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SUBJECT: Final Technical Report,
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This report describes research performed under NASA Contract No. NCC5-21. The objectives of this research were to compile and analyze seismic refraction and surface wave dispersion data on crustal and uppermost mantle structure for the North American continent and to compare these observations with long-wavelength gravity and magnetic anomaly data. Most of the research performed under this contract is described in the attached manuscript by L.W. Braile, W.J. Hinze, R.R.B. von Frese, and G. Randy Keller entitled "Seismic Properties of the Crust and Uppermost Mantle of North America". An additional publication which was partially supported by the subject contract is by P.R. Black and L.W. Braile entitled "P_n Velocity and Cooling of the Continental Lithosphere". A copy of this paper, which was published in the Journal of Geophysical Research (volume 87, pages 10557-10568) 1982, is included in this report. Additionally, three Masters theses were partially supported by Contract NCC5-21. The

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Bodnar, C.A., Crustal Structure of the Great Plains of North America from Rayleigh Wave Analysis, MS Thesis, University of Texas at El Paso, El Paso, TX, 62 pp., 1982.

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Russell, David, Constrained Inversion Techniques Applied to Surface Wave Analysis, Unpublished MS Thesis, University of Texas at El Paso, El Paso, TX, 1980.

Additional information related to the research reported here and supported under a previous NASA research contract (NAS5-25030) is contained in the following publications:

Austin, C.B. and Keller, G.R., A crustal structure study of the Northern Mississippi Embayment, U.S. Geol. Surv. Prof. Paper 1236, p. 83-93, 1982.

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Keller, G.R., Braile, L.W. and Schlue, J.W., Regional crustal structure of the Rio Grande Rift from surface wave dispersion measurements, in Rio Grande Rift: Tectonics & Magmatism, American Geophysical Union Monograph, 115-126, 1979.

The remainder of this report consists of the manuscript "Seismic Properties of the Crust and Uppermost Mantle of North America" by L.W. Braile, W.J. Hinze, R.R.B. von Frese and G. Randy Keller and a reprint of the paper "P_n Velocity and Cooling of the Continental Lithosphere" by P.R. Black and L.W. Braile.

SEISMIC PROPERTIES OF THE CRUST AND UPPER-MOST MANTLE OF NORTH AMERICA

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ABSTRACT

Seismic refraction profiles for the North American continent have been compiled from published and unpublished sources. The crustal models derived from these profiles were used to compile data on the upper mantle seismic velocity (P_n), the crustal thickness (H_c) and the average seismic velocity of the crystalline crust ($\bar{V}_p$). These data indicate continent-wide averages of P_n = 8.03 km/s, H_c = 36.2 km and $\bar{V}_p$ = 6.41 km/s. Comparison of compressional wave parameters with shear wave data derived from surface wave dispersion models at 51 North American locations indicate an average value for Poisson's ratio of 0.252 for the crust and of 0.273 for the uppermost mantle. Contour maps illustrating lateral variations in crustal thickness, upper mantle velocity and average seismic velocity of the crystalline crust show a number of features which are correlative with geological and tectonic provinces. Comparison of the distribution of seismic parameters with a smoothed free-air anomaly map of North America indicates that a complicated mechanism of isostatic compensation exists for the North American continent. Several features on the seismic contour maps also are correlative with regional magnetic anomalies.

INTRODUCTION

Seismic data have a major role in investigating the nature, composition, and configuration of the continental crust. Knowledge of the seismic properties of the crust has proven useful in studies of such diverse topics as basin development (e.g. Green, 1977), identification of tectonic provinces (e.g. Pakiser and Zietz, 1965), and characterization of geothermal anomalies (Bartelsen _et al_., 1982). A variety of seismic techniques have been employed in these studies, but refraction profiling and measurements of surface wave dispersion are among those methods most commonly employed for regional analyses. In this study, we have compiled refraction and surface wave results for continental North America (latitude 25°N to 60°N) for the purpose of analyzing regional variations in seismic properties of the crust and uppermost mantle and their relation to tectonic features and other geophysical data. Although several aspects of our approach are different, this study can in part be considered an extension and update (our compilation includes previously unpublished results and models published through 1982) of the overviews of Steinhart and Meyer (1961), Herrin and Taggart (1962), Pakiser and Steinhart (1964), Kanasewich (1966), Herrin (1969), Healy and Warren (1969), Warren and Healy (1973), Berry (1973), and Allenby and Schnetzler (1983). The accumulated seismic data provides useful statistics on the seismic properties of the continental crust and contour maps of these properties for the central portion of North America. These mapped variations of seismic properties are correlated with long-wavelength gravity and magnetic anomalies as an aid in their interpretation.

DATA COMPILATION AND PRESENTATION

In our compilation of refraction results, values for the thickness of the crust (H_c), the compressional wave velocity of the uppermost mantle (P_n), and the average compressional wave velocity of the crystalline crust ($\bar{V}_p$) were tabulated. Results for continental shelves were included but no oceanic data were considered. H_c is defined as the thickness of the crust from the surface to the Mohorovicic discontinuity (Moho). The P_n velocity is the velocity of the compressional head wave traveling in the uppermost mantle just beneath the Moho. Although P_n velocities are commonly reported and have been demonstrated to have tectonic significance (e.g. Pakiser and Zietz, 1965), this quantity, when measured by seismic refraction studies, represents limited penetration into the upper mantle. Thus, the P_n velocity values tabulated here may differ from values inferred from earthquake observations and seismic delay time studies (Herrin, 1969; Romanowicz, 1979; Dziewonski and Anderson, 1983) where the propagating paths sample a much larger region of the mantle.

The average velocity of the crust ($\bar{V}_p$) was calculated using the formula:

$$\bar{V}_p = [\sum_{i=1}^{n} h_i \;/\; \sum_{i=1}^{n} (h_i/V_i)]$$

where h_i and V_i are the thickness and velocity, respectively, of the ith layer for an n-layered crust (exclusive of the sedimentary layer). Smithson _et al_. (1981) have shown that $\bar{V}_p$ is an indicator of mean crustal composition.

Crustal models for 139 refraction profiles (Table 1) were compiled. The locations of these profiles are shown in Figures 1a and 1b and the sources are provided in Table 1. Histograms of the results are shown in Figure 2 and statistical summaries of the seismic data are given in

Table 3. The 187 values of H_c have a mean value of 36.21 km; the 154 values of $\bar{V}_p$ have a mean value of 6.411 km/s; the 191 values of P_n have a mean value of 8.030 km/s.

Contour maps of these values were constructed, but a discussion of the limitations of this process seems appropriate first. The discussion which follows is somewhat lengthy and could be interpreted as casting doubt upon the contouring process. This is not our intention, but we do wish to emphasize that care should be taken in interpreting and comparing such maps. Our comments are not intended as criticisms of particular studies (many are our own), but as reminders that logistics, restricted funding, limited numbers of instruments, etc. prevent the collection of an ideal data set.

The most obvious point is that the distribution of profiles is uneven (Figures 1a and 1b). Coverage in the western U.S. is sufficient to give an adequate regional picture in most areas, but coverage is very sparse in the craton. Another consideration is that there are large variations in the quantity and quality of data along individual profiles. In some cases, the station spacing is approximately 3 km while in others the station spacing is over 100 km. Signal-to-noise ratios for individual records is also highly variable. Finally, the data represented on Figure 1 were gathered over a period of three decades when rapid changes in instrumentation and recording technology, as well as interpretational methods, were occurring.

There are several other limitations that generally apply to results of seismic profiling experiments. Anisotrophy may be a factor in regard to P_n velocity determinations (Bamford _et al_., 1979); however, the averaging inherent in the contouring process and the approximately random orientation of the profiles suggest that any effect of anisotropy on regional determinations would be small. Another minor factor with regard to P_n velocities is that most studies assume for seismic modeling procedures that the earth is flat. Most studies do not state whether spherical or flat earth calculations were made. Consideration of a spherical earth would generally reduce the reported P_n velocity values by 0.03 to 0.06 km/s (Black and Braile, 1982). Interpretation techniques assume a one or two-dimensional earth and departures from this idealization can produce observed apparent velocities which vary considerably from the true velocities within the earth. This is particularly true of unreversed refraction profiles. In refraction profiling experiments, velocity determinations involve averaging over considerable horizontal distances; thus the results cannot truly be plotted at a point for contouring. Also, vertical sampling in the earth is seldom uniform. For example, profile 20 (Figure 1) mostly provides information about P_n velocity while profile 241 (Figure 1) mostly provides information about crustal velocity structure. These differences in coverage are primarily due to differences in station spacing, shot-receiver distances along the profiles and numbers and locations of sources. Finally, the problems of velocity inversions (low velocity layer) are well known and may have an effect on H_c and $\bar{V}_p$ determinations.

With all these considerations in mind, the values of H_c, P_n, and $\bar{V}_p$ are contoured in Figures 3, 4 and 5 respectively. Our procedure was to determine the values of H_c, P_n and $\bar{V}_p$ from velocity models presented by various authors listed in Table 1. Inferred sedimentary layers were deleted from the models in the calculation of $\bar{V}_p$ so that the value determined would indicate the average velocity of the crystalline continental crust. For crustal velocity models in which the Moho is inferred to a transition zone with velocity increasing over a small depth range, the depth to the Moho discontinuity was chosen as the center point of this gradient zone and the P_n velocity was selected as the velocity immediately beneath the Moho transition zone. For crustal models along observational profiles for which lateral velocity variation was inferred by the authors, multiple observations of H_c, $\bar{V}_p$ and P_n were tabulated. Because the seismic parameters determined may not be representative of crustal structure at the shotpoint locations, the values of H_c, $\bar{V}_p$, and P_n were initially plotted on a map at locations along the profile inferred to be most representative of the crustal structure. For example, P_n velocities along a reversed seismic refraction profile of several hundred kilometers in length are most representative of the upper mantle velocity near the center of the profile and in general do not necessarily indicate the upper mantle velocity beneath the shotpoint locations. Several seismic refraction profiles have been reinterpreted after the initial crustal model was published. In these cases, we have tried to use the most recent interpretations. Finally, interpretations along the same profile, or on intersecting profiles, or closely spaced observations may be contradictory. In these cases, we have favored the average value as the most representative interpretation. The contours were initially drawn by hand in such a way as to give little weight to major variations based on only one observation and to average discrepant values. Any contouring operation involves subjectivity, and the production of the maps shown as Figures 3, 4, and 5 was certainly no exception. However, our goal was to depict regional variations only. For certain regions where data coverage is sufficient (for example; the Basin and Range Province), a more rigorous contouring procedure could be employed. The hand-drawn contours were digitized at a 2° grid interval in order to allow flexibility in terms of scale and projection and for subsequent comparison with other data sets. The contours shown in Figures 3, 4, and 5 were machine contoured from the gridded data, but vary little from the original contouring. However, because of the 2° grid and machine contouring individual small-scale features in the contour maps may be smoothed and slightly displaced in location. Although no attempt is made to display the reliability of the data on the contour maps, a comparison of the contour data with the spatial distribution of observations (Figure 1b) provides an approximate indication.

No discussion of the seismic properties of the crust is really complete without considering shear waves. Several profiling experiments have deployed horizontal seismometers in an effort to record shear wave arrivals. To date, these efforts have met with limited success and are very limited in coverage (e.g. Braile et al., 1974; Keller et al., 1975) and are not enough of a factor to consider in this study. A significant body of information on shear wave velocity structure is available from studies of surface wave dispersion. These studies primarily concern Rayleigh waves which are most sensitive to shear wave velocity although they are also slightly affected by variations in density and compressional wave velocity (Der et al., 1970).

A variety of techniques have been employed to determine dispersion across arrays of three or more stations, between two stations, or between the source and a single station (see Kovach (1978) and Dziewonski and Hales (1972) for reviews of surface wave concepts and techniques). Earth models determined from such studies represent averages across the array, between two stations, or along the propagation path from a single station to the source. We have compiled the results from the dispersion studies shown on Figure 1a and tabulated them in Table 2. The points at which these results were plotted (Figure 1a) are the center of the array or the midpoint of the propagation path. We were able to determine 51 values of H_c' (thickness of the crust from shear wave data), 49 values of S_n (upper mantle shear wave velocity), and 51 values of $\bar{V}_s$ (average shear wave velocity of the crystalline crust). Note that the S_n velocity used here is derived from surface wave dispersion experiments and represents an average value of upper mantle shear wave velocity reflecting velocity structure over a considerable depth extent of the upper mantle. Uppermost mantle seismic shear wave velocity from refraction experiments would determine the velocity of the critically refracted head wave propagating just below the Moho discontinuity and could be distinctly different from the S_n velocity determined from surface wave dispersion modeling. In order to compare the compressional wave and shear wave results, the contours in Figures 3, 4, and 5 were interpolated to provide values of H_c, P_n, and $\bar{V}_p$ at the points on Figure 1 where values H_c', S_n and $\bar{V}_s$ were available. There are several limitations to this procedure, but since the experiments involved do not spatially coincide, some type of interpolation was required.

The values of H_c and H_c' are compared in Figure 6. If all the corresponding values of H_c and H_c' agreed, they would fall on the diagonal line across Figure 6. There is considerable scatter which is to be expected considering the interpolation required, but the means of the values of H_c and H_c' are very close (36.21 km and 37.48 km respectively).

A major goal of the shear wave velocity compilation was to obtain information on Poisson's ratio values in the crust and upper mantle. Thus Figure 7 was prepared in which corresponding pairs of $\bar{V}_p$ and $\bar{V}_s$ values are plotted as dots and corresponding pairs of P_n and S_n values are plotted as solid triangles. These data are plotted in two groups and indicate a mean Poisson's ratio for the crust (σ_c) of 0.252 and a mean Poisson's ratio for the upper mantle (σ_m) of 0.273 for continental North America. These observations support the commonly-assumed simplification of $\sigma = 0.25$ for seismic calculations and suggest that Poisson's ratio is slightly greater in the upper mantle than the continental crust.

REGIONAL VARIATIONS IN SEISMIC PROPERTIES OF THE CRUST AND UPPER MANTLE

A number of prominent regional variations in the crust and upper mantle structure and seismic velocity are visible on the contour maps shown in Figures 3, 4 and 5. The major features which are evident are generally consistent with those identified by previous workers. For example, Pakiser and Steinhart (1964) and, more recently, Allenby and Schnetzler (1983). Correlation of these regional variations in seismic properties with principal tectonic and geologic elements of the North American continent is facilitated by comparison of the contour maps with the tectonic and province map shown at the same scale in Figure 9. Examples are:

1) P_n velocity and crustal thickness are distinctly different between the western part of North America and the eastern part of North America. Generally, thin crust and low upper mantle velocity are characteristic of the North American continent west of the Rocky Mountains whereas relatively thick crust and higher upper mantle velocities characterize the craton.
2) Crustal thickness, P_n velocity and average velocity of the crystalline crust are all higher than average for the craton. A crustal thickness of approximately 42 km, P_n velocity of approximately 8.1 km/s and average crustal velocity of 6.5 km/s are characteristic of eastern North America.
3) The Basin and Range Province in the western part of the United States is one of the most anomalous regions in continental North America in terms of crustal seismic properties. Both a very thin crust and anomalously low upper mantle velocities are evident.

4) There is a general correlation between the distribution of P_n velocities and crustal thickness. Higher P_n velocities are usually associated with thicker crust.

5) Crustal structure on the Pacific and Atlantic continental margins are distinctly different. The crust thins gradually toward the oceanic plate and is underlain by normal velocity upper mantle for the Atlantic continental margin. In contrast, the crustal thickness at the Pacific continental margin is complicated by the presence of adjacent mountain ranges and is largely underlain by lower velocity upper mantle.

6) There appears to be no simple relationship between crustal thickness and regional topography. Many areas show relatively large crustal thickness without a corresponding regional elevation high. Similarly areas such as the Basin and Range Province, which has a regionally high elevation, are underlain by thin crust. An exception to these observations is the Sierra Nevada Mountain Range in which prominent mountain 'roots' are present.

Because of the addition of new data in the compilation of crust and upper mantle seismic properties and differences in analysis procedures from previous studies, several features are evident on the seismic properties contour maps (Figures 3, 4 and 5) which have not previously been described. Examples are:

1) The distribution of average crustal velocity as shown in Figure 5 has not been previously analyzed. Pakiser and Robinson (1966, 1967) and Smithson _et al_. (1981) have discussed the importance of seismic velocity of the crystalline rocks as an indicator of crustal composition. Smithson _et al_. note that the average velocity of the crust is an important parameter for interpreting

average crustal composition and understanding the genesis of the continental crust. The average seismic velocity of the crust throughout North America shows several prominent anomalies correlative with geologic features. The Basin and Range Province and Rio Grande Rift, where low average crustal velocities are evident, are perhaps the most prominent features seen on Figure 5. In addition, high average seismic velocities of the crust are present beneath the Williston Basin in the northern Great Plains and a region in the southeastern portion of the United States which roughly corresponds to the upper Mississippi Embayment and Southern Oklahoma Aulacogen. Distinct differences in average seismic velocity of the crust are also evident between Pacific and Atlantic continental margins. The Atlantic continental margin is particularly interesting in that the average crustal velocity decreases gradually towards the ocean suggesting the presence of a transitional continental to oceanic crust. The Snake River Plain in the western United States also shows up as a distinct anomaly in average seismic velocity of the crust. Several more subtle features are also evident which may correlate with regional geologic trends. For example, the small lows in average seismic velocity in the Pacific Northwest and upper Great Lakes region and the relative high in average seismic velocity over Grenville terrain in eastern Canada.

2) Our compilation includes a more recent and complete list of crustal seismic refraction data than previous workers and thus several areas of the maps are now more clearly defined. However, our analysis procedure in which 'single-point anomalies' and 'discrepant points' were given little weight in the contouring,

result in some differences in our maps from those presented by Allenby and Schnetzler. The most prominent differences are located in eastern Washington and in Mississippi where strong mantle upwarps are inferred by Allenby and Schnetzler based on limited data.

3) An interesting correlation of seismic properties is noted in the Williston Basin area of the upper Great Plains in which thick crust, high P_n velocity and large average seismic velocity of the crust all correlate. Basins associated with the Southern Oklahoma Aulacogen and Mississippi Embayment also display a similar, but less pronounced correlation of seismic properties.
4) A weakly defined east-west trending low in P_n velocity is associated with midwestern United States.

COMPARISON OF SEISMIC PROPERTIES WITH REGIONAL GRAVITY AND MAGNETIC ANOMALY MAPS

Regional gravity and magnetic anomaly maps are shown in Figures 9, 10 and 11 for comparison with the distribution of seismic properties illustrated in the contour maps (Figures 3, 4 and 5). The smoothed free-air gravity anomaly map (Figure 9) is approximately an isostatic anomaly map. There is no obvious relationship between the variations in crustal properties and the isostatic condition of the continental crust as reflected in the smoothed free-air gravity map. For example, several areas of relatively high average seismic velocity (and therefore presumably high average density) of the crust are roughly in isostatic balance at least partially due to crustal thickening beneath these higher density zones. Thus, the mechanism of isostatic balance for the North American continent appears to correspond to neither the Pratt nor the Airy hypothesis. Both lateral variations in density (as inferred from average seismic velocity) and crustal thickness contribute to the attainment of isostatic balance. Additionally, the position of the Moho discontinuity, while certainly affecting isostatic balance, does not provide the only mechanism for compensation. For example, in the Basin and Range Province (an area of relatively high elevation) a thin crust and therefore a mantle upwarp is compensated by the combined effects of relatively low density crust and low velocity (and presumably low density) upper mantle. Thus although the mechanism of isostatic compensation for the North American continent must involve lateral variations in density in both the crust and upper mantle and differences in crustal thickness, the compilations of crustal seismic properties presented here will provide for a useful comparison with regional gravity anomaly maps and density models to more quantitatively define the isostatic balance of the continent.

Regional magnetic anomaly maps of portions of the North American continent are shown in Figures 10 and 11. Figure 10 illustrates a reduced to radial polarization satellite magnetic anomaly map corresponding to an elevation of 450 km obtained from POGO data. Figure 11 shows a smoothed total field magnetic intensity anomaly map utilizing the U.S. NOO magnetic survey. The wavelength character of the two maps is distinctly different with the satellite map corresponding to more regional features and the NOO map indicating more local sources. The subdued character of the magnetic anomalies west of the Rocky Mountains (as noted by a number of investigators) correlates with the anomalous seismic properties of thin crust and low upper mantle seismic velocity and is probably a temperature effect. The most prominent correlation of the long-wavelength magnetic anomalies as illustrated by the satellite magnetic map is with the high average seismic velocity of the crust in the south-central portion of the United States which trends roughly east-west and correlates with the prominent east-west magnetic anomaly. The weakly defined low in upper mantle velocity in the midwest United States also roughly correlates with this strong east-west long-wavelength magnetic anomaly.

DISCUSSION AND CONCLUSIONS

The compilation of seismic properties of the crust and upper mantle for the North American continent provides important information on the distribution of physical properties of the upper continental lithosphere which can be used to correlate with other geophysical and geological features. A number of prominent correlations have been noted. New information which has been presented here includes an updated and more complete set of seismic refraction profile data, an analysis of Poisson's ratio in the crust and upper mantle based on a compilation of shear wave velocity models from surface wave dispersion experiments and subsequent comparison with the compressional wave data and a comparison of the seismic properties with gravity and magnetic anomaly data.

Although a number of observations and correlations concerning the distribution of seismic properties of the continental crust and relationships to potential field data have been made in this paper, many interesting questions arise from this qualitative view of these regional data. For example:

1) What is the cause of the regional variations in seismic properties? Black and Braile (1982) present evidence to suggest that temperature in the earth's mantle may be a primary control on the upper mantle P_n velocity and thus may account for the regional variations observed in Figure 4. Smithson *et al*. (1981) suggest that average seismic velocity of the crust is an indicator of average crustal composition and may be used to infer growth of the craton. However,

the pattern of regional variations in average seismic velocity of the crust, as shown in Figure 5, is complex and requires further study.

2) The difference in crustal structure associated with the Pacific and Atlantic continental margins suggests fundamental variations due to the differences in plate interactions at those margins. For example, the Atlantic continental margin represents a trailing edge of the continental crust and the gradual thinning and decrease in average seismic velocity of the crust toward the oceanic plate is an indication of a transitional continent to ocean crust. However, the mechanism and timing of the formation of this transitional crust (which requires a pronounced silicification in addition to thinning) is presently not know.

3) The combination of distribution of seismic properties in the crust and upper mantle and long-wavelength free-air gravity anomaly data provides important data for an analysis of the mechanisms of isostatic compensation for continental regions. However, it is clear that this mechanism involves both lateral density changes in the crust and upper mantle as well as variations in the depth to the Moho discontinuity.

4) Prominent lithospheric anomalies such as the Basin and Range Province in the western United States require explanation. It is well known that the Basin and Range represents an area of major Cenozoic crustal extension. However, any simple model of extension involving brittle failure (faulting) in the upper crust and ductile flow in the lower crust does not account for the prominent low in average seismic velocity in the crust. Some mechanism of thinning of the lower crust more than the

upper crust during stretching, 'subcrustal erosion', or addition of low velocity material to the upper crust is necessary in order to explain the anomalous seismic properties.

5) Although the craton displays relatively stable crustal seismic parameters with a crustal thickness of about 42 km and upper mantle P wave velocity of about 8.1 km/s and an average seismic velocity of the crust of about 6.5 km/s, some local variations in these properties are observed and the most prominent of them tend to be associated with areas of Phanerozoic basin development. A mechanism to explain this densification, thickening of the crust and subsequent basin development is needed.

In this paper, we have analyzed a large volume of crustal seismic velocity data and qualitatively compared the distribution of seismic parameters in the continental crust to geologic, tectonic and other geophysical features. These comparisons provide interesting correlations and patterns which aid in our understanding of the nature and development of the continent. However, perhaps the most important contributions of this paper is the presentation of data which warrant more quantitative analysis and which raise interesting questions concerning the origin and evolution of the continental crust.

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REFERENCES

Allenby, R.J. and C. Schnetzler, United States crustal thickness, Tectonophysics, 93, 13-31, 1983.

Austin, C.B. and G.R. Keller, A crustal structure study of the Northern Mississippi Embayment, U.S. Geol. Surv. Prof. Paper 1236, 83-93, 1982.

Baldwin, J.L., A crustal seismic refraction study in Southwestern Indiana and Southern Illinois, M.S. thesis, Purdue Univ., West Lafayette, IN, 1980.

Bamford, D., Refraction data in western Germany - A time-term interpretation, Z. Geophys., 39, 907-927, 1973.

Bamford, D., M. Jentsch, and C. Prodehl, P_n anisotropy in northern Britain and the eastern and western United States, Geophys. J.R. Astron. Soc., 57, 397-429, 1979.

Barr, K.G., Crustal refraction experiment: Yellowknife 1966, J. Geophys. Res., 76, 1929-1948, 1971.

Barrett, D.L., M. Berry, J.E. Blanchard, M.J. Keen and R.E. McAllister, Seismic studies on the eastern seaboard of Canada: The Atlantic coast of Novia Scotia, Can. J. Earth Sci., 1, 10-22, 1964.

Bartelsen, H., E. Lueschen, Th. Krey, R. Meissner, H. Schmoll and Ch. Walter, The combined seismic reflection-refraction investigation of the Urach geothermal anomaly, in The Urach Project, Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 237-262, 1982.

Bates, A., and D.H. Hall, Upper mantle structure in southern Saskatchewan and western Manitoba from project Edzoe, Can. J. Earth Sci., 12, 2134-2144, 1975.

Bennett, G.T., R.M. Clowes and R.M. Ellis, A seismic refraction survey along the southern Rocky Mountain trench, Canada, Bull. Seismol. Soc. Am., 65, 37-54, 1975.

Berg, J.W., Jr., K.L. Cook, H.D. Narans, Jr., and W.M. Dolan, Seismic investigation of crustal structure in the eastern part of the Basin and Range Province, Bull. Seismol. Soc. Am., 50, 511-535, 1960.

Berg, J.W., Jr., L. Trembly, D.A. Emilia, J.R. Hutt, J.M. King, L.T. Long, W.R. McKnight, S.K. Sarmah, R. Souders, J.V. Thiruvathukal, and D.A. Vossler, Crustal refraction profile, Oregon coast range, Bull. Seismol. Soc. Am., 56, 1357-1362, 1966.

Berry, M.J. and D.A. Forsyth, Structure of the Canadian Cordillera from seismic refraction and other data, Can. J. Earth Sci., 12, 182-208, 1975.

Berry, M.J. and K. Fuchs, Crustal structure of the Superior and Grenville provinces of the northeastern Canadian shield, Bull. Seismol. Soc. Am., 63, 1393-1432, 1973.

Berry, M.J., Structure of the crust and upper mantle in Canada: Tectonophysics, 20, 183-201, 1973.

Berry, M.J. and G.F. West, A time-term interpretation of the first-arrival data of the 1963 Lake Superior experiment, in The Earth Beneath the Continents, Geophys. Monogr. Ser., Vol. 10, edited by J.S. Steinhart and T.J. Smith, 166-180, AGU, Washington, DC, 1966.

Black, P.R. and L.W. Braile, P_n velocity and cooling of the continental lithosphere, J. Geophys. Res., 87, 10,557-10,568, 1982.

Bodnar, C.A., Crustal structure of the great plains of North America from Rayleigh wave analysis, M.S. thesis, Univ. of Texas at El Paso, El Paso, TX, 62 pp., 1982.

Braile, L.W., R.B. Smith, G.R. Keller, R.M. Welch and R.P. Meyer, Crustal structure across the Wasatch Front from detailed seismic refraction studies, J. Geophys. Res., 79, 2669-2766, 1974.

Braile, L.W., R.B. Smith, J. Ansorge, M.R. Baker, M. Sparlin, C. Prodehl, M.M. Schilly, J.H. Healy, St. Mueller and K.H. Olsen, The Yellowstone-Snake River Plain seismic profiling experiment: Crustal structure of the eastern Snake River Plain, J. Geophys. Res., 87, 2597-2609, 1982.

Carder, D.S., Trans-California seismic profile, Death Valley to Monterey Bay, Bull. Seismol. Soc. Am., 63, 571-586, 1973.

Carder, D.S., A. Qamar and T.V. McEvilly, Trans-Calfornia seismic profile Pahute Mesa to San Francisco Bay, Bull. Seismol. Soc. Am., 60, 1829-1846, 1970.

Chandra, N.N. and G.L. Cumming, Seismic refraction studies in Western Canada, Can. J. Earth Sci., 9, 1099-1109, 1972.

Clee, T.E., K.G. Barr and M.J. Berry, Fine structure of the crust near Yellowknife, Can. J. Earth Sci., 11, 1534-1549, 1974.

Cohen, T.J. and R.P. Meyer, The midcontinent gravity high: Gross crustal structure, in The Earth Beneath the Continents, Geophys. Monogr. Ser., Vol. 10, edited by J.S. Steinhart and T.J. Smith, 141-165, AGU, Washington, DC, 1966.

Cram, I.H., Jr., Crustal structure refraction survey in South Texas, Geophysics, 26, 560-573, 1961.

Der, Z., R. Masse and M. Landisman, Effects of observational errors on the resolution of surface waves at intermediate distances, J. Geophys. Res., 75, 3399-3409, 1970.

Diment, W.H., S.W. Stewart and J.C. Roller, Crustal structure from the Nevada test site to Kingman, Arizona, from seismic and gravity observations, J. Geophys. Res., 66, 201-213, 1961.

Dorman, J., J.L. Worzel, R. Leyden, T.N. Cook, and M. Hatziemmanuel, Crustal section from seismic refraction measurements near Victoria, Texas, *Geophysics*, *37*, 225-236, 1972.

Douglas, R.J.W., and R.A. Price, Nature and significance of variations in tectonic styles in Canada, in *Variations in Tectonic Styles in Canada*, *Geol. Soc. Canada Spec. Pap. 11*, edited by R.A. Price and R.J.W. Douglas, 625-688, 1972.

Dziewonski, Adam M. and Don L. Anderson, Travel times and station corrections for P waves at teleseismic distances: *Geophys. Res.*, *88*, 3295-3314, 1983.

Dziewonski, A.M. and A.L. Hales, Numerical analysis of dispersed seismic waves, *Methods in Computational Physics*, *11*, 39-85, 1972.

Eaton, J.P., Crustal structure from San Francisco, California to Eureka, Nevada, from seismic-refraction measurements, *J. Geophys. Res.*, *68*, 5789-5806, 1963.

Eaton, J.P., Crustal structure in northern and central California from seismic evidence in geology of northern California, *Calif. Div. Mines Geol. Bull.*, *190*, 419-426, 1966.

Ewing, M., D.B. Worzel, Ericson and B.C. Heezen, Geophysical and geological investigations in the Gulf of Mexico, Part I, *Geophysics*, *20*, 1-18, 1955.

Ewing, G.N., A.M. Dainty, J.E. Blanchard and M.J. Keen, Seismic studies on the eastern seaboard of Canada: The Appalachian system I, *Can. Earth Sci.*, *3*, 89-109, 1966.

Fenneman, N.M., Physical divisions of the United States, U.S. Geological Survey Map, scale 1:7,000,000, 1946.

Forsyth, D.A., M.J. Berry and R.M. Ellis, A refraction survey across the Canadian Cordillera at 54°N, *Can. Earth Sci.*, *11*, 533-548, 1974.

Gibbs, J.F. and J.C. Roller, Crustal structure determined by seismic-refraction measurements between the Nevada test site and Ludlow, California, *U.S. Geol. Survey Prof. Pap., 550-D*, D-125-D-131, 1966.

Gish, D.M., G.R. Keller and M.L. Sbar, A refraction study of deep crustal structure in the basin and range: Colorado plateau of eastern Arizona, *J. Geophys. Res.*, *86*, 6029-6038, 1981.

Green, A.G., O.G. Stephenson, G.D. Mann, E.R. Kanasewich, G.L. Cumming, Z. Hajnal, J.A. Mair, and G.F. West, Cooperative seismic surveys across the Superior-Churchill boundary zone in southern Canada, *Can. J. Earth Sci.*, *17*, 617-632, 1980.

Green, A.R., The evolution of the earth's crust and sedimentary basin development, in J.G. Heacock (editor): *The Earth's Crust Its Nature and Physical Properties*, *Geophys. Monogr. 20*, AGU, Washington, DC, 1-17, 1977.

Hales, A.L. and J.B. Nation, A seismic refraction survey in the northern Rocky Mountains: More evidence for an intermediate crustal layer, Geophys. J.R. Astron. Soc., 35, 381-399, 1973.

Hales, A.L., C.E. Helsey, J.J. Dowling and J.B. Nation, The east coast onshore-offshore experiment 1, The first arrival phases, Bull. Seismol. Soc. Am., 58, 757-819, 1968.

Hales, A.L., C.E. Helsey and J.B. Nation, Crustal structure study on Gulf Coast of Texas, Am. Assoc. Petrol. Geol. Bull., 54, 2040-2057, 1970.

Hall, D.H. and Z. Hajnal, Crustal structure of northwestern Ontario: Refraction-seismology, Can. J. Earth Sci., 6, 81-99, 1969.

Hall, D.H. and Z. Hajnal, Deep seismic crustal studies in Manitoba, Bull. Seismol. Soc. Am., 63, 883-910, 1973.

Hamilton, R.M., A. Ryall and E. Berg, Crustal structure southwest of the San Andreas fault from quarry blasts, Bull. Seismol. Soc. Am., 54, 67-77, 1964.

Healy, J.H. and D.H. Warren, Explosion seismic studies in North America, in P.J. Hart (editor): The Earth's Crust and Upper Mantle, Geophys. Monogr. 13, AGU, Washington, DC, 208-220, 1969.

Healy, J.H., Crustal structure along the coast of California from seismic-refraction measurements, J. Geophys. Res., 68, 5777-5787, 1963.

Herrin, E., Regional variations of P-wave velocity in the upper mantle beneath North America, in P.J. Hart (editor): The Earth's Crust and Upper Mantle, Geophys. Monogr. 13, AGU, Washington, DC, 242-246, 1969.

Herrin, E. and J. Taggart, Regional variations in Pn velocity and their effect on the location of epicenters, Bull. Seismol. Soc. Am., 52, 1037-1046, 1962.

Hersey, J.B., E.T. Bunce, R.F. Wyrick and T.F. Dietz, Geophysical investigation of the continental margin between Cape Henry, Virginia and Jacksonville, Florida, Geol. Soc. Am. Bull., 70, 437-465, 1959.

Hill, D.P., and L.C. Pakiser, Crustal structure between the Nevada test site and Boise, Idaho, from seismic-refraction measurements, in The Earth Beneath the Continents, Geophys. Monogr. Ser., Vol. 10, edited by J.S. Steinhart and T.J. Smith, 391-419, AGU, Washington, DC, 1966.

Hill, D.P., Crustal and upper mantle structure of the Columbia plateau from long range seismic-refraction measurements, Geol. Soc. Am. Bull., 83, 1639-1648, 1972.

Hobson, G.D., A. Overton, D.N. Clay and W. Thatcher, Crustal structure under Hudson Bay, Can. J. Earth Sci., 4, 929-947, 1967.

Hodgson, J.H., A seismic survey in the Canadian Shield, 1, Refraction studies based on rock-bursts at Kirkland Lake, Ontario, *Publ. Dom. Obs. Ottawa*, *16*, 111-163, 1953.

Jackson, W.H., S.W. Stewart and L.C. Pakiser, Crustal structure in eastern Colorado from seismic-refraction measurements, *J. Geophys. Res.*, *68*, 5767-5776, 1963.

Jackson, W.H. and L.C. Pakiser, Seismic study of crustal structure in the southern Rocky Mountains, *U.S. Geol. Survey Prof. Pap. 525-D*, D-85-D-92, 1965.

James, D.W., T.J. Smith and J.S. Steinhart, Crustal structure of the middle Atlantic states, *J. Geophys. Res.*, *73*, 1983-2007, 1968.

Johnson, L.R., Crustal structure between Lake Mead, Nevada and Mono Lake, California, *J. Geophys. Res.*, *70*, 2863-2872, 1965.

Johnson, S.H. and R.W. Couch, Crustal structure in the North Cascade Mountains of Washington and British Columbia from seismic refraction measurements, *Bull. Seismol. Soc. Am.*, *60*, 1259-1269, 1970.

Johnson, S.H., R.W. Couch, M. Gemperle and E.R. Banks, Seismic refraction measurements in southeast Alaska and western British Columbia, *Can. J. Earth Sci.*, *9*, 1756-1765, 1972.

Kanasewich, E.R., Deep crustal structure under the plains and Rocky Mountains, *Can. J. Earth Sci.*, *3*, 937-946, 1966.

Katz, S., Seismic study of crustal structure in Pennsylvania and New York, *Bull. Seismol. Soc. Am.*, *44*, 303-325, 1954.

Keller, G.R., R.B. Smith and L.W. Braile, Crustal structure along the Great Basin-Colorado Plateau transition from seismic refraction studies, *J. Geophys. Res.*, *80*, 1093-1097, 1975.

Keller, G.R., L.W. Braile and P. Morgan, Crustal structure, geophysical models in contemporary tectonism of the Colorado Plateau, *Tectonophysics*, *61*, 131-147, 1979.

Keller, G.R., L.W. Braile and J.W. Schlue, Regional crustal structure of the Rio Grande Rift from surface wave dispersion measurements, in *Rio Grande Rift: Tectonics & Magmatism*, edited by R.E. Riecker, 115-126, AGU, Washington, DC, 1979.

Kovach, R.L., Seismic surface waves and crustal and upper mantle structure, *Reviews Geophys. Space Phys.*, *16*, 1-13, 1978.

Langston, C.A. and D.V. Helmberger, Interpretation of body and Rayleigh waves from NTS to Tucson, *Bull. Seismol. Soc. Am.*, *64*, 1919-1929, 1974.

Losee, B.A., Rayleigh-wave dispersion applied to the lithospheric structure in Canada, M.S. thesis, Purdue Univ., West Lafayette, IN, 85 pp., 1980.

Lyons, J.A., D.A. Forsyth and J.A. Mair, Crustal studies in the La Malbaie Region Quebec, Can. J. Earth Sci., 17, 478-490, 1980.

Martin, W.R., A seismic refraction study of the northeastern basin and range and its transition with the eastern Snake River plain, M.S. thesis, Univ. of Texas, El Paso, 1978.

McCamy, K. and R.P. Meyer, A correlation method of apparent velocity measurement, J. Geophys. Res., 69, 691-699, 1964.

McCamy, K. and R.P. Meyer, Crustal results of fixed multiple shots in the Mississippi Embayment, in The Earth Beneath the Continents, Geophys. Monogr. Ser., Vol. 10, edited by J.S. Steinhart and T.J. Smith, 166-180, AGU, Washington, DC, 1966.

Mereu, R.F. and J.A. Hunter, Crustal and upper mantle under the Canadian shield from project early rise data, Bull. Seismol. Soc. Am., 59, 147-165, 1969.

Mereu, R.F. and G. Jobidon, A seismic investigation of the crust and Moho on a line perpendicular to the Grenville Front, Can. J. Earth Sci., 8, 1553-1583, 1971.

Mereu, R.F., S.C. Majumdar and R.E. White, The structure of the crust and upper mantle under the highest ranges of the Canadian Rockies from a seismic refraction survey, Can. J. Earth Sci., 14, 196-208, 1976.

Merkel, R.H. and S.S. Alexander, Use of correlation analysis to interpret continental margin ECOOE refraction data, J. Geophys. Res., 74, 2683-2697, 1969.

Mitchell, B.J. and M. Landisman, Geophysical measurements in the southern great plains, in The Structure and Physical Properties of the Earth's Crust, Geophys. Monogr. Ser., Vol. 14, edited by J.G. Heacock, 77-93, AGU, Washington, DC, 1971.

Mueller, S. and M. Landisman, An example of the unified method of interpretation for crustal seismic data, Geophys. J.R. Astron. Soc., 23, 365-371, 1971.

Olsen, K.H., G.R. Keller and J.N. Stewart, Crustal structure along the Rio Grande Rift from seismic refraction profiles, in Rio Grande Rift: Tectonics and Magmatism, edited by R.E. Riecker, 127-143, AGU, Washington, DC, 1979.

Pakiser, L.C., Structure of the crust and upper mantle in the western United States, J. Geophys. Res., 68, 5747-5756, 1963.

Pakiser, L.C. and J.S. Steinhart, Explosion seismology in the western hemisphere, in Research in Geophysics, 2, Solid Earth and Interface Phenomena, edited by J. Odishaw, 123-142, MIT Press, Cambridge, MA, 1964.

Pakiser, L.C. and I. Zietz, Transcontinental crustal and upper-mantle structure, Rev. Geophys., 3, 505-520, 1965.

Pakiser, L.C. and R. Robinson, Composition of the continental crust as estimated from seismic observations in J.S. Steinhart and T.J. Smith (editors): The Earth Beneath the Continents, Geophys. Monogr. 10, AGU, Washington, DC 620-626, 1966.

Pakiser, L.C. and R. Robinson, Composition and evolution of the continental crust as suggested by seismic observations, Tectonophysics, 3, 547-557, 1966.

Peselnick, L., J.P. Lockwood and R.M. Stewart, Anisotropic elastic velocities of some upper mantle xenoliths underlying the Sierra Nevada batholith, J. Geophys. Res., 82, 2005-2010, 1977.

Press, F., Crustal structure in the California-Nevada Region, J. Geophys. Res., 65, 1039-1051, 1960.

Prodehl, C., Crustal structure of the western United States, U.S. Geol. Surv. Prof. Pap. 1034, 1979.

Prodehl, C. and L.C. Pakiser, Crustal structure of the southern Rocky Mountains from seismic measurements, Geol. Soc. Am. Bull., 91, 147-155, 1980.

Richards, T.C. and D.J. Walker, Measurement of the thickness of the earth's crust in the Albertan plains of western Canada, Geophysics, 24, 262-284, 1959.

Roller, J.C., Crustal structure in the vicinity of Las Vegas, Nevada from seismic and gravity observations, U.S. Geol. Surv. Prof. Pap. 475-D, D108-D111, 1964.

Roller, J.C., Crustal structure in the eastern Colorado Plateaus province from seismic-refraction measurements, Bull. Seismol. Soc. Am., 55, 107-119, 1965.

Roller, J.C. and J.H. Healy, Seismic-refraction measurements of crustal structure between Santa Monica Bay and Lake Mead, J. Geophys. Res., 68, 5837-5849, 1963.

Roller, J.C., and W.H. Jackson, Seismic-wave propagation in the upper mantle: Lake Superior Wisconsin to Denver, Colorado, in The Earth Beneath the Continents, Geophys. Monogr. Ser., Vol. 10, edited by J.S. Steinhart and T.J. Smith, 270-275, AGU, Washington, DC, 1966.

Romanowicz, B.A., Seismic structure of the upper mantle beneath the United States by three-dimensional inversion of body wave arrival times, Geophys. J.R. Astron. Soc., 57, 479-506, 1979.

Romney, C., B.G. Brooks, R.H. Mansfield, D.S. Carder, J.N. Jordan and D.W. Gordon, Travel times and amplitudes of principal body phases recorded from Gnone, Bull. Seismol. Soc. Am., 52, 1057-1074, 1962.

Russell, David, Constrained inversion techniques applied to surface wave analysis, Unpublished M.S. thesis, Univ. of Texas, El Paso, 1980.

Ryall, A. and D.J. Stuart, Travel times and amplitudes from nuclear explosions, Nevada test site to Ordway, Colorado, J. Geophys. Res., 68, 5821-5835, 1963.

Sexton, J.L., W.J. Hinze, R.R.B. von Frese and L.W. Braile, Long-wavelength aeromagnetic anomaly map of the conterminous United States, Geology, 10, 364-369, 1982.

Shor, G.G., Jr., Seismic refraction studies off the coast of Alaska: 1956-1957, Bull. Seismol. Soc. Am., 52, 37-57, 1962.

Shor, G.G., Jr., P. Dehlinger, H.D. Kirk and W.S. French, Seismic refraction studies off Oregon and Northern California, J. Geophys. Res., 73, 2175-2194, 1968.

Sinno, Y.A., G.R. Keller and M.L. Sbar, A crustal seismic refraction study in west-central Arizona, J. Geophys. Res., 86, 5023-5038, 1981.

Slichter, L.B., Crustal structure in the Wisconsin area, Rep. N9, ONR86200, Office of Naval Research, Arlington, VA, 1951.

Smith, R.B., M.M. Schilly, L.W. Braile, J. Ansorge, J.L. Lehman, M.R. Baker, C. Prodehl, J.H. Healy, St. Mueller and R.W. Greensfelder, The 1978 Yellowstone-Eastern Snake River Plain seismic profiling experiment: Crustal structure of the Yellowstone region and experiment design, J. Geophys. Res., 87, 2583-2596, 1982.

Smith, R.B., L.W. Braile and G.R. Keller, Upper crustal low-velocity layers, a possible effect of high temperatures over a mantle upwarp at the Basin and Range - Colorado Plateau transition, Earth Planet. Sci. Lett., 28, 197-204, 1975.

Smithson, S.B., R.A. Johnson and Yun K. Wong, Mean crustal velocity: A critical parameter for interpreting crustal structure and crustal growth: Earth Planet. Sci. Lett., 53, 323-332, 1981.

Sparlin, M.A., L.W. Braile and R.B. Smith, Crustal structure of the Eastern Snake River Plain determined from ray-trace modeling of seismic refraction data, J. Geophys. Res., 87, 2619-2633, 1982.

Stauber, D.A. and D.M. Boore, Crustal thickness in northern Nevada from seismic refraction studies, Bull. Seismol. Soc. Am., 68, 1049-1058, 1978.

Steinhart, J.S. and R.P. Meyer, Explosion studies of continental structure, Carnegie Inst. Washington Publ. 622, 1961.

Steinhart, J.S. and R.P. Meyer, Explosion studies of continental structure, Carnegie Inst. Washington Pub. 622, 409 pp., 1961.

Steinhart, J.S., Z. Suzuki, T.J. Smith, L.T. Aldrich and I.S. Sacks, Explosion seismology, Year Book Carnegie Inst. Washington, 63, 311-319, 1964.

Stewart, S.W., Crustal structure in Missouri by seismic-refraction methods, Bull. Seismol. Soc. Am., 58, 291-323, 1968a.

Stewart, S.W., Preliminary comparison of seismic travel times and inferred crustal structure adjacent to the San Adreas Fault in the Diablo and Gabilan Ranges of Central California, in Geologic Problems of San Andreas Fault System Conference Proceedings, edited by W.R. Dickinson, Publ. Geol. Sci. 11, 218-230, Stanford Univ., Stanford, CA, 1968b.

Toppozada, T.R. and A.R. Sanford, Crustal structure in central New Mexico interpreted from the Gasbuggy explosion, Bull. Seismol. Soc. Am., 66, 877-886, 1976.

Tuve, M.A., The earth's crust, Year Book Carnegie Inst. Washington, 50, 69-73, 1951.

Tuve, M.A., The earth's crust, Year Book Carnegie Inst. Washington, 52, 103-108, 1953.

Tuve, M.A., The earth's crust, Year Book Carnegie Inst. Washington, 53, 51-55, 1954.

von Frese, R.R.B., W.J. Hinze and L.W. Braile, Regional North American gravity and magnetic anomaly correlations, Geophys. J.R. Astron. Soc., 69, 745-761, 1982.

Warren, D.H., Transcontinental geophysical survey (35'-39'N) seismic refraction profiles of the crust and upper mantle, U.S. Geol. Surv. Maps I-532-D, I-533-D, I-534-D, and I-535-D, 1968.

Warren, D.H. and J.H. Healy, Structure of the crust in the conterminous United States, Tectonophysics, 20, 203-213, 1973.

Warren, D.H., Seismic-refraction survey of crustal structure in central Arizona, Geol. Soc. Am., 80, 257-282, 1969.

Warren, D.H. and W.H. Jackson, Surface seismic measurements of the project Gasbuggy explosion at intermediate distance ranges, U.S. Geol. Surv. Open File Rep. 1023, 1968.

Warren, D.H., J.H. Healy and W.H. Jackson, Crustal seismic measurements in southern Mississippi, J. Geophys. Res., 71, 3437-3458, 1966.

Warren, D.H., J.H. Healy, J. Bohn and P.A. Marshall, Crustal calibration of the large aperture seismic array (LASA), Montant, U.S. Geol. Surv. Open File Rep. 1671, 1972.

White, W.R.H. and J.C. Savage, Seismic refraction and gravity study of the earth's crust in British Columbia, Bull. Seismol. Soc. Am., 55, 463-486, 1965.

Willden, R., Seismic-refraction measurements of crustal structure beneath American Falls Reservoir, Idaho, and Flaming Gorge Reservoir, Utah, U.S. Geol. Surv. Prof. Pap. 525-C, C-44-C-50, 1965.

FIGURE CAPTIONS

Figure 1A. Index map showing locations of seismic refraction profiles (solid lines) and approximate centers of surface wave dispersion arrays or two station path profiles (dots) used in the study of crustal and uppermost mantle structure of North America. Province boundaries are from Fenneman (1946) for the United States and from Douglas and Price (1972) for Canada. The numbers adjacent to the seismic refraction profiles refer to the profile names and references listed in Table 1. The numbers adjacent to the dots refer to the surface wave dispersion models referenced in Table 2.

Figure 1B. Index map of seismic refraction profiles for North America at a common scale with the contour diagrams presented in Figures 3, 4 and 5.

Figure 2. Histograms of crustal thickness (H_c), average crustal velocity ($\bar{V}_p$) and uppermost mantle seismic velocity (P_n) determined from the seismic refraction profiles illustrated in Figures 1A and 1B and listed in Table 1. *N* refers to the number of observations. Mean values are $\bar{H}_c$, $\bar{V}_p$ and $\bar{P}_n$ determined from the crustal thickness, average velocity and P_n velocity histograms respectively. s_x is the standard deviation.

Figure 3. Contour map of crustal thickness for a portion of the North American continent. Numbers show crustal thickness in km measured from the surface to the inferred Moho discontinuity.

Figure 4. Contour map of upper mantle seismic velocity (P_n). Contours give inferred P_n velocity in km/s.

Figure 5. Contours of average seismic velocity of the crust ($\bar{V}_p$) for a portion of the North American continent. Contours give values of $\bar{V}_p$ in km/s.

Figure 6. Scatter diagram indicating the relationship of crustal thickness as determined from refraction data (H_c) to crustal thickness as determined from surface wave dispersion models (H_c') at the same locations. H_c observations were interpolated from the contour map at the location of the surface wave dispersion crustal thickness determination (H_c').

Figure 7. Diagram illustrating the relationship between compressional wave velocity and shear wave velocity for average velocity of the crust ($\bar{V}_p$) and uppermost mantle velocity (P_n). Compressional wave velocities (V_p) are determined from the refraction data. Shear wave velocities are determined from the surface wave dispersion models. σ is Poisson's ratio.

Figure 8. Index map (at the same scale as Figures 2, 4, 5 and 6) of a portion of the North American continent showing principal tectonic units, geologic provinces and locations of major basins and uplifts. The long dashed line shows the approximate

limit of the North American continental craton which has remained relatively undeformed since Precambrian time. Short dashed line gives the approximate limit of the continental craton whose edges have suffered deformation since the Precambrian.

Figure 9. Smoothed free-air gravity anomaly map of North America. Free-air anomaly data have been filtered to remove anomalies with wavelengths smaller than approximately 8°. Amplitude range (AR) of the data is 62 to -60 mgals and the amplitude mean (AM) is -7.55 mgals. Contour interval (CI) is 10 mgals. The figure is from von Frese _et al_. (1982).

Figure 10. Radial polarization magnetic anomaly map of North America. The POGO satellite magnetometer observations were reduced to a uniform elevation of 450 km and spherically reduced to radial polarization by spherical equivalent source field calculations. Contour interval is 2 nT. The figure is from von Frese _et al_. (1982).

Figure 11. Filtered total magnetic intensity anomaly map of the United States. NOO magnetic anomaly data along north-south tracks were smoothed by applying a high-cut filter which attenuated wavelengths shorter than approximately 200 km. Contour interval is 100 nT with maxima indicated by a ruled pattern and minima by a dot pattern. Figure is from Sexton _et al_. (1982).

TABLE 1. SEISMIC REFRACTION PROFILES FOR NORTH AMERICA

No.	Profile	Reference
1	Ripple Rock	Richards and Walker, 1959
2	Greenbush Lake - Tumwater	Johnson and Couch, 1970
3	Greenbush Lake - Longmire	Johnson and Couch, 1970
4	Tracadie - Cheticamp	Ewing et al, 1966
5	Tracadie - East Point	Ewing et al, 1966
6	Mainland - Ferolle Point	Ewing et al, 1966
7	St. Anthony - Cape Freels	Ewing et al, 1966
8	St. Joseph - Hannibal	Stewart, 1968a
9	Hercules - St. Genevieve	Stewart, 1968a
10	Hanksville - Chinle	Roller, 1965
11	NTS - Kingman	Diment et al, 1961
11	Kingman - NTS	Roller, 1964; Prodehl, 1979
11	NTS - Tucson	Langston and Helmberger, 1974
12	San Francisco - Paraiso	Hamilton et al, 1964
13	Oregon Coast Range	Berg et al, 1966
14	Lake Mead - Mono Lake	Johnson, 1965
15	Manitou - Chelsea	Mitchell and Landisman, 1971
16	Gnome - N	Mitchell and Landisman, 1971
17	Gasbuggy - S	Toppozada and Sanford, 1976
18	San Francisco - Camp Roberts	Healy, 1963
19	Camp Roberts - Santa Monica Bay	Healy, 1963
20	Lake Superior - Colorado	Roller and Jackson, 1966
21	Tahawus - W	Katz, 1954
22	Milroy - E	Katz, 1954
23	Tahawus - S	Katz, 1954
28	San Francisco - Fallon	Eaton, 1963
29	Fallon - Eureka	Eaton, 1963
31	NTS - Ludlow	Gibbs and Roller, 1963
32	Pahute Mesa - San Francisco Bay	Carder et al, 1970
33	NTS - Ordway	Ryall and Stuart, 1963
35	Lake Superior	Berry and West, 1966
36	Gambler High	Cohen and Meyer, 1966
37	Gambler Low	Cohen and Meyer, 1966
38	Cleveland - Victoria, Texas	Cram, 1961
39	Victoria, Texas	Dorman et al, 1972
40	Cape Girardeau - Little Rock	McCamy and Meyer, 1966
41	Maryland Coast	Merkel and Alexander, 1969
42	S. Mississippi	Warren et al, 1966
43	Blue Mountain - Bylas	Warren, 1969
44	Gila Bend - Sunrise	Warren, 1969
45	SE Texas	Hales et al, 1970
46	American Falls - Flaming Gorge	Willden, 1965
47	E. Colorado	Jackson et al, 1963
48	S. Rocky Mountains	Jackson and Pakiser, 1965
49	Greenbush Lake - E	Chandra and Cumming, 1972
50	Rocky Mountain Trench	Bennett et al, 1975
51	Bird Lake	Johnson et al, 1972
52	Ripley Bay	Johnson et al, 1972
53	Superior	Berry and Fuchs, 1973
54	Front	Berry and Fuchs, 1973
55	Grenville	Berry and Fuchs, 1973
56	Cliff Lake - Big Sandy River	McCamy and Meyer, 1964
57	Big Sandy River - Fort Peck	McCamy and Meyer, 1964
58	Fort Peck - Garrison	McCamy and Meyer, 1964

No.	Profile	Reference
59	Cliff Lake - Sailor Lake	McCamy and Meyer, 1964
60	Garrison - S	McCamy and Meyer, 1964
61	Fort Peck - Acme Pond	McCamy and Meyer, 1964
62	Acme Pond - E	McCamy and Meyer, 1964
63	Sailor Lake - D	McCamy and Meyer, 1964
64	Lake Mead - Santa Monica Bay	Roller and Healy, 1963
66	Galveston	Ewing et al, 1955
68	Blake Plateau	Hersey et al, 1959
69	Jacksonville - E	Hersey et al, 1959
72	Edzoe - Fort McMurray	Mereu et al, 1976
75	NTS - Winnemucca	Stauber and Boore, 1978
76	Cooper Canyon Mine	Stauber and Boore, 1978
86	Port Hebert - Cole Harbour	Barrett et al, 1964
87	Hubley Lake - SE	Barrett et al, 1964
154	Dixon Entrance	Shor, 1962
157	Central Wisconsin	Steinhart and Meyer, 1961
158	Central Wisconsin	Slichter, 1951; Steinhart and Meyer, 1961
163	E. Tennessee	Steinhart and Meyer, 1961
167	California - Nevada	Press, 1960
173	Central Wisconsin	Slichter, 1951; Steinhart and Meyer, 1961
174	Central Wisconsin	Slichter, 1951; Steinhart and Meyer, 1961
175	E. Basin and Range	Berg et al, 1960
178	Great Plains	Hales and Nation, 1973
179	Columbia Plateau	Hill, 1972
184	Front Range	Jackson and Pakiser, 1965
185	Bingham - NE	Braile et al, 1974
193	Bingham - S	Keller et al, 1975
194	Rocky Mountains	Hales and Nation, 1973
195	Dice Throw	Olsen et al, 1979
198	Great Slave Lake	Barr, 1971
199	Superior - Churchill	Mereu and Hunter, 1969
200	Kirkland Lake	Hodgson, 1953
201	W. Manitoba	Hall and Hajnal, 1973
202	Manitoba - Ontario	Hall and Hajnal, 1973
204	Superior - Churchill - NS	Green et al, 1980
205	Superior - Churchill - EW	Green et al, 1980
206	La Malbaie	Lyons et al, 1980
207	Vancouver Island	White and Savage, 1965
208	Greycliff - Charleson	Warren et al, 1972
212	Eureka - Boise	Hill and Pakiser, 1966
216	Trans - California	Carder, 1973
217	Bird Lake - Prince George	Forsyth et al, 1974
218	Hudson Bay NW-SE	Hobson et al, 1967
219	Hudson Bay E-W	Hobson et al, 1967
220	Globe - Tyrone	Gish et al, 1981
221	Yellowstone	Smith et al, 1981
222	Conda - SP7, Y-SRP	Sparlin et al, 1981
223	S. Indiana - S. Illinois	Baldwin, 1980
225	Northwest Ontario	Hall and Hajnal, 1969
226	Parker - Globe, Arizona	Sinno et al, 1981
227	Oregon Coast	Shor et al, 1968
228	Oregon Coast	Shor et al, 1968
229	Delta - W	Keller et al, 1975; Mueller and Landisman, 19
230	Yellowknife NW-SE	Clee et al, 1974

No.	Profile	Reference
231	Bingham - N	Martin, 1978
232	Grenville	Mereu and Jobidon, 1971
233	Nitinat - Greenbush Lake	Berry and Forsyth, 1975
234	Greenbush Lake - McLeod Lake	Berry and Forsyth, 1975
235	Ripley Bay - Greenbush Lake	Berry and Forsyth, 1975
236	Quesnel	Berry and Forsyth, 1975
237	Shasta Reservoir - Mono Lake	Eaton, 1966
238	Mono Lake - China Lake	Eaton, 1966
239	Diablo Range	Stewart, 1968b
240	Gabilan Range	Stewart, 1968b
241	Eastern Snake River Plain	Braile et al, 1981
242	NTS - San Luis Obispo	Prodehl, 1979
243	China Lake - Santa Monica Bay	Prodehl, 1979
244	Mono Lake - Santa Monica Bay	Prodehl, 1979
245	Fallon - Mono Lake	Prodehl, 1979
246	Eureka - Lake Mead	Prodehl, 1979
247	Fallon - China Lake	Prodehl, 1979
248	Mojave - Ludlow	Prodehl, 1979
249	Gasbuggy - SW	Warren and Jackson, 1968
250	Gasbuggy - E	Warren and Jackson, 1968
251	Gasbuggy - N	Warren and Jackson, 1968
252	Gnome - E	Romney et al, 1962
253	Gnome - W	Romney et al, 1962
254	N. Middle Atlantic States - ECOOE	James et al, 1968
255	S. Middle Atlantic States - ECOOE	James et al, 1968
256	Saskatchewan - EDZOE	Bates and Hall, 1975
257	Chesapeake Bay	Tuve, 1951; Steinhart and Meyer, 1961
258	Keweenaw	Steinhart and Meyer, 1961
259	N. Minnesota	Tuve, 1953; Steinhart and Meyer, 1961
260	Puget Sound	Tuve, 1954; Steinhart and Meyer, 1961
261	E. Tennessee	Warren, 1968
262	Maine	Steinhart et al, 1962
263	S. Profile ECOOE	Hales et al, 1968

TABLE 2. Surface Wave Dispersion Models for North America

Location	Reference
S-1	Godlewski and West, 1977
S-2	Panza and Calcagnile, 1974
S-3	Dorman and Ewing, 1962
S-4	Greensfelder and Kovach, 1981
S-5	Braile, unpublished data
S-6	Keller et al, 1979
S-7, 8	Keller et al, 1979
S-9, 10, 11	Losee, 1981
S-12	McEvilly, 1964
S-13	Priestley and Brune, 1978
S-14	Austin and Keller, 1981
S-15	Brune and Dorman, 1963/?
S-16, 17, 18, 19, 20	Braile, unpublished data
S-21	Mikumo, 1965
S-22, 23, 24	Keller and Shurbet, 1975
S-25	Long and Mathur, 1971
S-26	Thatcher and Brune, 1973
S-28	Adams, 1975
S-29	Prewitt, 1968
S-30	Stanton, 1972
S-31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41	Wickens, 1977
S-42, 43, 44	Thompson and Talwani, 1964
S-45, 46, 47, 48	Wickens, 1971
S-49	Oliver et al, 1961
S-50, 51	Bache et al, 1978
S-52, 53	Bucher and Smith, 1971

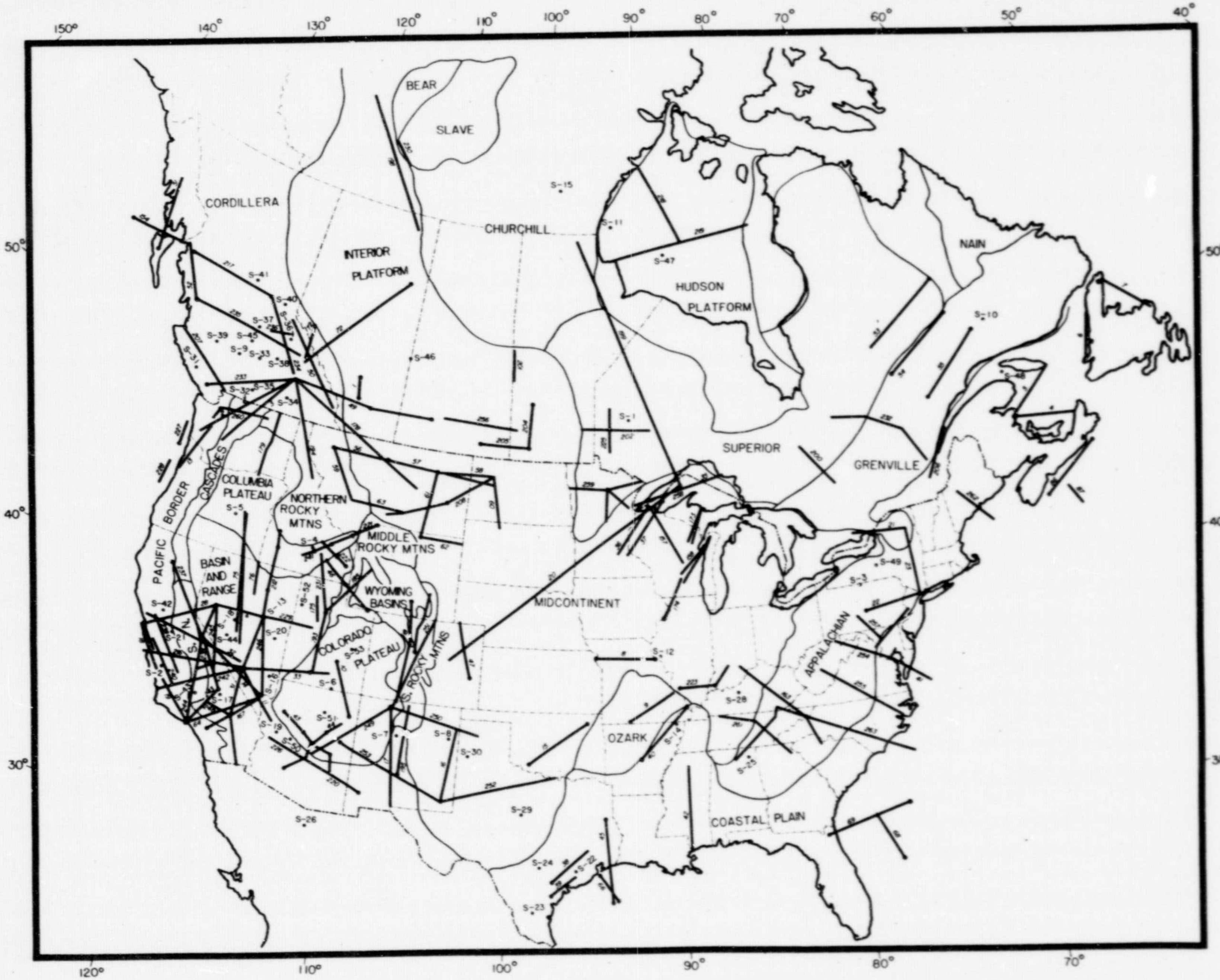
TABLE 3. Crust and Upper Mantle Model Statistics-Continental North America

Variable	Sample Size N	Mean $\bar{x}$	Standard Deviation s_x	Units
H_c	187	36.21	9.22	km
$\bar{V}_p$	154	6.411	0.207	km/s
P_n	191	8.030	0.204	km/s
H'_c	51	37.48	6.42	km
$\bar{V}_s$	49	3.650	0.141	km/s
S_n	51	4.471	0.162	km/s
σ_c	49	0.252	0.040	-
σ_m	51	0.273	0.021	-

Refraction Profile Results:
- H_c - Crustal thickness (Depth to Moho)
- $\bar{V}_p$ - Average compressional wave velocity of the crystalline crust
- P_n - Upper mantle compressional wave velocity (Moho velocity)

Surface Wave Dispersion Results:
- H'_c - Crustal thickness (Depth to Moho)
- $\bar{V}_s$ - Average shear wave velocity of the crystalline crust
- S_n - Upper mantle shear wave velocity (from dispersion models)

Poisson Ratio Results:
- σ_c - Poisson ratio for the crystalline crust
- σ_m - Poisson ratio for the upper mantle



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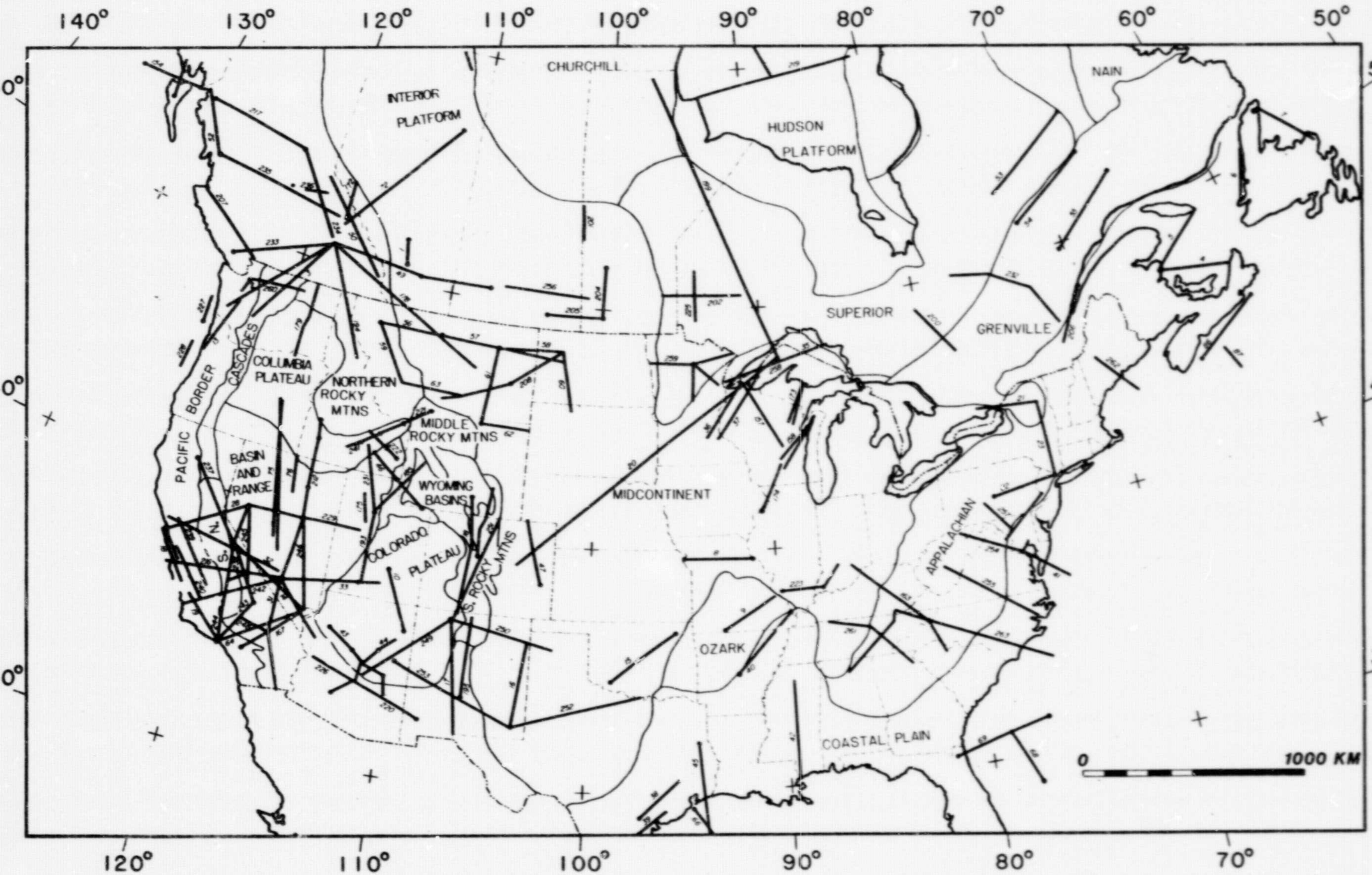

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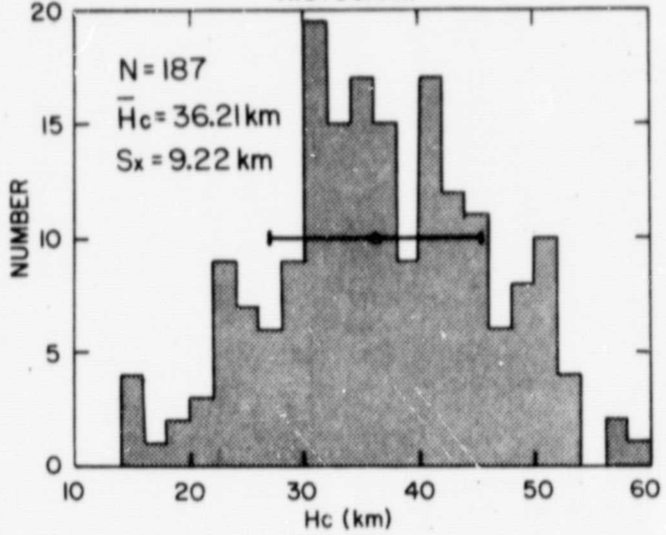
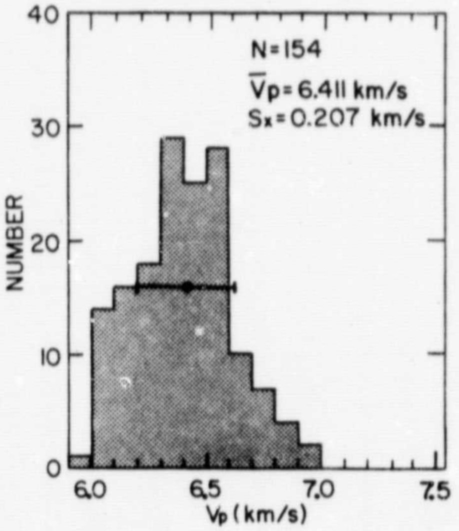
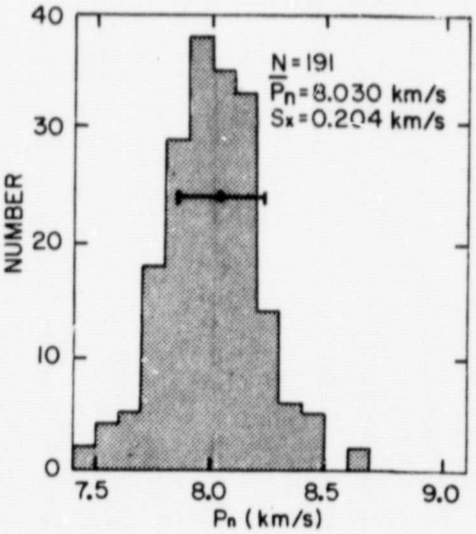
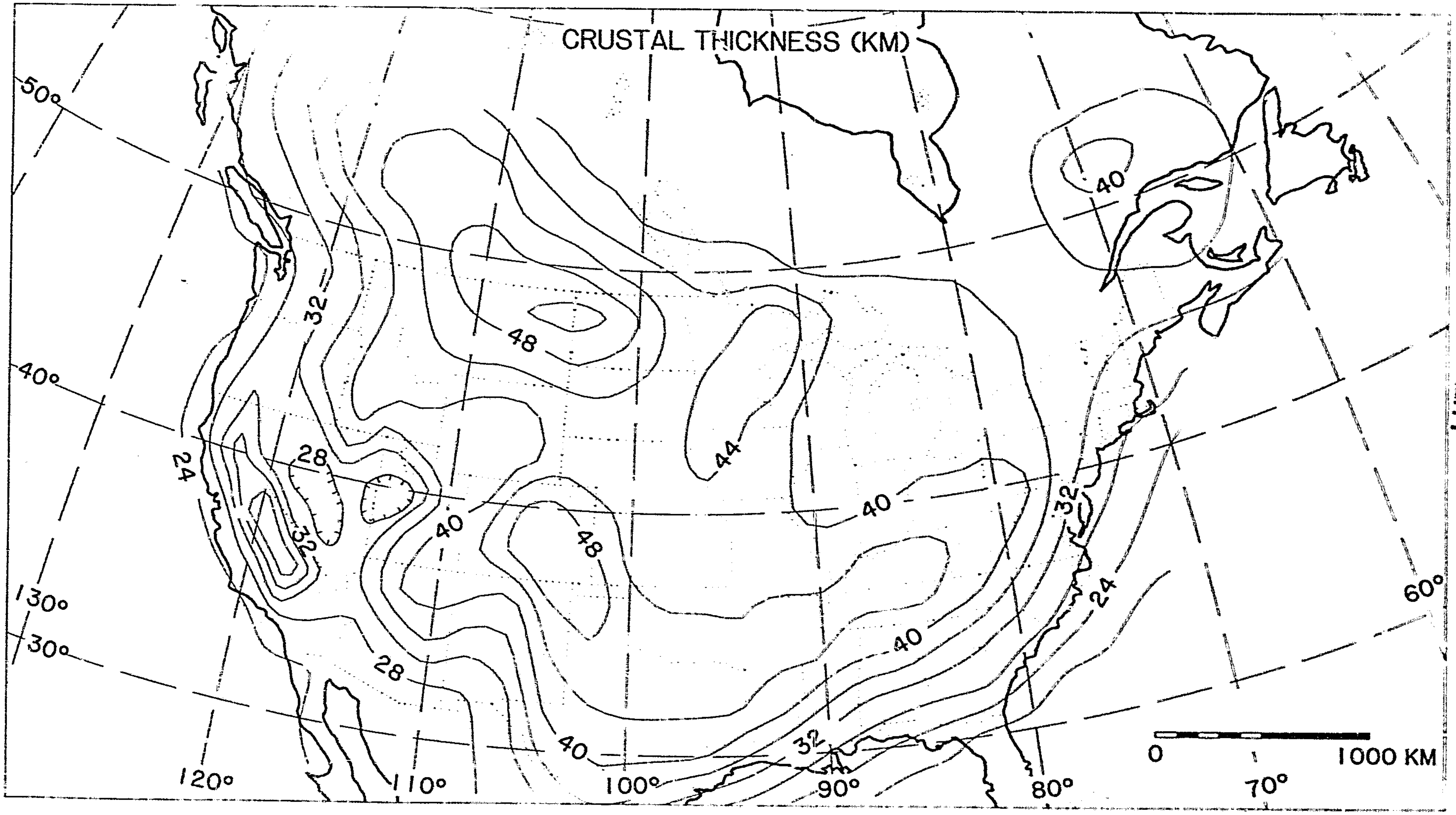

CRUSTAL THICKNESS HISTOGRAM


AVERAGE CRUSTAL VELOCITY HISTOGRAM


P_n VELOCITY HISTOGRAM



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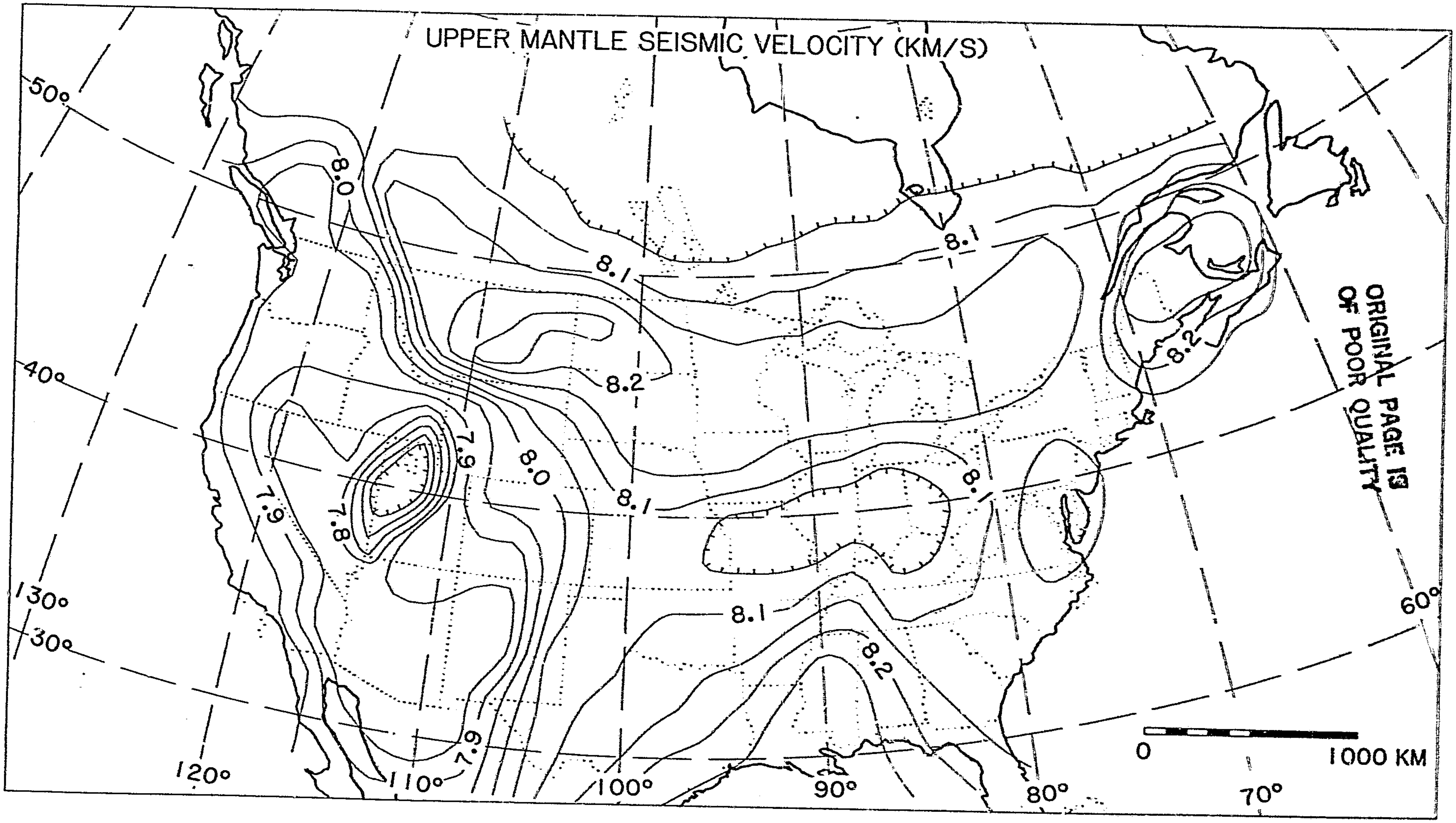

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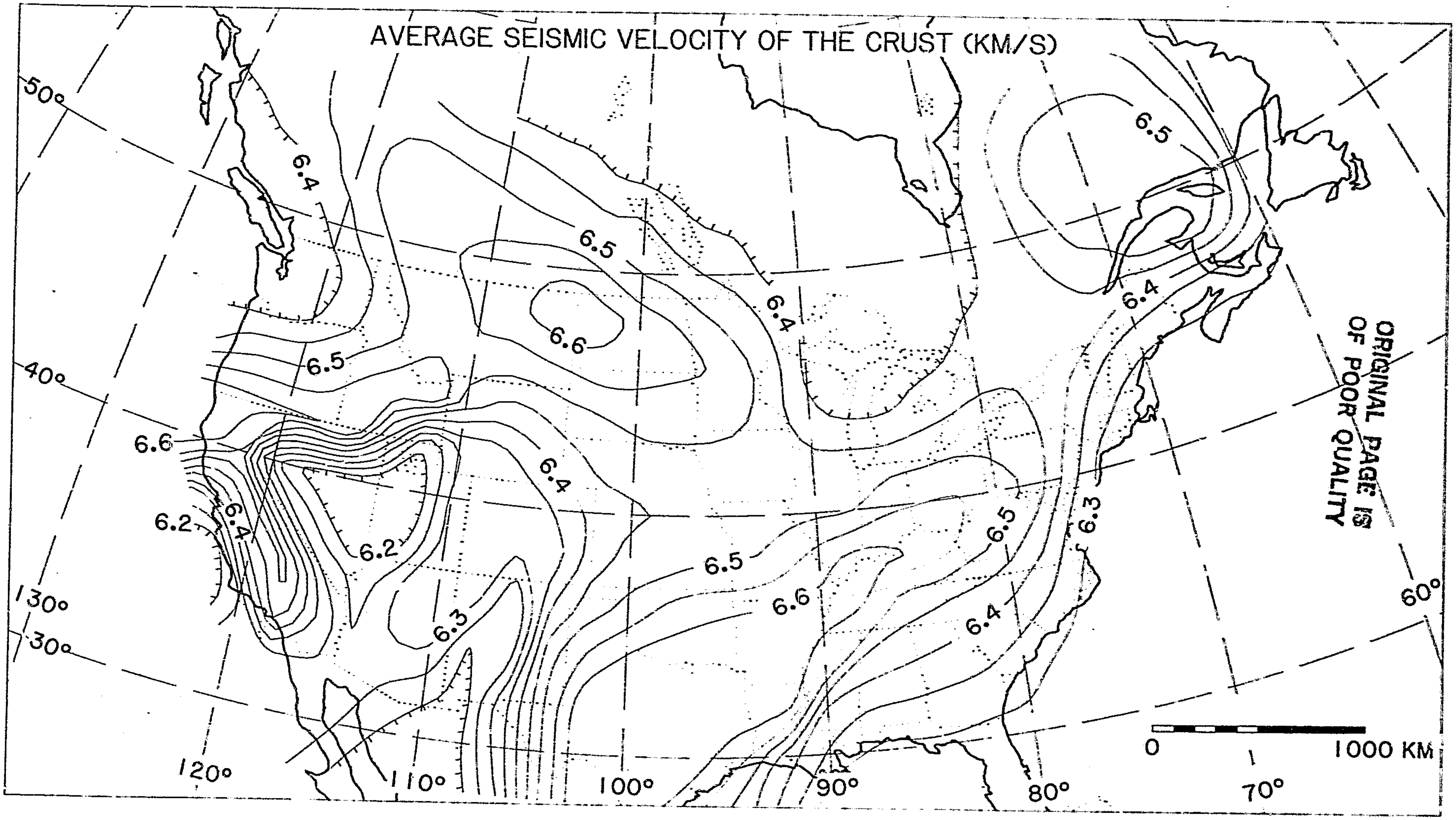

AVERAGE SEISMIC VELOCITY OF THE CRUST (KM/S)

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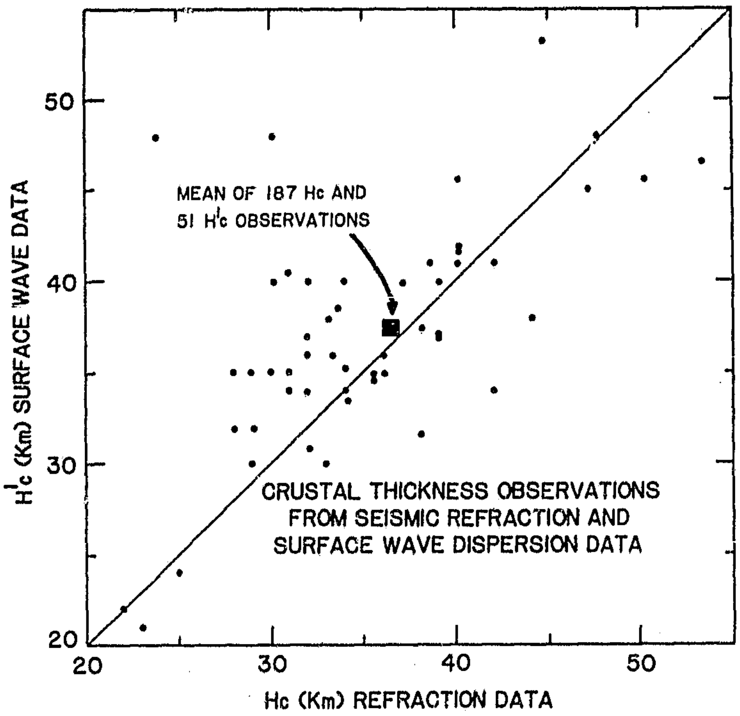
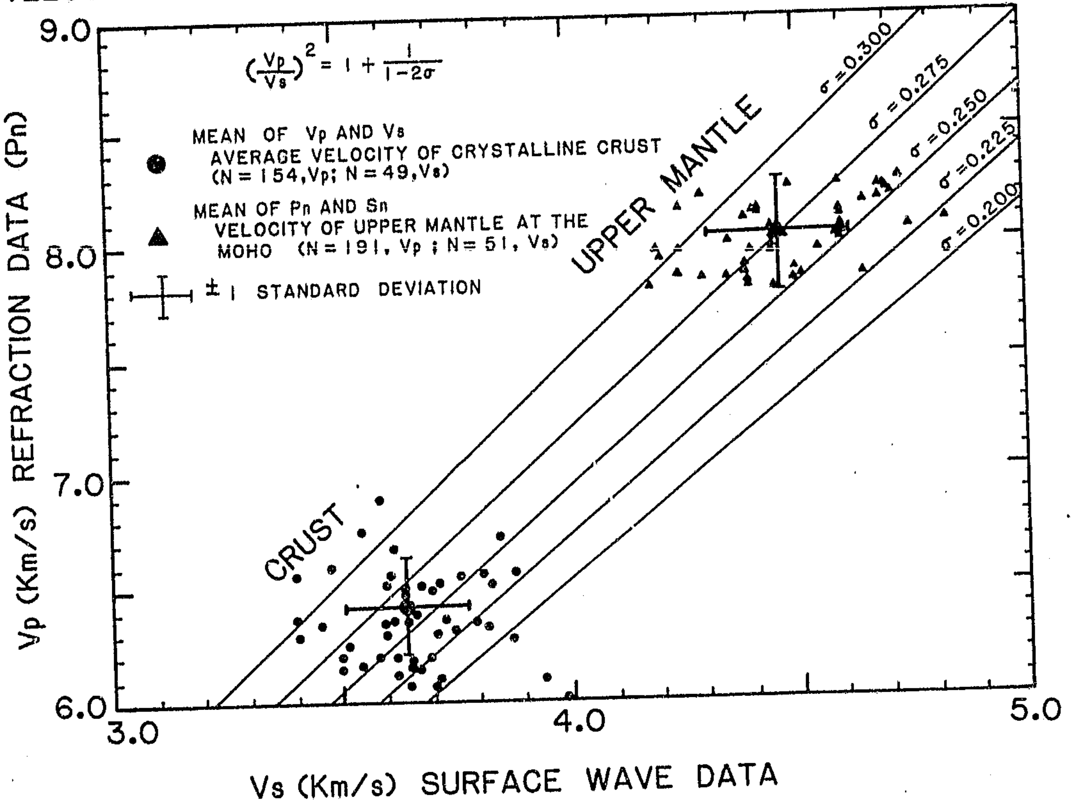
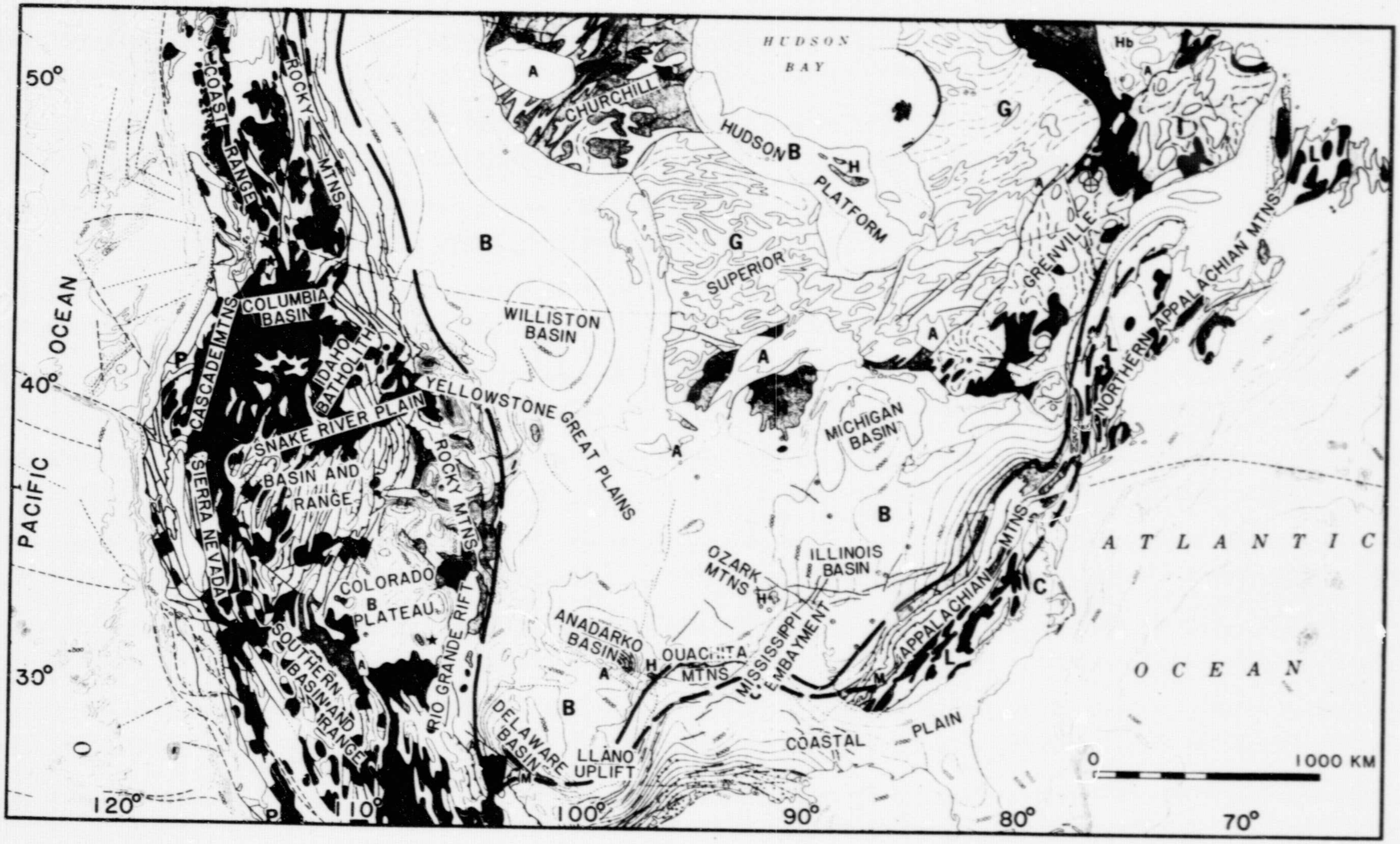
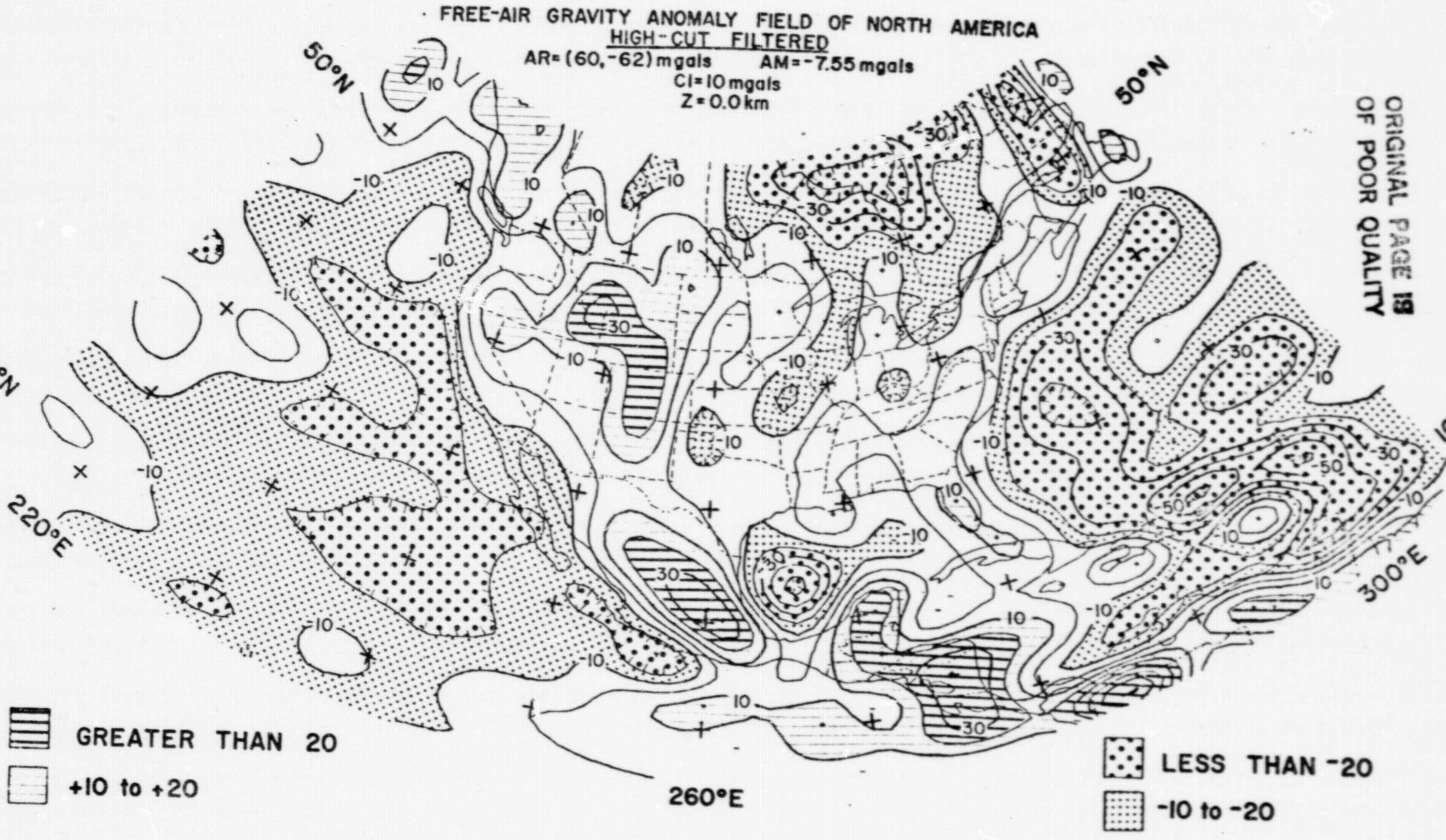




RELATION BETWEEN COMPRESSIONAL (Vp) AND SHEAR (Vs) VELOCITY–POISSON'S RATIO (σ) CONTINENTAL NORTH AMERICA


HUDSON BAY
Hb
A
CHURCHILL
HUDSON B
H
PLATFORM
G
L
COAST RANGE
ROCKY MTNS
B
G
SUPERIOR
GRENVILLE
NORTHERN APPALACHIAN MTNS
PACIFIC OCEAN
COLUMBIA BASIN
CASCADE MTNS
IDAHO BATHOLITH
WILLISTON BASIN
A
P
YELLOWSTONE
GREAT PLAINS
SNAKE RIVER PLAIN
SIERRA NEVADA
BASIN AND RANGE
ROCKY MTNS
MICHIGAN BASIN
B
ATLANTIC OCEAN
OZARK MTNS
ILLINOIS BASIN
COLORADO PLATEAU
RIO GRANDE RIFT
MISSISSIPPI EMBAYMENT
APPALACHIAN MTNS
C
ANADARKO BASIN
OUACHITA MTNS
H
SOUTHERN BASIN AND RANGE
DELAWARE BASIN
LLANO UPLIFT
COASTAL PLAIN
M
0
1000 KM
50°
40°
30°
120°
110°
100°
90°
80°
70°



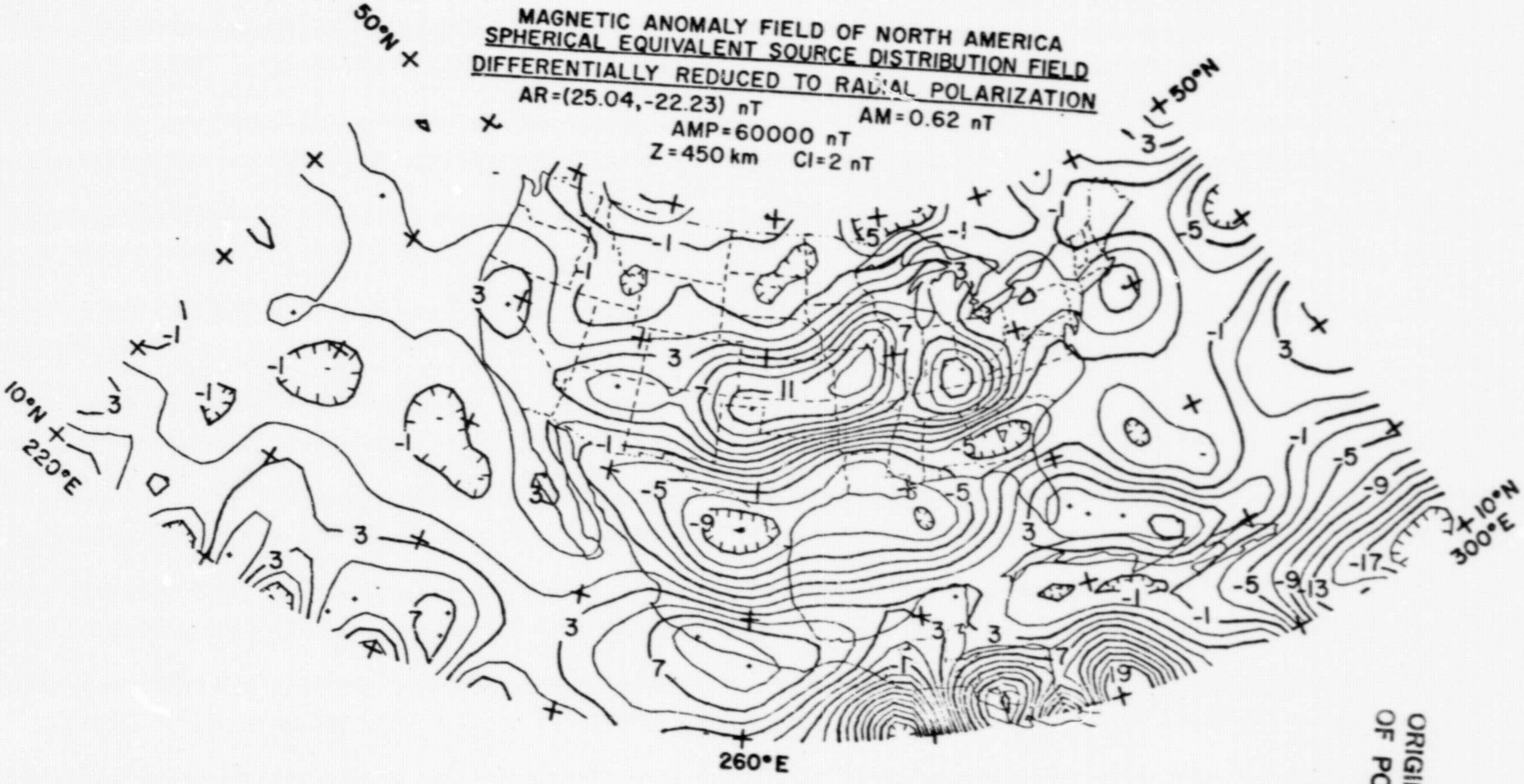
FREE-AIR GRAVITY ANOMALY FIELD OF NORTH AMERICA

HIGH-CUT FILTERED

AR=(60,-62) mgals AM=-7.55 mgals

CI=10 mgals

Z=0.0 km



MAGNETIC ANOMALY FIELD OF NORTH AMERICA
SPHERICAL EQUIVALENT SOURCE DISTRIBUTION FIELD
DIFFERENTIALLY REDUCED TO RADIAL POLARIZATION
AR=(25.04,-22.23) nT AM=0.62 nT
AMP=60000 nT
Z=450 km CI=2 nT

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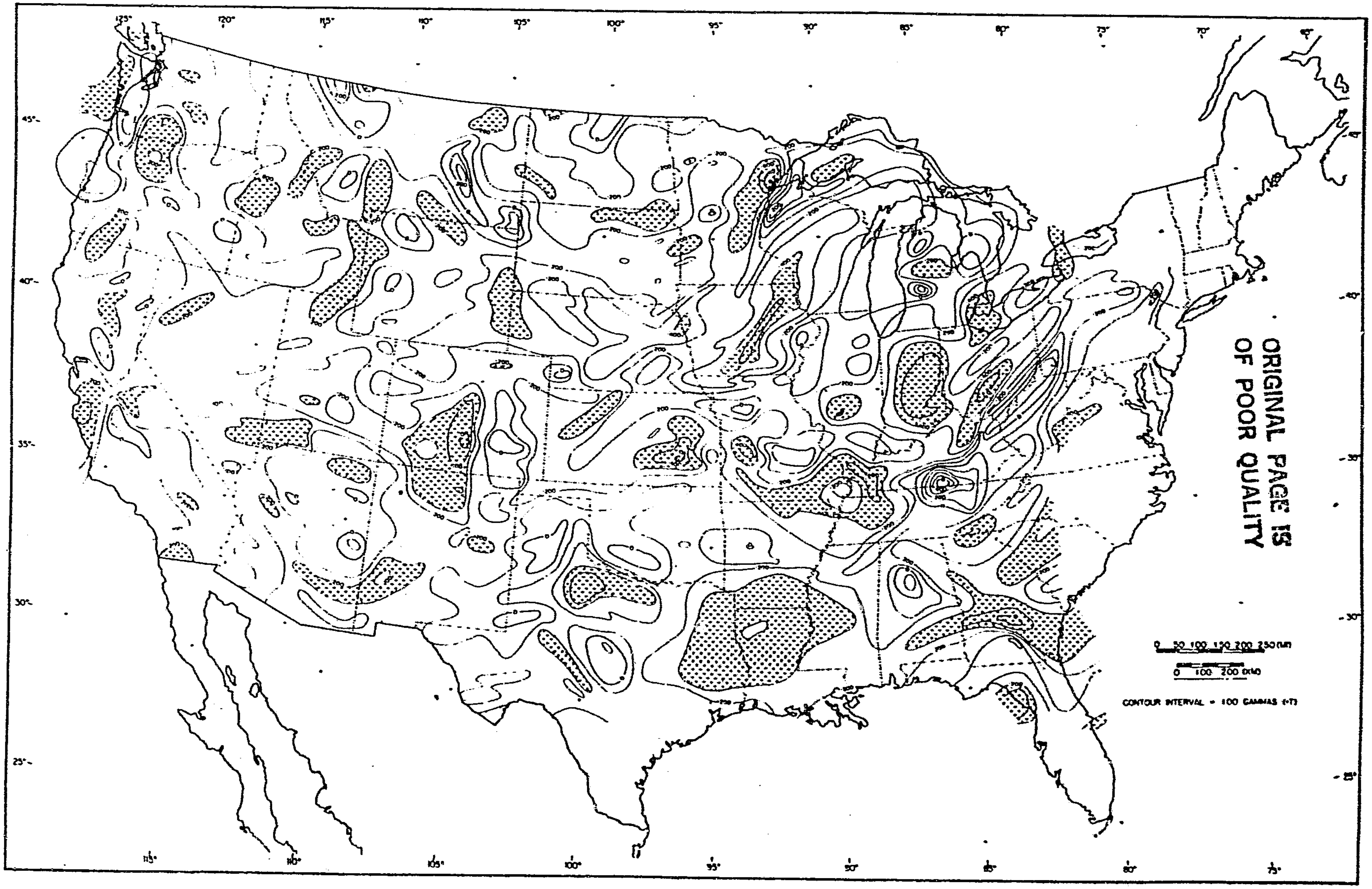

Figure 3. Low-pass ($\lambda \geq 200$ km) filtered total magnetic intensity anomaly contour map. Contour interval is 100 nT, with maxima indicated by ruled pattern and minima by dot pattern.