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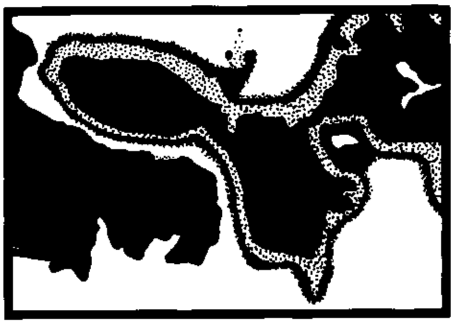

Proterozoic structural highs beneath the Mackenzie Mountains, northwest Canada, discovered with filtered potential field and seismic data

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SUMMARY

A linear belt of Mesoproterozoic (*ca.* 1.6 Ga) structural highs, some with more than 6-7 km of subsurface relief, underlies the Mackenzie Mountains in northwestern Canada over a distance of at least 1000 km from southeast to northwest. The trend is visible on isostatic gravity data that were bandpass filtered to wavelengths appropriate for intracrustal features, and on seismic reflection profiles that have images of buried Proterozoic anticlines associated with the gravity highs. The combination of filtered potential field data tied to seismic images of subsurface structure in key areas provides a powerful method to map intracrustal structures at long distances away from cross-sectional profiles.

RÉSUMÉ

Une bande linéaire de hauts structuraux du Protérozoïque moyen (*ca.* 1,6 Ga) est visible sous les monts Mackensie, dans le nord-ouest du Canada, et s'étale sur une distance d'au moins 1 000 km, selon une direction sud-est–nord-ouest; certains de ces hauts dépassant les six à sept km de dénivelé en subsurface. Cette bande linéaire ressort sur le tracé des données gravimétriques isostatique filtrées aux longueurs d'onde correspondant aux éléments intracrustaux, ainsi que sur les profils de réflexion sismique qui donnent des images d'anticlinaux protérozoïques souterrains associés aux hauts gravimétriques. La combinaison de données filtrées de champs de potentiel, et d'images sismiques des structures de subsurface en des endroits clé constitue une méthode très puissante permettant de dresser la carte de structures intracrustales situées à de grandes distance des profils de coupes.

INTRODUCTION

The Mackenzie Mountains in northwestern Canada are a convex northeastward Cretaceous–Paleocene deformed belt (Fig. 1) that formed as the result of plate interactions on the western margin of North America. Folding and faulting affected Proterozoic strata that have a composite thickness of 20 km or so and that were deposited between 1.8-0.55 Ga. However, the subsurface extent and thickness of these strata, and thus the nature of the crust beneath the Mackenzie Mountains, have been largely unknown.

This paper describes the discovery of a prominent trend of subsurface structural highs, here called the Natla trend after the Natla river that crosses it, whose flanks have been imaged on seismic reflection data, and that can be followed on potential field data for a distance of at least 1000 km from northeastern British Columbia to the northern Yukon. The Natla structures are outboard of (west), and subparallel to, the Fort Simpson potential field highs (FSa on Fig. 2) and associated structural highs that delineate the westernmost *bona fide* features of the Mesoproterozoic (*ca.* 1.9-1.8 Ga) Wopmay orogen (Hildebrand *et al.*, 1987; Cook *et al.*, 1999).

POTENTIAL FIELD DATA

Gravity anomaly data are presented in two forms (Fig. 2): (a) unfiltered isostatic anomalies, and (b) bandpass filtered anomalies to 160-14 km wavelengths. Bandpass filtering by 2D Fourier analysis allows spatially varying signals to be analyzed separately from the entire signal. In northwestern Canada, for example, the unfiltered isostatic anomalies are dominated by a prominent regional high that masks nearly all other, but more localized, signals (Fig. 2a). The cause of this regional high is the subject of ongoing study, but it is likely due either to excessively dense crust, to shallow crust that does not compensate the observed topography, or to dense mantle that is not included in the model calculation of the isostatic anomaly.

Bandpass filtering allows specified ranges of wavelengths to be retained so that regional effects, due either to deep sources or to wide, shallow sources, are minimized or removed. For example, a bandpass filter that retains wavelengths of 160-14 km arises from sources within the crust. The reason for this is that depth of a line source is about 0.5 times the anomaly width where the anomaly reaches half of its maximum value (Telford *et al.*, 1976, p. 61). Hence, a maximum wavelength of 160 km effectively restricts anomalies to sources that are shallower than about 40 km.

In the 160-14 km bandpass, the long wavelength regional high is removed

(Fig. 2b) and linear north-northwest trending anomalies are visible east of, and within, the Mackenzie Mountains. Two of these, FSa (Fort Simpson anomaly) and Natla trend, have seismic profiles across or adjacent to them thus providing subsurface geometric information described below. The FSa has been described previously (Cook *et al.,* 1991; 1999) and is a series of north trending gravity and magnetic anomalies associated with shallow arc-related granitic rocks that formed at about 1.845 Ga (Villeneuve *et al.,* 1991).

The Natla highs form a prominent convex northeastward arc that is located west of the Mackenzie Mountains deformation front. The trend is followed from northeastern British Columbia to the north side of the Mackenzie Mountains where it appears to connect to an isostatic high near the the Richardson Mountains (Fig.2b). It is not known at this time whether the Richardson high is a continuation of the Natla trend, but the apparent continuity of the isostatic trend is consistent with this interpretation.

SEISMIC REFLECTION DATA

Portions of four seismic profiles from the Richardson Mountains to northeastern British Columbia are presented to illustrate the subsurface geometry of the Fort Simpson and Natla structures. The locations of the profiles shown in Figure 3 are provided on Figures 1 and 2. Profile SNORCLE-1 (Fig. 3a) crosses the entire Fort Simpson high (Fig. 2b), and profile CC-56x (Fig. 3b) is located on the west flank of a possible northwest projection of FSa (Fig. 2b). Other profiles provide additional information for the subsurface geometry of FSa but are not shown here (Cook *et al.,* 1991; Clark and Cook, 1992; Mitchelmore and Cook, 1994; Cook and van der Velden, 1993).

All available profiles along the western flank of FSa have images of westward thickening layers above a west-dipping ramp (zone II on Fig. 3a; Cook *et al.,* 1991; Clark and Cook, 1992; Mitchelmore and Cook, 1994; Cook and van der Velden, 1993; Cook *et al.,* 1999). The nature of these layers is constrained by drill hole and outcrop information. For example, profile SNORCLE-1 crosses FSa near two drill holes that penetrated from Devonian strata into Proterozoic (*ca.* 1.845 Ga) granitic rocks, thus indicating that there are no lower Paleozoic or Proterozoic strata on the crest of FSa (Villeneuve *et al.,* 1991). However, more than 5-7 km of lower Paleozoic and Proterozoic strata are present in uplifts in the eastern portion of the Cordillera in the northeastern British Columbia Rocky Mountains (*e.g.,* Thompson, 1981) such that the thickened sedimentary section occurs in the same interval as the thickened seismic layering west of FSa. Accordingly, the seismic layers (II in Fig. 3a) are interpreted as having been deposited in a deep (up to 20 km) basin (Fort Simpson basin; Fig. 3a).

Profile MC-64x (Fig. 3c) crosses the gravity low associated with the Fort Simpson basin on the east side of the Natla trend (Fig. 2b), and profile CC-56x (Fig. 3b) crosses the north side of a small gravity high near the Natla trend (Fig. 2b). In both cases, the Natla and related gravity features coincide with prominent structural highs on the reflection profiles. On CC-56x, for example, the structural high has about 2.0-2.5 sec (about 6-7.5 km) of relief, and on MC-64x, the east side of the high has at least 2.0 s (about 6 km) of relief.

Finally, profile HC-26x (Fig. 3d) is located on the western flank of the Richardson Mountains and provides information on the geometry of the western flank of the Natla trend, assuming the Richardson high is a continuation of the Natla trend. Along this line, Proterozoic layers dip prominently westward and are overlain with angular unconformity by both Paleozoic sedimentary rocks and younger Proterozoic rocks (Fig. 3d; Hall and Cook, 1998).

INTERPRETATION

The filtered isostatic anomalies allow the geometric information from seismic reflection data to be extended along strike into the third dimension over a distance of approximately 1000 km. A basic result is that the isostatically high FSa and Natla

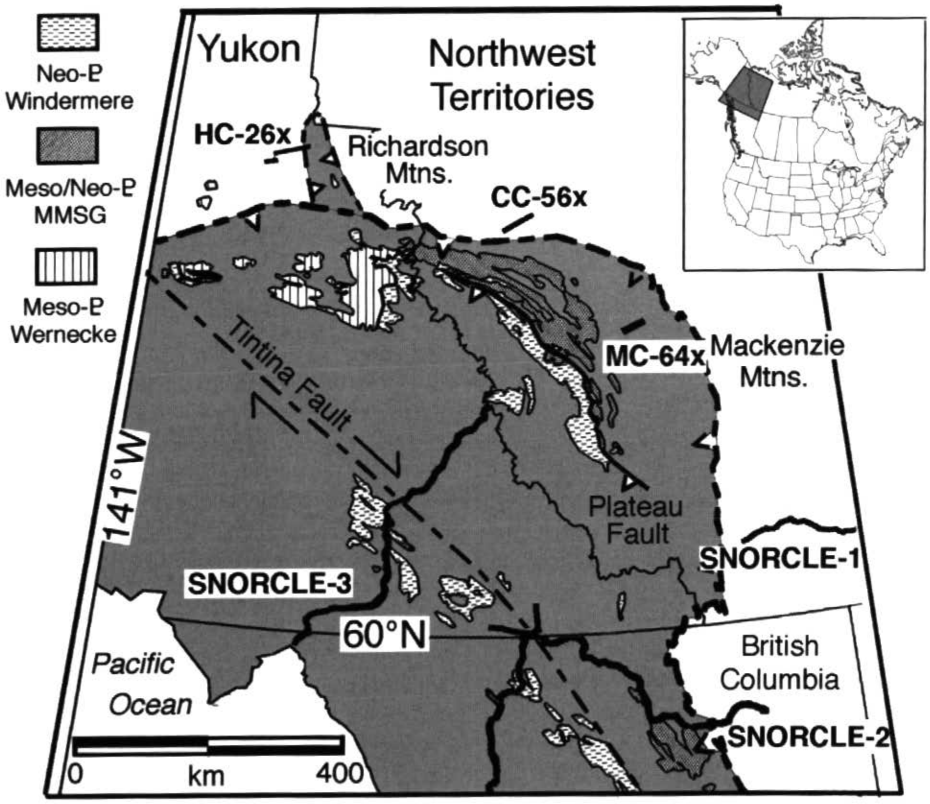


Figure 1 Map of northwestern Canada illustrating outcrops of Meso- to Neoproterozoic strata in the Cordillera. Positions of the seismic profiles discussed in the text are labeled, as are locations for Lithoprobe SNORCLE Lines 2 and 3. MMSG = Mackenzie Mountains Supergroup.

trends represent structural highs in the subsurface, and that the isostatic low between them represents a structural low (basin) that is filled with layered Proterozoic rocks. If the single profile west of the Richardson Mountain segment (HC-26x) is representative of the isostatic low west of and subparallel to the Natla structures, then that low may also arise from westward thickening Proterozoic layers (*i.e.,* another basin west of the Natla trend).

Major Reflection Sequences

Key observations that assist identification of sequences II through IV are:

1. Within the Natla highs and related structures, thick (about 5 sec, or 15 km) subparallel layers (sequence II) were arched prior to depostion of younger layers (Figs. 3b and 3c), and they are geometrically discordant with deeper rocks (sequence I).
2. There appear to be three generally recognizable, sequences overlying sequence II that are bounded by angular unconformities. Sequence III appears to onlap sequence II, but may itself be slightly deformed (MC-64x). Sequence IV is less deformed, overlies sequence III with angular unconformity, and is subparallel to Pz.

The lithologies and ages of zones I-IV are uncertain. However some broad ranges can be ascribed with some confidence, and more restricted ranges can be estimated. In general, Proterozoic rocks in this region are sedimentary with intrusive sills that are occasionally cross-cut by igneous dikes and rare plutons (*e.g.,* Delaney, 1981; Aitken *et al.,* 1973; Thorkelson *et al.,* 1998). Where present, drillholes also penetrate Proterozoic sedimentary rocks. Hence the interpretation of zone II-IV layers as stratigraphic (probably including sills) is the simplest and most consistent with the known geology, and these layers were deposited above basement (?) zone I.

In general terms, the layers and uplift must be older than Cambrian, because Cambrian sediments overlie them with angular unconformity, and they must be younger than ca. 1.85 Ga because the Fort Simpson magmatic arc underlies them on the east. In a recent compilation, Thorkelson *et al.* (1998) summarized stratigraphy and ages of

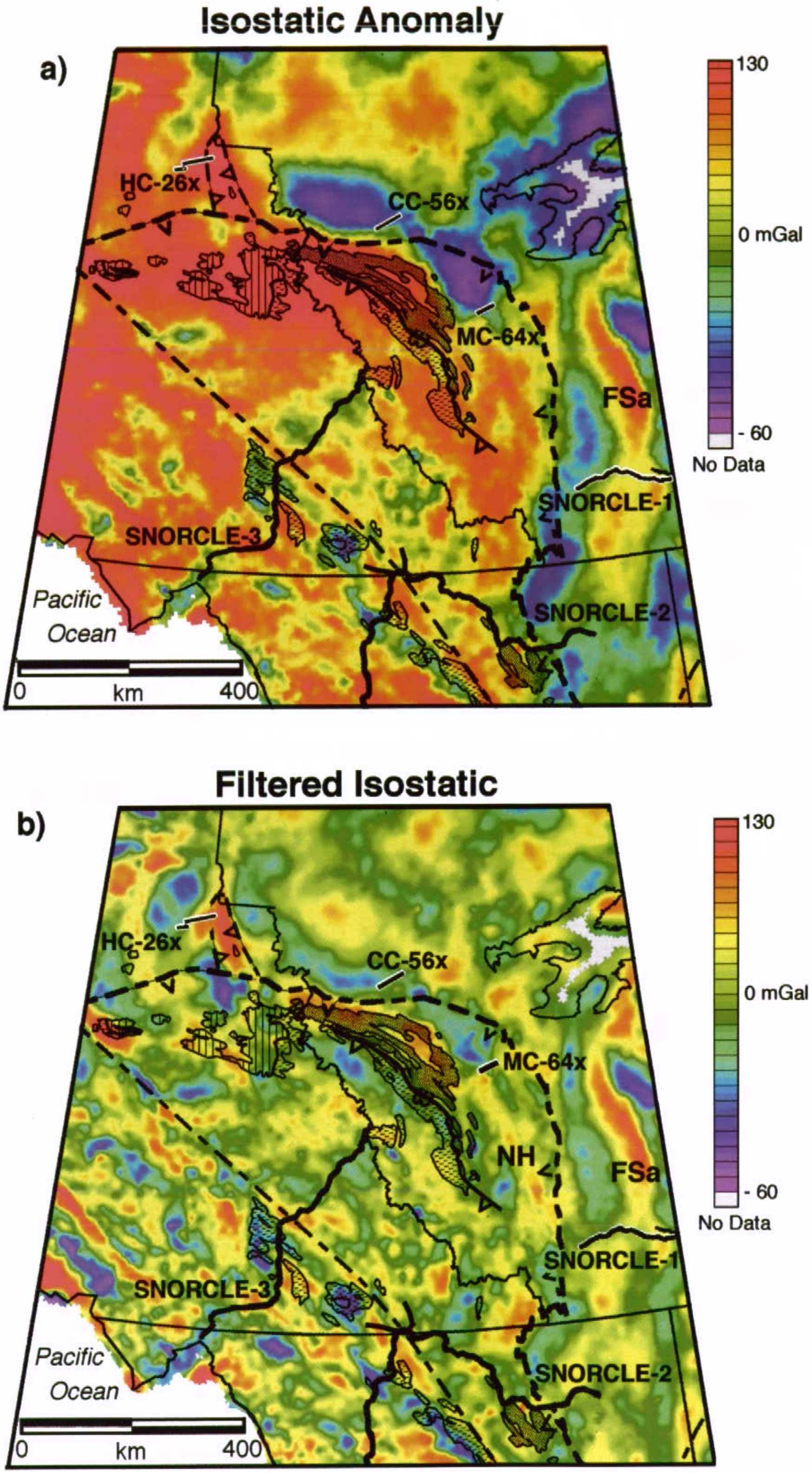


Figure 2(**a**) Isostatic gravity map of western Canada for the area shown in Figure 1. Note the regional high in the northern Cordillera, (**b**) Bandpass filtered isostatic anomaly of the same region, wavelengths 160-14 km, with outcrop locations of Proterozoic rocks superimposed. NH = Natla highs; FSa = Fort Simpson highs.

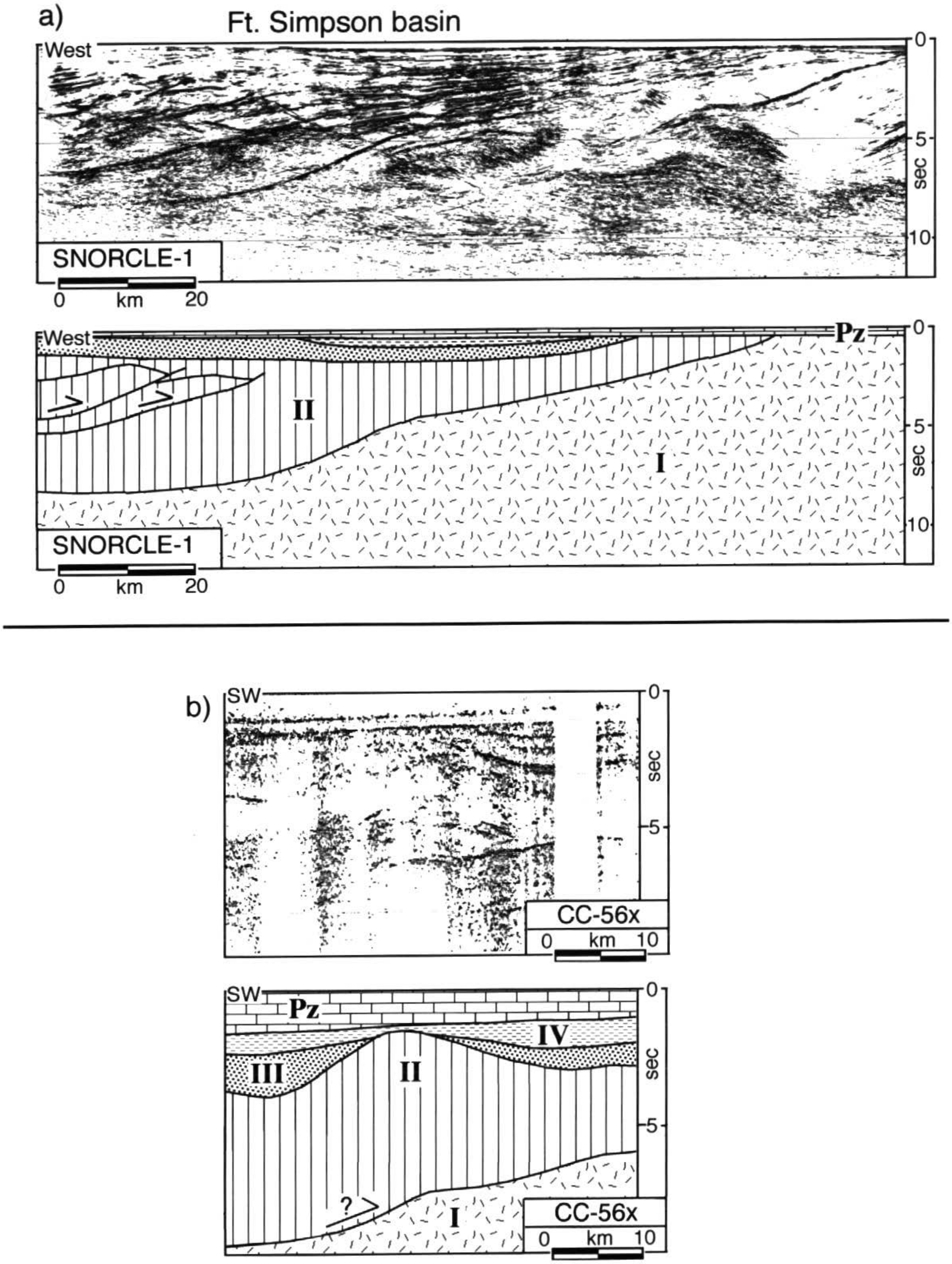
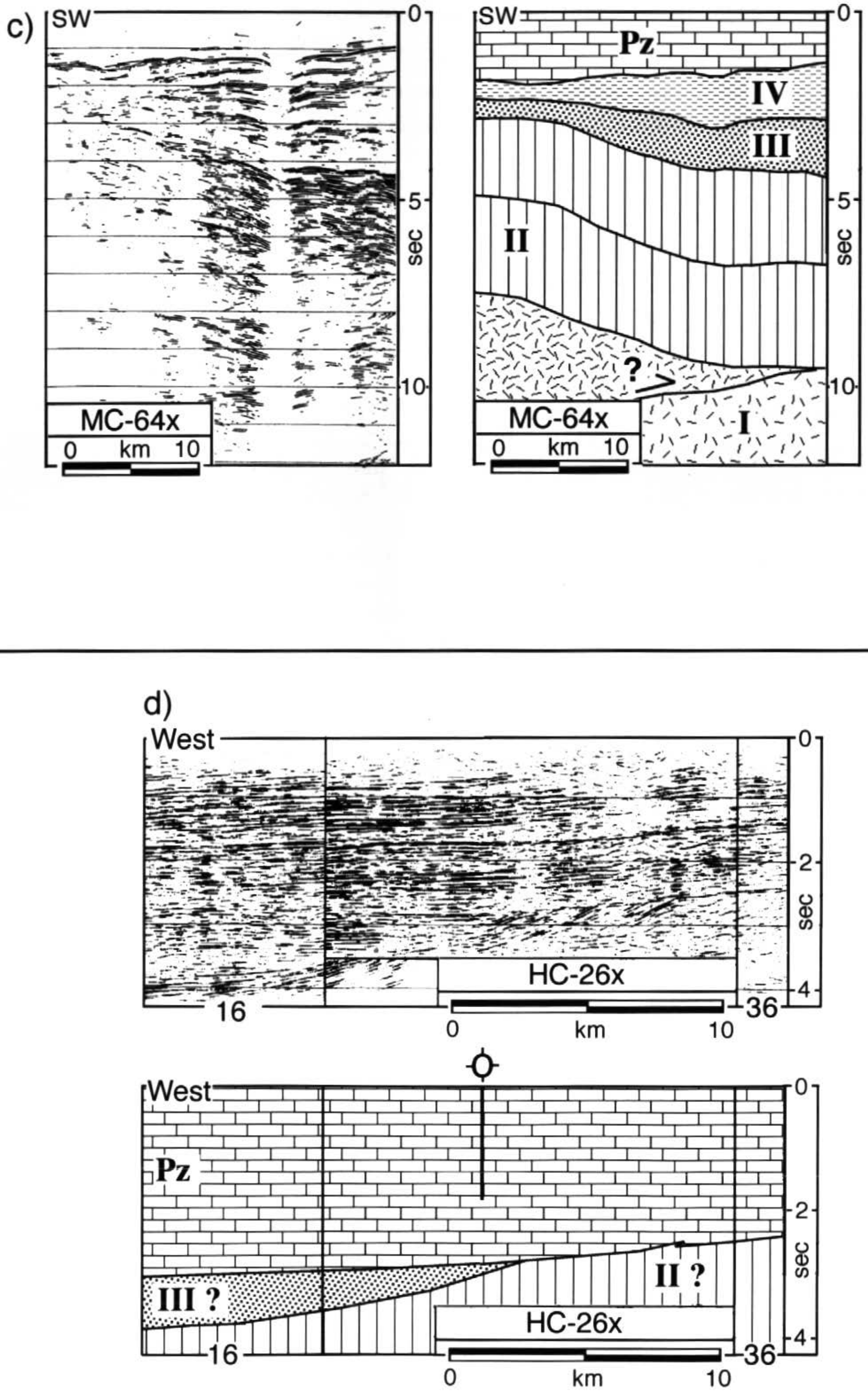


Figure 3 Examples of reflection data near Natla trend. In all of these figures, reflection zones I-IV represent Proterozoic rocks and Pz is Paleozoic. (**a**) Profile SNORCLE-1 illustrates the Fort Simpson basin (Cook *et al.*, 1999); (**b**) Profile CC-56x (Clark and Cook, 1992) crosses a small satellite high northeast of the Natla trend. The gap on the right side of the data is due to a river. This structural high is near the Natla trend and is interpreted to be caused by a westward thickening stratigraphic section that was inverted during contraction, although other interpretations are possible.



(**c**) Profile MC-64x (Mitchelmore and Cook, 1994) provides the clearest image of the eastern flank of the Natla high (note arching of zone II on west of profile). Gap near the center of the data is due to a river. (**d**) Profile HC-26x (Hall and Cook, 1998) shows zone II (?) reflections dipping west on the west flank of the Richardson Mountains.

Proterozoic rocks within this time interval for this region. Key points that emerge from this updated information are: 1) the crust was extended and thinned following formation of the 1.845 Ga Fort Simpson arc, 2) at least 14 km of generally conformable sedimentary rocks were deposited between about 1.8 and 1.6 Ga (Wernecke Supergroup), 3) Wernecke strata were subjected to major east-directed orogenic deformation at about 1.6 Ga which resulted in uplift and erosion, 4) two stages of deposition (Pinguicula Group-Mackenzie Mountains strata) began at about 1.38 Ga and ended at about 0.9 Ga, separated by a period of erosion and perhaps weak orogenic activity between about 1.3 Ga and 1.0 Ga, 5) west-directed folding associated with orogenic activity occurred at about 0.78 Ga, 6) deposition of Neoproterozoic Windermere Supergroup took place from 0.75-0.55 Ga, and 7) erosional truncation of all units preceded deposition of Phanerozoic sedimentary rocks.

Relationship of Seismic Structures to Regional Events

Although detailed correlation of the regional events to the seismic profiles is uncertain, seismic zone II probably represents Wernecke Supergroup strata (Clark and Cook, 1992; Mitchelmore and Cook, 1994), and seismic zones III and IV probably represent Pinguicula-Mackenzie Mountains and/or Windermere strata. As Mackenzie Mountains strata are exposed above the crest of the arch (Fig. 2b; Aitken *et al.*, 1973), zones III and IV most likely include these rocks. Accordingly, the Natla structures formed after deposition of the Wernecke Supergroup and prior to deposition of the Pinguicula Group, probably during the *ca.* 1.6 Ga orogenesis. Detrital zircons (*ca.* 1.86 Ga) in diamictites in Windermere strata of the Mackenzie Mountains (Ross and Villeneuve, 1996) may have been eroded from the Natla structures if some of the sub-Wernecke basement were exposed at that time.

Whether the Natla structures were formed by contraction (*e.g.*, Clark and Cook, 1992), or whether they formed during regional extension is unknown. They are tentatively shown here to have been uplifted during contraction to be consistent with: 1) regional contraction at ~1.6 Ga (Thorkelson *et al.*, 1998), 2) structural discordance between sequences I and II, especially along profile CC-64x (Fig. 3b), 3) apparent structural repetitions within sequence II on the west side of profile SNORCLE-1 (Fig. 3a), and 4) the necessity for high density material in the core of the Natla structures to account for the 30-40 mGal gravity highs.

The position of the Natla trend closely corresponds to the Mackenzie Arch described by Aitken et al (1973) and the Redstone arch shown by Ziegler (1967) for the east-central Mackenzie Mountains (Fig. 2b - east of the Plateau fault) and is therefore most easily interpreted as the subsurface expression of these features. This correlation would imply that the Proterozoic rocks exposed on the surface have not been translated very far eastward during formation of the Mackenzie Mountains, an interpretation that is consistent with retrodeformed cross sections (McMechan *et al.*, 1992). The Natla trend of potential field anomalies appears to continue both to the north and to the south of the Mackenzie arch and may thus be part of a major parautochthonous Proterozoic belt beneath the northern Canadian Cordillera.

CONCLUSIONS

The Natla trend is a series of Mesoproterozoic uplifts, some of which have at least 6-7 km of vertical relief, that is located west of the Mackenzie Mountain front and that can be followed for a distance of at least 1000 km. The Natla structures probably formed during ca. 1.6 Ga east-verging orogenesis, were likely emergent during deposition of Neoproterozoic sedimentary rocks, and appear to have affected depositional patterns in the Phanerozoic; they spatially coincide, at least partly, with the Mackenzie Arch. The uplifts are visible on seismic profiles and when correlated to filtered isostatic gravity maps, the trend may be mapped for a long distance away from the profiles. This approach provides an effective means to use a variety of geological and geophysical data in mapping 3-D structures over large regions.

ACKNOWLEDGMENTS

Research supported by Natural Sciences and Engineering Research Council of Canada. Seismic data for line CC-26x and MC-64x were donated by Chevron Canada. Line HC-26x was acquired through the National Energy Board of Canada, and SNORCLE-1 was recorded by JRS Exploration of Calgary for LITHOPROBE. Processing was accomplished at the LITHOPROBE Seismic Processing Facility at the University of Calgary. Kevin Hall wrote the software to calculate the bandpass filters and Elissa Lynn and Kevin Hall kindly assisted with Figures 1 and 2. Thoughtful reviews by Z. Hajnal and G. Stockmal improved the manuscript. LITHOPROBE contribution 1151.

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Accepted as revised 27 March 2000