Marble mylonites of the Bancroft shear zone: Evidence for extension in the Canadian Grenville

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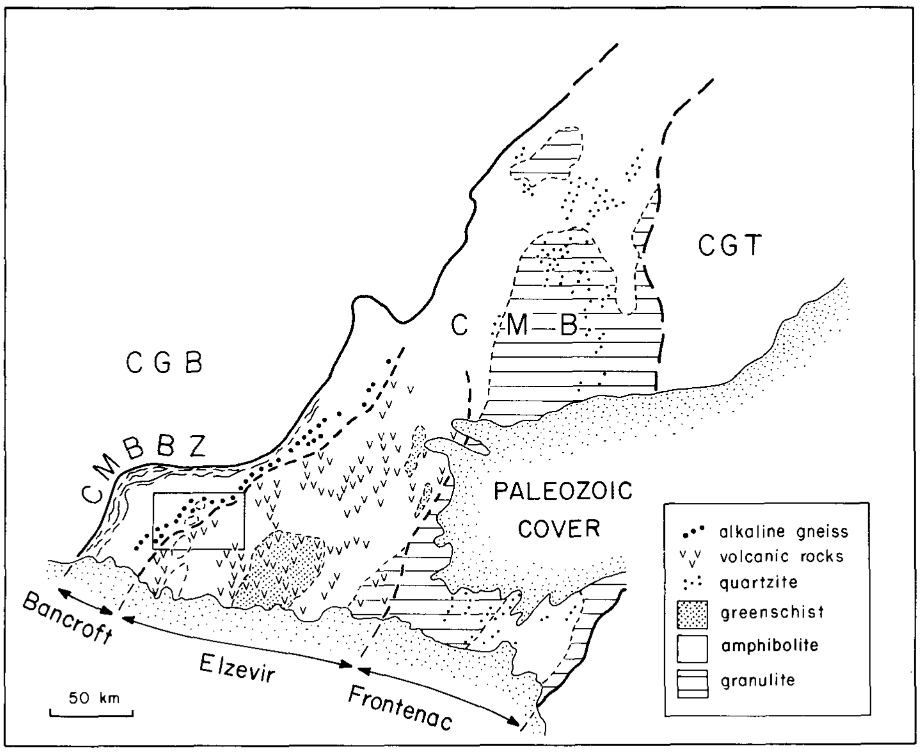
ABSTRACT

Detailed field mapping in marbles from the Central Metasedimentary belt (CMB) near Bancroft, Ontario, shows that isolated exposures of marble mylonite are part of a regionally extensive shear zone, the Bancroft shear zone. Shear-sense indicators in this southeast-dipping zone give movement of the hanging wall toward the southeast, indicating extension. Local crosscutting relationships indicate that the extension is younger than the regional thrusting event that produced the predominant structural fabric. On a regional scale, however, the extensional and compressional fabrics are essentially parallel. The marbles preserve a variety of textures ranging from light-colored, coarse samples to light-colored, weakly foliated samples with remnant coarse calcite grains to banded fine-grained samples to dark, extremely fine-grained samples. These various textures represent progressive stages in the development of marble mylonite, from protolith to ultramylonite. We conclude that the Bancroft shear zone marks the Bancroft-Elzevir subdomain boundary of the CMB and that late extension is responsible for the observed differences in lithology and metamorphic grade of these Grenville subdomains.

INTRODUCTION

Structural mapping in the southern Ontario segment of the Grenville province has shown that the region is dominated by northwest-directed thrusting (for example, Davidson and others, 1982). This paper describes the characteristics of a marble mylonite zone near Bancroft, Ontario, the Bancroft shear zone, and demonstrates that following thrusting, extension dominated the later part of the structural history. In an accompanying paper (van der Pluijm and Carlson, 1989), we have documented the retrograde nature of this shear zone, using calcite-graphite carbon isotopic thermometry, and we speculated on the tectonic significance of extension in the Grenville.

Wynne-Edwards (1972) divided the Grenville in southern Ontario into the Central Gneiss belt (CGB), the Central Metasedimentary belt (CMB), and the Central Granulite terrane (CGT) (Fig. 1, inset). The CGB consists mainly of amphibolite- to granulite-facies quartzofeldspathic



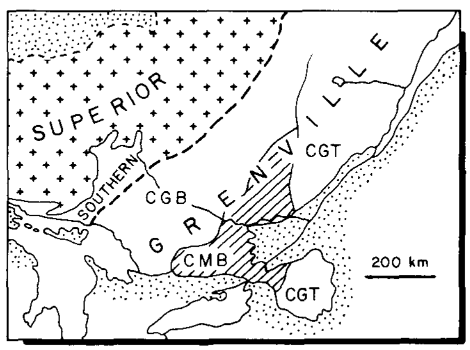


Figure 1. Map showing the subdivision of the Central Metasedimentary belt (CMB) and the diagnostic lithologies and approximate metamorphic grade (after Davidson, 1986). The Central Metasedimentary belt boundary zone (CMBBZ) lies along the western edge of the CMB and is denoted by wavy lines. The map area for this study (Fig. 2) lies near the CMBBZ and straddles the Bancroft-Elzevir terrane boundary (box). The inset gives the location of the CMB within the southeastern Grenville province. CGB, Central Gneiss belt; CGT, Central Granulite terrane.

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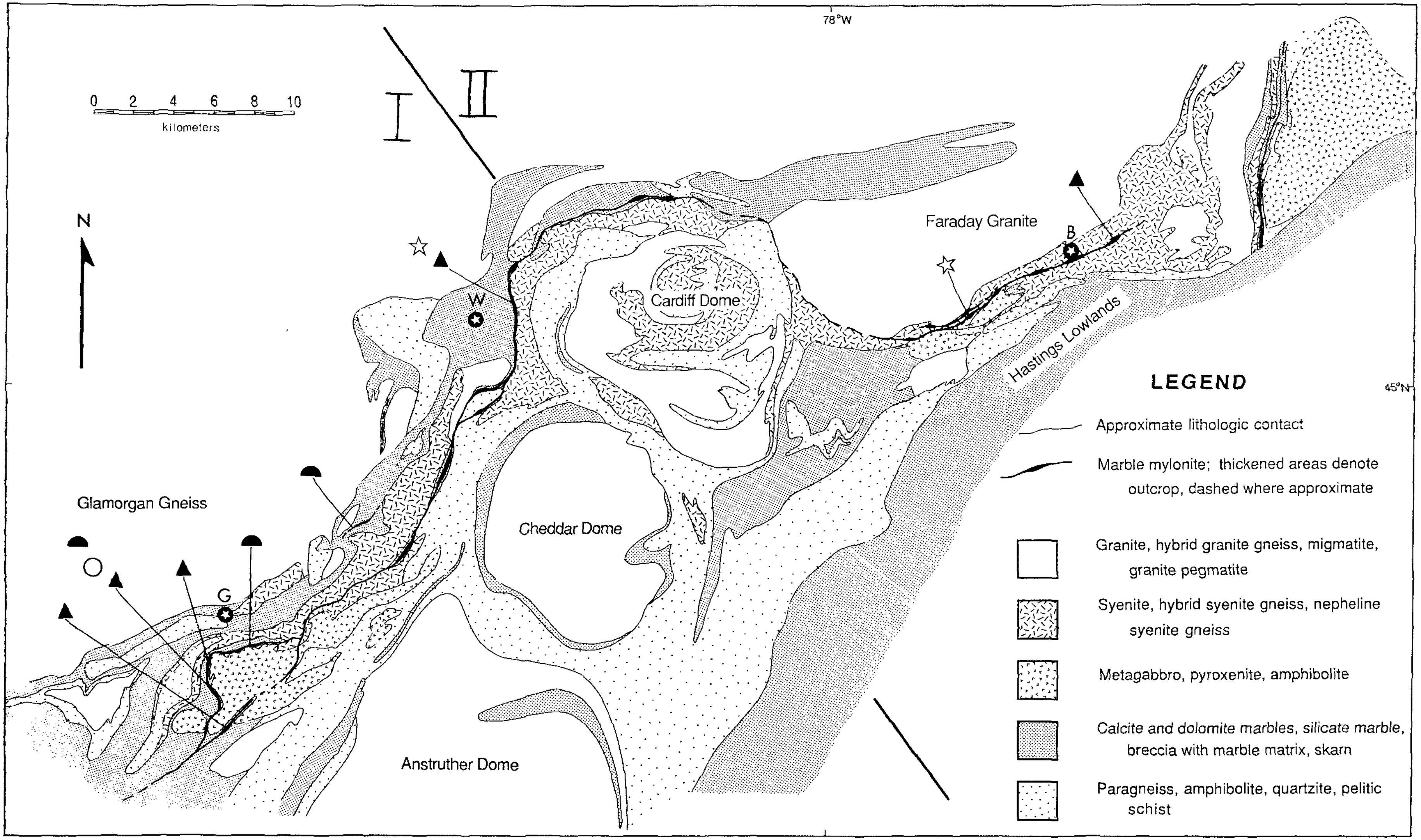

Figure 2. Lithologic map of the Bancroft area, showing the location of the extensional mylonite zone by a heavy line. Mylonite exposures are denoted by thickened areas along the line. Towns indicated are Bancroft (B), Gooderham (G), and Wilberforce (W). Symbols represent shear-sense indicators: triangle, rotated clast(s); circle, S-C mylonite; semicircle, shear bands; star, mica fish. The map is adapted from Anonymous (1957), Bright (1981), and Masson (1982a, 1982b) and includes mapping by Carlson.

gneisses and has been interpreted as a stack of thrust sheets on the basis of structural, metamorphic, lithological, and geophysical differences (Davidson and Morgan, 1981; Davidson and others, 1982; Culshaw and others, 1983; Davidson, 1984, 1986; Mawer, 1987). Shear-sense indicators in the high-strain domain boundaries consistently indicate overthrusting transport toward the northwest (for example, Davidson and others, 1982), which occurred as early as 1160 Ma (U/Pb, zircons; Van Breemen and others, 1986). The CMB is characterized by gently southeast-dipping lithologic layering. A well-developed gneissosity parallels the lithologic layering and contains a consistently southeast-plunging stretching lineation. The boundary between the CMB and the CGB, the Central Metasedimentary belt boundary zone (CMBBZ, Fig. 1), has been interpreted as an unconformity with a coarse clastic basal sequence (Schwerdtner and Lumbers, 1980; Lumbers, 1982) or as a tectonic boundary (Davidson and Morgan, 1981; Culshaw and others, 1983; Hanmer and Ciesielski, 1984; Hanmer, 1988). Hanmer and Ciesielski (1984) described a suite of shear-sense indicators near the CMBBZ that shows the regional penetrative fabric to be a product of northwest-directed thrusting. The timing of this thrusting event was dated as approximately 1060 Ma (U/Pb, zircons; Van Breemen and Hanmer, 1986). Davidson and others (1984) and Easton (1987) also described northwest-directed transport on southeast-dipping planes in several locations within the western CMB.

The CMB is lithologically diverse and has been subdivided into the Bancroft, Elzevir, and Frontenac terranes (roughly equivalent to IVA, IVB, IVC of Wynne-Edwards, 1972) on the basis of metamorphic grade and lithologic contrasts (Carmichael and others, 1978; Moore, 1982; Brock and Moore, 1983; Davidson, 1986) (Fig. 1). Our map area straddles the boundary between the Bancroft terrane, characterized by the presence of middle- to upper-amphibolite–grade orthogneisses, and the Elzevir terrane, which is composed mainly of lower-amphibolite- to greenschist-grade metavolcanics interlayered with marbles and clastic metasediments that were deposited from approximately 1280–1250 Ma (Easton, 1986).

The data presented in this paper were collected mainly in the region between Gooderham and Bancroft, Ontario, in the CMB (Fig. 2). The Glamorgan crystalline thrust sheet and the Faraday granite lie to the northwest of the study area and are separated from the Cardiff, Cheddar, and Anstruther granitic domes and the Hastings Lowlands by a zone of deformed marbles, calc-silicate paragneisses, amphibolites, syenite gneisses, and in some places metagabbros. The geology of this area has been summarized by Adams and Barlow (1910), Hewitt (1957, 1962), and Lumbers (1964, 1967). We have simplified the local geology from the Haliburton-Bancroft Map Sheet 1957b by using five lithologic units: granite, syenite, gabbro, marble, and paragneiss. Our study focused on the unit that is shown by the heavy line, which is the trace of marble mylonites of the Bancroft shear zone. In this paper, we describe the geometry, the kinematics, and the textural variation of the zone and discuss its significance for Grenville geology.

MYLONITE FABRIC: REGIONAL AND OUTCROP SCALES

The middle- to upper-amphibolite–grade marbles in the northwest half of the map area represent the protolith of the marble mylonites. They are typically white, coarse-grained (1–10 mm) graphite-bearing marbles with as much as 15% silicates, including, in approximate order of abundance, phlogopite, tremolite, diopside, plagioclase, alkali feldspar, quartz, and scapolite. Many outcrops contain centimeter- to meter-scale granitic, syenitic, and mafic clasts surrounded by a coarse white marble matrix. These "tectonic breccias" are more abundant toward the CMBBZ and emphasize the important mechanical role of the deforming marble units during large-scale flow (Hanmer, 1988). Nearly all of the high-grade marbles contain tabular blocks of paragneiss, some of which are folded, stretched, and rotated. Most of these coarse-grained marbles have a planar fabric defined by the concentration of silicates along thin layers. Where exotic clasts are abundant, these silicate layers define anastomosing patterns; where clasts are predominantly paragneissic and tabular in nature, these layers are approximately parallel to the regional lithologic layering and gneissosity. Elongate clasts within the marbles roughly define a lineation that parallels the regional stretching lineation observed in the gneissic units.

Locally, very fine grained, dark to banded mylonites, commonly with a well-developed linear fabric, occur within the high-grade marbles. A few

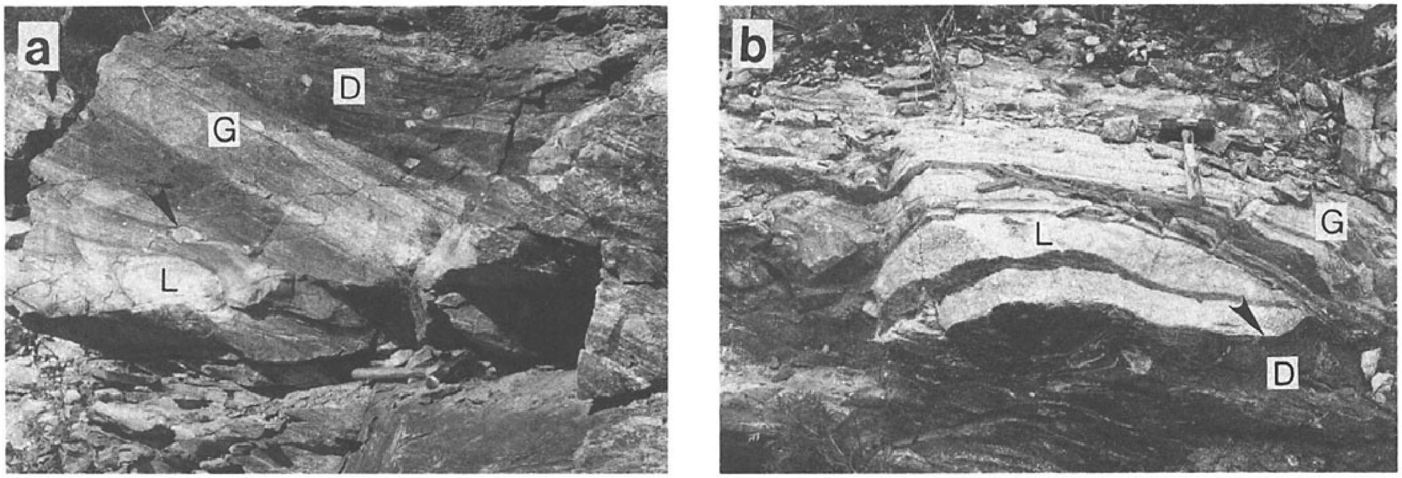

Figure 3. A well-preserved roadcut about 5 km south of Gooderham, showing the color and textural heterogeneity typical of the marble mylonite zone and classified as light, L; gray, G; and dark, D. (a) Alternating dark fine-grained and lighter coarser-grained layers dip to the southeast. Flow banding anastomoses and/or folds around rotated clasts. (b) White coarse-grained marble/paragneiss boudin within the mylonite. Note the sharp contrast in color and grain size along the boudin edges (arrow). Both photographs face northeast, with the lineation approximately in the picture plane. The hammer is 39 cm long. (Site coordinates: 44°52′45″N, 78°23′30″W.)

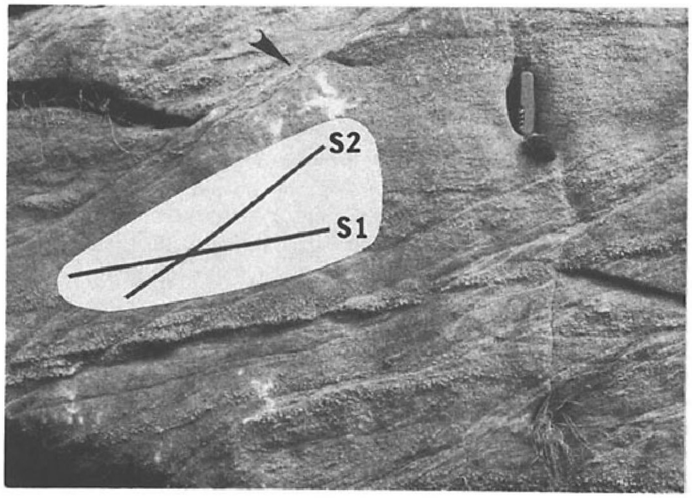

Figure 4. Crosscutting relationship between the regional foliation (coarse layers, S1) and the fine-grained mylonitic foliation (arrow, S2) indicates that the mylonite postdates the regional fabric. The viewer faces southeast, stretching lineation is oblique to the picture plane, and both fabrics dip away from the viewer. The knife is 8 cm long. (Site coordinates: 44°57′20″N, 78°17′25″W.)

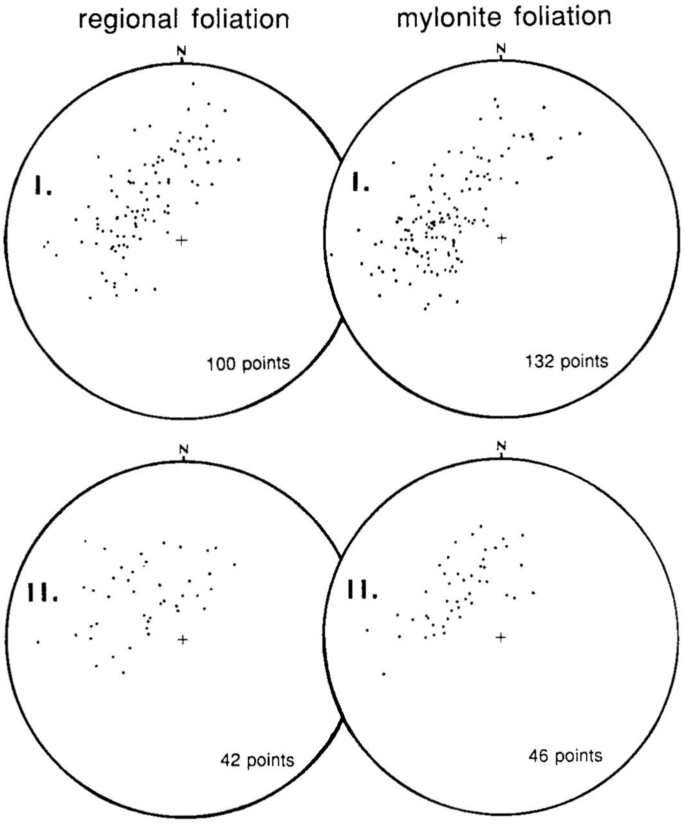

Figure 5. Lower-hemisphere equal-area projections of poles to foliation planes. Mylonite foliation and regional thrust-related foliation have similar distributions and are generally southeast dipping. Two domains have been separated and are shown in Figure 2. Regional foliation includes lithologic layering, regional gneissosity, and silicate layering in marbles.

exposures of these mylonites have earlier been mapped, mentioned, and/or briefly described by other workers (for example, Hewitt, 1957, 1960; Best, 1966; Lumbers, 1964; Masson, 1982a, 1982b; Hanmer and Ciesielski, 1984) and were variously labeled cataclasites, tectonic breccias, and mylonites; however, they have not been studied in detail nor have attempts been made to discover their significance. Through our mapping efforts, we have discovered many additional occurrences of marble mylonites, which are located along a sinuous trace. The unique fine-grained texture common to all of these mylonites, the observed shear sense, as well as their geographic distribution merit grouping them as exposures of a single shear zone. In this paper, we use the term "mylonite" to denote the relatively *fine-grained*, dark to banded marbles that may contain exotic clasts; "tectonic breccia" is used to refer to the *coarse* white marble units containing exotic clasts.

Several outcrop-scale characteristics of the marble mylonites are reflected in the regional map pattern. These include the anastomosing character of the shear zone, the textural variation within the zone, and the concentration of strain around competent clasts. Figure 3 shows a well-preserved mylonite exposure that demonstrates these features. Note the dark and light layering (Fig. 3a) that defines the mylonite flow planes and anastomoses on a centimeter to meter scale, especially around rotated clasts. This outcrop contains a wide variety of textures ranging from very dark gray, fine-grained areas to relatively light-colored finely banded areas. On closer inspection, the banded layers contain alternating discrete light calcitic and dark graphitic bands, which produces the overall light gray color in outcrop. Coarse-grained white marbles containing isolated, elongate graphite flakes are locally preserved as boudins within the mylonite (Fig. 3b). Transitions between the dark fine-grained texture and the light coarse-grained texture can be abrupt (arrow, Fig. 3b). Dark, fine-grained textures are focused in many cases around large competent clasts.

The Bancroft shear zone shows similar geometrical characteristics on the regional scale. The map pattern (Fig. 2) most clearly shows its anastomosing character south of Wilberforce and west of Bancroft, and the zone can be traced over a distance of at least 70 km. The maximum exposed thickness of individual branches of the mylonite zone is 15–20 m; however, most roadcut exposures give thicknesses of 2–10 m. Mylonitic textures are heterogeneous along the length of the zone, with uniformly dark, fine-grained mylonites occurring where the zone is closely bounded on both sides by more competent lithologic units such as granitic and syenitic gneisses (for example, near Bancroft; the segment west of the Cheddar Dome) and with lighter-colored, banded mylonites with only localized very dark zones occurring where the mylonite zone cuts through thicker layers of marble (for example, south of Gooderham; northwest edge of the Cardiff Dome). In these places, the mylonite is in all cases focused directly under competent units, for example the metagabbro sheets south of Gooderham and the syenite units along the west side of the Cardiff Dome (Fig. 2). Coarse marbles with very narrow centimeter- to millimeter-scale shear bands occur northwest of the main shear zone within the thick marble layers and are texturally somewhat analogous to the coarse boudins on the outcrop scale.

At several outcrops, the fine-grained mylonitic fabric can be seen to crosscut the layering of the coarse-grained marble protolith (Fig. 4), which indicates that the former is the younger of the two fabrics. Such crosscutting relationships, however, occur only locally and tend to be best represented where the mylonite fabric is not pervasive. Although the relative age determinations from these outcrops are convincing, the steeper attitude of the mylonite zones is not representative of the mylonite zone on a regional scale.

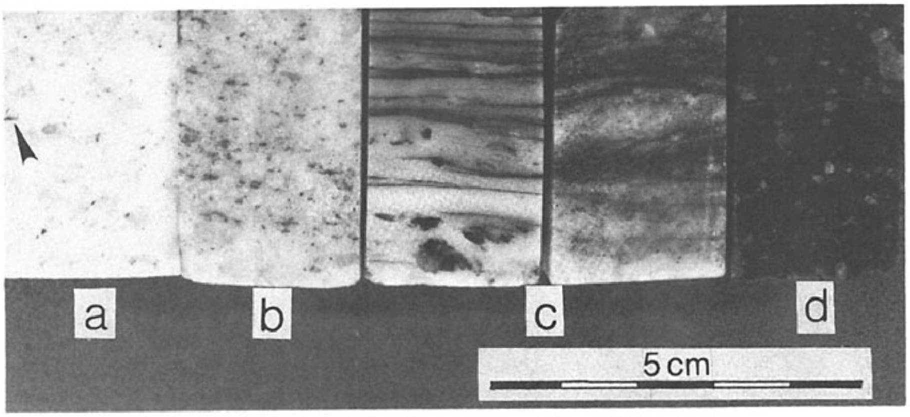

Figure 6. Polished rock chips showing the textural variation in the marbles. (a) White, coarse-grained marble (protolith) contains large, euhedral graphite flakes (arrow). (b) "Light" mylonite sample has small calcite grains along the grain boundaries of coarse elongate grains; preferred orientation of graphite further defines a weak planar fabric. (c) Two examples of "gray" mylonites with planar fabric defined by dark graphitic bands separated by light, fine-grained calcite. (d) "Dark" mylonite has uniform small grain size and dark color. Graphite is very fine grained and disseminated in the calcite matrix.

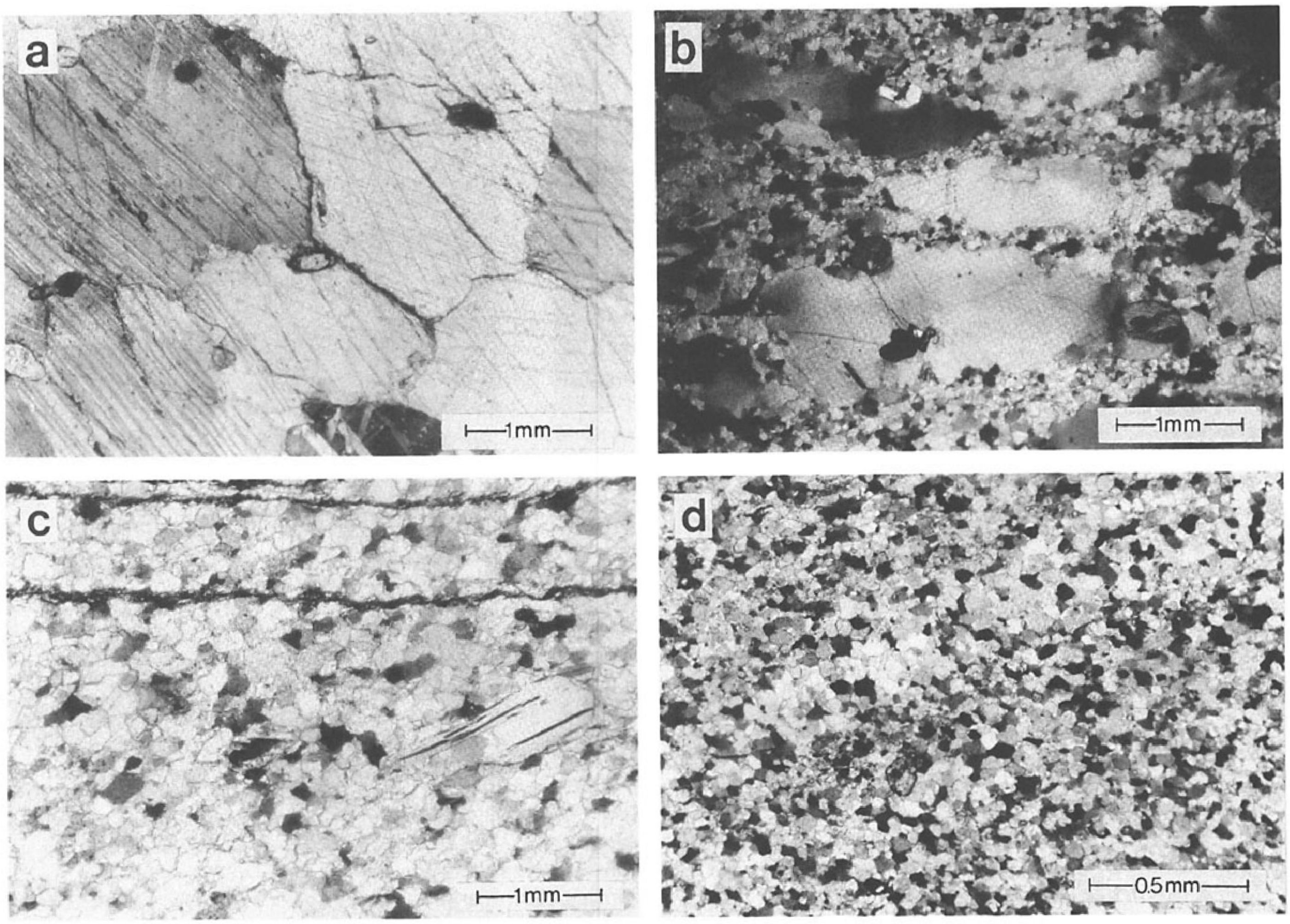

Figure 7. Photomicrographs showing the microstructural features of each mylonite type, corresponding to Figure 6. (a) Typical protolith has coarse equant calcite grains with straight grain boundaries (compare with Fig. 6a). (b) Bimodal grain size distribution with small (sub) grains lining the larger (parent) grain boundaries characterizes a "light" mylonite sample. Elongate larger grains define a weak planar fabric (compare with Fig. 6b). (c) "Gray" mylonite sample shows uniformly fine equant to slightly elongate calcite grains. Dark bands are graphitic (compare with Fig. 6c). (d) Typical "dark" mylonite with extremely fine equant to slightly elongate calcite. Graphite is extremely fine grained and evenly distributed in the calcite matrix (compare with Fig. 6d). All photomicrographs were taken in plane-polarized light. Note that the scale of part d is more than twice that of the others.

The orientation of the mylonitic fabric generally parallels the southeast-dipping thrust-related foliation. Orientation data for both the regional foliation (layering + gneissosity) and the mylonitic foliation are plotted in Figure 5. Both foliations vary considerably across the region but have the same range of dip and strike variation. A similar relationship holds for the lineations. In general, both the mylonitic fabric and the regional fabric dip moderately (30°–40°) to the southeast, with much of the variation due to the anastomosing character of both fabrics. Thus, although crosscutting relationships are locally observed, these two fabrics are essentially parallel and cannot be distinguished on the basis of orientation only.

MYLONITE FABRIC: MESO- AND MICRO-SCALES

We identify three general mylonite types in the field, based on the color of the calcite matrix: light, gray (light and dark bands), and dark. Grain size and S-L fabric development vary systematically with these colors, as we will demonstrate. First, we will describe the texture of the marble outside the shear zone, which represents the protolith; then, we will describe the textures of the light, gray, and dark mylonites.

The marble protolith is coarse-grained, relatively undeformed carbonate with varying amounts of silicates as noted earlier (Fig. 6a). Many of the protolith samples are tectonic breccias with a previous deformation history that is no longer preserved in their calcite texture owing to subsequent exaggerated grain growth (secondary recrystallization). The equant to irregularly shaped calcite grains are 1–5 mm in diameter and have straight to slightly sutured grain boundaries (Fig. 7a). Graphite occurs as large (1–5 mm) euhedral flakes and appears randomly distributed in the calcite matrix (see Fig. 6a).

Our first mylonite type, the light mylonites, occurs near the edges of the shear zone or as boudins within the gray mylonites (Fig. 3b). In hand sample, they are light colored and have a bimodal grain size distribution, with small calcite grains surrounding coarser grains (Fig. 6b). A weak planar fabric is defined by the dimensional preferred orientation of slightly elongate, coarse calcite grains, and a lineation is weakly expressed by the alignment of slightly elongate graphite flakes (stretching lineation). In thin section (Fig. 7b), the bimodal grain size is very distinctive, with the smaller grains ranging in diameter from 100 to 200 μm and concentrated along the boundaries of elongate, millimeter-size grains. The graphite flakes have ragged edges and are slightly elongate in the same direction as the coarse elongate calcite grains.

The gray mylonites, the second mylonite type, are characterized by alternating dark and light bands that define a well-developed planar fabric that locally anastomoses around clasts or is folded around rotated clasts. The 1- to 2-mm-thick dark bands (Fig. 6c) are graphite-rich layers separated by white fine-grained calcite layers. A very strongly developed lineation defined by graphite (stretching lineation) is present in the foliation planes. In thin section (Fig. 7c), we observe a relatively uniform calcite grain size of about 100–200 μm.

The most distinctive feature of the third mylonite type, the dark mylonites, is their uniformly very dark gray to black color in hand sample (Fig. 6d). Foliation and flow banding are only locally present in the extremely fine grained calcite matrix and are expressed as subtle color banding and parting planes. In thin section, we observe uniformly fine (20–50 μm) calcite grains (Fig. 7d). Some samples exhibit grain sizes as small as 5–10 μm. Graphite occurs as tiny flakes on the calcite grain boundaries and appears evenly distributed in the calcite matrix. Other opaques (for example, pyrite and magnetite) occur as equant grains at calcite triple junctions and, along with the fine grain size and distributed graphite, contribute to the dark color.

In some localities (for example, south of Gooderham), all three mylonite types occur in close proximity, with the white mylonite grading into gray and finally dark mylonite. The transition can be remarkably abrupt, as in the edge of the boudin shown in Figure 3b (arrow).

SHEAR-SENSE INDICATORS

A variety of shear-sense indicators were preserved in the marble mylonites of the Bancroft shear zone. They can be found in many different outcrops that are widely distributed along the shear zone (Fig. 2); we will show only the best examples, which occur at several outstanding exposures about 5 km south of Gooderham. The most abundant kinematic indicators observed in the field are rotated clasts, S-C structures, and shear bands (C′ structures); we also find mica-fish structures at the micro- to meso-scale. We briefly discuss the occurrence of each type of shear-sense indicator below. Consistent with the sense of shear from these indicators, Culshaw (1983, 1987) obtained asymmetric quartz c-axis fabrics in granite samples from the Cheddar Dome and in quartzite from northeast of Gooderham.

Rotated Clasts

As in the case of all shear-sense indicators, the interpretation of shear sense is dependent on accurately understanding the evolution of the structure in question (Simpson and Schmid, 1983). The clasts we observe in the field are elliptical to subequant inclusions of granite, syenite, or paragneiss. Rotated coarse calcite/paragneiss boudins are also common. These clasts in many cases have tails of recrystallized material or occur between dark and light flow bands, which are then dragged during rotation as in the δ-type classification of Passchier and Simpson (1986). When observed in the plane perpendicular to the flow plane and parallel to the stretching lineation, these clasts show unequivocally that the sense of movement within the mylonite was toward the southeast (Figs. 8a and 3a). Millimeter-scale δ-type clasts are also common in thin sections of the dark mylonites, which show little mesoscopic evidence of clast rotation owing to their uniformly dark matrix. These small clasts occur between thin graphitic bands that are wrapped around the rotated clast (Fig. 8b). Both meso- and micro-scale rotated clasts in the mylonite consistently indicate transport of the hanging wall toward the southeast.

Composite Planar Fabrics

Composite planar fabrics are less abundant than are rotated clasts and occur mostly in light to gray mylonites. S-C fabrics (Lister and Snoke, 1984) are well developed south of Gooderham and further support the top-to-southeast movement that was determined from rotated clasts (Fig. 8c). Also common are shear band foliations or asymmetrical extensional crenulations (Platt and Vissers, 1980), which occur along some minor anastomosing branches of the shear zone. The best examples are found northwest of the main mylonite zone where shear bands produce offsets in the silicate layers of the coarse-grained marble that are consistent with movement of the top toward the southeast.

Mica fish, much like those described in quartzofeldspathic mylonites (Lister and Snoke, 1984), are observed in some mylonite slabs and thin sections. In the samples described by Lister and Snoke (1984), these "fish" structures lie in the S-plane, which inclines upward in the direction of shear. Similarly, we observe a preferred orientation of mica inclined to the shear plane, which we interpret, by analogy, to indicate a southeast-directed sense of movement (Fig. 8d).

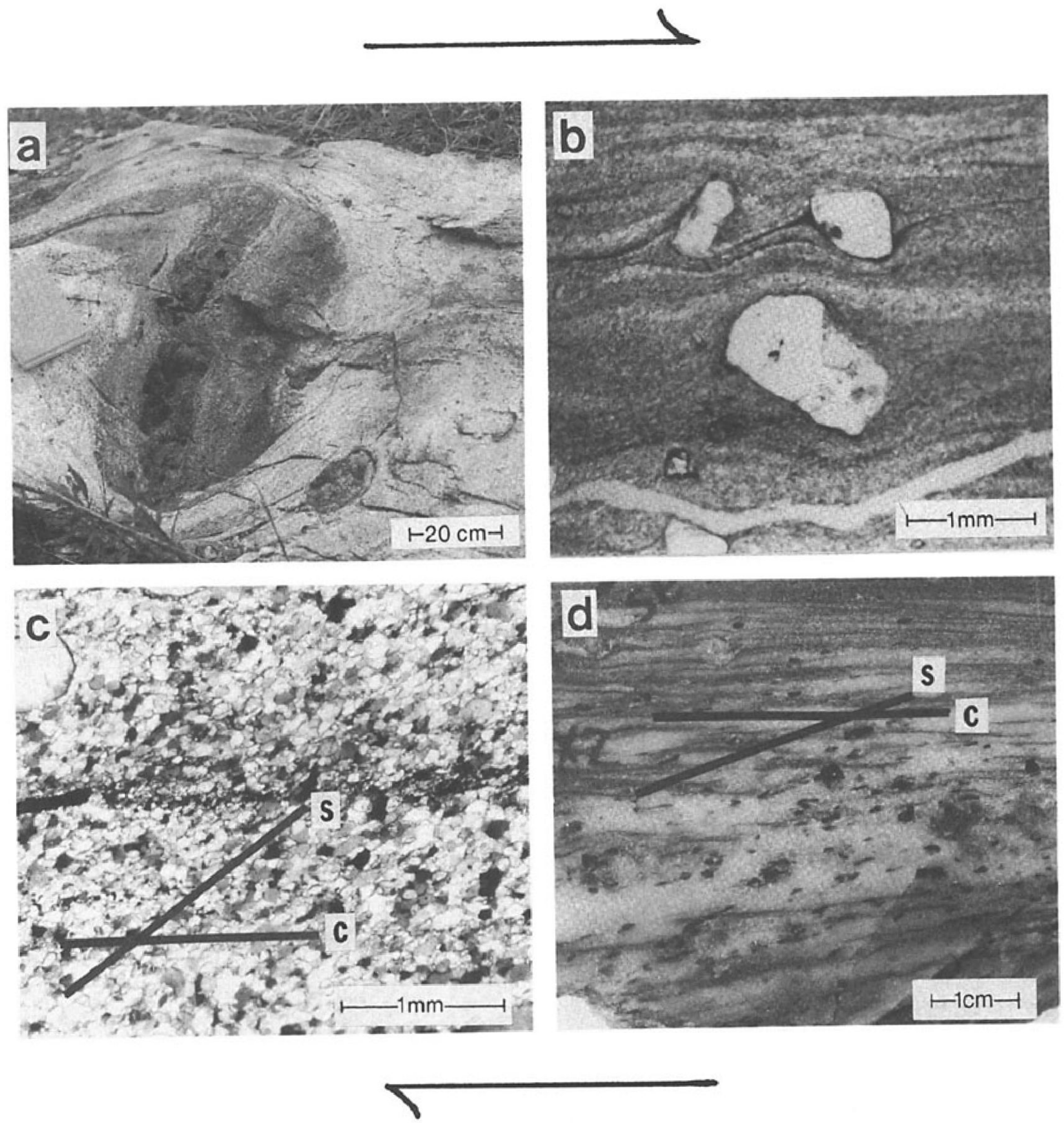

Figure 8. Shear-sense indicators in marble mylonite. (a) Northeast-facing view of a marble/paragneiss clast showing clockwise (southeastward) rotation. (b) Photomicrograph showing clockwise (southeastward rotation of millimeter-scale grains in a fine-grained calcite matrix. Black "tails" are composed mainly of graphite. (c) An example of a well-developed S-C mylonitic fabric defined by elongate calcite grains (S) and graphite stringers (C). (d) Mica "fish" in a banded marble mylonite slab. Gray graphitic bands define the flow plane (C), and phlogopite grains lie in the S plane. In all photographs, the viewer is facing northeast, and the stretching lineation is contained in the picture plane.

DISCUSSION AND CONCLUSIONS

A variety of textures is preserved within marble mylonites of the Bancroft shear zone, and the development of a planar and linear fabric (S-L tectonite) is accompanied by a change in grain size. In general, the color of the rock darkens with decreasing grain size and increasing S-L fabric, except in the darkest, finest-grained samples, in which the S-L fabric is destroyed. A similar range of textures has been described in natural marble mylonites by Heitzmann (1987), who interpreted them as stages of mylonite development, based on crystallographic fabric analyses. Schmid and others (1987) documented a similar sequence of textures in experimentally sheared marbles. By analogy, we interpret our series of white to dark mylonites as representing progressive mylonitization. The light mylonites represent the initial stage of mylonite development (protomylonite), the gray mylonites represent intermediate stages in which grain size is significantly reduced and S-L fabrics are well developed (mylonite), and the dark mylonites represent the most mylonitized samples (ultramylonite) with extremely fine grain size and a breakdown of the S-L fabric. The series of samples shown in Figures 6 and 7 represents this sequence of increasing mylonitization.

Shear-sense indicators within the southeast-dipping Bancroft shear zone in the CMB of the Ontario Grenville consistently show southeast-directed, extensional movement. It is an anastomosing zone that probably extends beyond the map area shown in Figure 2. For example, we have examined an exposure of marble mylonite northeast of Bancroft, near Grand Remous, Quebec, that exhibits the same range of textures and southeast-directed shear-sense indicators as we described in the Bancroft area mylonites. Furthermore, Langlais and Sawyer (1988) reported a late extensional marble mylonite in the CMB of Quebec, and marble mylonites occur several kilometers southeast of Gooderham near the Paleozoic onlap (R. M. Easton, 1988, personal commun.). Vertical displacement on this zone has been estimated to be 5–6 km at temperatures of 450–500 °C (van der Pluijm and Carlson, 1989, and unpub. data), which seems supported by recent $^{40}Ar/^{39}Ar$ thermochronology in the area (Cosca and others, 1989).

The marble mylonite fabric is essentially parallel to the older thrust-related fabric recorded in the protolith marbles and the gneisses of the area. The parallelism of these two fabrics of different age on a regional scale indicates that the development of the Bancroft shear zone was strongly influenced by the pre-existing regional anisotropy that was formed during earlier thrusting. Southeast-dipping layers of competent lithologies (for example, granites, syenites, metagabbros) concentrated the shearing within the weaker marble units.

The location of the Bancroft shear zone as mapped by us is essentially coincident with the Bancroft-Elzevir terrane boundary as drawn by Davidson (1986), except in the area of the Cardiff and Cheddar Domes. We propose that the present lithologic and metamorphic characteristics of the Elzevir terrane relative to the Bancroft terrane are due to offset across the shear zone, which juxtaposes a higher structural level (Elzevir) with a deeper structural level (Bancroft). The location of the Bancroft-Elzevir boundary should therefore be revised to follow the shear zone north of the Cardiff Dome. Recognizing that the Bancroft and Elzevir terranes are separated by a late extensional shear zone will have important implications for attempts at stratigraphic reconstruction and for interpreting the uplift history of the CMB.

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