Tectonic Interpretation Using Potential Field Data for the Sweetgrass Arch Area, Montana-Alberta, Saskatchewan

Clark Jorgensen
Big Sky Geophysics, Bozeman, Montana

ABSTRACT

I performed a basement tectonic interpretation for the Sweetgrass Arch area using public domain gravity and magnetic data from the USGS and Geological Survey of Canada (GSC). This study is timely because of a recent acquisition of data by the GSC and releveling of data by the USGS. The Sweetgrass Arch area's sedimentary geology and hydrocarbon distribution are strongly influenced by the basement fault structure. Even small offsets in the basement structure can generate hydrocarbon traps by creating structural or stratigraphic traps in the overlying sediments. I mapped the basement geology using the geophysical data, compare it to known oil and gas pool locations, and use this information to pick prospective areas for future exploration.

Clear association between the gravity and magnetic patterns and known oil and gas pools is observed. In some cases there is a direct correlation between major faults and hydrocarbon occurrences while in other cases these faults may be used to bound areas that are prospective to exploration. Some uplifts in the basement topography are evident in the gravity data as local highs and can be used to target structural traps. The magnetic data are most effective for mapping the faults and the gravity data are most effective for mapping uplifts.

Introduction

The area of interest straddles the provinces of Saskatchewan and Alberta and the state of Montana (**Fig. 1**). For simplicity, I call the area the Sweetgrass Arch area although the area is a large structural complex and may be divided into smaller geologic features including the Sweetgrass Arch, Bowdoin Dome, Bow Island Arch, and the Swift Current Platform. This complex area is significant because it has generally functioned as an uplift over geologic time separating the Alberta Basin from the Williston Basin (e.g. Wright, et. al., 1994).

Recently available data from the GSC and the USGS make this study timely. The USGS has releveled the regional airborne magnetic survey data in Montana (McCafferty, et al., 1998) greatly improving its quality and the GSC has newly acquired aeromagnetic data along the southern Alberta and Saskatchewan borders (Geophysical Data Centre, 2004). Also, the Saskatchewan Department of Energy and Mines and the GSC have recently processed and leveled numerous gravity surveys completed by industry in southern Saskatchewan (Miles, et al., 2000).

Figure 2 shows the major structural features based on a surface and structure map of the top to the Mississippian aged Madison Group. Faults are indicated by black lineaments, anticlines in red and synclines in blue. Areas where the Madison Group pinches out because of uplifts or intrusions are marked in black. The features were mapped based on well logs of drill holes that reached the Madison Group. The crystalline basement is composed of several different geologic provinces that have been either sutured together or accreted onto each other by continental collisions. The area has historically produced numerous economic oil and gas pools (**Fig. 3**) and continues to be an area of active exploration. Figures 2-8 are all drawn at the same scale and cover the area shown in Figure 1 for easy comparison.

Method

Data sources for the project area include aeromagnetic data flown by the USGS and the GSC and gravity stations collected by the USGS, GSC, and industry surveys that have been compiled by the GSC. The aeromagnetic data of the GSC are significantly better than the USGS data having been flown at tighter line spacing, flown closer to the earth, and most are digitally acquired. The GSC and USGS gravity databases are roughly of equal quality although data density is somewhat higher in the USGS data. The industry gravity data in southern Saskatchewan is roughly sampled at 10 times higher density than the GSC data but there are some problems with leveling the data to the combined USGS-GSC database.

I assume all magnetic and gravity responses are caused by features of the bedrock geology because density and magnetic susceptibility contrasts within the sedimentary section are small. The sedimentary rocks only generate small variations in magnetic and gravitational responses because they are of nearly uniform thickness and nearly horizontal. Density contrasts in the basement probably range from 2.6 to 3.2 g/cm3 (felsic to mafic units) and susceptibility contrasts probably range from 0.0001 to 0.02

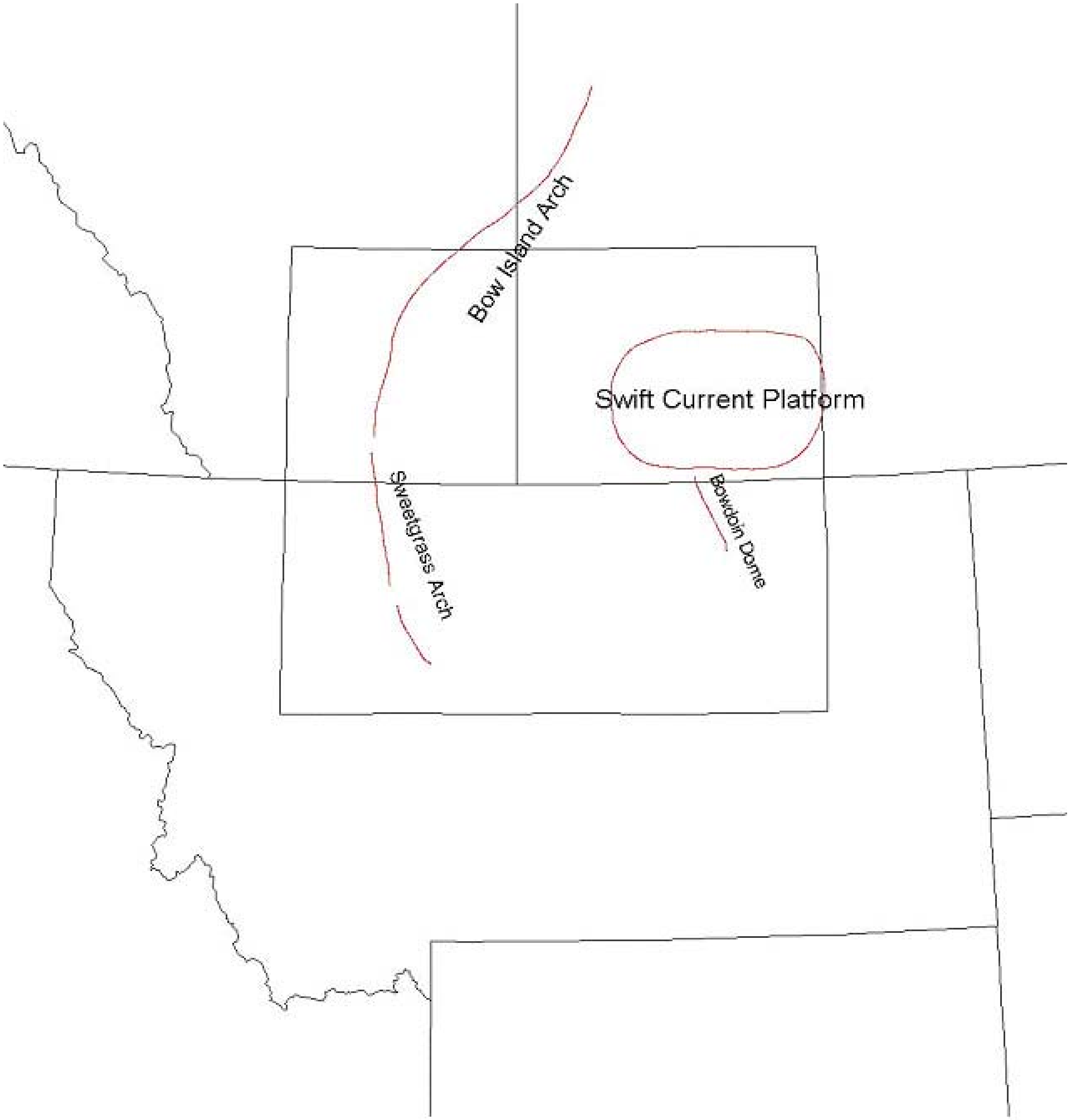

Figure 1. Sweetgrass Arch area on the Canadian-US border. The approximate locations of the Sweetgrass Arch, Bow Island Arch, Bowdoin Dome, and Swift Current Platform are indicated.

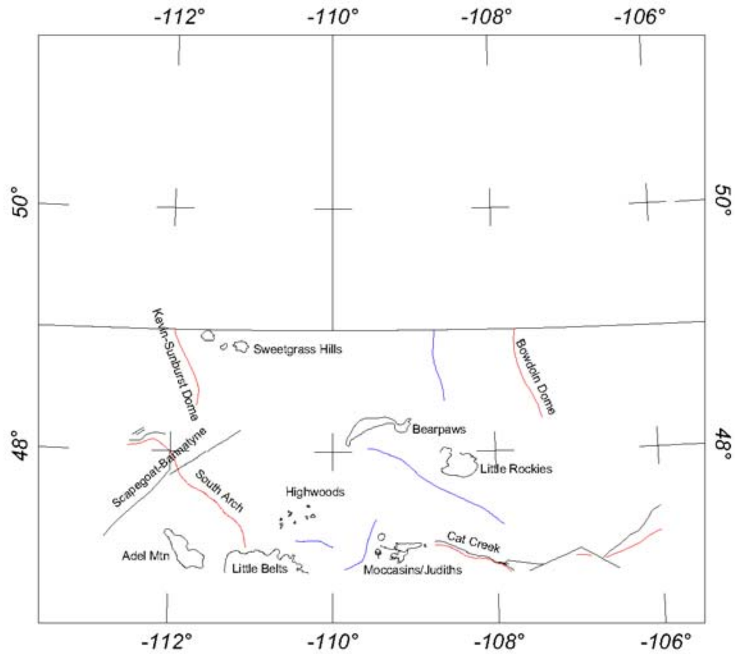

Figure 2. Structural features derived from mapping the top of the Madison Group in Montana. Intrusives that penetrate the Madison Group are outlined in black and named. Antiforms are colored in red and synforms in blue.

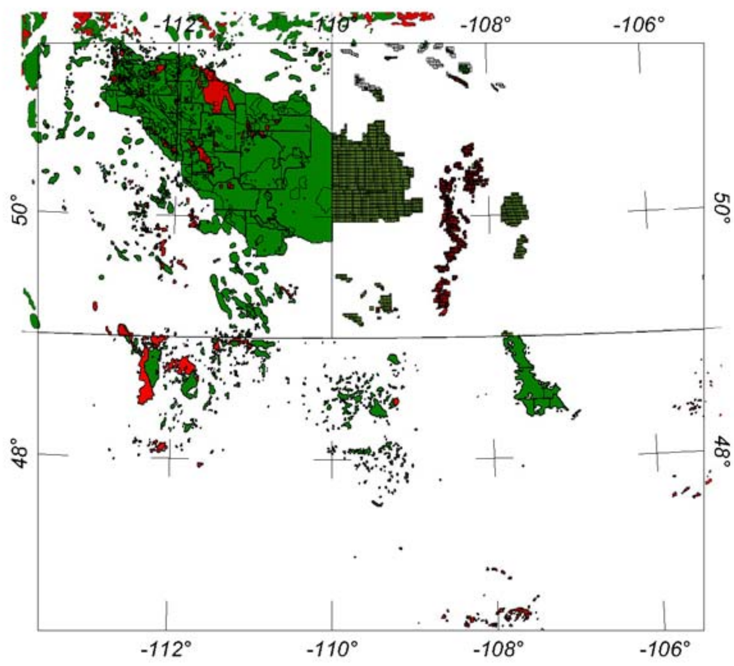

Figure 3. Oil (red) and gas (green) pools.

(felsic to mafic units, cgs units). Because of the large contrast in susceptibility values, the magnetic patterns in the data are most useful for mapping units in the Precambrian basement. Contrasts in the gravity data may be caused by different rock types or by relative changes in depth to the basement.

As a general interpretation technique, I first examine the total field magnetic and simple Bouguer anomaly maps and compare them to known geology. I then calculate the first vertical derivative of the magnetic and gravity fields. The calculated first vertical derivative is a mathematical high pass filter designed to accentuate the more detailed features. The vertical derivative of the magnetic data are used to create a structure map by marking the highs regardless of amplitude. This method accentuates the fabric of the data rather the magnitude of the responses. Offsets and other discontinuities are inferred where there are breaks in the responses. I then compare the marked offsets and discontinuities with the gravity and magnetic maps. If the offsets and discontinuities in the vertical derivative magnetic map concur with changes in the total magnetic intensity or simple Bouguer anomaly maps, I assume a major structural contact or fault exists. These contacts and faults may represent small offsets in the basement which control sedimentation patterns. The sedimentation patterns may include facies changes which can form excellent stratigraphic traps.

The gravity data are examined for relative highs. Gravity highs may reflect relative highs in the basement topography and potential domes in the sedimentary section. Since the interior of North America acted as an inland ocean for a significant portion of its history, the small vertical offsets may localize the formation of reefs. The simple Bouguer anomaly processing does not account for the gravitational effects caused by topography and isostatic effects caused by mountain ranges. Therefore, I calculate the first vertical derivative of the Bouguer anomaly to remove these effects.

Data

Figure 4 shows the total magnetic intensity field for the area of interest. Several important features are readily apparent. Intrusives have a characteristic circular pattern of moderate amplitude varying from high to low. Major lineaments have high amplitudes and continue in a straight line. Different geologic provinces in the basement structure may be recognized using the magnetic data. Each Precambrian province has its own characteristic magnetic fabric. These fabrics are identified by dominant trend directions, wavelengths of the features, and intensity of the anomalies. There is an obvious linear magnetic high-low-high pattern which corresponds with the Scapegoat-Bannatyne trend. North of this lineament, the magnetic fabric is relatively narrow and trends to the northwest while to the south, it is broader and trends to the northeast.

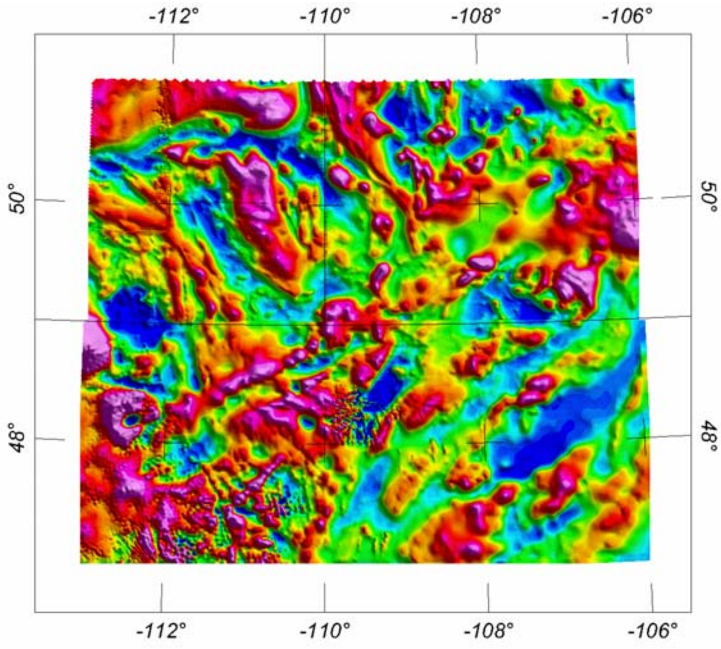

Figure 4. Total Magnetic Intensity map. High amplitudes are colored in pink and lows in blue. Shading has been added to enhance contrasts.

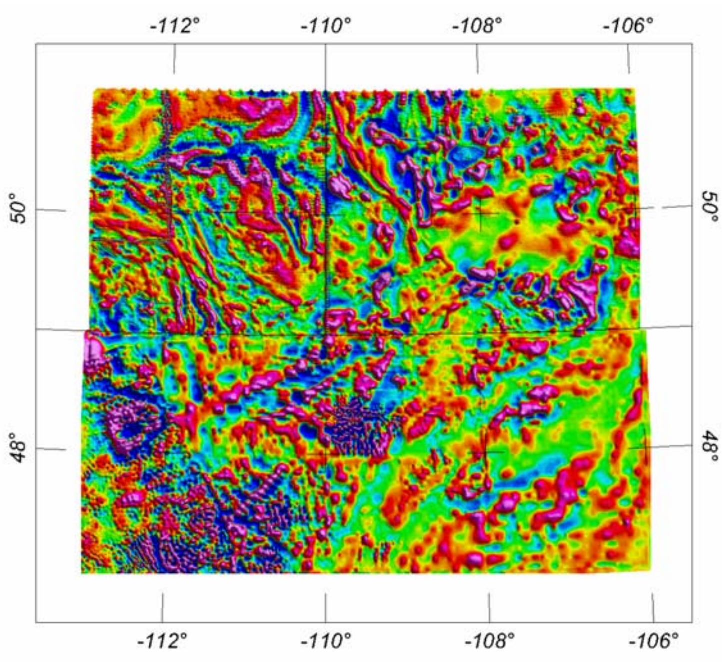

Figure 5. Calculated first vertical derivative of the total magnetic field data. High values are in pink and lows are in blue. Shading has been added.

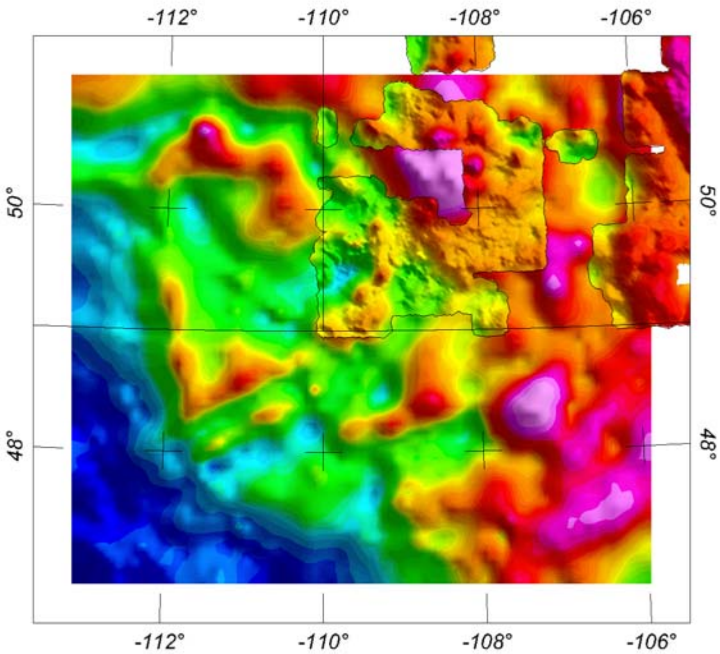

Figure 6. Simple Bouguer anomaly data with high resolution industry data inset into image. High values are in pink and lows in blue. Shading has been added.

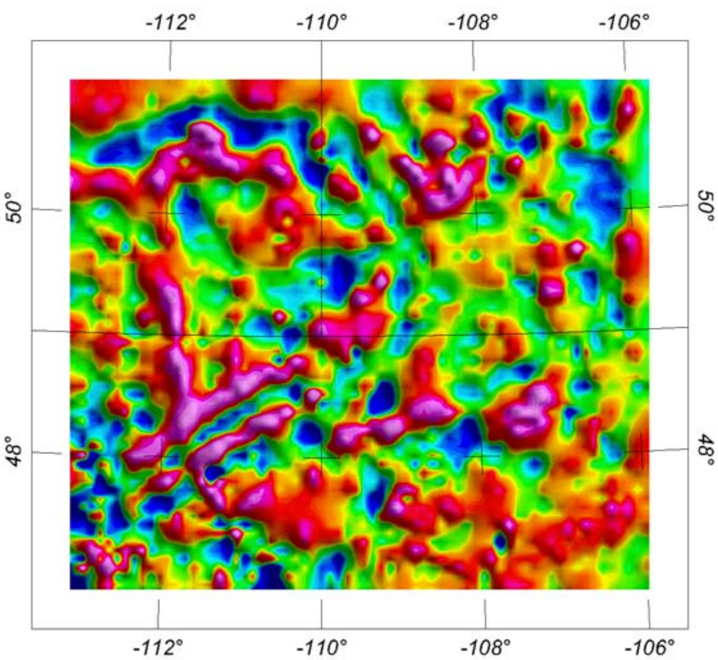

Figure 7. Calculated first vertical derivative of the regional Bouguer anomaly. High values are shown in pink and lows in blue. Shading has been added.

The simple Bouguer anomaly of the gravity field (**Fig. 6**) is also useful for determining geologic provinces and for mapping bedrock topography. The gravity data also have a high-low-high linear feature which is coincident with the location of the Scapegoat-Bannatyne Lineament. The higher resolution industry data set is inset into the image. A strong negative gradient trending to the southwest towards the fold and thrust belt is readily apparent. This low is partially caused by topographic and isostatic effects but is also caused by the Belt-Purcell Basin. The gravity low to the south is caused by the Helena Embayment of the Belt-Purcell Basin.

Interpretation

Figure 8 shows the major interpreted features compiled from the data sources. The dominant feature is the Great Falls Tectonic Zone. O'Neill and Lopez (1986) mapped a northeast trending series of faults which they named the Great Falls Tectonic Zone. They postulated this trend marked the boundary between the Wyoming Craton and the Hearne Province (Medicine Hat Block). I believe the Scapegoat-Bannatyne Lineament is the boundary between these two provinces because it has the classical geophysical signature of coupled magnetic and gravity highs and lows that characterize a geologic domain boundary (Wellman, 1998). It is probably a suture between the Medicine Hat Block and the Wyoming Craton. The other major trend in this area is the curvilinear Vulcan Low which has been examined previously in other studies (e.g. Ross, et al. 1991). This feature was originally believed to be a rift but now most researchers think it is a suture between two blocks of the Hearne Province (e.g. Villeneuve, et al. 1993, Hoffman, 1989). The final Precambrian province is the Trans-Hudson Orogen to the east. I believe this body has been significantly offset by sinistral movement along the Scapegoat-Bannatyne Lineament.

There are 11 intrusives or uplifts marked on the map. Seven of these objects are related to mountains or hills and are labeled as such. The mountains with smaller areal extent (Sweetgrass Hills, Moccasins/Judiths, and Little Rockies) have only subtle or no geophysical expression. These intrusives probably are not represented because the flight line spacing was too coarse to identify them. The intrusive labeled "Swiftcurrent" does not outcrop but has been identified as a Precambrian group of intrusives and volcanics by drilling (Burwash, et al., 1994). This intrusive may explain why the Swiftcurrent platform has historically acted as an uplift between the Alberta and Williston basins. Finally I have marked three features as "Unknown." I believe the two western bodies may be mafic intrusives and the eastern body may be a felsic intrusive. All of these intrusives probably occur near the Scapegoat-Bannatyne Lineament because the lineament represents a zone of weakness in the earth's crust.

I have also marked what I believe to be the major faults

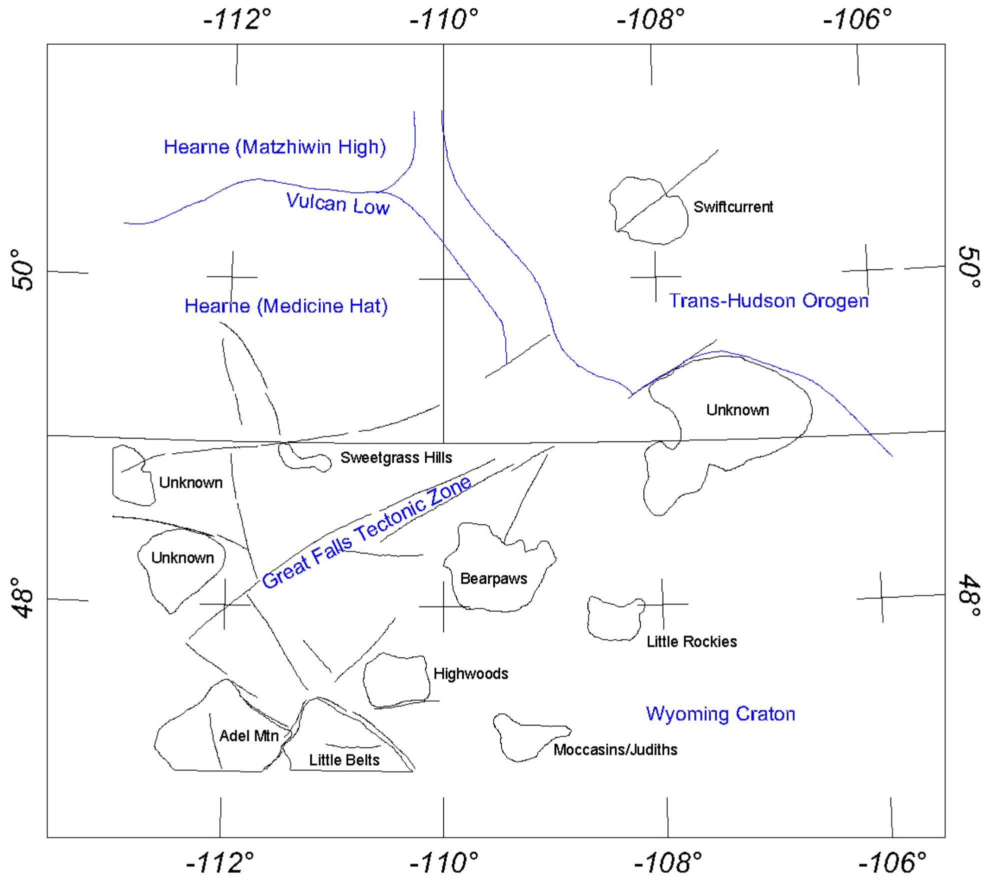

Figure 8. Interpretation of major structural features. Known mountain ranges and intrusives are outlined in black and labeled with the appropriate name. Three additional possible intrusives are marked and labeled "Unknown." Interpreted faults are marked in black. Precambrian provinces are marked and labeled in blue.

in this area. Most of the faults appear to be associated with the Scapegoat-Bannatyne Lineament. The exception is a series of northwest trending faults which mark the northern margin of the Helena Embayment. The mapped faults place important controls on the occurrence of hydrocarbons in the area. The extensive gas fields of the Alberta Basin stop abruptly at the Trans-Hudson orogen. No Alberta Basin oil or gas pools occur south of the Scapegoat-Bannatyne Lineament. None of the oil and gas pools associated with the Bearpaw Uplift extend north of the Scapegoat-Bannatyne Lineament. The oil and gas pools of the Kevin-Sunburst Dome are confined between two east-west trending faults. In other cases, it appears oil and gas pools are oriented along secondary faults discernable in the magnetic data but not marked on the map.

The gravity data can also be used to locate oil and gas pools, but not as reliably as using the magnetic data. There is clear association of gravity highs with the Sweetgrass Arch and Bowdoin Dome. Unfortunately there is also a gravity high associated with the Hogeland Basin (west of Bowdoin Dome). It is possible the gravity data are too coarsely spaced to identify domes associated with hydrocarbon pools. No conclusions can be drawn from the detailed industry data in eastern Saskatchewan because no oil or gas pools occur in this region.

Conclusions

Association between the gravity and magnetic patterns can be made with known oil and gas pools. By examining the potential field data, one can map faults and offsets in the basement geology. In some cases there is a direct correlation between major faults and hydrocarbon occurrences while in other cases these faults may be used to bound areas that are prospective for exploration. Some uplifts in the basement topography are evident in the gravity data as local highs and can be used to target structural traps.

While the public domain data effectively map the bedrock tectonic structure, additional gravity and airborne magnetic data would be useful. The Sweetgrass Arch area is a mature exploration target with a complex system of intrusives and faults. Additional higher resolution data would be useful for mapping more subtle features (and potentially more subtle hydrocarbon traps) in the bedrock topography. Also, incorporation of the potential field data interpretation with any seismic or drill hole data would be helpful.

References

Burwash, R.A., McGregor, C.R., and Wilson, J., 1994, Precambrian basement beneath the Western Canada Sedimentary Basin, in G.D. Mossop and I. Shetsen, comps., Geological atlas of the Western Canada Sedimentary Basin, http://www.ags.gov.ab.ca/publications/ATLAS_WWW/ATLAS.shtml.

Geophysical Data Centre, 2004, GSC data products: Geophysical Data Centre, Geological Survey of Canada, 1 Observatory Cresc., Ottawa, Ontario K1A 0Y3, Canada; http://nrcan.gc.ca/gsc/dataprod_e.php, as of February, 2004.

Hoffman, P.F., 1989, Precambrian geology and tectonic history of North America, in Bally, A.W. and Palmer, A.R., eds., The geology of North America - an overview, GSA, p. 447-495.

McCafferty, A., Bankey, V., Brenner, and K.C., 1998, Montana aeromagnetic and gravity map data, OFR 98-333, USGS Open File Report.

Miles, W.F., Roest, W.R., Kelley, L., Gent, M., 2000, Rationalized detailed gravity data southern Saskatchewan, OFR D3883, Geological Survey of Canada.

O'Neill, J.M., Lopez, D.H., 1985, Character and regional significance of the Great Falls Tectonic Zone, East-Central Idaho and West-Central Montana, AAPG Bulletin, v. 69, p. 437-447.

Ross, G.M., Parrish, R.R., Villeneuve, M.E., and Bowring, S.A., 1991, Geophysics and geochronology of the crystalline basement of the Alberta Basin, western Canada, Canadian Journal of Earth Science, v. 28, p. 512-522.

Villeneuve, M.E., Ross, G.M., Thériault, R.J., Miles, W., Parrish, R.R., and Broome, J., 1993, Geophysical subdivision and U-Pb geochronology of the crystalline basement of the Alberta Basin, Western Canada, Geological Survey of Canada, Bulletin 447.

Wellman, P., 1998, Mapping of geophysical domains in the Australian continental crust using gravity and magnetic anomalies, in J. Braun, J. Dooley, B. Goleby, R. van der Hilst, and C. Klootwijk, eds., Structure and evolution of the Australian continent, American Geophysical Union Geodynamics Series, v. 26, p. 59-71.

Wright, G.N., McMechan, M.E., Potter, D.E.G., 1994, Structure and architecture of the Western Canada Sedimentary Basin, in G.D. Mossop and I. Shetsen, comps., Geological atlas of the Western Canada Sedimentary Basin, http://www.ags.gov.ab.ca/publications/ATLAS_WWW/ATLAS.shtml.