The structure of the Heath Steele Mines region, Bathurst Camp, New Brunswick

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This paper deals with the structure of the region surrounding Heath Steele Mines, which is situated in the southern part of the Ordovician volcanic-sedimentary complex of the Bathurst Camp, New Brunswick. In this area, five generations of deformation structures are recognized on the basis of orientation, tectonic style, and systematic overprinting relationships.

The earliest recognizable deformation (D_1) is characterized by tight to isoclinal F_1 folds of a compositional layering (S_0). A cleavage (S_1) parallel to the axial plane of these folds was locally rotated into a transposition foliation (S_2) during the D_2 deformation. Where gently dipping, S_2 was cast into domes and basins in two events (D_v and D_5) of upright folding with axial plane cleavages S_v and S_5. Where steeply dipping, S_2 was subjected to recumbent folding (D_h) prior to the fifth deformation (D_5). Overprinting relationships between the D_v and D_h events are ambiguous, so their correlation with the third and fourth deformations remains open to interpretation.

The macroscopic structure in the Heath Steele Mines area is dominated by an open fold (the North Little River Lake Fold) of a belt of metasedimentary rocks and augen schists. This belt is host to the Heath Steele sulphide orebodies and is also an F_1 fold zone. The age of the macroscopic fold is not well constrained, but the asymmetry of second-order F_2 folds reverses across its hinge, and its southwestern limb is attenuated in a zone of high D_2 strain, suggesting that it is an F_2 fold. The zone of high D_2 strain separates the folded belt of metasedimentary rocks and augen schists from a pod of massive porphyry and granitoid rocks.

Cet article porte sur la structure de la région entourant les mines Heath Steele et se situant dans la partie méridionale du complexe volcano-sédimentaire ordovicien de Bathurst Camp, au Nouveau-Brunswick. Dans cette région, l'orientation des structures, le style tectonique et le caractère systématique des superpositions permettent de reconnaître cinq épisodes de déformation.

La déformation la plus ancienne à être reconnue (D_1) se caractérise par des plis F_1 serrés à isoclinaux affectant un rubanement de composition (S_0). Une schistosité (S_1), parallèle à la surface axiale de ces plis, se modifia localement, par rotation, en une foliation de transposition (S_2) durant la déformation D_2. Là où son pendage était faible, S_2 prit la forme de dômes et cuvettes en deux épisodes (D_v et D_5) de plissement vertical accompagnés de schistosités de surface axiale S_v et S_5. Là où son pendage était élevé, S_2 fut soumise à un plissement couché (D_h) précédant la cinquième déformation (D_5). Les superpositions relatives des épisodes D_v et D_h sont ambigües; leur corrélation avec les troisième et quatrième déformations reste à déterminer.

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La structure macroscopique dans les mines Heath Steele est dominée par un pli ouvert (le pli de North Little River Lake) au sein d'une ceinture de schistes oeillés et de roches métasédimentaires. Cette ceinture est l'hôte des gisements de sulfures de Heath Steele et elle est aussi une zone de plis F_1. L'âge du pli macroscopique n'est pas bien délimité, mais l'asymétrie des plis de deuxième ordre F_2 se renverse à travers sa charnière et son flanc sud-ouest est atténué dans une zone où la contrainte D_2 est élevée, ce qui porte à croire qu'il s'agit d'un pli F_2. Cette zone de contrainte D_2 élevée sépare la ceinture plissée de roches métasédimentaires et de schistes oeillés d'une intumescence de porphyre et de roches granitoïdes massifs.

[Traduit par le journal]

INTRODUCTION

This paper presents the results of a structural analysis of the Heath Steele Mines region, which is situated in the Bathurst Mining Camp of northern New Brunswick (Fig. 1). This study formed part of a government-funded project, specifically aimed at achieving a better understanding of the geometry and evolution of the base metal sulphide deposits (de Roo *et al.*, unpublished data). The regional mapping was supported by satellite image analysis and geophysical surveys, and also by a programme of trenching, conducted jointly with Noranda Exploration.

The Bathurst Camp contains a number of stratabound massive sulphide deposits, classified as volcanogenic by McAllister (1960), Harley (1979) and Franklin *et al.* (1981). They are hosted by a sequence of mafic and felsic volcanic and sedimentary rocks of the Ordovician Tetagouche Group (Skinner, 1974), which is within the Miramichi Tectonic Zone of the northern Appalachians (Fyffe *et al.*, 1981; Davies *et al.*, 1983; van Staal, 1987). In the Bathurst Camp the Tetagouche Group defines an arcuate complex, in which stratigraphy is difficult to establish because of lack of fossil control, complex primary facies changes and intense deformation (Skinner, 1974). Initial sedimentation is inferred to have terminated in the Early Ordovician, preceding a stage of felsic volcanism that was accompanied in the Middle Ordovician by mafic volcanism and renewed sedimentation (Helmstaedt, 1971; Davies *et al.*, 1983; van Staal, 1987). The Tetagouche Group was intruded by felsic plutons and gabbro, prior to regional low-grade metamorphism and deformation (Helmstaedt, 1971; Skinner, 1974; Irrinki, 1986; van Staal, 1987). A younger, more regional suite of bimodal intrusions accompanied renewed deformation, attributed to the Acadian orogeny by Fyffe *et al.* (1981).

THE GEOLOGY OF THE HEATH STEELE MINES REGION

Detailed mapping in the Heath Steele Mines region (Fig. 2) is hindered not only by the poor stratigraphic facies control, but also by poor exposure and lithological changes because of penetrative, locally intense, deformation (Fig. 3). Rock units may also be in tectonic contact with their neighbours, so structural analysis cannot rely on elaborate stratigraphy. We refer to existing lithographies (Davies *et al.*, 1983; Moreton and Williams, 1986; van Staal, 1987), but for mapping purposes, the various rock types have simply been grouped into seven units (Fig. 2).

One lithological unit is defined by phyllitic rocks of clastic and/or volcaniclastic origin. The metasedimentary rocks are juxtaposed with quartz (± feldspar) augen schists. Contacts between the two units are mostly sharp. The augen schists grade into felsic schists and phyllites, which contain horizons of meta-agglomerate. In domains of low strain, the phyllites grade into metarhyolite with relict amygdaloidal and spherulitic textures. Greenschists and green phyllites are also present. Pillow structures are locally preserved, indicating a mafic volcanic origin for some of these rocks. Some greenschists grade into massive metadiabase, which can be mapped as a separate unit. Massive quartz metaporphyry forms another lithological unit, located southwest of the Heath Steele Mines. The metaporphyry grades into foliated metagranitic rocks, which are presumably of Ordovician age (Fyffe *et al.*, 1977, 1981; van Staal, 1987).

The five major sulphide deposits ("A"-"E"; Fig. 2) at Heath Steele Mines are located at, or near, contacts between the metasedimentary rocks and the augen schists (McBride, 1976; Owsiacki, 1980). The contacts are also marked by mineral prospects, local sulphide disseminations and iron enrichments. In the mining area (between "B" and "D" in Fig. 2), the metasedimentary rocks and augen schists occupy elongate domains with a westerly strike. These domains are spatially associated, so that both rock types and their contacts define a mineralized belt. This belt stands out on Landsat images and airborne geophysical survey maps, and is warped into a broad arc west of the mine area (the North Little River Lake (NLRL) Fold; Figs. 1, 2). This fold has been subdivided into two structural domains, first of which is the northeastern limb of the fold. Because of poor exposure and consequent shortage of data, the hinge and southeastern limb of the fold were combined to form the second domain. A third tectonic domain has been distinguished on the basis of its generally weak foliation. This domain is also characterized by a large pod of quartz metaporphyry, and is here referred to as the "Porphyry Pod" (Fig. 1). The Porphyry Pod is separated from the folded belt of metasedimentary rocks and augen schists by a northwesterly striking zone of intensely folded rocks with strong foliations and lineations.

Polyphase deformation was recognized in key outcrops in each domain (Fig. 3). The distinction of successive generations of structures in these outcrops has been based on overprinting relationships on micro- and mesoscopic scales. Sets of structures were then correlated between outcrops using a combination of criteria, including style, orientation, and/or age, relative to other structures present. This procedure resulted in identification of five generations of structures (D_1, D_2, D_v, D_h, D_5) in the Heath Steele Mines region (Table 1).

The structural analysis concentrated on the mine area, so the structure of the northeastern limb of the NLRL Fold is discussed first. Next, the structural relationships are extrapolated to key outcrops in the two other tectonic domains.

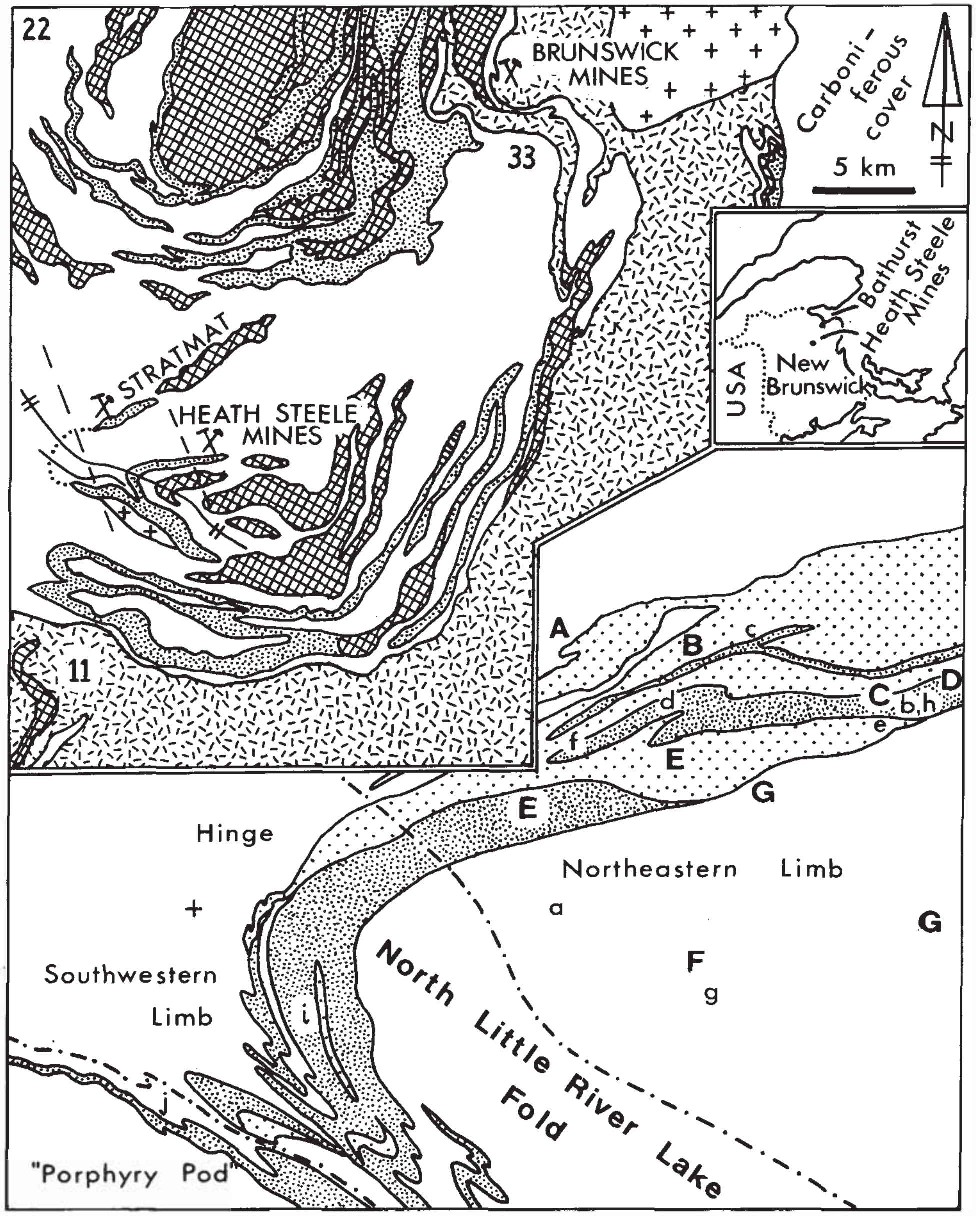

Fig. 1. Map of the southeastern part of the Bathurst Camp, New Brunswick (after Davies *et al.*, 1983; van Staal, 1987). Crosses = granite and metagranitoid rocks; white = felsic schist and metavolcanic rocks; hatching = mafic metavolcanic rocks, metagabbro, metadiabase; fine stipple = metasedimentary rocks, green phyllite; snow pattern = quartzite and phyllite. Dashes and form line refer to Figure 10. The map below highlights the belt of metasedimentary rocks (fine stipple) and augen schist (open stipple) at Heath Steele Mines. The fold in this belt (the North Little River Lake Fold) is dissected into two tectonic domains: one is the northeastern fold limb, the other consists of the hinge and southwestern limb. The "Porphyry Pod" constitutes a third domain. Dash-dots are domain boundaries. A-G mark the tectonic subdomains in Figure 7; a-j refer to Figure 3. 11, 22, and 33 (upper map) refer to Table 1.

THE NORTHEASTERN LIMB OF THE NORTH LITTLE RIVER LAKE FOLD

Small-scale structures

The earliest deformation (D_1) is represented by F_1 folds of tension veins and of a compositional layering (S_0; Fig. 3a). Locally, S_0 is marked by a preferred mineral orientation (Moreton and Williams, 1986). This fabric may well be tectonic in origin, but could also represent mimetic growth of phyllosilicates after primary fabrics (Williams, 1972; Maltman, 1981; Weber, 1981). The F_1 folds are accompanied by an axial plane cleavage (S_1) that in some rocks is defined by spaced, stylolitic seams of opaque minerals and phyllosilicates. In pelites, S_1 is commonly a differentiated layering. Although strongly refracted across parts of the deformed layering, S_1 is generally parallel to S_0 (Fig. 3a), and the presence of rootless F_1 folds within the layering is further indication of F_1 transposition of S_0 into S_1. The transposition foliation S_1 tends to dip steeply to the south (Fig. 4a), and locally contains an extension lineation (L_1; Fig. 4c). This

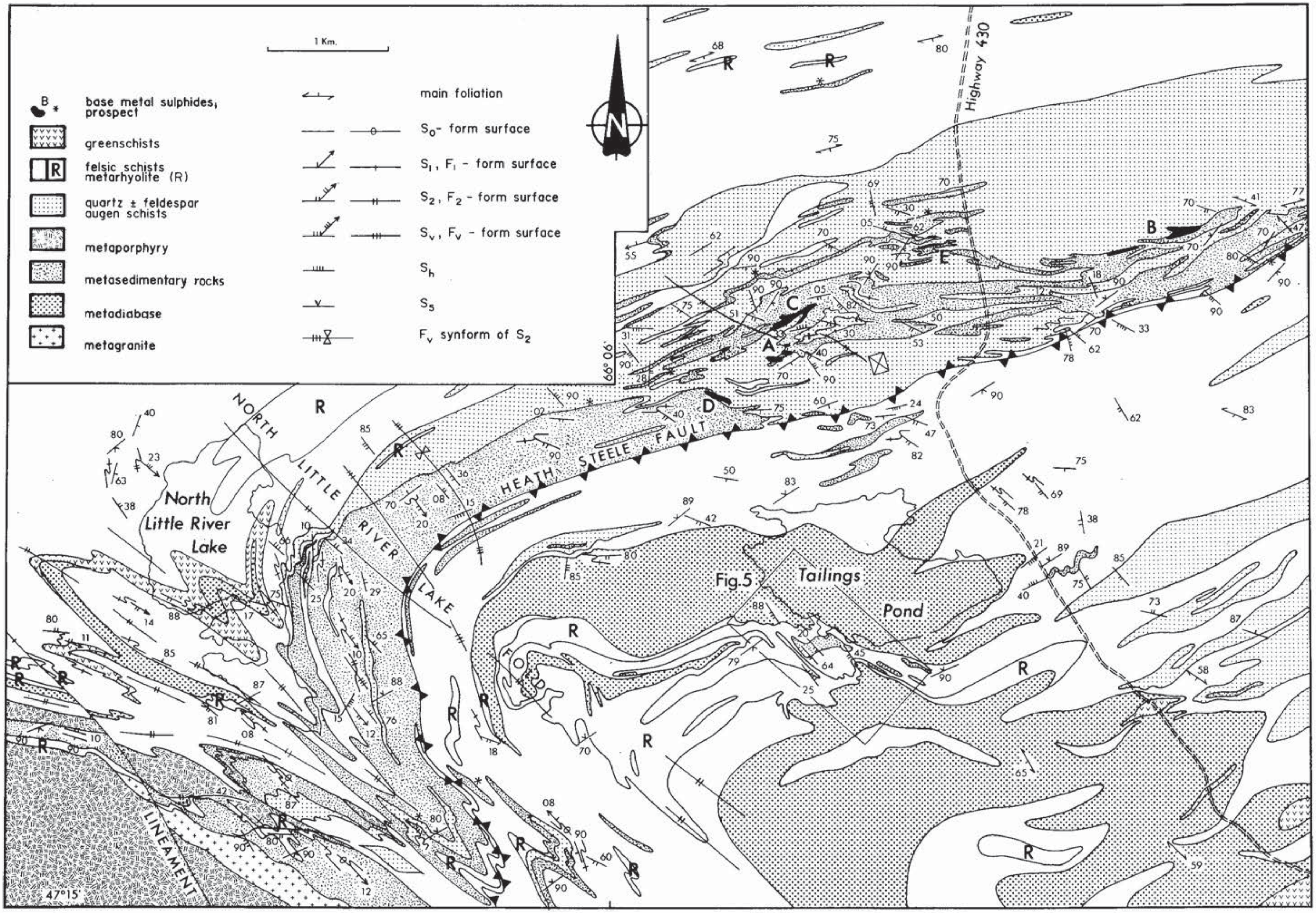

Fig. 2. Detailed map of the Heath Steele Mines region. The belt of metasedimentary rocks and augen schists in Figure 1 is marked by the presence of five major sulphide deposits (A-E). The belt is parallel to the strike of S_1 and is bound to the south by the Heath Steele Fault. The box represents the mine offices and ore processing plant.

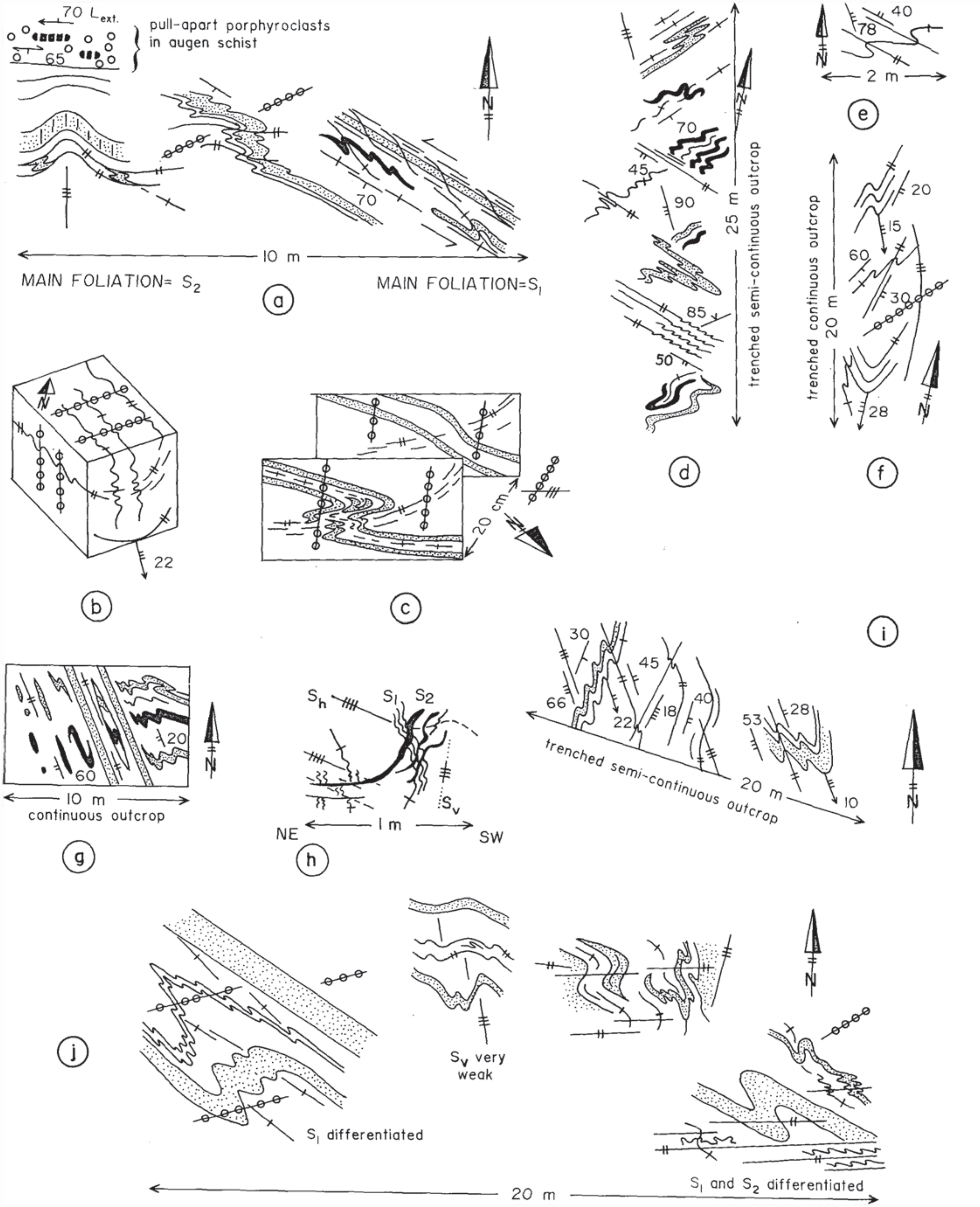

Fig. 3. (a-j) Field sketches: for location see Figure 1. Black = vein (differentiated cleavage in h); "pearl strings" = S_5 form surface; other structural symbols as in Figure 2. Note that (h) is a section, and that (b) and (c) are viewed in perspective; the other sketches represent plans.

Table 1. Comparison of the tectonic history proposed here with previous studies in the Bathurst Camp.

Age	Event	This study	McBride (1976)	Irrinki (1986)	Helmstaedt 1970	Helmstaedt 1971	van Staal and Williams (1984)
$\pm$470-458Ma (U/Pb)		FELSIC PLUTONISM(*2)					
CARADOCIAN TO LUDLOVIAN	D_1	D_1 shear zones F_1 conical S_1 transposition foliation	F_1 recumbent S_1 weak	F_1 S_1	F_1 S_1	F_1 S_1	D_1 thrusting F_1(a) + F_1(b) S_1
LATE SILURIAN TO EARLY DEVONIAN 394$\pm$1Ma (U/Pb)	D_2	D_2 shear zones; SB + FB F_2 tight-isoclinal (*1)S_2 transposition foliation FELSIC PLUTONISM(*3)	F_2 S_2 steep	D_2 FB F_2 S_2 flat	F_2 S_2	D_2 FB F_2 S_2 flat	D_2 SB F_2 S_2 steep
DEVONIAN?	D_3?	F_h recumbent folds of SB (*1)S_h horizontal	F_4 S_4				D_5 kinks and gentle F_5 recumbent folds
	D_4?	F_v upright folds of FB plunging folds of SB S_v NW-striking	F_3 S_3	F_3 S_3		F_3 S_3	F_3 S_3 NE-striking
	D_5	D_5 kinks F_5 upright folds of FB plunging folds of SB S_5 NE-striking	F_5 S_5	F_4 S_4	F_3		D_4 kinks F_4 (van Staal, 1987)
		Heath Steele Mines		area 11 (Fig.1)	area 22 (Fig.1)		Brunswick Mines (Fig.1)

D_x = deformation event with D_x tectonic features, F_x folds and S_x axial planar foliations. SB = steeply dipping foliations predominant ("Steep Belts"). FB = flat-lying foliations predominant ("Flat Belts"). *1: S_{hor} = S_2 or S_h (Fig. 4). *2: includes the metagranite in Figure 2. *3: the Pabineau Granite near Brunswick Mines (Fig. 1). The chronology of events (column left) refers to van Staal (1987) and unpublished data; radiometric Zircon U/Pb age dates are by Bevier (1988).

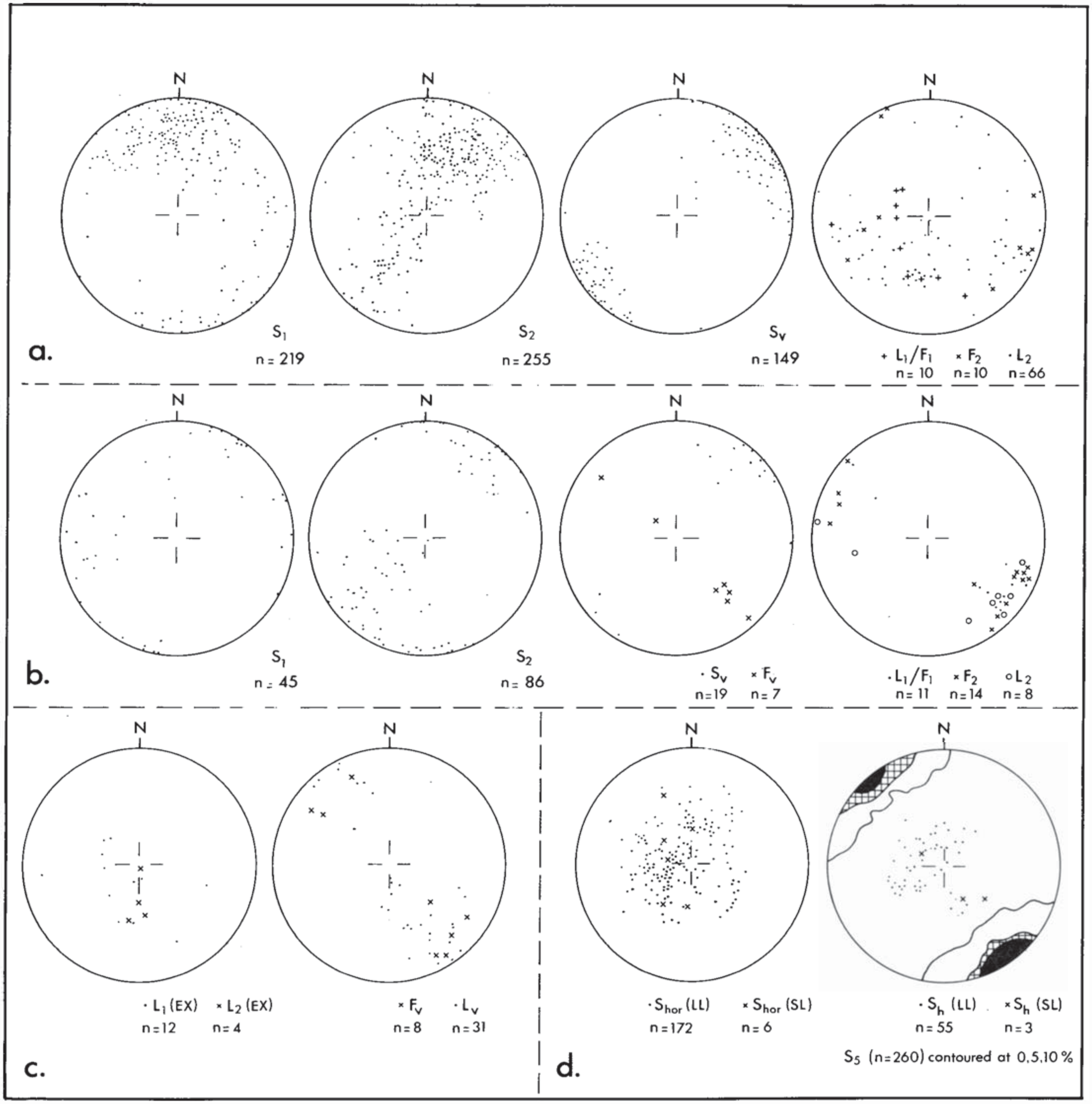

Fig. 4. Lower hemisphere of equal area projections, showing poles to planes (S_x), fold axes (F_x), intersection lineations (L_x), and extension lineations (L_{ex}). (a) Plots from the northeastern limb (LL) of the North Little River Lake Fold; (b) plots from the southwestern limb (SL) and hinge of this fold; (c) plots of D_1/D_2 extension lineations and of D_v linear elements from the LL fold domain; (d) plots of "S_{hor}" (= S_2 or S_h), and of a combination of S_h and S_5. Both plots combine data from both limbs (SL + LL) of the fold. The clusters of S_5 poles have been contoured.

lineation is defined by a phyllosilicate preferred orientation and by microboudinaged porphyroclasts of feldspar and quartz (de Roo and Williams, unpublished data).

S_1 is overprinted by F_2 folds with an S_2 axial plane cleavage. S_2 is locally a differentiated crenulation cleavage. At present, S_2 varies in orientation between flat-lying and subvertical, but generally strikes west-northwest (Fig. 4a). Some F_2 folds of S_1 are intrafolial in S_2, indicating local F_2 transposition of S_1. The variation in the intensity of F_2 folding and S_2 cleavage development suggests a heterogeneous D_2 strain distribution, which explains why the dominant foliation in outcrops throughout the area can be S_1 or S_2 (Fig. 3a-d). The orientation relationships between S_1 and S_2 have been further complicated by refraction of S_2 across the S_1 transposition layering (see also van Staal and Williams, 1984). In view of the local F_2 transposition, the subvertical mineral lineation in S_2 (Fig. 4c) could be interpreted as a rotated L_1 extension lineation.

The third and fourth deformations (D_3 and D_4) comprise folds with vertical and horizontal axial planar cleavages. Age relationships between these deformations are inconclusive, so they are referred to as D_v ("vertical") and D_h ("horizontal"), respectively (Table 1). D_v is represented in outcrop by a weak crenulation cleavage (S_v) in the axial plane of open F_v folds of S_2 (Fig. 3a, b, f). S_v has a northwesterly strike (Fig. 4a). A moderately dipping cleavage with a similar strike was observed in several locations, but could not be distinguished clearly as S_2 or S_v. Such surfaces are omitted from Figure 4, so that the average dip of S_v may be exaggerated. Most F_v fold axes and L_v lineations plunge gently to the northwest or southeast (Fig. 4c), indicating that F_v folds are upright and noncylindrical. Upright F_v folds alone cannot explain the present orientation distribution of S_2 (Fig. 4a), but there are also recumbent folds, representing the fourth, or third, deformation (D_h).

The F_h folds are open, locally chevron-style, structures or small crenulations. Their axial planes are marked by a horizontal, or gently dipping, crenulation cleavage (S_h; Fig. 4d). S_h has been observed only locally, but is typically well developed where it does occur, suggesting S_h is a penetrative structure that is regionally present. In the absence of overprinting relationships, flat-lying foliations can be either S_2 or S_h (= "S_{hor}"; Fig. 4d), and a distinction between the two is possible only where S_2 is moderately or steeply dipping in part of the outcrop (Fig. 3h). This distinction is complicated further by lack of conclusive overprinting relationships between D_v and D_h structures. In outcrops where both S_v and S_h are present as cleavages, S_h is better developed, but locally undulates and assumes the same strike as S_v (as in Fig. 3h), indicating that S_h predates S_v (Table 1).

Upright folds and crenulations of the flat-lying cleavages, and steeply plunging folds of S_v, mark a fifth deformation (D_5; S_5 in Fig. 3b, c, f). D_5 structures also include spaced kinks, which rarely occur in conjugate pairs. The folds are accompanied by an axial planar crenulation cleavage (S_5) that is easily recognized as a vertical foliation of evenly spaced, dark seams, striking southwest (Figs. 2, 4d).

Large-scale structures: the Tailings Pond quarries

Good exposure in quarries to the south of the mine area (Figs. 2, 5) allowed correlation of the small-scale structural observations with the macroscopic structure. The latter is outlined by detailed mapping of lithological boundaries. In the quarry area, metasedimentary rocks occupy the central part of an overall westerly striking sequence, and are flanked on either side by felsic phyllites and schists, metarhyolite, and massive metadiabase. The metasedimentary rocks have a distinctive compositional layering (S_0), the strike of which is mostly parallel to the strike of a slaty cleavage (S_1). S_1 is axial planar to tight or isoclinal F_1 folds of the layering, indicating transposition of the layering into S_1. Thus, the mesoscopic F_1 transposition, the general parallelism between S_1 and the trend of lithological boundaries, and the symmetrical distribution of rock types relative to the metasedimentary rocks suggest that the latter mark the hinge of a macroscopic F_1 fold of S_0 (Figs. 5, 6a; S_1 form surface).

The F_1 fold has been overprinted by an asymmetrical F_2 fold, which is the dominant structure in Figure 5. On the mesoscopic scale, F_1 folds are also deformed by F_2 folds, which have the same asymmetry as the macroscopic structure. A southwesterly dipping cleavage (S_2) is present in the axial planes of the F_2 folds. At "K" (Figs. 5, 6), S_2 is a crenulation cleavage of S_1, but in westerly and easterly directions away from this point S_1 is progressively transposed into S_2. By the obliteration of S_1 a domainal S_2 slaty cleavage is established, in which the preexisting layering is either dissected and drawn out into augen, or is preserved in intrafolial F_2 folds (Fig. 3g). This transition mainly reflects D_2 strain gradients normal to S_2, although D_2 strain also varies in a direction parallel to the strike of S_2. The D_2 deformation concentrated in two narrow shear zones, extending from A to A^1, and from B to B^1 (Figs. 5, 6). The S_0-trend has been rotated into parallelism with these zones, and various lithological units can be found in narrow lenses and mesoscopic boudins along the shear zones. This indicates that the overall asymmetry of the F_2 fold in Figure 5 is the result of the attenuation of its limbs in D_2 shear zones.

Along a traverse from point "K" to the attenuated limbs of the F_2 fold, both the D_2 strain and the dip of S_2 increase (Fig. 3g). At "K", a steeply dipping cleavage (S_v) can be distinguished from S_2. Although there are no mesoscopic F_v folds at this site, S_v and S_2 locally have a similar strike, suggesting that the rotation of S_2 resulted from open F_v folding. These relationships imply that in plan view the axial plane of the macroscopic F_2 fold is also the axial plane of an F_v monoclinal flexure of S_2 (Fig. 6a).

Large-scale structures of S_1 and S_2: evaluation of orientation distributions

S_1 and S_2 are generally similar in style, and both can be transposition foliations. Because of F_1 transposition, S_0 has not been distinguished from S_1 in the plot of the S_1 orientation distribution in Figure 4a, and S_1 and S_2 were only recorded where the two could be separated. Nevertheless, some of the readings of S_2 in Figure 4 are bound to represent transposed S_1 planes. Consequently, the plot of poles to S_1 is incomplete, and biased toward orientations that meet the overprinting criteria in the key outcrops. In order to further investigate the spatial relationship between S_1 and S_2, the northeastern limb of the NLRL Fold was divided into 7 structural subdomains (Fig. 1A-G), and poles to S_1 and S_2 were plotted per subdomain (Fig. 7).

Subdomain F represents the Tailings Pond quarries, in which S_1 and S_2 can be clearly defined in outcrop. Nevertheless, both cleavages show almost the same orientation distribution (Fig. 7F). Plots of the other subdomains show different clusters for S_1 and S_2, and indicate that S_1 either dips steeply to the south (Fig. 7B_1, E), or is subvertical, striking west-southwest (Fig. 7A, G). The two preferred S_1- strike-trends reflect the two strike trends of lithological contacts in the belt of metasedimentary rocks and augen schists: contacts north of the mine buildings

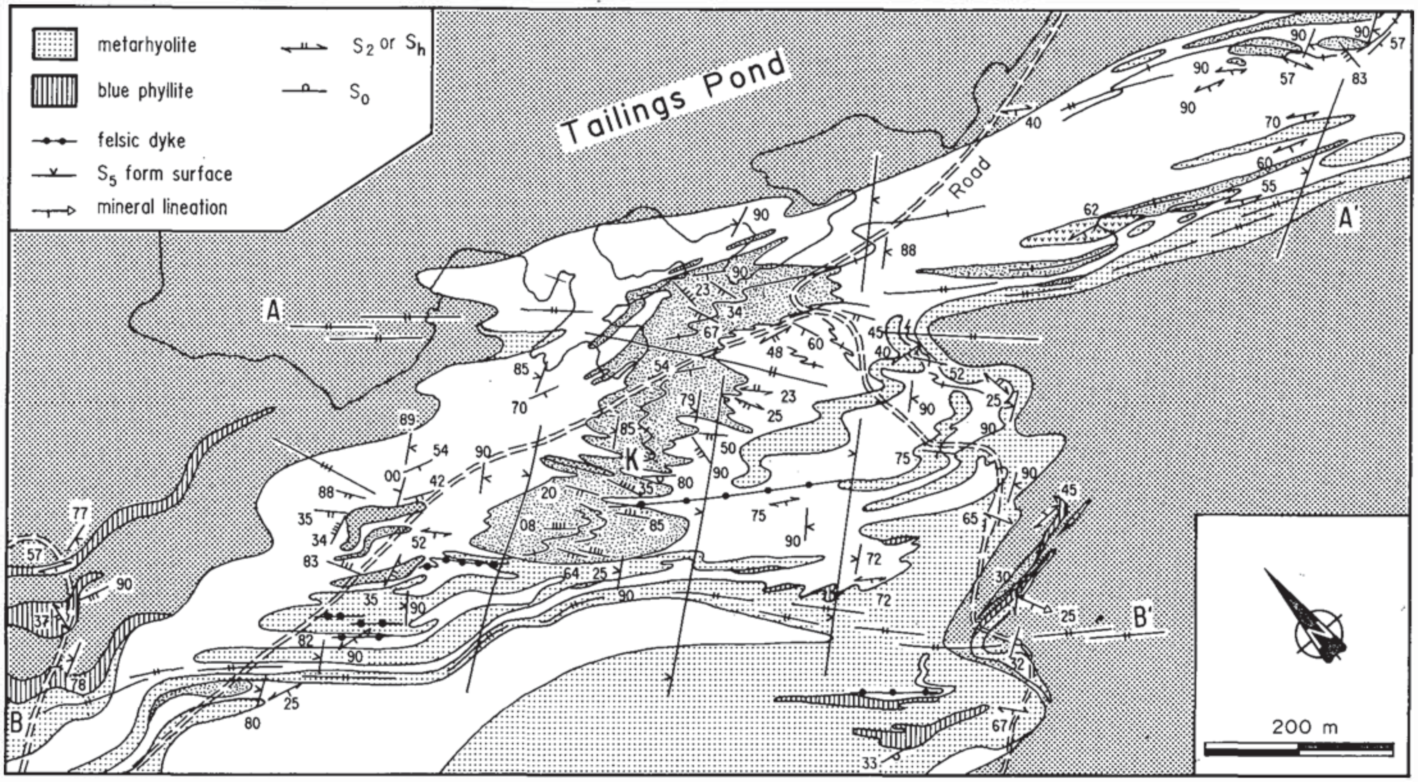

Fig. 5. Structural map of the quarry area south of the mine tailings pond. Legend as in Figure 2 unless indicated. For location, see Figure 2 (frame).

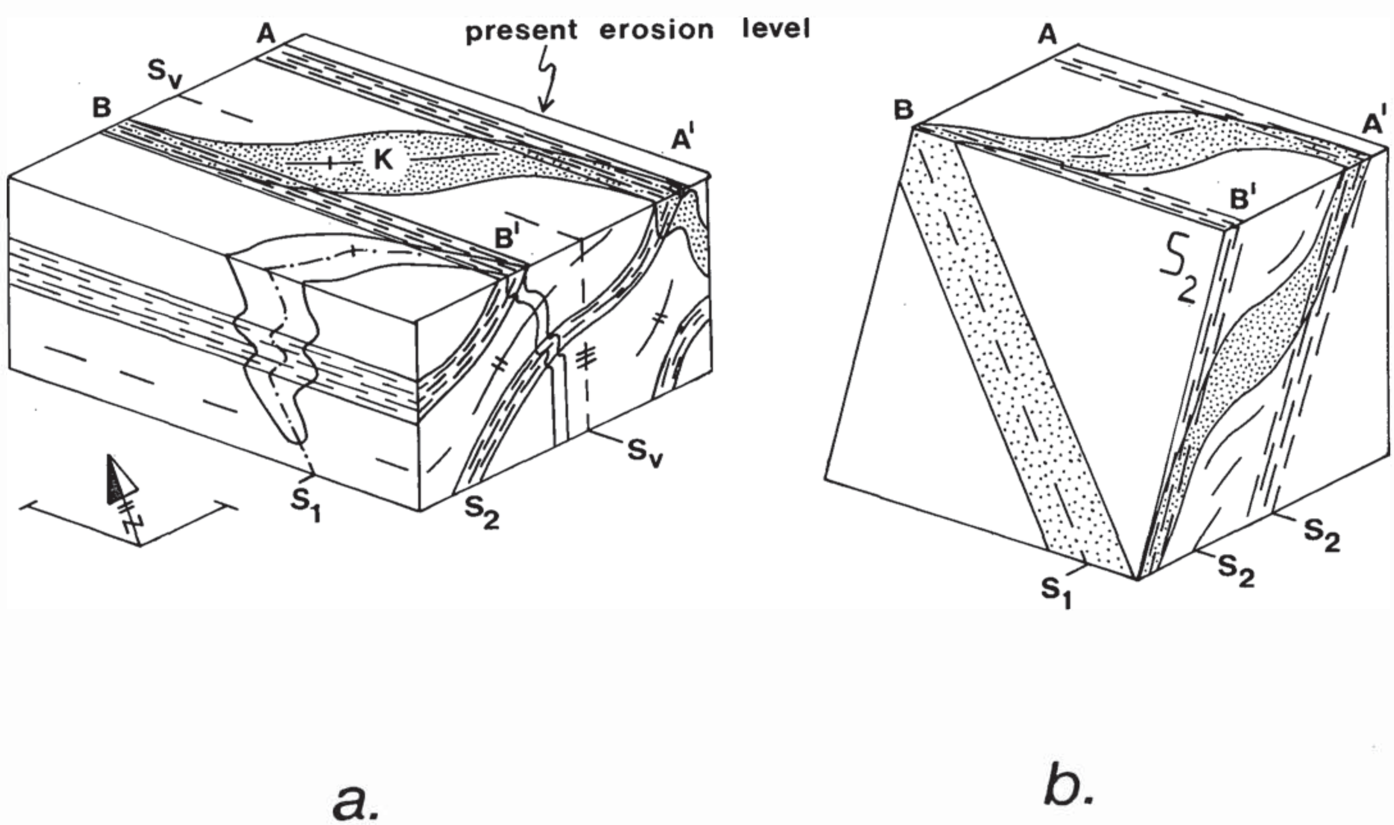

Fig. 6. Interpretative sketch of the structure of the Tailings Pond quarry area; (a) postulating an upright F_v morocline of S_2, and (b) postulating that the present structure was essentially in place before the D_v deformation. AA', BB', and K refer to Figure 5; the F_1 synform is added for descriptive purposes. Option (a) is favoured.

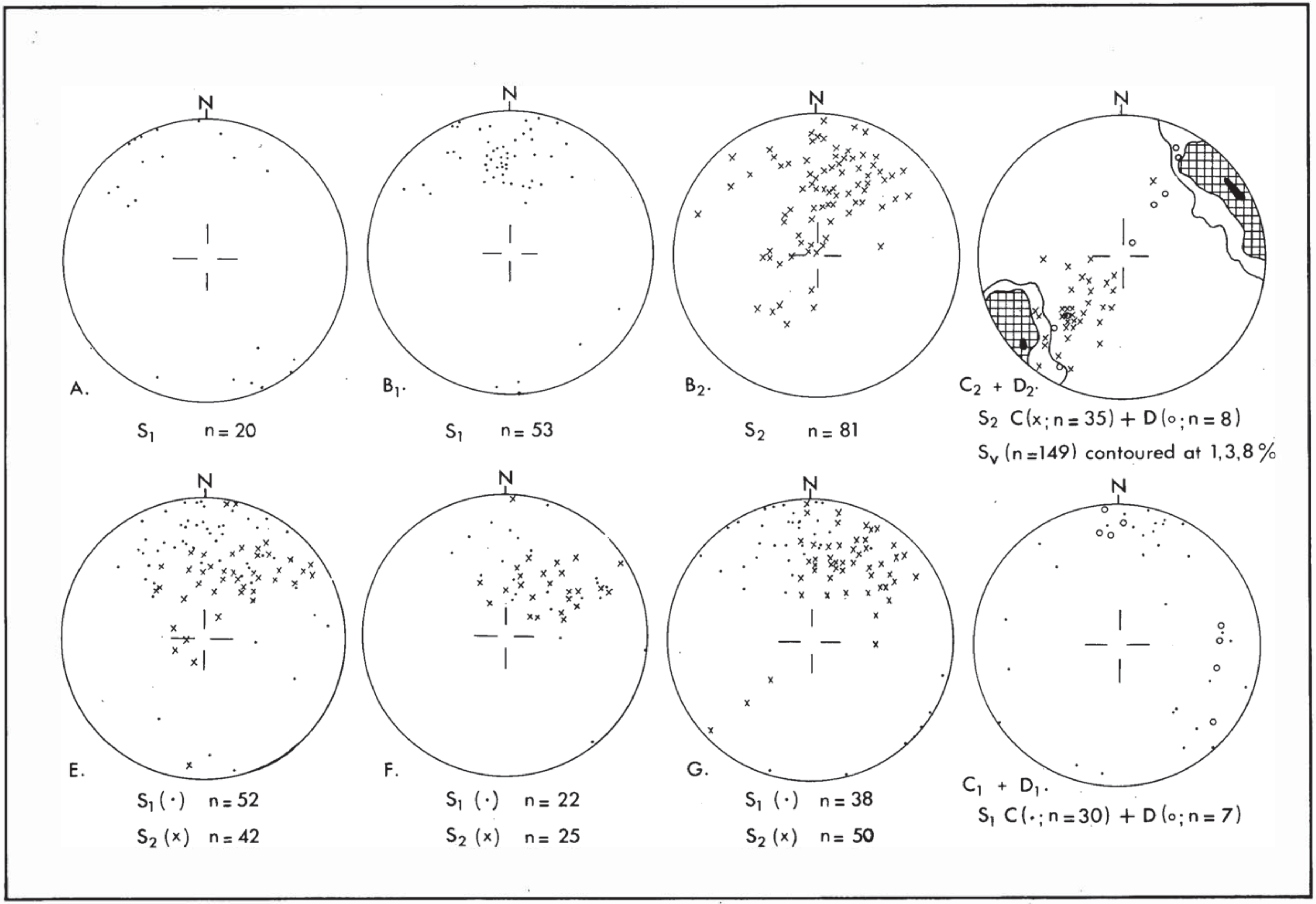

Fig. 7. Plots of poles to S_1 and S_2 in subdomains (A-G; location see Fig. 1) of the northeastern limb of the NLRL Fold. The S_v pole plot in Figure 4a is contoured in diagram $C_2 + D_2$.

(Fig. 2, box) strike west, whereas other contacts strike parallel to the Heath Steele Fault. Both sets of strikes are exposed in subdomains C and D. Conspicuously, the great circle distribution of some poles to S_1 in Figure 4a is almost entirely the result of contributions from these two subdomains (Fig. $7C_1 + D_1$).

Readings of S_2 from subdomains C and D plot in a distinct girdle with a concentration of poles in the lower left quadrant. In other subdomains, poles to S_2 are concentrated in a quadrant on the opposite side (Fig. $7B_2$, E, G), so that these plots complement Figure $7C_2 + D_2$ to form the full girdle, shown in Figure 4a. After contouring, the plot of poles to S_v in Figure 4a has been incorporated in Figure $7C_2 + D_2$, to illustrate the difference in strike between S_2 and S_v. This difference is independent of the local dip direction of S_2 (compare Fig. $7C_2 + D_2$ with Fig. 3d, e), and indicates that the girdle of poles to S_2 was established independent of the D_v deformation. The variation in dip of S_2 could be attributed to F_h recumbent folding, in which case the minimal dip variation of S_v requires that D_v postdates D_h (Table 1).

THE HINGE AND SOUTHWESTERN LIMB OF THE NORTH LITTLE RIVER LAKE FOLD

The main foliation in metasedimentary rocks and phyllites in the hinge of the NLRL Fold typically consists of a compositional layering (S_0) that is parallel to arrays of veinlets, and to a cleavage (S_1). The main foliation is overprinted by F_2 folds with an axial plane cleavage (S_2) that dips gently to the east (Fig. 2).

In metasedimentary rocks and phyllites on the southwestern limb of the NLRL Fold (Fig. 1) the predominant attitude of S_1 has changed relative to S_1 on the northeastern limb of the NLRL Fold (compare Fig. 4a, b), and S_2 has taken over as the dominant foliation. Also, the axes of F_1 folds and associated L_1 intersection lineation are parallel to their D_2 counterparts, which plunge gently (Fig. 4b). Although dip directions vary in both fold limbs, S_2 on the southwestern limb of the NLRL Fold mostly dips to the northeast, as opposed to the southwesterly dip of S_2 in the mine area (Fig. 4a, b). Also, the asymmetry of most F_2 folds (as represented by Fig. 3i) is opposite to the dominant F_2 asymmetry in the mine area (as represented by Fig. 3d, e).

The reversal of the F_2 fold asymmetry is accompanied by a reversal of the intersection asymmetry between S_2 and S_v (compare Fig. 3d, i). F_v folds on the southwestern limb of the NLRL Fold are open to tight, and S_v is a weak axial plane cleavage. The orientation of S_v and the style of F_v folding do not vary significantly on either limb of the NLRL Fold; in both limbs F_v fold axes plunge gently in opposite directions (Fig. 4b, c).

D_h structures have been detected only in a small number of locations on the hinge and southwestern limb of the NLRL Fold (Fig. 4d). The F_h folds are gentle warps or crenulations with a shallowly dipping axial plane (S_h), which is represented locally by a well-developed cleavage (Fig. 3i). The D_h deformation appears to have been similar in style in both limbs of the NLRL Fold. As in the mine area, foliations were recorded as "S_{hor}" in outcrops where distinction between S_h and S_2 was impossible (Fig. 4d).

Like their counterparts in the northeastern limb, F_5 folds in the southwestern limb of the NLRL Fold are open and tend to occur in groups. The folds are generally symmetrical crenulations, and their axial planar cleavage (S_5) has a similar orientation and tectonic style to its counterpart in the mine area.

THE THIRD TECTONIC DOMAIN: THE PORPHYRY POD

F_2 folds, L_2 intersection lineations, and S_2 cleavages are most strongly developed south of North Little River Lake (Fig. 2), where they form a northwesterly striking zone of high D_2 strain. A large body of massive metarhyolite, quartz metaporphyry and metagranite borders this zone to the south, and constitutes a separate tectonic domain (the "Porphyry Pod"; Fig. 1).

A lens of pelitic metasedimentary rocks bisects this domain. The pelites are intercalated with massive metarhyolite, forming a primary layering (S_0). This layering is well developed on the outcrop scale, striking approximately northwest (Fig. 3j). Thick layers have been deformed into open, asymmetrical F_1 folds whereas thinner layers are more tightly folded, so that the F_1 folds are disharmonic. Boundaries of the folded layers tend to be quite sharp, even in the fold hinges, where phyllosilicates show a strong preferred orientation along S_0.

A steeply dipping foliation (S_1) is present in the axial planes of the F_1 folds. S_1 is a differentiated crenulation cleavage of S_0, and has been overprinted by another differentiated crenulation cleavage (S_2). S_2 also dips steeply, and is axial planar to F_2 folds of S_1 that consistently have an opposite asymmetry relative to the F_1 folds of S_0 (Fig. 2, 3j). The F_2 folds have the same asymmetry as F_2 folds on the opposite side of the zone of high D_2 strain; i.e., on the southwestern limb of the NLRL Fold.

F_v folds of S_2 are rare, but appear to be similar in asymmetry and style to F_v folds on the northeastern limb of the NLRL Fold. The fold axial plane cleavage S_v is weakly developed, but is nearly parallel to S_v elsewhere in the region. Deviations in its orientation are interpreted to be a result of open F_5 warps (Fig. 3; compare j with f). S_5 is a distinct, vertical cleavage that overprints the earlier folds, and has the same orientation and style as S_5 in the two other tectonic domains (Fig. 2). D_h structures have not been detected in the Porphyry Pod.

REGIONAL LINEAMENTS

Digital Landsat image analysis by Torrance and Lodin (1988) indicated that the region is crosscut by numerous lineaments. Most of these represent minor faults, master joints and microjoint systems, and they tend to follow the preexisting cleavage planes S_1-S_5. The dominant set of lineaments strikes northwest, and is therefore parallel to S_v (Fig. 2). This set is marked by significant metal enrichments (J.G. Torrance, personal communication). Northwesterly striking lineaments, crosscutting the giant F_4 folds of van Staal (1987; Table 1), also appear on geological maps on the scale of the Bathurst Camp (Davies, 1979), and they can be recognized on topographic maps throughout the Maritime Provinces. In Nova Scotia they are manifested as swarms of ac-joints of Devonian age, reactivated as transfer faults during opening of the Atlantic Ocean in the Triassic (Williams and Hy, in press).

SYNTHESIS

Early deformations (D_1 and D_2)

The Heath Steele sulphide deposits ("A"-"E"; Fig. 2) and prospects form part of a westerly striking belt of metasedimentary rocks and augen schists. Metasedimentary rocks in this belt occupy lensoidal domains. Augen schists to either side of these lenses are mineralogically similar, and trenching of the tips of the lenses has shown that they are closures of noncylindrical folds, rather than stratigraphic pinch-outs (Moreton, 1990).

Two major fold closures are marked by the "A" and "C" zone sulphide deposits (Fig. 2). Structural mapping of trenches and natural exposures north and south of these folds has revealed that their axial plane cleavage (S_1) is crenulated across an S_2 cleavage overprinting both folds (Figs. 2, 3d). Hence, the folds are D_1 structures. Analysis of trenches and drill core has shown that the other three sulphide deposits are also associated with closures of F_1 folds (de Roo *et al.*, unpublished data). These folds are tighter and smaller than the "A" and "C" zone folds. Drill core analysis and detailed mapping underground in the "B" zone has shown that the local F_1 fold closures have a highly noncylindrical, sheath-like, geometry, and are also transected by S_2 (Moreton, 1990; our Fig. 8). The sheath-like folds occur in rocks that are strongly foliated (S_1) and lineated (L_1), and the augen schists in particular can be described as mylonites on the basis of their microstructure (de Roo and Williams, unpublished data). The L/S tectonites, the mesoscopic F_1 transposition, and the sheath-like folds indicate that the belt of augen schists, metasedimentary rocks and sulphide enrichment is a D_1 shear zone.

The D_1 shear zone is bound to the south by a tectonic contact (Dechow, 1960; McBride, 1976; Owsiacki, 1980). This contact (the Heath Steele Fault; Fig. 2) is the locus of relatively strong brittle-ductile D_1 deformation, separating the shear zone from felsic schists and phyllites, and massive metadiabase. To the north, the shear zone is bounded by relatively undeformed meta-agglomerate, felsic phyllite and metadiabase (Fig. 1).

A similar tectonic setting is exposed in the Tailings Pond quarries (Fig. 5), where highly deformed metasedimentary rocks are also separated by felsic schists and phyllites from weakly deformed metadiabase to either side. In this area, lithological contacts (S_0) are parallel to S_1 (Fig. 5; S_1 form lines), and both are overprinted by a crenulation cleavage (S_2) with a different strike. Locally however, S_0 and S_1 have been transposed into S_2 (Fig. 5; zones AA[1] and BB[1]). The transposition in these zones was accompanied by attenuation and boudinage of the primary layering, so that both D_2 shear zones form the long limbs of a macroscopic F_2 fold. This fold has the same asymmetry as mesoscopic F_2 folds.

The overall F_2 asymmetry in the Tailings Pond quarries is the same as in the mine area (Figs. 2, 8), but mesoscopic F_2 folds of S_1 on the southwestern limb of the NLRL Fold have an opposite asymmetry (Figs. 2, 3i). Also, F_2 folds of S_1 in the hinge of the NLRL Fold are symmetrical, so S_1 predates this fold. Since S_1 is parallel to the compositional layering (S_0) in outcrops in both limbs of the NLRL Fold, the enveloping surface of S_1 is assumed to be parallel to the trend of lithological contacts across the NLRL Fold. It follows that the belt of metasedimentary rocks and augen schists southeast of North Little River Lake can be regarded as the continuation of the D_1 shear zone at Heath Steele Mines.

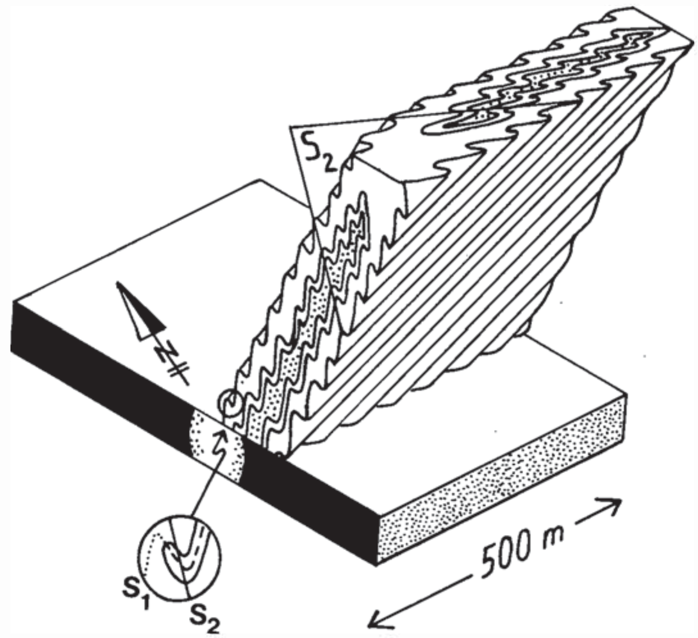

Fig. 8. Schematic structure of the "B" zone ore deposit (slab on horizontal pedestal), after Moreton (1990). The slab of ore symbolizes the enveloping surface of the steeply north dipping main foliation (S_1), which is axial plane to intrafolial F_1 folds, both on the small scale (inset) and on the large scale (the isoclinal antiform marked by metasedimentary rocks (stipple) within the slab). This dome of metasedimentary rocks has a westerly plunging axis, and is deformed into a cascade of westerly plunging F_2 folds with a southwesterly dipping axial plane cleavage S_2.

The (a)symmetry of the second-order F_2 folds suggest that the NLRL Fold is an F_2 structure, although the predominant dip direction of S_2 planes reverses across this fold, from south-southwesterly in its northeastern limb (Fig. 4a) to north-north-easterly on the other limb (Fig. 4b). On the northeastern limb of the NLRL Fold, the dip of S_2 varies from gentle to steep (Figs. 3g, b-f, 4a, respectively), and S_2 is axial planar to both steeply inclined and nearly recumbent folds. F_2 recumbent folds and local transposition of S_1 have also been recognized in areas to the northwest and southwest of Heath Steele Mines (Helmstaedt, 1971; Irrinki, 1986; Table 1). Northeast of Heath Steele Mines, F_2 folds are upright with axial planes steeply dipping to the west. Van Staal (1987) correlated this zone of upright F_2 folding with the zone of recumbent F_2 folding, and referred to them as "steep belts" and "flat belts", respectively (Table 1). The presence of overturned, noncylindrical F_1 folds in the steep belt at Brunswick Mines (van Staal and Williams, 1984; van Staal, 1985) illustrates the regional consistency of D_1/D_2 structural relationships (compare with Fig. 8).

The dip of S_2 in the Tailings Pond quarries is greatest in the D_2 shear zones (Fig. 6), which therefore can be considered as small-scale D_2 steep belts. A steep belt with steeply dipping S_2

cleavages and gently plunging fold axes is also developed south of North Little River Lake (Fig. 2). This zone of high strain occupies the attenuated, southwestern limb of the NLRL Fold.

Late deformations (D_3, D_4 and D_5)

On the outcrop scale, the variation in dip of S_2 is clearly the product of three stages of folding (D_v, D_h, D_5). Considering the limited variation in the orientation of S_v and S_h surfaces (Fig. 4), the D_5 deformation appears to be localized, although, according to mapping by one of us (van Staal), the giant, open folds that dominate the structure of the Bathurst Camp (i.e., the Tetagouche Lakes and Nine Mile Brook Folds; Skinner, 1974) are F_5 structures in our classification (Table 1). The D_5 deformation is distinct in style. Also, the orientation of the S_5 cleavage is independent of its position in any fold, including the NLRL Fold (Figs. 2, 4d), and does not vary throughout the region. Although the D_5 structures clearly postdate all others in outcrop, timing relationships between the other two late deformations (D_v and D_h) are inconclusive, which complicates the correlation of small-scale interference patterns in S_2 with the large-scale structure of S_2.

The D_v deformation produced mostly open folds with a northwesterly striking axial plane cleavage S_v, whereas the D_h deformation produced mostly gentle, recumbent, folds. The pole figures for S_v and S_h each show clear clusters of poles, and in both limbs of the NLRL Fold, plots of L_v, and of poles to S_v, look the same (Fig. 4; compare a and c with b), as do plots of poles to S_h (Fig. 4d; compare S_h with S_{hor}). On the basis of style the D_v structures can be correlated as a third generation (D_3) across the Bathurst Camp, whereas F_h recumbent folds are either late, or not recorded (Table 1).

The strike of S_2 varies at least 90 degrees relative to S_v in separate trenches (Fig. 3d, f), indicating the presence of F_v folds of a size, greater than the scale of both trenches. However, the difference in strike between S_2 and S_v, and, consequently, the sense of asymmetry of F_v folds of S_2, is independent of the dip direction of S_2 (Fig. 3d, e). This problem could be resolved by invoking a variation in plunge direction of F_v folds (Fig. 4c), but conical F_v folding fails to explain why F_2 folds of S_1 show an S-asymmetry, irrespective of the dip direction of S_2 (Figs. 3d, e, 8). The F_2 asymmetry and the orientation of S_2 can be explained more simply by F_h recumbent folding of S_2 prior to the D_v deformation (Fig. 9). This model also explains the observed

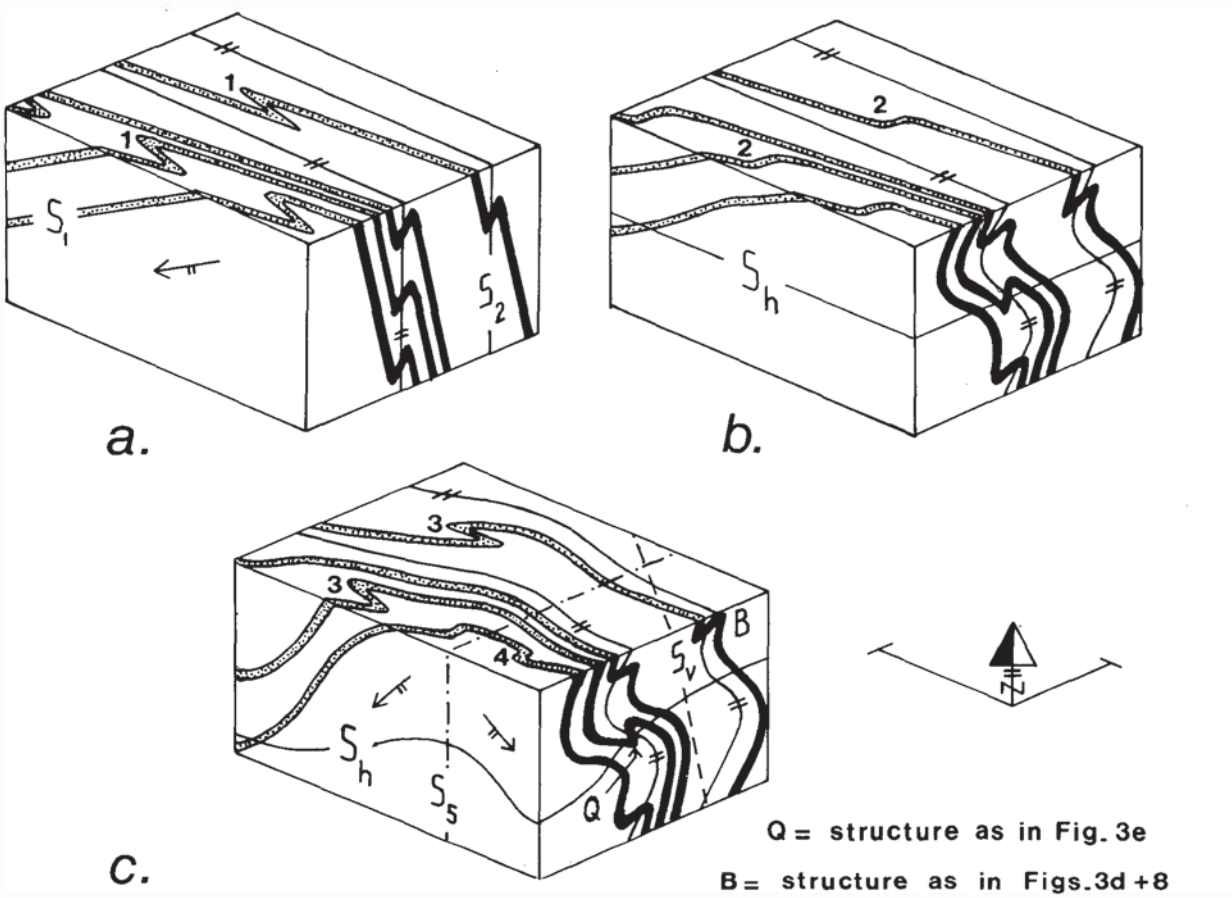

Fig. 9. A model of the structural evolution at C and D in Figure 1, showing F_2 folds of the main foliation ($S_0 = S_1$) in (a). In (b), S_2 is deformed in an F_h recumbent fold. In (c), the axial plane of this fold, S_h, is cast into a dome and basin pattern because of F_v and F_5 folding. This model assumes that F_2 folds originally plunged to the west, and shows them as cylindrical for simplicity. Structural symbols refer to Figure 2. Note that F_2 folds (1-3) are "unfolded" in (b), only to reappear in (c). This is a function of the rotation of their hinge and axial plane, as can be checked by folding a slip of paper (representing S_1), and then intersecting it with the erosion horizon while rotating the paper.

variation in plunge direction of D_2 fold axes and intersection lineations in the mine area (Fig. 4a; also compare the asymmetry of fold 4 in Fig. 9c with Fig. 3a). The prevailing S-asymmetry of F_2 folds in outcrop is interpreted as reflecting original S_1/S_2 intersection relationships (Fig. 9a).

Structural models of the NLRL Fold suffer from the same overprinting difficulties. In opposite limbs of this fold, the asymmetry of F_2 folds of S_1 is reversed, but so is the asymmetry of F_v crenulations of S_2. These relationships could be explained by assuming that the macroscopic F_2 asymmetry reversal is apparent, and in fact reflects the surface projection of a dip reversal of the F_2 fold axial planes (S_2) across an upright F_v synform of S_2 (Fig. 10a). Using this model, we have difficulty explaining the structure of the "Porphyry Pod" south of North Little River Lake.

On the basis of the dominant asymmetry of S_2 relative to S_1, the Porphyry Pod is part of the southwestern limb of the NLRL Fold (Figs. 2, 3j), although it is separated from the main belt of metasedimentary rocks and augen schists by a zone of high D_2 strain. S_v in the Porphyry Pod has an attitude relative to S_2 that is the reverse of the S_2/S_v asymmetry on the opposite side of the zone of high strain (compare Fig. 3i, j), but is the same as in the mine area (compare Fig. 3d, j). These relationships require that S_v crosscuts the NLRL Fold (Fig. 1, upper part; dashes), and argue against the possibility that this fold is an F_v structure, unless the zone of high D_2 strain is the locus of a major fault, in which case the structure of the Porphyry Pod has no bearing on the model of the NLRL Fold. Most D_2 and D_1 fold axes and lineations on the southwestern limb of the NLRL Fold, including the zone of high strain, plunge in a different direction to the F_v fold axes (Fig. 4b). This substantiates the model of transection of the NLRL Fold by S_v. Our preferred explanation of the F_v asymmetry reversal across the fold assumes, as in Figure 9, that the D_h deformation predated the D_v deformation (Fig. 10b, Table 1). In this scenario, the overprinted cleavage in the F_v folds northwest and southeast of North Little River Lake could be interpreted conveniently as S_h instead of S_2, so that there would no longer be a change in asymmetry of F_v folds of S_2 across the NLRL Fold. Consequently, only the F_2 asymmetry reversal remains, so that the NLRL Fold can be defined as an F_2 fold (Figs. 1, 10c). According to the dominant S_1/S_2 asymmetry in the mine area (Fig. 10c, right hand side of frontal section; compare with Fig. 9a) this fold must be a northwesterly plunging antiform, although D_2 linear element distributions and the S_1 pole figure indicate a southeasterly plunge (Fig. 4b). The plunge variation could be attributed to post-D_2 deformation. Firstly, the axial plane of the F_2 fold has been warped in folds with gently dipping axial planes (S_h). Subsequently, S_h was deformed into a northwesterly striking F_v synform (Fig. 10b) with a steeply dipping S_v cleavage that crosscuts the refolded F_2 NLRL Fold (Figs. 1, 10c). This fold was contorted even further in the D_5 deformation.

In this model, the Porphyry Pod can be considered as part of the southwestern limb of the F_2 NLRL Fold. Hence, assuming it persists along strike on, or below, the present erosion level, the Porphyry Pod can be traced around the F_2 fold (Fig. 1, upper part; stipple trail). In this case, the massive metarhyolite, quartz metaporphyry, and the intercalated lenses of metasedimentary

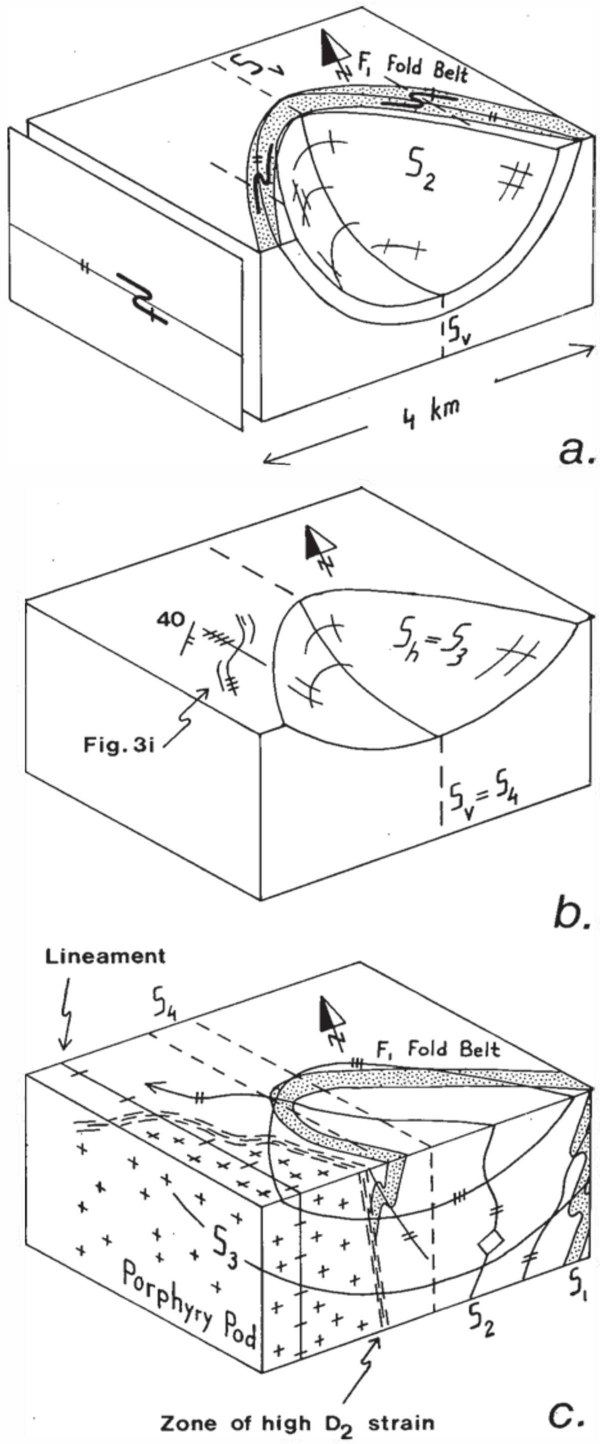

Fig. 10. (a) One explanation for the reversal of the F_2 and F_v fold asymmetry across the limbs of the NLRL Fold is an F_v synform of S_2, which originally was axial plane of recumbent, asymmetrical F_2 folds of S_1 (as shown in front panel). Prevalent dip directions of S_2 require that the F_v synform plunges to the southeast. (b) Same area, assuming S_h ("S_3") predates S_v ("S_4"), in which case overprinting relationships in Figure 3i can be reinterpreted. Comparison with actual S_h orientations shows that the "F_4" fold of "S_3" must be a gentle synform. (c) As (b), incorporating pre- "D_3" structures. Here, the F_2 asymmetry in section requires that the NLRL Fold is a northwesterly plunging F_2 antiform (compare with Figure 9a). Unlabeled form surface symbols refer to Figure 2.

rocks in the Porphyry Pod could be related to petrographically similar rocks north of the D_1 shear zone in the mine area.

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