Proterozoic Prism Arrests Suspect Terranes: Insights into the Ancient Cordilleran Margin from Seismic Reflection Data

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ABSTRACT

The Canadian Cordillera is one of the principal regions from which the hypothesis of exotic, accreted, or suspect terranes was developed a few decades ago. In an important modification to this hypothesis, new field mapping and seismic reflection profiling reveal a vast volume of Proterozoic strata of largely North American affinity along the margin, leaving little room for the suspect terranes. The Proterozoic strata, deposited in at least three distinct periods between 1.85 and 0.54 Ga, form a reflective tectono-depositional prism or wedge that has a volume greater than a million cubic kilometers, extends over 1000 kilometers in length, and makes up most of the crust of the Canadian Cordillera. The suspect terranes apparently grounded upon and were arrested by this metamorphosed sedimentary prism during a complex interplay of thrusting and strike-slip displacements 190–170 Ma. Thus, the Cordilleran suspect terranes, excepting Stikinia, have shallow roots only a few kilometers deep, with no deep crust or mantle attached.

INTRODUCTION

Large sediment fans along continental margins at the mouths of rivers such as the Indus, Ganges, and Amazon are among the most impressive geological features on Earth today (e.g., Clift et al., 2001). Ancient sedimentary prisms along rifted margins such as those found beneath the North Sea, the Gulf of Mexico, or the north shelf of Australia (Stagg et al., 1999), while less easily recognized, are equally major features. New deep crustal seismic reflection profiles collected in western Canada as part of the LITHOPROBE program (Clowes et al., 1999) reveal a tapering wedge of layered rocks that is interpreted here to be an ancient sedimentary wedge. This wedge or reflective prism was deposited in a rift margin along western North America that may have persisted from 1.85 to 0.54 Ga. (Ross et al., 2001; Thorkelson et al., 2001).

The presence of a thick sedimentary prism beneath the western Canadian Cordillera has important implications for the suspect terrane hypothesis. This hypothesis states that North America grew by addition of a series of exotic (sometimes called “suspect”) crustal and oceanic microplates along the Cordilleran (western) margin between 200 and 50 Ma (Coney et al., 1980). However, if much of the lower crust is of conformable North American affinity, as proposed here, the overlying exotic or suspect terranes must be thin thrust sheets, <10 km thick, with no deep crustal or mantle roots.

From 1999 to 2000, LITHOPROBE acquired nearly 1900 km of deep seismic reflection profiles in two transects of the North American Cordillera in British Columbia and the Yukon (Fig. 1). These profiles completed the SNORCLE (Slave Northern Cordillera Lithosphere Evolution) transect of western North America, which began with a 1996 survey from Yellowknife to Nahanni Butte in the Northwest Territories (Fig. 1; Cook et al., 1999). The combined SNORCLE profiles take advantage of the regional north-south orientation of Proterozoic and younger rocks in northwestern Canada to address the nature of continental evolution from the Early Archean of the Slave Province to the Modern convergent plate boundary between the North American and the Pacific plates in the area studied by the ACCRETE project (Fig. 1) (Morozov et al., 2001).

The Cordilleran survey used standard LITHOPROBE acquisition strategy for crustal scale profiling, this strategy being based on experience gained over two decades of similar activities. Five large Vibroseis trucks generated four 20 s 10–80 Hz sweeps at source points spaced 75 m apart. A 576-channel spread of 12-geophone receiver groups spaced 50 m apart recorded each sweep for 32 s. When processed, the data produced two continuous reflection cross sections across most of the Cordilleran mountain belt to depths as great as 100 km (equivalent to 22 s in Fig. 2).

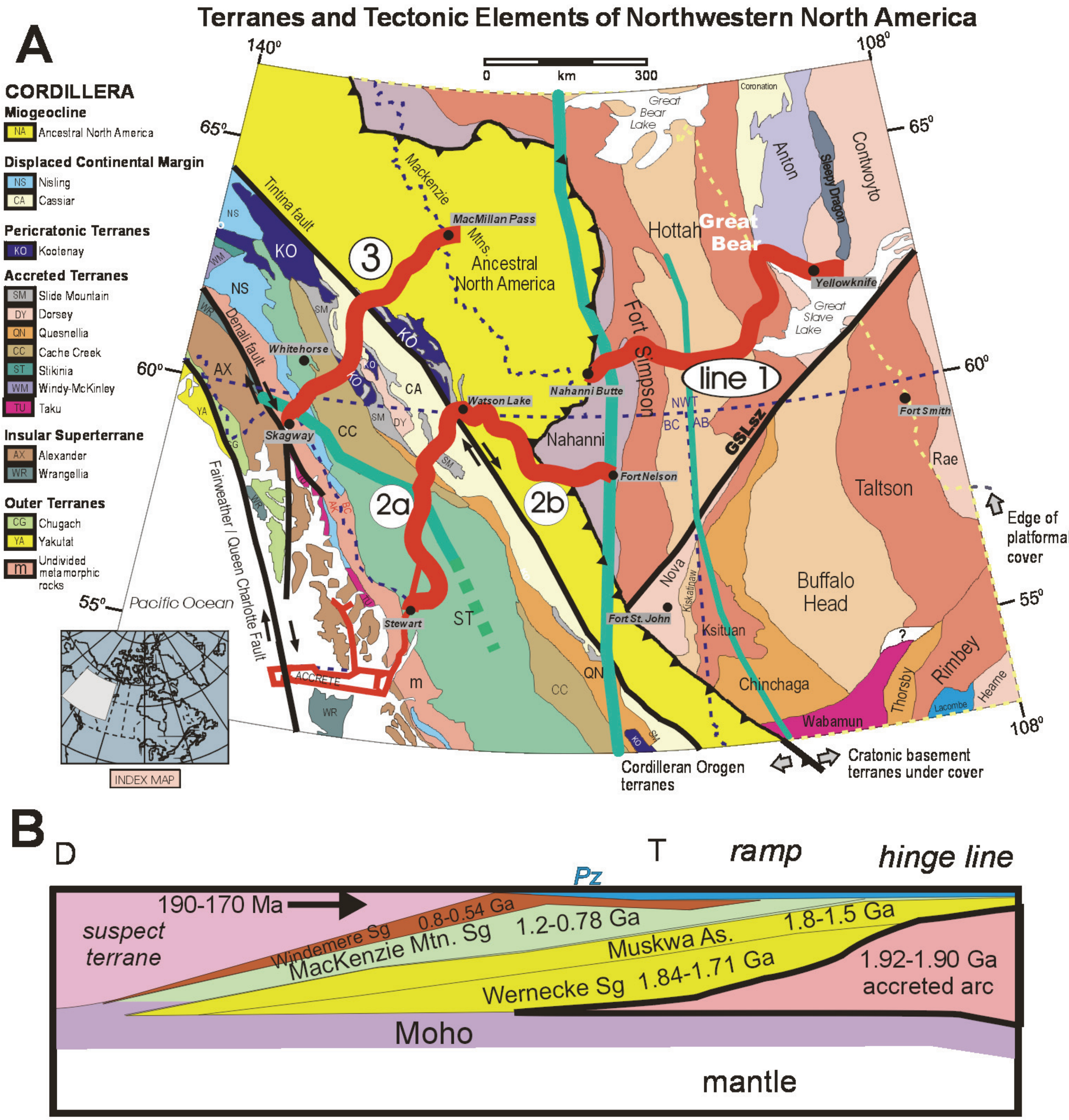
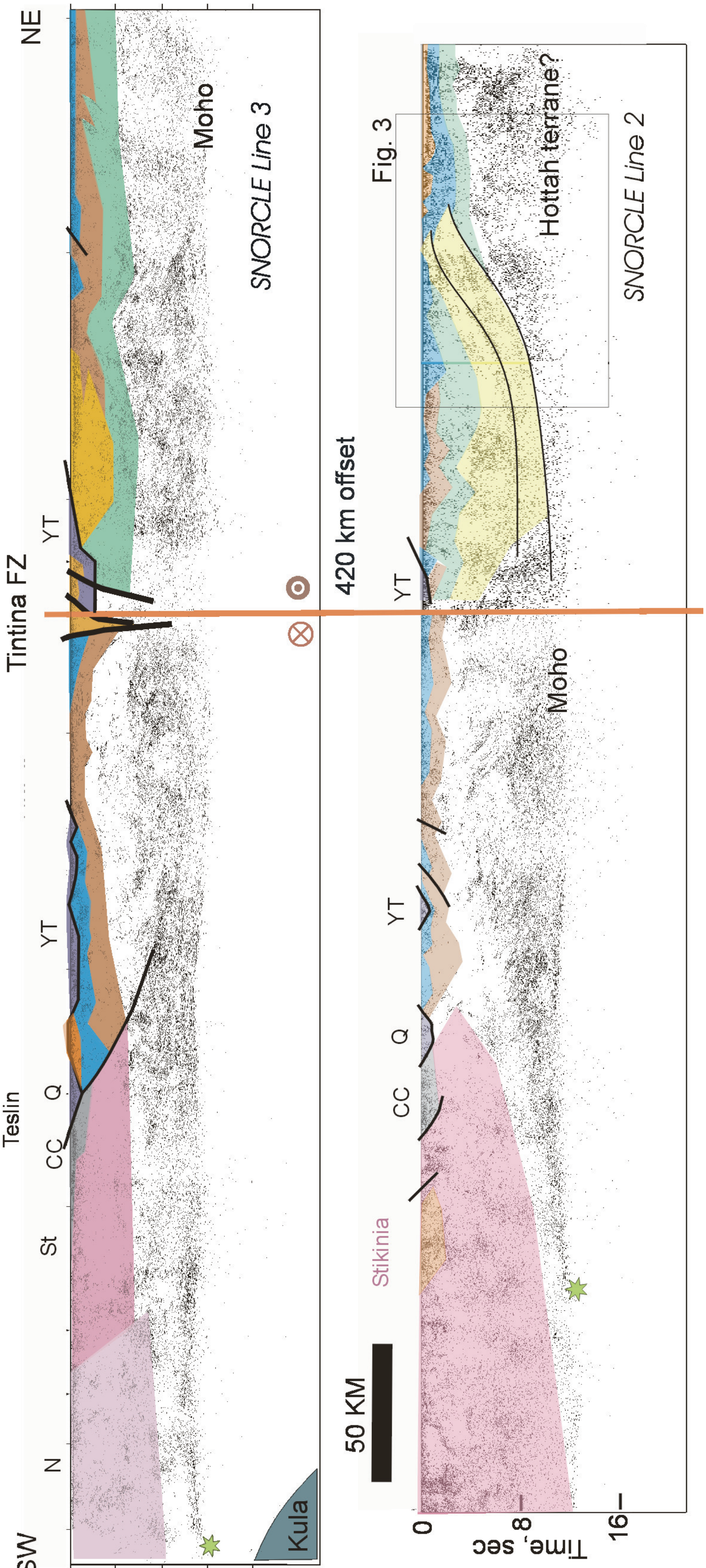


Figure 1. A: Location map of SNORCLE (Slave Northern Cordillera Lithosphere Evolution) transect study region and its four component seismic reflection profiles and related ACCRETE survey. Black dashed line with barbs marks structural frontal thrust of Cordillera. Thick blue-green lines mark limits of where Proterozoic strata are here interpreted to occupy much of the crust; thinner line marks continental "hinge line" where these sedimentary rocks begin to thicken significantly. **B:** Cartoon cross section illustrating main geological elements as interpreted from SNORCLE transect observations. Four main periods of sedimentation are indicated: 0.8–0.54 Ga Windermere, 1.2–0.78 Ga MacKenzie Mountain, and 1.84–1.71 Ga Wernecke Supergroups, and the lesser known 1.815–1.5 Ga Muskwa assemblage (Cook and MacLean, 1995; Ross et al., 2001). Ramp (Clark and Cook, 1992) coincides with eastern limit of thick strata shown in Fig. 1A. T, D are Tintina and Denali strike-slip fault zones. Section has 5:1 vertical exaggeration. Pz are Paleozoic strata.



NATURE OF SNORCLE REFLECTORS

When viewed as a whole, the newest SNORCLE seismic reflection sections are most notable for the triangular, or wedged-shaped, areas where reflections are more densely spaced or of higher amplitude than elsewhere (Fig. 2). Many earlier deep seismic sections showed prominent lower-crustal reflectivity (e.g., Klemperer and Hobbs, 1991), but none has shown systematic lateral variation or wedge-shaped areas as prominent as the westward tapering ones in the lower crust observed on the SNORCLE data.

The continuity of the SNORCLE profiles allows individual crustal reflective layers that make up these wedges to be mapped from the near surface along the eastern margin of the mountains, where they tie with outcrop (e.g., Young et al., 1979; Clark and Cook, 1992), to depths of 30 km beneath the western Cordillera (Fig. 2). Several decades of experience in acquiring deep seismic reflection data within the LITHOPROBE program and by similar international organizations have provided clues to the nature of these strong, continuous reflectors in the middle and lower crust. We know from up-dip projections and outcrop correlations in continental interior (shield) settings that the vast majority of the most prominent reflectors are mafic intrusions into the felsic upper crust, stratigraphic contacts, or major shear zones (Snyder and Hobbs, 1999, and references therein).

In an orogenic setting such as the Canadian Cordillera, such correlations are less certain because of complex structure. A series of sub-parallel reflections that correlates with stratigraphic contacts and

Figure 2. Composite seismic reflection section of SNORCLE lines 2 and 3. Line 3 is a single continuous section, compiled as it was acquired; line 2 is a composite of lines 2a and 2b with segments parallel to Cordilleran strike removed and the remaining segments projected onto a profile approximately parallel with line 3. Green star marks westernmost tip of reflective wedge on each profile. Black lines mark locations of faults, either mapped or inferred from offsets or truncations of reflections. Vertical orange line marks Tintina fault zone. If 420 km of right lateral offset is restored, the western part of line 3 will align with the eastern part of line 2 and the reflective wedge appears nearly continuous across this break. Suspect terranes: CC—Cache Creek; N—Nisling; Q—Quesnellia; St—Stikinia; YT—Yukon-Tanana. Orange colored units in near surface are Mesozoic igneous rocks or sedimentary rocks (at east end of Line 2). Paleozoic strata are colored blue, Windermere Supergroup strata are red-brown, MacKenzie Mountain Supergroup strata are green, and Muskwa-Wernecke Supergroup strata are yellow. Parts of the lower crust are left uncolored where interpretation is uncertain; our preference is that most parts in the eastern half are Muskwa-Wernecke Supergroup strata or basement. Hottah terrane is inferred Proterozoic magmatic arc crust. Kula is inferred subducted Kula oceanic plate based on clear dipping reflections from 16 to 20 s.

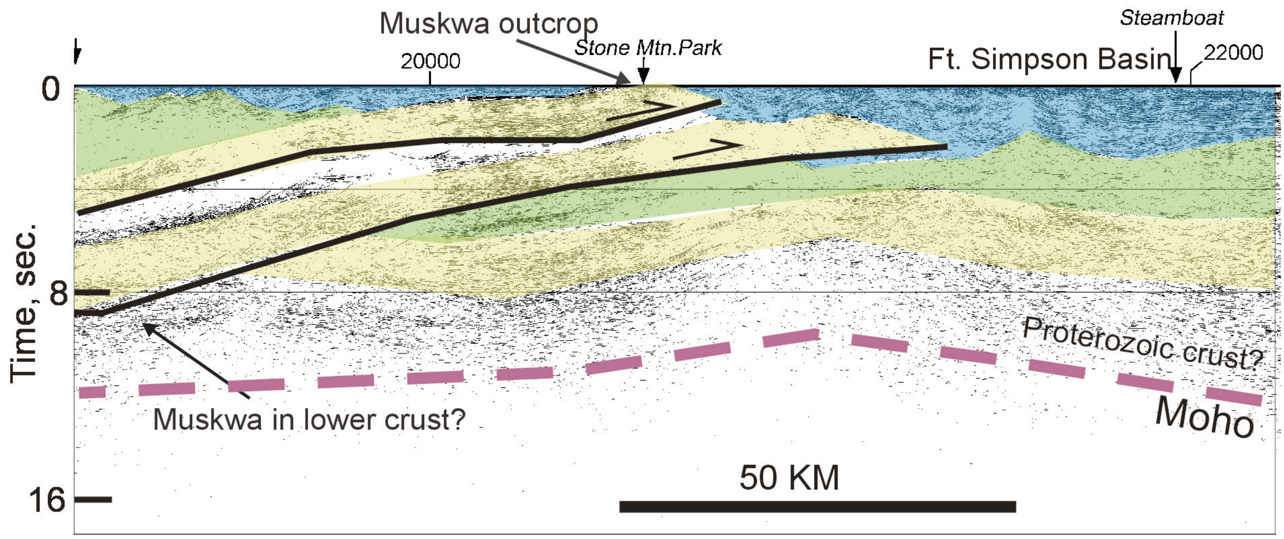


Figure 3. Detail of reflection section near Muskwa anticlinorium. This enlarged section illustrates that the westward-dipping geometries of thrust sheets (arrows show sense of offset), which bring Muskwa (Sequence A) strata to the surface near the Cordilleran frontal thrust (Fig. 1), can be traced continuously into the lower crust.

thrust faults at the surface, and that can be traced without breaks or offsets to depths of 20–25 km, can be assumed to represent those same features at depth. This is the case with the Muskwa anticlinorium (Figs. 2 and 3). Similarly, reflectors that correlate with outcrops of mafic intrusions and that continue into the mid-to-lower crust can be assumed to map the feeder system for those intrusions. Good examples of reflectors associated with mafic intrusions and unconformities appear on SNORCLE line 1 east of Yellowknife (Fig. 1) (Cook et al., 1999).

PROTEROZOIC STRATIGRAPHY

Within the part of the Cordillera studied by the SNORCLE profiles, outcrop correlations enable reflective layers to be matched with several Proterozoic sedimentary rock units that include the 0.8–0.54 Ga Windermere (Sequence C), the 1.2–0.78 Ga MacKenzie Mountain (Sequence B), and 1.84–1.71 Ga Wernecke Supergroups, and the lesser known 1.815–1.5 Ga Muskwa assemblage (Sequence A) (Fig. 1B) (Cook and MacLean, 1995; Ross et al., 2001). Collectively, these layers are interpreted as a clastic apron deposited along the rifting Proterozoic continental margin of ancient North America. The depositional environment of individual formations is described as varying from basin fill to prograding delta to shallow margin to deep-water turbidites (Aitken and McMechan, 1991). The sediment budget may be similar to that of the present-day Ganges-Brahmaputra system, where about one-third of the total sediment load that originates in the interior of the continent is stored in the Bengal fan (Goodbred and Kuehl, 1999). The other two-thirds are floodplain and deltaic components of the same sedimentary units, and in the Cordillera may be partly represented by the Athabasca and Thelon basins.

Stratigraphic studies of these Proterozoic sedimentary units, where type sections are exposed, document thicknesses of 7–21 km, but correlations with the seismic reflectors indicate a total sequence as thick as 25–30 km at the ancient continental slope or "ramp" (Fig. 1) (Clark and Cook, 1992; Cook et al., 1999). Within the eastern half of the clastic wedge, we estimate that 0–5 km of Windermere Supergroup strata overlie a combined 5–25 km sequence of Muskwa and Wernecke strata and crystalline basement layers or tectonically inserted thrust slices. These dimensions make the wedge comparable in scale to the modern Indus fan, but the Cordilleran wedge represents a compound feature deposited over a period up to 10 times longer.

We identify and map this distinctive wedge of predominantly lower continental crust using its characteristic bands of prominent reflectivity, as compared with the much less reflective overlying upper crust and underlying mantle. We interpret the wedge as predominantly Proterozoic strata through correlations with a few key outcrops in the east. Nevertheless, the depth to basement beneath the strata is uncertain.

Interpretation of SNORCLE line 1 in the Northwest Territories (Fig. 1) (Cook et al., 1999) indicates that older (1.92–1.845 Ga) magmatic arc crust underlies the wedge in the eastern part of the British Columbia profile and along regional tectonic strike (Fig. 2). The current high heat flow throughout the Cordillera (Lewis et al., 2002) and the great depth of burial of both wedge and underlying rocks, indicate that basement, Proterozoic strata, and Paleozoic rocks within the lower half of the wedge are now all metamorphosed into gneiss and granulites (e.g., Evenchick et al., 1984). Proterozoic sedimentary rocks could retain primary layering and structures during this metamorphism, but bulk physical properties such as seismic velocities and density would become largely indistinguishable from those of typical igneous rocks.

EVIDENCE FOR TECTONIC THICKENING

Numerous basins worldwide have been studied in detail because of their petroleum content. The bands of reflections that characterize the wedge

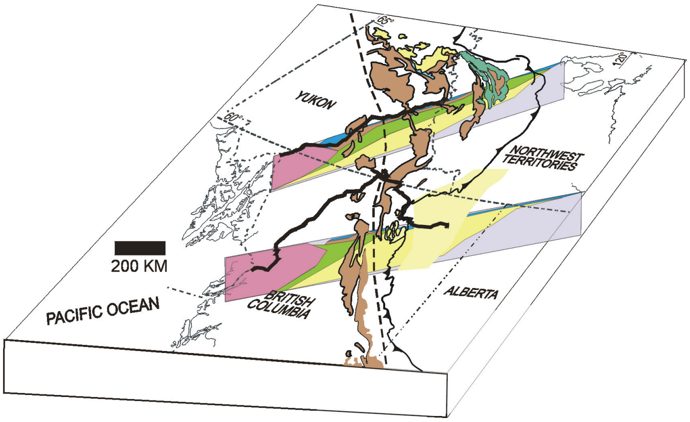


Figure 4. Three-dimensional perspective view of Proterozoic sedimentary rocks exposed in western Canada and crustal cross sections derived from seismic profiles. Outcrop locations are shown with respect to the seismic reflection profiles (heavy black lines) and major tectonic features such as the Tintina fault zone (dashed line), Cordilleran frontal thrust (barbed line) and Pacific coastline. Brown shaded units are Proterozoic Sequence C (Windermere Supergroup), green units are Sequence B (MacKenzie Mountains Supergroup), yellow shaded units are Sequence A (Muskwa assemblage), purple color marks exotic terrane Stikinia in cross section. Yellow area straddling the Northwest Territories and British Columbia border is subcrop of Muskwa assemblage as delimited by drill holes.

described here do not show geometries typical of these sedimentary rocks. For example, a prograding fan cannot be demonstrated directly from seismic sequence stratigraphy analysis of our data from lines 2 and 3. Instead, the bands are observed as gently folded and interleaved, but on scales of up to 10–15 km vertically and many tens of kilometers laterally. This deformation, due to horizontal shortening, occurred around the time of sediment deposition, in the late Proterozoic (Cook, 1988; Cook and MacLean, 1995) and again hundreds of millions of years later, when suspect terranes were accreted to North America and the mountains of the Cordillera formed. Truncations above these folded reflection bands by nearly horizontal reflections demonstrate that in most places the overlying crust moved obliquely toward the foreland over the top of the buried wedge.

The implied continuity of individual reflectors and groups of reflectors from surface outcrop to lower crustal depths leads us to conclude that most of the layered reflective wedge is sedimentary strata, metamorphosed to various grades according to their depths. We cannot exclude the possibility that some layers within the lower crust also include slivers of older crystalline continental crust, tectonically interleaved with the Proterozoic stratigraphic sequences.

Bands of reflections are generally continuous within the crustal wedge, but do not cross its base (at 11.5 s two-way traveltime). The gently undulating reflection Moho, near or at the crust-mantle boundary (e.g., Welford et al., 2001), does not appear to be locally deformed or offset. At the top of the wedge, gently westward-dipping reflections truncate eastward-dipping layers within it (Fig. 2). In a few locations along the imaged 500–700 km dip length of the prism, such as at the Muskwa anticlinorium (Fig. 3) (Thompson, 1991), the reflection geometries indicate that sedimentary rocks within the prism were thrust to the surface on faults rooted near the Moho.

CONTINUITY AND EXTENT OF THE WEDGE-PRISM

The Tintina–Northern Rocky Mountain trench fault zone is arguably the most striking single feature on geological and topographic maps of this part of the Cordillera (Wheeler and McFeely, 1991). The only location for which a break in the reflective wedge can be convincingly argued is where this fault zone crosses the seismic profiles (Fig. 2). If the minimum amount of the proposed 450–800 km of right-hand strike-slip displacement along this fault (Gabrielse, 1985) is restored, then the western part of the northern seismic profile becomes roughly aligned with the eastern part of the southern profile. The presence of the wedge on three widely separated cross sections after this reconstruction further confirms the large extent (>900 km reconstructed strike length) and uniformity of this reflective wedge along the continental margin. Furthermore, the inferred 1–10 million km^3 volume of layered rock deposited on the North American margin between 1.85 and 0.54 Ga, which now resides within the reflective prism, provides insight into the vast amount of material eroded from the continent during this time period.

The continuity of this reflective wedge, both along strike between the two SNORCLE profiles and across its width, is its most obvious and significant characteristic. One important factor is that this segment of the North American Cordillera has undergone only limited amounts of extension (i.e., <10%) in contrast to the considerable extension associated with the southern Canadian Cordillera (Cook and Varsek, 1994) or the western United States (e.g., Allmendinger et al., 1987). As a result, individual reflection packets observed in the northern Cordillera were not stretched or dismembered beyond recognition. However, due to lack of data we cannot presently assess the full northern or southern extent of the reflective wedge (Figs. 1 and 4).

THIN SUSPECT TERRANES

None of the numerous exotic (suspect) terranes that represent most of the surface rocks along the northwestern margin of North America (Wheeler and McFeely, 1991) are observed to break through this lower crustal reflective wedge. These terranes, some exotic to North America, some perhaps originally marginal to it, apparently grounded or arrested on top of the wedge of Proterozoic and early Paleozoic layers. Some terranes such as Yukon-Tanana, Cache Creek, and Quesnellia were detached from their roots and thrust 200–400 km onto the margin of North America as thin (<5 km) crustal flakes (Fig. 2). Other terranes, such as Stikinia, docked above and outside of the leading edge of the layered wedge and make up most of the crust there today (Fig. 2).

Most previous workers inferred that suspect terranes did not occupy the entire crust (e.g., Gabrielse, 1985) nor fully represent the deeper tectonics of the orogen (e.g., Oldow et al., 1990). The extreme thinness of some terranes and small volume represented collectively by these terranes implied by the seismic reflection data are new. The recognition that most of these terranes, as well as tectonic slices of North American

Precambrian strata, collectively form a hanging-wall block above a detachment surface at the top of the Proterozoic wedge helps to constrain the order and timing of their accretion to the North American continent. For example, if terranes occupy only the uppermost 10 km of crust, it becomes mechanically improbable that the various suspect terranes were stacked on top of one another or overrode one another. The simplest order of accretion is the obvious order in which the terranes appear at the surface today. The interpreted thinness of the terranes also de-emphasizes their volumetric importance in the overall architecture of the Cordillera. As a corollary, the recognition of the thin suspect terranes emphasizes the volumetric importance of lithospheric material, in the form of mantle detached from the suspect terranes, that has been recycled into the mantle.

DISCUSSION AND MORE GENERAL IMPLICATIONS

LITHOPROBE, with its component transects such as SNORCLE, is widely recognized for its interdisciplinary and collaborative studies (Clowes et al., 1999). Each transect is anchored by the subsurface geometries established by deep seismic reflection profiles that provide a complete two-dimensional image of structures well into the uppermost mantle. In most transects, a number of individual two-dimensional profiles provide some three-dimensional control on interpreted features. Supporting geophysical, geochronological, geochemical, and geological studies add multidisciplinary input and provide the broad geoscience context within which comprehensive interpretations and models of tectonic evolution are developed.

In SNORCLE, for example, geochemical analysis of mantle xenoliths entrained in Cretaceous to Recent volcanic eruptions indicates that the North American plate ends somewhere between the Tintina and Teslin zones (Fig. 2) (Creaser et al., 1997; Abraham et al., 2001). This implies that North American mantle underlies the Proterozoic North American sedimentary strata as interpreted from the reflection sections discussed herein. Heat flow studies throughout the Cordillera indicate that the average heat flow in the region of lines 2a and 2b is remarkably high, ~105 mW/m^2, resulting in high calculated crustal temperatures (Lewis et al., 2002). If similar temperatures existed during the orogenic evolution of the Cordillera, the only significant strength would be found in the upper crust, implying some form of middle to lower crustal detachment as proposed from the reflection data. Moreover, the high temperatures imply high-grade metamorphic rocks in the lower crust, again as inferred in our interpretation. In contrast, magnetotelluric results suggest a laterally varied mantle and crust (Ledo et al., 2002), in variance to the horizontally stratified wedge of reflectors described here. These observations are not incompatible; they require further study to determine the nature of the sub-Moho rocks on our SNORCLE sections. Is it highly attenuated North American continental lithosphere or of more primitive, oceanic affinity?

Although suspected from recent stratigraphic studies, the vast volume of Proterozoic sedimentary deposits along the western margin of North America requires rethinking of some long-held ideas. Are these deposits orogenic or rift related? Although the genesis is different, the final structure of a slowly filling rift or coalescing alluvial fans cannot be distinguished if only one margin is preserved (see Ross et al., 2001, and Thorkelson et al., 2001, for further discussion). Existing stratigraphic studies indicate that a long-lived, slowly subsiding rift is most probable. The rift basin was fed by at least four major sedimentation pulses that were widely spaced in time over about 1 b.y. Our Indus analogy would represent just one of these pulses. Potential source regions of these pulses include the Trans-Hudson Orogen of central Canada and most of the Precambrian age orogens recognized in North America.

The relatively shallow décollement between the prism and the overlying suspect terranes revisits concepts of thin-skinned thrusting and the compressive strength of the footwall material. Although much of the wedge of Proterozoic material is likely sedimentary in origin, it is now metamorphosed and deformed into gneiss and therefore acts mechanically as granitic basement. This describes a geometry very similar to those recognized in many locations worldwide as thin-skinned thrust zones, for example the Appalachians, Caledonides, and Urals. Sedimentary prisms of the volume described here are not known in those orogens, but perhaps are just not yet recognized.

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