Introduction

The Western Canada Sedimentary Basin (WCSB) rests on a foun- dation of Precambrian lithospheric mantle. The Phanerozoic Reference (or basement) surface is the buried extension of the Precambrian Canadian Shield. Geophysical data permit indirect examination of this lithosphere from two different perspectives. The first pertains to upper crustal (<15 km) structure and utilizes potential field data (aeromagnetic and gravity anomaly maps) to trace into the subsurface the variations in crustal structure that are apparent in the exposed shield. The second perspective pertains to the long-wavelength structure of the crust and upper mantle. Large subsets of potential field data and deep seismic reflection and refraction studies have addressed possible causative mechanisms associated with basin formation and subsidence patterns. However, distinguishing Precambrian lithospheric features from those acquired during Phanerozoic basin formation is problematic (see Stephenson et al., 1989, and Ross, 1993).

The purpose of this chapter is to provide a brief overview of potential field data and their interpretation in the Western Canada Sedimentary Basin. More detailed discussions may be found in Ross (1993), in press; Villeneuve et al. (1993) and Ross and Stephenson (1989). For a discussion of seismic refraction/reflection studies and electromagnetic-magnetotelluric studies the reader is referred to summary papers by Ross and Stephenson (1989), Sweeney et al. (1991) and Jones and Craven (1990), respectively.

A short review of the tectonic history of the exposed shield adjacent to the edge of the Phanerozoic strata precedes the presentation of potential field data and is intended to provide a context for the interpretation and inferred continuation of shield elements into the subsurface. An appreciation of the evolution of crustal fabric and evolution of the shield is relevant to subsequent chapters that examine the sedimentary section. In particular, the degree to which basement structures may have controlled anomalous sedimentation, tectonic, and stratigraphic patterns in both the Western Canada Sedimen- tary Basin and the adjacent Cordillera is controversial.

As this Atlas goes to press, LITHOPROBE is embarking on a five-year program to examine the deep crustal structure of Alberta and its influence on the evolution of the sedimentary units. These studies may provide much-needed constraints on the role of basement structure in the evolution of the Western Canada Sedimen- tary Basin.

Aeromagnetic Anomalies

The aeromagnetic anomaly map (Fig. 4.2) is plotted from a digital database (residuals after subtraction of Geomagnetic Reference Field), derived from a variety of sources. Derivatives of the total-field data set have been published by Dods et al. (1989). Data over the central and eastern parts of the Basin by the Geological Survey of Canada through contract surveys flown at an average terrain clearance of 305 m and a line spacing of 800 m. Data in the Interior Plains were acquired largely through donations from pro- troleum companies on surveys that were, for the most part, flown between 1956 and 1966. Details of the line spacing, line elevation and survey company commonly are unknown. The data were digitized from donated maps rather than from survey analog tape records.

Several, contracted surveys by Commonwealth Geophysical Ltd. and surveys by the Geological Survey of Canada, the latter between 52° and 54° in Alberta, have used better navigational techniques (Global Positioning System), magnetometers with improved sensitivity, and better quality control through monitoring of flight path and diurnal variations in the magnetic field, to produce excellent and very precise data sets. Regions of Saskatchewan, Manitoba and parts of southern Alberta remain to be covered but likely will be flown over the next few years. For the compilation of inferred basement domains shown in Figure 4.1, access to proprietary data was granted by Petro-Canada Ltd.

The aeromagnetic anomaly map in this Atlas was produced from data interpolated onto a 2-km grid. The use of artificial illumination to produce shaded relief (Dods et al. 1985; Broome, 1990) can dramatically improve the visibility of certain features, depending on the perspective of the interpreter. Reference is made to the angle of illumination in Figure 4.2. For Figure 4.2, we used an artificial illumination source from the southeast to emphasize the predominant northerly and northeasterly-trending structure of the region.

Aeromagnetic anomalies are interpreted as being sourced largely in basement rather than within the sedimentary section. This inter- pretation is supported by the similarity of wave number distribution of aeromagnetic data over the basin and data over the exposed shield which are characterized by effectively moving near-surface high-frequency components (Teskey et al. 1986).

In addition, the smooth form of sediment isopachs in the Western Canada Sedimentary Basin (Wright et al., this volume, Chapter 3) suggests that signal variation as a consequence of vari- able depth to low angle reflectors (e.g., Crays, 1985). Although, as suggested by Burguess et al. (this volume, Chapter 5), this may be a smoothing artifact introduced by the isochaping process. Inverted aeromagnetic anomalies may be present but recognition is difficult given the density and acquisition elevation of aero- magnetic observations.

Hydrocarbon-related magnetization, produced during the transformation of hematite to magnetite and/or pyrrhotite during fluid migration, is an intriguing concept that is being explored by the hydrocarbon industry (MacRae and Trowell, 1991) but the magnitude of the anomalies below detection limits at the scale of the present compilation.

Early studies of aeromagnetic data, although limited by the unavailability of public data, traced aeromagnetic domains of the shield into the subsurface as far west as the Cordillera (Garland and Burwash, 1959; Coles et al., 1976). Recent interpretations of modern aeromagnetic data have built on the early studies and formed the basis for the subdivision of the basement via extrapolation of exposed domains of the Canadian Shield and by using the shield to calibrate interpretation of subsurface anomalies (Ross et al., 1991, in press).

As in the shield, discrete domains are recognized by their intensity and textural characteristics, and relations to adjacent domains (Fig. 4.2). These subdivisions can be modified by examining gravity anomaly data (Fig. 4.3) and filtered subsets (Fig. 4.4). Subdivisions based on the interpretations of potential field data are "ground truthed" by U-Pb geochronology and Sm-Nd isotope geochronol- ogy, taking advantage of the extensive collection of basement drill core and cuttings recovered during hydrocarbon tests (Burwash, 1957; Burwash et al., 1962; Burwash et al., this volume, Chapter 5; Collerson et al., 1988; Ross et al., 1989, 1991, in press; Thierault and Ross, 1993; Villeneuve et al., 1991, 1993).

Aeromagnetic data from the exposed Canadian Shield provides a means of calibrating the interpre- tation and subdivision of subsurface aeromagnetic anomalies inferred to be present by the seismic data. This is not to say that this approach is simplistic, it is justified because many structures and domains can be traced from outcrop into the subsurface (with the exception of west-central and southern Alberta). Examination of aeromag- netic anomalies in the Canadian Shield suggests that, to a first-or- der approximation, lithology controls the aeromagnetic signal, with uncertain contributions from remnant magnetization and dipole effects.

Aeromagnetic data for the exposed Canadian Shield are domi- nated by remarkable high-amplitude curvilinear positive aeromagnetic anomalies that are among the most striking features of the aeromagnetic anomaly map (Fig. 4.2). These anomalies corre- spond to the magnetic rocks of the Great Bear Batholith, Wathamans-Chipewayan Batholith and Thelon-Talson Magmatic Belt, which form the magnetic wedges between formerly separate crustal fragments (Hoffman, 1989). The magnitude of the aeromag- netic field (up to 400 nT) is a direct reflection of the petrological properties of these rocks; that is, they are dominantly calc-alkaline magmatic rocks characterized by magnetite as the chief opaque accessory (Hoffman and McGlynn, 1977; Henderson et al., 1987), similar to the magnetite series plutons in Mesozoic magmatic belts (Castl et al., 1990). Major aeromagnetic highs in the subsurface are interpreted as magmatic bodies. In some of these areas, limited rock returns confirm the magmatic affinities, whereas in other areas (notably Eyebigh High in eastern Alberta) a high-grade meta- morphic origin is suggested.
The interpretation of regionally extensive negative aeromagnetic anomalies can be ambiguous. For example, depending on the ratio of characterizing regions on the basin, even magnetic rocks can produce a negative aeromagnetic signal. In some cases, negative aeromagnetic anomalies in the shield correspond to regions underlain by peraluminous plutonic rocks. A substantial part of the Taltson Belt contains a region of negative aeromagnetic character that is underlain by the Kambalda-type batholith characterized by magnetite garnet, cordierite, muscovite and sillimantite that continues into the subsurface. The main opaque phase in rocks of this composition is hematite, which is antiferromagnetic in comparison with magnetite and is the likely cause of the negative aeromagnetic signal (Strauch, 1970; Castil, et al., 1990). Regional metamorphism, which produces phase changes that transform Fe-oxides into Fe-silicates and/or oxidation of magnetic to hematite, may also account for regional aeromagnetic lows (Robinson, et al., 1985). The transformation of strongly antiferromagnetic Fe-oxides into antiferromagnetic Fe-silicates and/or hematite also occurs in shear zones as a consequence of hydration and metamorphism during deformation (Watanabe, 1966). Examples of this are seen in the Great Slave Lake Shear Zone and may account for the narrow aeromagnetic lows that contribute to the striated fabric typical of deformed magmatic rocks in the Taltson Belt. Loss of magnetizability during shearing is proposed here as an interpretation of prominent curvilinear aeromagnetic lows such as the Thorsby, Vulcan and Kaskatan lows in the subsurface of Western Canada.


diagram text

Gravity Anomaly Data

The Bouguer gravity anomaly map was constructed using data obtained from the National Geophysical Data Centre. The spacing of observations in the study area ranges from 6 to 13 km, with an average spacing of 8 km throughout most of the Prairie provinces. Gravity data have had a terrain correction applied, with sea level used as a datum, and have been interpolated onto a 4 km grid, offering a reasonable compromise between detail preserved by the data and artifacts introduced by the interpolation procedure.

The Bouguer anomaly map (Fig. 4.3) is dominated by the long-wavelength contribution to background gravity values associated with crustal thickening in the Cordilleran Province and the presence of high heat-flow in the southern Omineca Belt of the Cordillera (Gibbons, 1972; Swestney et al., 1991). Additional contributions may arise from variations in the thickness of continental crust and the thermal structure of the lithosphere (Stephenson et al., 1989; Ross and Stephenson, 1990; Pickington, et al., 1991) as well as a westward increase in sediment thickness. The strong regional gradient caused by these effects diminishes the visibility of fine detail in the gravity field related to upper crustal and basement structure beneath the Western Canada Sedimentary Basin, although several dramatic features are present. Both the Snowbird Tectonic Zone and the Vulcan Low in southern Alberta are visible in the Bouguer gravity map. The gravity break associated with the Snowbird Tectonic Zone has been known for some time and was originally referred to as the Ford du Lac gravity low (Walcott, 1968) or the Kasha-Kasko-Edmonton gravity low (Burwash and Culbert, 1976). The gravity signal associated with the Vulcan (aeromagnetic) Low is also a strong low and was originally interpreted as evidence for the presence of low-density Precambrian sedimentary rocks of the southern Alberta basin (Kanasewiche et al., 1969). However, an alternative interpretation is that it is largely an "edge" effect related to the juxtaposition of distinct crustal blocks (Gibbs and Thomas, 1976; Gillis et al., 1985).

In order to remove the relatively long-wavelength contributions from Cordilleran sources, a derivative version of the Bouguer field, a horizontal gravity gradient map (Shipton et al., 1987) is presented (Fig. 4.4). This depiction tends to accentuate the gravity anomalies and, by inference, density structure of the upper (aproximately) 15 km of crust. The use of horizontal gravity gradient data is an excellent indicator of the dominant structure of the upper crust, although it is not without its shortcomings. The presence of a gravity gradient reflects the juxtaposition of crustal bodies of contrasting density and/or thickness, similar to the paired positive-negative gravity anomalies recognized along Precambrian sur- faces by Gibbons and Thomas (1976). However, in the Canadian Shield there are examples where fundamental crustal breaks, recognized on the basis of shear zones that separate rocks of dramatically different ages, are not associated with a gravity gradient. The Great Slave Lake Shear Zone, for example, is a major transcurrent shear zone that accommodated the northeast translation of the Slave Craton during its collision with the Rae Province (Gibbs; 1978; Hoffman, 1987; Hamer, 1988) yet there is no associated gravity gradient, reflecting the similarity in density and thickness between rocks on either side of this discontinuity.

The horizontal gravity gradient data (Fig. 4.4) clearly illustrate the juxtaposition of contrasting crustal domains and can be used to characterize the nature of their gravity signature. The Snowbird Tectonic Zone, and its inferred extension into Alberta, forms one of the most dramatic gravity gradients on the entire map and continues from the frontal thrust of the Rockies northwestward to Hudson Bay. The Superior Province is characterized by an indistinct pattern of short linear segments; the Vulcan Low stands out as a persistent discontinuity within this pattern.
Figure 4.2 Aeromagnetic anomaly map of Western Canada. Compiled by the Geophysics Division, Geological Survey of Canada.
Figure 4.3: Bouger gravity anomaly map of Western Canada. Compiled by the Geophysics Division, Geological Survey of Canada.
Figure 4.4: Horizontal gravity gradient map of Western Canada. Compiled by the Geophysics Division, Geological Survey of Canada.
tainties that should be considered are the depths of the sources of the anomalies, which are difficult to determine with the available data, and the age of the anomalies. In other words, are the observed anomalies related to features of basin formation or are they inherited from the processes of crust formation and continental assembly in the Precambrian?

A particularly interesting set of maps from this perspective are the isostatic residual maps of Spence and Naranewicz (1982) and Stephenson et al. (1989) (Figs. 4.5 and 4.6). They computed isostatic residuals from the Bouguer gravity field for Western Canada and then filtered these residuals to retain different wavelength components of the gravity field (400-700 km and 700-1200 km). They utilized isostatic residuals of the gravity field, which take into account the effects of isostatically compensated topography (e.g., crustal roots to the Cordillera). However, rather than assuming local compensation (i.e., a crustal root as a direct function of topographic height), Stephenson et al. (1989) used a model of regional compensation that effectively considers the contribution of crustal strength to the support of topography. This contrasts with the approach of Goodacre et al. (1987) but appears to result in a more realistic model of the isostatically compensated gravity field.

On the 400 to 700 km wavelength image (Fig. 4.5), one of the most prominent patterns seems to be associated with the amplitude shift in the gravity along the Kaskia Lake-Edmonton gravity low - Thrust Low, suggesting that this discontinuity extends through much of the crust. Another interesting anomaly occurs in the region of the exposed shield in Manitoba and Saskatchewan, referred to as the Severn Arch (Porter et al., 1982). This positive anomaly is well defined on the 700 to 1200 km wavelength maps (Fig. 4.6) but is indistinct at shorter wavelengths. The size and wavelength of this anomaly suggest that it could correspond to a source within the mantle. In particular, it has been postulated on the basis of evidence from wide-angle seismic experiments that the mantle in Archean shield regions is thicker and less dense than in younger regions (Jordaan, 1988; Grand and Helmsberger, 1984; Anderson, 1990). The Proterozoic Trans-Hudson Orogen is noted for the presence of substantial tracts of juvenile Proterozoic crust (Patchett and Arndt, 1986). It may be that the Severn Arch is a reflection of the difference in mantle thickness and density between the Proterozoic region of Trans-Hudson Orogen and the adjacent Archean shield regions. An additional contribution may arise from the presence of intermediate-velocity lower crust, recognized empirically as being a fundamental part of Proterozoic, but not Archean crust (Durrheim and Mooney, 1991). Both of these features may give rise to long-wavelength positive anomalies. The latter is testable with seismic refraction studies.

Discussion

Potential field data from the Western Canada Sedimentary Basin can be used to elucidate the structure of the crust that underlies the basin. In contrast to Bouguer gravity anomaly data, aeromagnetic anomaly data provide an effective means of mapping the dominant structure of the shallow basement beneath the sedimentary cover.

In the case of the WCSB, calibration of aeromagnetic anomaly patterns with analogues exposed in the shield, where field relationships and kinematics are known, allows the mosaic of subfacial domains to be placed in a dynamic, tectonic framework (Ross et al., 1991; Ross, 1992). This exercise results in formulation of crustal geometries related to the process of tectonic accretion and amalgamation, which can be tested using seismic reflection profiling. As our understanding of the relation between crustal structure of the basement and sedimentary patterns becomes known, perhaps through the application of seismic reflection profiling, it may become possible to use potential field data to enhance the mapping of shallow basement in the subsurface and to elucidate the evolution of sedimentary and diagenetic patterns.

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