OBSERVATIONS ON DEEP THRUST FAULTS ON THE WEST SIDE OF THE SOUTHERN CANADIAN ROCKIES

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ABSTRACT

Thrust faults which formed at depths of 10 to 20 km are now exposed in the zone of transition between the foreland fold and thrust belt of the southern Canadian Rocky Mountains and the metamorphic core zone in southeastern British Columbia.

The thrust faults which formed at these depths are geometrically similar to the thrusts formed at much lesser depths in the frontal zone of the Rockies. There are, however, some differences in geometry as well as in the mesoscopic and microscopic structures of the fault zones which can be ascribed to increased ductility of the rock layers and to decreased ductility contrast between the layers.

Most of the individual thrust faults have displacements in the range of 3 km to 10 km adding up to 50 km of shortening in a 50°km wide zone. The gross mean rate of displacement was 1-4 mm/year. Pressure and temperature varied from 3.0 kb and 300°C at the shallower levels to 5 kb and 550°C at greater depths. Thrust faults did not form in the metasedimentary sequence at depths where load pressure was greater than 5.5 kb and the prevailing temperature greater than 550°C.

Introduction

In the southern Canadian Cordillera a wedge of sedimentary rocks overlies a Precambrian gneissic basement. The wedge, as thick as 15 km on its west side, is involved in the foreland fold and thrust belt (Price and Mountjoy, 1970). The configuration of the structures is such that the deepest structural levels are exposed to the west of the thrust belt in the metamorphic core zone of the orogen.

Thrust faults are present on the east flank of the core zone in terrains with a variety of metamorphic grades for which temperature and pressure estimates have been made. Mountainous relief, in conjunction with the axial plunge, permit us to observe faults over a 10 km depth range. The east flank of the core zone is therefore well suited for the study of thrusts, some of which must have formed at depths of 15-20 km.

In the last decade a group from the University of Calgary has been studying a segment of the east flank of the core zone in southern British Columbia (Fig. 1). It is an area 20-50 km wide and more than 150 km long parallel to the strike. The Trans-Canada Highway traverses its southeastern part. The rocks are Late Proterozoic (Hadrynian) and Cambrian sandstones, mudstones, limestones and their metamorphic equivalents. The Lower Cambrian quartzite, 800-1500 m thick, is an important, competent marker. The bulk of the deformation can be related to the Jura-Cretaceous Columbian Orogeny. The geometry and kinematics of the thrusts, as well as the parameters of temperature, load pressure, and displacement rate are described here.

Geometry of Individual Faults and Fault Zones

The geometric characteristics of thrust faults in the frontal zone of the southern Canadian Rocky Mountains have been admirably described by Bally, Gordy and Stewart (1964), by Dahlstrom (1970) and by Price and Mountjoy (1970). The thrusts at the rear of the Rocky Mountain fold and thrust belt share some of these characteristics but there are **some** differences.

1) Many faults cut through the stratified sequence at a low (10°-30°) angle such that the stratigraphic throw signifies large displacements. There are thrusts, however which cut layering at a high angle.

2) Some faults follow glide horizons linked by steps across competent layers and are typical stepped thrusts cutting up section in the direction of transport. There are others, however which cut obliquely through the layered sequence without showing any influence by the stratigraphy.

3) Thrust faults, and some normal faults, are intimately related to folds. Some thrusts are rooted in fold cores. Anticlines, outlined by competent quartzite embedded in slate are out by thrust faults high on the forelimb as predicted experimentally by Bell and Currie (1964). Several of the thrusts are themselves highly folded (Fig. 2).

4) Upward imbrication in the thrust sheet, so clearly documented in the eastern Rockies (Dahlstrom, 1970) can also be inferred for a number of the thrusts west of the Rockies. One good example of upward imbrication on a large scale was documented for a major thrust in the northern Purcell Mountains (Fig. 3) (Simony and Wind, 1970). This is presumably an example of "downward simplification" of the fault zone in terms of the interests of this Conference.

5) The field evidence is consistent with the thrust being listric with décollement above a gneissic basement. Where the thrust faults have penetrated the Precambrian gneissic basement they have done so on gently dipping surfaces producing thin basement sheets rather than uplift blocks.

As a result of the general southeasterly plunge along the length of the area, deeper and deeper levels are exposed northwestward such that a sheet of allochthonous basement gneiss - the Malton Gneiss - is exposed at the surface (Fig. 1) (Ghent et al., 1977). At the upper surface of the gneiss sheet a zone of high strain, with metamorphosed mylonite, separates the Proterozoic metasediments from the gneiss. The gneiss itself is carried over the western Rocky Mountain structures by the Purcell Thrust (Fig. 4), a major thrust with relatively late, post metamorphic movement.

Features of the Fault Zones

Cross-sections of faults are exposed in cliffs and in artificial rock cuts. There the faults can be sharply delineated and the fault zones observed. Nowhere, however, was a fault surface stripped bare by erosion to permit study of slickensides, fibers, steps and other fault surface features. In some examples little mesoscopic deformation was noted near the fault, while in others, minor thrusts, minor folds, and veins increase in importance as the fault is approached.

Where a thrust has slate, schist, calcareous phyllite or sandy phyllite in both the hanging wall as well as the footwall the fault cannot actually be pinpointed on the outcrop and must be parallel to clevage surfaces. Because of this some of the large thrusts would be missed were it not for knowledge of the stratigraphy.

Where competent rock such as quartzite or gneiss is in fault contact with layered and schistose incompetent rock, the latter shows little obvious evidence of deformation while the competent rock, (quartzite, gneiss etc.) is strongly affected. In quartzite at low metamorphic grade, a zone 10 to 60 m thick is present in which the quartzite is white, fine grained and "glassy"-looking even though the parent rock is coarse and has abundant sedimentary textures and structures. The "glassy" quartzite has strain shadows and deformation lamellae in some grains and an irregular development of very fine grained "mortar" on the margins of large quartz grains and as veinlets 0.2-0.5 mm thick (Fig. 5). Locally abundant quartz veins and the development of a mosaic of equant, strain-free grains testify to the importance of recrystal lization.

The décollement at the top of the Malton gneiss is as much as 200 m thick. It is characterized by strong layering, intense lamination and layers of fine grained quartzo-feldspathic gneiss that probably represent metamorphosed mylonite. Little obvious deformation is seen in the overlying Proterozoic schists.

Displacements

Individual thrust faults have been followed for strike lengths of 20 to 300 km. Because both hinge points have not been found for any one fault, the length to displacement ratio (Elliot, 1976) could not be determined. However most faults can be followed for 30 to 100 km. Displacements of 2 km to 20 km have been conservatively estimated for individual faults with most displacements falling in the range of 3 to 10 km. This implies a length to displacement ratio of 10, somewhat higher than that found by Elliot (1976). A rotation of 10°-15° of the hanging wall vs. the footwall was determined for one hinged thrust. These observations imply relatively small distortions of the thrust sheets along the strike to accommodate variations in displacement along the thrust surfaces.

The total shortening across a belt some 50 km wide is about 50%, that is, the folds and, primarily, the thrusts have narrowed to 50 km the width of a strip that used to be 100 km wide.

Displacement Rates

Wheeler et al. (1974) and Elliot (1976) have estimated that the gross mean rate of displacement for the southern Canadian Rockies as a whole as well as for individual thrusts in the eastern Rockies was of the order of millimeters per year. On regional considerations, (Wheeler et al.; 1974) Columbian Orogeny began, in the zone considered here, about160 Ma BP. Activity on the thrusts in that zone may have come to an end about 110 Ma BP, because at that time k/Ar dates were set in late kinematic mica porphyroblasts and unroofing by erosion was well on its way (Price and Mountjoy, 1970). Of course, passive carrying forward on lower, more easterly thrust did go on into the Paleocene. In other words, some 50 km of displacement on thrusts took place in some 50 Ma suggesting a gross-mean rate of 1 mm/year. By comparison the gross mean rate for the displacement of alpine nappes in Switzerland was of the order of 2 cm/year (Trümpy, 1974). Doubling the displacement and halving the time bracket in the Columbian orogen only changes the gross mean displacement rate to 4 mm/year; still an order of magnitude lower than that for alpine nappes, the San Andreas fault, or subduction of oceanic crust.

While 1 mm/year is only a gross mean rate taken over a long time bracket, some significance can however be attached to it in that rates of the same order of magnitude were determined for individual thrusts, in a different part of the orogen, over a shorter time interval. The geometrical and temporal interlocking of thrust faults with folds is consistent with low displacement rates and further suggests that thrust faulting at depth did not have much seismicity associated with it.

Temperature and Pressure

Metamorphic grade varies, within the area from chlorite zone to sillimanite zone of the Barrovian facies series. The metamorphic climax occurred after an early episode of thrusting and before a later episode. The temperatures and pressures estimated from the mineral assemblages are therefore maximum values. Depth of burial can also be estimated from a knowledge of the stratigraphy and the structure.

In the southeastern part of the area, the highest structural levels are observed. Taking the known thickness of the Paleozoic succession in conjunction with the structural configuration, we can estimate that Proterozoic rocks now at the surface were at a depth of 10 km during thrusting. This corresponds to pressures of about 3.0 kb and temperatures of about 300°C.

At deeper levels biotite grade was reached during thrusting and biotite lies on cleavage planes associated with folds which are in turn related to thrusts. There, temperatures of about 400°C and pressures of as much as 4.0 kb prevailed during thrusting. Both the metamorphic mineral assemblages (Jones, 1972) as well as structural considerations suggest such numbers.

In a general way plunges are to the southeast along the length of the area and progressively deeper levels are exposed northwestward. Concommittantly, metamorphic grade rises to the north and west such that in the vicinity of the Big Bend of the Columbia River, the Proterozoic strata were metamorphosed at sillimanite grade and migmatite formed (Ghent et al., 1977). Temperatures of about 600°C and pressures of 6.0 kb were estimated for the mineral assemblages by Ghent et al. (1979).

The Purcell Thrust carried this deformed and metamorphosed edifice upward and eastward over the west flank of the Rockies after the metamorphic climax (Craw, 1978). Folds associated with that movement, both in the hangingwall and footwall, formed after kyanite and garnet had ceased to recrystallize (Simony et al., 1980, in press) and one can estimate that the portion of the Purcell Thrust exposed now, was at a pressure of 5.0-6.0 kb and a temperature of **450-500°C.**

The décollement zone above the allochthonous Malton Gneiss was active during the earliest stages in the orogeny (Ghent et al., 1977), and locally preserved early mineral assemblages include biotite and almandine; Stratigraphic and structural reconstructions suggest a depth of burial for the décollement zone, while it was active, of some 15 km (Fig. 2). One can therefore estimate temperatures of 400-500°C and pressures of about 4.5-5.0 kb.

Conclusion

An area to the rear of an intraplate fold and thrust belt has been examined, where the transition to the metamorphic core zone occurs. Displacement rates of 1-4 mm/year, temperatures in the range of 300°C to 500°C and pressures in the range of 3.0 kb to 5.0 kb prevailed during thrusting in a depth range of 10 to 20 km. The thrusts exhibit many of the geometric and kinematic characteristics of thrusts which formed at much shallower depth in the frontal zone of the southern Canadian Rockies. There are features however which indicate the effect of decreased ductility contrast with increased ductility of the layered sedimentary sequence.

The array of thrust faults seen in a section along the Trans-Canada Highway (Wheeler., 1963; Simony and Wind, 1970) disappears northward and is replaced by a zone of intense and complex folding, where metamorphic grade rose to that of kyanite and sillimanite (Brown et al., 1978; Ghent et al., 1977). No thrusts formed west of the Purcell thrust in that high grade domain even during post-metamorphic movement. In the relatively ductile metasedimentary rocks, thrust faults did not develop at temperatures higher than perhaps 500°C where the load pressure was in the 5.0-6.0 kb range.

Whether thrusts will or will not form is a function not only of temperature and load pressure but also of the rock-type, pore fluid pressure, strain rate etc. However, for a typical shale, limestone and sandstone sequence in a Barrovian metamorphic regime, the data presented above suggest a relationship as shown in Fig. 6.

The increasing ductility with depth and the tendency for thrust faults to be listric and merge downward, suggest that thrust zones simplify with depth.

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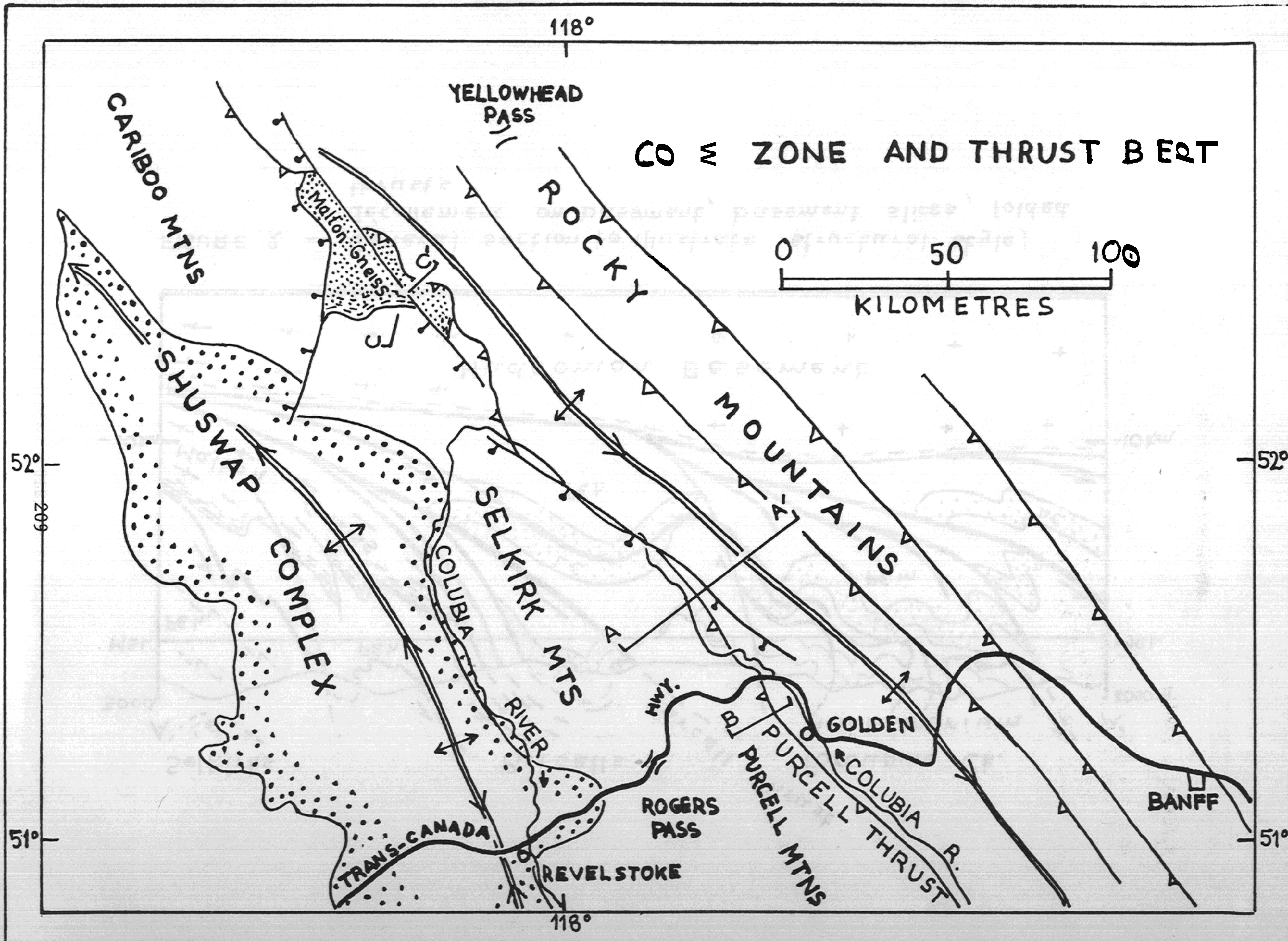

FIGURE 1 - Tectonic setting and location map

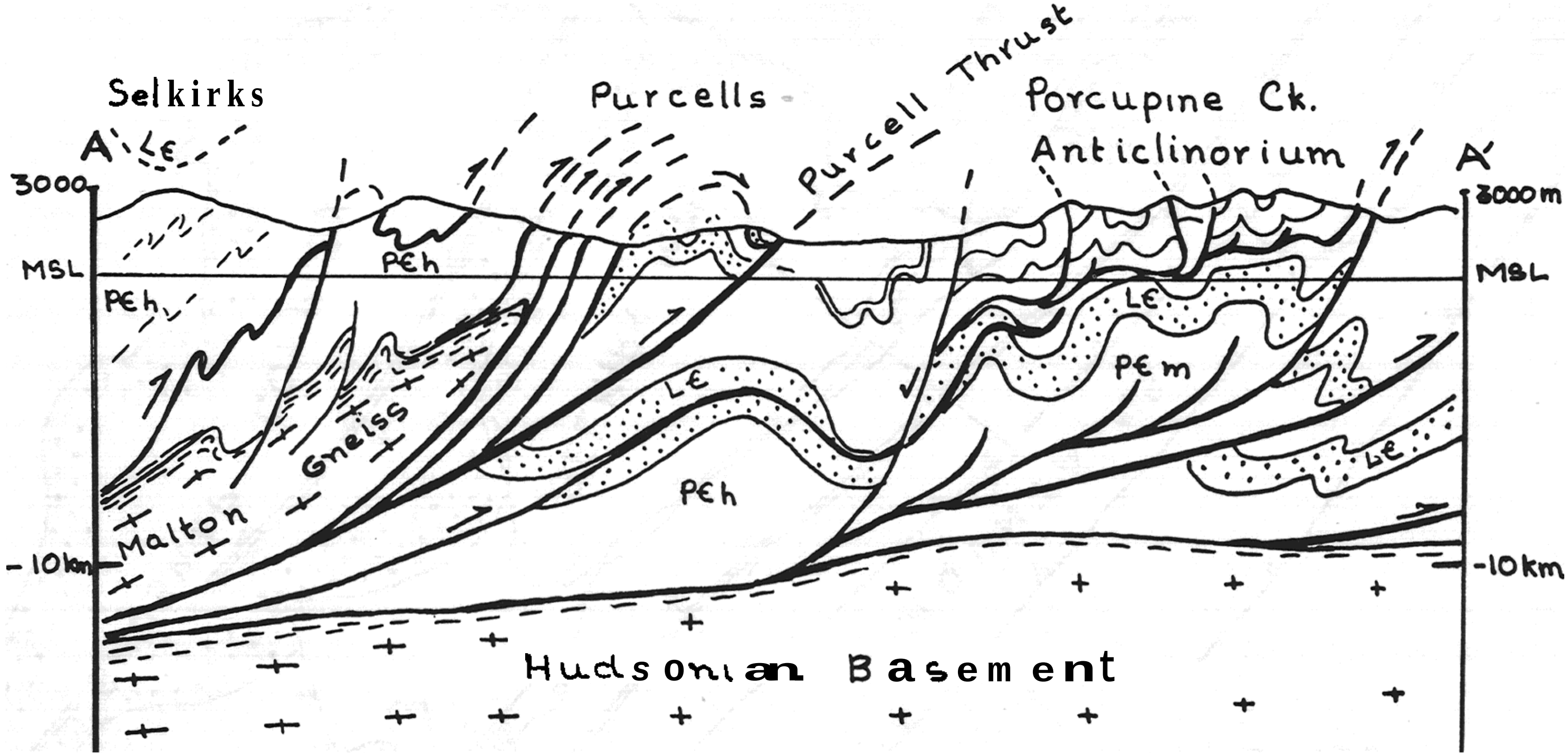

FIGURE 2 - General section to illustrate structural style; décollement on basement, basement slices, folded thrusts

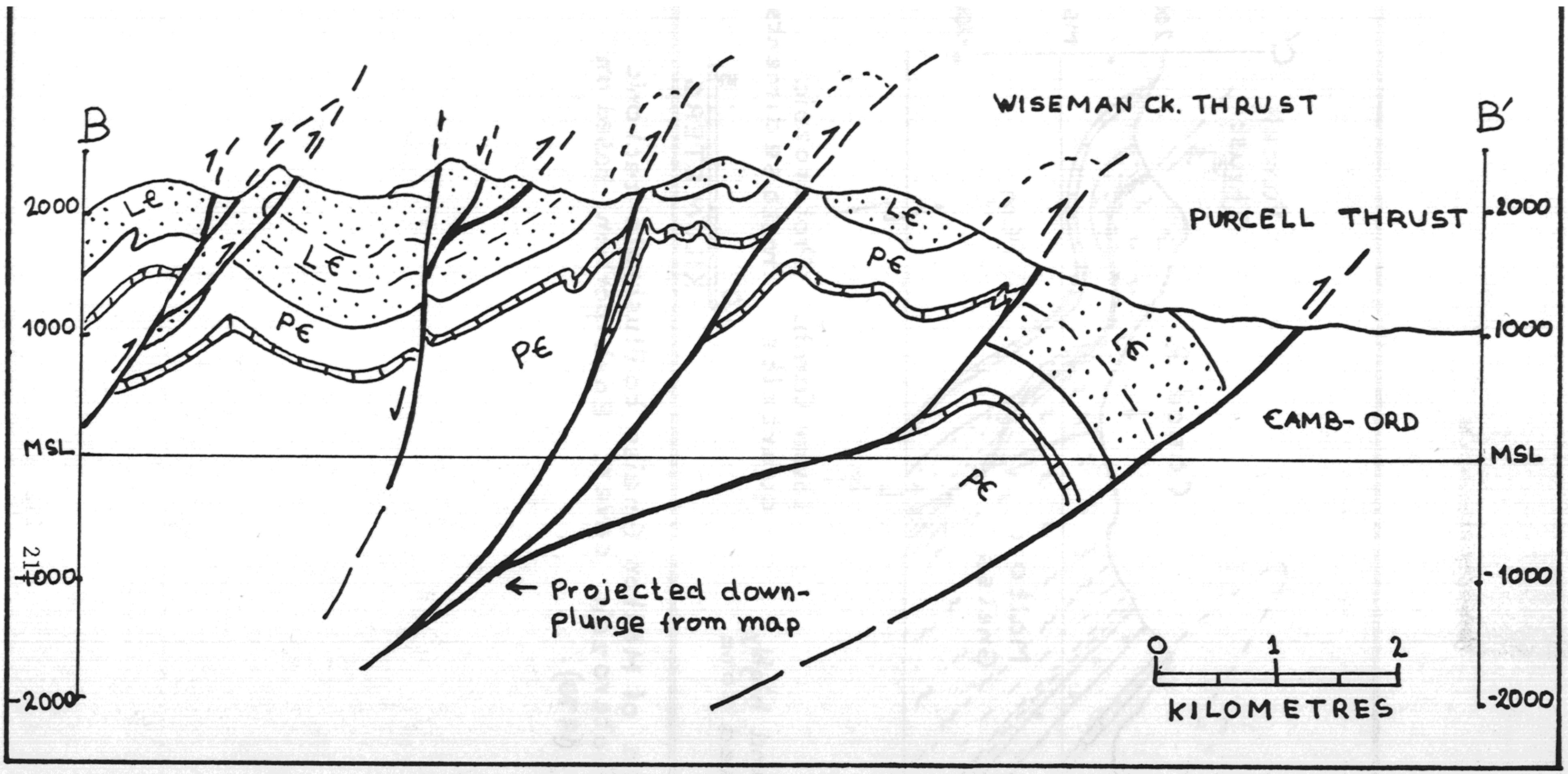

FIGURE 3 - Example of upward imbrication of a thrust and of anticlines cut on forelimb

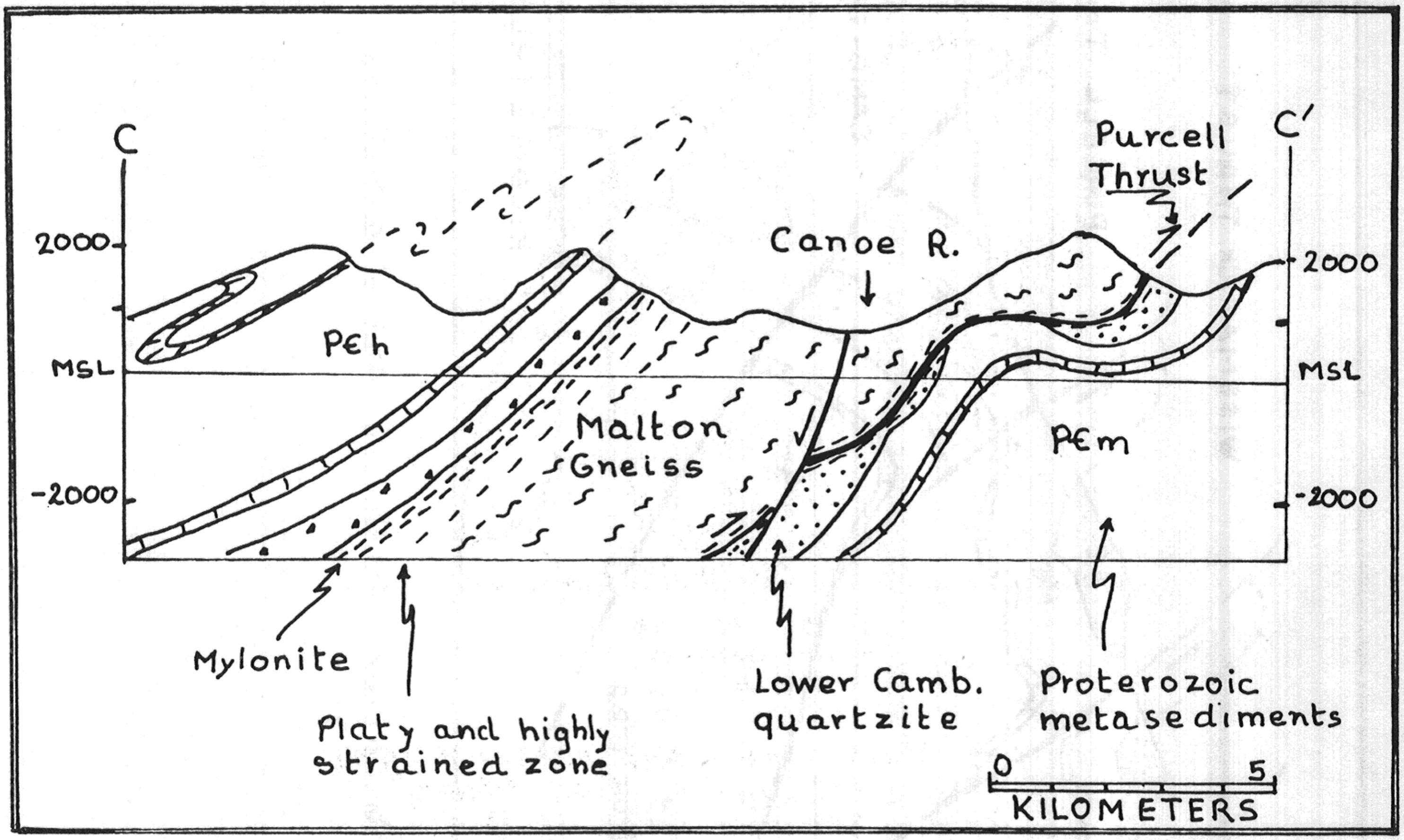

FIGURE 4 – Section of Malton Gneiss to illustrate tectonic contact with Proterozoic cover. East portion based on Price and Mountjoy (1970).

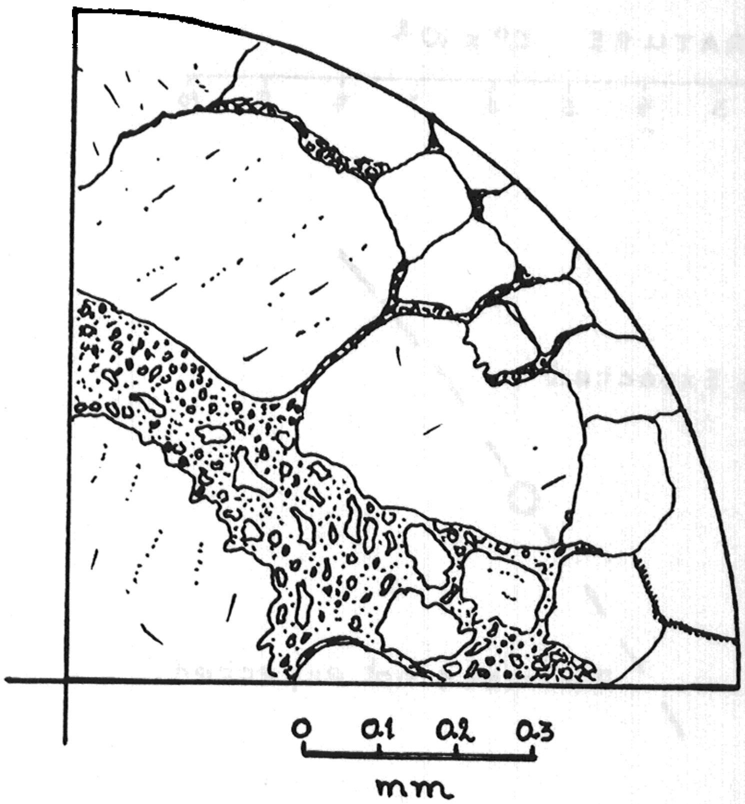

Figure 5 - Mortar vein and mortar margins around quartz grains. From "glassy" quartzite, Wiseman Creek fault zone.

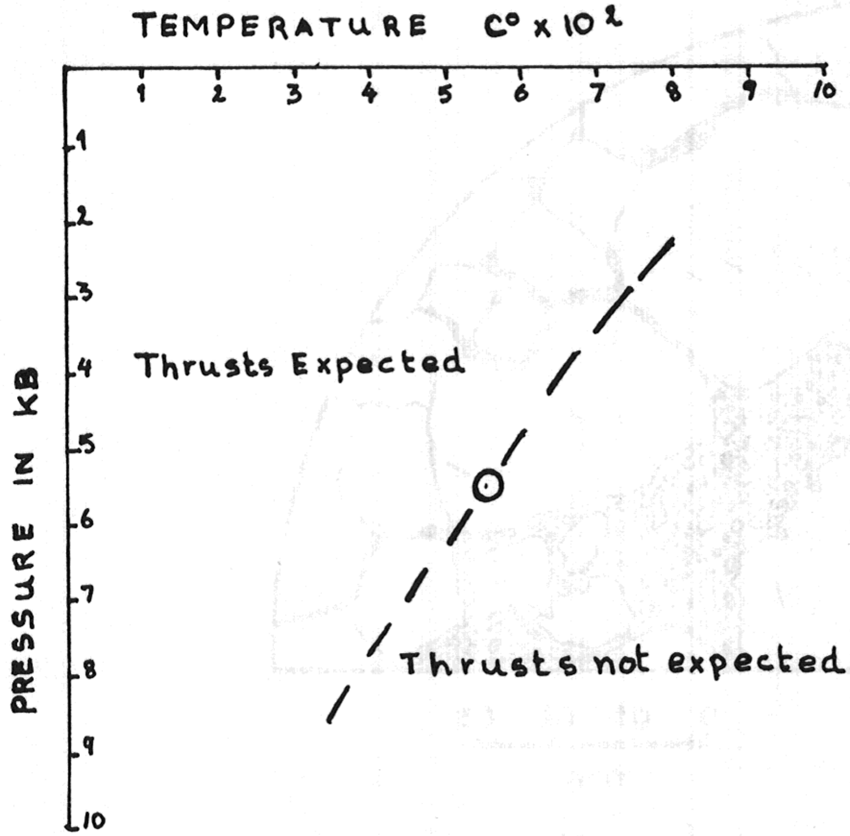

FIGURE 6 – P-T diagram for limit to thrusting in pelitic-psammitic sediments with displacement rates of mm/year.