Seismic and laboratory constraints on crustal formation in a former continental arc (ACCRETE, southeastern Alaska and western British Columbia)

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Received 28 December 2001; revised 29 May 2002; accepted 4 September 2002; published 25 January 2003.

[1] T6e ACCRETE project studies continent formation by assemblage of exotic terranes and arc magmatism. A marine-land seismic profile crosses the terranes with dense sampling and remarkably strong *S* waves as well as *P* waves. Unique, high-quality *S*-wave seismic data provide further constraints on interpretation and are used together with new laboratory *P*- and *S*-wave velocity measurements (corrected for high temperatures within and at the base of the crust) to make a lithologic and petrologic interpretation. V_P/V_S ratios indicate three distinct terranes that were assembled to form continental crust. These terranes are the outboard, accreted Alexander-Wrangellia terrane, the Coast Mountains Batholith (CMB) magmatic arc, and the inboard Stikinia terrane. Below the CMB, V_P and V_P/V_S to a depth of 10–15 km are appropriate for tonalite and diorite. The V_P and V_P/V_S increase with depth indicating that the rocks become more mafic, but V_P/V_S is not high enough for gabbro. The V_P and V_P/V_S of the lower crust are consistent with a mixture of mafic garnet granulite and restite, whose quartz content lowers the V_P/V_S ratio below that of gabbro. When corrected for high temperature and uplift due to exhumation, the crust under the CMB exhibits seismic properties of an average continental crust. These results suggest that gabbro could have intruded a metasedimentary pile in the deep crust to cause melting of the metasediments to form intrusions of the CMB, leaving behind a mixture of mafic garnet granulite and sillmanite-garnet-quartz restite and generating the deeper part of what becomes an average continental crustal section. *INDEX TERMS:* 5102 Physical Properties of Rocks: Acoustic properties; 7205 Seismology: Continental crust (1242); 7218 Seismology: Lithosphere and upper mantle; 8105 Tectonophysics: Continental margins and sedimentary basins; 8110 Tectonophysics: Continental tectonics—general (0905); *KEYWORDS:* Continental crust, seismic velocity, crustal growth, batholith, accreted tarranes

Citation: Morozov, I. B., N. I. Christensen, S. B. Smithson, and L. S. Hollister, Seismic and laboratory constraints on crustal formation in a former continental arc (ACCRETE, southeastern Alaska and western British Columbia), *J. Geophys. Res.*, *108*(B1), 2041, doi:10.1029/2001JB001740, 2003.

1. Introduction

[2] The ACCRETE program is a collaborative project to determine how continents grow by magmatic and terrane accretion, and to investigate the relative roles of these processes. The focus is on the Coast Mountains orogen of southeast Alaska and British Columbia (Figure 1). This orogen, one of the largest in the world, was formed during plate convergence between the Jurassic and Eocene, and by extension from Eocene to present. A primary target of the study is the characterization of processes of crustal formation as might be manifested by the observed seismic velocity and reflectivity structure within the crust and calibrated by laboratory velocity measurements.

[3] By combining geophysical and geological data, we are investigating the structure across the Coast Mountains orogen from the surface to the upper mantle. The central segment of the orogen, at the latitude of Prince Rupert, British Columbia, is an ideal location for a combined geophysical and geologic cross section because (1) inland marine waterways enable acquisition of seismic data across the orogen that are exceptional in quality and quantity, (2) rocks presently exposed at the surface were formed at midcrustal levels, and (3) midcrustal geological features can be projected from the surface downdip into the seismic section.

[4] ACCRETE resulted in a wide-angle seismic data set that is unique in its volume and quality of *S*-wave information. V_P/V_S ratios provide additional constraints on crustal

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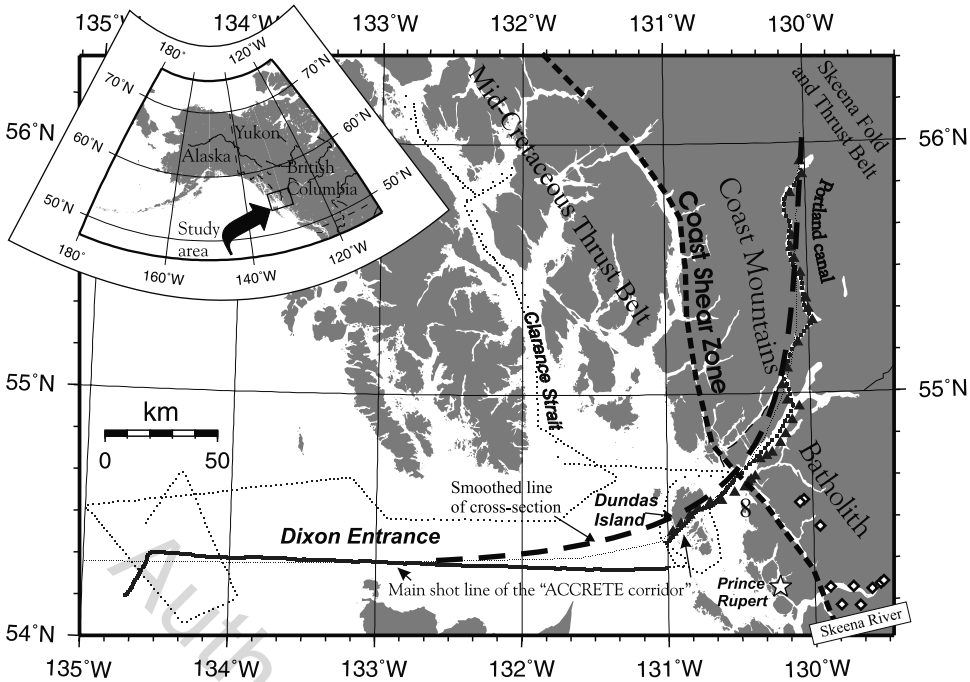

Figure 1. Location map of the ACCRETE wide-angle experiment area discussed in this paper. Triangles indicate REFTEK wide-angle recording sites; air gun shot lines are shown in dotted and solid lines, with solid lines corresponding to the shots used in this interpretation. Heavy dashed line is the smoothed line of the resulting cross-section shown in Figure 2. Station 8 (used in Figure 5 below) is indicated. White diamonds SE of the line show the locations of rock samples used in this study. Inset shows the location of study area.

composition besides those from *P*-wave velocities alone [*Zandt and Ammon*, 1995; *Christensen*, 1996]. This is particularly important because many common crustal rock types have similar *P*-wave velocities [e.g., *Birch*, 1960, 1961; *Christensen and Mooney*, 1995], but different V_P/V_S. Note that although it has become customary to associate V_P/V_S ratio with Poisson's ratio (which is a mechanical characteristic of the rock), in the following we use the direct V_P/V_S ratios, thus remaining closer to the observed properties.

[5] Previously published seismic results include a V_P velocity model across the Coast Mountains orogen [*Morozov et al.*, 1998], a V_P/V_S model [*Morozov et al.*, 2001], and summaries of the results from Multichannel Seismic (MCS) profiling [*Hollister et al.*, 1997; *Rohr et al.*, 2000]. The ACCRETE seismic line was extended into the interior of British Columbia, and these results were described by *Hammer et al.* [2000]. Geological interpretations pertaining to the ACCRETE cross section are given by *Hollister and Andronicos* [1997], *Klepeis et al.* [1998], *Chardon et al.* [1999], *Andronicos* [1999], *Evenchick et al.* [1999], and *Andronicos et al.* [1999, 2003].

[6] In this paper, we correlate the wide-angle crustal *P*- and *S*-wave velocity estimates beneath the Coast Mountains Batholith (CMB, Figure 2) [*Morozov et al.*, 1998, 2001] with laboratory measurements using samples from the ACCRETE study area. Our seismic velocity estimates are based on the ACCRETE marine-land recording in August and September 1994, using the air guns and streamer of the research vessel *Maurice Ewing* and REFTEKs on land. Acquisition in a fjord provided good geologic control, strong *P-S* wave coupling at its bottom, and resulted in unusually consistent and strong *P*- and *S*-wave energy in the seismic section [*Morozov et al.*, 1998]. Our laboratory study includes 20 rock samples collected within an area of the CMB (Figure 1) that projects downdip into the lower crust of the seismic cross-section [*Hollister and Andronicos*, 1997]. *P*- and *S*-wave velocities and anisotropy measured up to 1 GPa, together with temperature corrections for the geothermal gradient, provide representative sampling that can be correlated with the results of seismic imaging, thereby resulting in an unique opportunity to apply V_S and V_P/V_S constraints to compositional interpretation.

2. Tectonic and Geologic Setting

[7] The CMB (also called Central Gneiss Complex, or Paleogene arc) lies between the combined Alexander and Wrangellia (outboard) terranes to the west and the Stikinia (inboard) terrane to the east (Figures 1 and 2). The CMB consists of high-grade metamorphic rocks intruded by late Cretaceous to Eocene tonalite and granodiorite plutons [*Hutchison*, 1982; *Crawford et al.*, 1987]. Most of the surface of the area of the seismic section was exhumed during the early Eocene from depths of 15–25 km [*Hollister*, 1982], and most of the structures now at the surface were formed in the ductile deformation field.

[8] A prominent, crustal-scale feature, referred to as the coast shear zone (CSZ), separates the CMB from terranes to the west. The CMB has a markedly different thermal and structural history from these terranes, and the CSZ is thus the likely surface expression of a crustal-scale shear zone. At the surface, the CSZ can be traced for at least 800 km

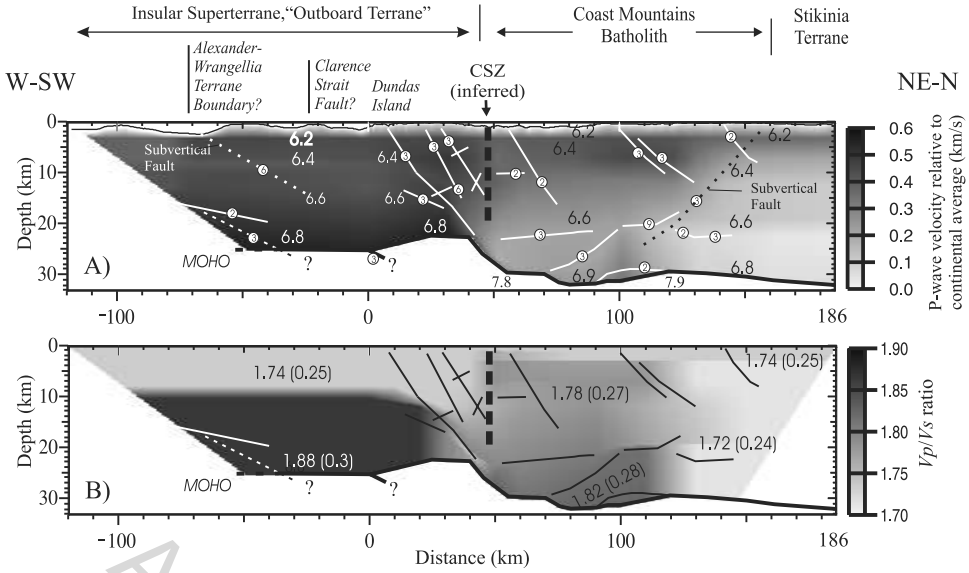

Figure 2. (a) *P*-wave velocity and (b) V_P/V_S models obtained by inversion of ACCRETE wide-angle seismic data [*Morozov et al.*, 1998, 2001]. Gray-scale shading in Figure 2a indicates *P*-wave velocity excess over the continental average profile [*Christensen and Mooney*, 1995], labels indicate seismic velocities. Solid lines show imaged dipping and out-of-plane reflectors. In Figure 2b, labels indicate the values of V_P/V_S, with the corresponding Poisson ratios (for isotropic rock) given in parentheses.

through southeast Alaska and northern British Columbia, and it may be over 2000 km long [*Cowan et al.*, 1997]. The CSZ is a candidate for the eastern boundary of the Kula plate during its transpressive to transcurrent motion relative to North America, between about 85 and 45 Ma. Earlier geological studies in the area of our seismic section showed that a mid-Cretaceous thrust belt west of the CSZ [*Crawford et al.*, 1987] extends close to the Moho [*Morozov et al.*, 1998], demonstrating that the thrust belt is "thick-skinned," as deduced from the surface geology. It is truncated by the CSZ showing that the CSZ is younger than mid-Cretaceous. In the seismic profile [*Morozov et al.*, 1998], a 4-km difference in depth to Moho underneath the mapped expression of the CSZ and the truncation of dipping reflectors to either side of it (Figure 2) strongly support an interpretation that the CSZ is the surface expression of a very important high temperature, nearly vertical, ductile shear zone that extends from the surface to across the Moho.

[9] Surface geological work shows that dextral transpressive displacement took place across the CSZ between 85 and 58 Ma [*Andronicos et al.*, 1999, 2003]. The amount of displacement is unknown, but it is likely substantial (over hundreds of kilometers) because measured shear strains are large across a wide zone of shear [*Andronicos et al.*, 1999, 2003]. The CSZ may thus be one of the most important known crustal shear zones in the world.

[10] Within the CMB, from the line of seismic section for some 100 km to the south, where rock samples were collected, layers of tonalite and gabbro within layers of migmatite project from the surface to the line of the seismic section [*Hollister and Andronicos*, 1997]. Within the migmatite are layers hundreds of meters thick of high-density restite composed of sillimanite, garnet, and plagioclase, and within the tonalite and gabbro, are layered mafic cumulates. The plutons are mostly concordant to the foliation of the enclosing high-grade metamorphic rocks and contain magmatic to solid state penetrative fabrics concordant to their contacts. Geological evidence for the role of basaltic liquid in the formation of the CMB [*Hollister and Andronicos*, 1997] suggested that the seismic study might also identify ponding and interlayering of this gabbro at the base of the crust [*Morozov et al.*, 2001].

[11] Geologically, the boundary between the CMB and the Stikinia terrane is defined by east-dipping normal shear zones between the migmatites of the footwall and the greenschist to amphibolite facies rocks of the hanging wall [*Andronicos*, 1999; *Andronicos et al.*, 2003]. The ACCRETE seismic images show that the normal shear zones can be traced to at least midcrustal depths (Figure 2). The extension which produced these shear zones occurred in the Eocene [*Hollister and Andronicos*, 1997; *Andronicos*, 1999; *Andronicos et al.*, 2003], and resulted in an asymmetric core complex with steep fabrics on its west side. This supports an inference that Eocene crustal scale extension thinned the crust; and it implies that the exhumation of the high metamorphic grade core of the CMB was in part due to tectonic unroofing.

3. Wide-Angle Seismic Results

[12] Figures 2a and 2b show the V_P and V_P/V_S crustal velocity cross-sections derived from a combination of wide-angle and MCS data by *Morozov et al.* [1998, 2001]. Unusually dense *S*-wave coverage resulted in a model of V_P/V_S velocity ratios (Figure 2b) that can be directly compared with the *P*-wave velocity structure in Figure 2a. Subsequently, we summarize the seismic results along this cross-section and concentrate on those beneath the CMB.

[13] From the variations in V_P and V_P/V_S, we identify three prominent crustal blocks (Figures 2a and 2b). Although

the variations of the crustal structure are pronounced in the *P*-wave model, these blocks are particularly distinct in the V_P/V_S domain (Figure 2b) [*Morozov et al.*, 1998, 2001].

[14] The average *P*-wave crustal velocity ranges between 6.5 and 6.6 km/s staying somewhat above the continental average profile within the major part of the section and probably approaching this average toward the Skeena fold and thrust belt at the NE as highlighted by the gray scale representation in Figure 2a. NE of the CSZ, under the CMB, the Moho deepens from 23 to 32 km, probably in two steps (Figures 2a and 2b). NE of 100 km of the profile (Figures 2a and 2b), a slight arch in the Moho might be related to extension of the crust, as suggested by *Hollister et al.* [1997]. Travel time data also show that between Dundas Island toward the CSZ from the west, the Moho shallows from 25 km to approximately 23 km near the CSZ (Figure 2a). Further west, mid- to lower-crustal velocities are somewhat higher than those under the CMB; for NE end of the seismic profile, the model shows velocities distinctly lower than under the CMB (Figure 2a), and results for the same area from *Hammer et al.* [2000] show a crust with low average velocity of 6.25 km/s.

[15] Within the crust of the Alexander-Wrangellia terrane (west of 20–40 km in Figure 2), we identify "normal" upper crust, with V_P/V_S = 1.74, whereas the middle and lower crusts exhibit the highest V_P/V_S in our section, near 1.88. For isotropic rock, such a range of velocity ratios would correspond to Poisson's ratios from 0.25 to 0.30. The V_P and V_P/V_S of the lower crust in this region correspond to those typical of gabbro [*Christensen*, 1996], suggesting that the base of the Alexander-Wrangellia terrane along the seismic profile is oceanic. The contrasts in V_P and V_P/V_S along the seismic profile at the CSZ (Figures 2a and 2b) thus suggest significant compositional differences of the outboard Alexander-Wrangellia terrane from the CMB.

[16] Beneath the western part of the surface expression of the CMB, the upper crustal layer with $V_P/V_S \approx 1.74$ is about 3-km thick, whereas the middle and lower crust show V_P/V_S values between 1.78 and 1.82. These values are lower than those normally associated with gabbros (about 1.85–1.86) [*Christensen*, 1996], and correspond to Poisson's ratios between 0.27 and 0.28. These values are similar to those determined for mafic garnet granulite and restites (see section 5 subsequently).

[17] NE of 120–130 km of our profile, the entire crust shows lower than "normal" V_P/V_S of 1.74, constant within the measurement error. Both V_P and V_P/V_S values in this region (apart from the suggested decrease in V_P/V_S with depth) are corroborated by the observations from the extension of the profile to the NE [*Hammer et al.*, 2000].

[18] To summarize the seismic results, we find (1) low V_P/V_S in the upper crust and high *P*-wave velocities and V_P/V_S in the lower crust of the Alexander-Wrangellia terranes, (2) a relative increase of velocity and V_P/V_S within the upper and midcrust, and decrease in the lower crust of the CMB, between 80 and 120 km, and (3) decrease of V_P and V_P/V_S approaching the Skeena fold and thrust belt (Figures 2a and 2b). Under the CMB, the velocities change from about 6.3 km/s at 5-km depth to over 6.4 km/s at 10 km, somewhat exceeding estimates of continental averages of 5.95 and 6.2 km/s, respectively (Figure 3) [*Christensen and Mooney*, 1995]. The V_P/V_S ratios within the CMB range between 1.78 near 10-km depth and 1.82 at the base of the crust, also exceeding an estimate of the continental average of 1.77 [*Christensen*, 1996]. After a correction [*Christensen*, 1974] for high heat flow and for uplift during exhumation, the CMB velocity-depth profile matches the continental average below 10-km depth (Figure 3). This correspondence suggests that a former continental arc represented by the CMB may present an example of new continental crust generated by terrane and magmatic accretion followed by subsequent extension and cooling.

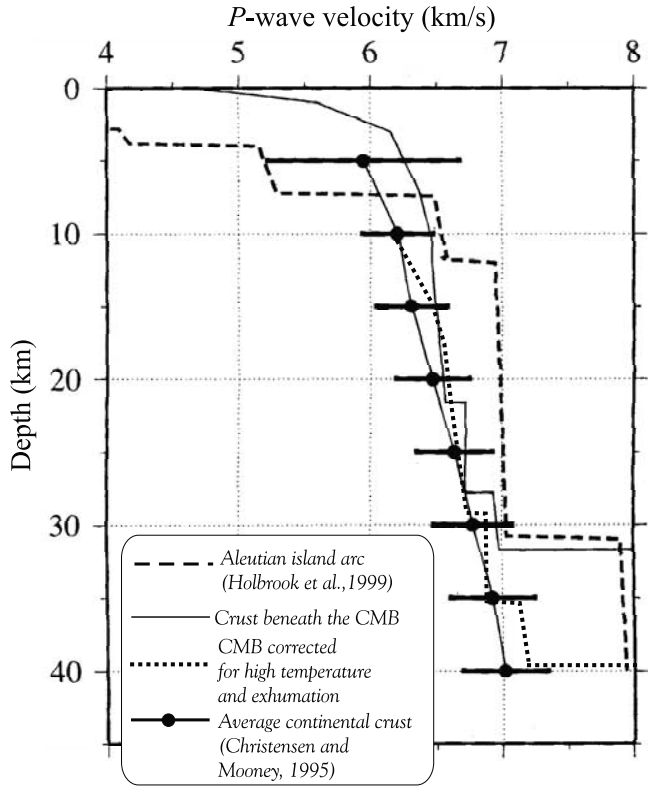

Figure 3. Velocity-depth profile beneath the CMB (75 km in the cross-sections of Figure 2). The average continental velocity profile from *Christensen and Mooney* [1995] is also shown together with its standard deviations at 5-km depth increments. Note that after removal of the effects of high-crustal temperature and uplift during exhumation, the observed CMB profile (dotted line) closely matches the continental average throughout the entire depth range. For comparison, velocity profile under the Aleutian island arc (dashed line) [*Holbrook et al.*, 1999] exhibits significantly higher velocities at mid to lower-crustal depths.

4. Laboratory Velocity Measurements

[19] We determined *P*- and *S*-wave velocities at pressures of up to 1 GPa for 20 rock samples from within the CMB. The samples represent important lithologies found within the CMB and projecting downdip into the lower crust of the portion of the seismic cross-section [*Hollister and Andronicos*, 1997]. The data are summarized in Table 1, and the locations of the samples are shown in Figure 1. The samples include plutonic rocks ranging in composition from granodiorite to diorite, orthogneiss, amphibolite, and paragneiss

Table 1. Mean Compressional Wave Velocities (V_P, km s^{-1}), Shear Wave Velocities (V_S, km s^{-1}), Poisson's Ratio (σ), Shear Wave Anisotropy at 400 MPa (ε, %) and Densities (ρ, kg m^{-3}) for ACCRETE Rocks at Room Temperature[a]

Rock	ρ	$P = 40$ MPa				$P = 100$ MPa				$P = 400$ MPa					$P = 1000$ MPa			
		V_P	V_S	V_P/V_S	σ	V_P	V_S	V_P/V_S	σ	V_P	V_S	V_P/V_S	σ	ε	V_P	V_S	V_P/V_S	σ
Intrusives																		
Ponder Pluton Granodiorite (BC-12)	2678	5.235	3.102	1.69	0.23	5.962	3.458	1.73	0.25	6.331	3.627	1.75	0.26	0.9	6.505	3.680	1.77	0.27
Kasiks Sill Diorite (BC-6)	2785	4.258	2.633	1.62	0.19	5.493	3.254	1.69	0.23	6.421	3.695	1.74	0.25	3.7	6.655	3.790	1.76	0.26
Kasiks Sill Diorite (BC-13)	2792	4.759	2.859	1.66	0.22	5.775	3.365	1.72	0.24	6.520	3.655	1.78	0.27	5.0	6.734	3.735	1.80	0.28
Quotton Pluton Diorite (BC-7)	2804	4.691	2.907	1.61	0.19	5.822	3.393	1.72	0.24	6.560	3.665	1.79	0.27	3.0	6.730	3.717	1.81	0.28
Paragneiss																		
Central Gneiss Complex Gray Gneiss (BC-5)	2787	4.545	2.700	1.68	0.23	5.540	3.157	1.75	0.26	6.231	3.469	1.80	0.28	10.8	6.461	3.568	1.81	0.28
Central Gneiss Complex Gray Gneiss (BC-4)	2797	4.734	2.864	1.65	0.21	5.517	3.214	1.72	0.24	6.204	3.499	1.77	0.27	15.0	6.473	3.605	1.80	0.28
Central Gneiss Complex Gray Gneiss (BC-10)	2789	4.589	2.722	1.69	0.23	5.552	3.222	1.72	0.24	6.456	3.639	1.77	0.27	6.4	6.726	3.745	1.80	0.28
Central Gneiss Complex Restite (BC-3)	2740	5.609	3.354	1.67	0.22	5.894	3.265	1.81	0.28	6.242	3.653	1.71	0.24	12.9	6.409	3.713	1.73	0.25
Central Gneiss Complex Restite (BC-14)	2984	5.464	3.211	1.70	0.24	6.327	3.642	1.74	0.25	6.980	3.929	1.78	0.27	4.8	7.230	4.027	1.80	0.28
Central Gneiss Complex Restite (TPR-30-cc)	2898	6.161	3.569	1.73	0.25	6.692	3.821	1.75	0.26	7.049	3.991	1.77	0.27	1.4	7.222	4.039	1.79	0.27

[a]Each velocity is the average of velocities measured in three mutually perpendicular directions. Shear wave anisotropy parameter is defined as $\varepsilon = (V_{S_{max}} - V_{S_{min}})/V_{S_{average}}$, where $V_{S_{max}}$ and $V_{S_{min}}$ are the maximum and minimum velocities measured in these three directions, respectively. A complete table of all measurements is available at http://w3.uwyo.edu/~seismic/accrete/accrete-samples.html.

restite represented by several garnet and sillimanite-rich gneiss samples. This rock type represents the residual solid component of partially melted arc-derived sediments from which melt had been extracted, i.e., a restite [*Hollister and Crawford*, 1990].

[20] Three mutually perpendicular cores were removed from each sample using a 1-in. (2.54-cm) diameter bit. For banded and foliated rocks, one core was taken normal to the planar structure, and the other two were oriented with their axes in plane. Of these two, one was oriented parallel to lineation, if present. Each core averages approximately 5 cm in length.

[21] The core ends were trimmed and ground flat and parallel to within 0.07 cm on a diamond-grinding disk. The volume of each core was measured from the length and diameter. The cores were weighed and densities were calculated from their weights and dimensions. Each core was then fitted with a soldered copper jacket to prevent penetration of high-pressure oil into the rock samples. To make velocity measurements, 1 MHz transducers were affixed to both core ends. Gum rubber tubing was placed over the sample assembly as a further prevention of leakage.

[22] Velocities were measured at room temperature and hydrostatic pressures up to 1 GPa (equivalent to ~35-km depth) using the pulse transmission technique described by *Christensen* [1985]. A pulse generator produced a 50-V square wave, simultaneously triggering a dual-trace oscilloscope. The pulse was sent to the sample sending transducers and to a calibrated variable length mercury delay line. The output signals were then viewed on the oscilloscope screen. The length of the delay line was varied until the first arrivals of the two signals coincided, corresponding to equal transit times. Readings were taken at 20, 40, 60, 80, 100, 200, 400, 800, and 1000 MPa and repeated for downgoing pressures. The delay line readings, the acoustic velocity in mercury, and the length of the sample permit calculations of the velocity in the sample.

[23] Table 1 summarizes the results of our measurements. In comparing seismic and laboratory velocity measurements, it is necessary to take into account the elevated temperatures within the study area [*Lewis*, 1997] leading to systematically reduced field velocity estimates. After correction for an estimated CMB geotherm, these laboratory measurements are compared to a cross-section of our seismic velocity model under the CMB (at 75 km on the profile) in Figure 4. The temperature correction is based on a thermal gradient derived from crustal thickness, low P_n velocity, and known paucity of heat producing elements in the rocks of the CMB [*Hollister*, 1982]. Taking crustal thickness to be 30 km and the mantle temperature just below the Moho to be 800°C [*Hyndman and Lewis*, 1999], and assuming no heat generation within the CMB, we obtain a temperature/pressure gradient within the crust of 0.8°C/MPa. For comparison, the seismic inversions at −50 and at 150 km, under the Insular superterrane and Stikine terranes, respectively, are also shown in Figure 4.

[24] The plutonic rocks show low anisotropies (Table 1). Petrographic examination of the velocity samples from the Kasiks and Ponder plutons shows no significant preferred mineral orientations. The restites, on the other hand, have significant (up to 13%) seismic anisotropy which originates for the most part from preferred mica orientation. Compres-

sional wave velocities are low normal to foliation and high for propagation in the foliation and parallel to lineation.

[25] Along with a systematic bias due to high crustal temperature, measurement errors are also inherently different for the two types of data presented in Figure 4. The average velocity values obtained by seismic travel time analysis (Figure 2) can be considered well constrained within the typical values of ±0.1 km/s (about 2%) for V_P and ±0.025 for V_P/V_S [*Morozov et al.*, 2001]. Due to their generation within the sedimentary column (including the sea bottom and the top of the basement), there is also an additional uncertainty in source location for *S* waves. This uncertainty does not exceed 0.2–0.6% for the typical sediment thicknesses <1 km and *SmS* propagation paths. Laboratory measurements provide very precise individual velocity measurements, within 0.5% [*Christensen*, 1996]; however, the resulting estimates of bulk rock properties are subject to uncertainties due to limited sampling. The effect of limited sampling can be estimated from the reported scatter (standard deviations) of velocity measurements in previous representative studies [*Christensen and Mooney*, 1995; *Christensen*, 1996]. A typical range of such scatter is 0.1–0.3 km/s for V_P and 0.1–0.2 km/s for V_S.

[26] Although the above uncertainties are difficult to evaluate more closely from the available data, their effects on bulk seismic velocities used in the interpretation should be reduced by spatial averaging inherent in field observations. The degree of such reduction depends on the statistical properties of the crust (e.g., scaling properties and clustering of the intrusions) and is largely unknown. Since the available data do not allow rigorous assessment of the resulting uncertainty in expected bulk velocity, we crudely estimate this uncertainty from the scatter in our lab measurements. This suggests a bulk V_P uncertainty of about 0.15 km/s (and a corresponding uncertainty in V_S), which should be taken into account in the interpretation of the $V_P - V_S$ relations in Figure 4.

5. Discussion

[27] Field and laboratory velocity data represent the bridge between seismology and petrology, but, as is well known, rock types cannot be interpreted uniquely from velocity. However, certain general relationships such as increasing density with increasing velocity exist. Shear wave velocity, V_S, is highly sensitive to the presence of quartz and to a lesser extent to plagioclase composition and amount of Fe-Mg substitution in olivine and pyroxene [Figure 9 of *Christensen*, 1996]. Increase of quartz content increases V_S and lowers V_P/V_S; increased anorthite content and/or amount of plagioclase increases V_P/V_S so that anorthosite has a very high V_P/V_S of 1.91. Our study supports the observation by *Christensen* [1996] of an approximately inverse linear relationship existing between SiO_2 and V_P/V_S between 55 and 75% silica content.

[28] Given both the field measurement error and scatter in lab data, what can reasonably be expected with regard to determining rock type from combined V_P and V_S measurements? Although many of the various rock types cluster close together in $V_P - V_P/V_S$ space [see Figures 8 and 9 of *Christensen*, 1996], with our *S*-wave data, seismic field determinations of V_P/V_S are good to about 0.025 [*Morozov et al.*, 2001], and some common rock types show good separation (Figure 4). Particularly important are granite-granodiorite, diorite, gabbro, anorthosite, and pyroxenite, which can be separated from each other. Garnet pyroxene granulite can probably not be distinguished from gabbro or from pelitic restite, unless the restite is quartz-rich. Thus from appropriately temperature-corrected seismic data, we should be able to recognize quartz-rich rocks like granite and related rocks, intermediate rocks like diorite, and mafic rocks like gabbro (including pyroxene granulite and garnet pyroxene granulite).

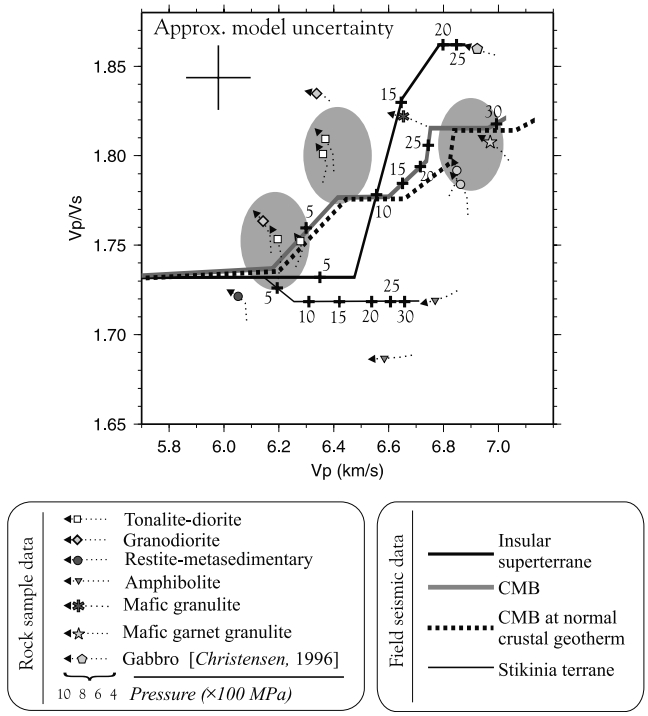

Figure 4. Comparison of V_P and V_P/V_S for ACCRETE rock samples (Table 1) with seismic measurements (Figures 2a and 2b). Laboratory velocities were corrected for high-crustal temperature under the CMB, using a temperature/pressure gradient of 0.8°C/MPa [*Christensen*, 1979]. Velocities between lithostatic pressures of 400 and 1000 MPa are shown, with solid ellipses corresponding to 800 MPa and arrows pointing in the direction of increasing pressure and temperature. Note that high-crustal temperature leads to velocities that are nearly constant or even decrease with increasing pressure. Average mafic (garnet) granulite and gabbro velocities are from *Christensen* [1996]. Shaded ellipses indicate the rock groups that can be unambiguously distinguished by use of combined V_P and V_P/V_S measurements. The lines represent velocity profiles across three locations in our velocity model (Figures 2a and 2b): Insular superterrane (–50 km of the profile), CMB (75 km of the profile), and Stikinia terrane (150 km shown in Figure 2). Heavy dotted line shows the CMB velocity profile corrected to a normal crustal temperature/pressure gradient of 0.6°C/MPa. Labeled crosses on the velocity profiles indicate depth levels in the model shown in Figures 2a and 2b.

[29] The laboratory measured tonalite and diorite data agree well with the CMB field measurements down to a depth of 10–15 km; therefore the CMB could be primarily composed of these rock types in the midcrust. Granodiorite cannot be a dominant lithology at depths greater than 10 km under the CMB. Below these depths, V_P increases from 6.4 to 6.6 km/s and then to 7.0 km/s as V_P/V_S increases to 1.82, indicating that batholithic rocks are becoming more mafic with depth, because both V_P and V_P/V_S become higher than the range of the measured tonalite to diorite samples, but fall in the range of mafic garnet granulite as well as two of our measured restites (Figure 4).

[30] Below about 15–20 km, mafic (garnet free) granulite might be a possible lithology for mafic underplating beneath the CMB (Figure 4); however, mafic garnet granulite is the metamorphic equivalent of tholeiite at temperatures of 700°–800°C and depths of over 15 km [*Ringwood*, 1975]. Given that V_P/V_S of sillimanite and garnet are about 1.8 and that V_P is 9.5 and 8.4 km/s, respectively, it is reasonable to conclude that the break in physical properties at about midcrustal depths reflect an increase of modal garnet and/or sillimanite. Increasing velocities in the mafic granulite field may originate from increasing garnet content.

[31] Seismic anisotropy studies may provide important information on the relative abundances of mafic garnet granulite and restite at lower-crustal depths. Mafic granulite is essentially isotropic [*Christensen and Mooney,* 1995], whereas restites from our study area show variable anisotropies that reach as high as 13% (Table 1). The field seismic interpretation is based on the fastest arriving *S*-waves [*Morozov et al.*, 2001]; therefore in the presence of significant lower-crustal anisotropy, our V_P/V_S profile (Figure 4) would be biased toward lower V_P/V_S values.

[32] The fact that field V_P/V_S are only slightly above the averaged V_P/V_S values from laboratory measurements of restites (Figure 4) suggests that the lower-crustal anisotropy does not significantly affect our measurements, either because of the absence of coherent, large-scale layering within the lower crust, or because restites are not the dominant lithology within it. This suggestion is supported by a preliminary estimate of shear wave splitting in wide-angle records (Figure 5). The splitting times are between 20 and 40 ms for both *Sg* and *SmS* between 60 and 110 km of offset, and thus the observed splitting is at the level 0.3–0.6% for these phases. Such moderate shear wave splitting estimates indicate that our overall *S*-wave velocity model is not significantly affected by anisotropy. However, the polarization patterns of *S*-wave arrivals appear to be complex (Figure 5) and not well understood, and further research including detailed modeling of *P*/*S* conversion at the base of the fjord and of crustal anisotropy [e.g., similar to *Guest et al.*, 1993] still holds promise for insights into the *S*-wave structure (Figure 2, bottom).

[33] On an average, the rocks under the CMB within the ACCRETE study area project downdip toward the northwest; therefore rocks found on the surface further to the SE should also be relatively more abundant at the base of the seismic cross section. In the field, restites increase in abundance toward the southeast part of Figure 1 and off the map further to the southeast. Our samples of restite show a range of velocities that are sensitive to their garnet and sillimanite contents, with higher velocities corresponding to higher modal garnet and sillimanite.

[34] Although at the base of the crust under the CMB we do not find velocities that would correspond to gabbro (Figure 4), the presence of quartz-bearing layers interlayered with gabbro could be another reason for the absence of "mafic" V_P/V_S ratios within the lower crust under the CMB, in particular, in its NE part (Figure 4). The garnet-sillimanite restites are a vestige of a metasedimentary component in the deep crust. The gabbro, now a mafic garnet granulite, could have provided a heat source for producing these restites from a metasedimentary component in the deep crust. A combination of basaltic liquid from which the mafic garnet granulite was produced and granitic liquid that was extracted from the restite may have been the result of batholith generation.

[35] Seismic *P*- and *S*-wave velocities show that the crust west of the mid-Cretaceous thrust belt is fundamentally different from the crust east of the CSZ (Figure 2). The contrast across the CSZ, between the crust of the CMB and of the mid-Cretaceous thrust belt is apparent in the V_P/V_S domain (Figure 2b) and is most likely related to the difference in their tectonic origin and composition. This demonstrates that the CSZ is, indeed, a fundamental crustal interface.

[36] The crustal thickness under the CMB (31–32 km) is significantly thinner than normal continental crust (41 km), and it is thinner than average for continental arcs (39 km); both averages are from *Christensen and Mooney* [1995]. Despite an increased temperature of the crust (see below), the average crustal velocity under the CMB (6.55 km/s) is somewhat higher than the continental average (6.45 ± 0.20 km/s) [*Christensen and Mooney*, 1995], but this excess is mostly due to higher velocities in the present upper to middle crust, between 4- and 20-km depth (Figures 2a and 2b). These observations support the great depth of exposure to middle-crustal levels inferred from the estimated 15–20 km of crustal exhumation [*Hollister*, 1982] that occurred concurrently with tonalite and granodiorite intrusion [*Andronicos*, 1999; *Andronicos et al.*, 2003].

[37] Higher than normal average crustal velocities in the CMB may reflect the fact that the normally lower velocity material of the upper crust has been removed tectonically and by erosion [*Morozov et al.*, 1998]. This result is consistent with earlier geologic studies [*Hollister*, 1982], which showed that there had been rapid decompression of the rocks presently exposed at the surface from depths of about 25 km to about 12 km. Thus formerly mid- to lower-crustal rocks are now exposed at the surface, and hence the upper (lower velocity) crust had been removed during erosional and tectonic denudation [*Heah*, 1991; *Hollister*, 1993; *Andronicos*, 1999; *Andronicos et al.*, 2003]. The CMB portion of the crustal section (Figure 2) can thus be considered to correspond to the lower two thirds of an average crustal section formed by inflation from intrusions of shallowly dipping tonalite to gabbro sills into a more felsic lower crust [*Hollister and Crawford*, 1990; *Morozov et al.*, 1998]. These sills project downdip from the surface to the line of seismic section, from where they are mapped in the vicinity of the Skeena River (Figure 1) [*Hollister and Andronicos*, 1997; *Andronicos*, 1999; *Andronicos et al.*, 2003].

[38] The uppermost-mantle (P_n) velocity of 7.9 km/s [*Morozov et al.*, 1998] is near the lower limit of the continental average (8.1 ± 0.2 km/s) and close to the average

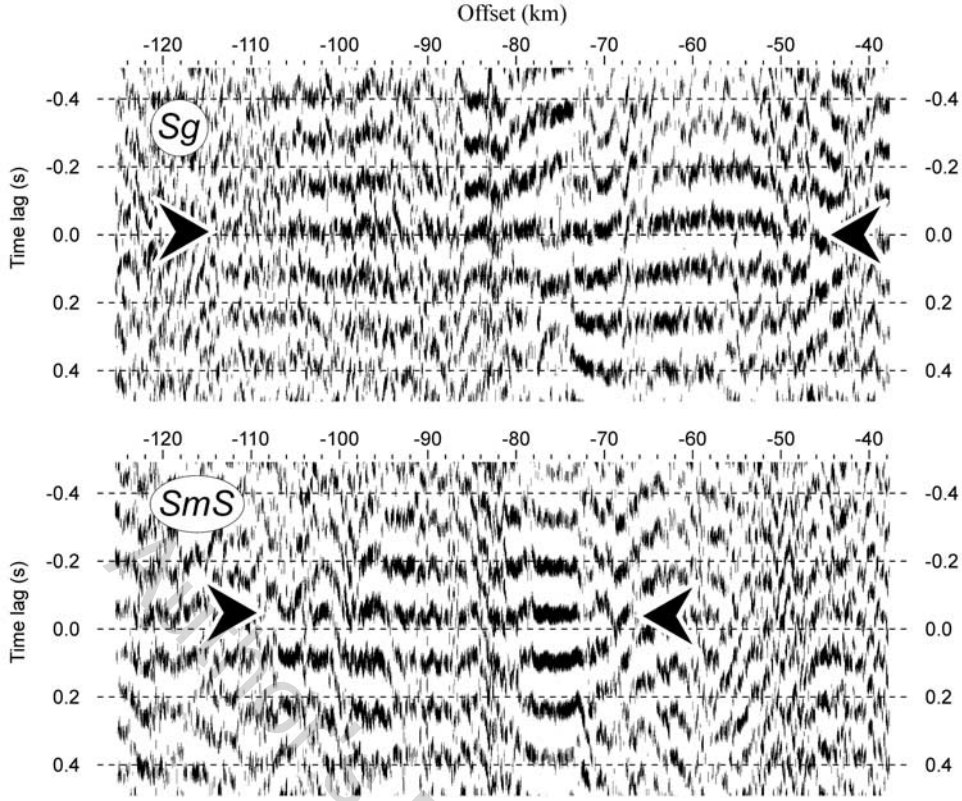

Figure 5. Preliminary measurement of shear wave splitting in the records from station 8 (Figure 1). Top: cross-correlation of the in-line and cross-line components of a direct *S*-wave arrival (*Sg*). Bottom: of *S*-wave Moho reflection (*SmS*). The arrows indicate the maximum amplitude peak of cross-correlation. Note that for both waves the horizontally polarized *SmS* is trailing the vertically polarized reflection by about 20–40 ms.

for continental arc regions (7.9 ± 0.2 km/s) [*Christensen and Mooney*, 1995]. *Hyndman and Lewis* [1999] correlate high heat flow (70–120 mW/m^2) and low *Pn* velocities across the Intermontain belt of British Columbia with high temperatures (800°–1000°C) at the Moho. The high-heat flow province appears, from sparse data, to extend under the Coast Mountains to Queen Charlotte Sound [*Hyndman and Lewis*, 1999]. Other *Pn* measurements [*Hammer et al.*, 2000] and heat flow measurements across British Columbia, west of the Tintina fault zone and Rocky Mountain trench, show that present-day heat flow is anomalously high, averaging 82 mW/m^2 near the Portland Canal fjord [*Lewis*, 1997]. These data support the inference that the low *Pn* velocities are due to anomalously high present-day temperatures in the upper mantle under the CMB. Given the very low heat productivity in the CMB rocks [*Hollister*, 1982], the present-day geothermal gradient can be approximated to be linear from the surface to the Moho. A sub-Moho velocity of 7.9 km/s corresponds to a temperature of about 850°C based on a low-*T* dunite velocity of 8.4 km/s and a $\delta V_P/\delta T$ of -0.6×10^{-3} km/s/°C [*Christensen*, 1979]. Such high temperatures at the Moho would put the present lower crust in the granulite facies of metamorphism. Mafic garnet granulite has the seismic properties corresponding to our seismic inversion results (Figure 4).

[39] Underplating by basaltic liquid had been proposed as an explanation for providing enough heat to melt a substantial portion of the crust in order to provide the voluminous granitoid magmas observed on the surface [*Hollister and Andronicos*, 1997]. Because the best match for the lower crust is for mafic garnet granulite and for sillmanite-garnet-quartz restite, the hypothesis of significant underplating by basalt during formation of the CMB is supported.

6. Conclusions

[40] The ACCRETE project resulted in a combination of high-quality wide-angle seismic data and laboratory measurements of seismic velocities in samples collected in the study area. Combined with geologic control and heat flow data, these data sets allow detailed interpretation of the seismic results in both *P*- and *S*-wave domains.

[41] The higher than average crustal velocities and V_P/V_S ratios under the CMB, especially in the middle crust, reflect the fact that lower-velocity, possibly granodioritic material of the upper crust has been removed during the exhumation [*Hollister*, 1982]. The present crust has the thickness and seismic properties typical of extended crust, and the surface geology [*Andronicos*, 1999; *Andronicos et al.*, 2003] also supports the hypothesis of such extension, the bulk of which occurred in the Eocene (55–50 Ma).

[42] Laboratory measurements of rock velocity show that the field-determined velocity structures can be interpreted in terms of compositions of the rocks exposed on the surface.

Temperature correction combined with a correction for exhumation depth raises the observed *P*-wave velocity in the lower crust to a velocity-depth pattern of a normal continental crust. V_P and V_P/V_S constrain composition and lead to a preferred interpretation of the lower crust consisting of mafic garnet granulite and metasedimentary (quartz-garnet-sillminite) restite related to the formation of the overlying batholith. The upper crust is interpreted as a mixture of tonalite, gabbro, and restite. 15–20 km of the upper crust has been removed tectonically, and the remaining 30-km thick crustal section represents the lower two thirds of normal continental crust. The mafic garnet granulite was formed from underplated basalt that provided the heat source for the batholith and melted the base of a metasedimentary pile. These results acquire particular importance because, as the seismic study suggests, the CMB may illustrate one of the likely scenarios of generation of a new continental crust, namely by combined magmatic and terrane accretion in the former continental arc.

[43] **Acknowledgments.** The ACCRETE project was supported by the Continental Dynamics Program of NSF through grants EAR-92-18482, EAR-92-19294, EAR-95-26753, EAR-97-96252, and EAR-95-26531.

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