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Constraining Foreland Belt thermal history using apatite fission track thermochronology and organic maturity: implications for Lewis Thrust, Flathead Fault and Waterton Gas Field in the Southern Canadian Cordillera

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Relationships between tectonics and thermal evolution influence chemical reactions, hydrodynamics, diagenesis, organic maturation, and thereby petroleum potential. The Canadian Rocky Mountain foreland thrust and fold belt is a prolific petroleum province. More than 900 Billion m^3 (~25.4 TCF) of in-place initial raw gas have been discovered (Stockmal et al., 2001). The Lewis-Eldorado-Hoadley thrust slab is one of the largest and farthest travelled thrust sheets in the Canadian Cordillera. It is >425 km long, has a maximum displacement of >90 km, and juxtaposes a very thick succession of Mesoproterozoic to Upper Cretaceous strata over late Campanian and older strata. Lewis thrust sheet has been folded by two younger antiformal thrust-duplex structures developed in underlying Phanerozoic carbonates. In the intervening Akamina syncline, the maximum preserved thickness of the thrust sheet is about 4 km (Price, 1962). The duplex structures contain large natural gas accumulations (Fermor and Moffat, 1992). Waterton Field, in the eastern duplex, is the largest field in the Canadian Rockies and one of the largest accumulations in Canada. It has an estimated ultimate in-place gas reserve of ~110 Billion m^3 (3.1 TCF), plus sulphur and condensate (Tippett et al., 1992). Eocene (and younger) normal faulting has created a unique opportunity to study the thermal evolution of Lewis thrust sheet and the rocks beneath it. Flathead fault is a listric southwest-dipping normal fault that merges at depth with Lewis thrust fault (McMechan, 1981, Constenius , 1996). Lower Cretaceous strata that are unconformably overlain by Eocene deposits in Flathead half-graben show that Lewis sheet succession was ~8 km thick, in the west limb of Akamina Syncline, when displacement began on Flathead fault. In the footwall of Flathead fault Upper Cretaceous strata are exposed in windows eroded through Lewis thrust. Petroleum exploration wells that penetrate these strata provide information on a Mesozoic and Paleozoic succession, about 4 km thick, which occurs in the western thrust-duplex structure beneath Lewis thrust. To the east, outcrops expose and wells penetrate the same succession. These wells and Flathead fault make possible the collection of fission track (FT) data from a section that was more than 12 km thick just prior to displacement on Flathead fault. Data from the same wells (courtesy Shell Canada Ltd.) indicate a present day geothernal gradient of 17^{o} C/km. All strata older than the half-graben fill have thermal maturities >0.7% vitrinite reflectance (VR).

Relationships between thrusting and the thermal history are enigmatic. The level of organic metamorphism in rocks below Lewis thrust sheet is much less than expected for the combination of time and depth of tectonic burial and the current geothermal gradient. Thrusting resulted in deep tectonic burial (>10 km, Price, 1994); but coalification appears to follow Hilt's

Law with respect to undeformed stratigraphic level. For example, Lower Cretaceous coals above and below Lewis thrust have similar organic maturities, ~1.2% VR, in spite of a structural separation >8 km. Intervening Upper Cretaceous strata have organic maturities of ~0.7% VR. The observed variations in coal rank appear to depend primarily on depth of stratigraphic burial prior to thrusting (Hacquebard and Donaldson, 1974). This relationship is unfavourable for petroleum accumulation, because it implies that petroleum generation occurred prior to trap formation. This model has not been reconciled with petroleum occurrences or geothermal observations. New data from FT analysis provide independent constraints on thermal evolution that are reconcilable with geohistory constraints, organic maturity and current geothermal data.

FT analysis uses the temperature sensitive nature of FT preservation in minerals to constrain maximum paleotemperatures and the history of subsequent temperatures. Under geological conditions apatite FT's (AFT's) anneal increasingly rapidly between ambient surface temperatures and ~110°C, though annealing is substantially more rapid at temperatures >60°C. With annealing the tracks shorten so that the longer a rock resides at higher temperatures the greater the proportion of track shortening. As the AFT age and length data reflect both the time over which tracks have been retained and the thermal history of the host material, the analysis of these two parameters distinguishes among possible thermal histories below temperatures of ~110°C (Gleadow et al., 1986). Gallagher (1995) has automated this procedure by combining calculated AFT parameters from numerous possible thermal histories with statistical tests against observations.

AFT clocks in rocks above and below Lewis thrust, and either in the footwall or hanging wall of Flathead fault, record different thermal histories that vary with structural and stratigraphic level. In the footwall of Flathead fault, FT data from Lewis sheet and underlying strata generally vary systematically with elevation, which is a proxy for structural position prior to displacement on Flathead fault. AFT ages decrease from ~70 Ma, at the highest elevations in Lewis sheet east of Flathead fault (> +2000 m), to ~30 Ma in the subsurface below Lewis thrust (~ –1000 m). In this profile there is a "dog-leg", or piece-wise, linear variation with elevation in the mean horizontal confined FT lengths (HCTL). Mean HCTL is >13 microns at the highest elevations. It decreases to ~12 microns at ~ +1400 m. At about +800 m mean HCTL is about 13 microns. This marks the top of a second segment of the profile. From there the mean HCLT decreases progressively to ~11.5 microns at < –500 m. Samples from Lewis sheet in the hanging wall of Flathead fault have AFT data of comparable age and comparable, or longer, mean HCTL relative to those from the highest samples in the footwall of Flathead fault. Rudaceous clasts of Lewis sheet rocks that occur in Kishenehn Fm. also have AFT data comparable to those at the highest elevations in the footwall of Flathead fault.

Rocks of Lewis sheet sampled in the keel of Akamina Syncline and as clasts in Kishenehn Fm. cooled rapidly from temperatures above ~110^{o} C, to temperatures where little subsequent annealing occurred (~70^{o} C) or lower, at about 75 Ma. At lower elevations in Lewis sheet, cooling began at the same time, but those rocks cooled only to temperatures where significant AFT length and age reduction continued, >70^{o} C. The Late Cretaceous cooling episode is not recorded by AFT data from rocks lying below Lewis thrust. The ~75 Ma cooling within Lewis thrust sheet began while strata of about the same age, that are that still preserved below Lewis thrust (Jerzykiewicz et al., 1996), were being deposited. The abrupt and profound cooling of Lewis sheet at ~75 Ma is interpreted as recording motion on Lewis thrust fault and exhumation and erosion of Lewis sheet. Strata below Lewis thrust subsequently reached peak temperatures in response to tectonic burial by Lewis sheet. Coalification patterns follow Hilt's law in these strata because of a large footwall flat in Lewis thrust, not because of predeformational sedimentation. Geothermal gradients attending peak coalification below Lewis thrust were much lower than both those responsible for coalification within Lewis sheet and those observed currently. Temperatures attending Lewis sheet coalification were sufficiently high that they completely reset AFT clocks, consistent with observed coal ranks. A syndeformational geothermal gradient like the present one and deep burial below the succession preserved in the hanging wall of Flathead fault would have totally reset AFT clocks in preserved Lewis sheet in the footwall of Flathead fault prior to motion on Flathead fault.

Rocks lying both above and below Lewis thrust in the footwall of Flathead fault record a second cooling that begins in mid-Eocene time. This cooling event is not observed in samples from the hanging wall of Flathead fault, but it is also observed some distance east of Flathead fault. This cooling coincides with extension on Flathead fault. It is consistent with stratigraphic constraints from Flathead half-graben (Contenius, 1996) and it links the formation of Flathead half-graben temporally to the epeirogenic uplift of the craton (Nurkowski, 1984) and a major extensional event in the Omenica belt, deeper in the orogen (Carr et al., 1987).

Temperature histories derived from AFT parameters are reconciled to stratigraphic, structural and coalification constraints. These models indicate that geothermal gradients vary with time, and that current values are generally higher than past values. Topographically driven hydrodynamic advective heat transfer depresses the current geothermal gradient. We infer that past lower geothermal gradients indicate more efficient advective heat transfer. Foreland Belt petroleum systems result from the specific deformation of particular stratigraphic successions with physical boundary conditions controlled by orogenic wedge characteristics. Boundary conditions and surface processes on orogenic wedge thermal history must be constrained, considered and modeled in the analysis Foreland Belt petroleum potential.

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