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Research paper

Subsurface faults inferred from reflection seismic, earthquakes, and sedimentological relationships: Implications for induced seismicity in Alberta, Canada

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ABSTRACT

Given the recent induced seismic activity in Alberta, identification of subsurface faults and areas of structural complexity has become increasingly important in improving our understanding of the controls on induced seismic events. Using a 3D geological model supplemented with 2D and 3D reflection seismic data, several basement-bounded and basement-rooted faults, which extend upward and into the Devonian strata, are identified in areas coincident with increased seismic activity. The presence of faults in the study area was confirmed through a statistically significant correlation of high-quality seismic event data from historical and recent (1970–2016) induced earthquakes in Alberta to the edge of the Devonian-aged Swan Hills platform. Along with the identification of faults using reflection seismic and earthquake hypocenter data, a review of the role of pre-existing structure on depositional patterns that has been previously used to infer deep structure in this area, is also presented in this study. Several pre-existing extensional and/or transtensional style faults in the deeper strata and shallow basement of the study area are consistent with structure influencing the sedimentation of the overlying stratigraphy. Therefore, a better understanding of genetic fault-reef associations and the relationship to overlying strata may aid in identification of fault locations, style, and orientation. Considering the advancement of proper avoidance strategies during the planning stages of unconventional resource development or storage, this paper demonstrates the use of geological knowledge and relationships to identify areas comprising faults that may be prone to reactivation.

1. Introduction

Alberta has experienced increased levels of induced seismic activity in recent years (Wang et al., 2016; Schultz et al., 2016, 2017). It has been determined through double difference and waveform modelling that the hypocentres indicate reactivation of faults located in or below the Duvernay Formation (structural top depths - 3300 to −1800 m subsea). The structural history of the Precambrian crystalline basement and its potential influence on basal sedimentary strata in the Western Canada Sedimentary Basin (WCSB) is poorly understood, due to the difficulty of identifying subsurface faults, especially with limited access to 2D or 3D reflection seismic. There are, however, geological features that may be used to infer faults. Inference of subsurface faults using geological proxies requires the faults to have exerted some recognizable control on sedimentation patterns or provided a conduit for fluid flow that resulted in localized diagenesis.

There are areas of the WCSB where basement faults have been observed and inferred to have influenced patterns of reef growth, such as the Peace River Arch, where faulted paleotopography clearly provided antecedent highs for the inception of fringing reefs (Fig. 1; Cant, 1988; Gosselin et al., 1989; O'Connell et al., 1990; Dix, 1990; Keith, 1990). Despite this, and numerous modern analogues, there is continued debate as to whether faults or underlying structure has controlled the inception of large reef complexes in the WCSB, in areas where faults have not been directly interpreted from reflection seismic (Andrichuk, 1961; Jones, 1980; Mountjoy, 1980; Viau, 1987; Wendte and Uyeno, 2005). Other fault proxies include localized, fault-related dolomitization in some carbonate successions, which provide evidence for the presence of deep-seated faults that acted as conduits for upward transmission of dolomitizing fluids derived from deeper in the stratigraphy (Mountjoy et al., 1999; Davies and Smith, 2006). More recently, the discovery that all of the induced seismic events recorded in Alberta's

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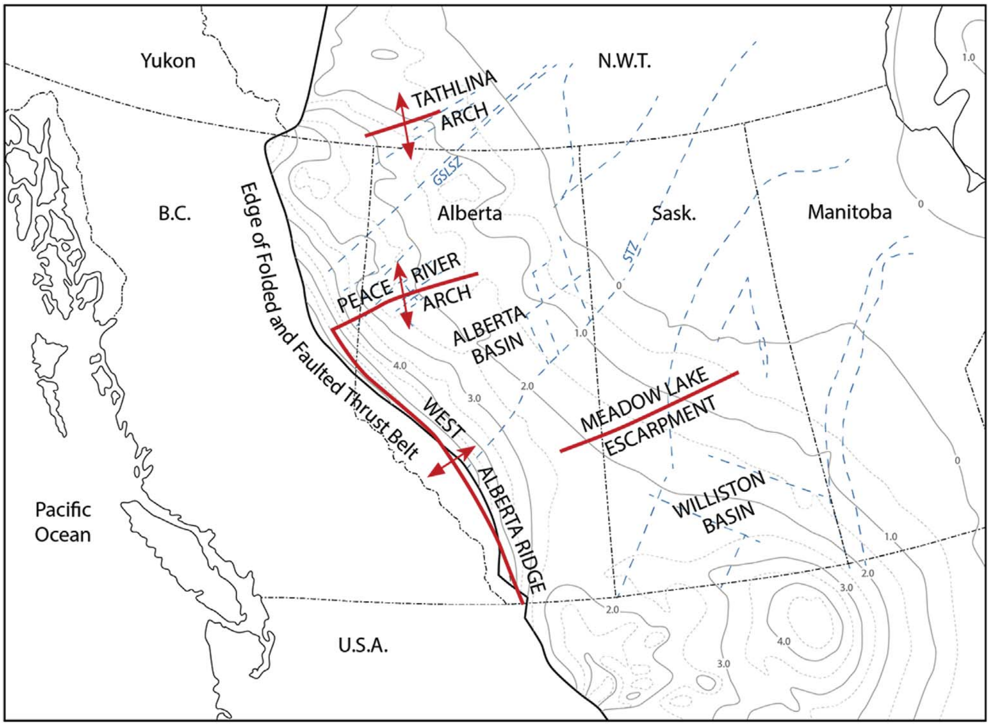

Fig. 1. Regional map of the Western Canadian Sedimentary Basin (WCSB) with contours showing approximate thickness (km) of Phanerozoic rocks and Precambrian structural features (modified from Wendte et al., 1992; Burwash et al., 1994; Ross and Eaton, 1999). Faults are shown in blue. STZ = Snowbrid Tectonic Zone and GSLSZ - Great Slave Lake Shear Zone. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

history, with the exception of one event in southern Alberta near the town of Cardston, have a statistically significant correlation to occurring within 10 km outside and 20 km inside of the edge of the Swan Hills Formation carbonate platform in west-central Alberta (Fig. 2; Schultz et al., 2016). This relationship implies that critically stressed faults are located in close proximity to the Swan Hills platform edge.. Previous studies have used the depths of the hypocentres of seismic events, relocated through double difference techniques on local arrays, to indicate that these faults are within the basal sedimentary strata (Schultz et al., 2017; Bao and Eaton, 2016). Faults are confirmed, as part of this study, in the vicinity of the Swan Hills platform edge through the interpretation of 2D and 3D seismic, along with the type of faulting observed. The mere presence of faults in the vicinity of the platform edge cannot definitively answer the historic question of fault-reef coupling in the WCSB; however, in consideration of previous evidence and new data to indicate that the relationship exists, our understanding of the nature of faults in this region can be improved through examining present day and past fault-reef analogues.

This objectives of this paper are as follows: 1) to present a compilation of inferred faults from the literature and recently interpreted faults from 2D and 3D seismic and the hypocenters of induced seismic events located in the study area (Fig. 2) and, 2) discuss the likelihood of a structural influence on the growth of the Swan Hills Formation carbonate platform through comparison to modern and ancient analogues, and 3) suggest that improved understanding of the relationship between faults and reefs may aid in developing avoidance strategies with respect to induced seismicity as development of unconventional resources continues. Overall, we aim to emphasize the utility of geological fault-proxies when evaluating the potential for fault reactivation in an area of hydraulic fracturing or injection.

2. Structural controls on deposition in the WCSB

A summary review of the literature relevant to the WCSB and then more specifically the west-central Alberta study area and the Swan Hills Formation is presented where faults have been inferred using depositional or diagenetic patterns (Figs. 1 and 2).

2.1. Basin-scale sub-Devonian structure

Little is known about structural features within deep sedimentary strata in the WCSB. Furthermore, beyond an understanding of the broad tectonic provinces within Precambrian basement rocks, less is known of the structure therein. Much of the structural data from the subsurface in Alberta was collected using aeromagnetic, gravity, electrical conductivity, and the 1994 Canadian Lithoprobe program seismic data (Wright et al., 1994; Ross et al., 1994; Eaton, 1995; Eaton et al., 1999; Hope and Eaton, 2002). Thinning and onlap of sedimentary strata are used to infer the presence of putative paleotopographic highs that may be related to structural offsets, and to estimate the length of time that they remained emergent. There are several large, regional scale sub-Devonian structural features that have continued to influence depositional patterns in the WCSB throughout its history. The most prominent basement features were identified early on in the history of petroleum exploration within the Alberta portion of the basin as paleotopographic highs, some that would have remained emergent through a significant part of the Paleozoic. The Tathlina Uplift, a basement high located just north of the Alberta and Northwest Territories border, was emergent until the Early to Middle Devonian (Fig. 1; Norris, 1965, Belyea, 1971, Meijer Drees, 1989). The Peace River Arch (PRA) is another prominent paleotopographic high that was present at least as early as the Cambrian and emergent throughout much of the Devonian, then eventually collapsed and was inundated by the beginning of the Carboniferous (Fig. 1; Cant, 1988; O'Connell et al., 1990; Eaton, 1995). The West Alberta Ridge (WAR), a feature that borders the Alberta Basin in the west, is recognized by thinning of Devonian carbonate rocks that onlap the high (Fig. 1; Cecile et al., 1997; Wendte et al., 1992). Finally, the Sweetgrass Arch (SA) is a large N-S striking structural feature in southeastern Alberta that divides the WCSB into the Alberta Basin and the Williston Basin, the latter being an intracratonic basin to the east-southeast of the SA arch (Kent and Christopher, 1994; Baird et al., 1995). These sub-Devonian highs are acknowledged as having influenced relative sea level changes and subsequent depositional patterns in the WCSB (Mountjoy, 1980; Wendte et al., 1992; Hope et al., 1999).