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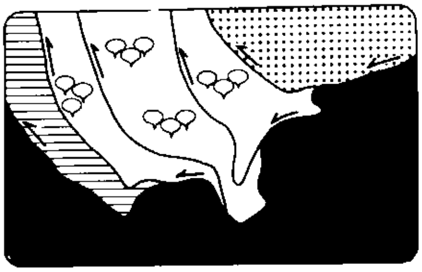

Tectonic controls on the thermal evolution of the Cape Smith Thrust Belt [1]

M.R. St-Onge and S.B. Lucas
Lithosphere and Canadian Shield Division
Geological Survey of Canada
588 Booth Street
Ottawa, Ontario K1A 0E4

Summary

Re-imbrication of the internal part of the Cape Smith Thrust Belt has resulted in the development of two distinct structural-metamorphic domains. In a southern (regular-sequence thrusting) domain, thermal peak metamorphism occurred after deformation, while in a northern (out-of-sequence thrusting) domain, it occurred during deformation (*i.e.*, re-imbrication). The interactions of tectonic and thermal processes have been studied using three methods: (1) qualitative evaluation of the timing between mineral growth and deformation; (2) analytical P-T paths from growth-zoned garnets; and (3) numerical modelling of vertical heat conduction. Analytical P-T paths suggest that uplift in the regular-sequence domain resulted primarily from erosion and isostatic unloading. In contrast, P-T paths in the out-of-sequence domain indicate that the northern portion of the thrust belt experienced faster unroofing relative to the regular-sequence domain. This has been attributed to both ramping of the out-of-sequence thrusts at deeper structural levels and possibly to extensional faulting at higher structural levels. Field and thin-section observations on the timing of metamorphism coupled with numerical modelling suggests that the thermal peak metamorphism documented in the regular-sequence domain is a consequence of the emplacement of the out-of-sequence thrust stack.

Résumé

La ré-imbrication de la partie interne de la bande du Cap Smith divise cette dernière en deux domains métamorpho-structuraux distincts. Dans un domaine sud, caractérisé par des chevauchements en-série, le métamorphisme suit la déformation. Par contre, dans un domaine nord, caractérisé par des chevauchements hors-série, le métamorphisme est synchrone avec la déformation (*i.e.*, la ré-imbrication). L'étude de l'interaction des processus tectoniques et thermiques dans la bande du Cap Smith a fait l'objet de trois approches différentes: (1) une évaluation qualitative de la croissance des minéraux métamorphiques et de la déformation; (2) la détermination des trajectoires P-T à partir de grenats zonés; et (3) la modélisation numérique de la conduction verticale de chaleur. Les trajectoires P-T suggèrent que le soulèvement tectonique de la zone de chevauchement en-série résulte vraisemblablement de l'érosion et d'un soulèvement isostatique. Dans le domaine hors-série les trajectoires P-T indiquent cette zone a subi des taux plus importants de soulèvement tectonique et d'érosion. Il est postulé que ces taux sont dûs à la présence de rampes de failles hors-série aux niveaux structuraux inférieurs et que peut-être le soulèvement a été facilité par le jeu de failles normales aux niveaux structuraux supérieurs. Les observations pétrologiques de terrain et en lame mince ainsi que la modélisation numérique indiquent que le paroxisme métamorphique dans le domaine en-série correspond à la mise en place des chevauchements hors-séries.

Introduction

Regional metamorphism in orogenic belts is a consequence of the often complex interplay of tectonic and thermal processes (*e.g.*, Spear *et al.*, 1984; Oxburgh *et al.*, 1987). Integrating structural, petrological and thermal studies therefore provides a means of constraining the tectonic evolution of young (*e.g.*, Selverstone, 1985, 1988) and old (*e.g.*, St-Onge and King, 1987) mountain belts. In the Cape Smith Belt of Early Proterozoic age, analytical P-T paths and observations on the timing of regional metamorphism and deformation were combined with the results of numerical modelling of vertical heat conduction. This has permitted evaluating the role of large-scale deformation structures in the thermal history of the thrust belt.

The tectonothermal evolution of the Cape Smith Belt is characterized by an interaction between (1) thrusting, (2) uplift and erosion, and (3) thermal equilibration of thickened crust. The south-verging thrust belt developed *ca.* 1920 to 1880 Ma (Parrish, 1989 - this issue, p. 126-130) during the Trans-Hudson Orogen in response to underthrusting of the northern Superior Province margin and obduction of an ophiolite from the overriding plate. Further thrust belt deformation occurred along out-of-sequence thrusts (Lucas, in press) between *ca.* 1880 and *ca.* 1840 Ma (Parrish, 1989 - this issue, p. 126-130). The deformation history of the thrust belt can be divided into three principal stages (Lucas and St-Onge, 1989a - this

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issue, p. 122-126); (1) early thickening by piggyback stacking of 0.5 to 7 km thick thrust sheets; (2) development of a ductile shear zone at the base of the thrust belt during relaxation of isotherms in the thickened crust; and (3) out-of-sequence thrusting and penetrative bulk shear deformation at syn- to post-thermal peak conditions. Field and thin-section observations have allowed the thrust belt to be divided into two principal structural and metamorphic domains; (a) a southern regular-sequence thrusting domain (Povungnituk Group mineral zones, Figure 1) which experienced stages 1 and 2; and (b) a northern out-of-sequence domain (Chukotat and Watts Groups mineral zones, Figure 1) which experienced all three deformation stages.

Recent studies (*e.g.*, Jamieson and Beaumont, 1988) have shown that the thermal history of a material point in a thrust belt is significantly dependent on the uplift mechanism and rate of the point, and its structural position in the belt. Significantly, out-of-sequence thrusting and normal faulting can substantially change a mountain belt's thermal history. In the Cape Smith Belt, the interaction of tectonic and thermal processes have been studied using three methods: (1) qualitative evaluation of the timing between mineral growth and deformation in pelitic assemblages; (2) quantitative P-T path determinations with growth-zoned garnets; and (3) numerical (finite difference) modelling of vertical heat conduction. Results, stemming from the use of each method, are described in the next three sections.

Mineral Growth and Deformation

In the regular-sequence thrusting domain, thermal peak mineral assemblages commonly postdate the establishment of the D_1 basal shear zone (Lucas and St-Onge, 1989a - this issue, p. 122-126). Garnet, kyanite, staurolite and plagioclase porphyroblasts in pelitic units overgrow the shear zone foliation. The garnet interiors are characterized by straight inclusion trails which are continuous with the fabric in the pelitic matrix. The unbroken map pattern of mineral isograds in the regular-sequence domain constrains the regional thermal peak equilibration to postdate major thrust displacements (Povungnituk Group mineral zones, Figure 1).

In the more internal out-of-sequence domain, thermal peak mineral growth is synchronous with deformation in the shear zones associated with the oldest D_1 out-of-sequence faults (Lucas and St-Onge, 1989a - this issue, p. 122-126). Garnets in pelitic units contain sigmoidal inclusion trails of quartz, tourmaline and opaque minerals. The matrix fabric is defined by quartz, tourmaline, opaque minerals, muscovite, biotite and kyanite, and is continuous with the inclusion trails at the rims of the garnet porphyroblasts. The map pattern of isograds in the out-of-sequence domain clearly demonstrates that thrust imbricates postdate thermal equilibration in this domain (Chukotat and Watts Group mineral zones, Figure 1).

Analytical P-T paths

Metapelitic layers within both thrusting domains, contain the following maximum phase assemblage: kyanite – garnet – muscovite – plagioclase – quartz ± staurolite ± chlorite. Six-phase subsets of this assemblage (plus H_2O) are univariant in the seven-component system SiO_2-Al_2O_3-FeO-MgO-Na_2O-K_2O-H_2O. Provided the garnets are chemically zoned, the subset assemblages offer the potential to model changing P and T conditions as recorded

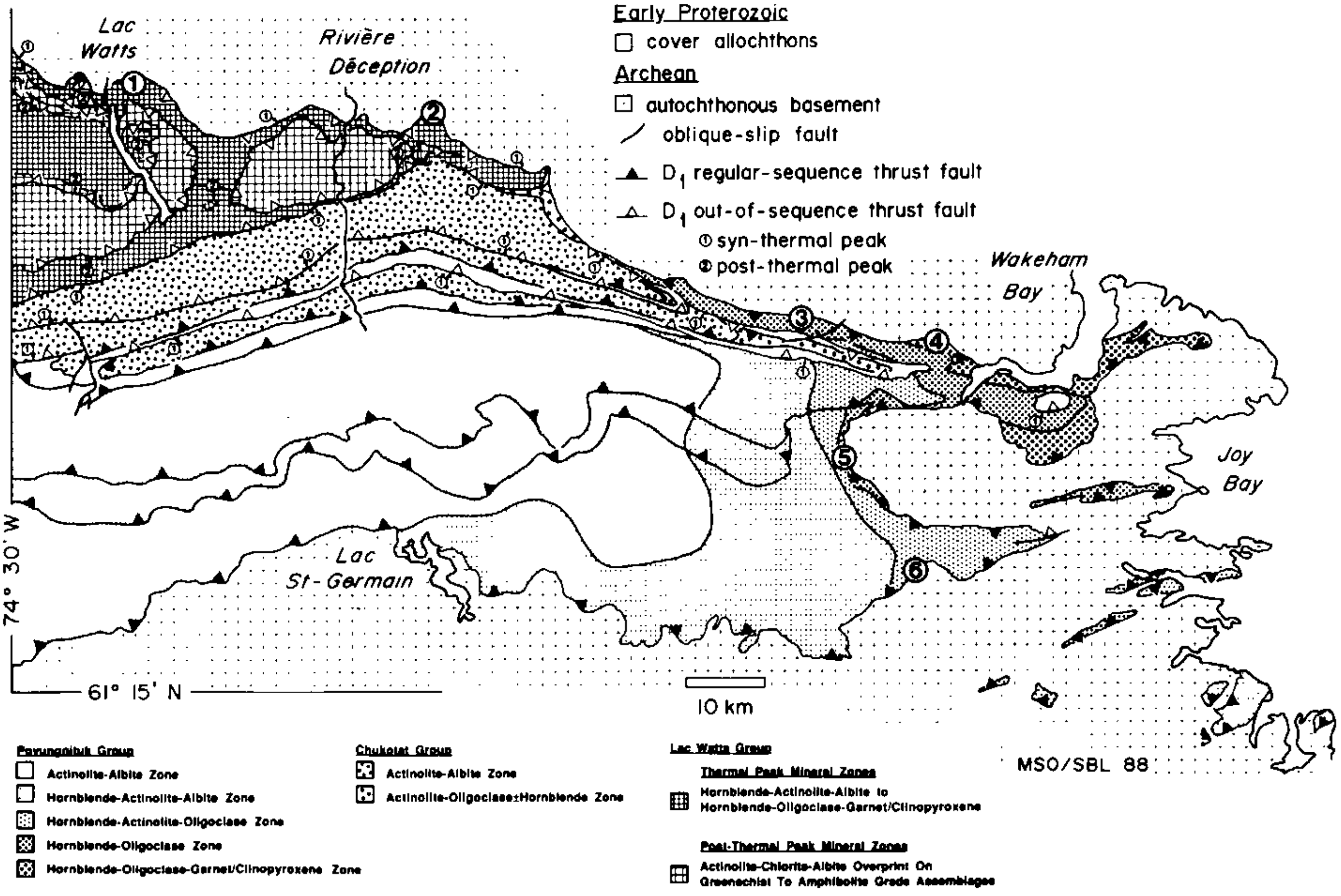

Figure 1 *Metamorphic map of the eastern portion of the Cape Smith Belt. The distribution of the metamorphic mineral zones is after Bégin* et al. *(1988). Thrust slices without a pattern lack sufficient mafic rocks to constrain the metamorphic mineral zone. Large circled numbers (1-6) refer to the locations of the samples used for the analytical P-T path determinations.*

during garnet growth (Spear and Selverstone, 1983).

Samples for microprobe analysis were selected from both the regular-sequence thrusting domain (samples #3-#6, Figure 1) and the out-of-sequence thrusting domain (samples #1-#2, Figure 1). The samples are from the eastern portion of the Cape Smith Belt and from within 200 m of the basement-cover contact. In each sample, the garnet with the greatest diameter was chosen in order to quantify the longest possible P-T path segment. The garnets were analysed along rim-core-rim traverses at regular (0.1 mm) intervals.

Concentric compositional zoning is well developed in the six analyzed garnets and is approximately symmetrical with respect to the porphyroblast core (*e.g.*, Figure 2). The compositional trends correspond to those predicted by a partial-equilibrium growth model (Loomis, 1983; and references therein). The absence of breaks or gaps in the zoning trends (Figure 2) suggests that: (1) the porphyroblasts are not the result of polymetamorphism; and (2) individual garnet growth is consistent with a single reaction such as:

Staurolite + Muscovite + Quartz =
Kyanite + Biotite + Garnet + H_2O

Temperature estimates were obtained from the analyses of the garnet rims and matrix biotites based on the Fe-Mg exchange equilibrium (Hodges and Spear, 1982). Pressure determinations were calculated with the analyses of garnet rims and matrix plagioclase based on the grossular-kyanite-anorthite-quartz equilibrium (Hodges and Spear, 1982; Hodges and Royden, 1984). With a starting P and T provided by the matrix-garnet rim assemblage, the thermodynamic modelling technique of Spear and Selverstone (1983) was used to "backtrack" and model the garnet chemical zoning from rim to core in terms of P and T increments. The six resulting P-T paths (Figure 3) record the decompression and unroofing of the thrust belt concomitant with prograde metamorphism.

Regular Sequence Domain. The four pelites from the regular-sequence thrusting domain record progressively higher thermal peak temperatures (430°C to 590°C) from external (southern) to internal (northern) sample locations (samples #6 to #3, Figure 3). In addition, the maximum pressures recorded for the four samples increase from 6.5 kb for the most external sample (#6) to over 9 kb for the most internal sample (#3), consistent with a foreland-tapering geometry for the thrust belt. The four paths are curvilinear and can be described as "nested" (Figure 3). This suggests that the samples experienced relatively similar decompression histories (*cf.* England and Thompson, 1984), possibly with uplift being isostatically driven in response to erosional unloading.

Out-of-Sequence Domain. The two samples from the out-of-sequence domain (samples #1, #2, Figure 3) yield distinctly different P-T trajectories in comparison with those from the regular-sequence domain. The out-of-sequence domain paths differ in two principal ways: (1) the paths for samples #1 and #2 are characterized by steeper dP/dT prograde segments recording nearly isothermal decompression; and (2) samples #1 and #2 record lower maximum temperatures than samples #3 and #4 from the regular-sequence domain, although from a similar D_1 structural position in the thrust belt (adjacent to the basement-cover contact).

The steeper dP/dT segments are probably a reflection of greater unroofing rates in the out-of-sequence domain. Considering the syn-tectonic nature of the analysed garnets, it is reasonable to suggest that ramping of the out-of-sequence faults contributed to the faster uplift rates experienced by these hanging wall samples. The lower thermal peak temperatures registered by samples #1 and #2 requires a mechanism that will interrupt the heating of samples #1 and #2 relative to samples #3 and #4 which are at a similar structural position. Syn-D_1 extensional faulting (*cf.* Burchfiel and Royden, 1985; Selverstone, 1988) at higher structural levels (now eroded) in the out-of-sequence domain may have been the mechanism responsible for faster unroofing and cooling of this domain relative to the regular-sequence domain.

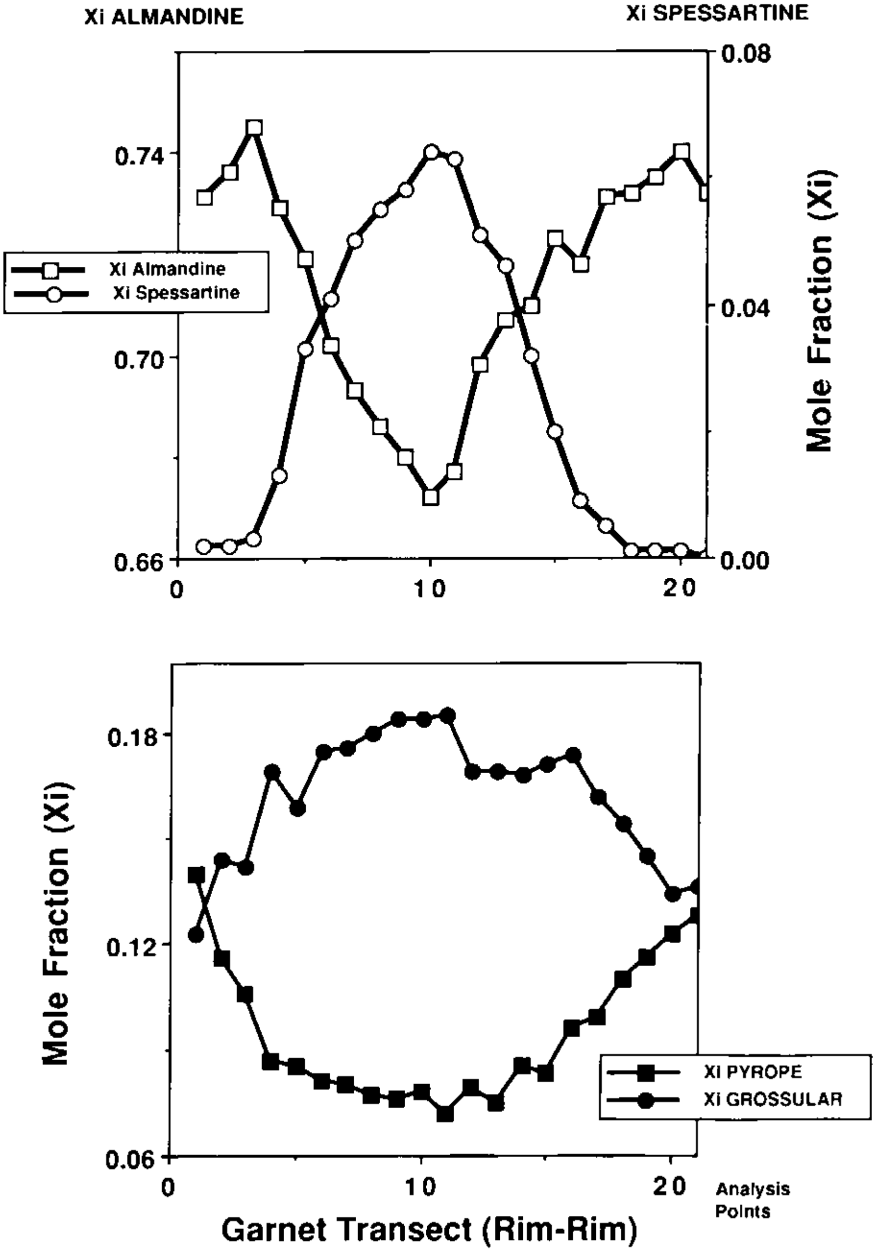

Figure 2 *Garnet zoning profiles for sample #4 (Figure 1). Numbers on vertical axes represent mole fractions of the four garnet end-member components. Horizontal axis represents full diameter of garnet grain (21 analysis points spaced at 0.1 mm intervals).*

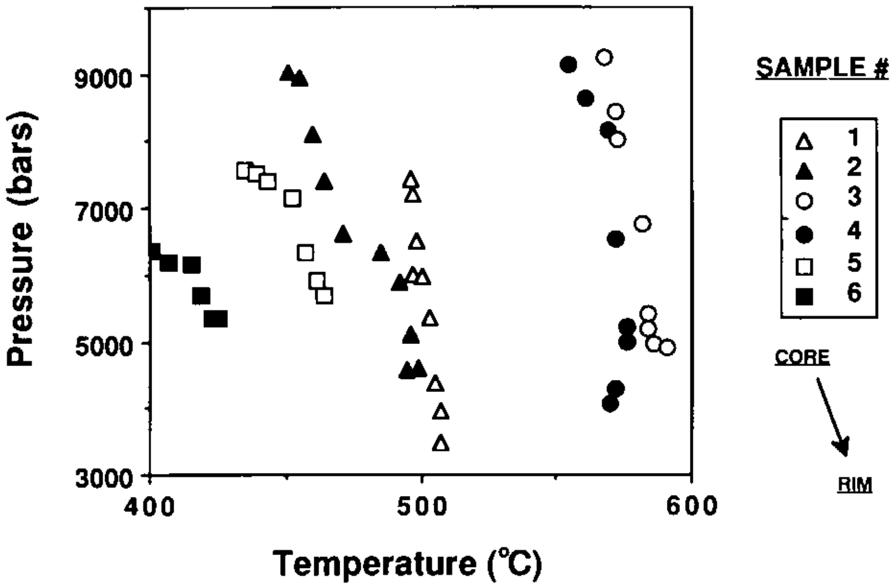

Figure 3 *Analytical P-T paths for the six metapelite samples of Figure 1, recording prograde decompression from garnet core to rim. Samples #3 to #6 are from the regular-sequence domain; samples #1 and #2 are from the out-of-sequence domain (Figure 1).*

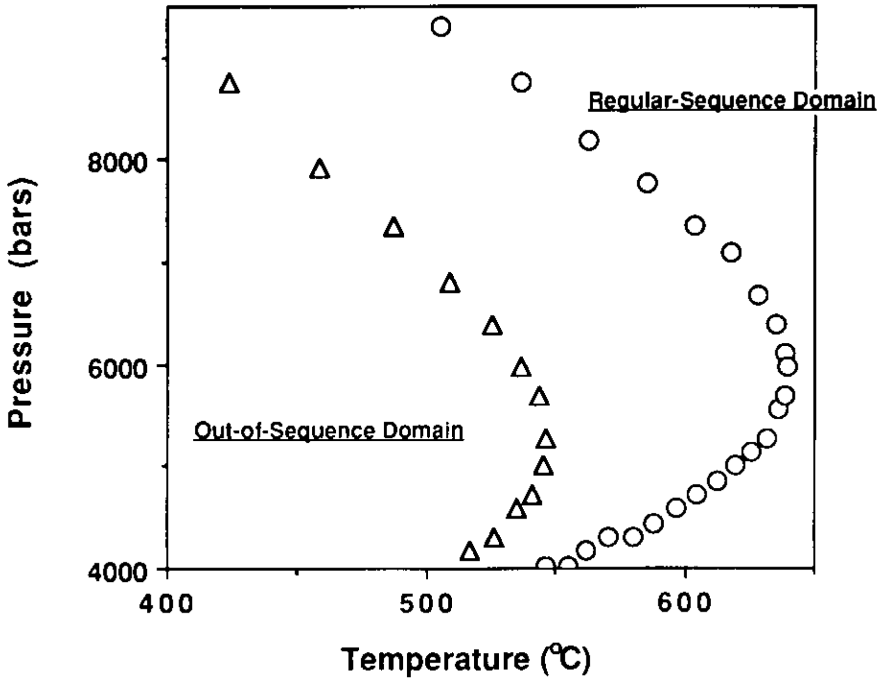

Figure 4 *P-T paths derived with the numerical heat conduction model. The two paths are for locations intended to represent the approximate structural positions of samples #2 (out-of-sequence domain) and #4 (regular-sequence domain) shown in Figure 1. In the model, the regular-sequence domain sample was buried 5 km deeper than the out-of-sequence domain sample.*

Numerical P-T Paths

The thermal evolution of the Cape Smith Belt during D_1 has been investigated with a numerical model which simulates deformation and heat conduction in a thrust belt (Lucas and St-Onge, 1989b - this issue, p. 158-163). The thermal history is examined by solving for the thermal structure of a vertical rock column as it passes through the thrust belt from foreland to hinterland. Deformation occurs incrementally (*i.e.*, in a discontinuous fashion) by translating the column along a horizontal décollement and by thickening it vertically through thrusting. The one-dimensional heat conduction problem is formulated to solve for temperature as a function of depth and time (T(z,t)) as follows (after England and Thompson, 1984):

$$\frac{\delta T}{\delta t} = \kappa \left[\frac{\delta^2 T}{\delta z^2}\right] + U(z,t)\left[\frac{\delta T}{\delta z}\right] + \kappa\left[\frac{h(z)}{K}\right]$$

where κ = thermal diffusivity; U = vertical velocity of a material point in a fixed reference frame; h = depth-dependent radiogenic heat production; K = thermal conductivity. The Crank-Nicholson implicit finite difference method (Smith, 1978) is used to solve this equation for the vertical column at each timestep. In this section, the results of model runs which test the thermal consequences of D_1 out-of-sequence thrusting are summarized and compared with the analytically derived P-T paths.

The numerically derived P-T paths (Figure 4) simulate a period of post-deformation decompression (starting 41 Ma after initiation of thrusting) due to erosion and isostatic uplift in a thrust belt. The model has not produced syn-deformation P-T paths, and thus the paths cannot be directly compared with the analytically derived paths for the out-of-sequence domain (Figure 3). The model results do suggest, however, that D_1 metamorphism in the Cape Smith Belt was due to thermal relaxation of thickened crust largely by vertical heat conduction. The results indicate that contributions to the thermal budget from (1) plutonic heat advection, (2) convection of heat with metamorphic fluids, and (3) residual heat from the *ca.* 1960 Ma rifting event (St-Onge *et al.*, 1989 - this issue, p. 119-122) are not significant at the scale of the mountain belt. The actual P-T values generated by the numerical model (Figure 4) do not match those in the analytically derived P-T paths. However, the general morphology and relative positions of the numerical model paths are similar to those shown for out-of-sequence and regular-sequence domains in Figure 3. This suggests that the observed post-deformation thermal peak metamorphism documented in the regular-sequence domain may be a thermal consequence of the emplacement of the out-of-sequence thrust stack. This is corroborated in the field by the presence of an overturned hornblende isograd in the footwall of the out-of-sequence domain (Figure 1; Bégin, 1989 - this issue, p. 151-154).

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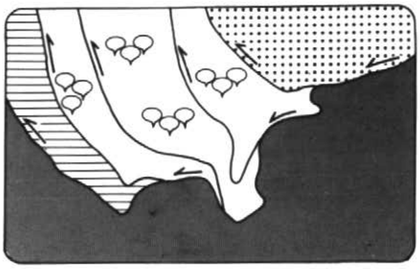

Shear zone softening at the base of the Cape Smith Belt: implications for the rheological evolution of thrust belts [1]

S.B. Lucas and M.R. St-Onge
Lithosphere and Canadian Shield Division
Geological Survey of Canada
588 Booth Street
Ottawa, Ontario K1A 0E4

Summary

The rheological and structural consequences of thrust belt metamorphism have been studied using both numerical thermal-rheological models and field and thin-section observations on ductile thrust zones in the Early Proterozoic Cape Smith Thrust Belt. Development of these ductile thrust zones had several important consequences for the evolution of the thrust belt: (1) penetrative bulk shear deformation of both hanging wall and footwall units leading to the development of mylonitic foliations; and (2) movement on a restricted number of relatively large displacement thrusts. Relatively broad ductile shear zones developed adjacent to thrusts during prograde metamorphism in order to accommodate movement on the thrusts, while relatively narrow shear zones developed adjacent to thrusts during retrograde metamorphism. The results of both the field studies and the thermal-rheological models suggest that temperature-(and time-) dependent weakening processes are strongly accentuated by lithological contrasts.

Résumé

Les conséquences du métamorphisme régional dans la bande du Cap Smith d'âge Protérozoïque inférieur ont été analysées d'une part à l'aide des observations de terrain et de l'étude de lames minces prélevées dans les zones de chevauchements plastiques et d'autre part à l'aide de modèles numériques thermo-rhéologiques. La formation des zones de chevauchements plastiques a eu plusieurs conséquences im-

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