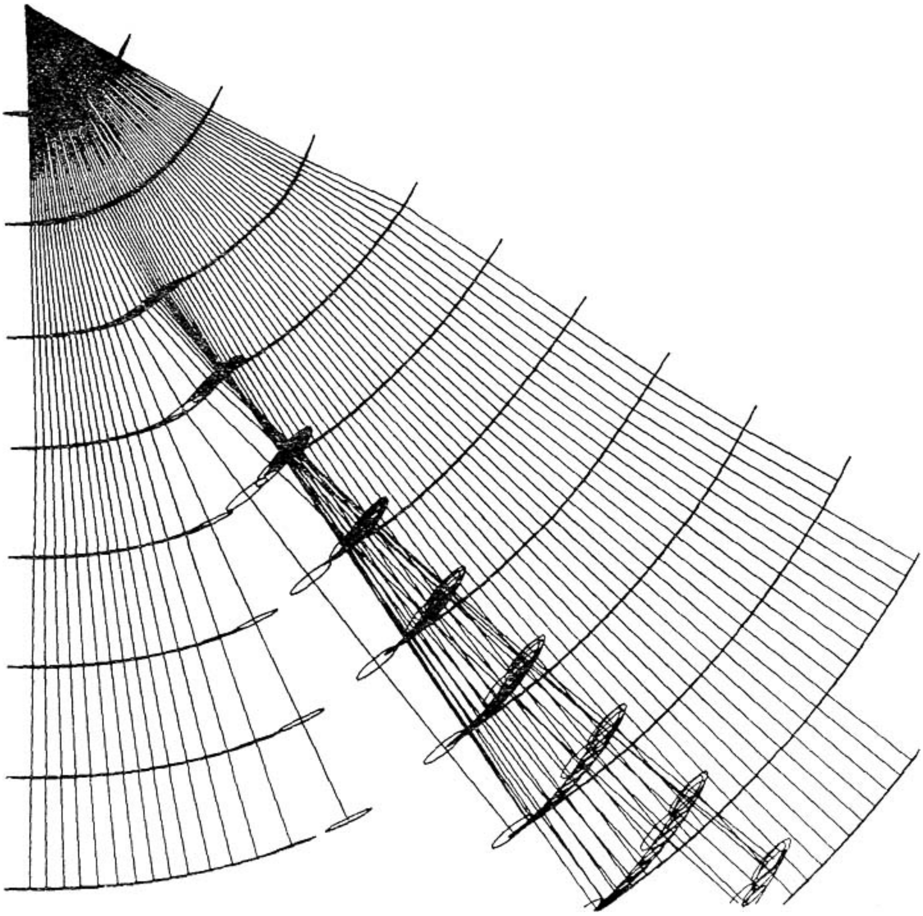

FIG. 3. Ray paths similar to those of Fig. 2, but for rays with an initial azimuth of 30° to the normal to the island arc.

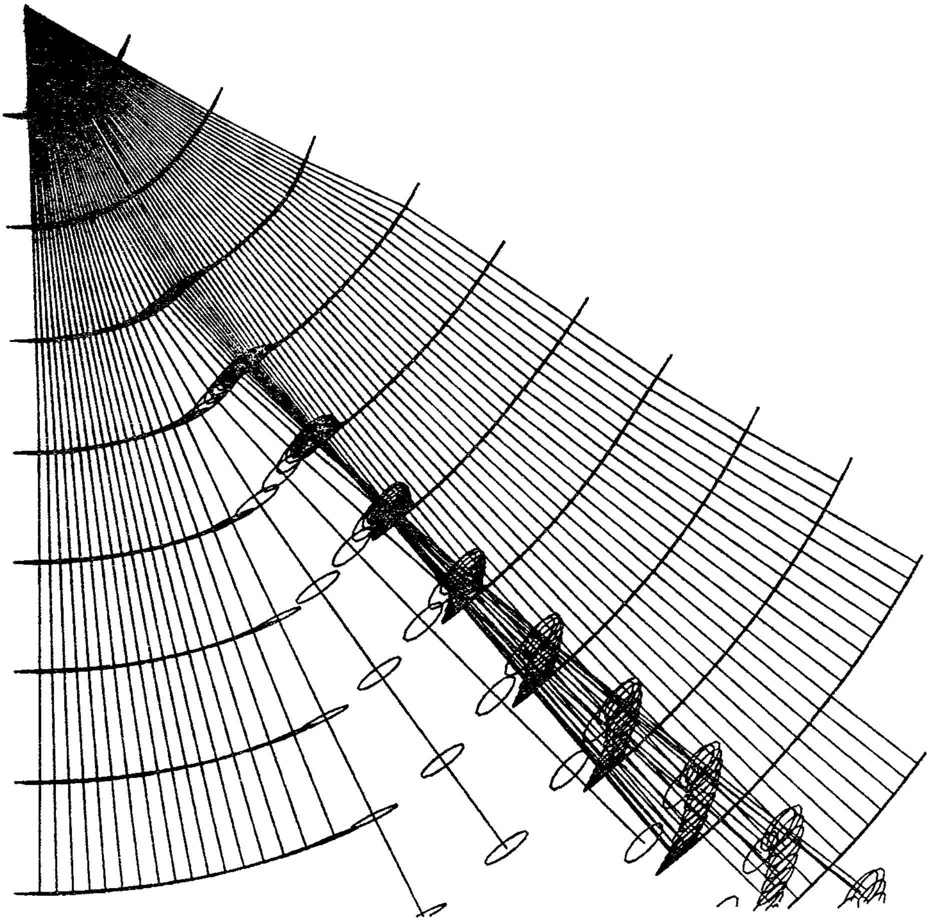

FIG. 4. Ray paths similar to those of Figs 2 and 3, for an azimuth 45° to the normal to the island arc.

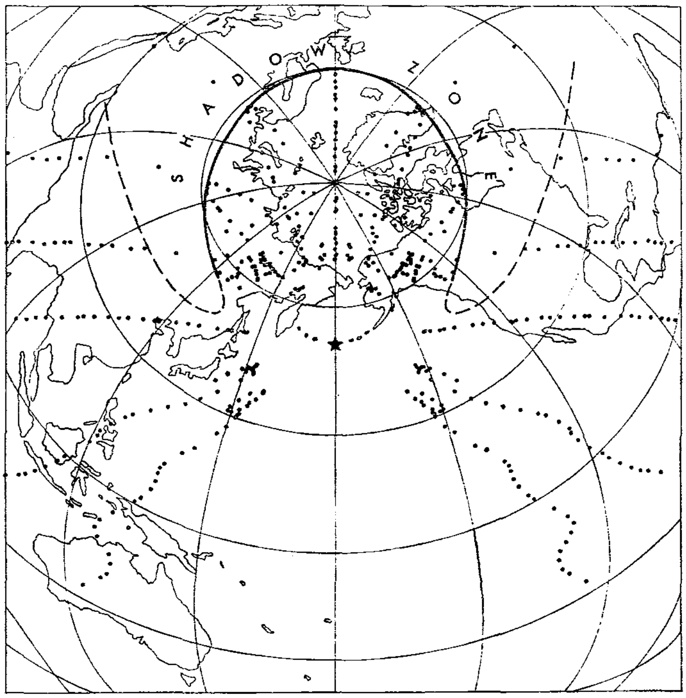

FIG. 5. Calculated emergence points on the Earth's surface for rays leaving Longshot at angles (with the vertical) spaced 1° apart and at azimuths of 0°, +20°, +40°, +60°, +70°, +80°, +100°, and +120°. Notice the large shadow zone, bounded by a caustic on the inner side. In the region to the north of the shadow, multiple arrivals are predicted. The projection is azimuthal equal area centred on Amchitka (starred).

In this paper we use a conventional map of the world rather than the seismically based focal sphere projection used in focal mechanism studies and in the travel-time study of DM. The reason is simply that the distortion of the focal sphere by a slab, as is obvious from Fig. 5 and Toksöz *et al.* (1971), makes use of that projection confusing for plotting properties of the short period *P*-wave.

Fig. 5 shows many features which we shall discuss later. In particular, a broad shadow zone (drawn by visual inspection only) is predicted, multiple arrivals are seen in many places coming from different azimuths and with different apparent $dT/d\Delta$ and the inner edge of the shadow is expected to be a region of high amplitude. The one weakness of this type of display is that it does not show relative arrival times, which must be obtained in an approximate way from Figs 2–4.

4. Analysis of the signal from Longshot

We shall attempt in this section to relate the extremely varied character of short period recordings of Longshot from a global network to the influence of the sub-Aleutian slab. This analysis is bound to be unsatisfactory and incomplete for many reasons—unevenly spaced and dissimilar observing stations, the lack of an adequate way of displaying waveforms as a function of geographic position, and our imperfect knowledge of the actual detailed structure of the sub-Aleutian slab are three of many reasons that our analysis can be only qualitative. Nevertheless, considerable success has been achieved, particularly in relating the pattern of observed amplitudes to the shadow of the slab.

We shall consider two basic parameters of the signal in our analysis: size and shape. Size will be measured by reference to the magnitude reported for a particular station. We shall rely on the reading of the seismogram by LVAG and their determination of magnitude and we shall apply no station magnitude corrections such as have been proposed to account for magnitude differences from station to station. This is not because we do not believe such terms to exist, but because we shall be looking for gross contrasts—certainly greater than 0·5 magnitude units, which is about as large as a compilation such as that of Carpenter, Marshall & Douglas (1967) proposes for station corrections.

In attempting to deal with signal shape we shall try to relate the character of the coda to that of the first part of the *P* wave. We are aware of the importance of signal generated noise at some stations as a constituent of coda and therefore will aim to discuss general features of the coda rather than those of particular stations. In addition to treating coda as part of the shape of the signal we will also note a few unusual features of *P* waves in certain areas. Wherever possible the discussion of *PcP* will be linked to that of *P*. *PcP* was very widely observed for Longshot and permits us to extend our coverage of the focal sphere and also to make comparisons of signal generated noise from *P* and *PcP*.

4.1 *Observed magnitude distribution*

Fig. 6 shows deviations of the short period *P* wave magnitudes reported by a selected group of stations from the mean of 5·85 obtained from all stations. We restrict our discussion to large scale features. Poor as may be the coverage of the

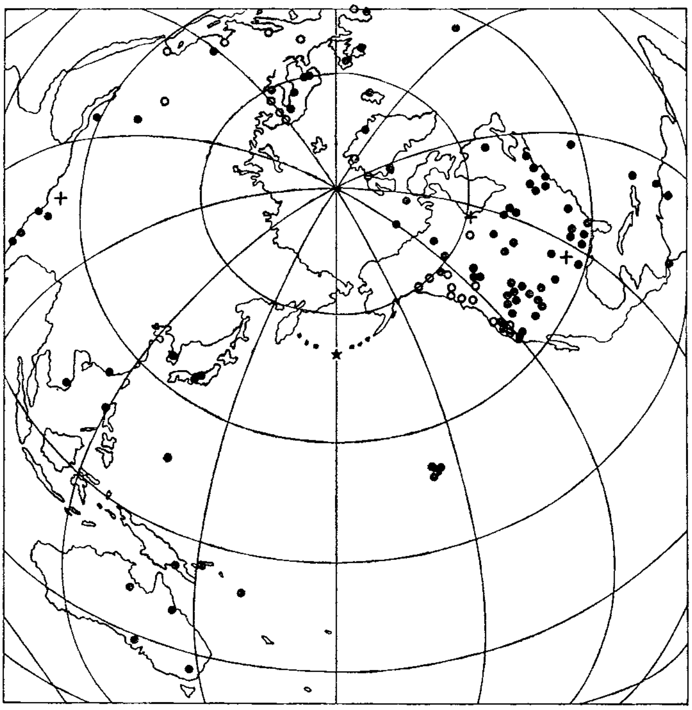

Fig. 6. The general character of observed magnitudes at stations for which a reliable determination could be made. An open circle indicates a value less than 5·4, a dot a value between 5·4 and 6·5, and a cross a value greater than 6·5.

globe, certain features are quite clear. Magnitudes seem to be normal in the south west quadrant. They also seem to be normal at distances greater than 50° in the NE quadrant and at most Californian stations. Other regions of the NE quadrant show much more complex structure. A region of dominantly large magnitudes in the eastern parts of the United States and Canada seems to be separated from a belt of very low magnitudes in western Canada. The extent of this magnitude variation is much greater than any proposed station terms for magnitude corrections.

The distinctly low magnitudes for Europe are obvious. Values as low as 4·6 were reported (at Trieste) and there seems to be quite good evidence that Southern and Central European stations must have been in shadow, so consistently low are the magnitudes. In Scandinavia the situation is more complex—magnitudes vary rapidly from Kevo (5·2), Tromso (5·9), Sodankyla (5·2), Kiruna (5·8), Umea (5·5), and Kajaani (5·4) in the North to Nurmijarvi (5·8), Uppsala (6·4), Kongsberg (6·4) and Oslo (5·6) in the South. Scandinavia appears to be near the inner edge of the shadow, where a caustic is predicted and small geographical shifts may thus produce substantial magnitude fluctuations. In this connection Båth (1970) has commented recently on magnitude differences between Uppsala and Kiruna of 0·7 for Andreanof Island events within 150 km of Longshot. It is also worth noting that there is a distinct absence of *PcP* phases from Scandinavia and indeed from all Europe. Many North

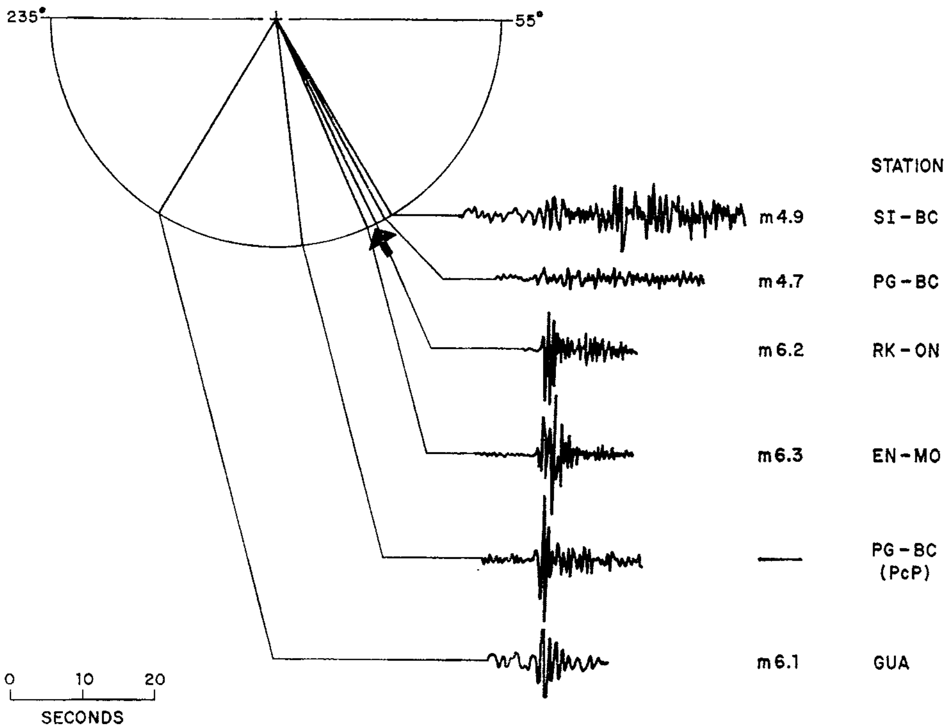

FIG. 7. A slice through the focal hemisphere beneath Longshot on an azimuth 55°–235°. Seismograms are shown emerging at the appropriate angle to reach the stations listed: SI–BC—Smithers, British Columbia; PG–BC—Prince George, British Columbia; RK–ON—Red Lake, Ontario; EN–MO—Ellsinore, Missouri; GUA—Guam. The arrow indicates the approximate trace of the slab at this azimuth.

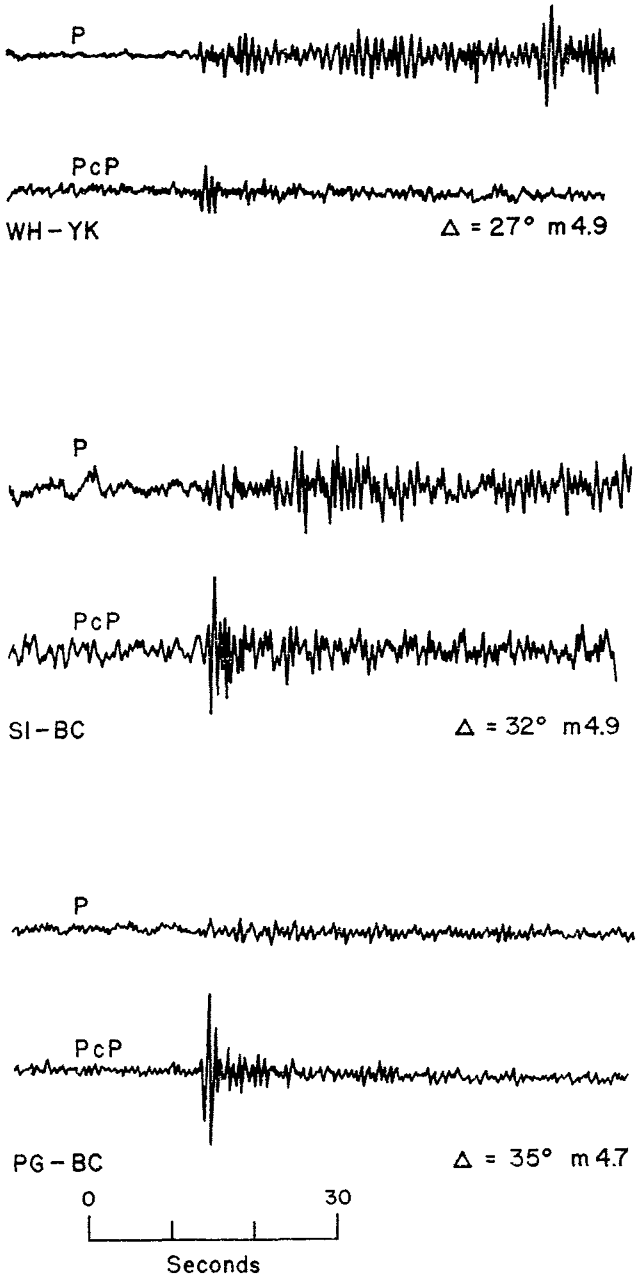

Fig. 8. Direct and core reflected traces at three stations in Western Canada. WH–YK is Whitehorse, Yukon. The other codes are given in the caption to Fig. 7.

American stations at the same epicentral distance as Scandinavia show clear *PcP* arrivals so it is likely that the shadow zone believed to blanket Southern Europe may well also reveal itself by extending into the core and suppressing *PcP*.

The magnitude variation in the north-east quadrant is shown particularly dramatically in Fig. 7, which shows a slice through the lower focal hemisphere at an azimuth of 55°–235°. Sample waveforms show the quite remarkable variation in signal character across this slice and the virtual disappearance of the *P*-wave in Western Canada. It is worth remarking the excellent *PcP* recorded at Prince George, British Columbia which suggests very strongly that it is not a property of Western Canada, as Key (1968) suggested, that causes the virtual obliteration of *P* waves. The set of seismograms in Fig. 8 confirms this argument. In all instances the *P*-wave is poor, the *PcP* clear, and near source structure seems the only possible way of explaining effects which vary so drastically with the take-off angle. Douglas, Marshall, & Corbishley (1971) have an explanation for low amplitudes for *P*-waves in Western Canada which is completely different from ours. They suggest strong attenuation of *P*-waves that leave Longshot in the direction of Western Canada. As mentioned above, the effects of shadowing and attenuation would be similar in some respects. Invoking attenuation seems an unnecessary complication, however, when ray tracing provides such a simple explanation.

The theoretical amplitudes corresponding to our model of the Aleutian slab are difficult to calculate, but they can be judged approximately from Fig. 5 which shows the calculated emergence points of the rays. The predicted position of the shadow is seen to agree quite well with the observed position, notably in western Canada and southern and central Europe. On the other hand, observations from eastern Canada and eastern U.S. are clearly not in accord with prediction. The region of very low magnitudes in Fig. 6, if it has a continuous character, suggests that the dip of the slab near Longshot is changing quite rapidly, with the dip increasing towards the west. This would be in accord with the idea that the dip changes from less than 45° in Alaska to 90° at the Komandorsky Islands—an idea which receives some confirmation from the limited deep seismicity in the area. A two-dimensional model is thus not a completely adequate representation of the mantle structure beneath Longshot.

4.2 *Signal shape*

For typical short period seismometers the response to an underground explosion in a spherically symmetrical earth is fairly well understood (Carpenter 1967) and many of the signals recorded for Longshot agree well with theoretical predictions. The simple pulse recorded at Charters Towers, Australia (Fig. 9) is a good example. At some stations, however, the signal is complicated by a large coda (signal arriving later than five seconds after the *P*-wave). Fig. 10, for instance, shows a coda of great complexity following a normal amplitude *P*-wave and with a relatively simple *PcP*. Coda is undoubtedly produced by many phenomena—signal generated ‘ noise ’ at source, receiver and along the propagation path and we attempt to discover how much of this has its origin in multiple refraction and reflection processes, possibly caused by the sub-Aleutian slab.

An immediate problem is a simple parametrization of the coda which does not discard too much of the information contained in the seismogram. We have used a number pair (m_1, m_2) to describe the seismic signal, where m_1 is the (conventional) magnitude and m_2 is the ‘ magnitude ’ of the coda in the time interval from 5 to 10 s. Against the many disadvantages of such a crude parameter, we can set only the great simplicity of calculation for large numbers of seismograms. It is obvious that such a parametrisation is related to the concept of ‘ complexity ’—either of the qualitative type (simple, medium, complex) or the quantitative type in which energies in two intervals on the seismogram are compared.

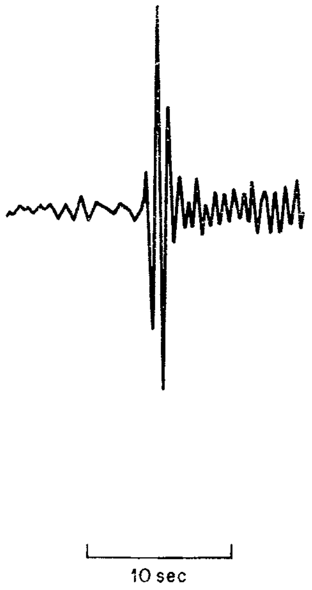

FIG. 9. The *P*-wave recorded at Charters Towers, Australia. Δ = 76·8° and the reported magnitude is 6·1.

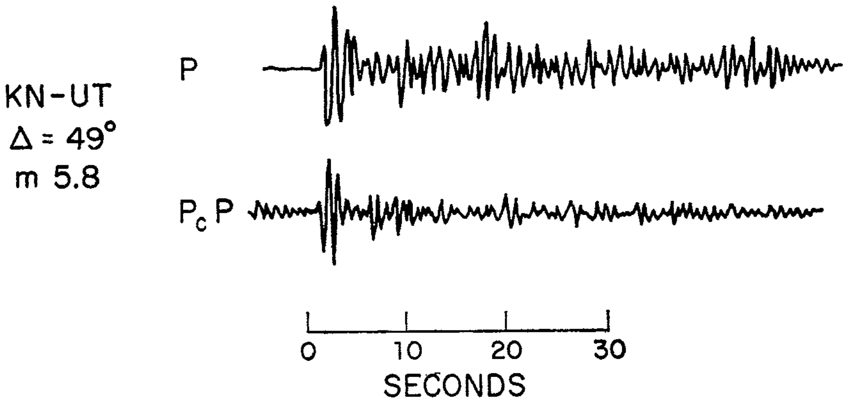

FIG. 10. *P* and *PcP* at Kanab, Utah.

If signal generated noise at or near the station were the only constituent of the coda we should expect that the 'magnitude drop' Δm ($= m_1 - m_2$) would be on average independent of the magnitude of the first incident *P* wave, m_1. Fig. 11 shows this assertion to be untrue. Although we do not choose to grace this diagram with a least squares line it is particularly evident that the coda at stations reporting low magnitudes is frequently as large as the *P* wave itself. In fact, it is more nearly accurate to say that the coda level, m_2, is independent of m_1. Thus the large apparent variations in the 'complexity' of the signal reflect primarily variations in the size of the *P* wave, due to such phenomena as shadowing and focusing, rather than variations in the coda. Furthermore, as Fig. 8 has already shown with some examples, *PcP* does not generate a large coda, even when the *P* wave does—further evidence that local scattering and reverberation near the station are not the phenomena responsible for the coda. Exactly the same arguments serve to rule out scattering and reverberation very close to the source (for instance, Rayleigh-*P* conversion); such a process cannot be strongly directional and the coda level for *PcP* should not be very different from that for *P*.

Thus we are faced with quite significant variations in the coda level from station to station, caused by reflection, refraction, and scattering processes in the mantle at a significant distance from either the source or receiver. That the sub-Aleutian slab is responsible for some of these phenomena is suggested by the fact that the coda level is greater for rays which travel through or near the plate for great distances than for rays which do not.

Stations for which the magnitude reported is relatively normal (5·6–6·3) but which have many clear large pulses in the coda (such as in Fig. 10) can be contrasted with single pulse events such as in Fig. 9. We observe that most stations in the Western U.S. record multiple pulses—probably an indication that there is multipathing in a region where rays have travelled a long distance in the vicinity of the slab and are thus likely to be followed by reflections and refractions. This issue clearly needs further study, as the evidence is by no means clear-cut.

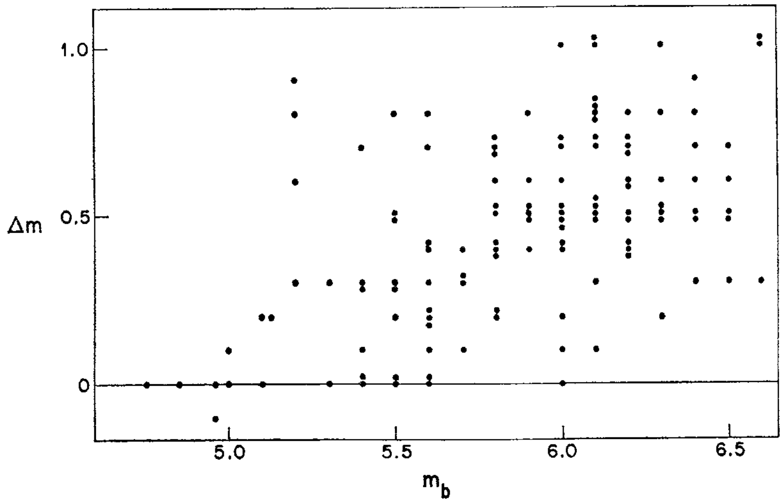

FIG. 11. The 'magnitude drop,' Δm, in the coda as a function of the conventional body wave magnitude.

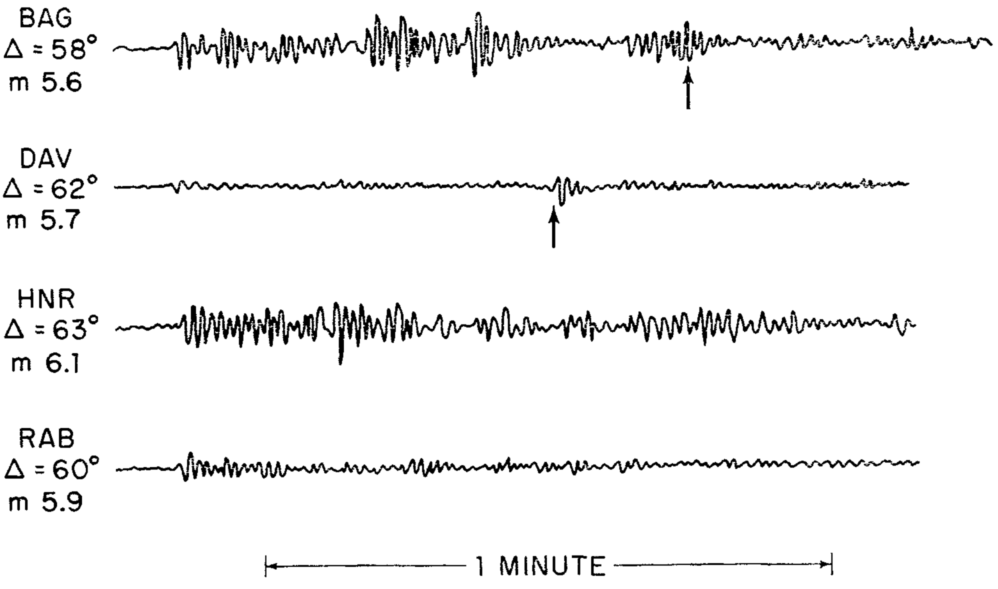

FIG. 12. Southern Hemisphere recordings of Longshot. *PcP*, is identifiable, is shown by an arrow. BAG is Baguio, Philippines; DAV is Davao, Philippines; HNR is Honiara, Solomon Islands and RAB is Rabaul, New Britain.

Four Southern Hemisphere stations' records are shown in Fig. 12. All four stations are in seismic areas where deep focus earthquakes are common and thus we expect unassimilated slab beneath these stations. In dealing with *P*-waves incident on such a slab *P* to *S* conversion at depth may be expected to play a major role in generation of the coda, and the presence of energy at least 40 s after the first *P*-wave arrival would be taken to be conversion at depths at least as great as 400 km. It can be seen that when a *PcP* phase is visible (Baguio and Davao in the Philippines) it is not followed by any major coda although itself at least as big as *P*. This suggests a coda creation mechanism sensitive to direction of approach and would be consistent with deep plate structure. Key (1968) noted that La Paz, Bolivia records explosions that are nearly always extended in character; this station too sits on a descending slab.

We consider finally a set of seismograms in which the interesting feature is a precursor to the main signal (Fig. 13). These are small in number and fall within a relatively small region of the Earth. Stations themselves on or near the slab are going to see Longshot through a very distorted window. So Fig. 13 gives only more distant examples. All these are in Western Canada as is Yellowknife where the precursor was first noticed (UKAEA 1966). Note that these are precursors to signals of normal amplitude and thus are probably due to the existence of at least two different paths from source to receiver rather than any shadowing phenomenon.

As the ray tracings discussed above show, (see Fig. 2 particularly) just such a precursor should occur near the inner edge of the shadow produced by the slab, which is where they are observed. It may be that these precursors exist much more extensively, but need high quality stations to reveal them. Certainly observations at LASA (Davies & Frasier 1970) suggest that precursors from Aleutian earthquakes are frequently recorded.

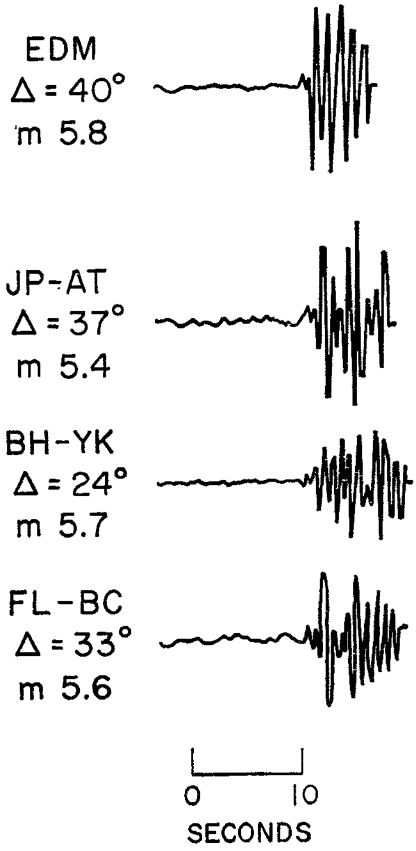

FIG. 13. Records from Canada showing a precursor to the large pulse. EDM is Edmonton; JP-AT is Jasper, Alberta; BH-YK is Burwash Landing, Yukon, and FL-BC is Fort Nelson, British Columbia.

5. Conclusions

We have attempted in this paper to predict teleseismic phenomena associated with events in the vicinity of a downgoing slab. The ray tracing approach is undoubtedly adequate only in a qualitative sense but in the absence of detailed near source structure anywhere in the world it can no doubt be defended in terms of making generalized predictions which are easily tested. We have restricted our study of actual waveforms to those from one well-documented nuclear explosion, and have found reasonable agreement between the predicted and observed geographic position of the shadow cast by the Aleutian slab. We believe it is possible to study coda and to assign portions of it to slab-generated multipathing. Some other quirks from Longshot also seem amenable to qualitative analysis.

Perhaps the most fundamental conclusion to be drawn from this study, however, is the immense importance of a network approach to signal characteristics. With individual stations it is possible to reach highly diverse conclusions, but when constrained to fit into a global analysis, we can search for regularities that can be attributed to the near source region. For instance, the criterion of signal complexity has been widely discussed in connection with discrimination between earthquakes and explosions (UKAEA 1965). Several numerical definitions have been given, but the

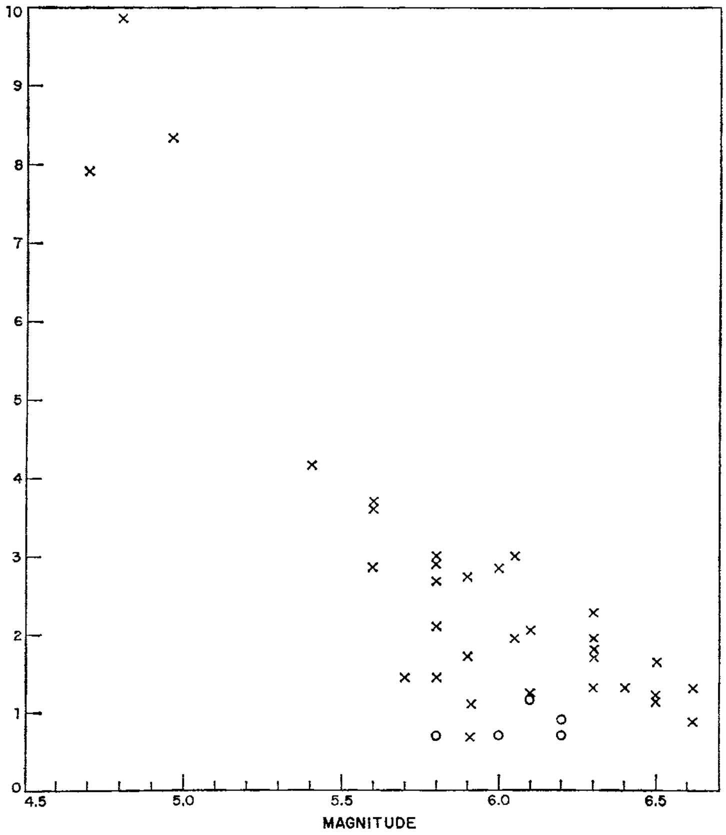

Fig. 14. Complexity as a function of apparent magnitude. The circles represent array stations.

one used by LVAG is suitable, being a ratio of power in two time windows, one in the coda, one in the *P*-wave. Fig. 14 shows all the determinations made by LVAG plotted as a function of observed magnitude. This seems to say the same as Fig. 11—that the coda can dominate if the *P*-wave is shadowed out. Thus complexity for Longshot would be a poor criterion if random stations were chosen. It is clear that in this case complexity is simply a decreasing function of magnitude and a network approach is necessary.

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