JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 104, NO. B10, PAGES 23,255–23,269, OCTOBER 10, 1999

Seismic-reflection and potential-field studies of the Vulcan structure, western Canada: A Paleoproterozoic Pyrenees?

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Abstract. The Vulcan structure is a major tectonic boundary between the Medicine Hat and Loverna Blocks, Archean crustal domains that are buried beneath the Western Canada Sedimentary Basin. It is characterized by prominent east-trending gravity and magnetic anomalies, more than 350 km in length, which cut across the potential-field fabric of southern Alberta at a high angle. Three decades ago, the Vulcan structure was the target of one of the first deep-crustal seismic profiles, and it has since been variously interpreted as a failed Proterozoic rift, an intraplate collisional zone, and (or) a largely amagmatic Proterozoic suture. Several recent Lithoprobe seismic-reflection profiles, coupled with new, coincident high-resolution gravity data, regional gravity data, and updated aeromagnetic coverage, provide the basis for a revised model of the crustal architecture in this region. We interpret the Vulcan structure to be a relatively narrow (40-70 km) axial zone of a continental collisional belt. The seismic images imply crustal delamination and south-directed subduction of the lower crust of the Loverna Block. The axial gravity low and corresponding magnetic anomaly are interpreted to originate from a large granitic pluton, while prominent gravity highs on the flanks of the structure are modeled as thrust slices of lower-crustal and/or mantle material brought up during the collision. Cross-cutting relationships inferred from aeromagnetic data indicate that the timing of collision postdated formation of Archean fabrics in the Medicine Hat Block but predated terminal collision in the adjacent TransHudson Orogen. The geographic extent, inferred net shortening and tectonic setting of the Vulcan structure appear to resemble the modern Pyrenees belt, although the deep structure appears to be more akin to the Scandinavian Caledonides. Either scenario is consistent with an interpretation of the Vulcan structure as the Proterozoic collisional suture between the Wyoming and Hearne Provinces of the Laurentian craton.

1. Introduction

Collisional and accretionary processes that contributed to the assembly of Laurentia are well documented in shield areas [e.g., *Hoffman*, 1988] but are less well understood in contiguous platform regions, such as the Western Canada Sedimentary Basin (WCSB), where the craton is covered by Phanerozoic sedimentary rocks. Three decades ago, several deep-crustal seismic reflection profiles, among the first ever recorded, were undertaken to investigate an enigmatic gravity and aeromagnetic anomaly within the platform caused by crustal elements underlying the WCSB [*Kanasewich et al.*, 1969]. This feature, herein referred to as the Vulcan structure after a small town situated within it, extends in a generally east-west direction for at least 350 km, cutting across the regional potential-field fabric at a high angle. The nature and tectonic significance of the Vulcan structure, as well as its possible westward extension beneath the Canadian Cordillera, have since been the subjects of recurring debate.

On the basis of early seismic and gravity studies, the Vulcan structure was originally interpreted as a Precambrian rift [*Kanasewich*, 1968; *Kanasewich et al.*, 1969]. These and followup studies provided evidence for significant Moho topography [*Clowes and Kanasewich*, 1972] and demonstrated a positive spatial correlation between high-velocity zones at shallow crustal levels and Bouguer gravity highs [*Chandra and Cumming*, 1972]. However, because the Vulcan structure lacks characteristics of a thermally mature continental rift [*Hoffman*, 1988] and its geometry more closely resembles convergent orogens (see below), several alternative models have since been proposed. On the basis of continent-scale gravity-gradient trends, the Vulcan structure was postulated to be the principal suture between the Archean Hearne and

Paper number 1999JB900204.
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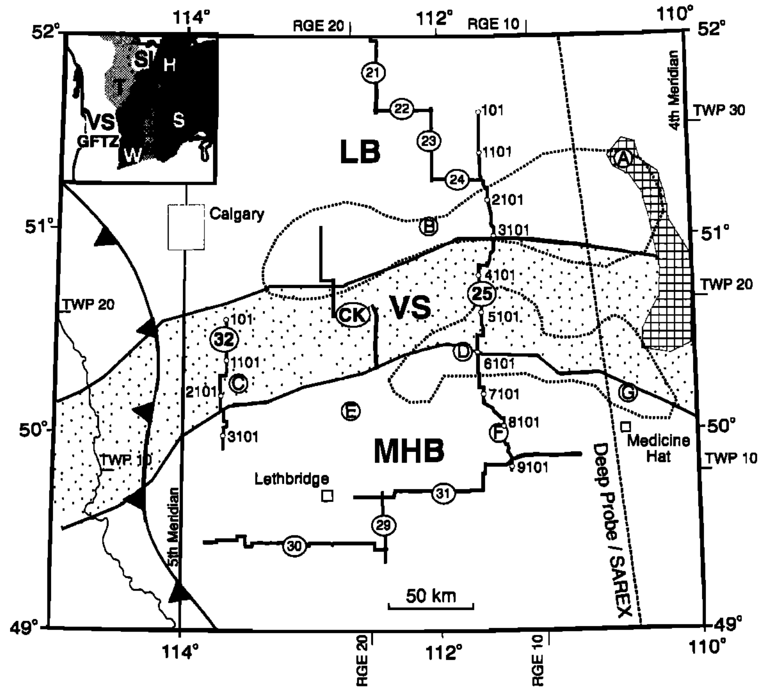

Figure 1. Simplified tectonic domain map of the study region, showing location of the Southern Alberta Lithospheric Transect (SALT) seismic profiles (numbered 21-32, with station numbers indicated for lines 25 and 32), profile CK from *Clowes and Kanasewich* [1972], refraction profile (dashed line) and basement boreholes A-G. Stippled region denotes the Vulcan structure; cross-hatched region represents inferred distribution of 1.78 Ga anorogenic granites that crosscut the Vulcan structure. Dotted lines indicate location of two flanking Bouguer gravity highs, north and south of the Vulcan structure (VS), within the Loverna Block (LB) and Medicine Hat Block (MHB). Lithologies and ages of basement rocks are: A, granite, 1.78 Ga; B, hbl-bio-granitoid, 2.59 Ga; C, garnet metabasite, 2.63 Ga; D, pegmatitic granitic gneiss, 2.72 Ga; E, granodiorite gneiss, 2.61 Ga; F, biotite quartz monzonite, 2.72 Ga; G, granodiorite gneiss, 2.7-2.8 Ga [*Villeneuve et al.*, 1993]. Inset shows location of the Vulcan structure in relation to tectonic provinces of Laurentia: T, Taltson-Wopmay; Sl, Slave; W, Wyoming; H, Hearne; TH, TransHudson; S, Superior; GFTZ, Great Falls Tectonic Zone. Dotted line shows approximate western limit of the exposed shield.

Wyoming Provinces [*Thomas et al.*, 1987; *Hoffman*, 1988], a tectonic boundary previously thought to coincide with the Great Falls Tectonic Zone (GFTZ) south of the United States-Canada border. Considering the asymmetry of the associated potential-field anomalies, *Ross et al.* [1991] refined this model and ascribed the Vulcan structure to a fossil north-dipping subduction zone. On the basis of then available Sm-Nd isotopic data suggesting a slightly younger mean crustal age for this region than for the Wyoming craton, *Hoffman* [1990] reinterpreted the Vulcan structure as an internal component of the Hearne Province. In contrast, the present study supports an interpretation of the Vulcan structure as the Hearne-Wyoming suture and suggests, on the basis of lower-crustal seismic geometries, that the fossil subduction zone is probably south-dipping.

As part of a multidisciplinary investigation of the crystalline crust underlying the WCSB [*Ross et al.*, 1997], the Canadian Lithoprobe program conducted a number of geophysical surveys in southern Alberta during 1995. This work included two overlapping refraction/wide-angle reflection experiments, Deep Probe and Southern Alberta Refraction Experiment (SAREX), designed to determine the structure of the crust and upper mantle over a large region that encompasses the Vulcan structure (Figure 1). Preliminary results of the Deep Probe data [*Henstock et al.*, 1998] indicate that the Wyoming Province is characterized by a thicker crust (~ 50 km) than the Hearne Province (~ 40 km). In addition, the Wyoming Province is underlain by a thick high-velocity (> 7.0 km/s) layer, which is conspicuously thinner beneath the Hearne Province. The transition from Wyoming-type to Hearne-type crust is not well defined by the Deep Probe data due to the large source spacing used, but it is constrained to lie well north of the GFTZ. Preliminary interpretations of the SAREX data [*Burianyk et al.*, 1997] reveal a planar Moho above which a moderate degree of lateral velocity heterogeneity exists at midcrustal to lower-crustal levels, in the vicinity of the Vulcan structure.

The Southern Alberta Lithospheric Transect (SALT), the seismic-reflection component of the 1995 Lithoprobe program in Alberta, consisted of 832 km of vibroseis data acquired along nine profiles (Figure 1). One of the main objectives of SALT was to image the crustal architecture of the Vulcan structure at several locations to gain a better understanding of its geometry at depth and variability along strike. The SALT program included two north-south crossings of the Vulcan structure, lines 25 and 32, which are separated by 150 km. Because of limited availability of suitable roads for the reflection profiles and restrictions on shot locations for the refraction work, both SALT profiles are located west of the SAREX/Deep Probe line. The reflection program was complemented by a coincident high-resolution gravity survey, as well as aeromagnetic data acquisition south of the Vulcan structure. Drawing from the results of these initiatives, the aims of this paper are to present a joint interpretation of the seismic and potential-field data across the Vulcan structure and to comment on the role of the Vulcan structure in the tectonic assembly of western Laurentia.

2. Basement Tectonic Domains

The SALT seismic program traverses a broad region of buried Archean crust of the Hearne (+ Wyoming?) Province that comprises the metamorphic hinterland to the Paleoproterozoic TransHudson Orogen [*Ross*, 1997]. The crystalline crust of this region has been subdivided into tectonic domains that are recognized on the basis of aeromagnetic expression and drill core samples [*Ross et al.*, 1991; *Villeneuve et al.*, 1993]. The Medicine Hat Block (MHB), the southernmost tectonic domain in the present study area, is a region of Archean gneissic basement (2.65-3.27 Ga) that straddles the Alberta-Montana border. It is characterized by a north-northwest trending pattern of linear, moderate-intensity aeromagnetic anomalies that reflect the tectonic fabric in the upper part of the crystalline basement (Plate 1). To the north, the aeromagnetic anomaly trends of the MHB are truncated sharply against a prominent, east-trending magnetic low associated with the Vulcan structure. Although less distinct, gravity anomaly trends in the MHB occur parallel to the magnetic anomalies (Plate 2).

The Loverna Block (LB), extending north of the Vulcan structure to at least 54°, is a crustal domain that lacks a well defined potential-field fabric orientation, although regions of distinct northwest to northeast trending anomalies are present (Plates 1 and 2). Eight dated basement drill intersections (e.g., locations A and B in Figure 1) consist of granitoid rocks and coincide with local, subcircular magnetic highs [*Villeneuve et al.*, 1993]. The range of crysallization ages in the LB, from 2.71 to 1.78 Ga, coupled with the complex potential-field anomaly patterns, suggest that the LB is composed of numerous small terranes that were formed at different times or suggest that it is an Archean crustal domain that is overprinted by Proterozoic magmatic activity. North of the present study area, there is also evidence that the LB underwent large-scale crustal imbrication and pervasive Paleoproterozoic reworking [*Ross et al.*, 1995]. To the west, the LB is bounded by low-grade metasedimentary rocks [*Boerner et al.*, 1995] and a possible subduction-related magmatic arc [*Eaton and Cassidy*, 1996].

With only a single cored basement intersection that has been dated (well C, Figure 1), interpretation of the extent of the Vulcan structure has been derived primarily from potential-field analysis. The Vulcan structure is clearly expressed in maps of both the total-field aeromagnetic and Bouguer gravity data (Plates 1 and 2). Wavelength filtering of the magnetic data (Figure 2) indicate that the anomaly associated with the Vulcan structure is dominated by wavelengths > 65 km, whereas adjacent regions include shorter-wavelength spectral components that most likely originate from sources that extend up to the basement-cover contact, at a depth of 2 - 4 km (see below).

In previous work, *Ross et al.* [1991] and *Villeneuve et al.* [1993] distinguished between the Vulcan low, the sinuous magnetic low that truncates the MHB fabric, and the Matzhiwin high, an adjacent region with a positive aeromagnetic signature that is north of, and in part parallel to, the Vulcan low. Although the entire region of the Matzhiwin high is characterized by elevated magnetic intensity values, it has an internal structure with two discernible components. A short-wavelength (< 65 km) component of the magnetic anomaly fabric (Figure 2a) is characterized by weak northeast trending aeromagnetic fabrics parallel to the trends in the LB. Longer wavelengths (>65 km; Figure 2b) include a positive magnetic trend parallel to the Vulcan magnetic low, as well as a positive anomaly near 113°W that correlates to a broad gravity high east of Calgary.

Some inconsistency arises from these previous tectonic subdivisions, since a large segment of the gravity low associated with the Vulcan structure then falls within the boundaries of the Matzhiwin high (Plate 2). Here, we show that a more robust tectonic subdivision is possible. Figure 3 shows average magnetic and gravity profiles across the Vulcan structure, computed from a set of equally spaced, north-south profiles between 113.6° and 110.9°W by aligning each profile with respect to the Vulcan aeromagnetic low. These stacked profiles show that the magnetic anomaly is more accurately described as a negative-positive couplet, rather than an isolated low, and that the average gravity anomaly is actually a central low flanked by gravity highs. Since the terrain in this area is essentially flat lying, the gravity anomaly is uncorrelated with present-day topography. It is worth noting that similar gravity anomalies are observed at fossil Proterozoic plate boundaries elsewhere in the Canadian Shield [*Gibb and Thomas*, 1976; *Pilkington*, 1990], although not all of these fossil plate boundaries have associated magnetic anomalies. On the basis of these observations, we interpret the east trending, longer wavelength component of the aeromagnetic high, formerly designated as part of the Matzhiwin high, to be part of the Vulcan structure. Remaining parts of the former Matzhiwin high that do not show a clear east-west trend are classified herein as part of the LB.

New aeromagnetic data in southwestern Saskatchewan show that east of the present study area, the Vulcan structure curves toward the southeast and merges with aeromagnetic fabrics associated with the TransHudson orogen [*Ross*, 1997]. The western limit of the Vulcan structure remains poorly defined, although autochthonous North American basement is known to extend beneath the Canadian Cordillera at least as far as the southern Rocky Mountain trench, and possibly much farther west [*Cook et al.*, 1992]. Difficulties in extrapolating the potential-field data beneath the Cordillera arise from westward reduction in the amplitude of aeromagnetic anomalies due to progressively deeper burial of basement rocks and overprinting of the gravity anomaly by much larger signals associated with the Cordilleran Bouguer gravity low [*Cook et al.*, 1995]. Nevertheless, various stratigraphic and structural evidence suggest that basement tectonic elements along the projected strike of the Vulcan structure may have exerted a profound and long-lived influence on the development of the Cordillera [*Kanasewich*, 1968; *Price*, 1996].

3. Seismic Reflection Data

The SALT profiles were acquired in 1995 along a series of gravel roads in southern Alberta, Canada. The acquisition parameters (Table 1) were modified slightly from typical Lithoprobe surveys, to balance the requirements for dense spatial and temporal sampling, needed to resolve shallow features in the WCSB, with long recording times and large offsets needed to record coherent deep-crustal reflections [*Eaton and Ross*, 1996]. The recording system (ARAM-24) provided 24-bit dynamic range capability, with 480 receiver groups deployed over a symmetric split spread 12-km long. The source consisted of four Hemi-50 vibroseis units that executed 20-s sweeps from 10 to 80 Hz. The data were

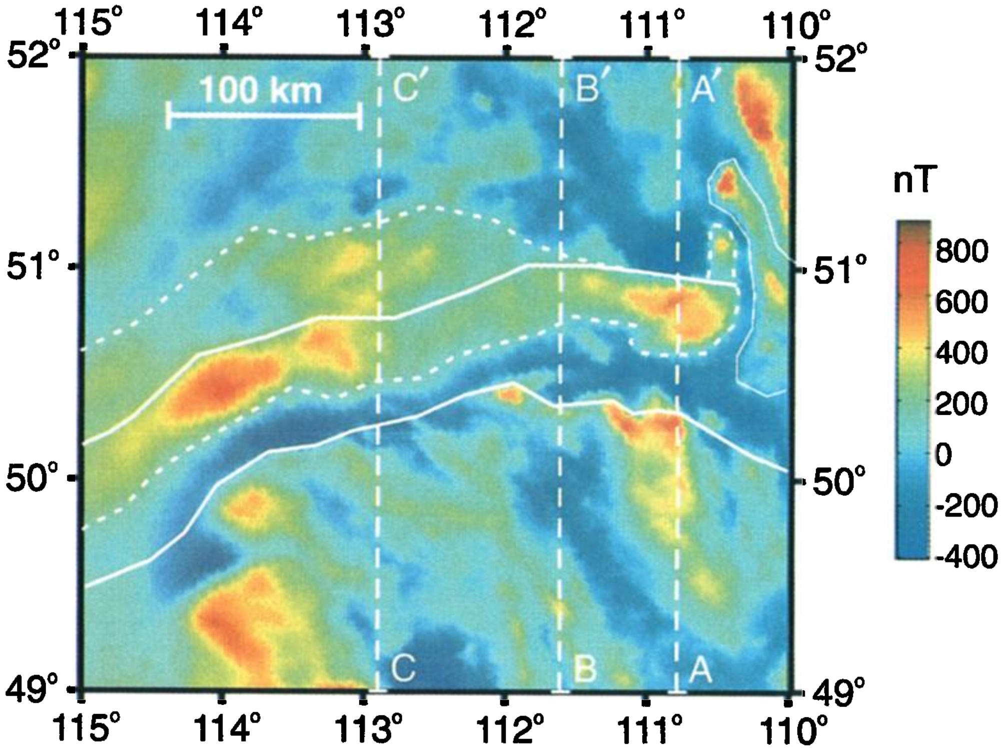

Plate 1. Total-field aeromagnetic anomaly map of the study area, gridded at a 2-km interval. Thick solid line indicates the Vulcan structure (this study); thin solid line indicates the 1.78 Ga anorogenic granite suite; short dashes represent the Matzhiwin high [*Villeneuve et al.*, 1993]. Profiles A-A', B-B' and C-C' are shown in Figures 8-10.

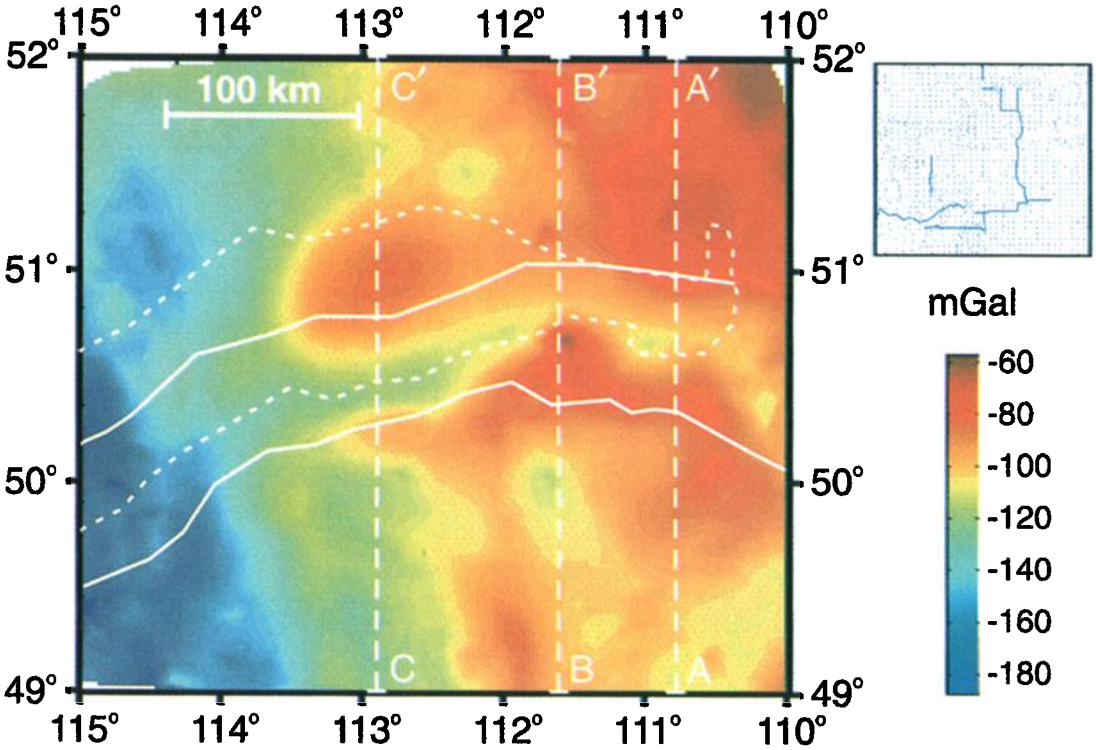

Plate 2. Bouguer gravity map of the study area, gridded at a 5-km interval. Thick solid line indicates the Vulcan structure (this study); short dashes represent the Matzhiwin high [*Villeneuve et al.*, 1993]. Profiles A-A', B-B', and C-C' are shown in Figures 8-10. Inset shows location of gravity stations used, including the new high-resolution survey along the seismic lines.

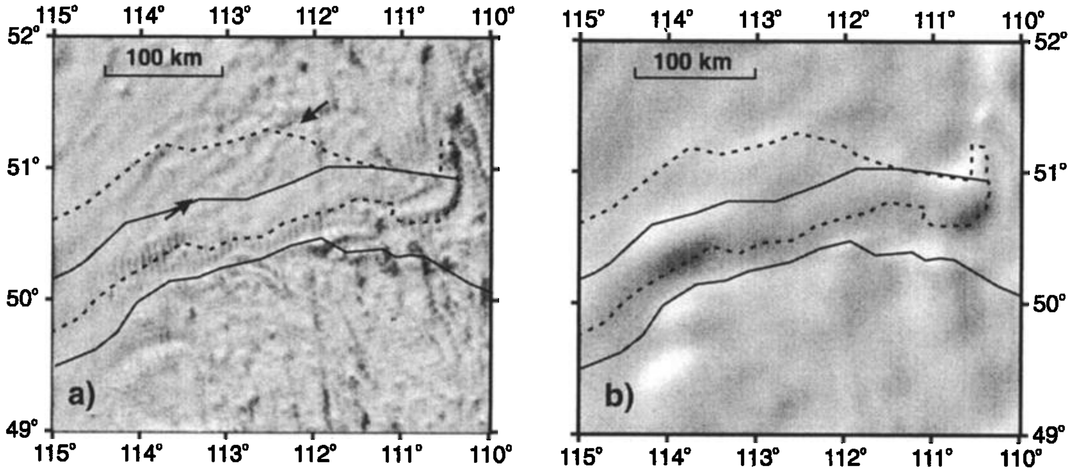

Figure 2. Wavelength-filtered aeromagnetic data using (a) high-pass, and (b) low-pass fourth-order Butterworth filters, each with a 65 km corner wavelength. Solid line indicates the Vulcan structure (this study); dashed line indicates the Matzhiwin high [*Villeneuve et al.*, 1993]. Figure 2a illustrates the continuation of the weak linear fabric from the Loverna Block into the area of the Matzhiwin high (black arrows) and truncation of Medicine Hat Block aeromagnetic fabric by the Vulcan structure (white arrow). Figure 2b shows enhancement of the positive component of the roughly east-west trending Vulcan anomaly (white arrows) and a long-wavelength anomaly in the Matzhiwin high (black arrow).

processed to final stack by a commercial contractor, with subsequent noise attenuation and migration applied in-house (Table 2). Although uncorrelated records extended only 12 s after the sweep, the data were processed to 18 s using extended-correlation techniques. For migration, a velocity profile derived from the nearby SAREX refraction experiment [*Burianyk et al.*, 1997] was used, with trace padding to preserve dipping events near the ends of the profiles.

Line 25 provides the only complete crossing of the Vulcan structure. The observed reflectivity along this profile can be classified as follows: horizontal, laterally continuous reflections from 0.3 to 1.8 s two-way time (TWT), representing Phanerozoic stratigraphic contacts within the WCSB in the upper 2.0 to 2.2 km of the crust (shown as 1 in Figure 4d); less continuous, horizontal events and dim zones between 2 and 4 s that are manifestations of multiple reverberations within the sedimentary layers (shown as 2 in Figure 4d); variably reflective and/or diffractive units in the crystalline upper and middle crust, extending to a maximum TWT of ~ 10 s (3-7 in Figure 4d); reflective lower crust (8 and 9 in Figure 4d); and unreflective upper mantle, below 14 - 15.8 s TWT (10 in Figure 4d). This subdivision of the crust into distinct zones based on reflectivity characteristics provides a framework for our overall interpretation. Individual reflection zones are described in detail below.

Upper crustal reflection zones along line 25 delineate an apparent crustal culmination that coincides roughly with the Vulcan structure. At the north end of the profile, reflection zone 3 represents the upper crust of the LB. It contains areas of diffractions and discontinuous reflection segments which

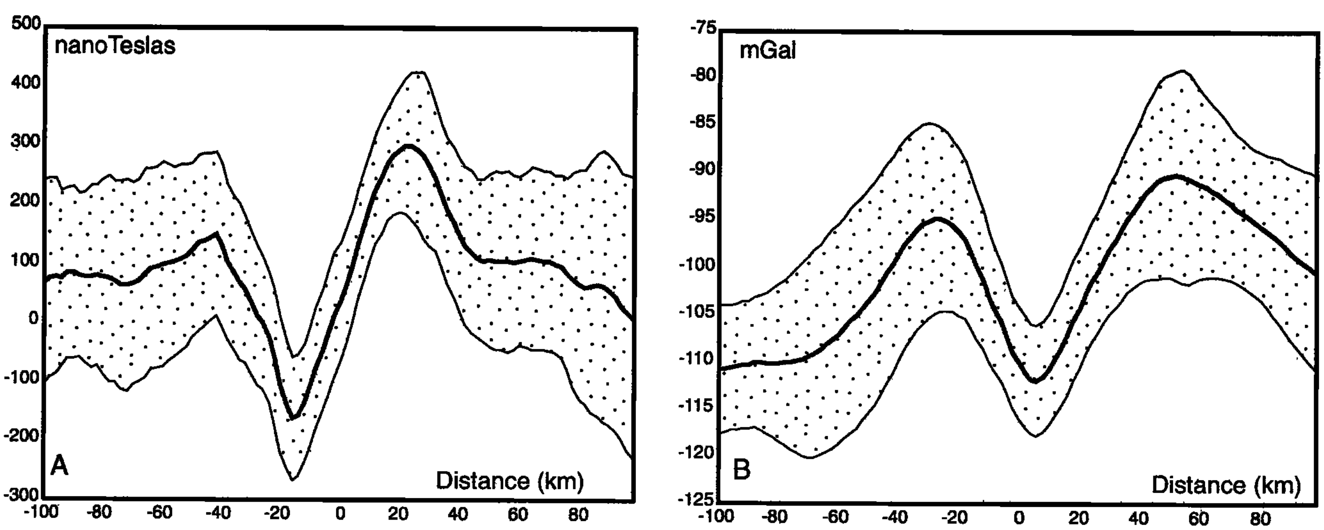

Figure 3. (a) Average magnetic and (b) gravity anomaly profiles across the Vulcan structure, constructed by selecting 100 north-south profiles between 110.9° and 113.6°W, aligning each with respect to the minimum magnetic value in the Vulcan structure and computing the average. Stippled region extends 1 standard deviation to either side of the mean.

Table 1. Acquisition Parameters for the SALT Survey

Parameter	Value
Source type	4 × Hemi 50 truck mounted vibroseis
Vibroseis sweep	8 × 10-80 Hz linear, 20 s duration
Source array	100 m
Recorder	GeoX Systems ARAM 24
Sample rate	2 ms
Record length	32 s uncorrelated records to tape
Station interval	25 m
Source interval	100 m
Spread type	Symmetric split spread, 6125 m far offset
Number of channels	480

are subhorizontal, or dip shallowly to the north and south. This crustal unit appears to be bounded below by a discontinuous but correlatable series of north dipping reflection segments (see Figure 5) that extend from the base of the sediments, near station 2800, to the top of the lower crust beneath station 1101. Between stations 2200 and 3500, at about 5 s TWT (12 km depth), abundant incoherent short reflection segments (diffractions?) are evident and collectively identified as zone 4. Reflection zone 5, which occupies the bulk of the upper and middle crust within the Vulcan structure, contains few correlatable events. One exception is a discrete, subhorizontal reflection (R1) that extends for ~15 km between stations 5101 and 4101, at a depth just below the top of zone 4 (Figure 6a). Reflection R1 appears to be truncated by a package of south dipping reflections (zone 6A) that flatten and become less prominent with depth (zone 6B). The inferred subcrop extent of zone 6A at the base of the WCSB correlates with a broad gravity high in the southern part of the Vulcan structure. Situated at the southern end of line 25, reflection zone 7 contains few reflections and coincides with an area of low Bouguer gravity values in the MHB.

With the exception of zones 4 and 6A, the lower crust beneath line 25 is substantially more reflective than the upper crust. Beneath the LB, the lower crust (zone 8) is about 15-km thick and is underlain by a relatively sharp reflection Moho between 14 and 16 s (Figures 4-6). The basal lower crust is represented by a distinctive zone of abundant kilometer-scale reflection segments, above which individual reflections can be correlated over considerably greater distance (Figure 5). The Moho beneath the LB exhibits undulations in reflection time, with a wavelength of ~ 70 km, which appear to correlate with undulations in the Bouguer gravity profile (Figure 4b). Near station 3101, in the northern part of the Vulcan structure, the reflection Moho appears to be deflected downward toward the south. Beneath the MHB, the lower crust (zone 9) has markedly different reflection characteristics. Here the reflection Moho is a diffuse boundary at > 15 s TWT, above which the strongest reflectivity occurs near the top of the lower crust (zone 9A). The level of reflectivity in the lowermost crust diminishes noticeably between stations 4101 and 6101. Within this interval, arcuate south dipping reflections in zone 9A appear to structurally overlie reflection zone 8. The boundary between zones 8 and 9 is delineated by a conspicuous, piecewise continuous series of arcuate reflections (R2) between stations 5101 and 2800 that flatten at 8.5 s TWT (Figure 6b). This series of reflections is nearly centered on the Vulcan gravity low.

On the basis of along-strike correlation of aeromagnetic anomaly trends, line 32 appears to cover an interval of the Vulcan structure that corresponds with the segment of line 25 between stations 3101 and 7101. Thus it is doubtful if any of the LB upper crust is imaged along line 32. As in the previous case, zones 1 and 2 (Figure 7) represent the sedimentary cover sequence and multiple reverberations, respectively. Multiple reflections are more prevalent here than along line 25, and individual multiple reflections (including one at twice the two-way time to the top of basement) can be correlated over large distances. Zone 3 is a region of generally incoherent reflectivity that may be equivalent to zone 5 on line 25. A small package of coherent, south dipping reflections near station 3000, between 8-10 s, stands out from the otherwise nearly featureless background of zone 3. As discussed below, zone 4 is an interval of high apparent attenuation in the crystalline crust. Zone 5 contains at least three distinctive, laterally continuous subhorizontal reflections. *Mandler and Clowes* [1998] have interpreted these reflections as part of a regionally extensive package of reflections in the MHB, the Head-Smashed-In (HSI) reflection sequence. These reflections are probably caused by midcrustal sills that intruded the MHB prior to formation of the Vulcan structure.

In order to preserve dipping reflections near the end of the profile, line 32 was padded with zero traces prior to migration. The north end of line 32 (Figure 7) contains a discernible zone of south dipping reflections at ~ 15 s TWT (zone 6) that would otherwise have largely disappeared after migration, without trace padding. The absence of reflectivity beneath this zone, and its relative position within the Vulcan structure (for example, its position beneath the Bouguer gravity low), suggest that zone 6 may correlate with the lower crust and Moho of the LB. As in the case of line 25, the reflection Moho beneath the MHB is diffuse and therefore difficult to identify with precision. At the south end of the line, however, there does appear to be a zone of enhanced reflectivity (zone 7A) that may be equivalent to zone 9A on line 25. If this correlation is correct, the reflection Moho beneath the MHB is probably at about 14 s TWT.

At station 2101, the lower crustal reflectivity in zone 7A and the HSI reflections terminate abruptly toward the north. This apparent near-vertical boundary is suspicious, and we attribute the termination of these reflections to lack of signal

Table 2. Processing Parameters for the SALT Survey

Processing step	Parameters
Sweep correlation	18 s correlated trace length using self-truncating sweep
Amplitude recovery	500 ms AGC
Refraction statics	2-layer solution, 1200 m datum
Deconvolution	Multiple design window, zero-phase output
Spectral balance	Zero-phase, multigate design and application
Trace balance	Amplitude balance on entire trace
CMP gather	Crooked line geometry with bin balancing
Normal moveout	Velocities based on interactive coherency spectra every 1.5 km
Residual statics	Automatic surface-consistent, 300-3000 ms window, max. static = 20 ms
CMP stack	60 fold
Coherency filtering	Semblance criterion, 25-trace sliding window
Migration	Phase-shift algorithm using SAREX refraction velocities

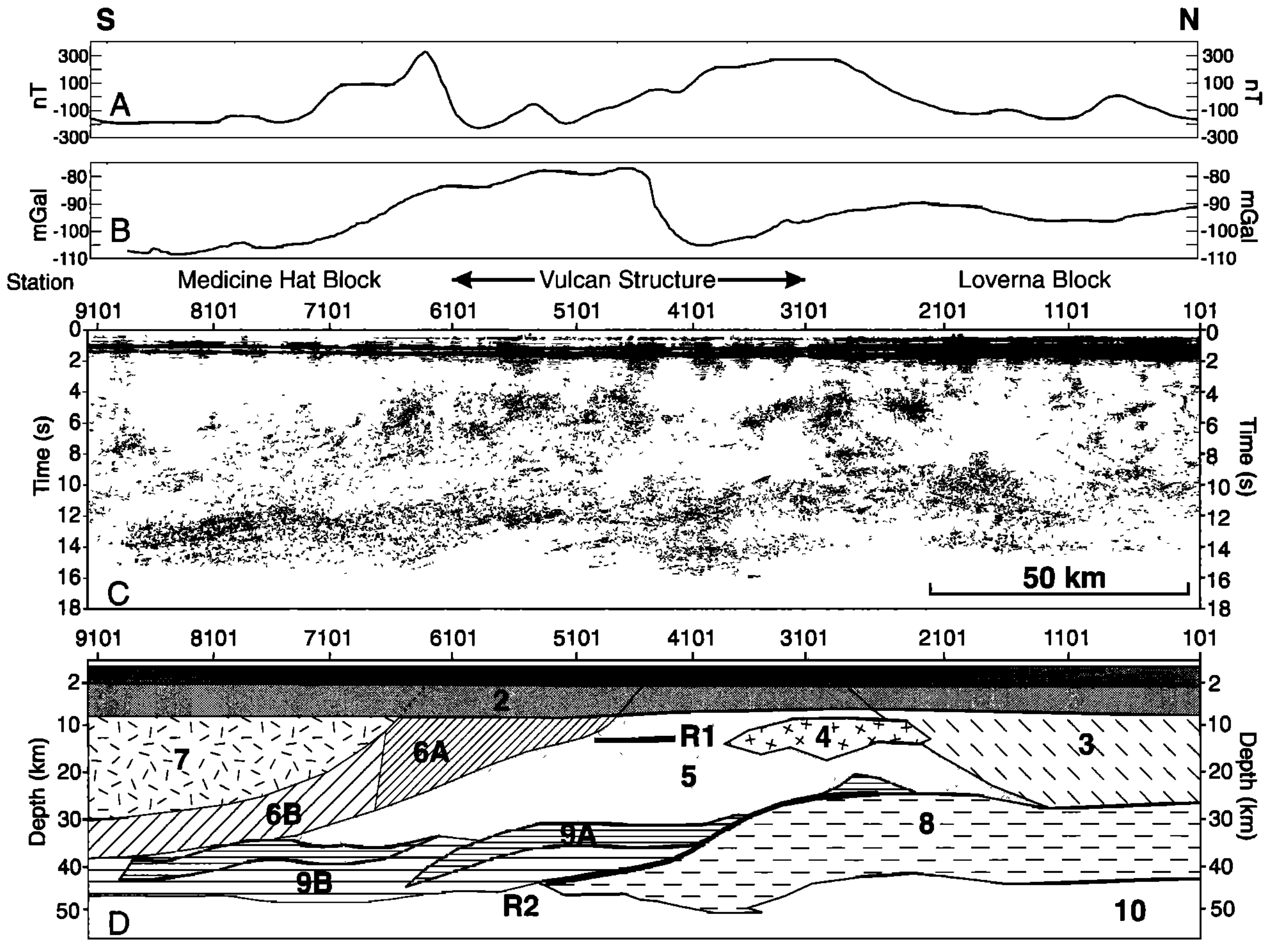

Figure 4. Summary of geophysical data along SALT line 25, showing (a) total-intensity magnetic profile, (b) Bouguer gravity data, (c) migrated and coherency filtered seismic section at approximately 1:1 scale, and (d) subdivision of the seismic data into distinct reflectivity packages. The numbers in Figure 4d represent the following: Phanerozoic sediments in the Western Canada Sedimentary Basin (1), zone of multiple contamination (2), upper crust of the Loverna Block (3), zone of strong diffractions (4), Vulcan structure (5), zone of south-dipping reflections (6), subdivided into zones of strong (6A) and weak (6B) reflectivity, unreflective upper crust of the Medicine Hat Block (7), lower crust of the Loverna Block (8), lower crust of the Medicine Hat Block, (9), subdivided into zones of strong (9A) and weak (9B) reflectivity; undifferentiated upper mantle (10), subhorizontal mid-crustal reflection (R1), and dipping lower crustal reflection (R2) (see text). Note that the datum elevation for this profile (1200 m) is ~ 400 m higher than the mean surface elevation, delaying the start time of the data to 0.3 s. Conversion from time to depth in Figure 4d uses the known Phanerozoic isopach of 2.0 to 2.2 km [*Wright et al.*, 1994], an average velocity of 6.6 km/s for the crystalline crust [*Burianyk et al.*, 1997] and an assumed upper mantle velocity of 8.1 km/s.

penetration in zone 4, rather than structural truncation. There are strong indications that zone 7A reappears farther north, near station 1101, suggesting that the lower crust may continue across this interval but is not imaged by the seismic profile. The northward termination of the MHB lower crust against the LB lower crust, as indicated in Figure 6d, is speculative.

Several seismic profiles recorded across and along the Vulcan structure in the late 1960s (e.g., CK in Figure 1) are situated between lines 25 and 32, and thus provide additional along-strike information. In Figure 8, a migrated line drawing from *Clowes and Kanasewich* [1972] is compared with migrated data from line 25. Profile CK reveals a shallower reflection Moho with greater apparent structural relief than line 25. For example, the Moho occurs between 11.6 - 14.5 s TWT in profile CK, compared with 14-16 s for line 25. Notably, profile CK traverses a higher-amplitude gravity high on the north flank of the Vulcan structure than does line 25. Both profiles exhibit a comparable thickness of reflective lower crust (~ 15 km), as well as a similar wavelength of undulating Moho topography. The original interpretation of profile CK by *Clowes and Kanasewich* [1972] featured a series of steep-sided horst and graben fault blocks (Figure 8a), but the newer data along line 25 argue for a greater degree of lateral continuity in the lower crust of the LB and a low-angle detachment near the Moho in the Vulcan structure.

4. Potential-Field Interpretation

In the present study, gravity forward modeling has been undertaken within three north-south corridors to investigate similarities and differences in crustal architecture along the

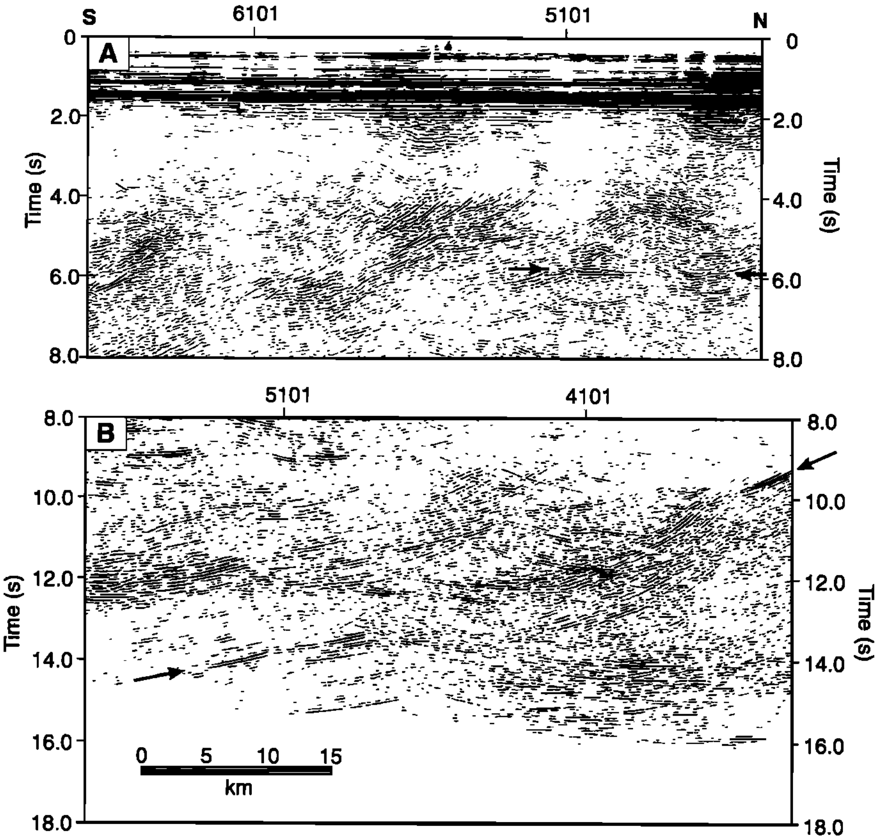

Figure 5. Portion of migrated seismic data from line 25, comparing crustal reflectivity of (a) the Medicine Hat Block (MHB) with (b) the northern Vulcan structure and Loverna Block (LB). The crust thickens toward the south, based on an increase in Moho (M) reflection time from 14.2 s beneath the LB to ~ 15.3 beneath the MHB. The upper crust is unreflective in the case of the MHB but contains areas of incoherent reflectivity (diffractions?) between 4.0 and 6.0 s in the Vulcan structure. The arrows in Figure 5b indicate a discontinuous north dipping reflection that is inferred to

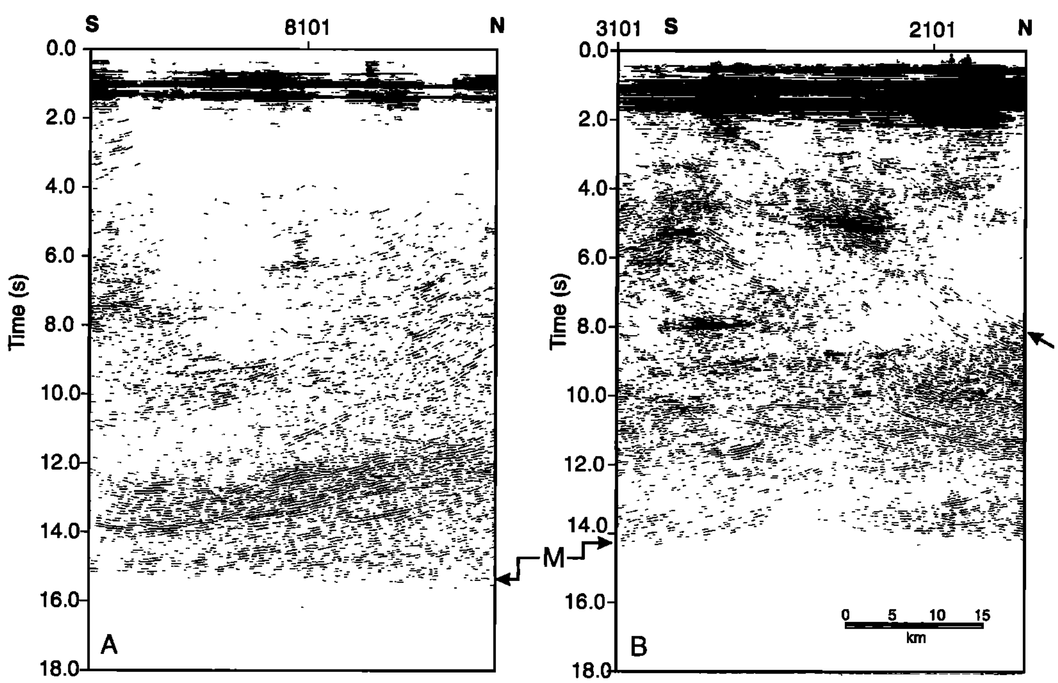

Figure 6. Portion of migrated seismic data from line 25, showing truncation of midcrustal reflection R1 (arrows) by south dipping reflec
crustal units by reflection R2, beneath the central and northern Vulcan structure. Loss of reflec
2.0 and 4.0 s in Figure 6a is due to contamination by multiples. Loss of reflectivity below ~ 16 s in Figure 6b signifies the top of the upper mantle, which is seismically transparent. Plot scale is approximately 1:1.

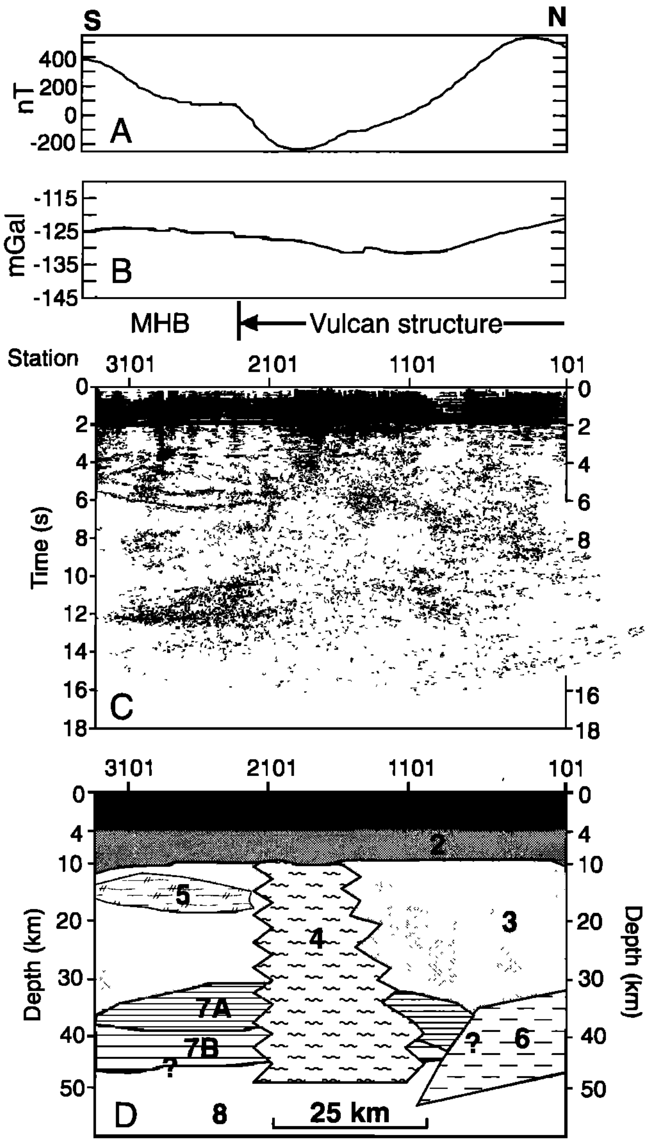

Figure 7. Summary of geophysical data along SALT line 32, showing (a) total-intensity magnetic profile, (b) Bouguer gravity data, (c) migrated and coherency filtered seismic section, and (d) subdivision of the seismic data into distinct reflectivity packages. Prior to migration, the section was padded with blank traces to preserve events that would otherwise migrate off the section (e.g., lower crustal reflectivity at north end of the profile). The numbers in Figure 7d represent the following: Phanerozoic sediments of the WCSB (1), zone of strong multiple contamination (2), undifferentiated upper crust of the Vulcan structure and Medicine Hat Block (MHB) (3), region of inferred high attenuation (4), Head-Smashed-In reflection sequence [*Mandler and Clowes*, 1998] (5), lower crust of the Loverna Block (6), lower crust of the MHB (7), subdivided into zones of strong (7A) and weak (7B) reflectivity, undifferentiated upper mantle (8). Conversion from time to depth in Figure 7d uses the known Phanerozoic isopach of 3.7-3.8 km [*Wright et al.*, 1994], an average velocity of 6.6 km/s for the crystalline crust [*Burianyk et al.*, 1997] and an assumed upper mantle velocity of 8.1 km/s.

strike of the Vulcan structure. The three profiles are located, respectively, near the Deep Probe line (profile A-A'), along Lithoprobe line 25 (profile B-B'), and close to seismic line CK (profile C-C'). Typical problems of nonuniqueness in gravity modeling are mitigated by the incorporation of available constraints from the seismic reflection and refraction profiles. Each anomalous body in the gravity models is represented by a polygonal prism of constant density that strikes perpendicular to the profile. Independent end corrections have been applied to account for finite eastward and westward strike length of anomalous masses (so-called "2.75-D" modeling), by using the magnetic anomaly and Bouguer gravity maps (Plates 1 and 2) to estimate the lateral extent of these features.

It is worth noting that the application of simple, widely used interpretive formulas to the average gravity and magnetic profiles across the Vulcan structure (Figure 3) yield depth estimates that imply a midcrustal source. For example, the application of Smith's rule [*Reynolds*, 1997, p. 81] for a two-dimensional body to the local extrema of the gravity profile yields an estimated maximum depth of 17.5 ± 2.5 km, whereas the application of Peter's half-slope method [*Reynolds*, 1997, p. 178] to the magnetic profile yields a minimum depth of 10 km for the top of the magnetic source. Since both anomalies are probably produced by a single source, the depth is roughly constrained to be in the range of 10-20 km (more detailed analysis of the gravity anomaly is presented below). We note also that magnetic anomalies produced by sources at middle to lower crustal depths are consistent with regional heat flow data. Southern Alberta is situated within the lowest heat flow region in western North America, with basement heat flow of ~ 40 mW/m^2 [*Bachu*, 1993]. Geotherms for shield regions with surface heat flow in this range [e.g., *Pinet et al.*, 1991] exhibit Moho temperatures that are well below the minimum Curie temperature for magnetite (463°C).

Profile A-A' (Figure 9) is situated at 110.8°W and coincides approximately with a 320-km segment of the Deep Probe/SAREX refraction line. Along this segment, the preliminary velocity model obtained by the Deep Probe working group [*Henstock et al.*, 1998, Figure 3] indicates northward crustal thinning, from ~ 48 km within the MHB at the United States - Canada border to ~ 42 km at the north end of the present gravity profile (52°N). The northern part of the Wyoming Province (MHB) is characterized in the Deep Probe data by a ~ 25-km thick high-velocity layer in the lower crust, which thins to ~ 15 km farther north within the Hearne Province. The precise location of this transition from Wyoming-type to Hearne-type crust is not well defined by the Deep Probe data due to the large source spacing used.

Figure 9 shows a crustal density model along profile A-A' that satisfies the intermediate to long-wavelength (> 50 km) gravity trends. This model also tests the possibility that the Wyoming-Hearne transition occurs across the northern part of the Vulcan structure. No attempt is made here to fit shorter wavelength gravity anomalies, since such features (which must have their source in the upper crystalline basement) are presently unconstrained by other sources of information. Note that although the crustal thinning implied by the Deep Probe velocity model is qualitatively consistent with the northward increase (by ~ 30 mGal) in the Bouguer gravity profile, an unrealistically small Moho density contrast is needed to fit the observed gravity gradient in the absence of any crustal mass anomalies. By allowing a lower crustal layer with a positive density contrast of 100 kg/m^3 to thin toward the north (Figure

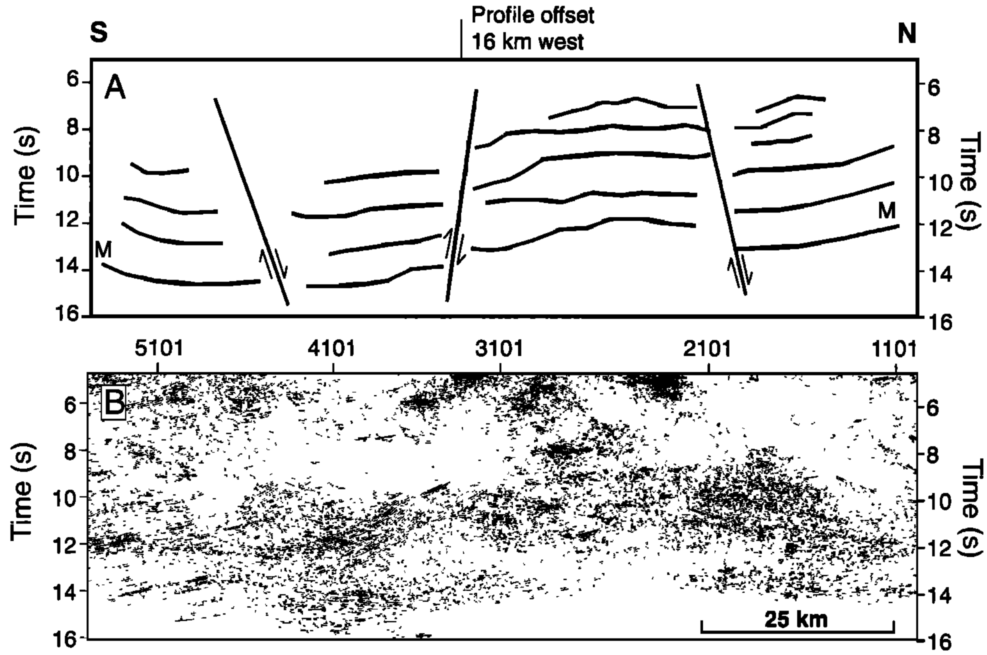

Figure 8. Comparison of (a) migrated line drawing of lower-crustal reflectors from profile CK, showing original interpretation of *Clowes and Kanasewich* [1972], with (b) the corresponding segment of SALT line 25. M = reflection Moho.

9), a better fit to the long-wavelength gravity data is achieved with a more realistic Moho density contrast (300 kg/m^3).

The axial gravity low that characterizes the Vulcan structure has been represented here by a midcrustal mass deficiency with a density contrast of -120 kg/m^3. Since it is difficult to achieve a reasonable fit to the profile with a deeper body, the top of this low-density feature should be regarded as its maximum depth. Another important element of the model occurs in the transitional region north of the low density body, where a relative gravity high flanks the Vulcan low. In the scenario depicted in Figure 9, this relative high is produced by localized thickening of the lower crust. The flanking gravity high can thus be explained by mass excess in the lower crust, consistent with lower-crustal imbrication suggested by the seismic geometries evident along line 25 (Figure 4).

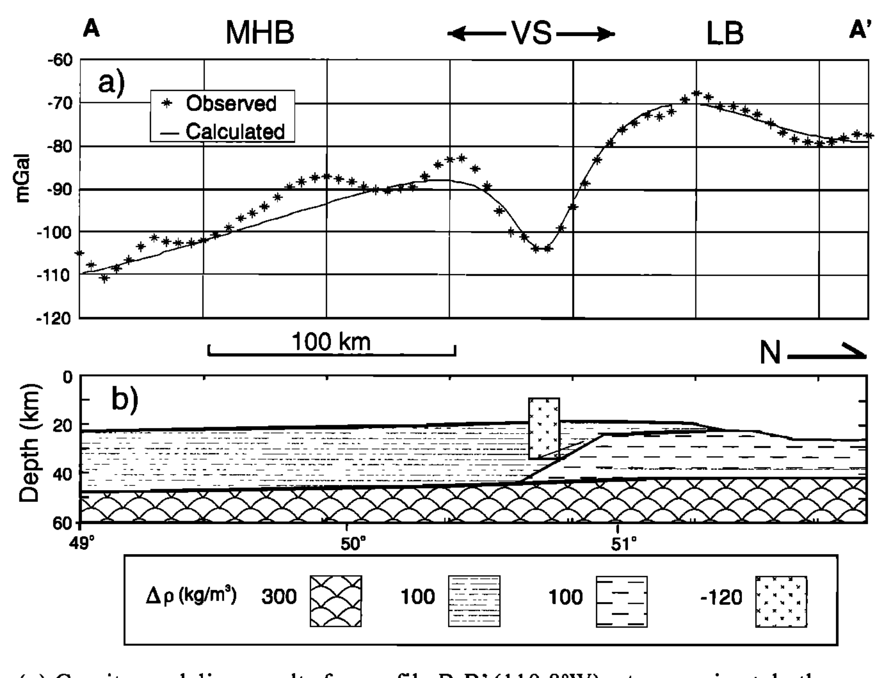

Figure 9. (a) Gravity modeling results for profile B-B' (110.8°W), at approximately the same longitude as the Deep Probe/SAREX surveys. (b) Crustal density model, shown at 1:1 scale. The abbreviations are: MHB, Medicine Hat Block; VS, Vulcan structure; LB, Loverna Block.

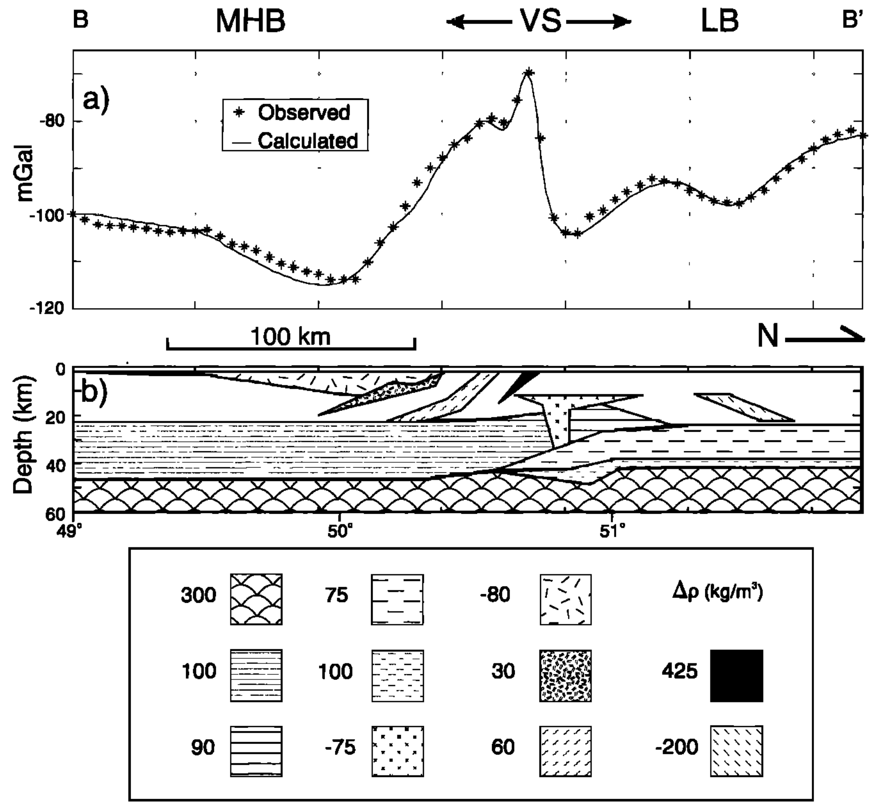

Figure 10. (a) Gravity modeling results for profile A-A' (111.6°W), at approximately the same longitude as SALT line 25 (Figure 4). (b) Crustal density model, shown at 1:1 scale. The abbreviations are: MHB, Medicine Hat Block; VS, Vulcan structure; LB, Loverna Block.

Profile B-B' (Figure 10) falls near Lithoprobe line 25 at 111.6°W, where the most complete seismic-reflection control is available. The lower-crustal configuration from profile A-A' was used here as a starting point. The model was then modified to incorporate reflectivity domains apparent in the seismic reflection interpretation (Figure 4). Conversion of reflectivity domain boundaries from TWT to depth has been made using the known thickness of Phanerozoic sediments [*Wright et al.*, 1994] in conjunction with the average basement velocity of 6.6 km/s obtained from the SAREX survey [*Burianyk et al.*, 1997]. In the lower and middle crust, the main features of the model are (1) a lower crustal ramp, across which the MHB overthrusts the lower crust of the LB, and (2) a diapiric body with low density situated in the core of the Vulcan structure. The former is implied by the seismic geometry from line 25 and is consistent with, but not required by, the potential field data. The latter is required to fit the intermediate-wavelength gravity low which is common to all three profiles.

It is assumed for profile B-B' that the top of the diapiric body coincides with the zone of prominent diffractions (zone 4) and reflection R1, observed on line 25. The lower crust of the LB is modeled using two layers, consistent with distinct basal reflectivity in the LB lower crust along line 25, whereas the lower crust of the MHB is treated as a single unit. Modeling tests indicate that the undulating gravity trends along the northern part of line 25 cannot be explained by similarly undulating Moho topography, since the gravity signal that would be produced by such a Moho configuration would have a longer wavelength than that which is observed. An alternative explanation for the apparent Moho undulations along line 25 is velocity pull-up associated with changes in the average crustal velocity, due to the presence of dense, high-velocity material at shallow levels in the crust.

Compared with the average gravity anomaly (Figure 3), an unusually large Bouguer gravity anomaly, with ~ 44 mGal of net relief, is present on the southern flank of the Vulcan structure (Figure 10). Superimposed on the broad high is a narrow peak, associated with a gravity high of limited strike extent (Plate 2). Given the limited lateral extent and short wavelength of this feature, a tectonic sliver of material with a high density contrast (425 kg/m^3) is required to fit the gravity data. This high-density feature is situated within a zone of south dipping reflection fabric (zone 6A, Figure 4) that extends toward the lower crust.

The crustal model for profile C-C', corresponding approximately with profile CK (112.9°W), has the simplest structure of the three considered here. The overall south-north gravity gradient is smaller than either of the other profiles, suggesting a reduced Moho slope compared with profile B-B'. The dominant flanking gravity high in this case is north of the Vulcan structure. In the scenario depicted in Figure 11, we associate this gravity high with overthrusting of the LB lower crust by the MHB. Unlike the previous two profiles, in this case the lower crustal thrust sheet is emplaced at shallower crustal levels than in the other profiles. Some of the seismically apparent undulation in the lower crust and Moho of the LB along profiles CK and 25 (Figure 8) may be attributable to velocity pull-up. This interpretation is consistent with the correlation between positive gravity anomalies and high

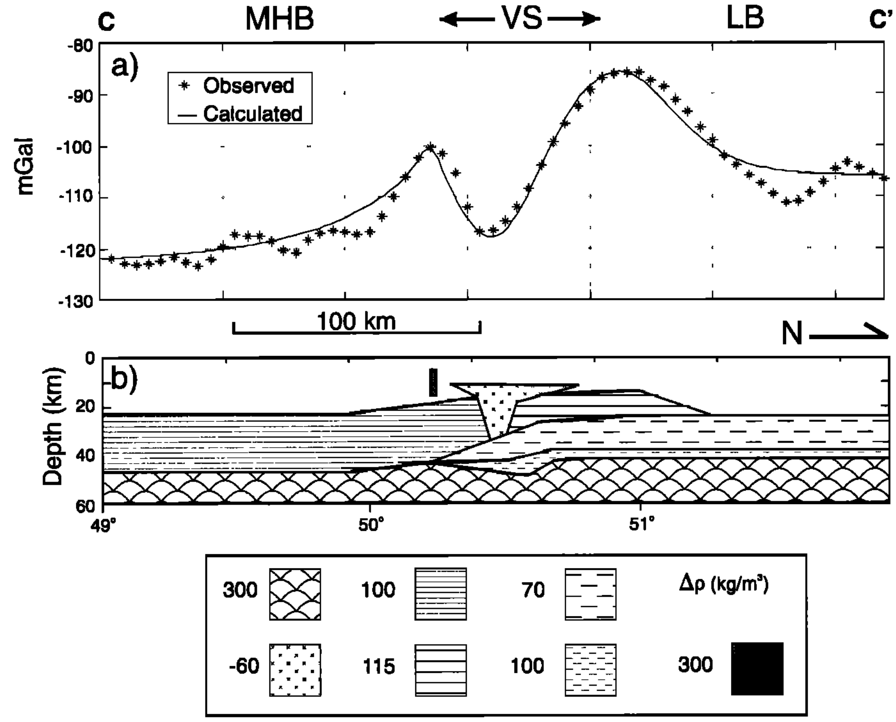

Figure 11. (a) Gravity modeling results for profile C-C' (112.9°W), at approximately the same longitude as profile CK (Figure 8). (b) Crustal density model, shown at 1:1 scale. The abbreviations are: MHB, Medicine Hat Block; VS, Vulcan structure; LB, Loverna Block.

seismic velocities in the middle and upper crust noted by *Chandra and Cumming* [1972].

In summary, gravity modeling along three profiles across the Vulcan structure suggests that (1) the Bouguer gravity data are consistent with northward crustal thinning and step-like transition from Wyoming-type crust to Hearne-type crust, as implied by the preliminary Deep Probe velocity model [*Henstock et al.*, 1998]; (2) the axial gravity low that occurs along the length of the Vulcan structure can be fit using a midcrustal mass deficiency, with a range of density contrast in these models from -60 to -120 kg/m^3; and (3) flanking gravity highs, not considered to be part of the Vulcan structure in previous tectonic subdivisions [e.g., *Villeneuve et al.*, 1993], can be explained by lower crustal imbrication and/or uplift of dense material to shallow crustal levels. The axial gravity and magnetic anomaly are probably produced by a common source, implying that the source body has both low density and relatively high magnetic susceptibility.

5. Discussion

In view of the constraints imposed by the seismic profiles, potential-field models and basement drillcore, a viable model for the origin of the Vulcan structure must be compatible with the following first-order characteristics: (1) juxtaposition of distinct blocks of old, continental crust (MHB and LB) across a relatively narrow (40-70 km) belt of regional strike extent (at least 350 km); (2) an E-W strike direction that forms a high angle to older tectonic fabrics, such as NNW striking Archean trends in the MHB, and younger tectonic elements such as the TransHudson orogen; (3) contrasting aeromagnetic anomaly fabrics on either side of the structure; (4) axial gravity and magnetic anomalies of midcrustal origin that persist along the full length of the Vulcan structure; (5) intermittent trends of gravity highs that flank the axial gravity low; (6) overthrusting of the LB lower crust by the MHB lower crust; and (7) limited coeval metamorphism and deformation in the upper crust, but possible melting at lower crustal levels beneath the MHB [*Davis et al.*, 1995]. The contrasting orientation of aeromagnetic fabrics and the overlapping (shingled) reflection geometry in the lower crust both strongly suggest a collisional origin for the Vulcan structure and are inconsistent with the original rift hypothesis suggested by *Kanasewich* [1968].

Although clearly younger than the Archean tectonic fabric in the MHB, the precise age of the Vulcan structure is uncertain. A metabasite within the Vulcan structure has a well-defined Archean primary igneous age of 2.63 Ga, based on U-Pb dating of zircons, but has a less well defined U-Pb age of 2.1 Ga in titanite [*Villeneuve et al.*, 1993]. A younger age of ~ 1.88-1.85 Ga is indicated by widespread K-Ar ages [*Burwash et al.*, 1962] and paleomagnetic data [*Özdemir et al.*, 1988]. Northeast of the Vulcan structure, a biotite granite from well A (Figure 1) has a zircon age of 1.78 Ga [*Villeneuve et al.*, 1993], contemporaneous with the terminal collision of the TransHudson orogen toward the east. This intrusion produces a strong magnetic anomaly that crosscuts the Vulcan structure, implying that deformation associated with the Vulcan structure predates terminal collision in the TransHudson. Recent data from lower crustal xenoliths indicate that juvenile mafic rocks (1.69 - 1.81 Ga) were emplaced in the lower crust during a Proterozoic thermal event [*Davis et al.*, 1995]. If this marks the age of the lower crustal high-velocity layer identified from the Deep Probe data [*Henstock et al.*, 1998], then a post-1.8 Ga age for the Vulcan structure is implied.

In formulating a model for ancient tectonic features such as the Vulcan structure, valuable insight can often be gained by comparisons with modern orogenic belts. The Pyrenees represent an extensively studied modern orogen of comparable geographic extent (450 km) that exemplifies most of the characteristics listed above. The Pyrenean mountains are the product of Late Cretaceous to Tertiary relative rotation and collision between two continental plates, Iberia and Europe, along a trend that forms a high angle with the slightly younger Alpine belt. An axial Bouguer gravity low, the consequence of an isostatic root beneath the crest of the mountain belt, is flanked by an intermittent trend of gravity highs in the upper plate that have been modeled as blocks of mantle material emplaced at midcrustal depths [*Casas et al.*, 1997]. Seismic profiling across the orogen shows that the lower crust and lithospheric mantle of Iberia were delaminated and subducted beneath Europe [*ECORS Pyrenees Team*, 1988; *Choukroune and ECORS Team*, 1989]; yet the Pyrenean chain is one of the few mountain belts where syncollisional metamorphic or plutonic products are absent in exposed rocks [*Muñoz*, 1992].

Assuming that the Pyrenees are a valid analog for the Vulcan structure, the LB can be likened to Iberia, inasmuch as it forms the lower plate in the collision. In the case of the Vulcan structure, contrasting patterns of lower-crustal reflectivity and aeromagnetic fabric orientation fit easily into this model, since the MHB and LB are represented here as originally disparate continental fragments that may have experienced some degree of rotation prior to collision. Moreover, the inferred presence of dense material in the middle and upper crust of the Vulcan structure is consistent with gravity observations at similar relative locations in the Pyrenees.

Several dissimilarities in crustal structure hint at important differences between the Pyrenees and the Vulcan structure. There is no evidence in the Pyrenees, for example, for a midcrustal plutonic body, whereas gravity and magnetic data indicate that a significant volume of low-density, high-magnetic susceptibility material exists at midcrustal levels along the entire length of the Vulcan structure. This combination of low density and high susceptibility is best explained by magnetite-series granitoid rocks [*Clark*, 1997]. In drillcore samples of basement rocks beneath the WCSB, calc-alkaline plutonic suites contain magnetite as the chief opaque mineral phase [*Villeneuve et al.*, 1993] and possess the unusual combination of high-magnetic susceptibility and relatively low density [*Burwash and Burwash*, 1989] required to fit the observed data. Other possible rock types characterized by this combination of properties, such as felsic metavolcanic rocks and granitic rocks formed in other tectonic settings, are not common in this suite of drillcore samples. As such, we tentatively ascribe the Vulcan anomaly to a narrow magnetite bearing granitic pluton emplaced in the middle crust, perhaps as the product of anatectic melting during crustal thickening. We note that such an interpretation readily accounts for the continuity of this feature along strike. Such midcrustal entrapment is rheologically plausible, as the brittle-ductile transition zone has been suggested as a natural barrier, below which ponding of magma during crustal anatexis is expected to occur [*Raia and Spera*, 1997].

Another significant difference between the Pyrenees and the Vulcan structure is the level at which thrust structures root. In the case of the Pyrenees, the upper crust behaved as an orogenic lid, beneath which thrust structures root at midcrustal depths (Figure 12). Restored sections across the Pyrenees show that the upper crust is up to 110 km longer than the layered lower crust, because delamination and subduction of Iberian lower crust [*Muñoz*, 1992]. In contrast, thrust faults within the Vulcan structure appear to root in the lower crust or at the Moho and lower crustal units are stacked and imbricated, leading to an excess length of lower crust. Studies of the kinematic evolution of the lower plate in the Scandinavian Caledonides, a considerably larger Phanerozoic continent-continent collision belt, offer a possible explanation for the lower crustal reflection patterns observed in the Vulcan structure. On the basis of evidence from seismic reflection, refraction, eclogite geobarometry and gravity modeling, *Hurich* [1996] has postulated that the Baltic lower crust underwent subduction and was then imbricated and exhumed along zones of weakness associated with eclogite phase transformation. In this model, the mantle of the upper plate provides a rigid backstop that drives the deformation in the subducting continental plate. After breakup of part of the slab, bouyancy forces eventually lead to partial exhumation of subducted material to crustal depths.

The reflection images of the Vulcan structure exhibit the greatest degree of similarity to *Hurich*'s [1996] reconstruction of Caledonian crustal structure during Late Silurian to Early Devonian time, prior to orogenic collapse (Figure 12). Using this reconstruction as a template, we speculate that reflection zones 9A and 9B (Figure 4) may be composed of previously subducted lower crustal material from the LB that has been imbricated along zones of weakness and detached from the subducting slab. Reflection zone 8 (Figure 4) is interpreted here as unsubducted lower crust. In this scenario, the principal detachment separating subducted from unsubducted lower crust is represented by reflection R2. Moreover, the overlap in lower crustal layers (Figure 12) implies a minimum net shortening of about 100 km, similar to the net shortening of 147 km in the central Pyrenees [*Muñoz*, 1992].

The GFTZ is a distinct tectonic element, situated south of the Vulcan structure (Figure 1), that has often identified previously as the northern limit of the Wyoming craton. Recent geophysical data, however, show that the GFTZ lacks the geoelectric characteristics of a Proterozoic suture [*Boerner et al.*, 1998] and does not correspond with any significant change in crustal velocity structure [*Henstock et al.*, 1998]. A previous assertion that the Nd crustal residence ages from the MHB are significantly younger than the Wyoming Province [*Hoffman*, 1990] formed a basis for the view that the two regions were widely separated before 2.55 Ga [*Boerner et al.*, 1998]. However, a more recent compilation of isotopic data from the Wyoming Province [*Frost*, 1993] shows a range of Nd crustal residence ages of 2.8-3.8 Ga that largely overlap with crustal residence ages from the MHB of 2.8-3.4 Ga [*Frost and Burwash*, 1986; *Villeneuve et al.*, 1993]. Taken together, the data discussed here favor an interpretation of the Vulcan structure as the main Proterozoic collisional suture between the Wyoming and Hearne Provinces. The absence of a wide hinterland zone in the upper crust, as documented by seismic reflection and aeromagnetic patterns, implies a rigid, block accretionary style of cratonic assembly that distinguishes the Vulcan structure from other nearby Proterozoic orogens [*Ross*, 1997].

6. Conclusions

The Vulcan structure is a 40-70-km-wide belt defined by a prominent east trending Bouguer gravity low and associated aeromagnetic anomaly extending for over 350 km across southern Alberta. It separates two variably reworked Archean

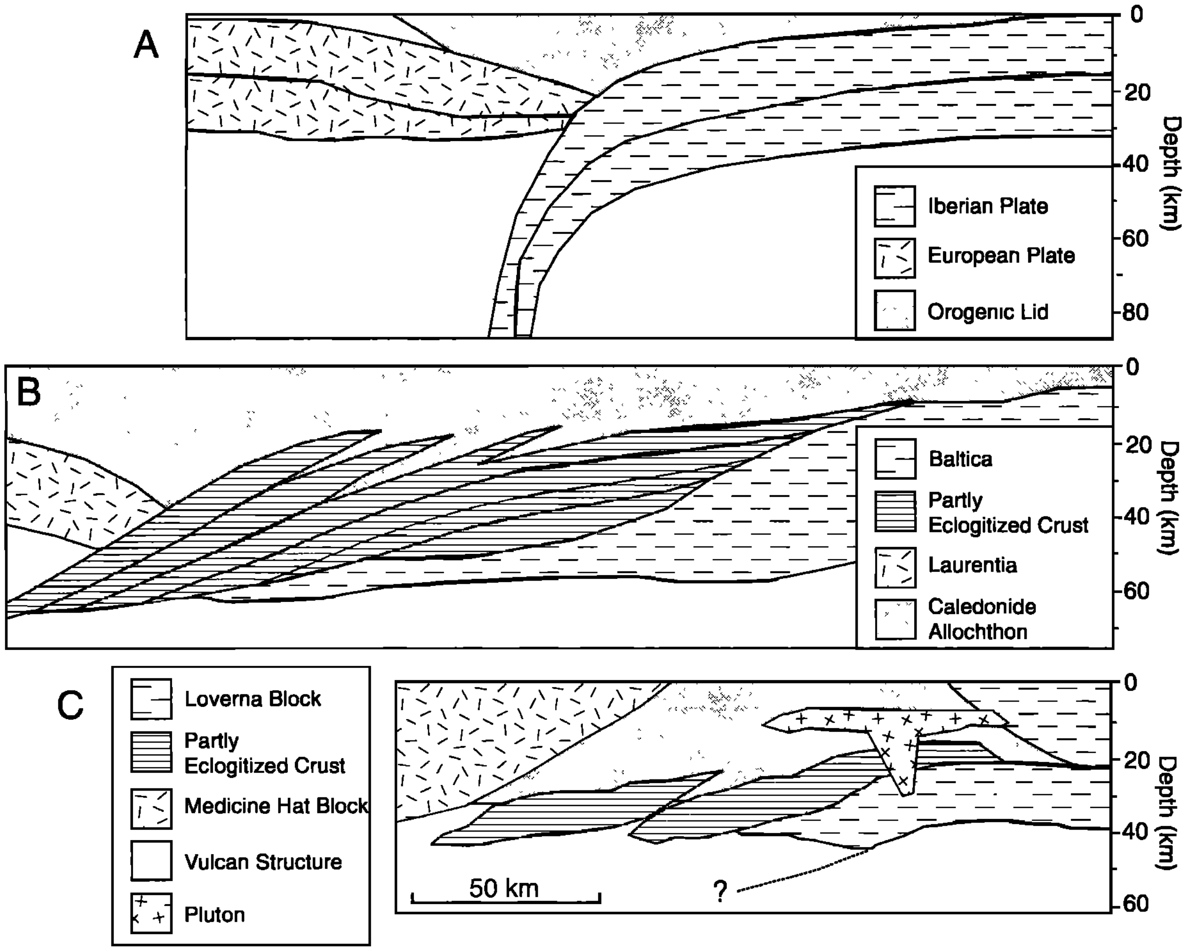

Figure 12. Comparison of the generalized crustal structure of (a) the central Pyrenees [after *Muñoz*, 1992], (b) the Scandinavian Caledonides in the Late Silurian - Early Devonian, prior to orogenic collapse [after *Hurich*, 1996] and (c) the Vulcan structure, based on seismic-reflection profiles and potential-field modeling.

crustal blocks, the Loverna Block and the Medicine Hat Block, that are buried by several kilometers beneath the Western Canada Sedimentary Basin. We have proposed a slightly revised interpretation of basement tectonic domains in Alberta in which the term Matzhiwin high is dropped, and the Vulcan structure is expanded to include the parallel segment of the adjacent magnetic high. Gravity and magnetic interpretation incorporating a new high-resolution gravity survey and recently enhanced aeromagnetic coverage shows that the potential-field signature of the Vulcan structure is best explained by midcrustal sources. The axial potential-field anomaly is interpreted as a midcrustal pluton, and flanking gravity highs are interpreted as thrust-imbricated lower crustal material.

Two recent Lithoprobe seismic reflection profiles reveal contrasting patterns of lower crustal reflectivity on opposite sides of the Vulcan structure. Seismic reflection geometries suggest crustal delamination and underthrusting of the lower crust of the Loverna Block beneath the Medicine Hat Block, implying southward subduction. Drawing on analogies from Phanerozoic orogens, we interpret this feature as a continental collisional belt involving partial subduction of continental crust. The inferred net shortening, tectonic setting, and geographic extent of the Vulcan structure are similar to the Pyrenees belt, but the deep crustal architecture resembles recent tectonic reconstructions of the Scandinavian Caledonides. The Vulcan structure is the most likely location, if any, for the collisional suture between the Hearne and Wyoming Provinces. Timing constraints based on drilling samples of the upper basement, xenoliths and cross-cutting relationships from magnetic anomaly data suggest that the Vulcan structure may be approximately coeval with, but slightly older than, terminal collision in the TransHudson Orogen.

Acknowledgments. This work was supported by the Natural Sciences and Engineering Research Council of Canada and the Geological Survey of Canada. This paper benefited from constructive reviews by Karl Karlstrom, Alan Levander, and Paul Hoffman. We would like to thank the seismic acquisition and processing contractors, Pioneer Exploration and Pulsonic Geophysical, for their excellent work. Arie VanderVelden assisted in the seismic processing of lines 25 and 32. Lithoprobe contribution 1035.

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(Received August 3, 1998; revised April 15, 1999; accepted June 7, 1999.)