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Basement Tectonics and Fault Reactivation in Alberta, Canada

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Summary

Injection-induced seismicity in western Canada and elsewhere in North America has drawn considerable recent interest. Current models indicate that induced earthquakes occur on reactivated basement faults, which can be challenging to detect using seismic-reflection data. Here we use regional gravity and magnetic datasets, together with LITHOPROBE crustal seismic profiles, to investigate basement tectonics and crustal structure in an area of western Canada that is prone to induced seismicity. Previously mapped basement faults that were active during the Paleozoic can be recognized on the basis of pronounced curvature, truncations and/or offsets of stratigraphic marker horizons. Within the Precambrian crystalline basement, however, brittle faults are poorly imaged by seismic data due to various factors such as the obscuring effect of multiples. Regional potential-field fabrics are critical to establish the tectonic setting of basement domains, with complementary information provided by magnetic, Bouguer and isostatic residual gravity anomalies. Based on 2D modelling constrained by seismic profiles, however, individual faults appear to lack diagnostic expression in regional potential-field anomaly data since the anomalies are dominated by the effects of larger-scale crustal structures. We show evidence that large-scale basement faults can potentially be recognized on the basis of truncation and offset of distinct horizons within the Winagami Reflection Sequence (WRS), which is interpreted as a regionally-extensive mid-crustal sill complex emplaced during a Proterozoic magmatic pulse. An abundance of caution is necessary to interpret these features, due to complications arising from out-of-plane reflections at long reflection times.

Introduction

During the last decade, exploitation of unconventional resources, including low-permeability hydrocarbons, has been a major focus of oil and gas development in North America. One emerging area of concern is induced seismicity, which has led to a renewed interest in faults as well as the structural architecture of Precambrian basement. Recent studies of injection-induced seismicity in parts of western Canada (Schultz et al, 2016; Bao and Eaton, 2016; Schultz et al., 2017) have highlighted the probable role of pre-existing basement faults in controlling the distribution of induced earthquakes. Although some basement-related faults in this region have been identified using seismic-reflection images (e.g., Eaton et al., 1999a, Green and Mountjoy, 2005; Chopra et al., 2017), faults that may control the location of induced earthquakes are often challenging to detect using seismic-reflection images alone. Problematic cases include faults with a geometry that is unfavourable for seismic mapping in horizontally stratified rocks, such as subhorizontal thrust faults or vertical strike-slip faults, or brittle faults hosted within crystalline basement rocks that lack clear marker reflections. The latter is particularly true in the shallow crystalline basement in western Canada, where basement structure may be difficult to discern in the presence of strong multiple reflections (Eaton et al., 1995).

Modelling and interpretation of regional gravity and magnetic data can provide valuable insights for understanding crustal structure beneath sedimentary basins (e.g., Pilkington et al., 2000; Hope and Eaton, 2002), including constraints for understanding geological risk factors for induced seismicity (Shah and Keller, 2017). Models derived from magnetic and gravity data, due to their non-uniqueness, are usually combined with other geological and geophysical information (e.g. seismic and well data), to provide insights into the geometry of the subsurface (Hope and Eaton, 2002). The Western Canada Sedimentary Basin (WCSB) is a mature hydrocarbon basin, where extensive public-domain datasets are available, including regional-scale gravity and magnetic anomaly data as well as crustal seismic profiles. To complement the potential-field data, this study uses crustal seismic-reflection data from the Alberta Basement Transects (ABT) Peace River Arch Industry Seismic Experiment (PRAISE) project (Hope et al., 1999), part of Canada's LITHOPROBE program (Clowes et al., 1999).

The objective of this contribution is to present new insights arising from geophysical imaging and mapping of representative basement fault structures, together with a discussion of how they may be significant as a framework for understanding induced seismicity. The LITHOPROBE seismic profiles intersect structural boundaries that are seen on the regional aeromagnetic and gravity mapping. Our interpretation approach involves mapping and identification of basement structures, followed by 2-D gravity and magnetic modelling for selected features. Since the gravity and aeromagnetic data span a large geographical area they are useful to characterize large-scale trends, whereas the 2-D seismic lines give detailed constraints for building a model, such as fault throw and timing. Potential-field data thus give a more complete tectonic picture of the area by filling in the gaps between areas of seismic coverage, providing an opportunity to improve our understanding of the structural framework.

Conclusions

In this study, potential-field methods are combined with seismic and well data to investigate basement structure in Alberta. Our analysis shows that regional gravity anomaly patterns primarily reflect large-scale crustal features while the magnetic-anomaly maps provide the primary method for delineating the extent of basement tectonic domains (Ross et al., 1991). Isostatic-residual gravity anomalies are characterized by longer wavelength than magnetic anomalies. While the magnetic anomalies predominantly reflect the magnetic susceptibility of the uppermost basement (Villeneuve et al., 1993), due to the wavelength difference the gravity anomalies are primarily sensitive to deeper crustal levels. This difference in depth sensitivity may explain why the observed isostatic gravity and magnetic intensity fabrics are poorly correlated. Moreover, based on the available regional datasets the (likely subtle) magnetic and gravity expression of basement faults appears to be overwhelmed by anomalies produced by large-scale crustal features. This suggests that a good strategy to improve the sensitivity of potential-field methods to detect and constrain basement faults is to acquire densely sampled data and apply a well-characterized regional-residual separation.

There is evidence to suggest that the southern Chinchaga domain is a distinct block from the northern Chinchaga domain, although basement drillcore samples are too sparse to either validate or falsify this interpretation. The Chinchaga domain has primarily negative magnetic anomaly values throughout its north-south extent, but there are distinct characteristics of the magnetic anomalies in the southern part that are dissimilar from magnetic-anomaly characteristics in the north. Specifically, the southern Chinchaga domain has a more muted negative character, with distinct internal positive anomalies that are absent in the north. In contrast, the northern Chinchaga domain is characterized by high-amplitude negative anomalies. In addition, the southern Chinchaga domain has strikingly rectilinear boundaries, in contrast to the arcuate nature of internal and bounding fabrics in the north. There are north-south trending magnetic anomalies in the southern Chinchaga domain that have an orientation consistent with observed induced-seismicity focal mechanisms, so this distinction may be important in terms of fully understanding the relationships of magnetic anomalies to induced seismicity.

As indicated by a LITHOPROBE seismic profile across the Tangent fault in the Peace River Embayment, despite a sharp offset at the top of crystalline basement, the seismic expression of faulting of Paleozoic layers is dominated by folding. This draped seismic expression supports the use of seismic curvature attribute analysis (Chopra et al., 2017) for mapping potential fault structures. In the shallow basement, faults in the WCSB are difficult to map due to the lack of coherent reflections and the obscuring effects of multiple reverberations. On the other hand, disruption and offset of reflections within the Winagami Reflection Sequence (WRS) provides a potential opportunity to pinpoint loci of crustal-scale faulting at depth as an aid in the interpretation of basement faults. This interpretation approach relies on an assumption that these bright reflections represent mafic sills that were originally more laterally continuous than at present, such that observed offsets can be reasonably interpreted as post-intrusion fault deformation. Extrapolation to the top of basement of the tentatively interpreted crustal-scale reverse fault would bring this fault to the base of the WCSB close to several interpreted faults in close proximity to a major Leduc reef edge.

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