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Structural analysis of sheath folds with horizontal X-axes, northeast Canada

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Abstract—Early Proterozoic supracrustal rocks occur below a thick nappe of Archaean basement gneiss in the Melville Peninsula where sheath folds are exposed in a wide zone of middle Proterozoic dynamothermal metamorphism. Outcrop patterns of truncated isoclinal sheath folds resemble cylindrical folds except in relatively small areas around the paraboloidal caps. Bulk extension axes are parallel to strike in the belt as shown by isoclinal sheath folds with horizontal central axes (X-axes), as well as similarly aligned mullion structure and rotated scapolite prisms. Extension axes converge from northeast to southwest in the apparent flow direction.

INTRODUCTION

AN ARCUATE zone of ductile deformation extends across the northern part of the middle Proterozoic Hudsonian Orogen in northeast Canada. This zone is revealed in Melville Peninsula and Baffin Island by dynamothermally metamorphosed Aphebian (early Proterozoic) supracrustal gneisses and reworked Archaean basement gneisses. Reesor *et al.* (1975) and Okulitch *et al.* (1977, 1978a) mapped at the scale 1 : 50,000 most of the deformed zone exposed in the southern Melville Peninsula where the Aphebian Penrhyn Group and its Archaean basement complex comprise the Foxe Fold Belt. Their maps show that NE–SW and E–W striking upright folds largely account for the regional trend of lithologic units in the fold belt. Okulitch *et al.* (1978b) suggested that the upright folds are superimposed on several fold or thrust nappes. This paper describes some mesoscopic and macroscopic sheath folds with horizontal central axes that account for some of the complex outcrop patterns in the Foxe Fold Belt. It is concluded that sheath folds may have formed in a deep-crustal horizontal shear regime below a thick nappe.

REGIONAL GEOLOGY

The major structural element of the Hudsonian Orogen in northeast Canada appears to be a more or less triangular-shaped metamorphic core area centred near Cumberland Sound in Baffin Island (Fig. 1). Migmatitic granulite facies gneisses make up most of the metamorphic core complex. These gneissic rocks are intruded by numerous syn- to postkinematic Hudsonian granites (Jackson & Morgan 1978).

Several more or less arcuate belts of mainly amphibolite facies Aphebian supracrustal gneisses occur on the periphery of the high-grade core region. North and west of the core region deformed and metamorphosed Aphebian sedimentary sequences define the Foxe Fold Belt in Baffin Island and the Melville Peninsula (Jackson & Taylor 1972). In the Melville Peninsula, the Aphebian Penrhyn Group, which consists of a basal quartzite formation, a middle marble and calc–silicate gneiss formation, and an upper pelitic and psammitic gneiss formation, has been distinguished from an Archaean basement complex of mainly granitic gneisses (Henderson in press).

South of the Cumberland Sound metamorphic core area, the limit of Hudsonian dynamothermal metamorphism is defined by an abrupt decrease in the intensity of metamorphism and deformation within the Aphebian supracrustal rocks composing the fold belts facing the Archaean craton in the Ungava Peninsula (Davidson 1972, Dimroth & Dressler 1978). North and west of the Cumberland Sound core area, the intensity of deformation and metamorphism displayed by the Aphebian rocks composing the Foxe Fold Belt apparently does not decrease, and the extent of Hudsonian reworking within the Archaean basement gneisses is not known.

According to studies of coexisting Fe–Mg silicate minerals collected from the Foxe Fold Belt in the Melville Peninsula, the climactic metamorphic conditions were about 650°C and 500 MPa (Mazurski 1980, Henderson in press). A Rb–Sr whole-rock isochron study of the Penrhyn paragneisses carried out the Geological Survey of Canada indicates an age of 1804 ± 16 Ma (λ^{87}Rb = 1.42 × 10^{-11} a^{-1}) for the Hudsonian metamorphism in The Melville Peninsula.

Outline of the regional structural geology

In the eastern Melville Peninsula at least seven open, upright folds can be detected by noting regional variations in the direction of dip of isoclinally folded foliations (Fig. 2). Near the Foxe Basin the axial traces of individual upright folds are spaced 10–30 km apart; they become progressively more closely-spaced towards the west-southwest, and they form a tight bundle of upright folds north of Lyon Inlet. Although the upright folds are large and tend to form the dominant element of the structural grain in the Melville Peninsula they are second-order structures. The first-order structures are fold and

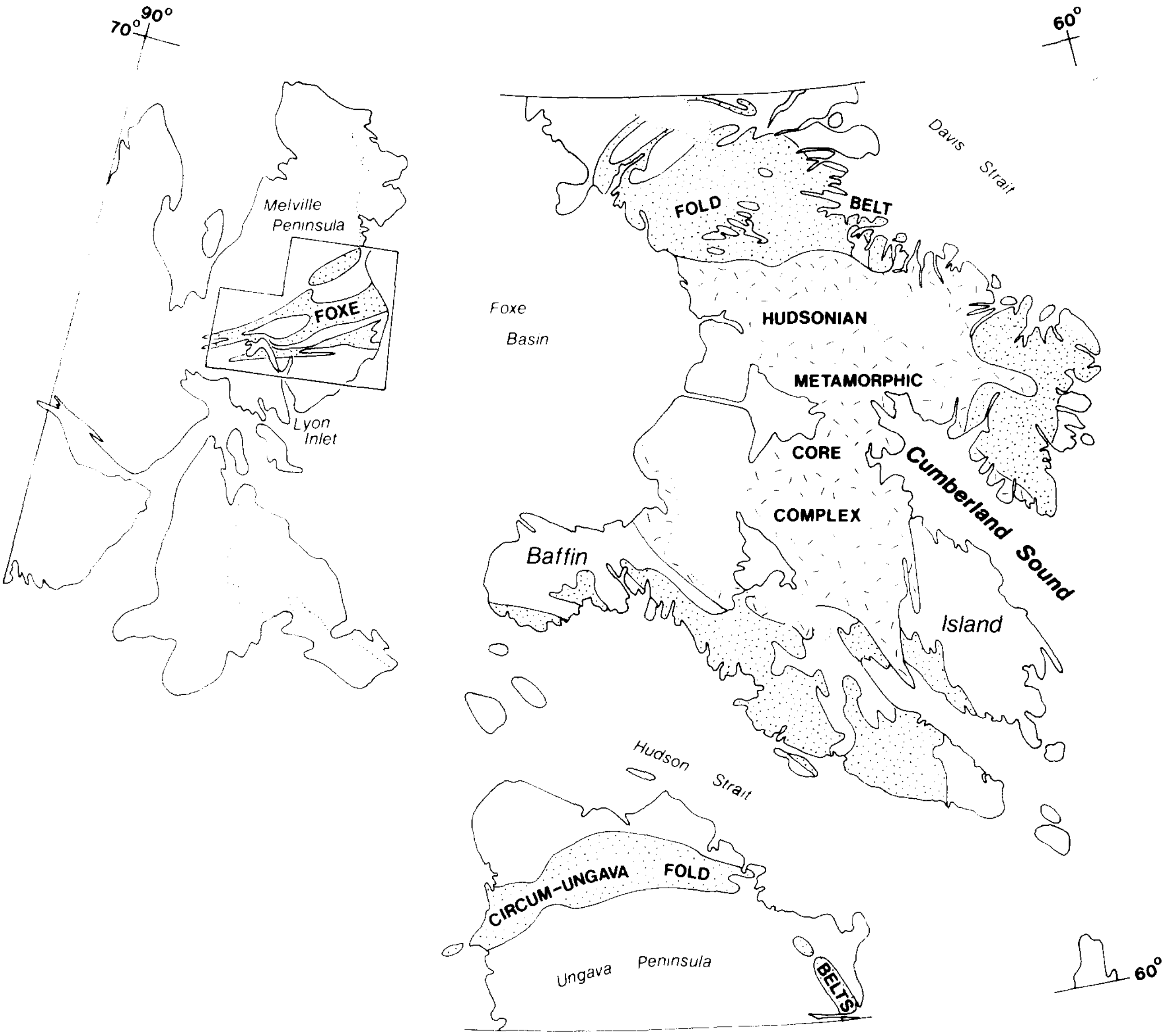


Fig. 1. Major structural elements of the Hudsonian Orogen in northeast Canada. Aphebian supracrustal rocks are shown by stippled dots. The Melville Peninsula (Fig. 2) is outlined.

thrust nappes which are revealed within extensive areas containing an inverted stratigraphic sequence. For example, Fold 1 (Fig. 2) exposes Aphebian supracrustal rocks in an antiformal window, and Fold 2 preserves Archaean basement gneiss in a synformal klippe. In a simplified cross-section of the Foxe Fold Belt (Fig. 3), Penrhyn Group rocks may be shown to occur below two large nappes composed of Archaean basement gneiss. In the restored part of the cross-section it is suggested that Archaean rocks in the Upper Nappe originally covered all of the Aphebian rocks exposed in the eastern Melville Peninsula. On the map (Fig. 2), the Archaean rocks in the Lower Nappe may be traced on the north-dipping limb of Fold 5 from the line of the cross-section to the head of Lyon Inlet where they curve northwards towards a group of intricately-folded bands of Archaean basement gneiss. In the cross-section (Fig. 3) this structurally complex region is projected diagrammatically as the upward curling bulge in the Lower Nappe. Southwest of Lyon Inlet the Penrhyn Group is apparently not exposed and the Foxe Fold Belt loses its identity in reworked Archaean basement gneisses and Hudsonian granites.

STRUCTURAL FABRICS

Planar elements

In most of the Penrhyn Group relict bedding is defined by 0.1–1.0 m-thick lithological layering. Most pelitic gneisses are migmatitic and contain 20–40% coarse grained leucosome in 1.0–10 cm-thick bedding-parallel laminae. In pelitic gneiss and marble, disseminated flakes of biotite and graphite define a weak bedding-parallel mineral foliation. Archaean basement gneisses are commonly differentiated into granitic and granodioritic layers, and the gneissic layering is conformable near contacts with the Penrhyn Group. Nearly all the rocks from the region which were examined in thin section display granoblastic, mosaic or micrographic textures.

Linear elements

A mineral lineation occurs in some impure marbles where tetragonal prisms of scapolite define a linear

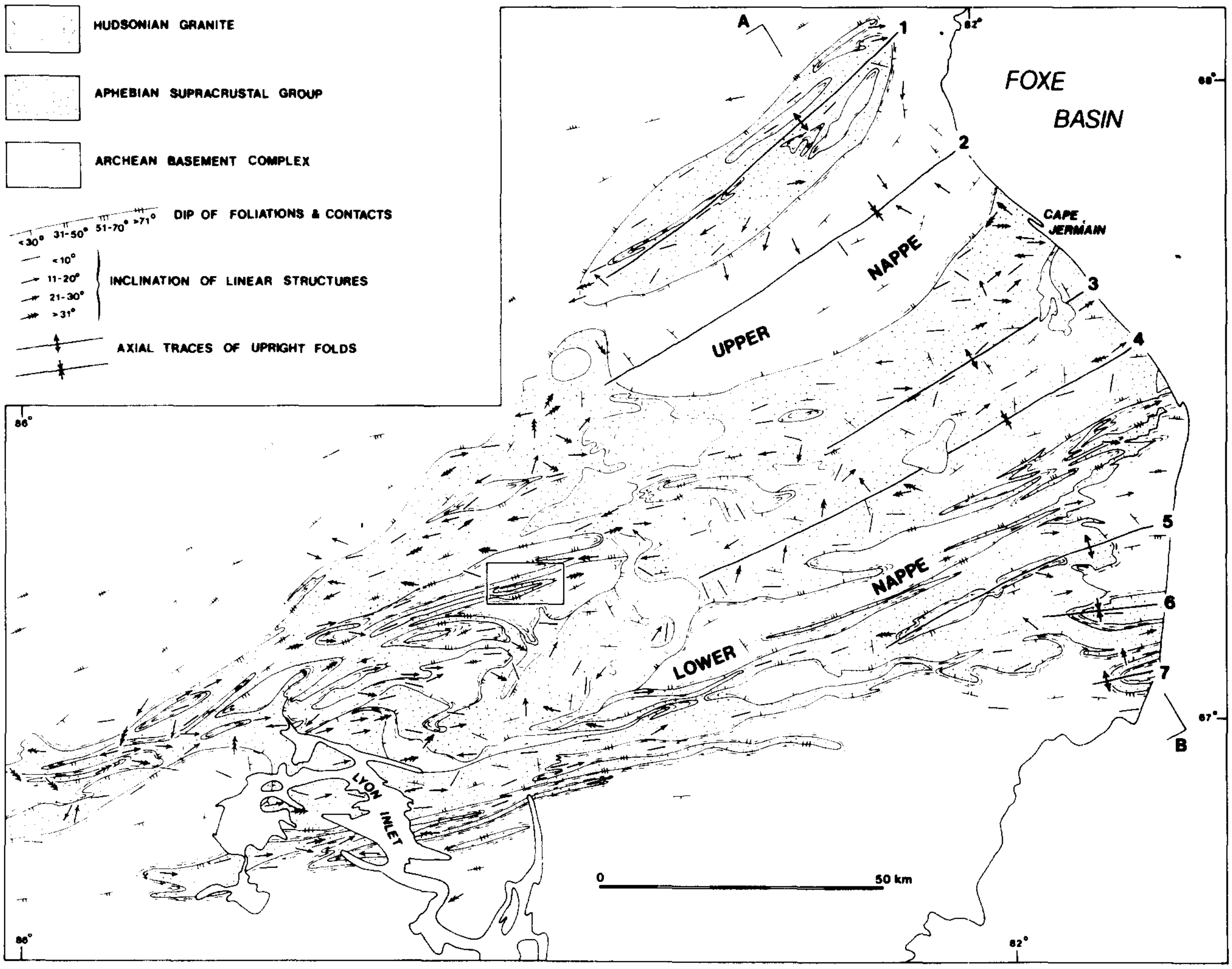


Fig. 2. Major structural elements of the Foxe Fold Belt in the Melville Peninsula. Axial traces of seven upright folds in isoclinally folded foliations are shown. The line of cross-section A–B (Fig. 3) is indicated, and the area north of Lyon Inlet (Fig. 7) is outlined.

structure (Fig. 4). This linear pattern was apparently formed by the modification of an earlier planar fabric pattern by passive rotation of brittle scapolite porphyroblasts in a ductile calcite matrix. For example, Hill (1978) observed in marble near Cape Jermain that rocks with moderately to strongly aligned scapolite contain broken and boudinaged crystals, and that long fibres of calcite are aligned parallel to the lineation direction in the pull-apart regions.

Interbedded marble and calc–silicate sequences in the Penrhyn Group commonly show mullion structure (Wilson 1953). Bedding mullions are defined by more or less parallel wrinkles and corrugations on the surfaces of calc–silicate beds that were in contact with calcite marble (Fig. 5). Commonly, several sets of bedding mullions appear to intersect at a small angle. On a slightly larger scale cylindrical intrafolial folds with semicircular profiles are called fold mullions. Where they occur in proximity, mullion structure and scapolite lineation are similarly aligned.

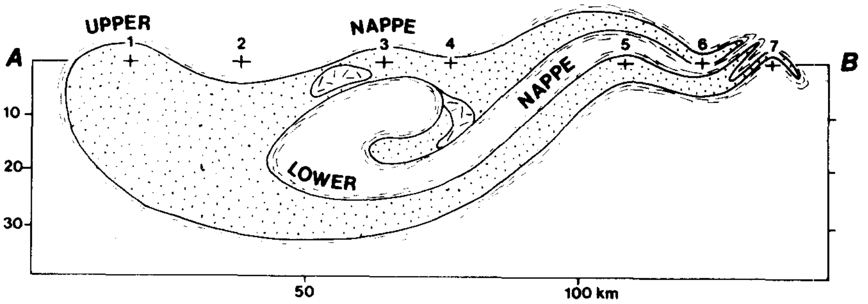


Fig. 3. Simplified cross-section of the Foxe Fold Belt (view northeast between A–B in Fig. 2). Upright folds 1–7 are labelled. Aphebian supracrustal rocks are shown by stippled dots; Hudsonian granites are shown by stippled dashes.

SHEATH FOLDS

Folds possessing paraboloidal forms occur in marble and calc–silicate beds exposed near Cape Jermain. In the classification of noncylindrical folds by Williams & Chapman (1980), the paraboloidal folds in the Foxe Fold Belt are mainly isoclinal domes. Some of these folds closely resemble the sheath folds described by Minnigh (1980), and his terminology is used in this paper. The central axis of a sheath fold is the X-axis, and the long and short axes of elliptical sections normal to X are referred to as Y and Z respectively. The sides of sheath folds which are more or less parallel to the XY-plane are called the limbs of the sheath fold. The elliptical paraboloid that is formed where the X-axis pierces the sheath fold is called the cap.

Mesoscopic sheath folds

Sheath folds are obvious only in rare exposures like those shown in Figs. 6(a–d). In Fig. 6(a) a sheath fold is exposed in the XY- and YZ-section, and in Fig. 6(b) a sheath fold is exposed in the YZ-section. In the Melville Peninsula sheath folds which are truncated normal to the X-axis are generally not regularly oriented ellipses. The Y-axis may be vertical or horizontal, or the YZ-section may be nearly circular. Also in YZ-section the limbs may form upward-curving or downward-curving crescents or the limbs may be involuted in more complex fashions than those shown in Fig. 6. The X-axes of sheath folds in the region are nearly horizontal and they are parallel to mullion structure developed on the limbs.

A pattern displayed by a group of isoclinal sheath folds exposed in the XY-section is shown in Figs. 6(c) and (d) and in Fig. 7. In Fig. 7 the X-axes of the sheath folds are nearly coincident with the surface of the outcrop. The limbs of the sheath folds are more or less horizontal and the bedding traces outline nearly symmetrical folds in XY-sections. Some of the sheath folds in Fig. 7 resemble cylindrical folds with vertical axes at the level of truncation shown, whereas other sheath folds shown in Fig. 7 resemble cylindrical folds with easterly and westerly inclined axes.

Three-dimensional model of sheath folds

Figure 8 is an attempt to depict in three dimensions a group of sheath folds with horizontal X-axes similar to the truncated folds shown in Figs. 6 and 7. In Fig. 8 it may be seen that if the two sheath folds with caps convex towards the left were truncated at the level coincident with their XY-plane, they would appear to be vertical cylindrical folds, but if they were truncated at levels parallel to, but higher or lower than, their XY-plane they would appear to be cylindrical folds plunging towards the left or plunging towards the right. It may be seen also in the model that the YZ-sections of the two sheath folds with caps convex towards the left are nearly circular, and that YZ-sections of the sheath folds with caps convex towards the right are upward-curving and downward-curving crescents. If the X-axes of the sheath folds depicted in the model were inclined slightly, elliptical, crescent-shaped and isoclinally folded sections would occur at the same level of truncation.

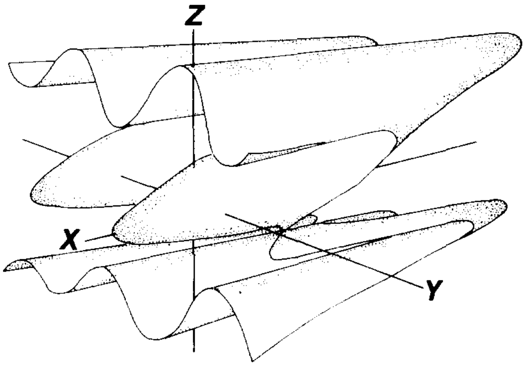


Fig. 8. Three-dimensional model of sheath folds with horizontal X-axes.

As a general rule it may be stated that an isoclinal sheath fold with a horizontal X-axis will resemble a cylindrical fold in most sections. This rule is especially true in horizontal sections where closed bedding traces do not occur and it is only in relatively small areas that the truncation surface intersects the sheath fold cap. For the geologist mapping in the field, exposures of sheath fold caps may be very rare.

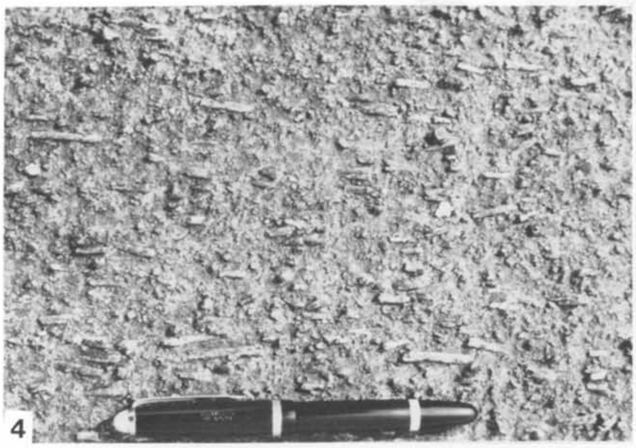
Geometry of a macroscopic sheath fold

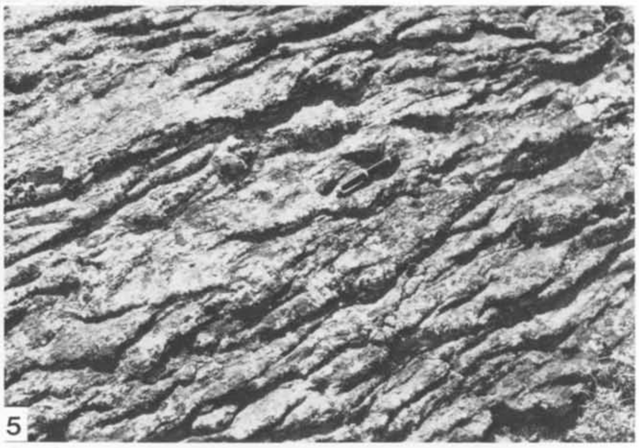
A particularly clear example of a truncated macroscopic sheath fold was mapped in the region north of Lyon Inlet (Fig. 9). In this area several belts of steeply inclined and isoclinally folded Penrhyn strata occur between elongate massifs of granitic basement gneiss on the upward-curling bulge of the Lower Nappe (Fig. 2). In the area shown in Fig. 9 the Archaean–Aphebian contact surface apparently defines an isoclinal syncline here called F_1, and the axial surface of the F_1 syncline apparently defines an isoclinal antiform here called F_2. Foliations on the limbs of the F_2 antiform are more or less vertical, and in the region of the 180° closure, where the crest of the F_2 antiform intersects the ground surface, the minimum dip is about 40°. Because the Penrhyn basal quartzite generally fills the space in the trough of the F_1 syncline it may be argued that the Archaean–Aphebian contact surface is nearly coincident with the level of erosion on the limbs and crest of the F_2 antiform.

The sheath fold shown in Fig. 10 seems to satisfy the foregoing constraints imposed on the Archaean–Aphebian contact surface. With reference to the three-dimensional model of mesoscopic sheath folds shown in Fig. 8 it appears that the sheath fold in Fig. 10 is identical to the sheath fold in the lower-right of Fig. 8.

PRINCIPAL STRAIN AXES INDICATED BY THE STRUCTURES

The sheath folds described in this paper deform Aphebian bedding surfaces, and apparently record bulk distortions imposed on those surfaces during the Hud-





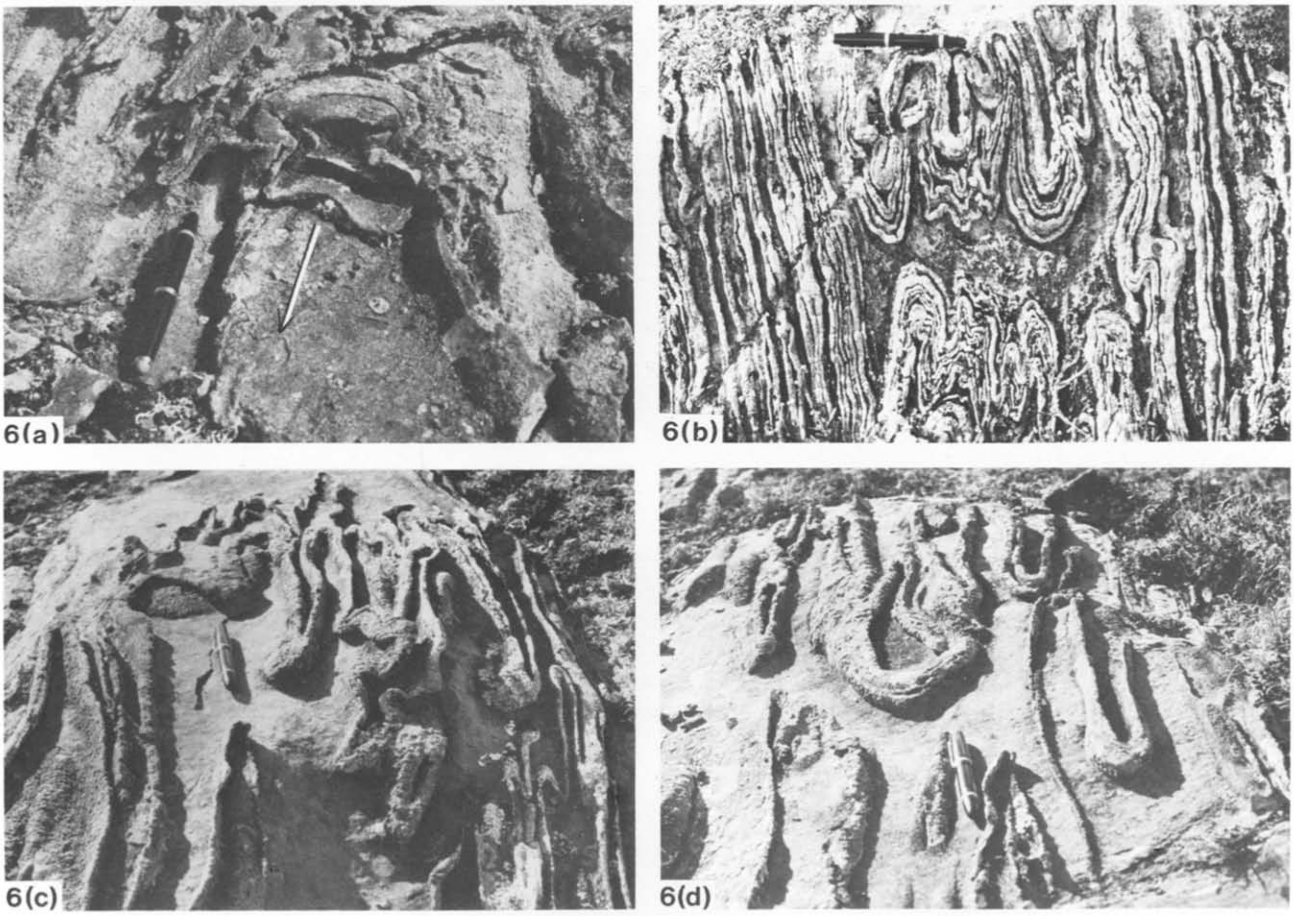


Fig. 4. Vertical view of moderately aligned scapolite porphyroblasts in a calcite marble located near Cape Jermain (Fig. 2). The pen shown for scale (13.5 cm) is parallel to the linear structure.

Fig. 5. Nearly vertical view of bedding mullions in calc-silicate gneiss located near Cape Jermain. Pen for scale (13.5 cm) is in centre of the photograph.

Fig. 6. Mesoscopic sheath folds in calc-silicate and marble beds located near Cape Jermain. (a) Oblique view of a truncated sheath fold. The arrow drawn in the photo is parallel to the X-axis (the arrow points 280° at an inclination of 20°). The pen lies on the surface of a bed in the lower limb, and the doughnut-shaped bedding traces are nearly parallel to the YZ-plane. In three dimensions the beds form a paraboloidal cap that is convex towards the background. (b) View parallel to sheath fold X-axes. The horizontal pen is parallel to the Z-axes in the vertical exposure. (c) Oblique view of isoclinal sheath folds exposed in horizontal XY-section. The pen is parallel to the X-axes. The beds shown can be seen in vertical view in Fig. 7. (d) Oblique view of isoclinal sheath folds exposed in a horizontal XY-section. The pen is parallel to the X-axes.

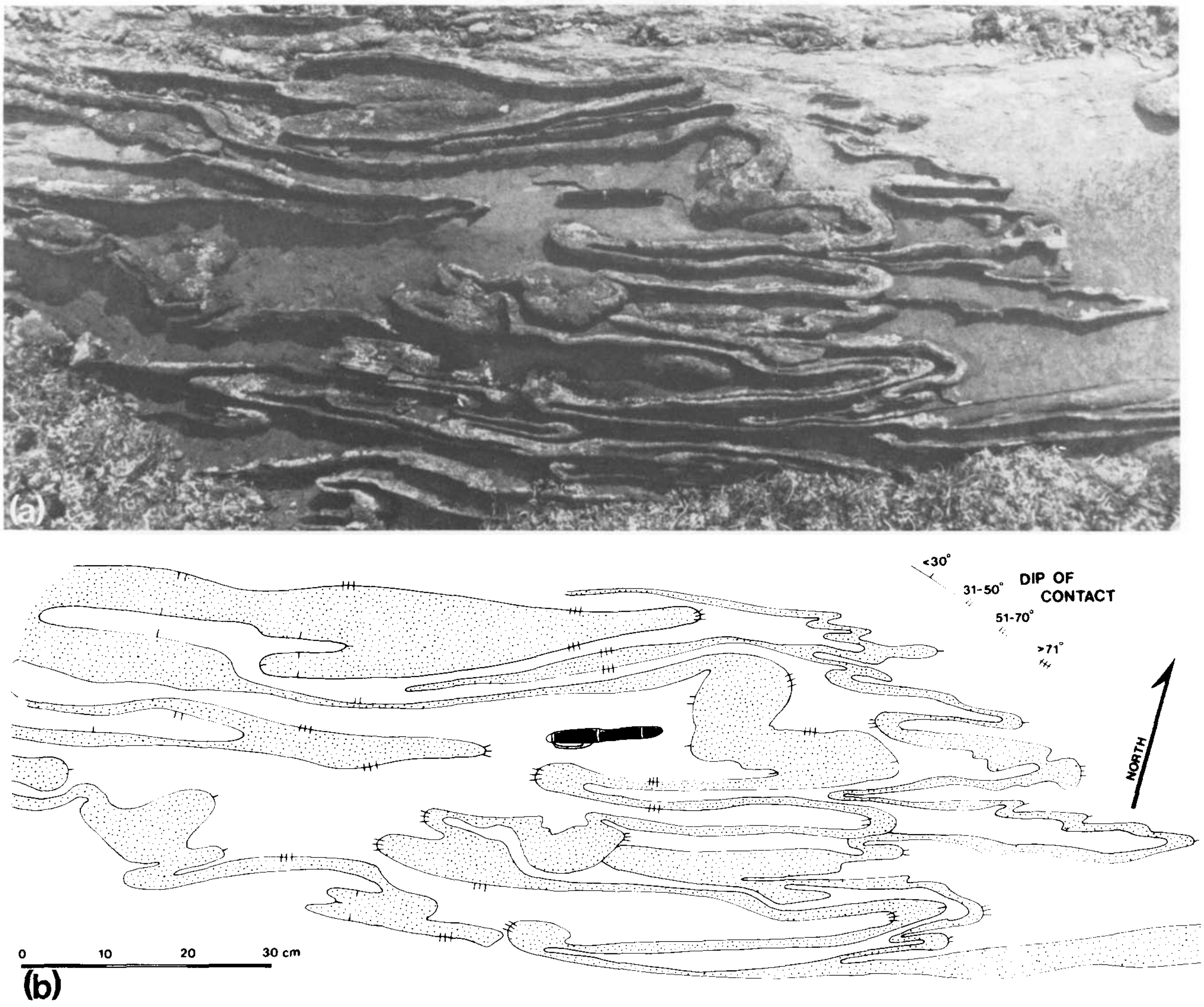


Fig. 7. (a) Vertical view of sheath folds exposed in a horizontal XY-section. The pen in the photo is aligned parallel to the X-axes of the sheath folds (declination of the pen is 070° to the right). (b) Geological map of sheath folds drawn from a photograph of the outcrop shown in Fig. 7(a). The calc–silicate bed is shown by stippled dots; marble beds are not ornamented.

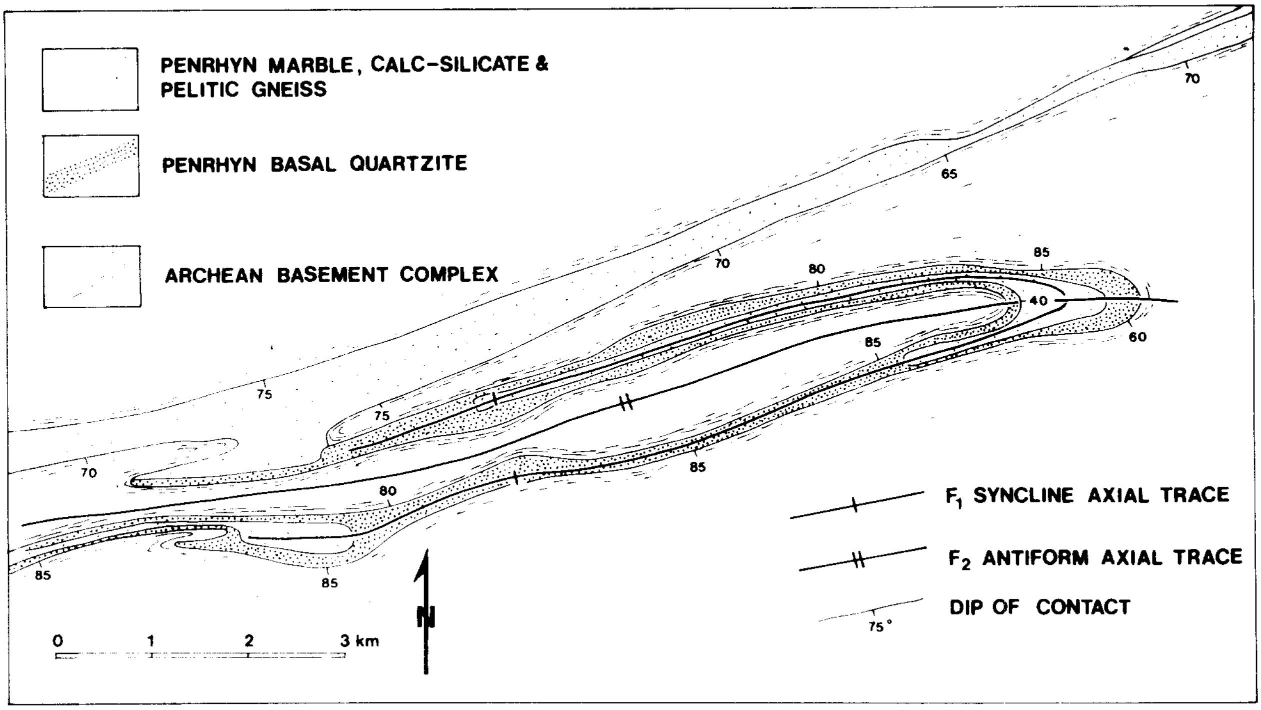


Fig. 9. Geological map of the region around a truncated macroscopic sheath fold located north of Lyon Inlet (Fig. 2).

sonian Orogeny. The sheath folds are mainly isoclinal and their X-axes are parallel to the direction of maximum elongation of the bulk strain ellipsoid. Stretched scapolite prisms, parallel to the X-axes of sheath folds indicate that the principal extension of the late-stage incremental strain ellipsoid was coaxial with the bulk principal extension direction. The direction of intermediate bulk strain is not defined by mesoscopic structures. It can be argued however that the intermediate direction of bulk strain is horizontal because the first-order structures in the region are nappes.

KINEMATIC INTERPRETATION

Although sheath folds themselves are indicative only of the bulk strain ellipsoid, their occurrence in the Melville Peninsula below the Upper Nappe of basement gneiss may have a kinematic significance. For example, Cobbold & Quinquis (1980) show that in XZ-section, asymmetric sheath folds may indicate the relative shear sense of bulk plane strain. If one considers the map surface to contain the shear direction in the Melville Peninsula, a consistent left-hand shear sense is indicated by asymmetric folds in the trace of the contact between Archaean and Aphebian rocks where they are exposed on the north-dipping limb of Fold 5 (Fig. 2). This interpretation suggests that the sheath folds were formed in a horizontal shear regime beneath the Upper Nappe. Using the Lower Nappe (Fig. 2) as a reference surface, the overlying rocks would appear to have flowed southwest relative to the rocks below. Also, the apparent south-westwards convergence of extension axes would appear to correspond to a parallel convergence in the flow lines, which according to Price (1972) is characteristic of extending flow. The kinematic model is consistent with the notion that the root zone of the nappes is in the metamorphic core region centred around Cumberland Sound (Fig. 1).

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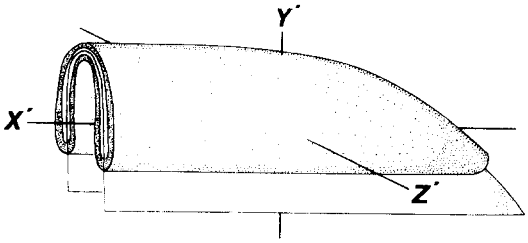

Fig. 10. Three-dimensional model of a sheath fold as suggested by the geometry of F_1 and F_2 folds mapped in the area shown in Fig. 9. The $X'Y'$-plane is coincident with the axial surface of the F_2 antiform, and the $X'Z'$-plane is coincident with the level of erosion in the area (see Fig. 9).

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