A structural analysis of the upper Swift River area (105B/3), Yukon, Part I: Dan Zn occurrence and implications for sulphide mineralization[1]

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ABSTRACT

Marble, calc-silicate rock and pelitic layers of the Ram Creek assemblage surrounding the Dan Zn (± Cu-Pb-Ag) occurrence display ample evidence of a monocyclic structural evolution with three main events of progressive deformation (D_1-D_3). These events developed a tightly folded package of west-northwest-trending tectonites. Primary planar structures (S_0) generally lie sub-parallel to two tectonic foliations (S_1 and S_2), which dip shallowly to steeply southwest. Inter-foliation slip (D_3) resulted in a transverse, sub-vertical foliation (S_3) that dips generally shallowly to moderately north. Cross-sections based on new mapping and fold analysis indicate that similar folds containing stratabound zinc-sulphide mineralization should be present south of the Dan occurrence, as part of regional north-northeast-verging folds or a thrust-fault-repeated succession.

RÉSUMÉ

Les couches de marbre, de silicate calcique et de pélite de l'assemblage de Ram Creek entourant les indices de zinc (± Cu-Pb-Ag) Dan renferment de nombreuses indications révélant qu'elles ont été l'objet d'une évolution structurale monocyclique qui comprend trois principales déformations progressives (D_1-D_3). Ces phases de déformation ont été à l'origine de la formation d'un ensemble de plis fortement serrés formés de tectonites orientées ouest-nord-ouest. Les textures planaires primaires (S_0) sont en général presque parallèles aux deux foliations tectoniques (S_1 et S_2), de pendage sud-ouest faible à prononcé. Le glissement inter-foliation (D_3) a produit une foliation subverticale transversale (S_3) de pendage nord généralement faible à modéré. Les coupes basées sur une nouvelle cartographie et une analyse des plis montrent que des plis similaires renfermant une minéralisation de zinc et de sulfure stratiforme sont vraisemblablement présents au sud des indices Dan. Ils feraient partie des plis de vergence nord-nord-est d'importance régionale ou d'une succession répétée par des failles de chevauchement.

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INTRODUCTION

This paper reports on detailed structural studies carried out in the Swift River area of stratabound zinc mineralization in southern Yukon Territory. The study area is accessed by mineral exploration roads, about 24 km northwest of the Pine Lake airstrip near the Alaska Highway at kilometre 1162. Massive sulphide mineralization was discovered in the area in 1946 by Hudson Bay Mining and Smelting Co. Ltd., and examined intermittently since then, most recently by First Yukon Silver Ltd., Cominco Ltd. and Birch Mountain Resources (Indian and Northern Affairs Canada, 1993; Burke, 1998). Although the area has been regionally mapped (Poole et al., 1960; Stevens and Harms, 2000) and the Dan area mapped in detail (Bremner and Liverton, 1991), there has been no structural analysis of the complex folds in the mineralized areas. The man-made bedrock exposures described here comprise the east and west showings of the Dan zinc occurrence (also known as the BAR; Yukon MINFILE, 1997, 105B 027), where the largest claim owner is currently First Yukon Silver Ltd. Along the structural trend to the west are the Lucy, Gossan and Atom showings (the latter is the Crescent occurrence, Yukon MINFILE, 1997 - 105B 026). A similar structural study was carried out on the nearby TBMB claims (Fig. 1; D'el-Rey Silva et al., this volume).

REGIONAL GEOLOGY

The western headwaters of the Swift River encompass the northeastern edge of the Dorsey Terrane (Gordey et al., 1991), where it borders on the western edge of the Cassiar Terrane (Fig. 1). Dorsey Terrane is divided into litho-tectonic assemblages (Stevens and Harms, 1996), which in the upper Swift River area include Ram Creek (metavolcanic rocks, meta-siliciclastic rocks, marble and meta-plutonic rocks), Dorsey (predominantly chlorite-muscovite-feldspar-quartz schist), and Swift River (dark argillite and chert, with quartzite intervals) assemblages (note that Dorsey assemblage is a subset of Dorsey Terrane). The assemblages trend southeast, as do intrusions which separate the first two: the Ram stock, a ~ 259 Ma old deformed granodiorite (Stevens, 1996), and a diorite of probable Jurassic age. The contact between Ram Creek assemblage and Cassiar Terrane lies covered beneath the upper Swift River valley, and is thought to be a fault zone. The Dan occurrence is less than 10 km northeast of the Cretaceous Seagull Batholith and less than 2 km southwest of the Cassiar Batholith.

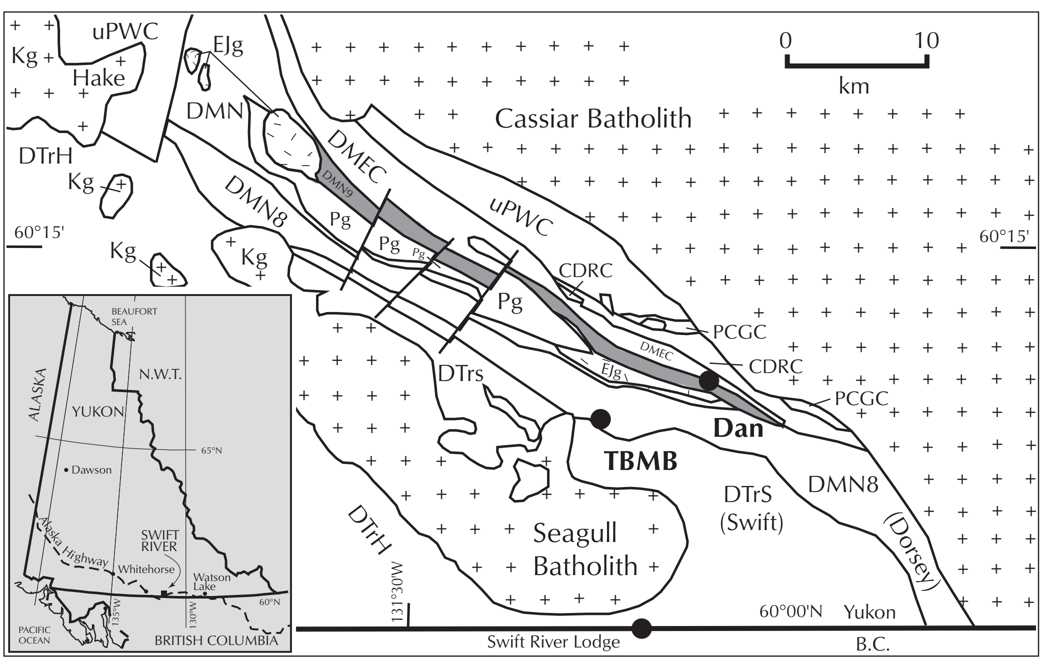

Figure 1. *Location of the Swift River area in southern Yukon. Geology adapted from Gordey and Makepeace (1999). Labelled units are: Kg – Cretaceous intrusions; EJg – Jurassic intrusions; Pg – Ram stock (Permian); DTrH – Klinkit assemblage; DTrS – Swift River assemblage; DMN8, DMN – Dorsey assemblage; DMN9 – Ram Creek assemblage (shaded); and rocks of the Cassiar Platform, including: DMEC – Mid-Paleozoic argillite; CDRC, PCGC – Lower Paleozoic carbonate; and uPWC – Late Proterozoic clastic rocks. The area of Figure 2 is covered by the dot marking the Dan occurrence. (The TBMB claims, the subject of D'el Rey Silva et al. (Part II, this volume) are also shown).*

GEOLOGY OF THE SWIFT RIVER AREA

The relatively low elevation showings of the Dan occurrence are hosted by the Ram Creek assemblage, containing metavolcanic rocks (felsic, intermediate and mafic protoliths are suspected), argillite, meta-siltstone and marble, all of which have been deformed and metamorphosed to at least upper greenschist facies. Compositional contacts are the only primary feature remaining, with the exception of probable igneous-flow texture (fiamme) observed in thin sections of metavolcanic layers (S. Gordey, pers. comm., 1995) and beta-quartz phenocrysts (pers. comm., First Yukon Silver Resources Ltd., 1995; pers. comm., Birch Mountain Resources Ltd., 1998). Marble is only abundant in the vicinity of the Dan occurrence, but was intersected in drill core to the west (beneath Lucy showing; T. Liverton, pers. comm., 2000). In the area of the Dan occurrence, the pelitic rocks are a contact-metamorphosed succession of garnet-diopside-actinolite calc-silicate hornfels, and the marble contains bands of diopside and garnet. Disseminated to banded and massive pyrrhotite and magnetite with some sphalerite, chalcopyrite and pyrite is distributed in pods and blebs along the deformed contact between white and green calc-silicate rock (possibly meta-tuff) and the marble. The sulphide layers appear to follow a branching system of reverse faults and steeply dipping cross-faults of minor displacement (Bremner and Liverton, 1991). At other occurrences, the mineralization style is similar but the host rock varies: dark metavolcanic rock predominates at the Lucy showing, whereas at the lower Atom showing, the alternating tectonic bands of garnet-epidote and quartz-chlorite are similar to non-mineralized parts of the Dan showings. Another mineralized area, 4 km southwest of Dan (the TBMB claims; Yukon MINFILE, 1997, 105B 029) is discussed in D'el Rey Silva et al. (Part II, this volume). Previously all the mineralization was interpreted as skarn (Abbott, 1986; Bremner and Liverton, 1993), but is here considered sedimentary (possibly volcanic-) exhalative, deformed and subsequently contact metamorphosed by much later intrusions.

METHODS

The Dan occurrence has eastern and western showings (Fig. 2) that are outcrops enhanced by bulldozer excavation and pressure washing (H. Hibbing and D. Schellenberg, pers. comm., 1990). The resulting surface is roughly planar to the north-facing slope (Fig. 3) that is largely controlled by shallowly dipping fractures.

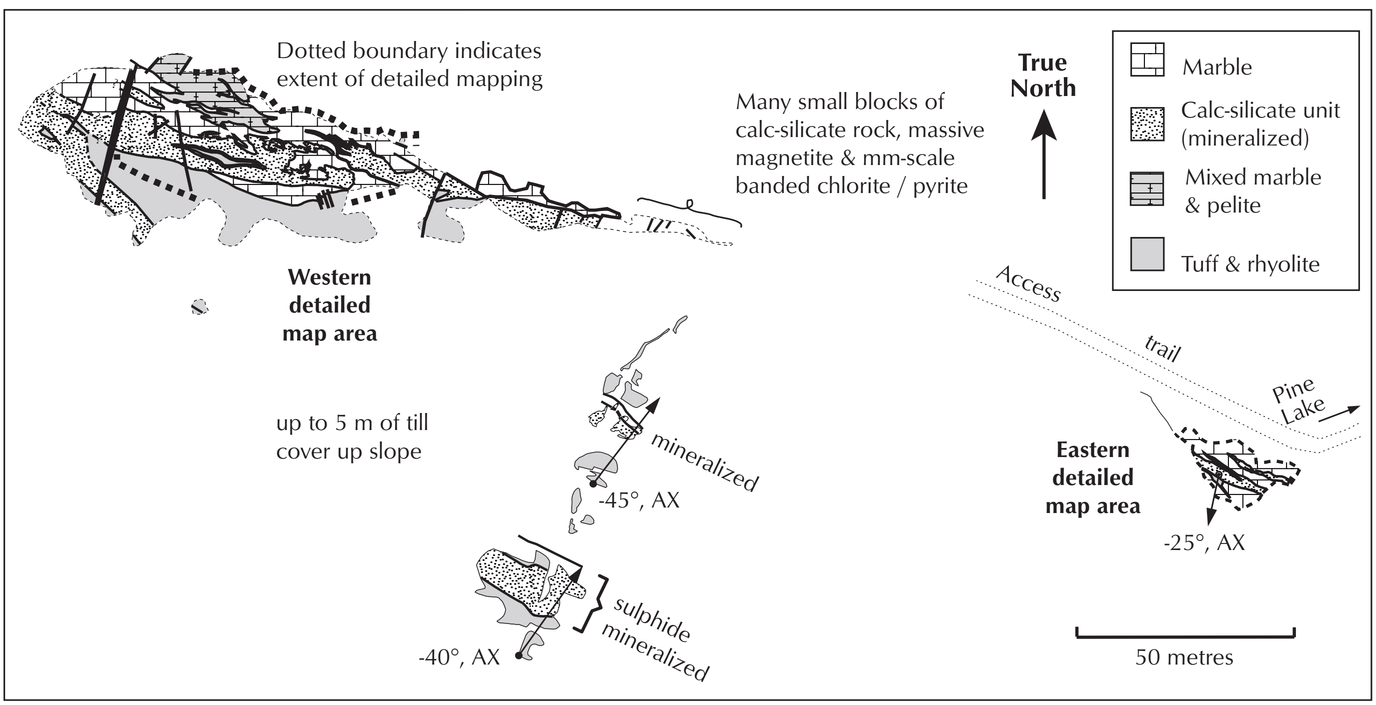

Figure 2. *Exposure of the Dan Zn-Pb-Ag occurrence, indicating the western and eastern parts (Figs. 4a and 5) that have been mapped in detail by the second author during 1990, 1996 and by the first author during this study. Arrows on three exposures indicate drill holes with plunge and core size (AX).*

Mapping at 1:100 and 1:200 scales was performed with the aid of a plane table, alidade, and tape, and fold hinges, fold limbs, contacts, and intersecting structures were precisely located. Contacts and folds were drawn directly on the plane table whilst still at the outcrop; such documentation helped the authors understand the effects of fold superposition, particularly in the western part of the Dan. At every change in direction of the contact between the marble and calc-silicate rock, an F_1, F_2, or both types of fold could be identified. Samples of different rock units and different types of ore were collected in the field. Studies of the petrology and mineralogy of the host rocks, as well as analyses for stable and radiogenic isotopes (O, C, Sm-Nd) are in progress.

The resulting geological maps are simplified in Figures 4a and 5. Some F_1 and several F_2 folds are large enough to show on the maps. All attitudes mentioned herein follow the dip-direction method.

Figure 3. *Eastward view of washed bedrock at western showing, showing a thin, dark calc-silicate layer interleaved with light marble. The ladder was used in taking the photograph of the fold shown in Figure 8.*

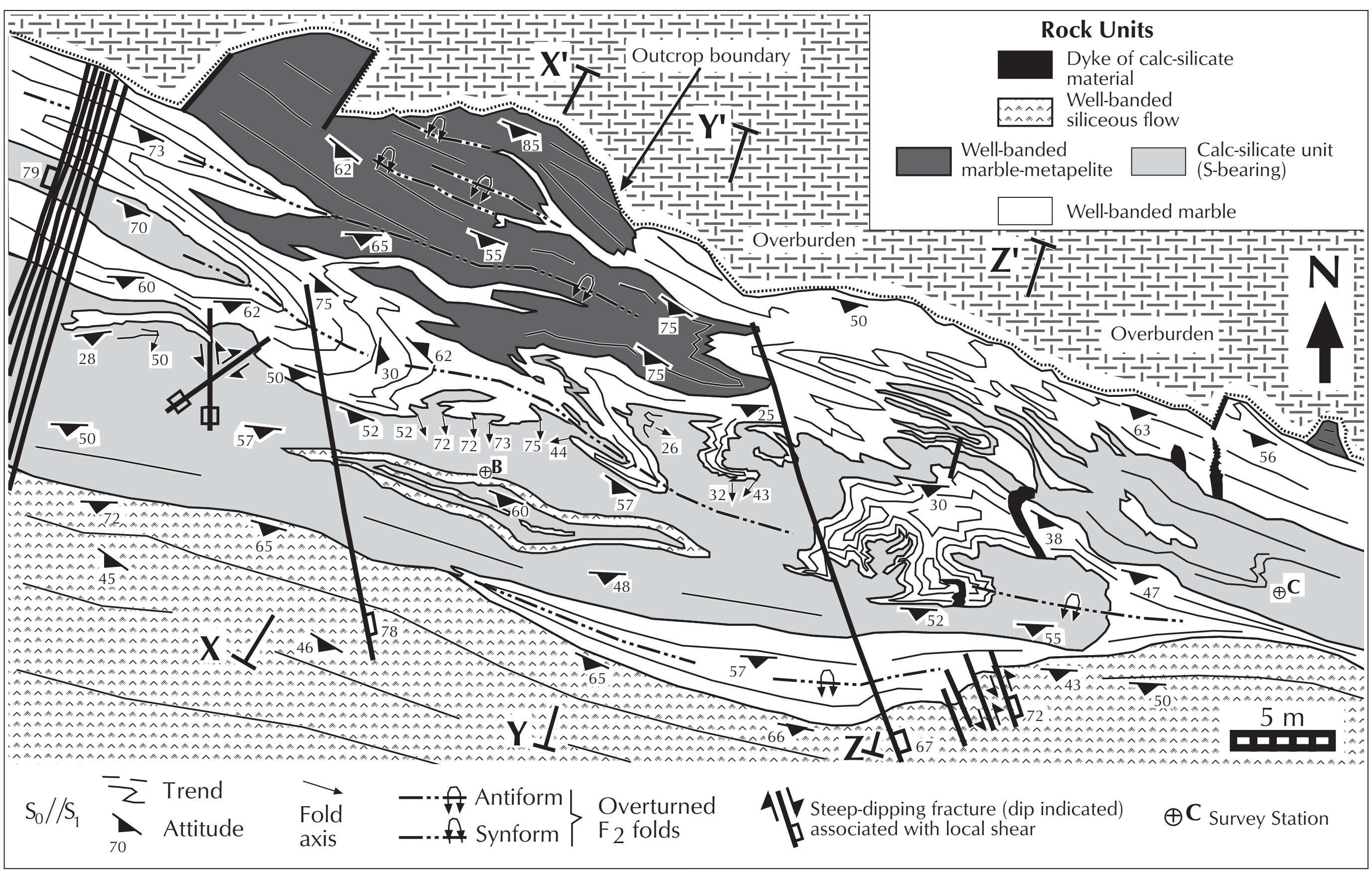

Figure 4a. *Lithostructural map of the western part of the Dan occurrence (reduced from 1:200-scale mapping) showing cross-section locations (XX', YY' and ZZ').*

SUMMARY OF STRUCTURES AND

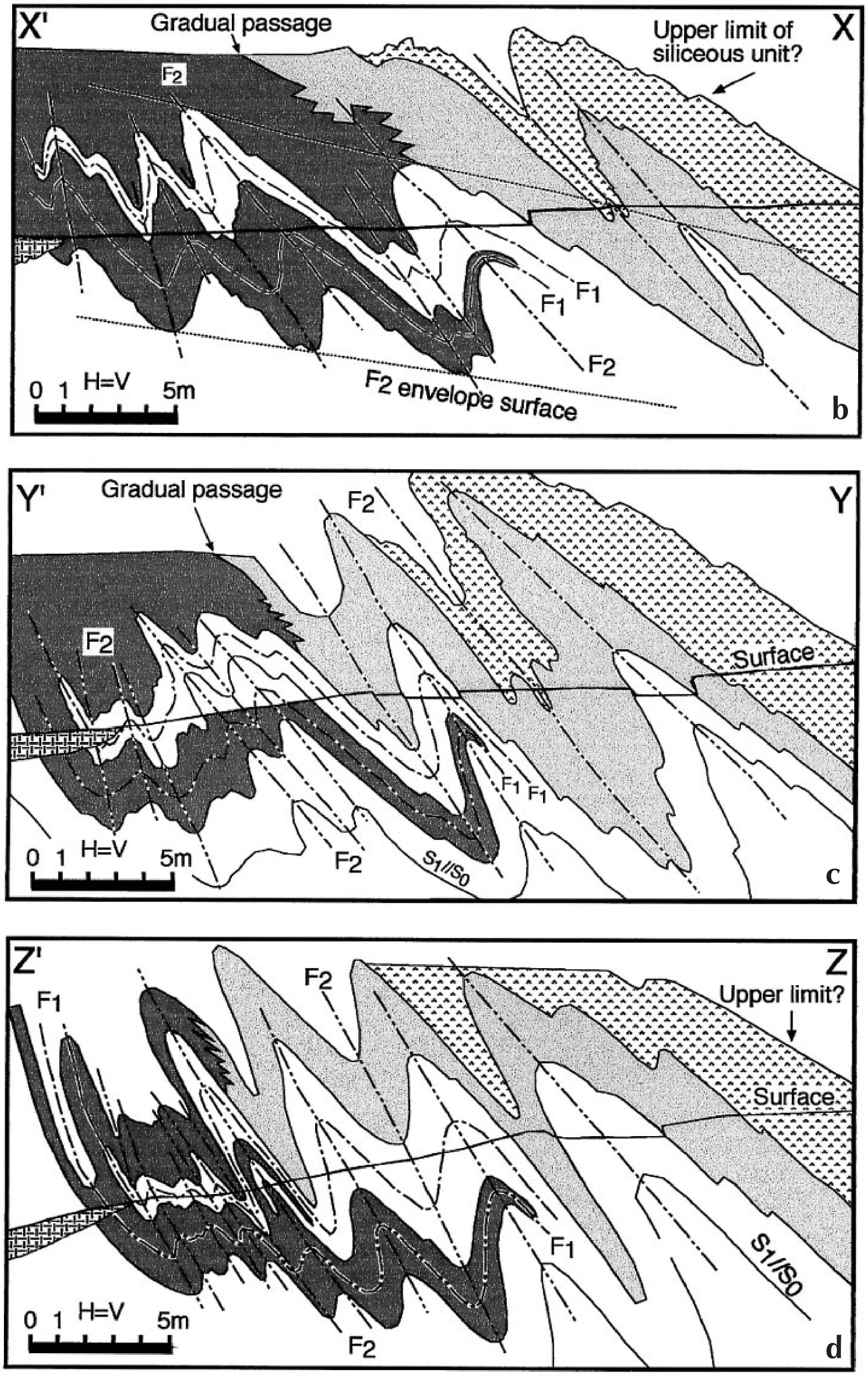

Fig. 4b,c,d. *Vertical cross-sections for the western part of the Dan occurrence. Structures related to the D_3 event, such as sub-vertical fractures and sub-vertical faults, have been omitted for clarity. H = V: horizontal = vertical.*

DEFORMATION

Structures in the studied area result from two events of highly ductile deformation (D_1-D_2) and from a late event of brittle-ductile deformation (D_3). The two earlier events imprinted several micro- to mesoscopic-scale structures on the sedimentary layering (S_0), such as folds (F_1, F_2) and their associated planar and linear fabric elements: axial plane foliations (S_1, S_2), intersection lineations (L_{1-0}, L_{2-1}) and fold axes (B_1, B_2).

As a consequence, the area consists of a packet of east-southeast-trending S-tectonites containing three planar foliations ($S_0//S_1//S_2$) commonly sub-parallel and dipping shallowly to steeply to the southwest. Linear structures such as L_1, L_2-1, B_1, B_2 are also sub-parallel and trend southeast, with a gentle plunge commonly to northwest or southeast.

The D_3 event developed folds (F_3) with their associated planar structures, such axial planar foliation (S_3). A set of shallowly dipping fracture planes (S_{3a}) are tertiary fractures that exacerbated glacial erosion. Linear structures of D_3 (fold axis and intersection lineation) are controlled by the dip of $S_0//S_1//S_2$. They are not discussed further because they do not affect the distribution of rocks and mineralization.

PRIMARY LAYERING (S_0)

The intercalation of metasedimentary and metavolcanic rocks with markedly different compositions occurs on scales between 1 and 10 m. On a small-scale, S_0 is marked by cm- to dm-thick beds of different colour within each sedimentary unit. For example, within the marble unit, beds of grey meta-pelites are intercalated with dominant beds of white marble.

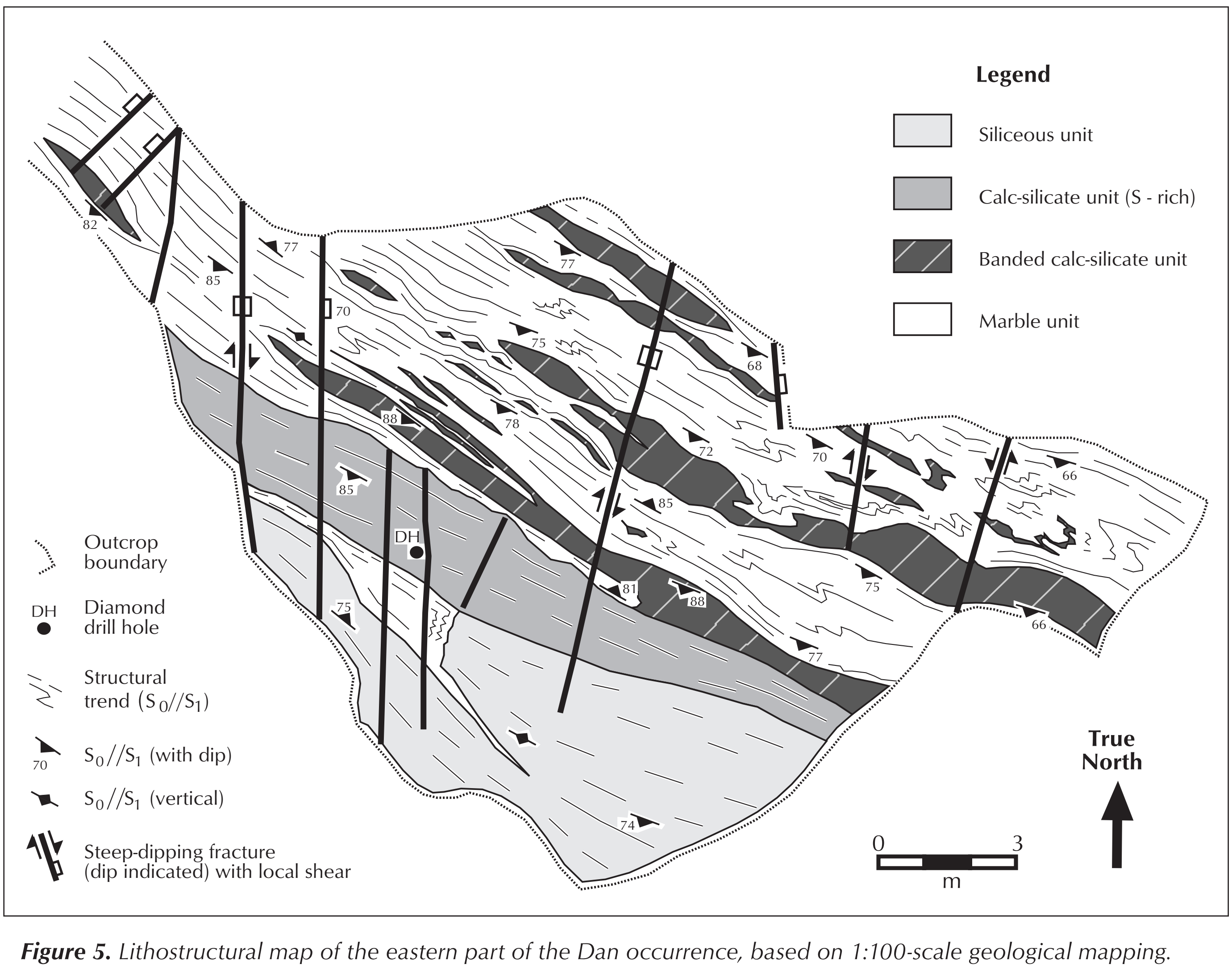

Figure 5. Lithostructural map of the eastern part of the Dan occurrence, based on 1:100-scale geological mapping.

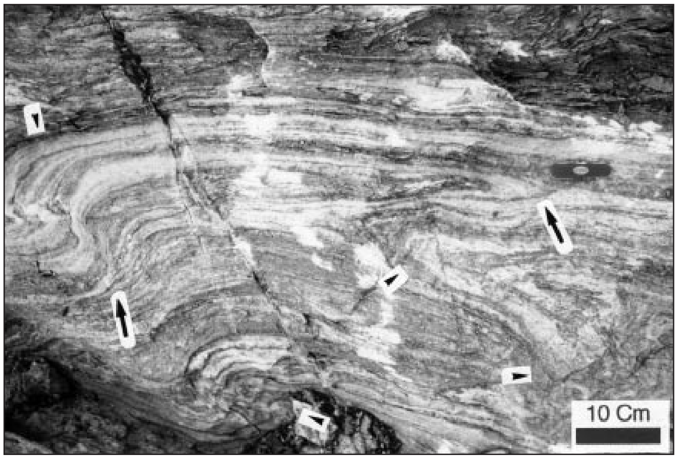

Figure 6. *F_1 folds in the white marble unit of the eastern part of the Dan occurrence. Thick arrows indicate two hinges. The whole package displays $S_0//S_1$ and is co-axially refolded by F_2 folds (other arrows). F_1 and F_2 folds display Z and S asymmetry, respectively.*

THE D_1 DEFORMATION

This event is characterized by isoclinal folds (F_1) and their associated axial planar foliation (S_1). This folding affected S_0 throughout the area and developed a longitudinally continuous packet of well-layered, low-grade metamorphic rocks, within which the F_1 fold hinges can be traced easily in many places. These hinges are contained within the packet of layers and commonly exhibit an amplitude of 0.1-1.0 m, whereas the fold limbs are several metres to tens of metres long. This supports the interpretation that D_1 was an event of very ductile deformation, and the F_1 folds compare well with class 3 folds of Ramsay (1967). F_1 folds have a strong axial planar foliation (S_1) that is sub-parallel to S_0, except in the F_1 hinges, where S_1 cuts across the primary layering (Fig. 6).

S_0-S_1 forms a set of southeast-trending planar structures that dip from 40° to 80° generally southwest, everywhere in the Swift River area. However, the average dip angle of S_0-S_1 is greater in the eastern (Fig. 7a) than in the western part (Fig. 7b) of the Dan. The F_1 fold axes (B_1) plunge shallowly to NW or to SE, in the Dan (Fig. 7g) and also regionally.

The S_1 foliation is commonly defined by flattened crystals of carbonate and quartz, and phyllosilicates such as fine-grained white mica (sericite), chlorite and some biotite. A slaty cleavage is visible in some fine-grained siliciclastic units. The S_1 / S_0 intersection lineation ($L_{1\text{-}0}$) is parallel to the B_1 fold axes (Fig. 7g).

THE D_2 DEFORMATION

The D_2 event of deformation is defined by several pairs of mesoscopic F_2 folds and their associated axial plane foliation (S_2) that affect S_0 and all D_1 tectonic structures. The F_2 folds are co-axial with F_1 (Fig. 8), as indicated by the S_0-S_1 stereograms (Fig. 7-b). However, by comparison with the stereograms of B_1 + $L_{1\text{-}0}$ and B_2 + $L_{2\text{-}1}$, the poles of B_1 and $L_{1\text{-}0}$ are generally dispersed around southerly directions (Fig. 7g), partly because F_1 are non-cylindrical folds (Williams and Chapman, 1979) may have evolved into sheath folds (discussed later).

The F_2 folds are southeast trending, commonly tight, display m to 10-m scale, and are moderately inclined to up-right (Fig. 8). F_2 axial planes dip between 80° and 90° northeast and southwest in the eastern part of the Dan (Fig. 7c), and around 40°-60° to the southwest in the western part (Fig. 7d). In contrast, the fold axes exhibit a plunge to northwest or southeast in both parts of the area (Fig. 7h). These folds have a strong and penetrative axial planar foliation (S_2) with similar orientation and associated mineralogy as S_1. The authors therefore interpret similar conditions of deformation during D_1 and D_2. The intersection between planes of S_2 with S_1 and S_0 develops a penetrative lineation that overprints $L_{1\text{-}0}$ in most of the area. It is generally hard to separate these two lineations in the field, but both may be identified locally.

The F_1 and F_2 folds are difficult to distinguish because their respective structures are generally parallel. Numerous examples of fold interference were found in the mapped area. During mapping, a fold was identified as F_1 only if it could be shown to be affected by another fold (F_2), although this method is equivocal in some cases.

SHEATH FOLDS AND THE FOLD INTERFERENCE MAP PATTERN

Sheath folds are a common feature at the Dan occurrence and can be identified along folded contacts. Sheath folds are tight to isoclinal and show hinge lines bent more than 90°, resulting from superposition of fold phases or very high strain on folds with curving hinges (Ramsey and Huber, 1987, p. 638). The F_1 sheath folds at the Dan occurrence are best observed between the marble and calc-silicate units in the western part of the study area where they are 1-3 m in amplitude (perpendicular to the axis of the sheath B_1 + $L_{1\text{-}0}$; Fig. 9).

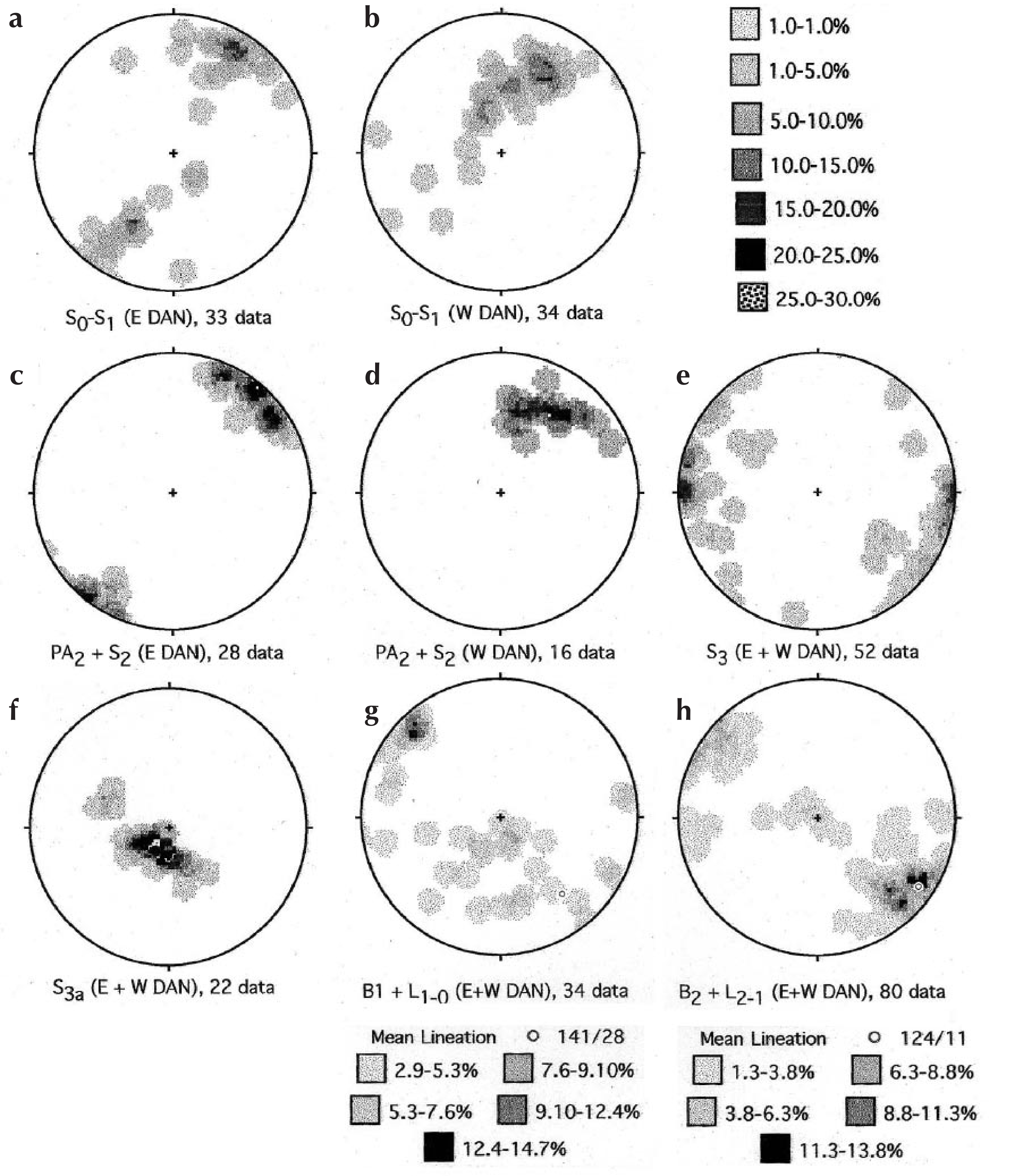

Figure 7. *Lower hemisphere Schmidt equal area density stereoplots for: (a-f) poles to: planar structures developed during* D_1 *-* D_3*; and (g,h) main linear structures developed during* D_1 *and* D_2*. Sources are eastern and western showings of the Dan occurrence, as noted.*

The interpretation that the sheaths are F_1 folds is based on the observation that the axial plane of the sheaths dip at intermediate angles to south-southwest, sub-parallel to the dip of the layers, and that the sheath folds are affected by F_2 folds of dm- to m-scale. Sheath folds of F_2 have not been identified. The repetition of layers in outcrop suggests large-scale co-axial folds, which are used in drawing north-northeast-trending cross-sections.

VERTICAL CROSS-SECTIONS

The vertical cross-sections of the western Dan showing depend upon an interpretation that the layers of marble and pelitic material (in the north) undergo a metamorphic facies transition southward into the calc-silicate unit. This gradual transition is consistent with the observation that they are spatially related in the centre of the western part of the Dan (Fig. 4b); both layers are in contact with the marble unit; both lie along the same trend, and are separated by a few metres. The internal consistency of structural observations allows us to construct other cross-sections up plunge to the west.

The sections display a syncline-anticline pair of isoclinal F_1 folds for which the axial planes dip generally at low angle to south-southwest, but steeper dips are also common due to several F_2 folds with axial planes dipping 45°-75° south-southwest. The enveloping surfaces of the F_2 folds are interpreted to dip shallowly to the south-southwest, parallel to the hinges of F_2 antiforms and synforms.

Actually, a sequence of m-scale folds in the part of the outcrop close to survey station C (right side of Fig. 5a) implies that the sulphide-bearing layers structurally overlie the marble unit in that outcrop. The intense ductility during D_1 and D_2, coupled with the presence of sheath folds visible at surface (and are likely present in the sub-surface) preclude fully balancing the cross-sections.

The outcrop pattern of the layers record, in map view and in cross-section, progressive folding (F_1 + F_2) with a general vergence to north-northeast. As a consequence, the layers became interleaved on a scale compatible with the thickness of the original beds (cm-dm), because the F_1 folds are isoclinal and the length of their limbs is great compared to the wavelength, particularly if compared to that exhibited by the F_2 folds.

THE D_3 DEFORMATION

This event imprinted folds (F_3), axial plane foliations (S_3), and a set of low-angle-dipping fracture planes (S_{3a}) that affect the D_1-D_2 tectonites in a sub-perpendicular relationship that is systematic across the study area, although D_3 structures are not relevant to spatial distribution of the layers.

The F_3 folds (Fig. 10) are gentle to open, with an S_3 axial plane foliations all trending south, on average, with a steep to sub-vertical dip to westerly and easterly directions, as statistically demonstrated for the eastern and western parts of the Dan occurrence (Fig. 7e). The

__Figure 8.__ A thin layer of calc-silicate rock (dark) interleaved with the marble unit (white) indicates F_1 x F_2 co-axial interference pattern. Note the long limbs of F_1 folds refolded by F_2. From the eastern end of the western showing of the Dan occurrence. Larger view shown in Fig. 3.

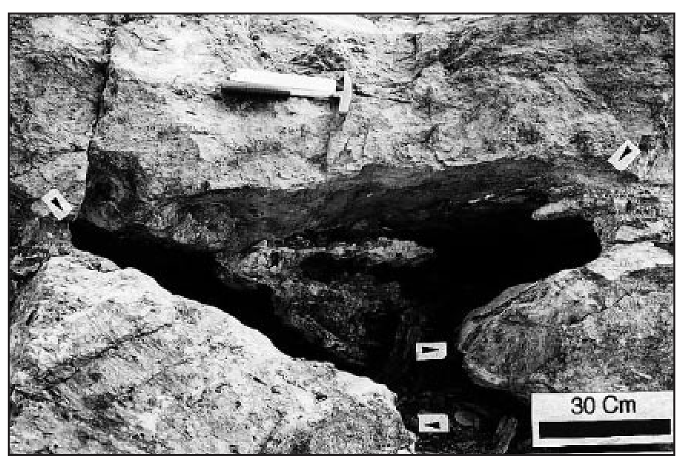

__Figure 9.__ Eroded hole left by m-scale core of an F_1 sheath fold that affects calc-silicate rock and marble. The four F_1 hinges indicated by the arrows all plunge about 72° to the south-southeast.

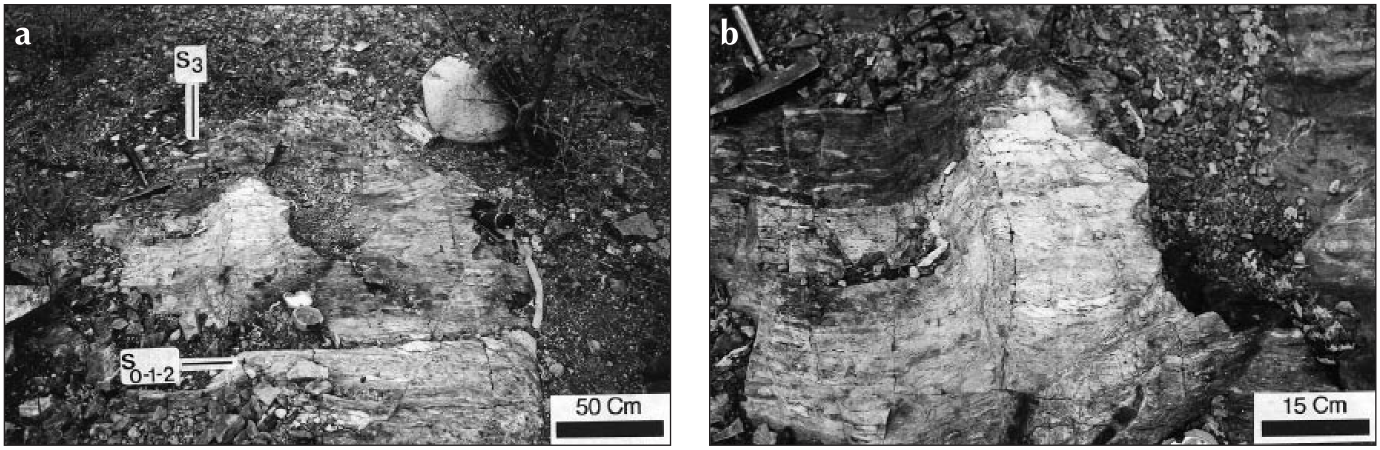

Figure 10. *(a) Southward view of siliceous (light) and calc-silicate (dark rock) tectonites, which display a east-southeast-trending anisotropy composed of S_0, S_1 and S_2. All are sub-parallel to surface (labeled $S_{0\text{-}1\text{-}2}$ in the picture), and affected by open to tight F_3 folds associated to a well developed, northerly trending, sub-vertical S_3 foliation, shown in detail in (b). Note geometry of F_3 and the pressure-solution-type S_3 foliation.*

folds are sub-vertical bends that affect the anisotropic packet described in the previous sections, so the fold axes and the intersection lineation (B_3 and $L_{3\text{-}2/1/0}$) generally plunge steeply to the south, as it is controlled by the dip of S_0, S_1, or S_2, or even by the dip of all of these, together. The F_3 bends are generally 1 m in size, and commonly display a kink-style.

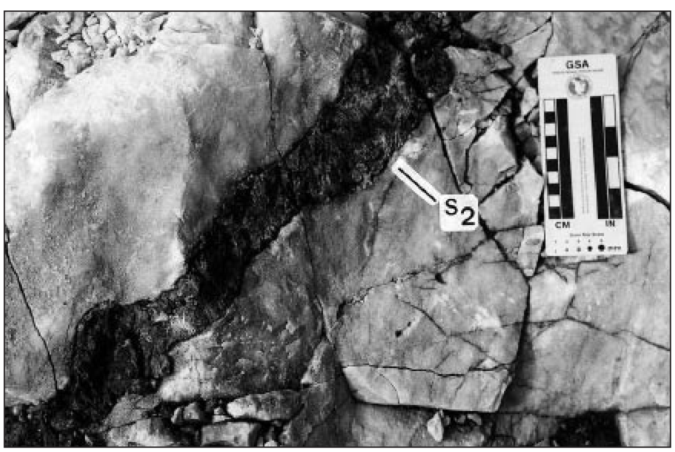

Figure 11. *Dyke of calc-silicate material fills a north-trending extensional fracture in the marble unit, western part of the Dan occurrence. The dyke cuts across D_1-D_2 structures (S_2 foliation is labeled), but is also affected by dm-scale folds and crosscut by their axial plane foliation, both developed late in the D_2 event. The plunge of the fold axis (and dyke) is sub-vertical, controlled by the dip of the extension fracture.*

Two sets of D_3 planar foliations are common in the study area. The S_3 foliation is generally a well developed, sub-vertical, spaced cleavage locally displaying a component of pressure solution. The S_{3a} foliation is a spaced cleavage that trends generally west-northwest and dips shallowly to the north (Fig. 7f). The ubiquitous S_3 foliation is not always associated to F_3 folds. The west end of the western outcrop of the Dan is marked by a closely spaced set of S_3 planes (Fig. 4a). The layers are so intensely crosscut that they give the impression of a fault zone although no significant displacement was determined. Carbonate veins are also found along the planes of S_3 and S_{3a}.

In the western part of the Dan a south-trending sub-vertical set of brownish green dykes (Fig. 11) cuts S_1-S_2 and is affected by dm- to m-scale folds with sub-vertical axial planes and vertical fold axes that the authors interpret as late S_2.

CONCLUSIONS

The trenches in the lower part of the Dan occurrence are along the normal limb of a major F_2 fold, which is aligned with other F_1 and F_2 folds. The authors suggest that additional stratiform mineralization could be present in folds up slope to the south of the Dan, beneath overburden. It is a new strategy for mineral exploration in the upper Swift River area.

The F_3 folds and the S_3 foliation may be understood in terms of a layer-parallel compression that took place as soon as the rocks in the area attained the east-southeast regional trend with dips to south. The rocks then behaved as a more competant anisotropic package. The authors envisage a progressive evolution of deformation for D_1-D_3 in the upper Swift River area in a single tectonic cycle. The attitude of the dykes and their shortening by an overall N-S compression illustrate the orientation of maximum compressive stress. In contrast, the S_{3a} foliation is sub-horizontal and may have assisted erosion. Hence S_{3a} planes control the slope of the outcrop.

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