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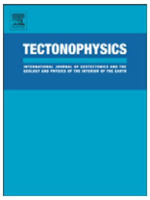

A revised crustal stress orientation database for Canada

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ABSTRACT

The Canadian database on contemporary crustal stress has not been revised systematically in the past two decades. Here we present the results of our new compilation that contains 514 new data records for the orientation data of maximum compressive horizontal stress and 188 data records that were re-assessed. In total the Canadian stress database has now 1667 data records, which is an increase of about 45%. From these data, a new Canadian Stress map as well as one for the Province of Alberta is presented.

To analyse the stress pattern, we use the quasi median on the circle as a smoothing algorithm that generates a smoothed stress map of the maximum compressive horizontal stress orientation on a regular grid. The newly introduced quasi interquartile range on the circle estimates the spreading of the data and is used as a measure for the wave-length of the stress pattern. The result of the hybrid wavelength analysis confirms that long spatial wavelength stress patterns ($\geq$1000 km) exist in large areas in Canada. The observed stress pattern is transmitted through the intra-plate regions.

The results reveal that shorter spatial wave length variation of the maximum compressive horizontal stress orientation of less than 200 km, prevails particularly in south-eastern and western Canada. Regional stress sources such as density contrasts, active fault systems, crustal structures, etc. might have a significant impact in these regions. In contrast to these variations, the observed stress pattern in the Alberta Basin is very homogeneous and mainly controlled by plate boundary forces and body forces. The influence of curvature of the Rocky Mountains salient in southern Alberta is minimal. The present-day horizontal stress orientations determined herein have important implications for the production of hydrocarbons and geothermal energy in the Alberta Basin.

1. Introduction

Understanding of the in-situ stress tensor in the Earth's crust is of key importance to a number of major scientific, economic and societal issues. Knowledge of the crustal stress is key to understanding plate tectonics or earthquake cycles. Such knowledge is also crucial for drilling as crustal stresses influence well-bore stability, reservoir operation and stimulation, cap rock integrity, induced seismicity and the long-term stability of underground constructions. Consequently, knowledge of the contemporary crustal state of stress is of great importance to resource-rich nations such as Canada whose economies depend on the efficient and safe extraction of minerals and hydrocarbons and who is under pressure to do better at protection of the environment.

There are several methods used to estimate both stress orientation and magnitudes from borehole observations (e.g. Amadei and Stephansson, 1997; Ljunggren et al., 2003; Schmitt et al., 2012; Zang and Stephansson, 2010; Zoback et al., 2003). These methods include overcoring, analysis of the orientation of borehole breakouts and drilling induced tensile fractures, hydraulic fracturing (leak-off, mini-frac, micro-frac, etc.), earthquake focal mechanisms and geological indicators. The results from these methods may represent the stress state at scales of a few decimetres up to tens of kilometres (Ljunggren et al., 2003). However, obtaining the complete state of stress (i.e. the six independent components of the stress tensor) remains a challenging task. All techniques have in common the fact that they can provide at least the maximum compressive horizontal stress (S_{Hmax}) orientation, or perpendicularly to it, the minimum horizontal stress (S_{hmin}) azimuth; only a few methods deliver further components of the stress tensor. Furthermore, the vertical stress magnitude (S_V) can be estimated from the weight of the overburden and the S_{hmin} magnitude from leak-off tests or hydraulic fracturing (e.g. Haimson and Fairhurst, 1969; Hubbert and Willis, 1957; White et al., 2002). However, in particular the reliable estimation of the S_{Hmax} magnitude remains difficult as the numerous assumptions to be made impose high uncertainties.

Consequently, stress maps have primarily focussed on illustrating the S_{Hmax} azimuth. The first systematic compilation of orientation data

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by Sbar and Sykes (1973) mapped the S_{Hmax} orientation over North America, by means of focal mechanisms, geological indicators, overcoring and hydraulic fracturing. Stress mapping accelerated significantly with the findings of Bell and Gough (1979) and Hottman et al. (1979) that the azimuth of borehole breakouts (Babcock, 1978) indicates the S_{Hmax} orientation. The acquisition of such data is relatively easily found by means of oriented calliper log data as is provided, for example, by dipmeters (e.g. Plumb and Hickman, 1985). The compilation of stress data in North America in the subsequent years by Adams (1987), Adams and Basham (1989), Adams and Bell (1991), Bell et al. (1994), Fordjor et al. (1983), Gough et al. (1983). Zoback and Zoback (1980, 1981, 1989, 1991) showed, that the pattern of S_{Hmax} orientations is frequently uniform over thousands of kilometres. These observations were used as evidence that the tectonic stress field is controlled by plate boundary forces and body forces; these are first order stress sources (Zoback, 1992). This hypothesis was studied globally by the continued compilation of stress data in the framework of the World Stress Map project (WSM) and is confirmed in first order (Richardson, 1992; Zoback, 1992; Zoback et al., 1989). Besides the first order main driving forces of plate tectonics, there are several stress perturbations of the second and third orders, which can strongly overprint the regional stress field in some areas (Heidbach et al., 2007; Zoback, 1992). Such local or regional effects can be detected only in the case of the availability of dense stress observations of sufficient quality.

In the two decades after the initial phase of the WSM project (1986–1992), data entries in the recent global database have been tripled (Heidbach et al., 2010). Despite this global increase there has not to our knowledge been a substantial systematic revision nor extension on the Canadian stress database for about two decades (Adams and Bell, 1991; Bell et al., 1994) with the exception of some additional work focussed on specific geological targets (e.g. Bachu et al., 2008; Bell and Bachu, 2003, 2004; Bell and Grasby, 2012). In the Western Canada Sedimentary Basin with more than 700,000 wells, a considerable amount of geophysical logging image and dipmeter has been collected, but most of this remains inaccessible. In principle, the extraordinary data density would allow a far more detailed study of second and third order stress deviations. A revised stress data compilation and analysis from the Alberta Basin which represents the foreland basin of Western Canadian Cordillera would allow the comparison of stress patterns in similar geologic settings as the Subalpine Molasse Basin, a foreland basin of the Alpine orogenic belt in Germany (Reinecker et al., 2010).

The first objective of this paper is to update and revise the stress map of Canada by adding all new stress orientation data to the existing data set. As much of the new data comes from the portions of the Western Canada Sedimentary Basin in Alberta, the pattern analysis will focus on the overall stress there. All 1153 data records from the WSM 2008 database release (Heidbach et al., 2010) were cross-checked and state of the art quality ranking was applied. By adding 514 data records from new publications and a data set from the Alberta Geological Survey (AGS), the number of S_{Hmax} azimuth records in the research area is increased by 45% to 1667.

The second objective of this work is the investigation of the S_{Hmax} orientation pattern in Canada and again in detail for Alberta, by means of the updated database. A hybrid wavelength analysis technique based on the algorithm from Heidbach et al. (2010) is developed further and presented here.

Furthermore, the data set showcases a more homogeneous stress pattern along the length of Alberta. In particular this new compilation appears to show that the S_{Hmax} orientations in the Alberta foreland basin are not always perpendicular to the front of the Rocky Mountains as had previously been believed (e.g. Bell and Gough, 1979). That is the first and second order patterns dominate over Alberta despite the existence of large bounding geomorphological features such as the Rocky Mountains and the Rocky Mountains Trench further to the west. This is in contrast to other regions such as the St. Lawrence Lowland where a good observation density suggests a stress field dominated by the second and third order stress sources (e.g. fault zones).

2. Crustal stresses

2.1. Indicators of stress orientation

The full stress tensor consists of six independent components none of which can be measured directly. Most of our stress knowledge comes from stress indicators that are observed by the use of a variety of methods from boreholes. These methods (for overview see Ljunggren et al., 2003) may be distinguished as they provide either data on crustal stress orientations only or they give knowledge of the stress magnitudes and/or faulting regime. Here, we will focus only on those methods which allow for estimation of the stress orientation.

Since the 19*th* century, structural geologists have interpreted and quantified rock deformations under the assumption that ancient stress conditions lead to the observed deformation pattern in the rock mass. Therefore recent crustal deformation is interpreted to be caused by the recent stress field or remnant stresses such as those induced by glacio-isostatic rebound from Pleistocene glaciations (Sbar and Sykes, 1973, and references therein). Precise dating of stress indicators helps to exclude palaeo-stress indicators. Stress- and strain markers in rock can be variable depending on rock type, deformation rate and stress regime potentially causing shear, shortening or extension. Among others geological indicators include dykes or volcanic vent alignments (GVA) (Nakamura, 1977; Nakamura et al., 1977), fault slip data (GF) (e.g. Angelier, 1979, 1984) and pop-up structures or joint systems (Hancock, 1991; Hancock and Engelder, 1989).

Bell and Gough (1979) and independently Hottman et al. (1979) were the first to recognize that borehole breakouts (BO), which were known for some years (e.g. Babcock, 1978; Cox, 1972), are an indicator of the orientation of stresses in the crust. Breakouts are borehole segments of several metres or more along which the borehole wall has spalled preferentially at diametrically opposed azimuths. As such, the diameter across the BO must be greater than that for the drill bit; and this major axis points in the direction of S_{hmin}. The breakouts occur due to concentration of the combined horizontal stresses at the borehole wall (e.g. Haimson and Song, 1993; Schmitt et al., 2012; Zoback et al., 1985, 2003). There are several geophysical logging methods to identify elliptical borehole sections that include ultrasonic acoustic imaging as produced by the borehole televiewer (Zemanek et al., 1969, 1970), electrical resistivity imaging methods such as produced by micro-resistivity tools (Ekstrom et al., 1987), and simpler mechanical oriented-calliper logs like four-arm up to multi-finger dipmeter/calliper logs (e.g. Babcock, 1978; Plumb and Hickman, 1985; Reinecker et al., 2003).

Drilling induced (tensile) fractures (DIF) also provide stress orientation data. They are also related to the superposition of the far-field

Table 1
Type and quality of the S_{Hmax} orientation data from Canada and surrounding (latitude - 41°N, longitude 142°W to 46°W).

Data type	Complete dataset		New data only	
	A–E	A–C	A–E	A–C
	Quality		Quality	
Focal mechanisms (FMF, FMS, FMA)	767	516	212	132
Borehole breakouts (BO, BOT)	657	389	181	38
Drilling-induced tensile fractures (DIF)	42	38	42	38
Geological: fault–slip (GFM, GFS)	6	6		
Hydraulic fracturing (HF, HFG, HFM)	43	13	20	4
Overcoring (OC)	91	12	53	4
Geological: volcanic alignment (GVA)	53	3		
Petal centreline fractures (PC)	4	4	4	4
Shear wave splitting (SW)	4		2	
Total	1667	981	514	220