In-situ stress regime in the Viking Formation, southwest Saskatchewan

C.D. Hawkes and O. Hamid
Department of Civil and Geological Engineering – University of Saskatchewan, Saskatoon, SK, Canada

ABSTRACT
In-situ stresses have a critical influence on petroleum drilling, completion and production operations. This paper presents the results of an investigation of in-situ stress magnitudes conducted for the Viking Formation in southwest Saskatchewan. Analyses of vertical (σ_V) and minimum horizontal (σ_{Hmin}) stress magnitudes were conducted using bulk density logs and fracture stimulation data, respectively. Both of these stress components were found to be dominantly controlled by present-day burial depth. σ_V magnitudes exceed 27 MPa in the structural low that exists between the Battle-Creek Anticline and the Swift Current Arch, and are less than 10 MPa at the relatively shallow burial depths occurring at the northern edge of the study area. σ_{Hmin} magnitudes in the 16-19 MPa and 9-10 MPa ranges occur in the former and latter locations, respectively. The average σ_{Hmin} orientation roughly parallels the trend of the Rocky Mountains. Based on limited available σ_{Hmax} data, a strike-slip fault stress regime (transitional to a normal fault regime) is interpreted for the study area.

RÉSUMÉ
L'état de contraintes dans le souterrain a une influence critique sur les opérations d'exploitation pratiqué par l'industrie pétrolière. Ce document présente les résultats d'une recherche sur l'état de contraintes dans la formation Viking, dans le sud-ouest Saskatchewan. Les contraintes verticales (σ_V) and horizontal minimum (σ_{Hmin}) sont principalement commandé par profondeur d'enterrement. σ_V dépasse 27 MPa près du coin de sud-ouest du secteur d'étude, ou la profondeur atteint son maximum, et σ_{Hmin} est approximativement 16-19 MPa. σ_V est moins de 10 MPa dans le nord, ou la profondeur atteint son minimum, et σ_{Hmin} est approximativement 9-10 MPa. L'orientation de σ_{Hmin} est nord-ouest – sud-est. Basé sur des données disponibles limitées, σ_{Hmax} est égal ou légèrement plus grand que σ_V.

1 INTRODUCTION

The in-situ stress state at depth has a strong influence on a number of geomechanical processes that affect petroleum exploration and development. Notable examples include (1) wellbore stability while drilling; (2) casing design; (3) solids production; (4) fracture stimulation; (5) induced seismicity; (6) orientations of hydraulically open natural fractures; and (7) matrix permeability of soft formations such as coal. All of these factors are relevant in the southwest Saskatchewan, especially (4), (6) and (7). However, other than stress characterization previously conducted at the regional scale for the Western Canada Sedimentary Basin (Bell et al., 1994), there has not yet been a study focused solely on Cretaceous-age strata in Saskatchewan.

2 IN-SITU STRESSES

2.1 Definitions, Framework and Sign Convention

In sedimentary basins with relatively flat-lying strata and limited ground surface relief, it is reasonable to assume that the vertical stress at any point within these strata is due simply to the weight of the overburden. Further, there are no shear stresses acting in the vertical direction in such a setting, hence the vertical stress is a principal stress component. Due to the orthogonal nature of principal stresses, the other two principal stresses lie in the horizontal plane, and are oriented at right angles to one another. As such, the in-situ stress state at any point may be fully defined by specifying the magnitudes of the vertical stress (σ_V), the maximum horizontal stress (σ_{Hmax}) and the minimum horizontal stress (σ_{Hmin}), as well as the orientation of either one of the horizontal stresses. In this paper, compressive stress magnitudes are considered positive.

2.2 Previous Regional-scale Results

The above-noted conditions are assumed to be valid for the Western Canada Sedimentary Basin (WCSB) in Saskatchewan; hence, the work presented in this paper will focus on vertical and horizontal stress magnitudes and orientations.

The regional-scale work by Bell et al. (1994) on in-situ stresses in the WCSB has established the general trend of horizontal stress orientations in western Canada, and identified the stress regimes believed to exist across the basin. These regional-scale results indicate that (1) southwest Saskatchewan lies in a strike-slip fault regime, meaning that σ_V is intermediate between σ_{Hmax} and σ_{Hmin}; and (2) σ_{Hmax} in southwest Saskatchewan trends roughly northeast-southwest, with a slight inflection occurring near the Swift Current Arch.

3 THE VIKING FORMATION

3.1 Geology

The Viking Formation is characterized by mudstone, siltstone, silty sandstone, sandstone and conglomeritic elements in vertically-repeated, coarsening-upwards lithologic sequences (Christopher et al., 1971). Figure 1 shows a depth map for the top of the Viking Formation, generated using public-domain data, superimposed on the location of basement tectonic features identified by Christopher et al. (1971). Generally, the Viking Formation decreases in depth from south-southwest to north-northeast in the study area, from a maximum close to 1200 m to a minimum close to 400 m.

3.2 Why Study the Viking Formation?

Sandstone strata within the Viking Formation have been extensively explored and produced in southwest Saskatchewan. Oil and gas wells completed in the Viking Formation are frequently subjected to hydraulic fracture stimulation treatments. As such, this formation was selected for study because (1) it extends throughout the entire study area; and (2) the amount and coverage of hydraulic fracturing data, which are used for minimum horizontal stress interpretation (to be described later), is relatively good. Given that the Viking Formation sits within a succession of Cretaceous-age clastic sedimentary rocks, which formed during the foreland basin stage of WCSB development, it seems reasonable to expect that the results obtained for this formation may be used to gain insights into the stress state throughout this succession.

4 METHODOLOGY

4.1 Vertical Stress Magnitude

Subsurface rock units carry the weight of the overlying rocks, sediments and pore fluids. The vertical stress at a given depth, z, results from this weight. The magnitude of this vertical (or "overburden") stress, σ_V, can be calculated by integrating bulk density measurements as follows:

$$\sigma_V = 10^{-6} \cdot \int_0^z \rho_b g dz \qquad [1]$$

Where:
σ_V = vertical in-situ stress (MPa)
ρ_b = bulk density (kg/m^3)
z = depth from ground surface (m)
g = acceleration due to gravity (9.81 m/s^2)

Vertical in-situ stress magnitudes were calculated in this project using bulk density data acquired from geophysical logs for 179 wells in the study area. Well locations were chosen to be as uniformly distributed as possible throughout the study area, penetrate to depths at least as great as the top of the Mannville Group (which lies beneath the Viking and Joli Fou formations), and with preference given to wells logged with relatively modern tools (e.g., post 1980s).

For each well used in the vertical stress calculations, quality control was conducted by examining borehole enlargement, and by examining the magnitudes of bulk density corrections reported by the logging company (to compensate for the effects of borehole enlargement or excessive mudcake thickness). Ninety-five percent of the data used for vertical stress calculations had hole diameters that were near-gauge (i.e., ranging from 0.95 to 1.15 times the drill bit diameter), and 95% of the data had density corrections that were less than 6% of the bulk density of the overburden, on average. The few lower quality datasets that were retained for use were obtained from areas where well coverage was relatively sparse.

Two issues pertaining to near-surface bulk density data merit discussion: (1) Bulk densities are not usually logged at shallow depths (e.g., above surface casing), hence it was necessary to estimate bulk densities for unlogged intervals; and (2) glacial deposits – possessing bulk densities markedly lower than most sedimentary rocks - cover the bedrock throughout the study area. To overcome the first issue, the average bulk density trend through the shallowest intervals logged was linearly extrapolated to the depth corresponding to the top of bedrock. In some cases, it was possible to reduce the size of the interval requiring extrapolation by splicing together bulk density datasets from neighbouring wells. In order to address the second issue, 35 bulk density logs were found in the study area that were shallow enough to measure the thickness and bulk density of glacial deposits. Densities in these wells ranged from 1760 to 2095 kg/m^3. Thicknesses interpreted from this dataset, combined with a glacial deposit isopach map reported by Fenton et al. (1994), ranged from a few tens of metres to roughly 200 m. These data were used to estimate the thickness and bulk density of glacial deposits for each well included in the vertical stress investigation.

4.2 Minimum Horizontal Stress Magnitude

Micro- and mini-frac tests are generally regarded as the best methods of estimating the minimum horizontal stress magnitude (σ_{Hmin}). These tests involve initiating a hydraulic fracture within a short packed-off interval by slowly injecting a relatively small volume of solids-free fluid (e.g., water or hydraulic fracturing fluid), and monitoring the pressure decline after injection ceases. A schematic pressure time record for such a test is illustrated in Figure 2. Key pressures to note on this figure are the instantaneous shut-in pressure (ISIP) and the fracture closure pressure (FCP). FCP is reached when pressure within the fracture matches the minimum in-situ stress magnitude (which in most cases, including this project, corresponds to σ_{Hmin}). ISIP is the pressure in a hydraulic fracture immediately after pumping has stopped. In theory, because it tends to be slightly larger than the minimum in-situ stress, it is less desirable than FCP as a stress indicator (e.g., De Bree and Walters, 1989). However, ISIP does have the advantage of being more easily interpreted than FCP; further, particularly in stress tests involving multiple cycles of injection and shut-in, the ISIP's measured on the latter of these cycles are believed to be good stress magnitude indicators.

A review of publicly accessible data, as well as data provided by operating and service companies active in southwest Saskatchewan, failed to find any micro- or mini-frac tests in the Viking Formation. In light of this fact, it was decided that hydraulic fracture stimulation data should be used for interpreting minimum horizontal stress magnitude in the study area. In principle, a hydraulic fracture stimulation treatment is similar in many ways to a mini-frac test. As in the case of the latter, fluid is injected into an isolated interval in order to create a hydraulic fracture. Key differences between the two, however, include the following: (1) The volume and rate of fluid injection is much larger for a stimulation treatment; (2) the fluid injected may be a two-phase (gas-liquid) mixture or even pure gas; (3) bottomhole pressures are typically not measured, hence they must be estimated based on pressures measured at the wellhead and knowledge of the properties of the fluid(s) in the well; and (4) once a fracture has been initiated, a relatively coarse sand or some other type of proppant is added to the injection fluid with the intent of permanently placing these solids within the fracture.

The pressure record for a hydraulic fracture stimulation will usually look similar to the mini-frac dataset illustrated in Figure 2, but the duration of injection (hence fracture propagation) will be longer, and there may be no clearly defined fracture closure event. While it is acknowledged that these data are less accurate than micro- and mini-frac tests, they have the advantage of being more readily available.

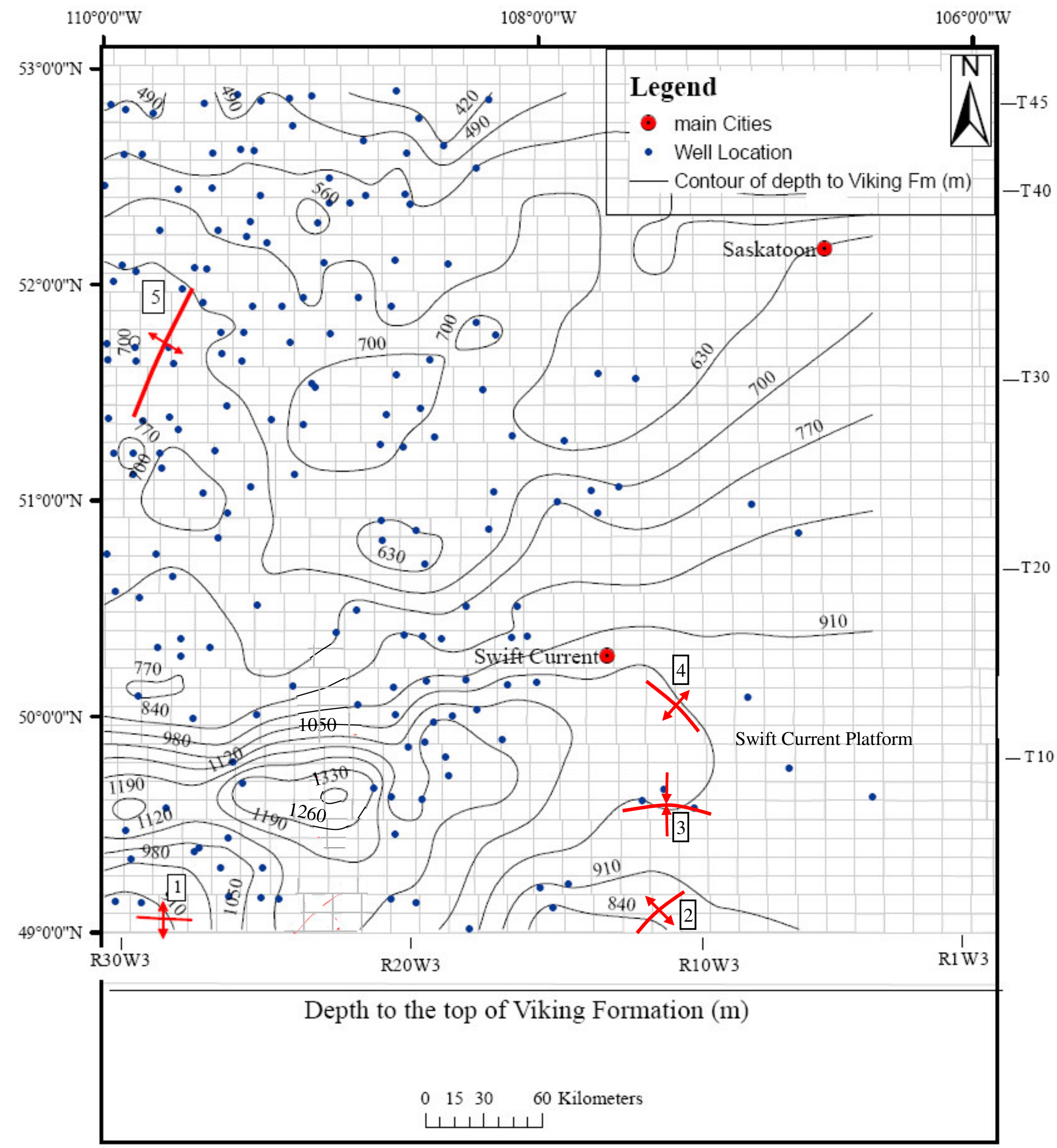

Figure 1. Depth (from ground surface) to the top of the Viking Formation. Basement tectonic features (after Christopher et al., 1971) are: (1) Battle Creek Anticline, (2) Val-Marie Arch, (3) Ponteix Syncline, (4) Swift Current Arch, and (5) Sweetgrass-North Battle Arch.

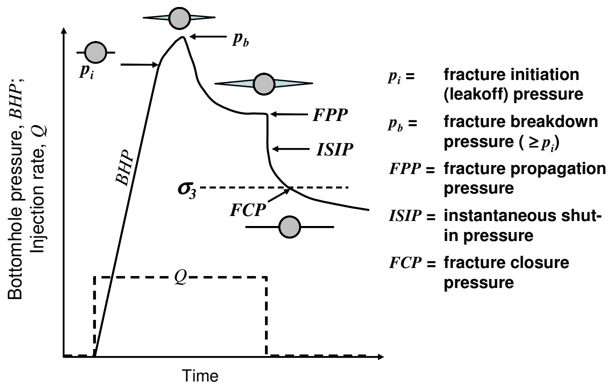

Figure 2. Typical pressure-time record for a micro- or mini-frac test. [Note: Fracture initiation pressure and fracture breakdown pressure may occur at the same point, especially in the case of a solids-free injection fluid.]

This component of the project was conducted using a database summarizing key parameters measured during fracture stimulation records conducted by BJ Services Canada (BJ) in southwest Saskatchewan. The database contained 2,225 Viking Formation treatment summaries, dating from 1972 to 2005. Rather than using the entire dataset for minimum horizontal stress interpretation, however, it was necessary to extract the results that were most appropriate for this task. Factors considered while extracting data for use in this project included the following:

1. Given that bottomhole pressures were not measured during these treatments, calculated values for this parameter are more likely to be accurate for certain testing conditions (e.g., single-phase fluids; large cross-sectional flow areas). Treatments for which these conditions existed were preferentially selected.
2. Preference was given to relatively recent data (BJ personnel indicated that algorithms for calculating bottomhole pressures have become more accurate in recent years).
3. Treatments runs in wells with limited pressure depletion were preferred, as it is known that pressure depletion will reduce horizontal stresses to some extent (e.g., Addis, 1997). The database did not include reservoir pressures. As such, treatments run in reservoirs with limited production (as assessed using public-domain production data) were preferred. Where this could not be avoided, preference was given to oil reservoirs, in which pressures tend to decrease less with depletion compared to gas reservoirs.
4. Wells that had sanded off (i.e., slurry injection terminated prematurely when the fracture stopped accepting proppant, resulting in a sudden pressure increase) were not used.

Compromises were made on some of the above-noted selection criteria, where necessary to obtain as much data coverage as possible. Even so, it was not possible to find data for the entire study area.

One hundred and six Viking Formation stimulation treatments were ultimately selected for minimum horizontal stress analysis. ISIP's were included in these treatment record summaries. However, as noted above, FCP is generally regarded as the best estimate σ_{Hmin}. To quantitatively assess the relationship between ISIP and FCP in the Viking Formation, post-fracture pressure shut-in data were analyzed in detail for a limited number of the treatments. This was accomplished using treatment data provided by BJ, which included measured wellhead pressures, calculated bottomhole pressures, and fluid (or slurry) injection rates recorded over the duration of each treatment.

Figure 3a shows the shut-in data from one of the Viking fracture stimulation treatments. The figure shows that injection stopped approximately 40.8 minutes after the treatment began. Pressure dropped rapidly after shut-in. The bottomhole ISIP interpreted from this graph is 14.3 MPa. Figure 3b shows the same shut-in data, plotted against the square root of time. Following the extremely rapid pressure drop observed in the early time data, a linear trend is observed in the pressure decline range from approximately 14.2 to 13.9 MPa. Based on the flow regime framework established by Cinco and Samaniego (1981), a linear trend in pressure versus square-root-time space is indicative of a *formation linear flow regime*; i.e., linear flow from the fracture into the formation is dominant, which indicates that the fracture is hydraulically propped open. As pressure progressively dissipates during this flow regime, a point will be reached where the fluid pressure no longer exceeds the minimum in-situ stress, and the fracture will close. If the fracture closes "completely" (i.e., fracture permeability = formation permeability), a radial flow regime will develop. Pressure decline during this regime is a linear function of log(t). [Note: In reality, the final regime is often termed "pseudo-radial," as the fracture retains a higher permeability than the formation. It is important to note, however, that the fracture permeability after closure is significantly lower than it was in the preceding flow regimes, when it was being held open by high fluid pressures.] The first deviation from the linear trend associated with formation linear flow occurs at 13.9 MPa, which is hence interpreted as the fracture closure pressure (FCP).

Fracture closure pressure interpretation was conducted for ten Viking stimulation treatments in total, using the MinFrac computer program (Meyer and Associates, 2006). Several interpretation methods are available in this software. All of these methods, including the square root time method illustrated in Figure 3b, are based – in one fashion or another - on the identification of Cinco and Samaniego's (1981) flow regime transitions. The results obtained using these different methods tended to provide similar results for the data analyzed in this project. Table 1 summarizes the FCP's and ISIP's interpreted for these ten stimulation treatments. On average, FCP is 0.90 times the ISIP, and the standard deviation of 0.04 is relatively small. [Note: Similar comparisons were made for two stimulation treatments that were conducted in Mannville Group strata. FCP/ISIP ratios of 0.89 and 0.90 were found, which compares favourably with the average Viking Formation result.]

There are two points worth noting about the results presented in Table 1. Firstly, they provide justification for a relatively simple means for estimating minimum in-situ stress magnitudes (i.e., multiplying ISIP by 0.9) in settings where fracture stimulation data are available, but mini-frac and micro-frac test data are not. Service companies tend to have "rule of thumb" ISIP multipliers that are similar to the 0.9 obtained in this work, but – to the authors' knowledge - no public-domain documentation of such ISIP multipliers exists.

The second point of note is that, for nine of the ten wells analyzed (and the two Mannville Group results not presented in this paper), σ_{Hmin} was less than σ_V. This suggests that either a normal fault or strike-slip fault stress regime is predominant in the study area.

4.3 Maximum Horizontal Stress Magnitude

There is no direct measurement technique for measuring the maximum horizontal stress magnitude (σ_{Hmax}). Possibly the best available method for estimating the magnitude of σ_{Hmax} is to back-calculate its value from a micro- or mini-frac test that was run in an uncased borehole in competent rock. If a bottomhole measurement of fracture breakdown pressure is available for such a test, as well as the σ_{Hmin} magnitude interpreted from either ISIP or FCP, σ_{Hmax} can be calculated using linear elastic analysis of borehole stresses (e.g., Hubbert and Willis, 1957):

$$\sigma_{H\max} = 3\sigma_{H\min} - P_i + T_0 - P_0 \qquad [2]$$

Where P_i is the fracture initiation pressure (commonly close in magnitude to the fracture breakdown pressure, when injecting solids-free fluids), T_o is the rock tensile strength (commonly assumed to be negligible in clastic sedimentary rocks), and P_o is the native pore pressure. The magnitude of σ_{Hmax} can be calculated in cases were all of the parameters on the right hand side of equation 2 are known.

Table 1. Fracture close pressures and instantaneous shut-in pressures interpreted from fracture stimulation data for ten Viking Formation wells.

Well location	Depth (m)	σ_V (MPa)	ISIP (MPa)	FCP (MPa)	FCP/ISIP
08-34-042-23W3	541.0	11.67	11.88	10.54	0.89
11-29-039-25W3	608.3	13.02	12.97	11.40	0.88
15-31-031-17W3	609.0	12.87	13.37	11.76	0.88
06-14-029-17W3	694.0	14.82	15.31	14.02	0.92
02-24-028-23W3	721.0	15.61	14.67	13.43	0.92
10-02-028-17W3	724.0	15.59	14.31	12.47	0.87
02-12-027-20W3	720.0	15.52	14.09	11.71	0.83
10-06-026-17W3	672.5	14.49	13.10	11.66	0.89
06-04-026-14W3	604.0	12.93	12.71	11.62	0.91
12-07-025-17W3	643.4	13.80	14.30	13.90	0.97
				Average:	0.90
				Standard Deviation:	0.04

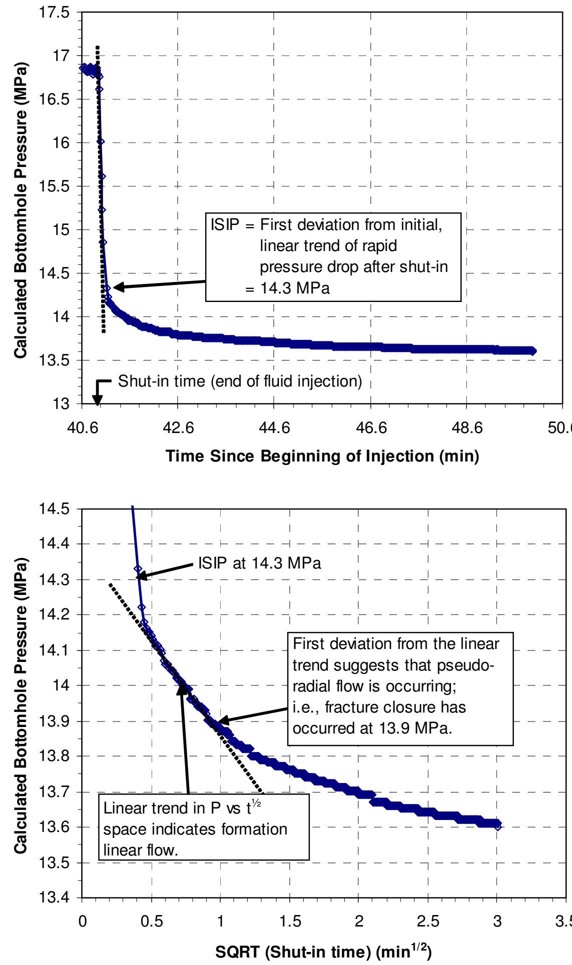

Figure 3. (a) Post shut-in pressure decline data and (b) shut-in pressure versus the square root of time for a fracture stimulation treatment in the Viking Formation, well 12-07-025-17W3.

4.4 Horizontal Stress Orientations

A commonly used method for estimating stress orientations is the analysis of borehole breakouts (e.g., Plumb and Hickman, 1985; Bell, 2003; Zoback et al., 2003). These breakouts are intervals in a well where caving has occurred on opposite sides of a borehole, so that it is laterally elongated, and are indicative of anisotropic compression around the borehole (i.e., $\sigma_{Hmin} \neq \sigma_{Hmax}$). In near-vertical wells (i.e., within 5° of vertical) through transversely isotropic rocks, breakout caving elongates the wellbore parallel to σ_{Hmin} (Figure 4). Breakouts are best displayed on borehole imaging logs, but logging tools possessing oriented calipers (e.g., dipmeter logs) are also suitable for documenting breakouts. As such, vertical wells in the study area possessing image logs and dipmeter logs were sought for analysis in this project.

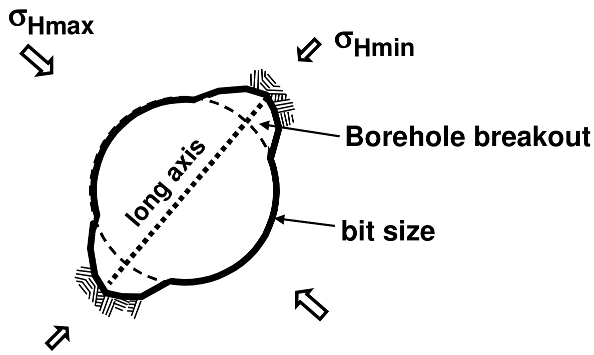

Figure 4. Orientation of a borehole breakout in a vertical well indicates the direction of the minimum horizontal stress.

5 RESULTS

5.1 Vertical Stress Magnitude

Figure 5 shows a contour map of vertical stress magnitude at the top of the Viking Formation. This general trend is consistent with burial depth (see Figure 1). Vertical stresses are highest - around 27 MPa – where burial depth is greatest. This occurs near the southwestern corner of the study area, in the structural low that exists between the Battle-Creek Anticline and the Swift Current Arch. Vertical stresses are lowest - under 10 MPa - at the northern edge of the study area (in the North Battleford – Lloyminster area), where burial depths are relatively shallow.

Although not shown in this paper (see Hamid (2008) for additional contour maps), the vertical stress gradient at the top of the Viking Formation was also calculated and mapped. In this project, stress and pressure gradients were calculated as secant gradients. For example, vertical stress gradients were calculated as follows:

$$\mathrm{Grad}[\sigma_V] = \frac{\sigma_V}{vertical \quad depth} \qquad [3]$$

The results obtained show a slight decrease is vertical stress gradient – from roughly 22.2 kPa/m to 20.2 kPa/m - from west-southwest to east-northeast across the study area, indicating a slight decrease in overburden density. This is consistent with the trend observed in the Alberta Basin by Bachu and Michael (2002).

5.2 Minimum Horizontal Stress Magnitude

A contour map of minimum horizontal stress magnitudes interpreted from fracture stimulation data in the Viking Formation is shown in Figure 6. It is more difficult to identify trends in this dataset, due to the uneven data coverage. However, it is apparent that depth exerts a strong control on σ_{Hmin}. Maximum values in the 16 to 19 MPa range occur near the southwest corner of the study area, where depths are greatest, while minimum values in the 9 to 10 MPa range occur at the northern edge of the study area.

It is significant to note that the minimum horizontal stress magnitudes are less than the vertical stress magnitudes throughout the entire map, which is consistent with the expectation that σ_{Hmin} is the least principal stress in the study area.

A contour map of minimum horizontal stress gradients (presented in Hamid (2008), but not shown in this paper) show that these gradients generally fall in the 18 to 21 kPa/m range throughout the northern half of the study area, and in the 14 to 17 kPa/m range near the southern edge. Two possible reasons for the relatively low stress gradients in the south are proposed, as follows:

1. All else being equal, shales and shaley rocks tend to have higher horizontal stresses than sandstones (e.g., Warpinski et al., 1989). This is generally attributed to the higher Poisson's ratios of clay-rich rocks, relative to sandstones. As noted by Christopher et al. (1971), there is a facies change in the Viking Formation from southwest to northeast, from a relatively thick succession of predominantly sandy strata to a much thinner Viking sequence containing siltstone and mudstone elements. This lithology change might account, in part, for the higher stress gradients observed in the north-northwest part of the map area. More investigation of lithologies and rock mechanical properties throughout the map area is required to assess this effect more thoroughly.
2. It is well established, both theoretically and from field data (e.g., Addis 1997; Soltanzadeh and Hawkes 2007), that relatively low pore pressures are a common cause of low horizontal stress magnitudes. Given that data exist for hundreds, if not thousands, of well tests in the Viking Formation in the study area, it would be possible to compile these results and map pore pressures throughout the study area. Due to time constraints, however, it was not possible to do so during this investigation. Given that a comprehensive investigation of pore pressures in the Mannville Group has been conducted by Christopher (2003), this dataset was used for a preliminary investigation of the relationship between pore pressure and horizontal stress in the Viking Formation. The use of Mannville pore pressure data to assess stresses in the Viking Formation may be justified, in part, by Christopher's (2003) interpretation that hydraulic communication between the Mannville and underlying strata occurs through faults and fractures in parts of southern Saskatchewan. In spite of this justification, comparison of Christopher's (2003) pore pressures and this study's σ_{Hmin} magnitudes does not reveal any systematic relationship. In fact, Mannville pore pressure gradients in the southern part of the study area are relatively high (e.g., 7 to 10 kPa/m) in the southern part of the study area compared to values in the northern part (6 to 8 kPa/m). This is opposite to the trend in σ_{Hmin} gradients. Future study of pore pressures in the Viking Formation itself would be required to more confidently refute or confirm a relationship between pore pressure and σ_{Hmin}.

5.3 Maximum Horizontal Stress Magnitude

No suitable data for estimating the value of σ_{Hmax} were found within the study area. The only remotely relevant σ_{Hmax} values reported in the literature (Bell et al., 1994) were interpreted from two micro-frac tests conducted in the Cambrian-age Deadwood Formation at depths of 2168 m and 2213 m in Regina (well location 3-8-17-9W2). For these two tests, σ_{Hmax} values were, on average, 1.33 times larger than σ_{Hmin} and virtually equal to (i.e., 0.99 times) σ_V. These data are consistent with a present-day stress regime that is transitional between strike-slip and normal faulting. This is somewhat consistent with stress regime information interpreted by Gendzwill and Stauffer (2006). Based on seismic data obtained in the vicinity of the potash mine near Colonsay, Saskatchewan (which is east of the study area), they reported numerous normal faults at shallow depths (< 400 m) which they attribute to Tertiary through Quaternary extensional tectonics.

Given that the study area is slightly closer to the Rocky Mountains than the Regina test well and the Colonsay mine site, it is suggested that the σ_{Hmax}:σ_{Hmin} ratio should be slightly higher than 1.33, which would generally result in σ_{Hmax} magnitudes that are close to - but slightly greater than - σ_V magnitudes.

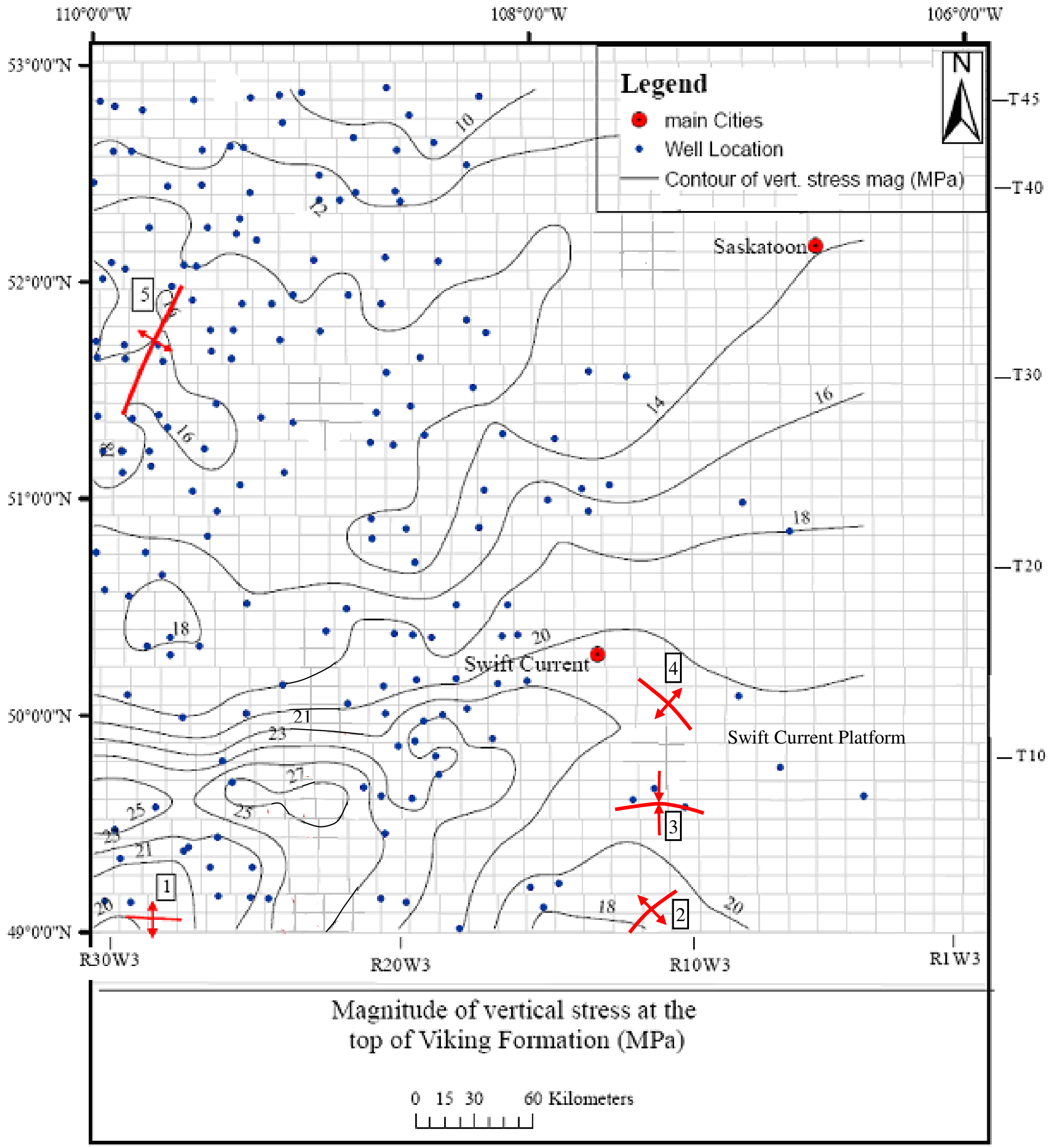

Figure 5. Vertical stress magnitude at the top of the Viking Formation. Basement tectonic features (after Christopher et al., 1971) are: (1) Battle Creek Anticline, (2) Val-Marie Arch, (3) Ponteix Syncline, (4) Swift Current Arch, and (5) Sweetgrass-North Battle Arch.

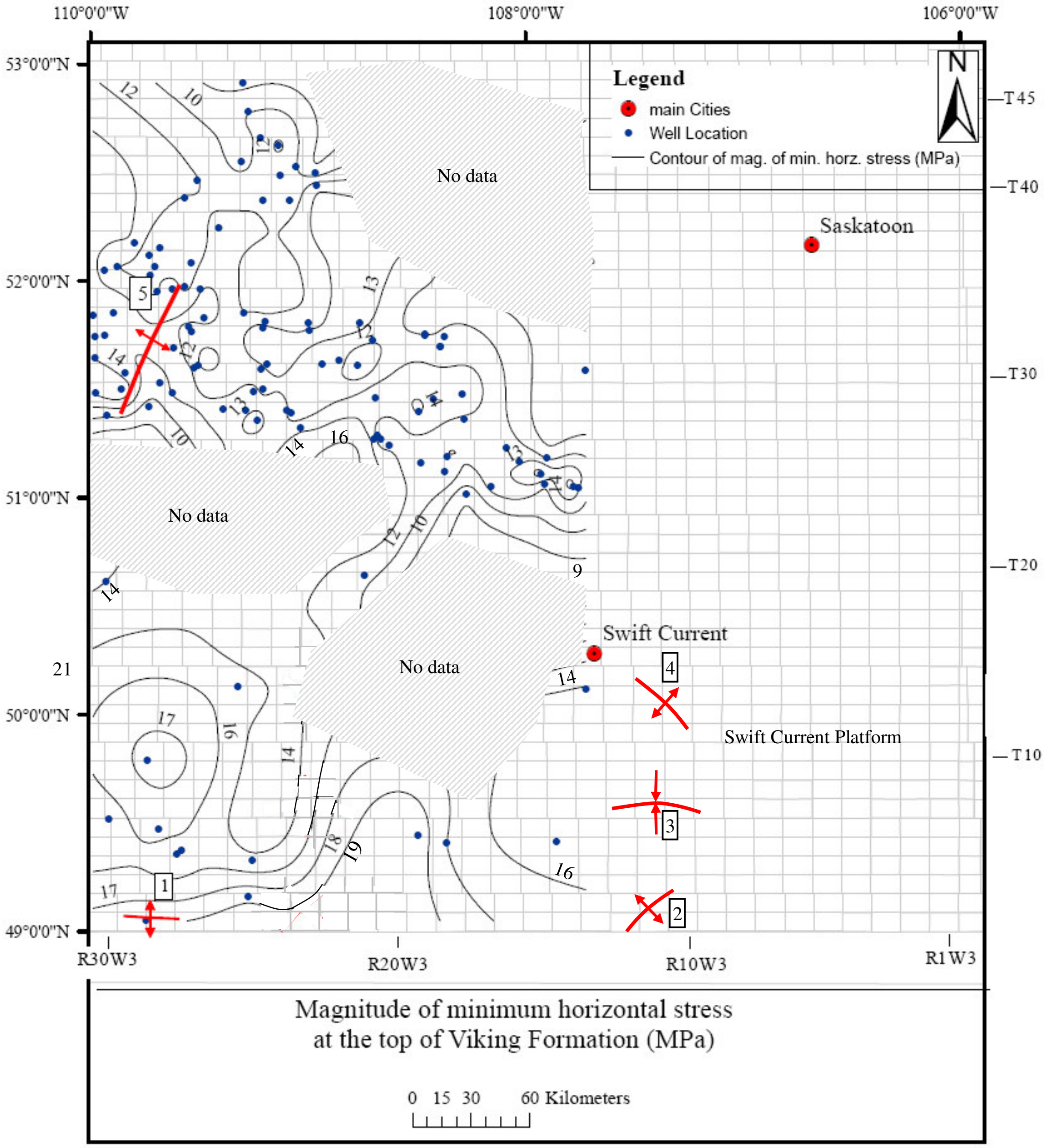

Figure 6. Minimum horizontal stress magnitude at the top of the Viking Formation. Basement tectonic features (after Christopher et al., 1971) are: (1) Battle Creek Anticline, (2) Val-Marie Arch, (3) Ponteix Syncline, (4) Swift Current Arch, and (5) Sweetgrass-North Battle Arch.

5.4 Horizontal Stress Orientations

Six measurements of horizontal stress orientation in the study area were previously reported by Bell et al. (1994). During this project, five new measurements were interpreted from Formation MicroImager (FMI) logs retrieved from the well-file library of Saskatchewan Energy and Resources in Regina. Two additional stress orientations interpreted by Husky Energy were also provided to the investigator. Table 2 and Figure 7 summarize these stress orientation measurements. The average minimum horizontal stress orientation is 137º, with a circular standard deviation of 12º. In other words, the general trend of σ_{Hmin} in the study area is northwest-southeast, which (as expected) is parallel to the trend of the Rocky Mountains. Maximum horizontal stress orientations (which represent the directions in which inducted hydraulic fractures would propagate) are rotated 90° from the σ_{Hmin} orientations given.

The results obtained in this project are consistent with horizontal stress orientations inferred from the analysis of natural fractures, as reported by Stauffer and Gendzwill (1987). They studied fracture systems in late Cretaceous to late Pleistocene strata in Saskatchewan, and found a consistent pattern of orthogonal fractures trending northeast-southwest and northwest-southeast. They attributed the origin of the fractures to uplift and tectonically derived stresses

Table 2. Orientation of minimum horizontal stresses in southwest Saskatchewan.

UWI	σ_{Hmin} Azimuth	Source
06-28-04-27W3	100°	Bell et al. (1994)
11-05-05-27W3	127°	Bell et al. (1994)
16-07-09-18W3	143°	Bell et al. (1994)
06-01-21-19W3	124°	Husky Energy
16-30-22-17W3	170°	Husky Energy
10-28-28-24W3	142°	FMI log
09-06-35-26W3	151°	Bell et al. (1994)
02-16-36-28W3	144°	FMI log
11-36-38-27W3	137°	Bell et al. (1994)
12-05-39-26W3	137°	Bell et al. (1994)
09-29-42-25W3	118°	FMI log
06-07-43-24W3	163°	FMI log
21-10-52-23W3	121°	FMI log

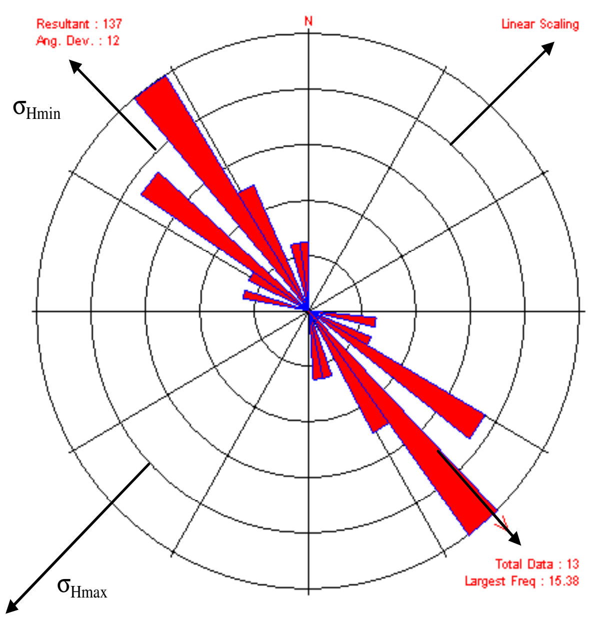

Figure 7. Roseplot of minimum horizontal stress orientations in southwest Saskacthewan.

6 SUMMARY AND CONCLUSIONS

Vertical in-situ stress magnitudes at the top of the Viking Formation were calculated using bulk density logs from 179 wells distributed throughout southwest Saskatchewan. The results show that vertical stress magnitudes are dominantly controlled by present-day burial depth. Vertical stresses are highest - around 27 MPa – in the structural low that exists between the Battle-Creek Anticline and the Swift Current Arch. Vertical stresses are lowest - under 10 MPa - at the northern edge of the study area. A slight reduction in vertical stress gradients occurring west-southwest to east-northeast across the study area suggests that decreasing overburden densities have a secondary effect on vertical stresses.

Work conducted for this project has shown that minimum horizontal stresses can be estimated in the study area by multiplying the instantaneous shut-in pressure measured during a hydraulic fracture stimulation by a factor of 0.9. Results were obtained by this method for 106 wells in the study area. Although the data coverage is less extensive and uniform that the vertical stress dataset, it is apparent that depth also exerts a strong control on minimum horizontal stress magnitudes. Maximum values in the 16 to 19 MPa range occur near the southwest corner of the study area in the above-noted structural low, while minimum values in the 9 to 10 MPa range occur at the northern edge of the study area. Minimum horizontal stress gradients appear to be lower in the southern part of the study area. Possible explanations for this difference include lithological changes and subnormal pore pressures, but neither has been investigated in depth or confirmed at this time.

No suitable data for estimating maximum horizontal stress magnitudes were found in the study area. Based on results published for south-central and southeast Saskatchewan, and given the tectonic setting of the current study area, it is suggested that σ_{Hmax}:σ_{Hmin} ratios should be slightly more than 1.33. This would generally result in σ_{Hmax} magnitudes that are close to – but slightly greater than - σ_V magnitudes. As such, the stress regime for the study area is interpreted to be a strike-slip fault regime; albeit near the normal fault / strike-slip fault regime transition.

Based on six previously published measurements and seven new measurements obtained in this study, the average minimum horizontal stress orientation in southwest Saskatchewan is 137º; i.e., the general trend of σ_{Hmin} is northwest-southeast, which (as expected) is parallel to the trend of the Rocky Mountains.

ACKNOWLEDGEMENTS

The authors would like to thank the Petroleum Technology Research Centre for funding this project, and the following individuals for their help and support: Robert Hawkes and Keri Yule of BJ Services Canada, Pat McLellan of Advanced Geotechnology, Melinda Yurkowski of Saskatchewan Energy and Resources, Craig Lamb of Husky Energy, and Mel Stauffer, Doug Milne and Jitendra Sharma of the University of Saskatchewan.

REFERENCES

Addis, M.A. 1997. The stress-depletion response of reservoirs, SPE Paper 38720, *Proceedings of the SPE Annual Technical Conference and Exhibit*, San Antonio, USA: 55-65.

Bachu, S. and Michael, K. 2002. *Hydrogeology and Stress Regime of the Upper Cretaceous-Tertiary Coal-bearing Strata in Alberta*, EUB/AGS Earth Sciences Report 2002-04, Alberta Geological Survey, Edmonton, Canada.

Bell, J.S. 2003. Practical methods for estimating in situ stresses for borehole stability applications in sedimentary basins, *Journal of Petroleum Science and Engineering*, 38: 111-119.

Bell, J.S., Price, P.R. and McLellan, P.J. 1994. In-situ stress in the Western Canada Sedimentary Basin, *Chapter 29 - Geological Atlas of the Western Canada Sedimentary Basin*, comp. G.D. Mossop and I. Shetsen, Canadian Society of Petroleum Geologists and Alberta Research Council, Calgary, Canada: 439–446.

Christopher, J.E. 2003. *Jura-Cretaceous Success Formation and Lower Cretaceous Mannville Group of Saskatchewan*, Report 223, Saskatchewan Industry and Resources Geo-Publications, Regina, Canada.

Christopher, J.E., Kent, D.M. and Simpson, F. 1971. *Hydrocarbon Potential of Saskatchewan*, Saskatchewan Energy and Mines, Report 157, Saskatchewan Industry and Resources Geo-Publications, Regina, Canada.

Cinco, H. and Samaniego, F. 1981. Transient Pressure Analysis for Fractured Wells, *Journal of Petroleum Technology*, 33(9): 1749-1766.

de Bree, P. and Walters, J.V. 1989. Micro/minifrac test procedures and interpretation for in situ stress determination, *International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts*, 26: 515–521.

Fenton, M.M., Schreiner, B.T., Nielsen, E. & Pawlowicz, J.G. 1994. Quaternary geology of the western plains, *Chapter 26 - Geological Atlas of the Western Canada Sedimentary Basin*, ed. G. Mossop & I. Shetsen, Canadian Society of Petroleum Geologists, Calgary, Alberta & Alberta Research Council, Edmonton, Canada.

Gendzwill, D. and Stauffer, M. 2006. Shallow faults, Upper Cretaceous clinoforms, and the Colonsay Collapse, Saskatchewan, *Canadian Journal of Earth Science*, 43: 1859-1875.

Hamid, O. 2008. *In-Situ Stress Analysis of Southwest Saskatchewan*, M.Sc. Thesis, University of Saskatchewan, Saskatoon, Canada.

Hubbert, M.K. and Willis, D.G. 1957. Mechanics of hydraulic fracturing, *Transaction of the American Institute of Mining, Metallurgical, and Petroleum Engineers*, 210: 153-166.

Meyer and Associates. 2006. *Meyer Fracturing Simulators*, 4th edition, Meyer and Associates, Inc., Natrona Heights, PA, USA.

Plumb, R.A. and Hickman, S.H. 1985. Stress-induced borehole elongation: A comparison between the four-arm dipmeter and the borehole televiewer in the Auburn geothermal well, *Journal of Geophysical Research*, 90(B7): 5513-5521.

Soltanzadeh, H. and Hawkes, C.D. 2007. Predicting the stress changes induced by fluid production and injection in porous reservoirs, *Rock Mechanics - Meeting Society's Challenges and Demands: Proceedings of the 1st Canada-US Rock Mechanics Symposium*, Vancouver, BC: 1609-1616.

Stauffer, M.R. and Gendzwill, D.J. 1987. Fractures in the northern plains, stream patterns, and mid-continent stress, *Canadian Journal of Earth Science,* 24, 1086-1097.

Warpinski, N.R. 1989. 'Elastic and viscoelastic calculations of stresses in sedimentary basins, *SPE Formation Evaluation*, 4(4): 522-530.

Zoback, M.D., Barton, C.A., Brudy, M., Castillo, D.A., Finkbeiner, T., Grollimund, B.R., Moos, D.B., Ward, C.D. and Wiprut, D.J. 2003. Determination of stress orientation and magnitude in deep wells, *International Journal of Rock Mechanics & Mining Sciences*, 40: 1049-1076.