Meteoric fluid isotopic signatures of thrust-fault-related veins in the Livingstone Range anticlinorium and their significance for syn-deformational regional fluid migration

Michael A. Cooley*, Raymond A. Price, John M. Dixon, and T. Kurtis Kyser
Department of Geological Sciences and Geological Engineering
Queen's University, Kingston, Kingston, ON, K7L 3N6
cooleym@students.geol.queensu.ca

ABSTRACT
$\delta^{13}C$ and $\delta^{18}O$ isotope values of calcite in veins and host rocks from thrust fault zones indicate that fluids with meteoric isotopic signatures were present along thrust faults and infiltrating the tip-lines of minor thrusts during the formation of fault-propagation folds in the Livingstone Range Anticlinorium of southwest Alberta. Isotope geochemistry of cross-fault veins indicates that formation fluids predominated within the transverse structures, implying that cross faults were not conduits for local downward infiltration of meteoric water.

Meteoric fluids must have been flowing eastward along the major thrust faults from a recharge area in the topographically higher hinterland to the west during formation of the thrust and fold belt. The incursion of meteoric waters coincided with hydrocarbon migration as indicated by hydrocarbon residues within thrust-fault-related calcite veins.

Introduction

The Livingstone Range of the southern Alberta foothills comprises the easternmost surface exposures of Carboniferous rocks in the southern Canadian Cordillera (*Fig. 1*). The Livingstone Range is an anticlinorium that developed where the Livingstone thrust cuts up-section in its hanging wall from a regional detachment in the upper Palliser Formation, through the overlying Mississippian Rundle Group and younger strata to an upper detachment within the Jurassic Fernie Formation. The anticlinorium comprises two to three adjacent fault-propagation fold anticlines which contain thrust faults that die out upwards into the cores of the folds. These blind thrusts increase in displacement down-dip and splay from the underlying Livingstone thrust which continues to the west in the subsurface and eventually links up with the basal detachment.

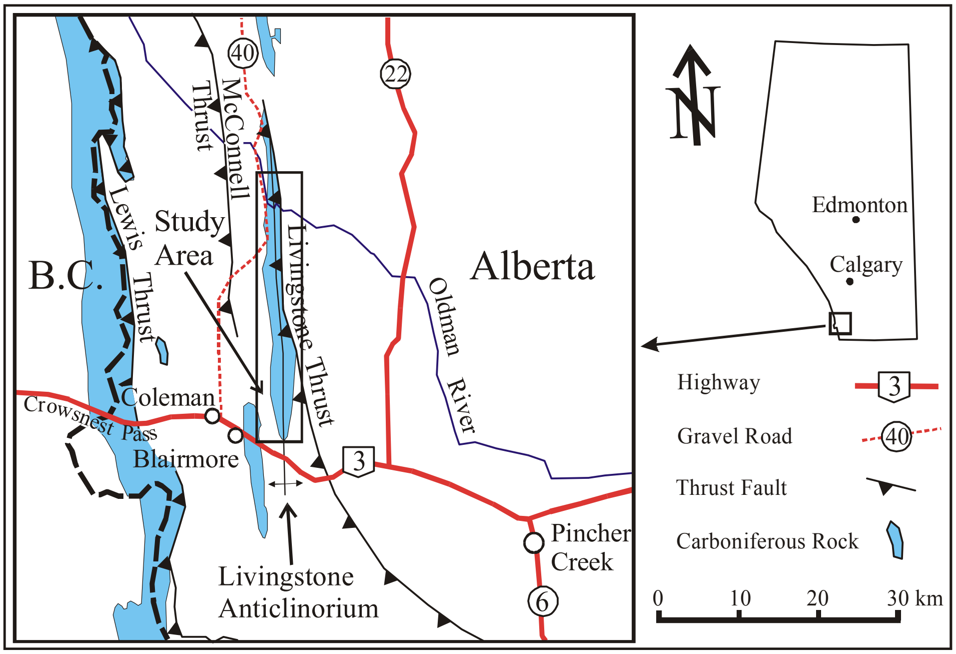

Fig. 1. Location map of the study area at the southern end of the Livingstone Range, southern Alberta foothills. The Livingstone Range is an anticlinorium comprising Carboniferous and younger rocks in the hanging wall of the Livingstone Thrust.

Thrust faults have long been considered as potential major conduits of fluid migration during deformation, and fluid migration is very likely a necessary feature that facilitates movement of faults.

Sibson and Poulsen (1988) have suggested that high angle reverse faults undergo movement by a fault-valve mechanism, where local fluid pressure builds until it reaches a critical pressure at which the fault fails, releasing or pumping the fluids along the fault zone. Although the work of Sibson and Poulsen (1988) deals with deep reverse faults in crystalline rocks, a similar behaviour is expected for the shallower thin skinned deformation of thrust and fold belts, where fluid pressures and movement along the thrust faults is also episodic and migratory.

The deformation associated with the formation of thrust and fold belts proceeds from hinterland to foreland, and the migration of fluids associated with this deformation has also been suggested to travel in the same direction. Previous workers have documented a west to east migration of fluids related to the eastward propagation of the deformation front of the foreland fold and thrust belt of the North American Cordillera.

Burtner and Nigrini (1994) identified a pulse of hot fluids that migrated from west to east through the foreland of the Idaho-Wyoming Thrust Belt during the Sevier Orogeny, locally raising the temperatures and initiating hydrocarbon maturation. Following this flushing of hot fluids was thrusting deformation which also migrated from west to east, progressively disturbing the hot hydrodynamic system and allowing the infiltration of meteoric waters which cooled the deforming rocks. This is indicated by the eastward-younging of apatite fission track cooling dates (Burtner and Nigrini, 1994).

The same pattern of west to east flushing of hot fluids has been outlined by Enkin et al. (1997) for the southern Canadian Cordillera. Enkin et al. (1997) document a west to east chemical remagnetization of paleomagnetic signatures of the rocks which they attribute to an eastward flush of warm fluids in front of the developing foreland fold and thrust belt.

Deep infiltration of meteoric waters in the Canadian Cordillera has been suggested by fluid inclusion and isotope work of Nesbitt and Muehlenbachs, 1995. Coal rank studies and fission track analyses of rocks below and above the Lewis thrust indicate that the >8 km thick Lewis thrust sheet was rapidly cooled by deep penetration of meteoric water during thrusting (Price et al., 2001).

Flow of meteoric fluids in a thrust belt begins in the topographically higher hinterland where faults exposed at surface allow deep penetration of surface waters which then infiltrate thrust faults and favourable bedding horizons. Because the foreland is topographically lower than the hinterland, the fluids are driven towards the foreland by the difference in topographic head (Hitchon, 1984), and perhaps also by the pumping action of the thrust faults (Sibson and Poulsen, 1988).

It is very likely that meteoric waters infiltrated the basal detachment and the interconnected system of thrust faults of the foreland fold and thrust belt very early during its formation. The meteoric waters would have migrated eastward along with the thrusts, perhaps penetrating as far as the tip lines of the thrusts as they were propagating.

Isotope Geochemistry Of Some Livingstone Range Samples

Preliminary results from 36 isotopic analyses are presented in *Figs 2 and 3*. *Fig. 2* shows the isotopic trend for samples collected from seven sites in and around thrust faults and from the core of the Centre Peak anticline. *Fig. 3* shows the results for samples collected from six cross faults.

For both figures, the isotope trend lines joining the host rocks with associated veins show a distinct pattern that readily distinguishes thrust-fault samples from those of cross-faults.

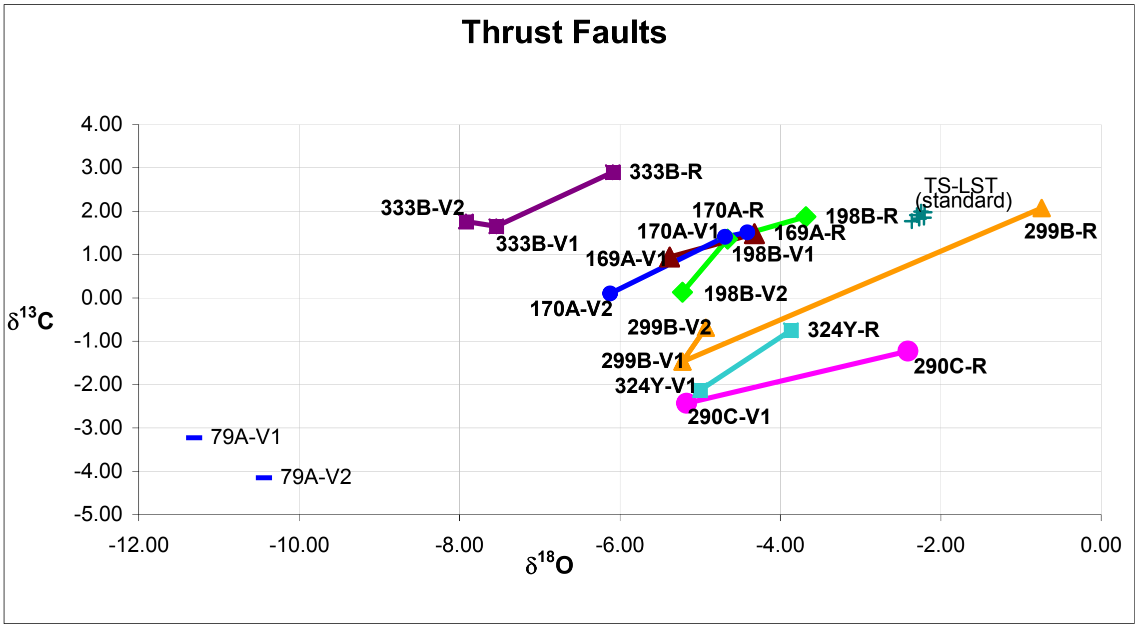

Fig. 2. Isotope data for samples collected from thrust-fault zones. All the vein isotopic signatures plot below and to the left of their respective host rocks, indicating host-rock-derived fluids mixed with meteoric waters to produce the calcite veins. The R at the end of the sample number indicates the host-rock sample. The V at the end of the sample number indicates vein material was analysed. V1 and V2 indicate an older vein (V1) cut by a younger vein (V2). Samples 79A-V1 and 79A-V2 (lower left of diagram) are included to illustrate a strongly meteoric signature from samples collected from an out-of-the-syncline thrust fault that cut through sandstones of the Fernie Formation in the Green Creek syncline.

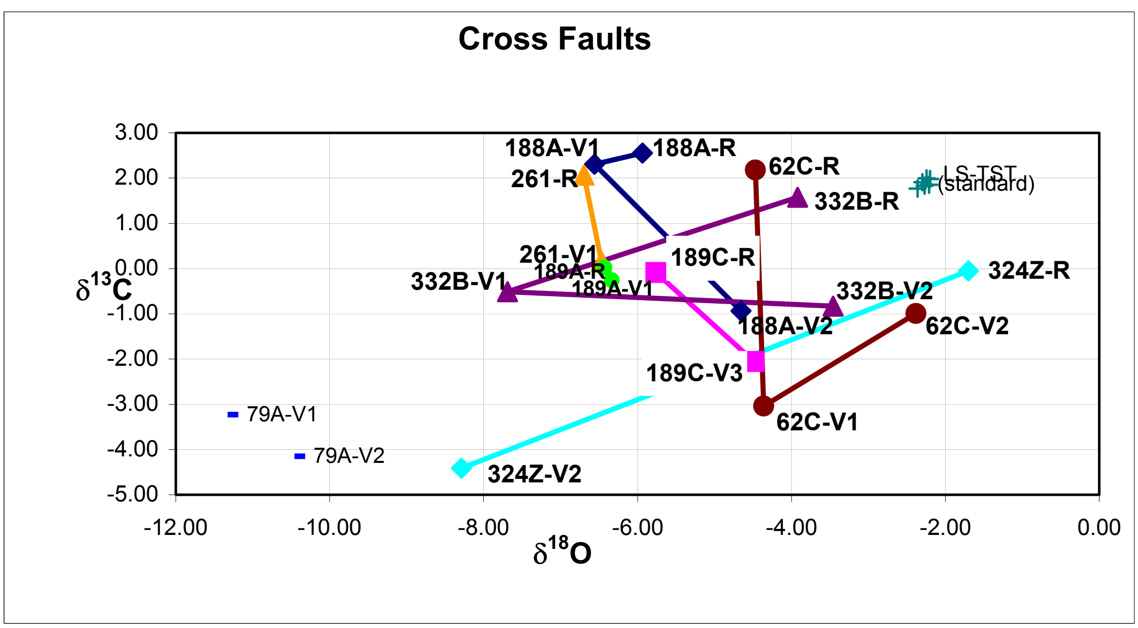

Fig. 3. Isotopic trends for samples collected from cross-fault zones. Veins within the cross faults tend to have an isotopic signature that is higher in $\delta^{18}O$ and lower in $\delta^{13}C$ than the host rock, indicating that the veins formed from a mixture of host-rock-derived fluids and formation waters. Samples 79A-V1 and 79A-V2 are included to illustrate a strongly meteoric signature.

Thrust fault samples are from calcite veins on fault surfaces and from veins in fractures within a few centimetres of the fault surfaces. These also include samples from within the core of the Centre Peak Anticline (samples 169, 170 and 198B), a fault-propagation fold with a blind thrust fault in its core. These three samples are from within a duplex structure with multiple vein sets that are related to duplex formation near the tip line of the blind thrust. All thrust-related veins (*Fig. 2*), including the Centre Peak back-thrust (sample 333B), contain vein calcite with isotopic signatures that suggest mixing occurred between a fluid derived from host rocks and a fluid of meteoric origin. The isotope values of the veins all plot down and to the left of their corresponding host rock isotopic values, along a line which trends towards the meteoric end of the system (*Fig. 2*).

Calcite veins from cross faults were also collected for isotope geochemical analysis. Cross faults include small faults that cut across the Centre peak anticline at regular intervals (150m) but that do not cut into the overlying Mount head Stratigraphy. They also include two samples from the Morin Creek tear fault that cuts across the Livingstone thrust sheet (samples 189C, 261). The overall trend for the cross-fault samples (*Fig. 3*) points down to the right, indicating mixing between fluids derived from the host rocks and typical formation fluids that were high in $\delta^{18}O$ and low in $\delta^{13}C$. For a few samples, the first vein set (V1) lies along a line that indicates a meteoric signature for infiltrating fluids during earlier deformation (samples 188A-V1 and 332B-V1), but these are cut by later V2 veins that have a formation-fluid signature. One exception is sample 324Z-V2 which is from a cross fault located at the Oldman River Gap, where the calcite from the cross fault likely formed from very late infiltration of local surficial meteoric water.

The difference in fluid sources between thrust faults and cross faults suggests that the two fault types did not share fluids with each other during formation of calcite veins.

Conclusions

The meteoric fluid trend for all samples from thrust fault zones indicates that meteoric fluids were present within the thrust faults during thrusting. The consistent meteoric signature of thrust-related calcite veins from the tip line area of the blind thrust fault in the core of the Centre Peak anticline implies that meteoric fluids were migrating at the very forefront of the deformation within the foreland fold and thrust belt.

Cross faults cut across thick stratigraphic packages, providing ideal conduits for infiltration of formation waters, and also provide an ideal plumbing system for hydrocarbon migration and trapping. The consistent difference between fluid sources for veins in thrust faults and for veins in cross faults is a good indication that the network of cross faults was not an open system. If veins in the cross faults had meteoric signatures, this would imply that meteoric fluids had migrated along the thrust faults and through the cross faults, a scenario which would have effectively flushed the system clean of formation fluids, including water and hydrocarbons. The formation fluid signatures of cross-fault veins identified by this study indicates formation fluids stayed in the system.

Further isotopic analyses of samples collected from zones where cross faults and thrust faults intersect will be conducted to determine the degree of fluid mixing between these faults.

The meteoric fluid source for the veins that formed within thrust-fault zones is most likely from a recharge area tens of kilometres to the west, where topographically high parts of the emerging Canadian Cordillera allowed deep penetration of meteoric water that infiltrated thrust faults and was flushed to the east along thrust surfaces during deformation (Hitchon, 1984). This regional fluid flow may have been responsible for regional epigenetic dolomitization, the formation of some early veins, the possible formation of Pb-Zn deposits (Nesbitt and Muehlenbachs, 1994), as well as accelerated hydrocarbon maturation and migration (Burtner and Nigrini,1994), and a chemical resetting of paleomagnetic signatures (Enkin et. al, 1997).

Acknowledgements

This research has been supported by NSERC research grants to Raymond Price and John Dixon. We gratefully acknowledge the financial assistance of the sponsors of the Fold Fault Research Group, the excellent field assistance of Greg Cameron, Scott Conley and Kyle Larson, and the access to well logs provided by Nexen.

References

Burtner, R. L. and Nigrini, A., 1994. Thermochronology of the Idaho-Wyoming Thrust Belt during the Sevier Orogeny: a new, calibrated, multiprocess thermal model. AAPG bulletin, v. 78, (10) p. 1586, 1612.

Enkin, R. J., Osadetz, K. M., Wheadon, P. M. and Baker, J., 1997. Paleomagnetic constraints on the tectonic history of the Foreland Belt., southern Canadian Cordillera: preliminary results. Canadian Journal of Earth Sciences, v. 34, p. 260-270.

Hitchon, B., 1984. Geothermal gradients, hydrodynamics, and hydrocarbon occurrences, Alberta, Canada. American Association of Petroleum Geologists Bulletin, v.68, p.
713-743.

Nesbitt, B. E. and Muehlenbachs, K., 1994. Paleohydrogeology of the Canadian Rockies and origins of brines, Pb-Zn deposits and dolomitization in the Western Canada Sedimentary Basin, Geology, v. 22, p. 243-246.

Nesbitt, B. E. and Muehlenbachs, K., 1995. Geochemistry of syntectonic, crustal fluid regimes along the Lithoprobe Southern Canadian Transect. Can Journ Earth Sci. 32: 1699-1719

Price, R. A., Osadetz, K. A., Kohn, B. P., Feinstein, S., 2001. Deep refrigeration of an evolving thrust and fold belt by enhanced penetration of meteoric water; the Lewis thrust sheet, southern Canadian Rocky Mountains. Abstracts with Programs - Geological Society of America, 33 (6), p. 52, 2001.

Sibson, R. H., and Poulson, K. H., 1988. High angle reverse faults, fluid pressure cycling, and mesothermal gold-quartz deposits. Geology, v. 16, p. 551-555.