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Article abstract

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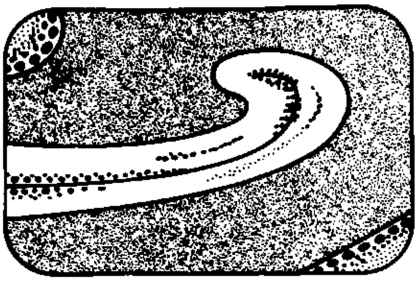
In most outcrops local younging of strata is readily determined from graded beds. When bedding and local younging are projected onto the axial planar cleavage, the structural facing of the folds and the stratigraphic younging of the succession as a whole is in the direction of the younger strata along a line at right angles to the trace of bedding in the cleavage. At Hazelwood Lake the trace of bedding on the cleavage is commonly subvertical and therefore the structural facing of the folds is primarily side ways. Reversals in the structural facing direction imply that these F2 folds were generated in previously folded strata.

A succession of metavolcanic rocks in contact with the polyphase deformed meta-sedimentary terrain appears also to have been folded by the F2 event.

The nature of the contact prior to the F2 folding, the presence of previous folds in the metavolcanic rocks, and their stratigraphic position with respect to the grey-wackes and slates are not clear from the available data.



Use of Stratigraphic and Structural-Facing Directions to Delineate the Geometry of Refolded Folds Near Thunder Bay, Ontario

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Summary

North and west of Thunder Bay Archean rocks of the western Superior province consist of metasedimentary schists, gneisses, migmatites and granitic plutonic rocks of the Quetico belt in contact with metamorphosed pillow lavas and various volcanoclastic rocks of the Wawa belt.

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A succession of metavolcanic rocks in contact with the polyphase deformed metasedimentary terrain appears also to have been folded by the F_2 event.

The nature of the contact prior to the F_2 folding, the presence of previous folds in the metavolcanic rocks, and their stratigraphic position with respect to the greywackes and slates are not clear from the available data.

Introduction

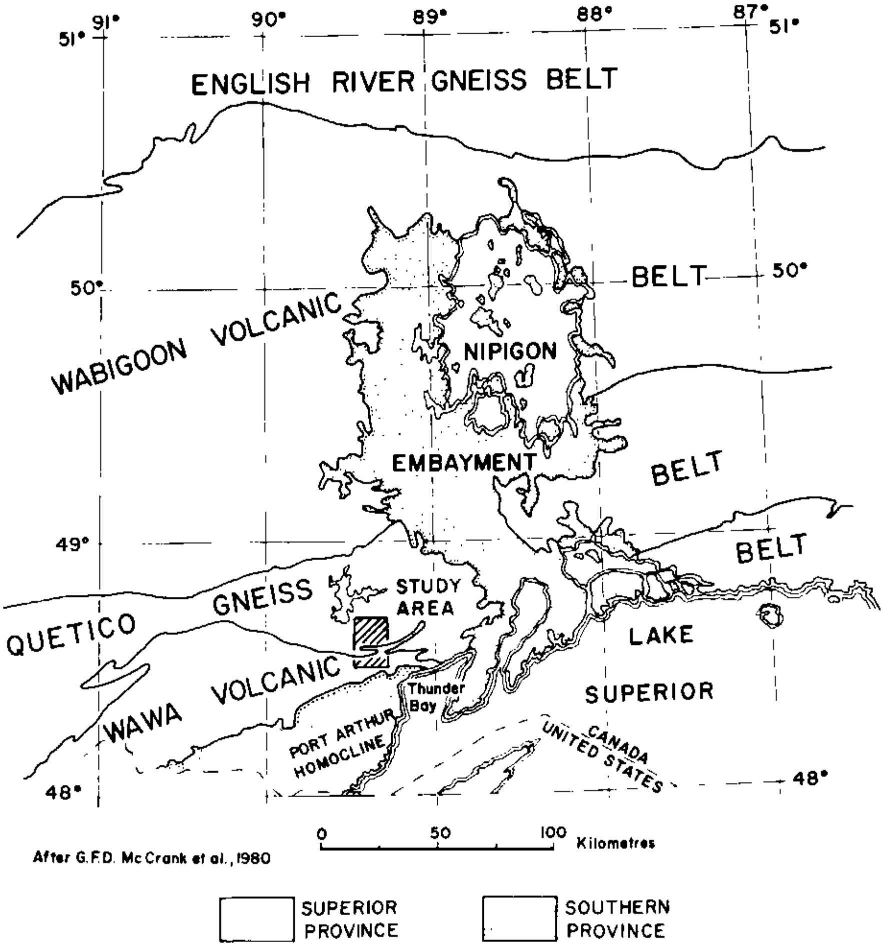
The Archean rocks of the western Superior province of the Canadian Shield have been grouped into a number of subprovinces or belts (Stockwell, 1970). The Quetico subprovince (Fig. 1) is one of several belts in which linear structures possess predominantly easterly trends. The Wawa subprovince is an example of those portions of the Superior province where curvilinear structures prevail (Stockwell, 1964).

In addition, broad lithological associations also appear to be typical of each type of belt. In the region north and west of Thunder Bay, the Quetico gneiss belt is primarily composed of metasedimentary schists and gneisses, migmatites and a variety of granitic to intermediate plutonic rocks. In contrast the Wawa volcanic belt is represented by a terrain in which basic, intermediate, and felsic volcanic flows and volcanoclastic rocks generally occur in close proximity to large granitic bodies.

Although these lithological characteristics are useful in identifying large portions of the Archean crust as either volcanic or gneissic belts, they appear to be less reliable as criteria on which to base the position of belt boundaries.

It is a familiar occurrence to find boundaries drawn parallel to a contact between metavolcanic and metasedimentary rocks, although these rocks may occur interlayered over appreciable distances on either side of such a boundary. In the region, which includes the area of the present study (Fig. 1), the boundary between the Quetico and Wawa subprovinces is shown parallel to a geological contact separating metavolcanic and metasedimentary strata (McCrank *et al.*, 1980).

At Hazelwood Lake the contact between metasedimentary rocks and metavolcanic succession, including basic flows and intermediate to felsic volcanoclastic rocks, is parallel to the southern shoreline Fig. 2). East and west of the Lake the greywackes and slates are exposed farther south and are separated from the main metasedimentary terrain by narrow, discontinuous



After G.F.D. McCrank et al., 1980

Figure 1 *Map of part of the Western Superior province showing a number of subprovinces and their boundaries* zones of basic to intermediate volcanic rocks.

North of Hazelwood Lake the metamorphic grade of the rocks increases gradually. Near the contact with the grey and pink biotite gneisses and migmatites (Fig. 2) cordierite-staurolite-, garnet- and sillimanite-bearing assemblages are common. Several porphyritic quartz-monzonite plutons (Kehlenbeck, 1977) and hornblende-biotite granites intrude the Archean rocks. In most exposures of the metasedimentary rocks it is possible to establish the local younging direction based primarily on graded bedding.

The metavolcanic terrain consists mainly of volcanoclastic rocks. However, basic pillowed flows do occur and from some of these exposures bedding and local younging directions may be determined (Borradaile, 1982b; Borradaile and Poulsen, 1981).

A series of well-stratified siliceous siltstones, conglomerates, arkoses and iron formation is exposed within the metavolcanic terrain (Fig. 2). These sedimentary rocks lack primary structures; therefore, the determination of local younging directions is difficult. Macdonald (1939) suggested that these sediments (post-Keewatin) overlie the metavolcanic rocks (Keewatin) and that the latter are underlain by the sequence of greywackes and slates (Coutchiching). Macdonald based his conclusions on a number of outcrops of metasedimentary and metavolcanic rocks in which the local younging direction is consistently southward.

Structural Elements

The overall geometry of the structure is interpreted on the basis of the detailed structural mapping in the metasedimentary rocks at Hazelwood Lake and the immediate surrounding area.

Orientations of bedding planes (S_0) were readily obtained from exposures of the well stratified sequence of greywackes and slates (Fig. 3A). In these rocks, grain size gradation makes it possible to determine the local younging direction in most outcrops (Fig. 3A). In the metavolcanic rocks exposed just south of Hazelwood Lake, bedding was difficult to establish. In one exposure of basic pillowed flows (Fig. 3A) the local younging component and bedding orientation could be resolved.

A well developed cleavage (S_1) is present in almost all outcrops (Fig. 3B). Careful examination of a number of thin sections showed that the rocks possess only one cleavage (Fig. 4). In the coarse-grained rocks, individual well-rounded quartz grains are enclosed by dark-coloured cleavage folia producing an overall anastomosing pattern. In some examples, larger quartz grains are truncated by cleavage folia, suggesting dissolution of quartz at these

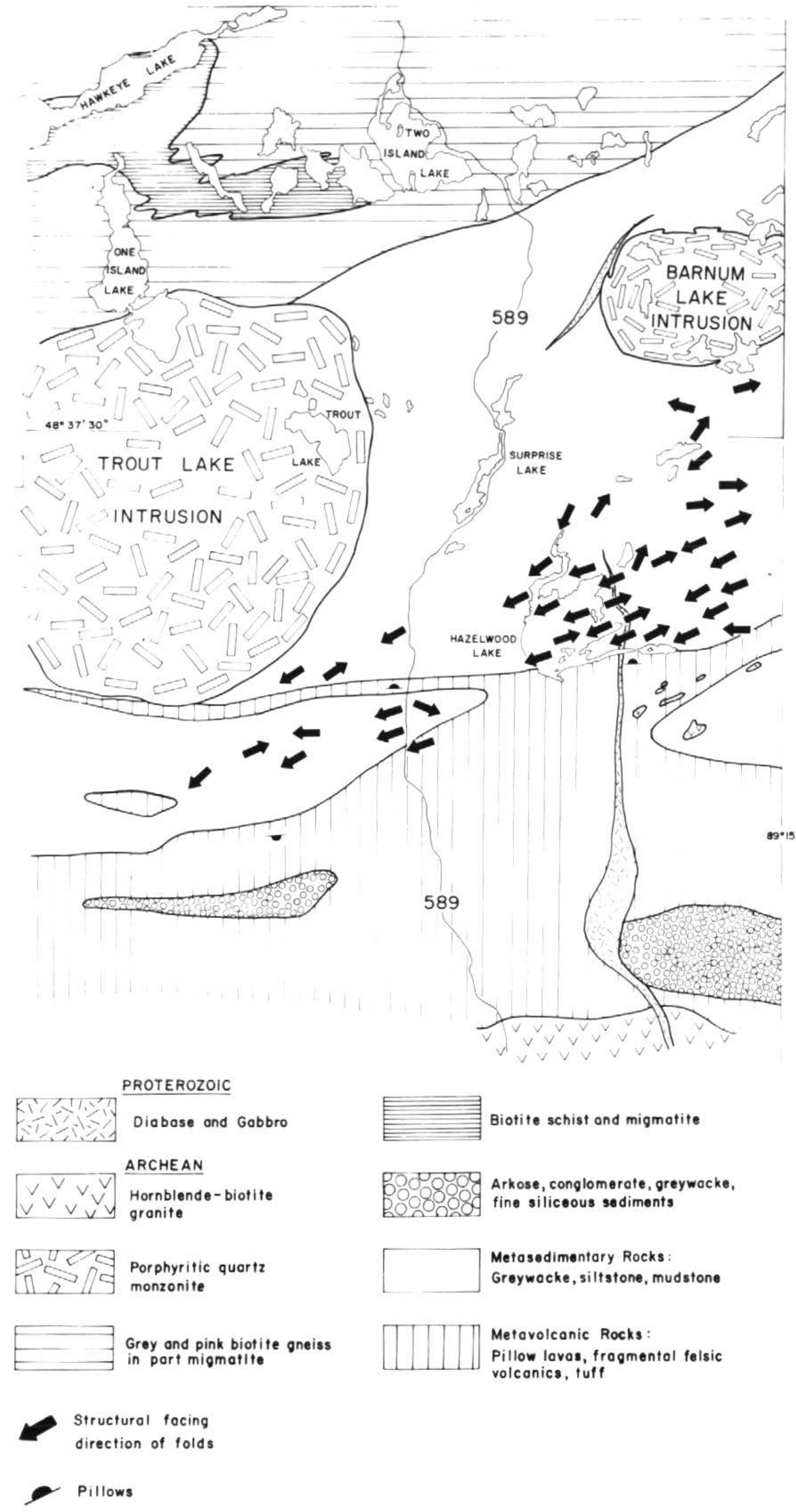


Figure 2 *Distribution of the main rock types and structural facing of dominant folds north of Thunder Bay, Ontario*

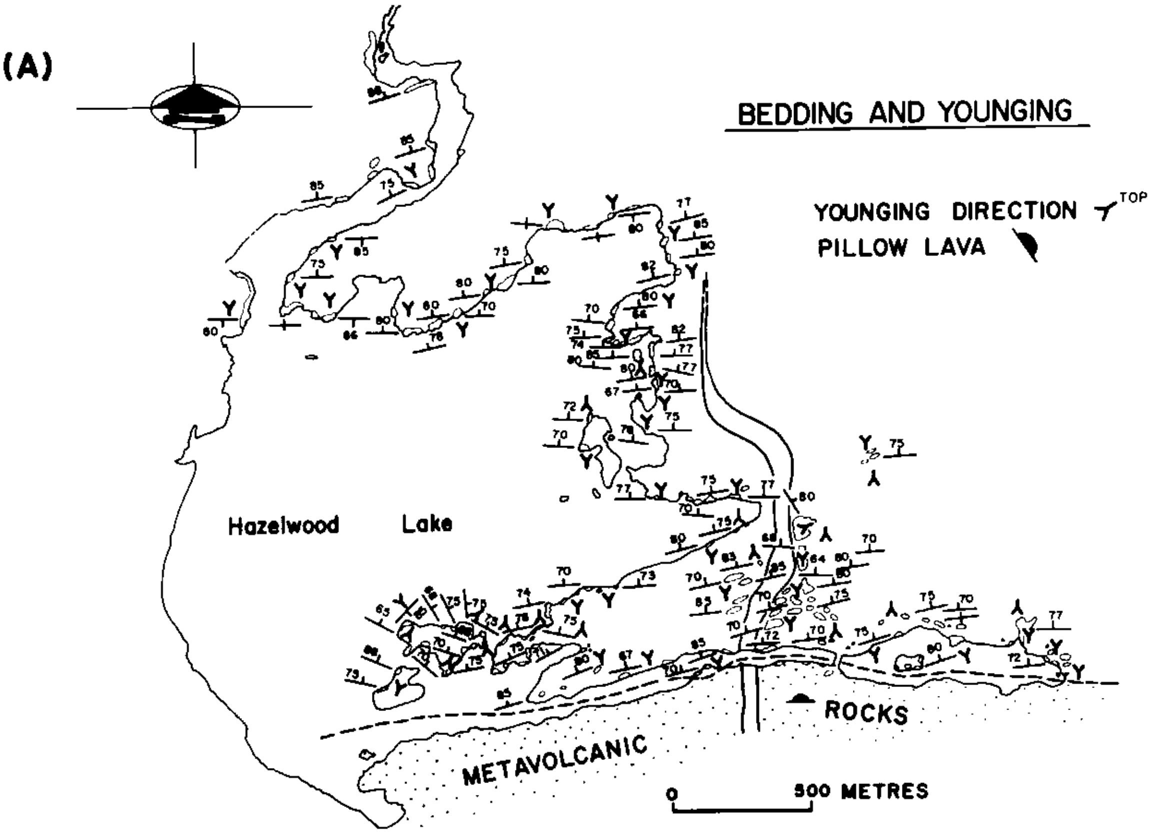


Figure 3A *Attitudes of bedding planes and local younging directions at Hazelwood Lake*

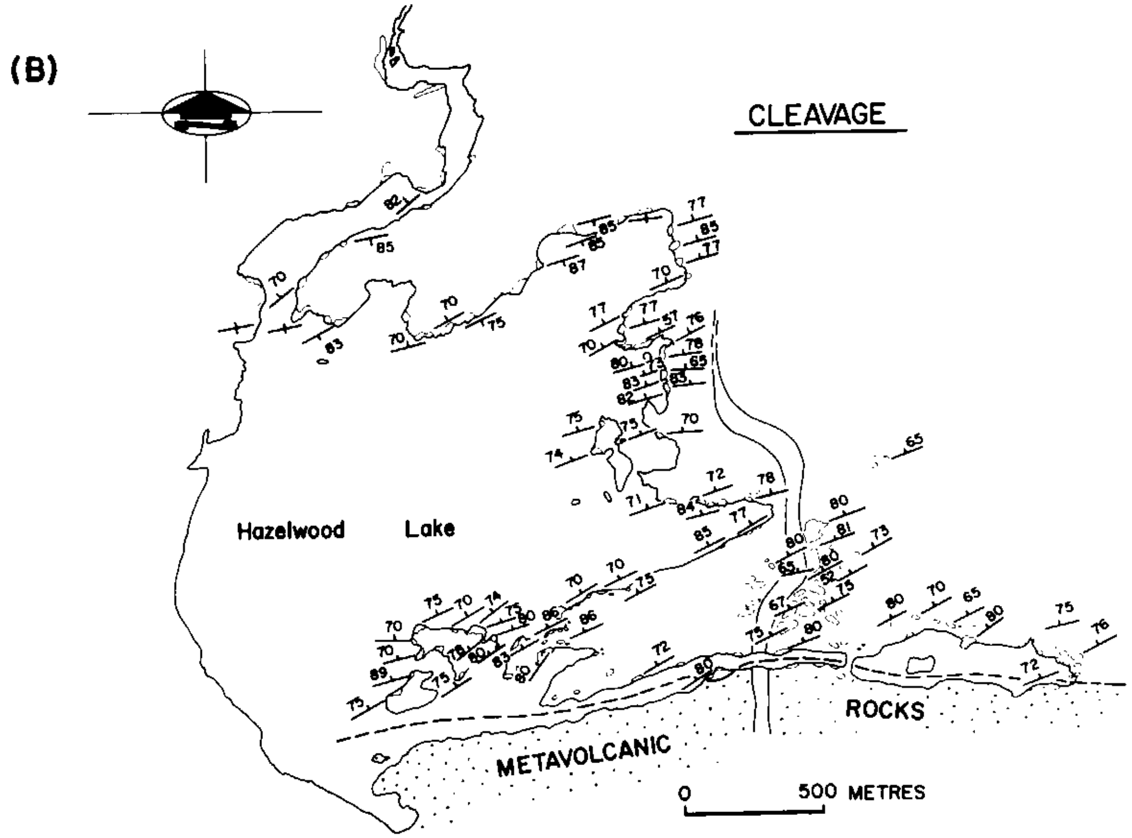


Figure 3B *Attitudes of cleavage planes at Hazelwood Lake* boundaries. Similar textures are reported by Powell (1982a, p. 300-302). In some sections closely spaced cleavage folia occur, and here elongated quartz grains of smaller size are typically encountered.

In some examples of the interbedded slaty rocks, small dikelets composed of quartz grains have been intruded downward into the underlying slaty material parallel to the cleavage direction (Fig. 4D). Immediately above these dikelets, concentrations of opaque material mark the place from which the clastic dikelet was derived. Maxwell (1962) cites a similar example of a sand dikelet which was injected downward from the source bed by a jet of water-soaked clay. Powell (1982b, p. 320) has suggested that such features and their parallelism to the cleavage demonstrate that the cleavage was initiated by liquefaction during tectonic dewatering of the rocks. Pressure solution, recrystallization and rotation during continued strain subsequently modified the initial fabric.

In Figure 4 examples of individual layer contacts show the development of load casts and flame structures. These features generally occur at the contact between different rock types or rocks of different viscosities, and may be a response to progressive compressive strain parallel to the layer boundary (Ramsay 1967, p. 382-386). In the present examples, these features typically occur at the base of individual graded beds where the less viscous underlying E horizons of the turbidite sequence (Bouma, 1962) project upward in flame-like structures into the overlying A horizons. Similarly, the structures occur also within individual graded beds at contacts separating rocks of different viscosities.

Bedding-cleavage intersection lineations were measured in the field wherever possible; the orientation of the lineation was obtained stereographically where direct measurement could not be made.

The stereograms (Fig. 5) summarize the attitudes of bedding (S_0), cleavage (S_1) and bedding-cleavage intersection lineation (S_0/S_1). Poles to bedding planes are distributed along a great circle girdle with a strong maximum (Fig. 5A). The pole of this girdle corresponds closely to the maximum of bedding-cleavage intersection lineations. Conversely, poles to cleavage are clustered about a maximum (Fig. 5B). Bedding-cleavage intersection lineations lie along a great circle girdle (Fig. 5C). The significance of this distribution will be discussed later. The synoptic diagram (Fig. 5D) shows the relationship between the planar and linear data.

Dominant Folds

A number of dominant folds were recognized in the field. The folds have steeply plunging hinge lines which parallel the dip direction of the axial surface. For this reason the folds close sideways and are neutral (Ramsay, 1967, p. 358). Two examples are given in Figures 6 and 7. Borradaile (1982) has pointed out that the cleavage associated with folds is an axial planar cleavage if angle $d = \Delta = 0$. In the present study, values of d are readily measured in the fold profile between the trace of the axial plane of the fold and the cleavage trace. In the case of the steeply plunging folds at Hazelwood Lake, the value of Δ is a measure of the difference in the dip amounts of the axial plane of the fold and the cleavage plane. Close examination of individual folds like those presented in Figures 6 and 7 shows that $d \simeq \Delta \simeq 0$ and that the S_1 cleavage is therefore coplanar, or nearly so, with the axial plane of the folds. In these single folds, bedding-cleavage intersection lineations measured in opposite limbs of the same fold are essentially coaxial.

Borradaile (1978) has shown that in cases of a nonaxial-planar cleavage typical of transected folds, the intersection lineations vary systematically in orientation when traced over the folded surface. In the present study, the S_1 cleavage is axial planar to a dominant set of folds, and the application of bedding-cleavage relationships is a useful mapping tool.

Structural Facing of Dominant Folds

The concept of structural facing was first used by Cummins and Shackleton (1955). Shackleton (1958) expanded the idea and defined it as the younging direction of strata at the hinges of primary folds. Borradaile (1976) extended the application of structural facing. He showed that the structural facing direction of primary folds can be obtained at any point on a folded surface by projecting the younging direction at that point onto the axial planar cleavage. This projected direction will be everywhere the same as the younging direction at the fold hinge and will reflect the direction in which the stratigraphy as a whole is getting younger. It should be noted that local younging directions derived from graded bedding or other primary structures may vary considerably around a fold. For this reason local younging recorded in individual outcrops of folded rocks should not be extended over large areas, nor should

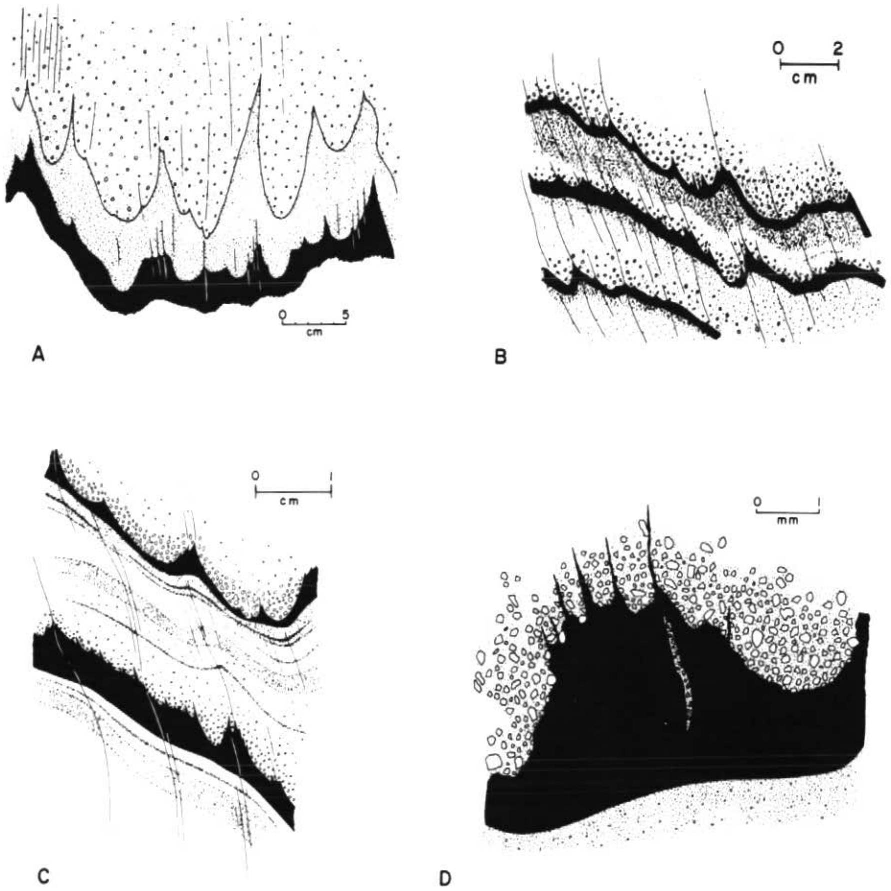


Figure 4(A-C). *Development of load casts and flame structures, possibly in response to a progressive compressive strain acting parallel to layer boundaries. Less viscous pelitic layers (black) project upward into more viscous silty and sandy layers.* **(D).** *Small clastic dikelet intruded downward into pelitic layer. Cleavage traces show refraction across the individual layers* the younging of the stratigraphic succession as a whole be implied from such data.

The use of structural facing was further extended to polyphase deformed terrains (Poulsen *et al.*, 1980). In such terrains the structural facing of later folds can be obtained by projecting local younging directions onto their accompanying axial planar cleavage. Reversals in the structural facing of folds make it possible to identify areas where the stratigraphy was previously affected by earlier folding episodes (Fig. 8).

For the two examples of individual folds (Figs. 6 and 7), the structural facing direction is toward the northeast everywhere, indicating a general younging of the stratigraphy in that direction. When these folds are traced eastward along the trace of the axial planar cleavage, a number of reversals in the structural facing direction occur (Fig. 9A). Such reversals also occur in parts of the area where no dominant folds have been observed in outcrop (Fig. 10). Reversals in the structural facing direction also occur in similar rocks to the southwest and northeast of Hazelwood Lake (Fig. 2).

Figure 9B is a schematic diagram based in part on the data presented in Figure 9A. The diagram shows a dominant fold with axial planar cleavage. Portions of this fold may be mapped using bedding-cleavage relationships, local younging directions and the asymmetry of minor folds as observed in individual outcrops. For example, data obtained from exposures A-B-C-D allow the construction of a part of the fold designated as zone 1 (Fig. 9B) in which the structural facing direction is consistently oriented to the southwest. Similarly, outcrops O-P-R-S and Q-T provide the required data to map out zones 2 and 3 of the fold, respectively. The structural facing direction in zones 1 and 3 is to the southwest. In zone 2, the direction in which the stratigraphy as a whole is getting younger, is to the northeast. Traverses parallel to the axial planar cleavage of the fold, through outcrops A-O-P-Q or D-R-S-T, indicate systematic reversals in the structural facing direction of the fold and local younging directions of the strata. However, the corresponding cleavage-bedding relationships and the asymmetry of minor folds observable in these outcrops do not change. These observations imply that the reversals in younging and structural facing directions reflect earlier folds and that the reversals mark the position of the axial planar trace of these folds. The constant nature of bedding-cleavage relationships and the asymmetry of minor folds in this example reflects the position of these outcrops on the limb of the later fold. It is important to recognize that the presence of folds cannot be ruled out solely on the basis of constant bedding-cleavage relationship or asymmetry of minor folds.

A summary of the structural facing directions for the dominant folds at Hazelwood Lake is shown in Figure 11. The stereograms show that these folds face either northeast or southwest and hence represent refolding of earlier folds. If there were

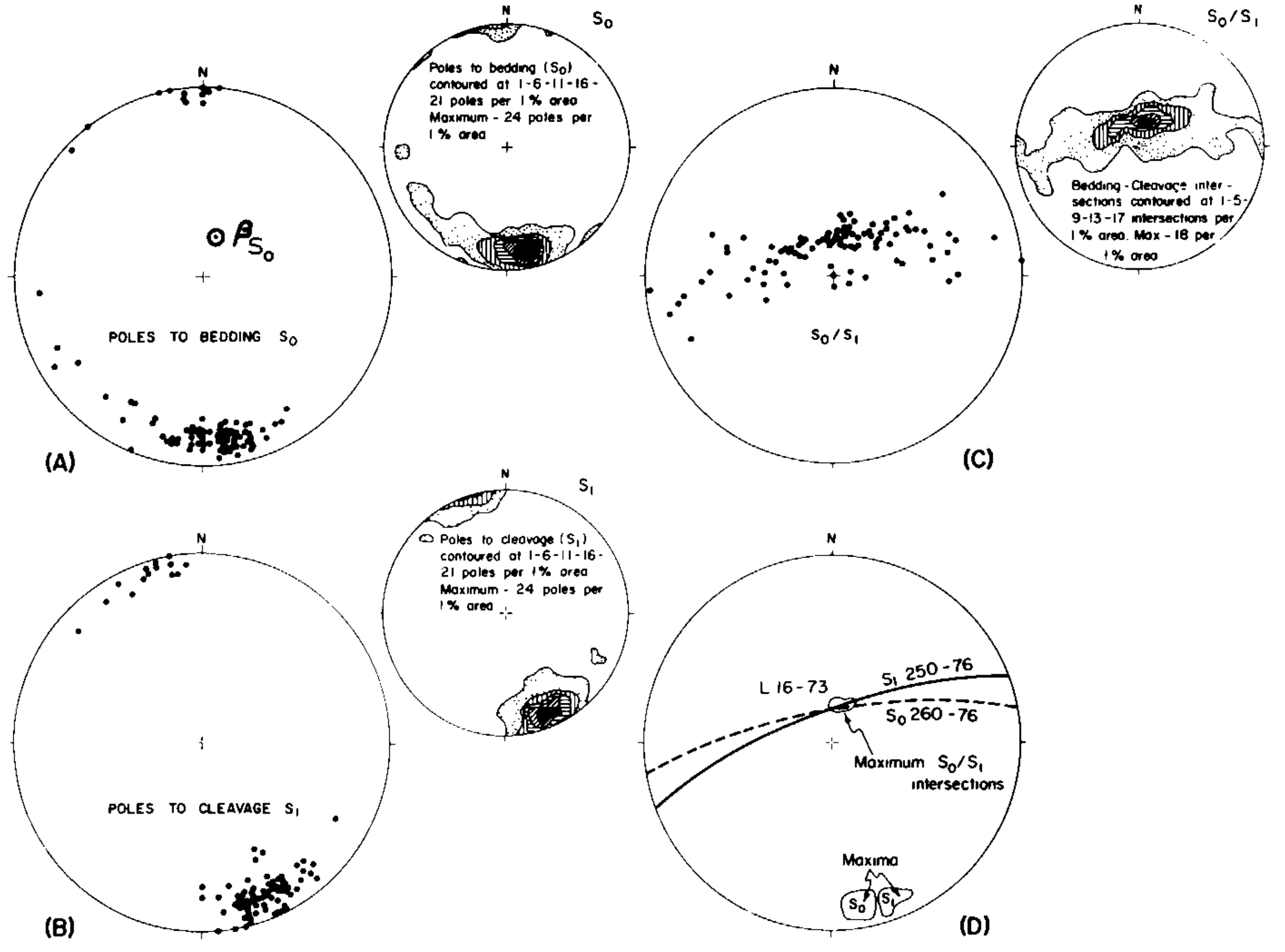


Figure 5 *Lower hemisphere, equal area projection of structural data from Hazelwood Lake*

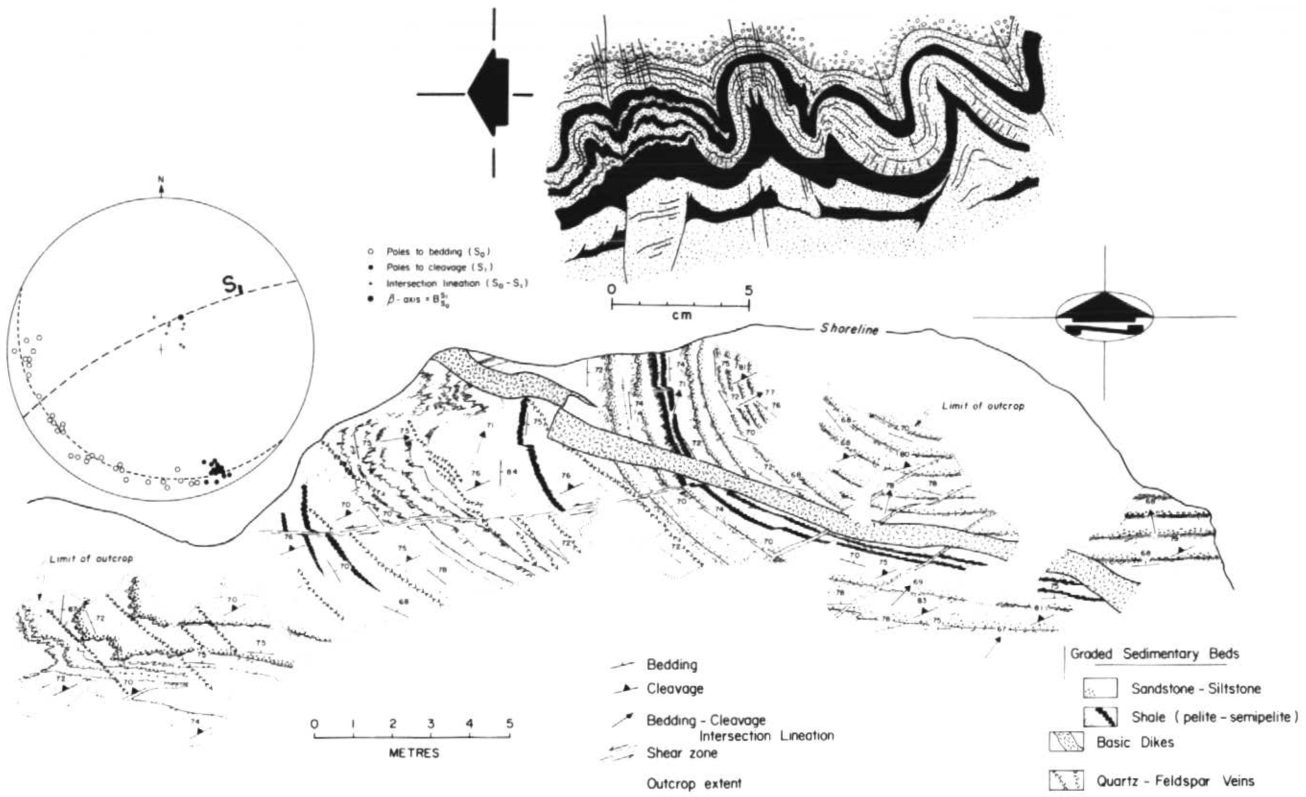


Figure 6 *Detailed map of a single exposure showing the hinge zone of a dominant plane cylindrical fold and accompanying axial planar cleavage. The structural facing of the fold here is northeastward, corresponding to the local younging direction at the fold hinge. The buckled layers (inset) are from the central portion of the outcrop about 2 metres south of the shoreline. See Figure 7 for location of this outcrop*

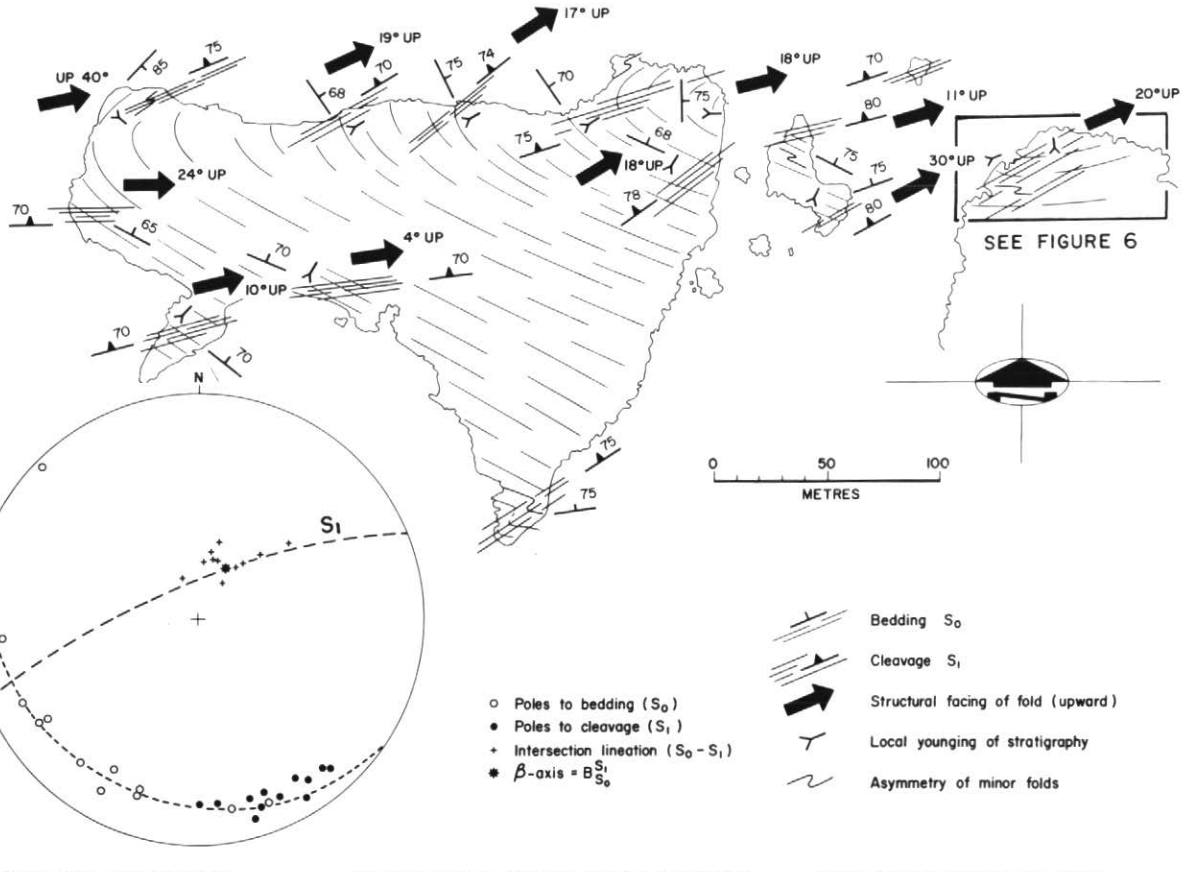


Figure 7 *Dominant plane cylindrical fold exposed on an island in the southwestern part of Hazelwood Lake. Note the consistent structural facing direction of the fold and the variably oriented local younging directions*

only one episode of folding, then the folds would face in a constant direction. The plunge of the structural facing direction of the folds is generally less than 30°; accordingly, these folds are designated as "sideways-facing".

Axial Distribution of Dominant Folds

It has been shown that the bedding-cleavage intersection lineations measured on opposite limbs of single folds (Figs. 6 and 7) are general coaxial. A review of Figure 5C shows that the intersection lineations representative of the entire area at Hazelwood Lake conform to a great circle girdle. The pole of the L-girdle corresponds closely to the maximum of the poles to the S_1 axial planar cleavage, suggesting that the S_1 cleavage was imprinted on a previously folded bedding surface (Turner and Weiss, 1963, p. 186). As Figure 5B shows, the axial planar cleavage has a fairly constant orientation. Ramsay (1967, p. 538) points out that the axial surfaces of new folds typically display little variation in attitude even when other planar and linear elements vary widely.

The attitude of S_0/S_1 lineations is effected by the variation in orientation of the surface undergoing folding. Where this variation in orientation is great, the new fold axes (S_0/S_1 lineations) will have a wide range in attitude, and this will result in a low axial distribution stability (Ramsay, 1967, p. 538-541). Similarly, low axial distribution stability in new fold axes may result where the initial angle between the axial surface of the new folds and the surface undergoing folding is small. Here slight variations in orientation of the surface being folded are inherited into the new fold geometry and are expressed by a wide range in axial direction (Ramsay, 1967, p. 542).

In most of the dominant folds observed at Hazelwood Lake, it appears that the surface undergoing folding varied little in attitude and that the initial angle between the S_1 axial planar cleavage of these folds and the surface being folded was relatively large. These conditions result in the high axial distribution stability of the folds (Figs. 6 and 7). Elsewhere in the area, significant variations in attitudes of S_0 have contributed to the wide range in S_0/S_1 orientations and a low axial distribution stability.

The S_0/S_1 lineation has a shallow plunge when S_0 and S_1, with different dips, have approximately the same strike. In this case the structural facing direction (perpendicular to the S_0/S_1 lineation) is approximately vertical and either up or down. The S_0/S_1 lineation is a near vertically plunging line when S_0 and S_1 have different strikes and very steep dips. In these cases, the structural facing is sideways. Between these extremes, variably oriented S_0/S_1 lineations will be reflected by ranges in the

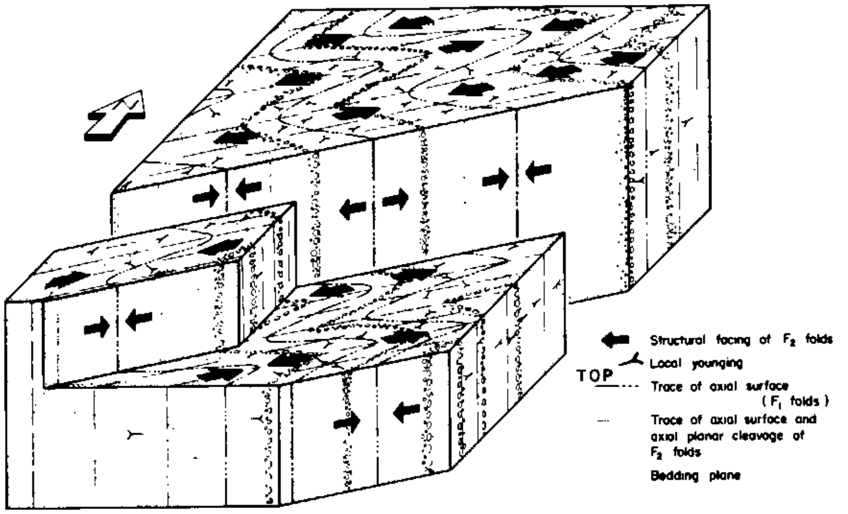
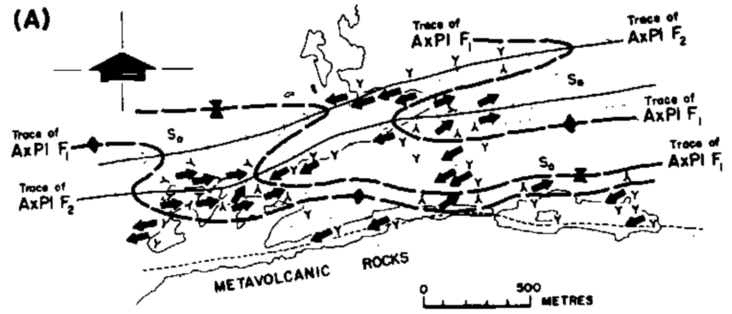


Figure 8 *Schematic diagram of vertically plunging plane cylindrical F_2 folds developed in limbs of horizontal normal upright F_1 folds. The structural facing of the F_2 folds on the accompanying axial planar cleavage is sideways. The structural facing direction of the F_2 folds as seen in map view is to the northeast in one limb of the F_1 structures and to the southwest in the other limb*



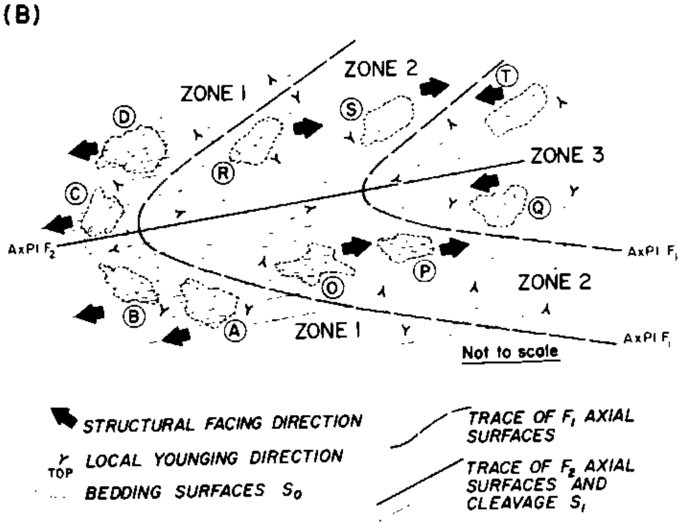


Figure 9A *Distribution of bedding (dotted line), younging directions (Y), structural facing directions of dominant F_2 folds (arrows), and axial surface traces of F_1 and F_2 folds from the southern part of the area.*

Figure 9B *Schematic diagram of a number of typical outcrops near the hinge of F_2 folds. See text for explanation* structural facing from upward to sideways to downward. However, the direction of structural facing of later folds will be consistent over areas bounded by the axial surfaces of the earlier folds.

Borradaile (1982a) reports a similar distribution for S_0/S_1 lineations measured in folded rocks at Calm Lake, near Flanders, Ontario. There, the structural facing direction of a set of first generation folds is consistently to the northeast. The folds, however, range from upward- through sideways- to downward-facing, implying that the hinges of the major folds are curvilinear and that the folds are plane noncylindrical folds (Turner and Weiss, 1963, p. 109).

Discussion and Conclusion

It now appears appropriate to refer to the dominant folds at Hazelwood Lake as F_2 folds to which the S_1 cleavage is axial planar. These F_2 folds developed in bedding surfaces of variable orientation resulting at least in part from a previous folding episode. A number of exposures provide evidence of such refolded F_1 structures (Fig. 12).

The prevalance of steeply plunging F_2 hinge lines results in the dominant sideways structural facing of F_2 folds. Occurrence of upward- or downward-structural facing of F_2 folds, in places, where the plunge of the S_0/S_1 intersection lineation is low to moderate, may indicate geometric properties of the earlier structure, such as F_1 hinge zones.

The three-dimensional diagram (Fig. 13A) shows the refolding of the earlier F_1 folds by F_2. A possible distribution of strata resulting from the refolding of F_1 anticlines and synclines is given in Figure 13B. Lack of recognizable stratigraphic markers prevents the mapping of individual stratigraphic horizons and makes it difficult to speculate on the geometry of the F_1 structure. Nevertheless, the representations appear to be in good agreement with the data collected during the structural mapping.

The structural complexities recorded in detail at Hazelwood Lake have also been found to occur outside the area of the present study. Reversals in the structural facing direction on the S_1 cleavage in identical rocks are present southwest and northeast of Hazelwood Lake as shown in part by Figure 2. To the southwest, the outcrop extent of the metasedimentary strata is bounded by the metavolcanic rocks. Isolated exposures of volcanoclastic rocks also occur sporadically within the metasedimentary terrain. In exposures of both types of rock, the S_1 cleavage is prevalent. Lack of primary structures in the metavolcanic suite make it impossible, in most cases, to determine the local young-

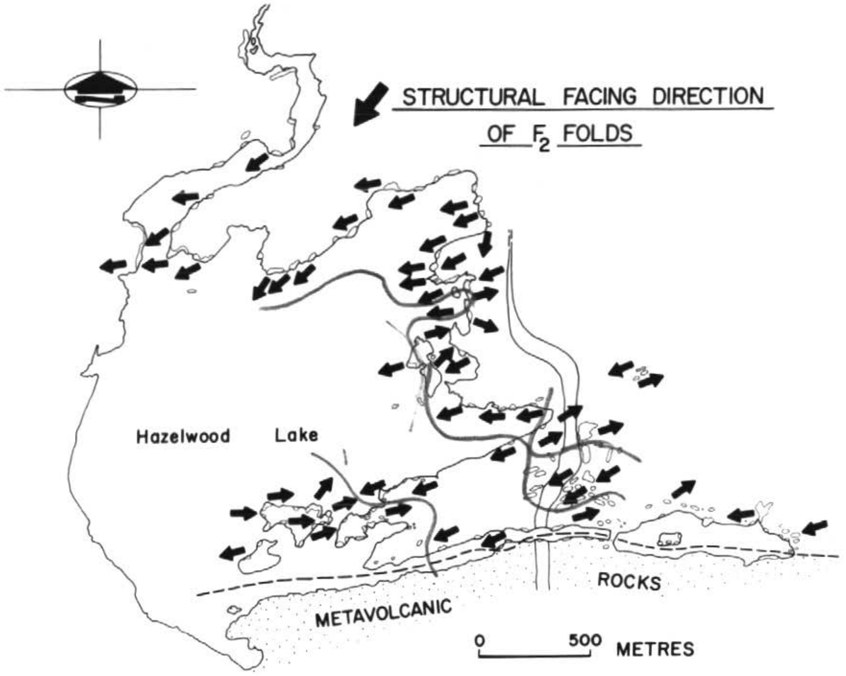


Figure 10 *Distribution of structural facing direction of dominant F_2 folds at Hazelwood Lake. The dashed line paralleling the south shore is the contact with metavolcanic rocks*

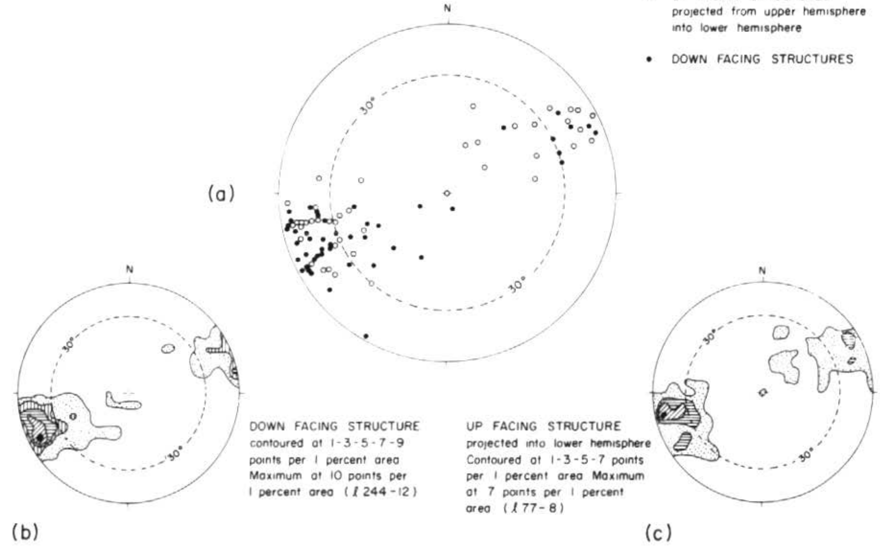


Figure 11 *Distribution of structural facing directions of dominant F_2 folds at Hazelwood Lake. The contoured diagrams show that most F_2 folds face sideways*

ing direction and bedding. Consequently, structural facing data are generally unobtainable.

Percival (1983) suggests that the metavolcanic rocks in this area form a part of the Wawa belt, and that they stratigraphically overlie the sequence of greywackes and slates that are supposedly within the Quetico subprovince. Percival bases his conclusions on consistent southward younging directions observed in a number of outcrops of greywackes and slates. In the present study, local younging directions of diverse orientation have been documented from this area and it has been shown that the stratigraphic succession as a whole becomes younger to the northeast or southwest.

West of this area, in similar metasedimentary rocks in the Quetico subprovince, the local younging directions are reported to be dominantly northward (Giblin 1964; Pirie and Mackasey, 1978). In the Quetico Belt near Calm Lake, Ontario, Borradaile (1982a) has documented both north and south younging in the metasedimentary strata and has shown that the stratigraphy as a whole becomes younger to the northeast.

In the light of such evidence of diversely-oriented younging directions, Percival (1983) suggests that the contact between metavolcanic and metasedimentary rocks at Hazelwood Lake and vicinity comprises a complex fold-fault geometry.

Based on the present study, it appears reasonable that the F_2 folding episode documented in the greywackes and slates at Hazelwood Lake and in similar rocks to the northeast and southwest also affected the metavolcanic rocks exposed south of Hazelwood Lake and their mutual contact. Absence of structural facing directions in the metavolcanic terrain make it premature to speculate on the presence of F_1 structures and on the nature of the contact which existed between these terrains prior to the F_2 folding episode.

In the present study, no evidence was found to suggest the presence of faults in the vicinity of the contact, although the possibility of the existence of such structures cannot be ruled out entirely.

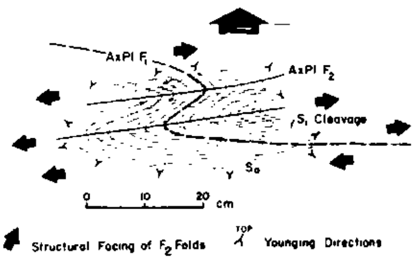


Figure 12 *Outcrop sketch map of finely bedded turbidites (S_0) showing the refolding of earlier F_1 structures by later F_2 folds. Note that the axial planar cleavage (S_1) of the F_2 folds appears deceptively axial planar to the F_1 fold in this example from Hazelwood Lake*

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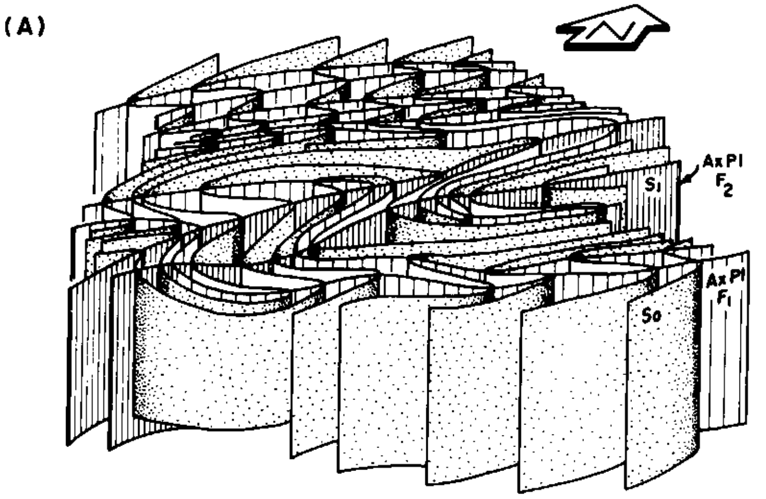

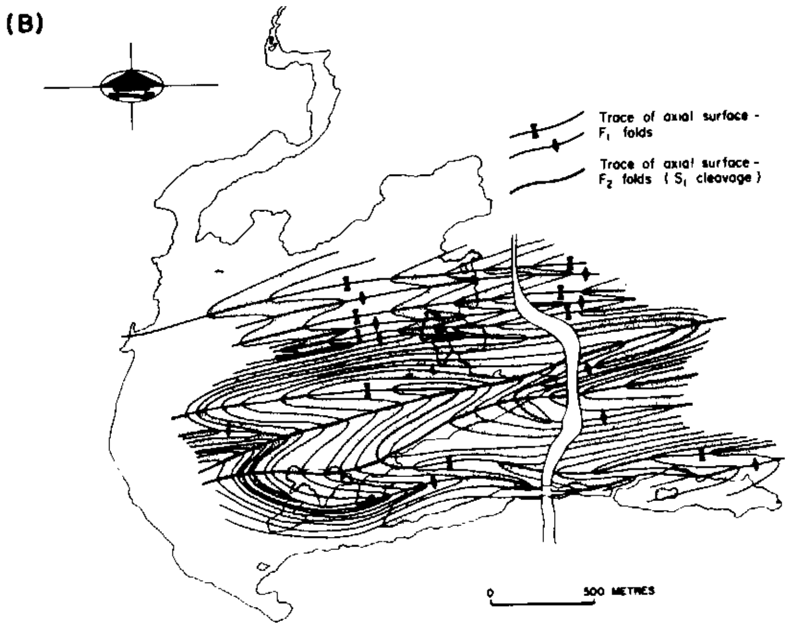

Figure 13A *Three-dimensional diagram of the structural geometry of the folds at Hazelwood Lake. The stippled surfaces (S_0) represent generalized bedding planes.*

Figure 13B *Distribution of axial surface traces of F_1 and F_2 folds at Hazelwood Lake. The stippled and blank surfaces represent generalized bedding surfaces*

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Captions For Figures