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Seismic Structure of the Crust and Uppermost Mantle of North America and Adjacent Oceanic Basins: A Synthesis

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Abstract We present a new set of contour maps of the seismic structure of North America and the surrounding ocean basins. These maps include the crustal thickness, whole-crustal average *P*-wave and *S*-wave velocity, and seismic velocity of the uppermost mantle, that is, *Pn* and *Sn*. We found the following: (1) The average thickness of the crust under North America is 36.7 km (standard deviation [s.d.] ±8.4 km), which is 2.5 km thinner than the world average of 39.2 km (s.d. ± 8.5) for continental crust; (2) Histograms of whole-crustal *P*- and *S*-wave velocities for the North American crust are bimodal, with the lower peak occurring for crust without a high-velocity (6.9–7.3 km/sec) lower crustal layer; (3) Regions with anomalously high average crustal *P*-wave velocities correlate with Precambrian and Paleozoic orogens; low average crustal velocities are correlated with modern extensional regimes; (4) The average *Pn* velocity beneath North America is 8.03 km/sec (s.d. ± 0.19 km/sec); (5) the well-known thin crust beneath the western United States extends into northwest Canada; (6) the average *P*-wave velocity of layer 3 of oceanic crust is 6.61 km/sec (s.d. ± 0.47 km/sec). However, the average crustal *P*-wave velocity under the eastern Pacific seafloor is higher than the western Atlantic seafloor due to the thicker sediment layer on the older Atlantic seafloor.

Introduction

The construction of continent-scale maps of geophysical properties provides a broad picture of the structure of the Earth. For example, a map of crustal thickness indicates the areal extent of tectonic provinces such as highly extended regions and orogenic zones. Likewise, maps of crustal seismic velocities can delineate the third dimension of platforms, shields, sedimentary basins, and exotic accreted terrains. Complementary maps of magnetic and gravity anomalies are regularly constructed that show tectonic features buried beneath surficial cover and indicate the presence of mineral resources. Maps of potential fields are particularly effective in revealing sutures, rift boundaries, and other relics of the crust's tectonic evolution. Together, geophysical maps provide a means of identifying crustal properties that delineate geologic provinces (e.g., Prodehl, 1984; Meissner, 1986; Collins, 1988; Braile, 1989; Blundell *et al.*, 1992; Pavlenkova, 1996; Yuan, 1996).

We present a new set of contour maps based on seismic refraction and other seismic data for the region of North America and the surrounding ocean basins. The main geologic provinces of North America are presented in Figure 1. There are several reasons why new maps are appropriate. First, the quantity and quality of data has grown substantially in the dozen years since the last such maps were produced (Braile *et al.*, 1989; Mooney and Braile, 1989). New seismic surveys have been conducted that cover unexplored regions and provide better resolution in previously studied areas. The quality of the latest data is improved as well due to technological advances in field equipment and in analytical techniques. These new data have been merged with the older data into a new, more comprehensive seismic database (Chulick, 1997; Mooney *et al.*, 1998; Web site address provided at end of article). Locations for all seismic data points are shown in Figure 2. A data point consists of the extraction of a one-dimensional velocity-depth function from a published crustal model. More than 85% of all data points were extracted from two-dimensional seismic-velocity cross sections derived from seismic-refraction data. Every effort has been made to include results published through the year 1999. Some important, recently completed seismic surveys, particularly those recorded in Canada under the LITHOPROBE program (Clowes *et al.*, 1996, 1999), have not yet been included in our compilation.

A new aspect of our study is that we have compiled enough *S*-wave data to present, for the first time, contour maps and statistical analyses of the *S*-wave velocity of the crust and Moho. Such presentations are particularly relevant, given the recent production of tomographic *S*-wave velocity maps of the North American mantle (Grand, 1994; Grand *et al.*, 1997; van der Lee and Nolet, 1997).

The maps presented here include crustal thickness (H_c), average *P*-wave velocity of the whole crust (P_c) and of the

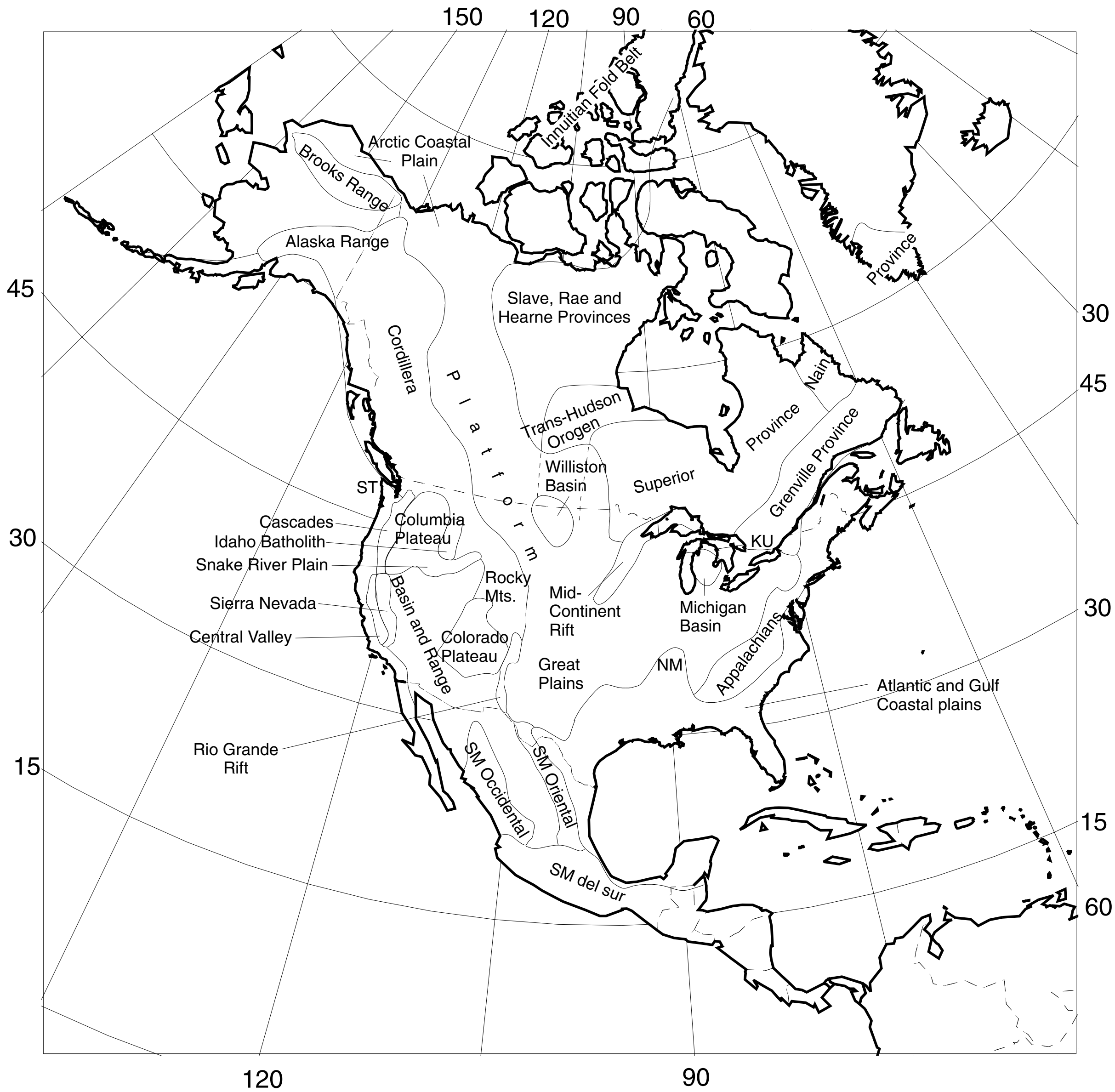

Figure 1. Geologic province map of North America (modified from King and Edmonston, 1972) showing the main features referred to in the text. NM, New Madrid Rift; KU, Kapuskasing Uplift; SM, Sierra Madre; ST, Siletz Terrain.

crystalline crust (P_{cc}), sub-Moho *P*-wave velocity (*Pn*), average *S*-wave velocity of the whole crust (S_c) and of the crystalline crust (S_{cc}), and sub-Moho *S*-wave velocity (*Sn*). Furthermore, we provide a statistical analysis of these parameters, as well as of the velocity ratios P_c/S_c, P_{cc}/S_{cc}, and *Pn*/*Sn*.

Previous Work

Pakiser and Steinhart (1964) produced the first maps of deep crustal properties for North America based on seismic-refraction data. These contour maps included crustal thickness (H_c), average whole-crustal *P*-wave velocity (P_c), and sub-Moho *P*-wave velocity (*Pn*). The maps showed general trends rather than details, which was appropriate given the scarcity of data at the time. The crustal thickness map of Pakiser and Steinhart (1964) was the first to delineate the extent of thin (25–30 km) crust beneath the Basin and Range Province and thick (>45 km) crust under the Great Plains. Moreover, their maps were the first also to show the correlation between thin crust and low values of P_c and *Pn* in the Basin and Range Province.

James and Steinhart (1966), citing Herrin (1966), produced a somewhat more detailed contour map of *Pn* under the United States and southern Canada. In particular, this map was the first to reveal detailed variations of *Pn* velocity, with the highest values (8.2–8.3 km/sec) beneath the central United States.

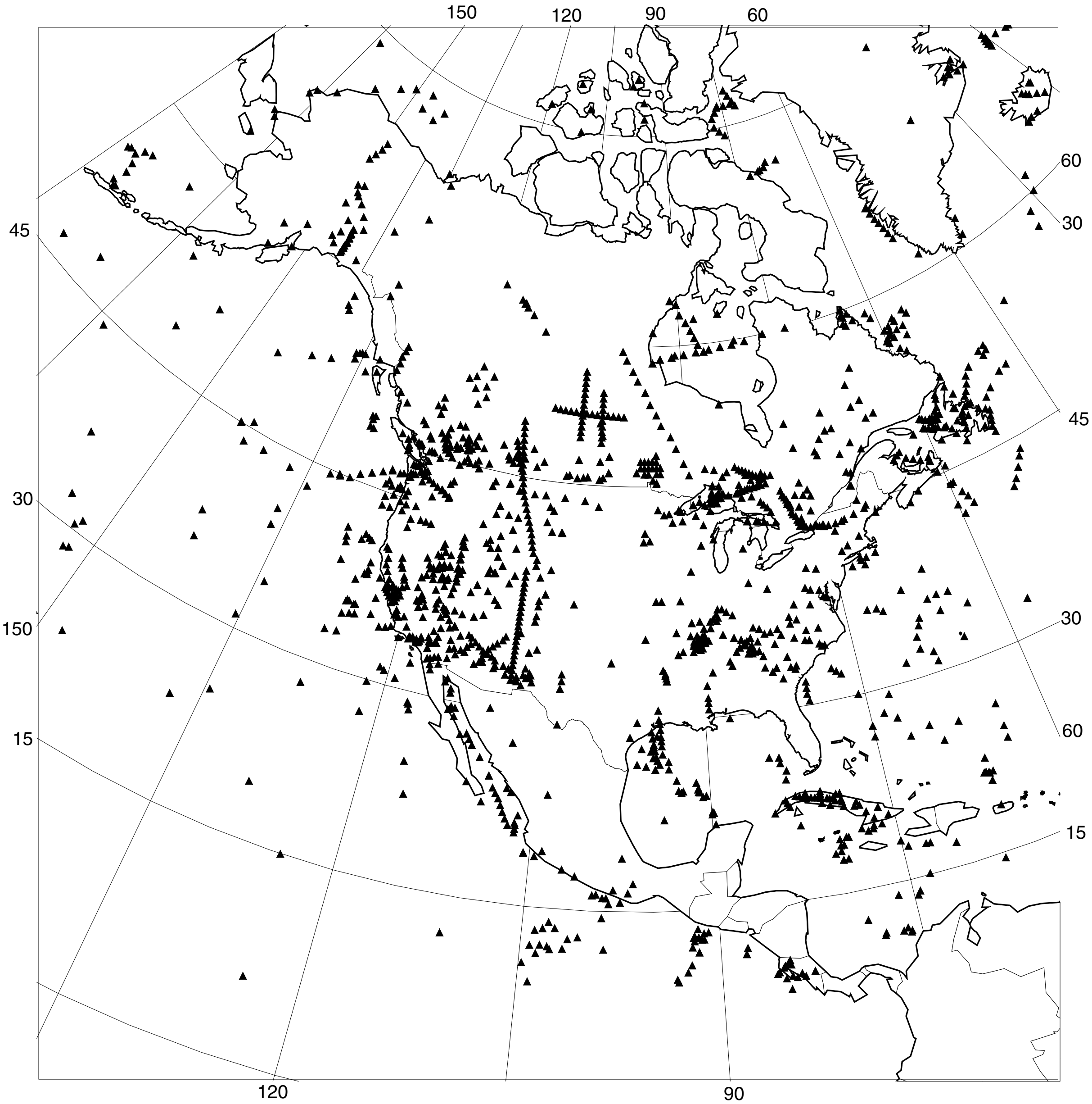

Figure 2. Location map of the ~1400 one-dimensional seismic *P*-wave velocity-depth functions used in this study. Each velocity-depth function was extracted from a published seismic velocity model. More than 85% of the functions are derived from seismic-refraction data. Data sources are tabulated in Table 3. Results published through the year 1999 are included here.

The unpublished work of Blair (1980) included a set of maps of H_c, P_c, and *Pn* for North America and the northern Pacific Ocean. These maps reconfirmed many of the observations of Pakiser and Steinhart (1964) and showed a general correlation between contours of crustal and mantle properties and the age of the crust in the Pacific Ocean. At approximately the same time, Soller *et al.* (1982) produced the first detailed worldwide map of crustal thickness (H_c) using a 2508 point database composed of H_c and *Pn* values. This map was the first to provide an overview of the global variations in crustal thickness. Allenby and Schnetzler (1983) constructed maps of H_c, *Pn*, and the lowermost crust under the conterminous United States. Among their discoveries was the extension of the thin crust of the Basin and Range Province into Oregon and Washington.

Braile *et al.* (1989) exploited a large increase of seismic-refraction data to produce new maps of H_c, P_c, and *Pn* for the United States and southern Canada. These maps were constructed from a set of 337 continental data points and were accompanied by the first detailed statistical analysis of crustal thickness and average crustal velocity (Table 1). The map of crustal thickness generally reconfirmed the findings

Table 1
Comparison of Statistical Analyses of Braile *et al.* (1989) (North America), Christensen and Mooney (1995) (global), and this study (North America)

		Braile *et al.* (1989)	Christensen and Mooney (1995)	This Study (Continental Crust Only)	This Study (All Crust)
H_c (km):	n	337	560	997	
	x	36.10	39.17	36.72	
	$\pm\sigma$	8.97	8.52	8.39	
	$\pm$e	0.48	0.36	0.27	
P_{cc} (km/sec):	n	255	560	983	
	x	6.435	6.45	6.456	
	$\pm\sigma$	0.235	0.23	0.244	
	$\pm$e	0.015	0.01	0.008	
S_{cc} (km/sec):	n	67		127	129
	x	3.639		3.726	3.724
	$\pm\sigma$	0.163		0.149	0.157
	$\pm$e	0.02		0.013	0.014
Pn (km/sec):	n	320	560	906	1238
	x	8.018	8.07	8.033	8.041
	$\pm\sigma$	0.205	0.21	0.186	0.215
	$\pm$e	0.01	0.01	0.006	0.006
Sn (km/sec):	n	76		112	114
	x	4.471		4.571	4.574
	$\pm\sigma$	0.165		0.144	0.146
	$\pm$e	0.019		0.014	0.014

H_c, crustal thickness; P_{cc} (S_{cc}), average *P*-wave (*S*-wave) velocity of the crystalline crust (i.e., below sediments); *Pn* (*Sn*), *P*-wave (*S*-wave) velocity of the uppermost mantle; n, number of data points; x, average value; $\pm\sigma$, standard deviation. The statistical error, $\pm e = \sigma \div$ square root of n.

of previous authors but provided additional details in the eastern and central portions of the continent. However, the contour map of *Pn* velocity of Braile *et al.* (1989) disagrees substantially with that of James and Steinhart (1966) outside the southwest United States, as discussed subsequently.

An extension of these maps to nearly all of North America, except for portions of Central America and the West Indies, were produced by Mooney and Braile (1989). These new maps show regions in which little prior information was available, such as in Alaska and Arctic Canada, and showed such features as very thick (50 km) crust beneath southern Alaska. Chulick (1997) presented detailed contour maps of H_c, P_c, P_{cc}, and *Pn* for the central United States. These maps resolved detailed structure in the vicinity of the New Madrid fault zone and defined the deep structure of the Mid-Continental Rift (Halls, 1982). North American crustal structure is also included in these three global crustal models: 3SMAC (Nataf and Ricard, 1996), CRUST 5.1 (Mooney *et al.*, 1998), and CRUST 2.0 (Bassin *et al.*, 2000).

Data and Preparation

We have compiled a global catalog of the seismic structure of the crust and uppermost mantle that includes all types of seismic data, including that from refraction profiling, surface-wave and receiver-function analysis, and local earthquake tomography. Our global catalog currently contains over 5000 velocity-depth functions (data points), of which some 1400 are used in the present study. About 85% of the velocity-depth functions were derived from seismic-refraction data. Given the ambiguity in determining the thickness of sediments for each individual data point, we have adopted a velocity horizon to define the depth to the top of the crystalline, or consolidated, crust. A value of 5.8 km/sec was chosen for this seismic velocity horizon because it is higher than the velocities in most sedimentary rocks but lower than the minimum velocity (~5.9 km/sec) found in virtually all granitic rocks.

The accuracy of contour maps is directly related to the uncertainties in the published interpretations of crustal structure. Useful reviews of the methods used to determine the structure of the crust and subcrustal lithosphere were provided by Mooney (1989) and Bostock (1999). The uncertainties in crustal models arise from such factors as the survey method, analysis technique, and spatial resolution of the survey, that is, parameters such as the spacing of shot points and recording stations. Typically, the uncertainty in the calculated depth is approximately 5–10%. Thus, a reported crustal thickness of 40 km has an uncertainty of ± 2–4 km. Seismic velocities determined from refracted first arrivals (e.g., *Pn*) are typically accurate to within a few hundredths of km/sec (Mooney, 1989; Chulick, 1997).

Results

North American geological provinces and place names are presented in Figure 1, and the locations of the compiled *P*-wave velocity-depth functions are shown in Figure 2. Statistical analyses for each of the seismic parameters are presented in Tables 1 and 2. The data types (e.g., seismic refraction, receiver functions, etc.) and data quantity used in the construction of the maps are presented in Table 3. The contour maps presented in Figures 3–8 were constructed using commercial software employing the natural-neighbor technique for gridding. Certain regions with very sparse data (e.g., parts of Alaska, Baja California, Central America, the West Indies, and Greenland) yielded clearly erroneous contours. The contours in these regions were edited to avoid, for example, oceanic crustal thickness from appearing on continental crust. (The raw data used are available at the Web address provided at the end of this article.)

Crustal Thickness (H_c)

Our map of the thickness of the crust under North America and the surrounding ocean basins (Fig. 3) refines the definition of many of the structures that were evident on previously published maps. Examples include the thin crust of the Basin and Range Province and the thick crust of the Great Plains (United States). However, our maps also reveal a number of new features. (1) We resolve a northward extension of thin crust from the Basin and Range Province into

Table 2

Statistical Analyses of the Crustal and Mantle Parameters Presented in This Study

Parameter	Average	Standard Deviation	Number of Data Points
H_c (continental) (km)	36.72	8.39	997
H_c (oceanic) (km)	8.21	4.90	352
P_c (continental) (km/sec)	6.287	0.315	983
P_c (oceanic) (km/sec)	5.716	0.635	348
P_{cc} (continental) (km/sec)	6.456	0.244	983
P_{cc} (oceanic) (km/sec)	6.609	0.475	348
Pn (continental) (km/sec)	8.033	0.186	906
Pn (oceanic) (km/sec)	8.064	0.279	332
S_c (continental) (km/sec)	3.650	0.174	127
Sn (continental) (km/sec)	4.571	0.144	112
P_c/S_c	1.735	0.0412	124
P_{cc}/S_{cc}	1.730	0.0318	123
Pn/*Sn*	1.756	0.0458	110

H_c, crustal thickness; P_c (S_c), average *P*-wave (*S*-wave) velocity of the whole crust (i.e., including sediments); P_{cc} (S_{cc}), average *P*-wave (*S*-wave) velocity of the crystalline crust (i.e., below sediments); *Pn*(*Sn*), *P*-wave (*S*-wave) velocity of the uppermost mantle.

Table 3

Distribution of Data Points for Each Crustal and Uppermost Mantle Parameter Mapped in This Study According to Crustal Type and Source Method

	H_c	P_c	*Pn*	S_c	*Sn*
Total number of control points	1388	1363	1285	130	114
Number of continental control points	985	960	896	128	112
Number of oceanic control points	403	403	389	2	2
Control points from:					
Reversed seismic refraction surveys	770	757	730	47	38
Unreversed seismic refraction surveys	186	186	180	16	14
Split seismic refraction surveys	47	47	46	4	4
Receiver functions or earthquake models	92	88	58	37	32
Time-term analysis of Seismic refraction data	195	187	187	23	23
Tomographic inversion	13	13	13	0	0
Surface-wave analysis	7	7	7	3	3
Other methods	78	78	64	0	0

H_c, crustal thickness; P_c (S_c), average *P*-wave (*S*-wave) velocity of the whole crust (i.e., including sediments); *Pn* (*Sn*), *P*-wave (*S*-wave) velocity of the uppermost mantle.

the western Canadian Cordillera. (2) We find a crustal thickness of less than 40 km in much of northern Canada, including the region of Hudson Bay. (3) Our contour maps present an improved definition of the continental margins on the east and west coasts. Whereas the western margin (the zone between the 10 km and 30 km contours) is narrow, the eastern margin is wide. Both margins correspond well to the width and location of the continental shelves. (4) Far to the north, the thick (40–45 km) crust of the Brooks Range, northern Alaska, is evident. The average thickness of the crust is 36.7 km, with a standard deviation of [s.d.] 8.4 km (Table 1).

Average Crustal *P*-Wave Velocity (P_c)

The average crustal P-wave velocity under North America and the surrounding ocean basins is presented in Figure 4. A new feature of this map is a close correspondence between continental regions of high average crustal velocity and compressional orogens (e.g., the Trans-Hudson, Grenville, northern Appalachians, and Alaskan Range) (Fig. 1). We also reproduce the previously known close correspondence between extended and/or rifted crust and regions of low average crustal velocity (e.g., the Basin and Range and the Atlantic and Gulf Coastal Plains).

This contour map also shows a contrast between a relatively low average crustal velocity (~6.0 km/sec) for the Atlantic seafloor and a relatively high velocity (~6.4 km/sec) for the eastern Pacific seafloor. This appears to reflect the greater thickness of sediment on the older, slowly opening Atlantic seafloor, in contrast to the younger, fast-spreading eastern Pacific seafloor.

Crystalline Crustal *P*-Wave Velocity (P_{cc})

Regions with thick accumulations of low-velocity sediments strongly influence the contour map of whole-crustal *P*-wave velocity. Thus, we have also calculated the average *P*-wave velocity in the crystalline crust (i.e., below surficial sediments, here taken as $V_p < 5.8$ km/sec). The largest regions with high P_{cc} velocities (6.8 km/sec) are within ocean basins (Fig. 5). Continental crust generally has lower P_{cc} velocities (6.4–6.8 km/sec). A close examination of Figure 5 reveals several important features. First, there are a number of continental regions of anomalously high (6.8 km/sec) velocity. These include the Kapuskasing Uplift of southern Canada, where high-velocity lower crustal rocks have been thrust to shallow depth, the mafic volcanic crust of the Mid-Continental Rift (Fig. 1), and Cambrian rifted crust of eastern Texas.

There are also a number of regions with relatively low P_{cc} velocity, for example, the Basin and Range Province, much of the state of California, and much of northwestern Canada, including the Canadian Cordillera. Many of these are regions of recent crustal extension and have relatively high heat flow. Low P_{cc} velocity also underlies portions of the southern Atlantic Coastal Plain and Appalachian Mountains.

Sub-Moho *P*-Wave Velocity (*Pn*)

The contour map of *Pn*, the seismic velocity of the uppermost mantle, is presented in Figure 6. Note that there is insufficient azimuthal coverage to make corrections for seismic anisotropy, which may amount to 2%–6% for *P* waves in the uppermost mantle (e.g., Anderson, 1989). The East Pacific Rise spreading ridge shows quite prominently as a region of low *Pn* due to high mantle temperatures. As in previous maps, the extent of low *Pn* in the western United States is clearly delineated. Much of the continental interior is underlain by mantle with a *Pn* velocity of 8.1 ± 0.1 km/

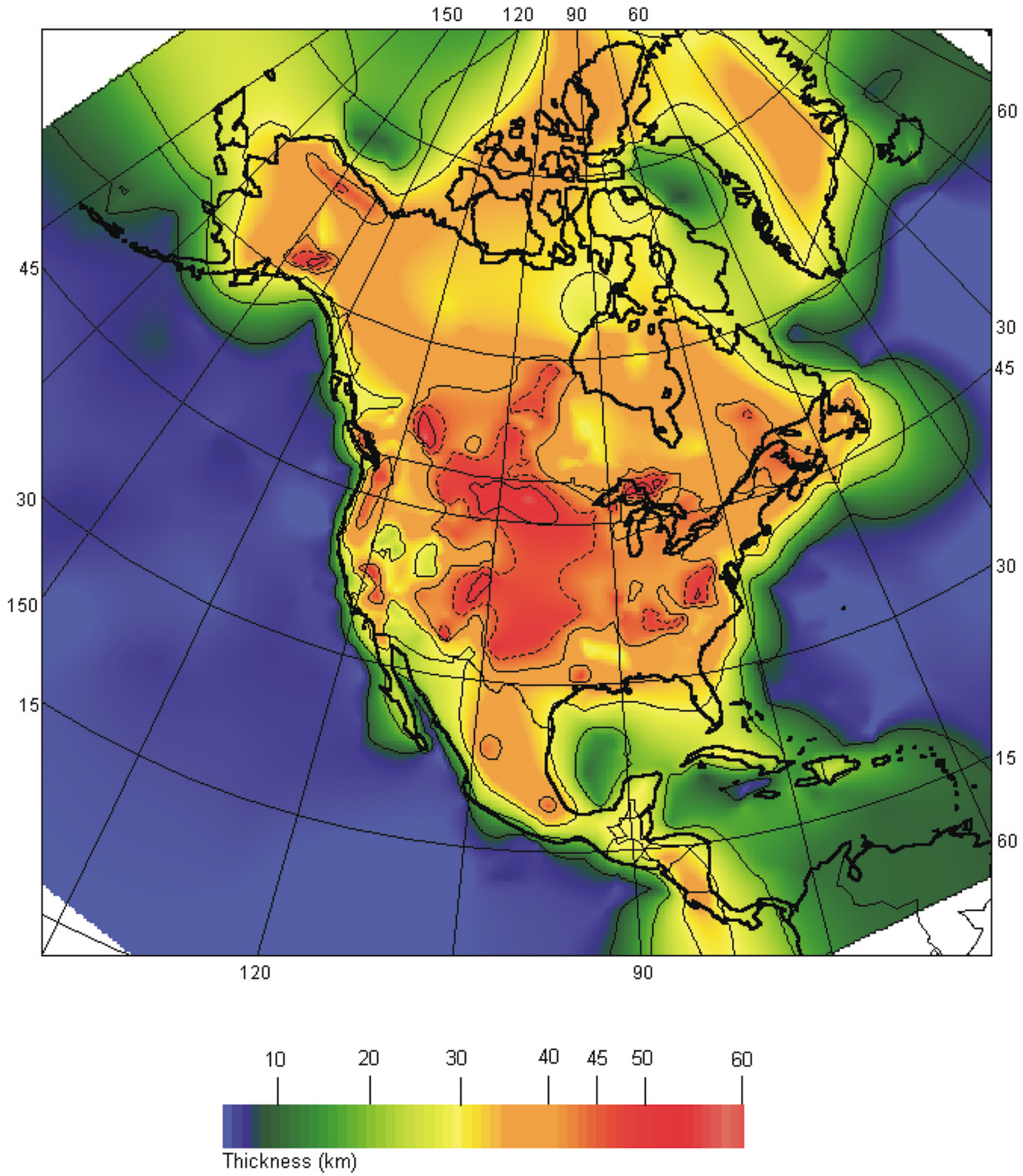

Figure 3. Contour map of crustal thickness, H_c, under North America and the surrounding ocean basins. The average thickness of the continental crust, including the continental margins, is 36.7 km, with a standard deviation (s.d.) of 8.4 km. This map is based on approximately 700 new data points compared to earlier maps (see text).

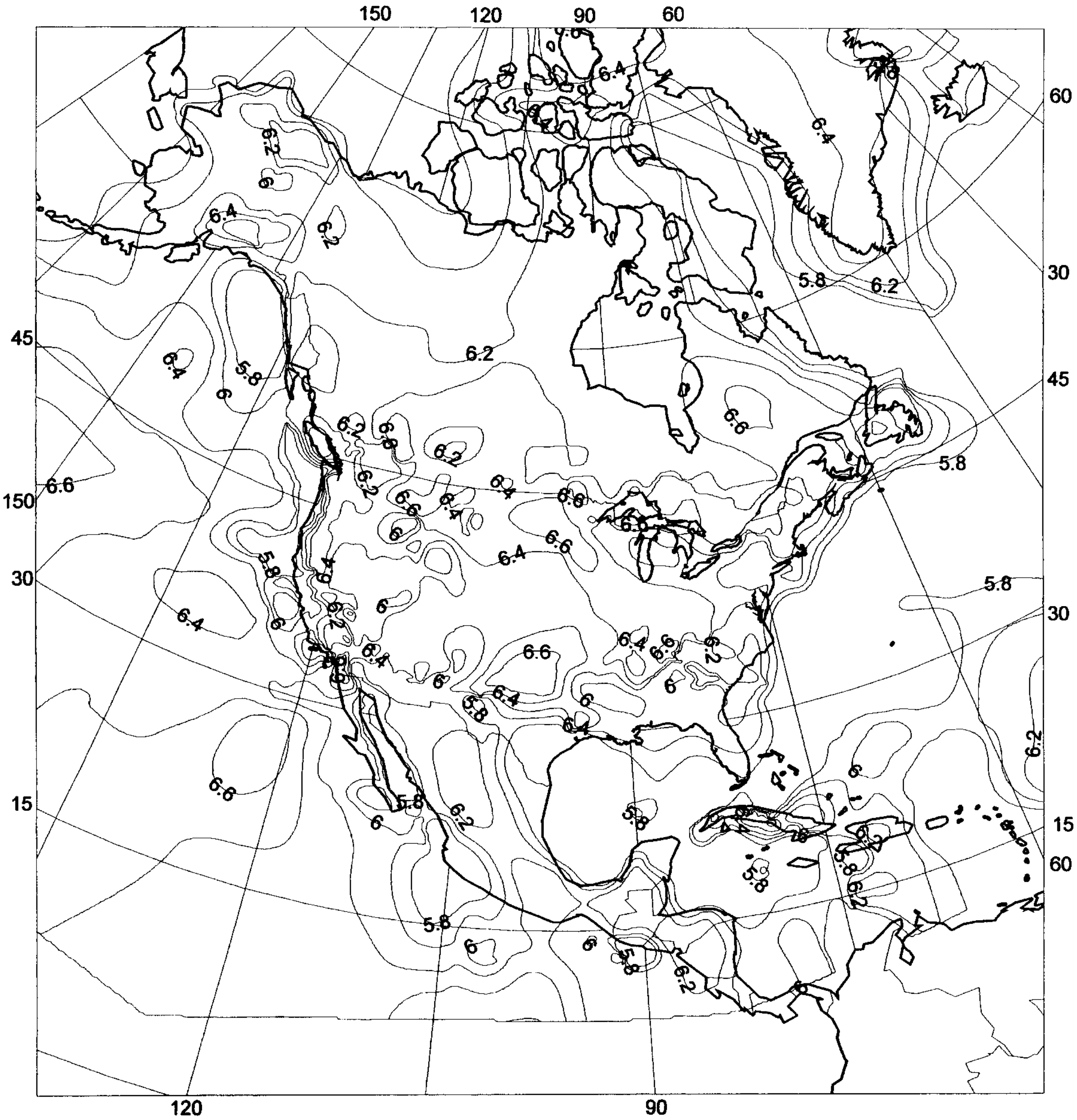

Figure 4. Contour map of average whole-crustal *P*-wave velocity, P_c. This average includes the sedimentary cover. The average value for all of North America is 6.29 km/sec. Regions of recent crustal extension (e.g., the Basin and Range and the Rio Grande Rift) show low P_c velocities. Thick sedimentary basins along the edge of the continent also stand out as regions of low (<6.0 km/sec) P_c velocity. There is a striking difference in P_c velocity between the eastern Pacific Ocean crust and the western Atlantic Ocean crust that we attribute to the thicker sedimentary cover in the western Atlantic. On the continent, high (>6.4 km/sec) P_c values mostly occur in the older (Precambrian) crust of central and eastern North America.

sec. We note that there are relatively few publications from North America reporting *Pn* velocities greater than 8.3 km/sec. However, *Pn* velocities as high as 8.6 km/sec have been reliably determined in central Canada (Németh and Hajnal, 1998). These high *Pn* velocities were measured along the fast direction of a mantle with 4%–5% seismic anisotropy.

Our contour map of *Pn* indicates values that are intermediate between those of James and Steinhart (1966) and Braile *et al.* (1989). For example, the map of James and Steinhart (1966) showed the highest *Pn* velocities (8.2–8.3 km/sec) under the Great Plains with a gradual fall-off in values to less than 8.1 km/sec toward the southeast. The *Pn* velocity map of Braile *et al.* (1989), on the other hand, shows lower values for *Pn* (8.0–8.1 km/sec) under the central Great Plains, with slightly higher values to the east and the highest values (>8.2 km/sec) under the Gulf Coast. Our contour

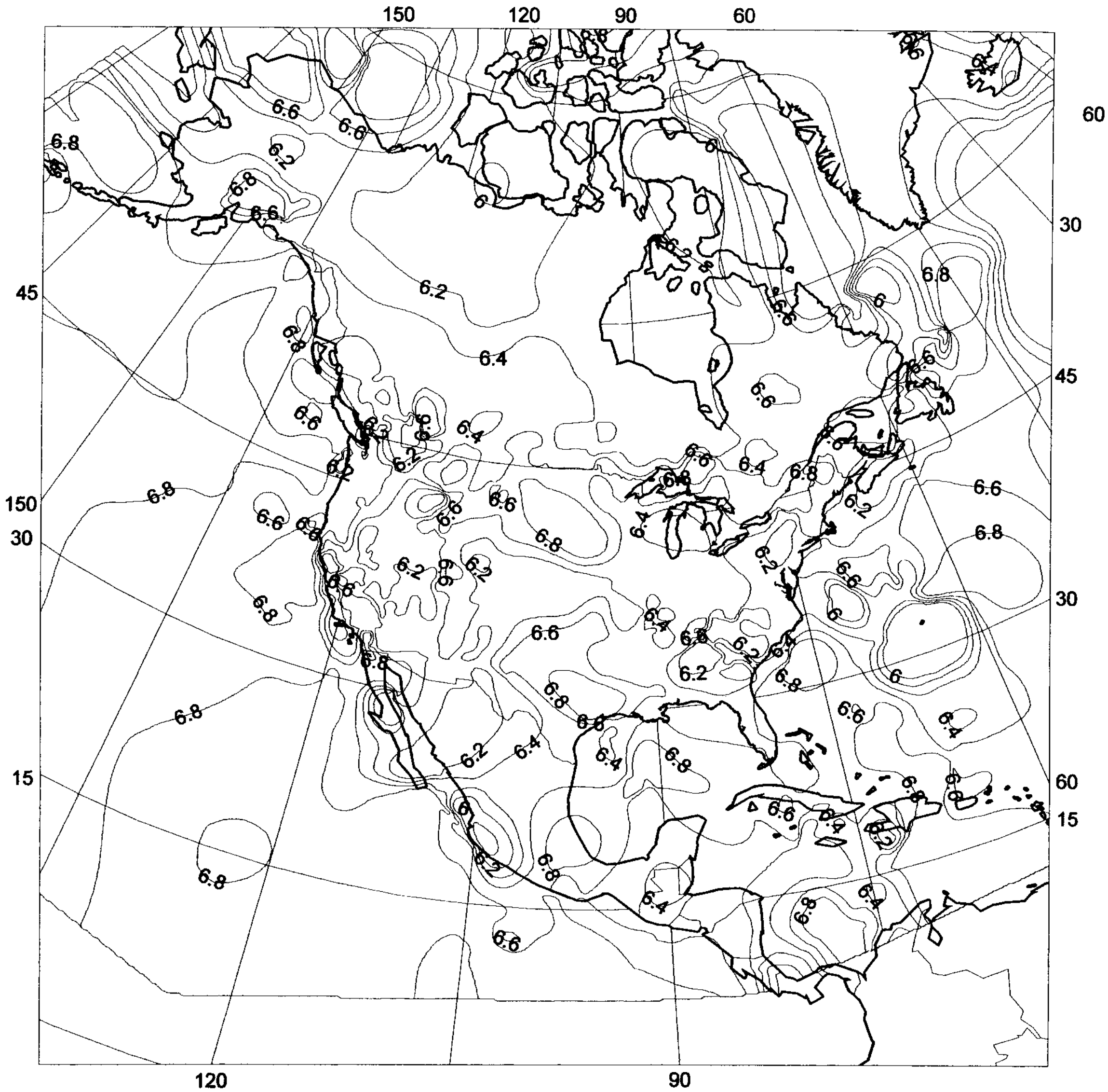

Figure 5. Contour map of P_{cc}, the average *P*-wave velocity of the consolidated (crystalline) crust. The P_{cc} velocity differs from P_c (Fig. 4) in that surficial sediments (in fact, velocities <5.8 km/sec) are excluded from the calculation. The average velocity on continental crust is 6.45 km/sec; on oceanic crust it is 6.61 km/sec. These averages confirm the well-known fact that the crystalline oceanic crust is mafic (basaltic), whereas the continental crust is intermediate (equivalent to a diorite) (e.g., Christensen and Mooney, 1995).

map shows a combination of these features, with (1) high values (8.2 km/sec) following a north-to-south trend under the Great Plains; (2) lower values (~8.0 km/sec) under the Midwest; and (3) somewhat higher values (>8.1 km/sec) under the Appalachians and the Gulf Coast (Fig. 6). The *Pn* velocity structure of the continent warrants further analysis, especially with a more thorough consideration of seismic anisotropy.

Average Crustal *S*-Wave Velocity (S_c)

There are substantially fewer measurements of whole-crustal *S*-wave velocity (S_c) than of P_c velocity. The locations of data points and contours of S_c are shown in Figure 7. Given the sparse quantity of data (127 values), it is premature to draw detailed contour maps of this parameter. The current volume of S_c data is similar to that for P_c approximately 30 years ago, and thus our map for S_c is reminiscent of the P_c contour map of Pakiser and Steinhart (1964). Our simplified contour map of S_c indicates high *S*-wave velocities (>3.7 km/sec) under the craton and platform in central and eastern North America. In contrast, low *S*-wave velocities (<3.4 km/sec) appear under parts of western North America. The low S_c region in the west partially correlates with the low P_c region, and both correspond to regions with

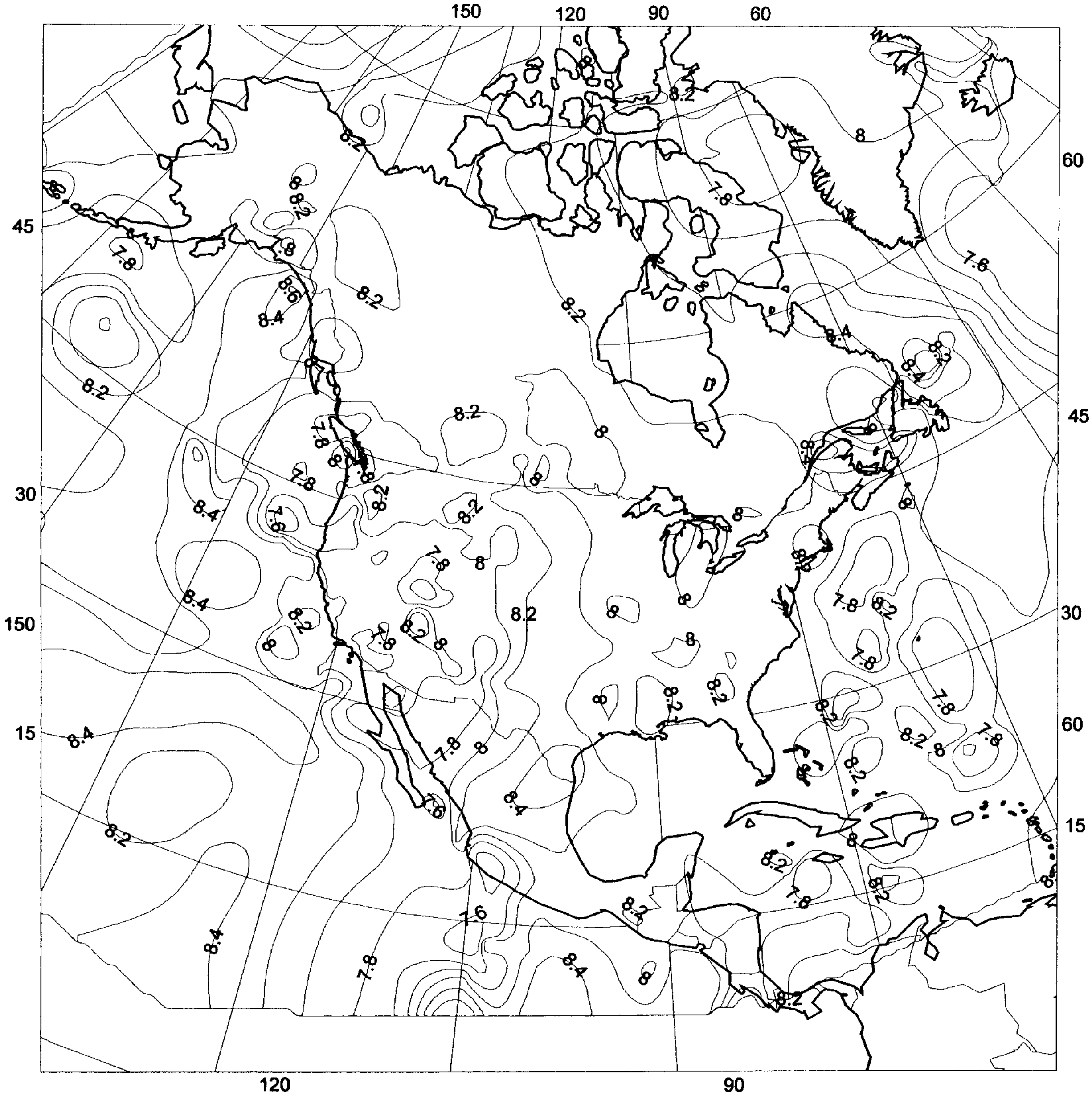

Figure 6. Contour map of sub-Moho *P*-wave velocity, *Pn*. The average velocity beneath continents and oceans are nearly equal (8.03 km/sec and 8.06 km/sec, respectively). There is a large contrast in values on either side of the Rocky Mountains: *Pn* values of 7.8 km/sec are common to the west, whereas values are more than 7.9 km/sec to the east. A roughly north–south zone of high (8.2 km/sec) *Pn* velocity lies along the western edge of the Great Plains. Further east, lower values (~8.0 km/sec) are typically measured.

high heat flow and extended crust. Intermediate values of S_c correlate with the Rocky Mountains and Atlantic and Gulf Coast plains.

Crystalline Crustal *S*-Wave Velocity (S_{cc})

The average *S*-wave velocity in the crystalline crust (Fig. 8) was calculated in a manner analogous to that for P_{cc} velocity. We assumed that a minimum value of 3.35 km/sec defined the top of the crystalline crust. This map shows many of the same general trends as the map of S_c (Fig. 7), including high velocities in the midcontinent and low velocities in the west.

Sub-Moho *S*-Wave Velocity (*Sn*)

Only 114 data points are available to define the contour map of *Sn* velocity beneath North America (Fig. 9). Given the sparse data, this map should be considered as preliminary. A comparison to the *Pn* velocity map (Fig. 6) shows

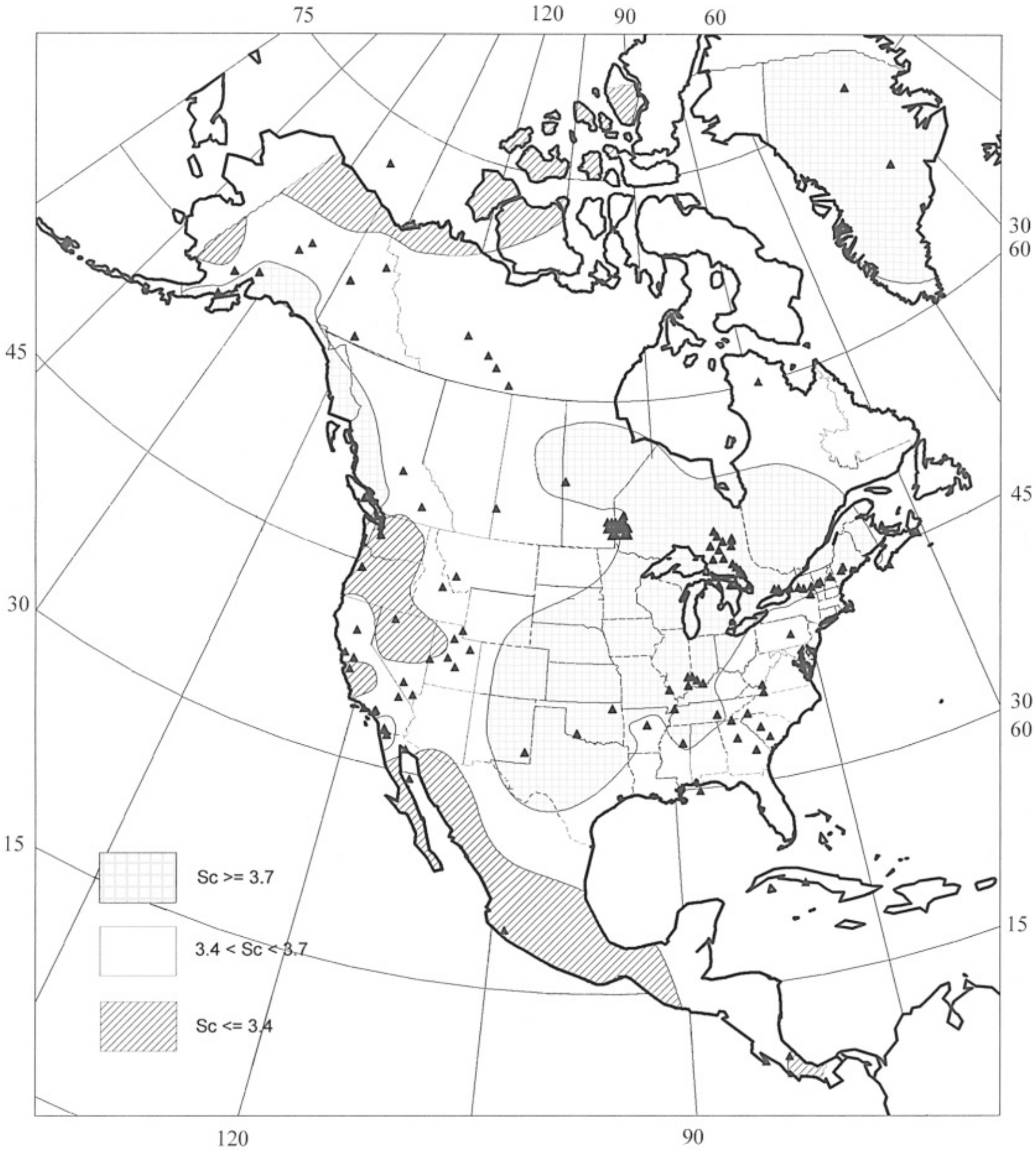

Figure 7. Contour map, with data points (triangles), of the average whole-crustal *S*-wave velocity. This map is preliminary because of the large gaps in data coverage; oceanic regions have few measurements and have not been considered. Regions of low velocity correlate with the high heat-flow region of the western United States and the volcanic province of Mexico. The cold Precambrian crust of the central United States and Canada (cf., Artemieva and Mooney, 2001) correlates with high S_c velocity.

a general correlation with low velocities under the western United States and higher velocities under the Great Plains and the southeast United States.

Statistical Analysis of the Geophysical Parameters

Statistical analyses of the seismic parameters appearing in the contour maps are presented in Tables 1 and 2. The ratio of some seismic parameters (P_c/S_c, P_{cc}/S_{cc}, and Pn/Sn), are also presented in Table 2. However, due to insufficient data density, these ratios are not presented in the form of contour maps. For comparison, we present the previous statistical analyses for North America of Braile *et al.* (1989) and the global statistical analyses of Christensen and Mooney (1995) in Table 1. The work of Christensen and Mooney (1995) was based on a worldwide set of 560 continental seismic-refraction data points. Histograms of these seismic parameters are presented in Figures 10 and 11.

Our average value for crustal thickness, H_c, for North America (36.7 km) is essentially the same as that obtained by Braile *et al.* (1989) (36.1 km) but is 2.5 km smaller than the global continental value of H_c (39.2 km) from Christensen and Mooney (1995). The difference between the North

Figure 8. Contour map, with data points (triangles), of the average *S*-wave velocity of the consolidated (crystalline) crust, S_{cc}. This map is preliminary because the data coverage is sparse. The general pattern is similar to that of the S_c contour map (Fig. 7): low S_{cc} velocities are found in the provinces with high heat flow in the western United States and Mexico, and high S_{cc} velocities correlate with the cold Precambrian crust of the central United States and Canada.

American and global averages can be attributed to several factors: (1) the large number of measurements of thin (25–30 km) crust in western North America; (2) an underrepresentation of measurements in central North America where the crustal thickness is 40–45 km; (3) the scarcity of North American crust with exceptional thickness (>50 km), such as that found beneath the Tibetan Plateau or the South American Andes; (4) the inclusion here of marine measurements made on the shallow and thin (20–25 km thick) continental shelf, which were not included in the analysis of Christensen and Mooney (1995).

We have quantitatively investigated the first and second factors. We used an interpolation technique to calculate crustal thickness for 2° by 2° cells and used these values to obtain an area-weighted average crustal thickness. The resultant value (36.8 km) is statistically identical to our simple average. Hence, the difference with respect to the global average of Christensen and Mooney (1995) can be attributed to factors three and four above.

All three analyses in Table 1 give an average value for P_{cc} (*P*-wave velocity of the crystalline crust) of between 6.44 and 6.47 km/sec, with an overall average near 6.45 km/sec. Because the global average as determined by Christensen and Mooney (1995) is also 6.45 km/sec, we believe that

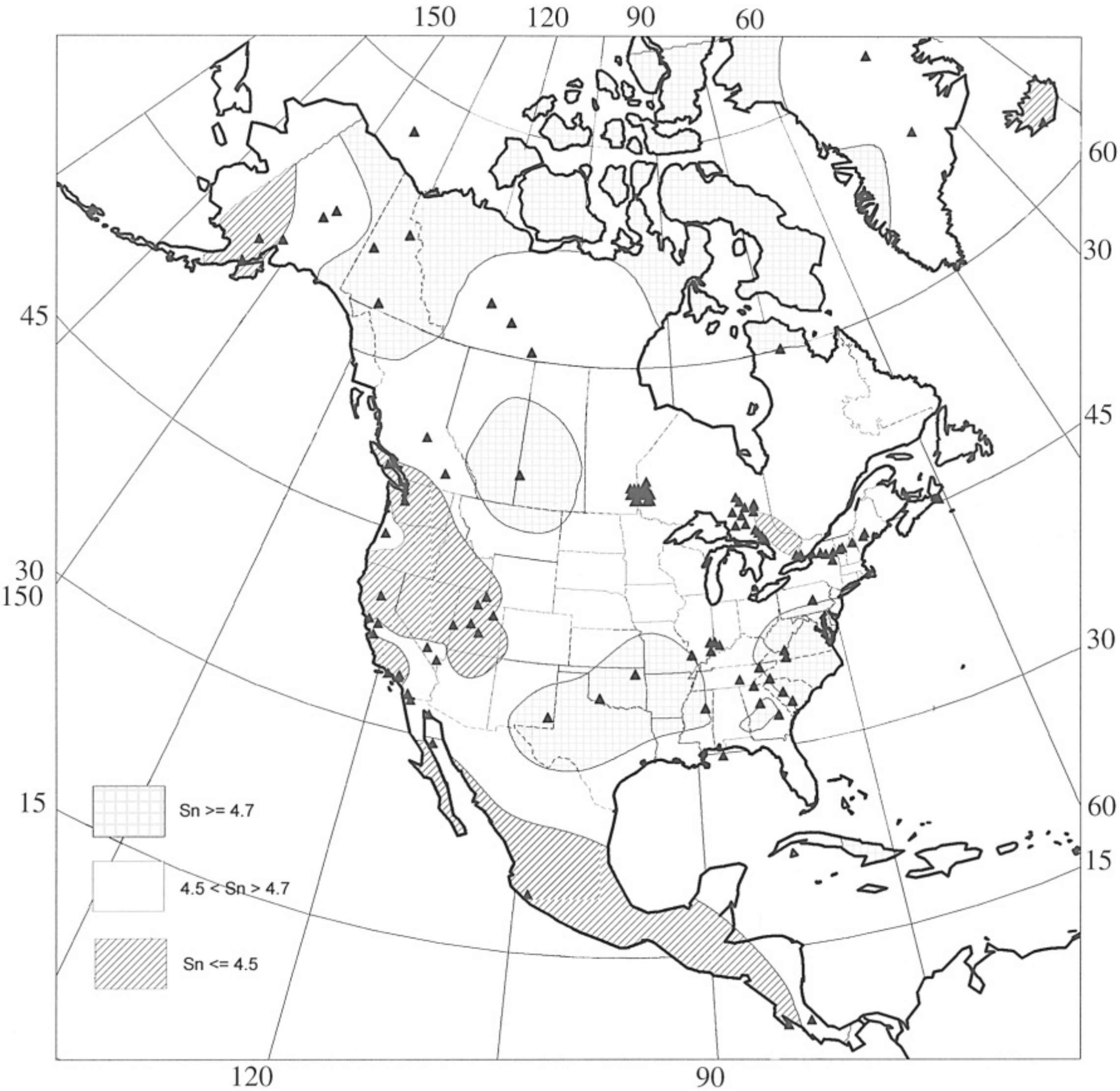

Figure 9. Contour map, with data points (triangles), of *Sn*, the sub-Moho *S*-wave velocity. The map is preliminary because of sparse data coverage. The general pattern of low velocities in the western United States and Mexico and of high velocities in the Precambrian and Paleozoic United States, as observed in the map of S_{cc} velocity (Fig. 8), is also evident in this map of *Sn* velocity. There is also a good correlation with the much more detailed map of *Pn* velocity (Fig. 6).

further analysis of P_{cc} data from other continents should arrive at the same result.

Our average value for the *Pn* velocity under North America (8.03 km/sec) is essentially identical to that of Braile *et al.* (1989) (8.02 km/sec) Both of these estimates are only slightly lower than the 8.07 km/sec global average of Christensen and Mooney (1995). Thus, both the North American and global continental estimates of average *Pn* velocity appear to be well-determined values that are unlikely to change as additional measurements are compiled. We emphasize that all of these statistical analyses assume a seismically isotropic mantle. An estimated 6% anisotropy will provide local variations in *Pn* velocity of ± 0.5 km/sec (i.e., 7.5–8.5 km/sec). Variations in mantle composition and especially temperature are also important factors for determining *Pn* velocity.

Histograms for the data used for the contour maps of Figures 3–8 provide additional insights into the properties of the crust. It is evident that the modal (i.e., most frequent) value of crustal thickness is 30 km (Fig. 10), a value that may be considered as thin crust on a global basis (Christensen and Mooney, 1995). As discussed previously, this low modal value is due to the numerous crustal profiles in western North America and the relative paucity of data from the middle of the continent. Figure 10 also shows that 95% of all measurements fall in the range 20–50 km, and there are

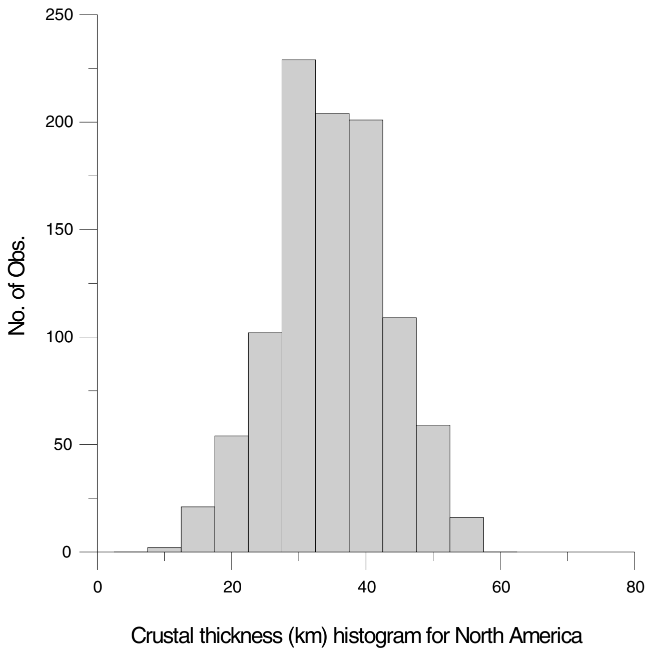

Figure 10. Histogram of continental crustal thickness, H_c, for North America, including the continental shelf (water depth <500 m). The most frequently reported value (mode) is 30 km; the average value is 36.7 km with a standard deviation of 8.4 km. Crustal thickness in excess of 50 km is rare. The average thickness of the crust is 2.5 km less than the global value (39.2 km) of Christensen and Mooney (1995), who did not include measurements on the continental shelf in their analysis.

no measurements in North America with a crustal thickness greater than 56 km.

The histograms for P_c and S_c (Fig. 11A, B) and for P_{cc} and S_{cc}, (Fig. 11C, D) show two modest peaks in the distribution. Thus, the average velocity of the continental crust has a bimodal distribution for both *P* and S waves. Our global database shows that similar plots of P_{cc} for all the other continents (with the exception of Antarctica, where data are extremely sparse) display the same bimodality. We interpret this bimodality as indicating the existence of two end-member types of continental crust. What distinguishes these two crustal types is the presence or absence of a high-velocity (6.9–7.3 km/sec) lower crustal layer. Thin (20–35 km) crust commonly lacks a high-velocity lower crustal layer and has a low (<6.3 km/sec) average crustal velocity (Meissner, 1986; Mooney *et al.*, 1998). Thick (35–50 km) crust, particularly that of stable continental interiors (i.e., platforms and shields), often has a high-velocity lower crustal layer and therefore has a relatively high (>6.5 km/sec) average crustal velocity. Together, these two crustal types provide a mean average crustal velocity of 6.45 km/sec.

Pn velocity is sharply peaked around the average value of 8.03 km/sec (Fig. 11E). Most measurements of *Pn* velocity are in the range 7.8–8.2 km/sec. Continental-scale variations in *Pn* velocity largely correlate with the thermal state of the lithosphere, with lower *Pn* velocities being associated with higher lithospheric temperatures (e.g., Mooney and Braile, 1989). *Sn* velocity peaks around 4.6 km/sec (Fig. 11F).

Conclusions

New contour maps and statistical analyses of the seismic structure of the crust and uppermost mantle of North America and the surrounding ocean basins have been constructed using a large volume of new measurements, including data from some previously unexplored regions. We have primarily used results from seismic-refraction surveys, with additional data (~15%) (Table 3) coming from earthquake tomography studies, surface-wave analyses, and receiver functions. From these data we conclude the following:

1. The average of 997 measurements of continental crustal thickness (H_c) for North America is 36.7 km. This is 2.5 km less than the global average of 39.2 km (Christensen and Mooney, 1995) and reflects the inclusion in our analysis of numerous marine measurements made on the shallow and thin (20–25 km) continental shelf and the paucity of regions in North America with very thick (>50 km) crust.
2. Thin (28–35 km) crust extends from the Basin and Range Province into the Canadian Cordillera and correlates with low average crustal velocities and low mantle (*Pn*) velocities. The thickest (40–56 km) crust occurs under the central Great Plains and Mid-Continental Rift. The transition from continental to oceanic crust is a wide zone on the passive eastern margin of North America and is a narrow zone on the active western margin.
3. Histograms of whole-crustal average *P*- and *S*-wave velocities and of the crystalline crust are bimodal. A lower average crustal velocity (<6.3 km/sec) correlates with thin crust that lacks a high-velocity (6.9–7.3 km/sec) lower crustal layer, and a higher average crustal velocity (>6.6 km/sec) correlates with the thick (40–56 km) crust of the continental interior that includes a high-velocity basal crustal layer.
4. The average *P*-wave velocity of the eastern Pacific Ocean crust is higher than that of the western Atlantic Ocean crust due to a thinner sediment layer (layer 1) in the eastern Pacific Ocean.
5. The average *P*-wave velocity of the crystalline crust of North America is equal to the global average of 6.45 km/sec (Christensen and Mooney, 1995). Since average crustal velocity is directly related to composition, the uniformity of this parameter strongly supports the hypothesis that crustal formation has been a uniform process on a global scale for at least the past 3.0 Ga.
6. The average *Pn* velocity under North America is 8.03 km/sec with more than 90% of all measurements falling in the range of 7.8–8.2 km/sec. Locally, 4%–5% seismic anisotropy in *Pn* velocity has been reported. However,

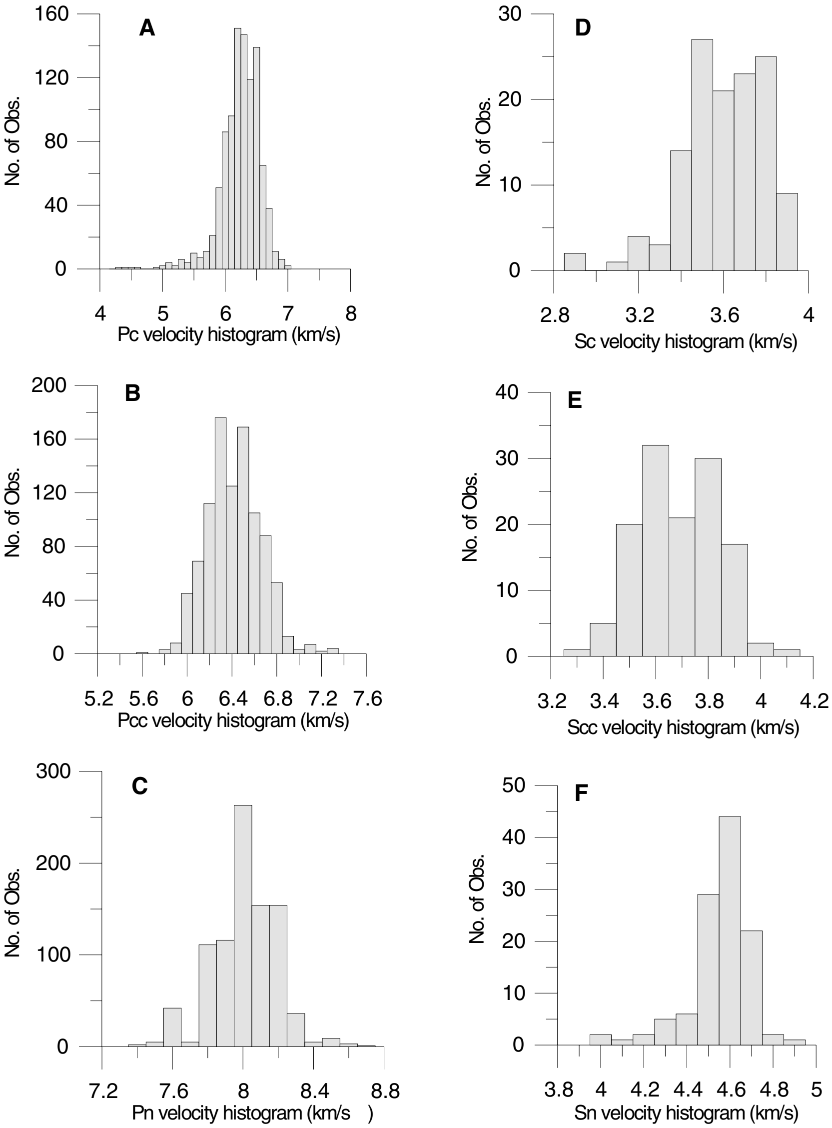

Figure 11. Histograms for six seismic parameters for continental North America: (A) P_c, (B) P_{cc}, (C) *Pn*, (D) S_c, (E) S_{cc}, and (F) *Sn*. The histograms for P_c and P_{cc} (A and B) are bimodal. The higher valued peak (e.g., 6.5 km/sec for P_{cc}) correlates with continental crust that has a high-velocity (6.9–7.3 km/sec) lower crustal layer. In contrast, extended continental crust often lacks this layer and has a lower (6.2 km/sec) P_{cc} velocity. Most *Pn* velocities (C) fall in the range 7.8–8.2 km/sec, with some reported values as high as 8.5–8.6 km/sec. The histograms for S_c and S_{cc} (D and E) show the same bimodality as the histograms for P_c and P_{cc}. The plot of *Sn* shows a clear peak at 4.6 km/sec. The *Pn*/*Sn* ratio is 1.76, close to the ideal value of 1.73 (square root of 3).

the continental-scale variation in *Pn* velocity can be attributed primarily to variations in lithospheric temperatures (e.g., Artemieva and Mooney, 2001).

The complete North American database and the associate list of source references may be obtained on the Internet from the authors at *http://quake.wr.usgs.gov/research/structure/CrustalStructure/nam/index.html.*

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