Ductile thrusting at mid-crustal level, southwestern Grenville Province[1]

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The northwestern boundary zone of the Central Metasedimentary Belt (Grenville Province) in the Haliburton area (Ontario) is a stack of alternating tonalitic and syenitic crystalline thrust sheets, transported toward the northwest on out-of-sequence, upper amphibolite facies, ductile thrust zones during the Grenvillian Orogeny, at 1060 Ma, approximately 100 Ma after the initiation of thrusting in the underlying Central Gneiss Belt. Kinematics of the deformation are complex. Predominant northwestward thrusting was, at least partly, coeval with subordinate northeastward thrusting. Late synmetamorphic extensional shears cut both thrusts and thrust sheets. Minor late thrusting on discrete ductile shear zones postdates the extensional structures. Belts of mechanically weak pelite(?) appear to have localised the thrust sheets. Highly mobile marble behaved as a relatively low viscosity fluid during transport, able to intrude and erode more competent wall rock.

La limite nord-occidentale de la Ceinture metasédimentaire centrale (Province de Grenville) dans la région de Haliburton (Ontario) comprend une pile de lambeaux tectoniques crystallins intercalés, à composition tonalitique et syenitique, chevauchés vers le nord-ouest pendant l'orogènese grenvillienne il y a 1060 Ma, soit 100 Ma après le commencement d'une phase de chevauchement qui a eu lieu dans la Ceinture gneissique centrale sous-jacente. La cinématique de la déformation à été complexe. Une composante dominante de chevauchement vers le nord-ouest s'accompagnait d'une composante moins importante de chevauchement vers le nord-est. Des cisaillements ductiles additifs recoupent les chevauchements ainsi que les lambeaux transportés. Une phase mineure de chevauchements discrets est posterieure aux cisaillement additifs. Des zones pélitiques(?) auraient déterminé la localisation des zones cisaillantes. Du marbre hautement mobile se serait comporté en fluide peu visqeux, capable d'infiltrer et de briser l'encaissant plus rigide.

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Introduction

The geological literature abounds with detailed descriptions and analyses of thrust belts at upper crustal levels (e.g., Price and McClay 1981; Boyer and Elliot 1982; Dahlen *et al.* 1984; Butler 1985 and references therein). Such thrusts are readily identified by the truncation of both structure and stratigraphy as a result of fault motion along a stair-step geometry of ramps and flats. In contrast, studies dealing with deep-seated ductile thrusting in middle to lower continental crust (Escher and Watterson 1974) tend to be broad based and concerned with the larger scale aspects of mountain belts (e.g., Coward *et al.* 1982; Coward and Daly 1984; Coward and Butler 1985; Platt 1986). Few examples of thrusting at very high metamorphic grade have been documented in detail (e.g., Le Fort 1981; Davidson 1984). Given the metamorphic conditions of deformation and the consequent rock rheology, simple ramp and flat geometry is not to be expected (Knipe 1985; Butler 1985), nor is the preservation of recognisable stratigraphy. In addition, since quartzo-feldspathic rocks are unlikely to remain rigid under such metamorphic conditions (e.g., Sibson 1977), identification of a deep-seated thrust sheet depends upon the recognition of the nature and extent of the bounding belts of high shear strain (ductile thrust zones). In this regard, very few studies are specifically concerned with the development and recognition of high-strain tectonites in high-grade metamorphic terranes (Myers 1976, 1978, 1984; Coward 1984; Davidson 1984). The classical confusion of mylonites with layered supracrustal rocks is exacerbated in well-annealed, high-grade crystalline gneiss terranes (Hanmer 1987). It is perhaps for this reason that the spectacular thrusting in the Grenville Province, southeastern Canadian Shield (Figs. 1 and 2), has only recently been identified (e.g., compare Dewey and Burke 1973 with Davidson 1984 and Wardle *et al.* 1986). A number of authors have attempted to draw, or hint at, analogies between the tectonics of the Grenville Province and that of the Himalayas, usually with a view to using the younger, still active orogen as a model to help elucidate the deeply excavated roots of the older belt (Dewey and Burke 1973; Baer 1974; Davidson *et al.* 1982; Windley 1986). Given the depth of erosion in the Grenville Province, the new perspectives now coming into focus on its structure (e.g., Davidson 1984; Moore *et al.* 1986) should shed useful light on the architecture and processes presently inaccessible in the deeper levels of younger mountain belts.

In the southwestern Grenville Province, the Central Metasedimentary Belt, principally represented by the ca. 1300–1250 Ma Grenville Supergroup (Moore and Thompson 1972), is a volumetrically important pile of metasediments, metavolcanics, and plutonic rocks separating the Central Gneiss Belt from the Adirondack Mountains (Fig. 1; Wynne-Edwards 1972). This paper will attempt to show (1) that the boundary zone of the Central Metasedimentary Belt in the Haliburton area is a stack of alternating tonalitic and syenitic, laterally discontinuous, crystalline thrust sheets (horses), transported towards the northwest on upper amphibolite facies ductile shear zones during the Grenvillian Orogeny; (2) that the thrust stacking order is not a simple "piggy back" sequence: shear zones bounding the present thrust sheets cut through an earlier sandwich of two crystalline thrust sheets separated by metasediments and hence the younger shear zones are out-of-sequence thrusts; (3) that the kinematics of the deformation are complex: predominant northwestward thrusting was, at least partly, coeval with subordinate northeastward thrusting; late synmetamorphic extensional shears cut all layered tectonites in the stack; and (4) that pelite(?) and marble played a mechanically significant role during localization and transport of the

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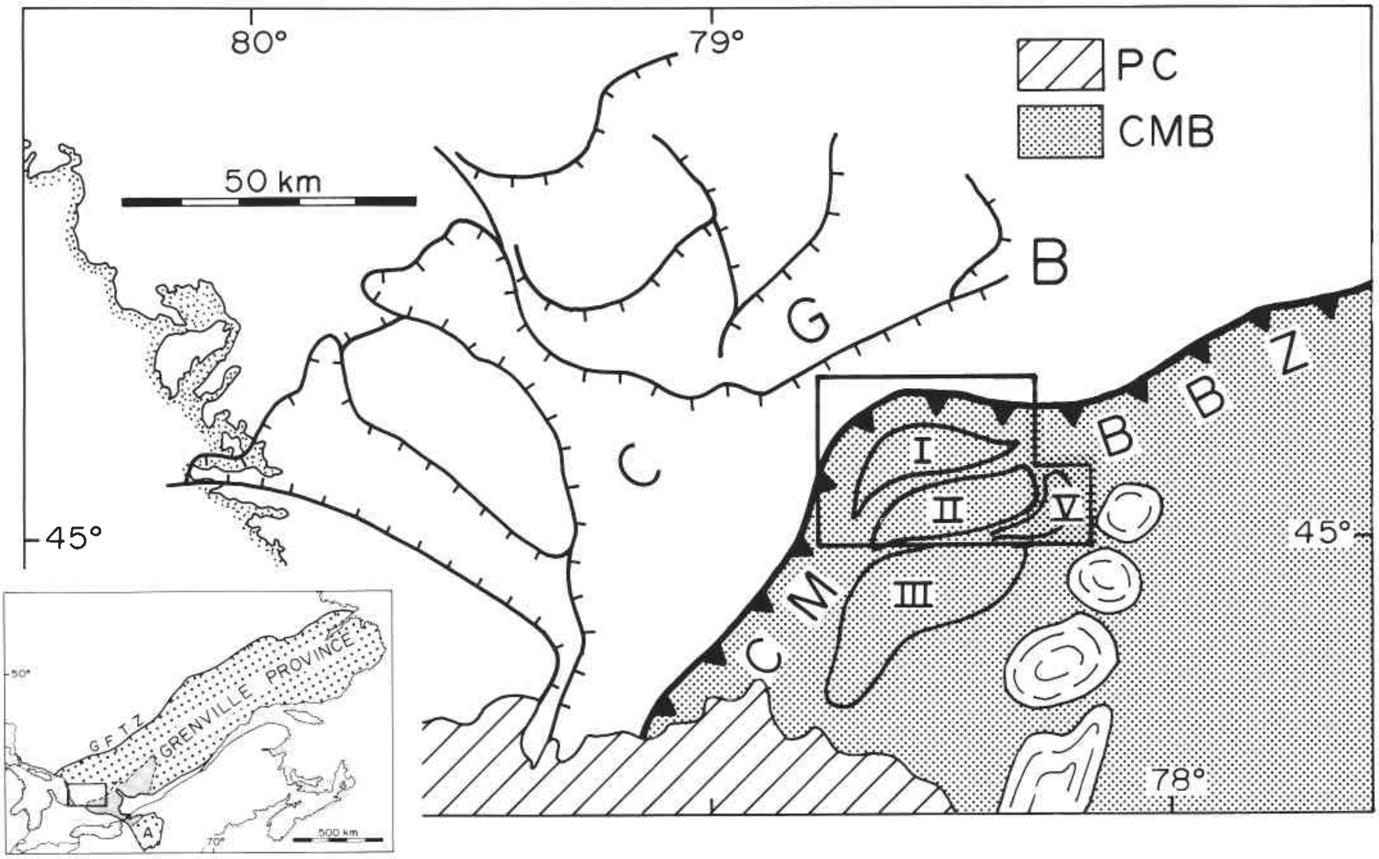

FIG. 1. Inset is location of the Central Metasedimentary Belt (fine stipple) within the Grenville Province (dots) of the southeastern Canadian Shield. Adirondack Mountains (A) and Grenville Front Tectonic Zone (GFTZ) indicated. Box = location of main figure. Location of study area and Fig. 2 (box) in the Central Metasedimentary Belt boundary zone (CMBBZ). Representation of ductile shear zones within the Central Gneiss Belt (CGB) taken from Davidson (1984). Lower limit of the CMBBZ schematically illustrated as heavy toothed line. I, II, III, and V are the Redstone, Dysart, Glamorgan, and Grace thrust sheets, to the east of which lies a prominent line of domes, the Harvey-Cardiff Arch. CMB = Central Metasedimentary Belt; PC = Paleozoic cover.

thrust sheets: belts of mechanically weak pelite(?) appear to have localized the thrust sheets, while highly mobile marble behaved as a relatively low viscosity fluid during transport, able to intrude and erode more competent wall rock.

Geological setting

In recent years, reconnaissance-scale mapping has successfully penetrated the apparent structural and metamorphic monotony (Wynne-Edwards 1972) of the granulite to upper amphibolite facies Central Gneiss Belt (Davidson and Morgan 1981; Davidson *et al.* 1982; Culshaw *et al.* 1983; Davidson 1984). These workers have recognised a number of overlapping, laterally discontinuous, southeast-dipping large-scale thrust sheets, separated from one another by relatively narrow belts showing extremely straight gneissic layering (Fig. 2). The presence of polyphase isoclinal (sheath) folds, progressive transposition of initially cross-cutting structures, and significant syntectonic grain size reduction demonstrates that the belts are high-strain zones. A widespread assemblage of mechanically independent, kinematically consistent shear-sense indicators, associated with a gently southeast plunging extension lineation, together with the occurrence of higher grade metamorphic rocks structurally overlying lower grade ones, indicates that the belts are northwestward-directed ductile thrusts (Davidson 1984). U–Pb dating of syntectonic pegmatites indicates that ductile thrusting was already active in the Central Gneiss Belt at 1160 Ma (van Breemen *et al.* 1986).

In the northwestern boundary zone of the Central Metasedimentary Belt in Ontario, recent reconnaissance work (Hanmer and Ciesielski 1984; but see also Adams and Barlow 1910; Hewitt 1957) and preliminary 1 : 50 000 scale mapping (Hanmer *et al.* 1985) suggest that the boundary zone is a major southeast-dipping, upper amphibolite facies ductile shear zone with a northwestward sense of overthrusting, involving tonalitic and syenitic crystalline thrust sheets together with marbles and metapelites(?) of the Grenville Supergroup (Figs. 2 and 3; see also Schwerdtner and Mawer 1982; Culshaw 1983, 1986; Easton and Van Kranendonk 1984, 1987; Easton 1985, 1986*a*, 1986*b*). The Haliburton area (Fig. 2) is particularly instructive in this regard, since it is underlain by the only part of the boundary zone of the Central Metasedimentary Belt where the internal structure has been mapped and the age of ductile shearing radiometrically determined (van Breemen and Hanmer 1986). However, in the absence of either structural or topographical relief, no meaningful cross sections can be drawn through the area.

Tectonite types

In mapping variably strained rocks such as those that occur along the boundaries of deep-seated thrust sheets, it is essential

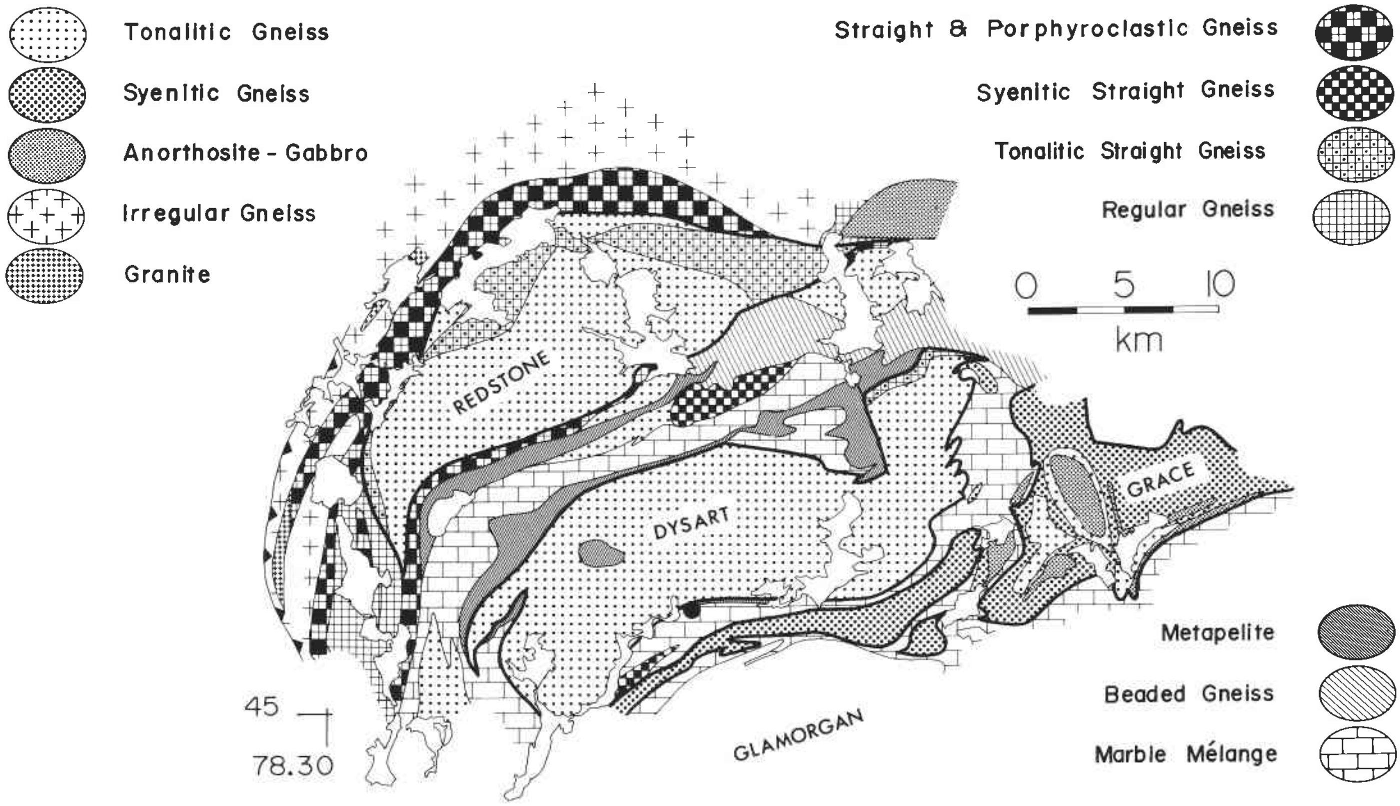

FIG. 2. Geological map of the Central Metasedimentary Belt boundary zone in the Haliburton area (discussed in text). Thrust sheets are named. Foliations (not shown) strike parallel to lithological contacts at this scale except within and below the anorthosite sheet in the northeast (see text). All dips are approximately 20° to the east or southeast. Heavy lines are faults. Toothed fault is carbonate slide. Note that all of the contacts are inferred to approximate. Geology by the author and assistants except for the east margin of Dysart thrust sheet (modified after Culshaw 1986) and the eastern part of Grace thrust sheet (from Culshaw 1983). Large dot = Haliburton.

to delimit tectonic as well as lithological units. Hence, it is appropriate here to clarify the relationship between the gneissic aspect of a tectonite and finite strain (Figs. 4 and 5). The following terms have proven to be generally useful in mapping the high-grade tectonites of the Grenville Province (see also Davidson *et al.* 1982; Hanmer and Ciesielski 1984; Davidson 1984).

Straight gneiss—A gneiss consisting of extremely continuous, rectilinear layers generally composed of granitic and amphibolitic gneiss, centimetres to metres in thickness (Fig. 4*a*). The layering results from the demonstrable progressive transposition and attenuation by high-magnitude strain of (1) granitoid or mafic vein networks intruded into host gneiss, (2) mafic gneiss inclusions in granitoid orthogneiss, and (3) folded gneissic layering. Isoclinal folds and rootless fold closures are common. Microscopically the gneiss is well annealed with grain size in the range 500 − 1000 μm.

Porphyroclastic gneiss—This is a variant on the straight gneiss theme. It is an often subtly banded, rectilinear " S > L" tectonite comprising a host quartz − feldspar − biotite − hornblende gneiss of variable composition containing isolated, round monocrystalline fragments, aggregates, and streaks of K-feldspar and plagioclase aligned in the foliation. Coarse-grained granitic pegmatite and folded gneiss (apparent precursor to the host gneiss) form discrete inclusions up to several metres in size (Figs. 4*b* and 4*c*). Locally, all states of disaggregation, from discrete isotropic pegmatite to isolated feldspar inclusions, are present within a single outcrop and are interpreted to be a function of the strain state of the pegmatite, using the attenuation of quartz and the development of a foliation as qualitative strain indicators. The isolated feldspars are therefore porphyroclasts. Microscopically the porphyroclastic gneiss resembles the straight gneiss, the fundamental difference between them being the remarkably homogeneous distribution of the imposed bulk strain, at the grain scale, in the straight gneiss. In the field, the one may pass laterally into the other.

"*Regular gneiss*"—A well-layered gneiss whose $Y-Z$ sections (perpendicular to both foliation and lineation; $X > Y > Z$, Flinn 1962) show low-angle discordant features, that is, cross-cutting veins, mafic blocks, or inclusions, fold interlimb angles, and fold axial planes oblique to layering. However, these features are all transposed in $X-Z$ sections.

"*Irregular gneiss*"—A gneiss showing low-angle discordant features, that is, cross-cutting veins, mafic blocks or inclusions, fold interlimb angles, and oblique fold planes in all sections perpendicular to layering.

Marble tectonic mélange—A very coarse (1 − 2 cm) marble with variable proportions of silicates (e.g., phlogopite, clinopyroxene, serpentine, chondrodite, hornblende, tremolite, feldspar) and other minerals (e.g., pyrite, graphite, apatite), containing scattered misoriented inclusions of fine graphitic quartzite, graphitic K-feldspar or plagioclase gneiss, syenitic gneiss, foliated granite, and isotropic granitic and syenitic pegmatite. The marble matrix is generally layered on a centimetre scale. The size (centimetres to 10's of metres) and spac-

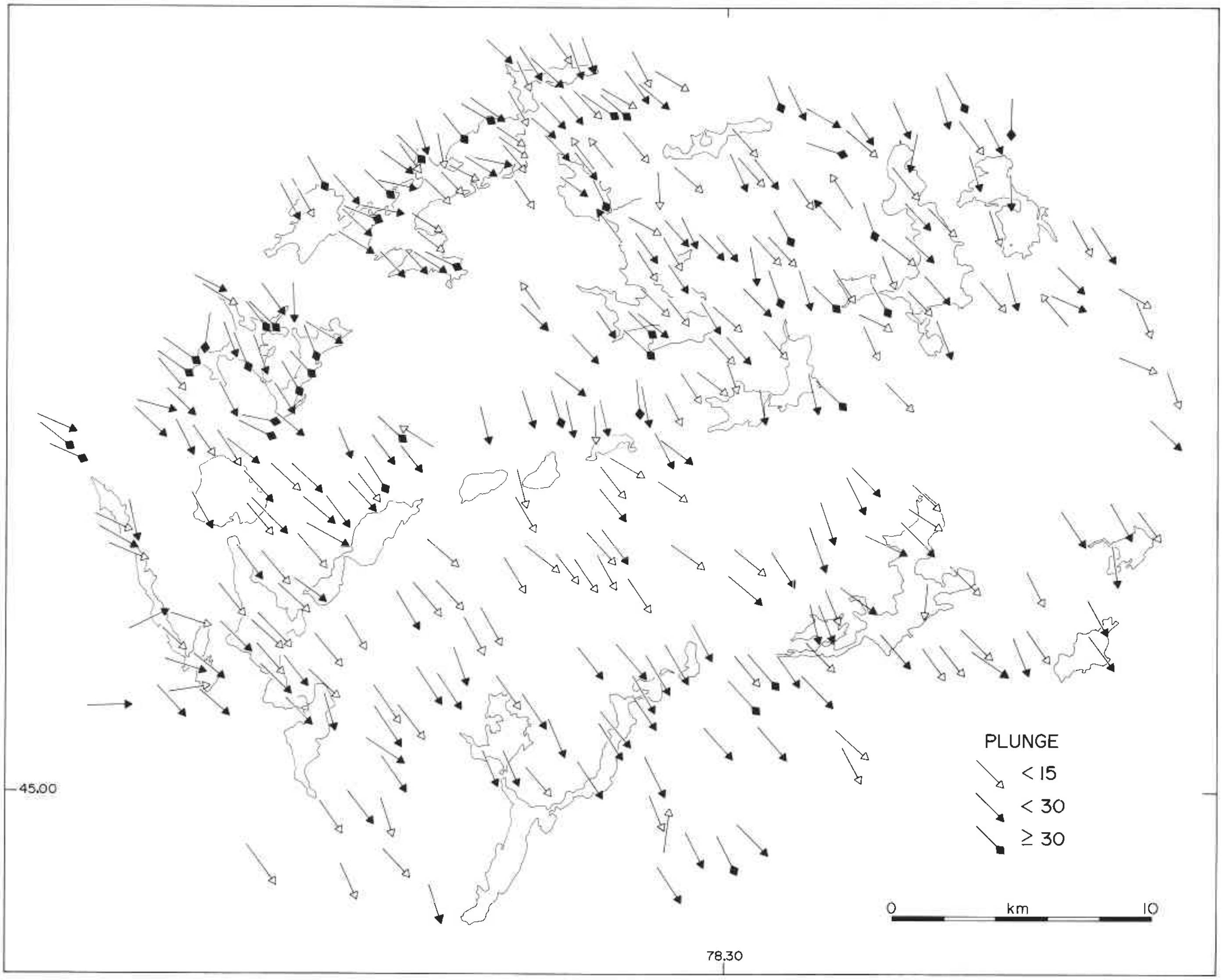

FIG. 3. Map of extension lineations in the Central Metasedimentary Belt boundary zone in the Haliburton region. Note that arrow heads mark the station location, shafts point up-plunge. Lineation pattern to the east of this map (i.e., in the Grace thrust sheet) is identical to that shown here (Culshaw 1983).

ing of the inclusions are highly variable (Fig. 4*d*). If the inclusions are interpreted as pull-aparts, their large separation implies very large extensional strains within the marble. Extreme wrapping of the marble layering around the inclusions, and the preservation of pristine preincorporation structures and textures in the inclusions, indicate the very high degree of ductility of the tectonically flowing marble. For example, coarse isotropic pegmatite sheets are severely broken into angular boudins and chaotically misoriented within the marble matrix, yet they preserve rectangular corners and show no internal deformation. Hanmer and Ciesielski (1984) have illustrated the ability of the marble to penetrate along foliation planes and gneissic layering so as to spall off slivers of gneiss from the parent body (Fig. 5*a*). Clearly, such a weak material can absorb significant strains and can undergo important displacement with respect to the major thrust sheets it surrounds; this frustrates any attempt to reconstruct possible prethrusting geometries.

The classification of silicate tectonites used here is to a large degree *utilitarian* inasmuch as it only reflects the present aspect of the gneiss. Mesoscopic gneissic fabrics are, at least in part, rheologically controlled. Because of the different sensitivites of different lithologies to changes in boundary conditions, that is, strain rate, P_{H_2O}, temperature, etc., such changes could lead to the disruptive extension or folding of particular layers within a statistically homogeneous straight gneiss. Moreover, a folded straight gneiss into which enough discordant veins are intruded will lose its straight character, perhaps resembling the "irregular" gneiss described above. Therefore, this tectonite classification is not a direct reflection of accumulated strain. It should be understood that a map of the above tectonite types (e.g., Fig. 2) is a representation of the spatial distribution of zones of a final *finite increment* of high strain (or loci of high strain rate), but not necessarily of *total* accumulated strain.

Gneiss sheets

Given the absence of either topographic or apparent structural relief, the following descriptions are essentially two

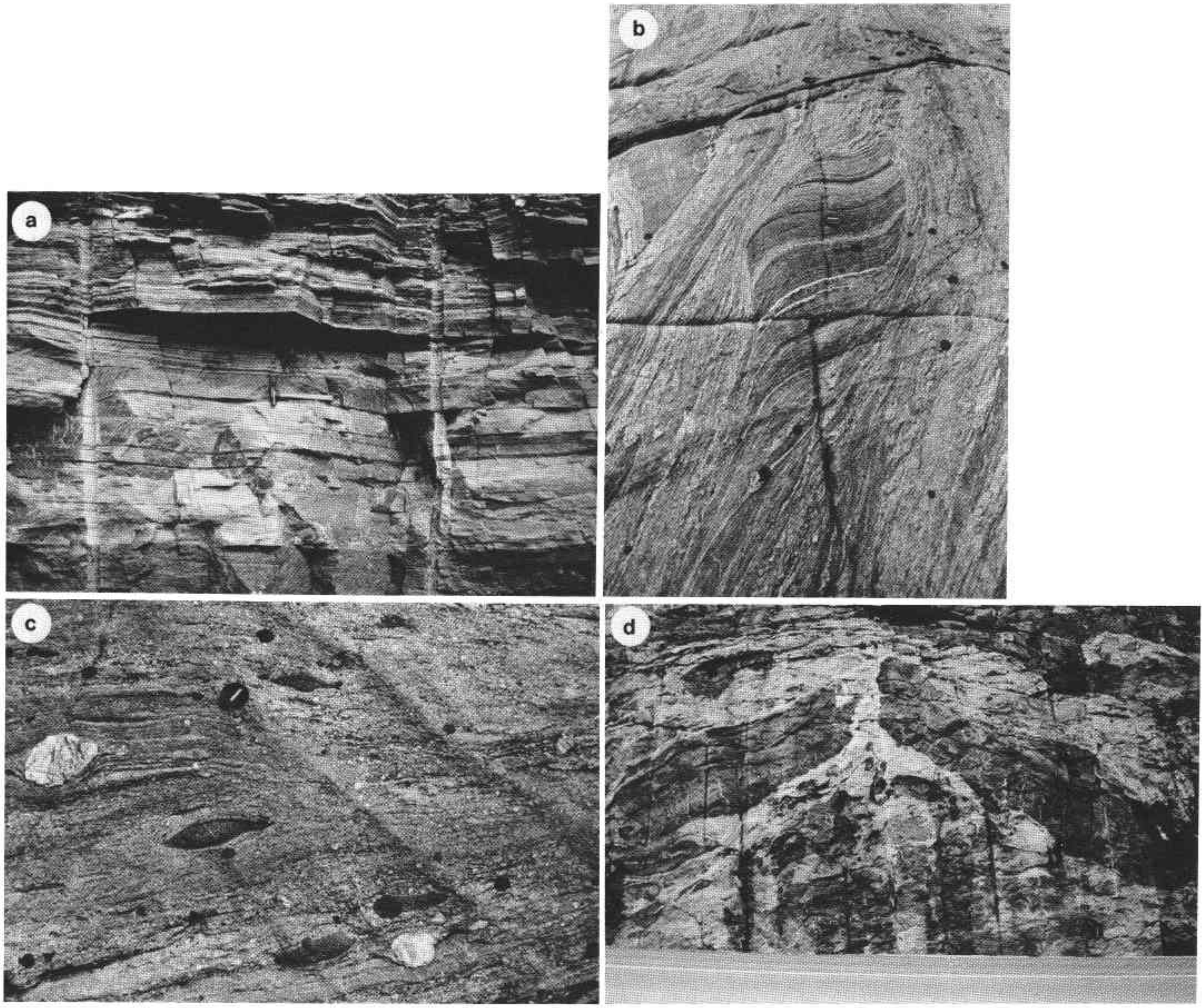

FIG. 4. (*a*) Subhorizontal rectilinear straight gneiss of granitic composition with thin continuous transposed amphibolite layers. (*b*) Very coarse, blocky aspect of porphyroclastic gneiss. Metre-scale relic blocks of layered host gneiss are preserved within well-layered porphyroclastic gneiss matrix into which they themselves are transposed. Feldspar porphyroclasts are visible as white spots. (*c*) Porphyroclastic gneiss with isolated inclusions of amphibolite (dark) and very isolated monocrystalline feldspar inclusions derived by the mechanical disaggregation of very coarse pegmatite. Smaller porphyroclasts are also visible. (*d*) Misoriented isolated blocks of quartz syenite tectonically eroded from larger nearby mass in layered very coarse marble tectonic mélange. Outcrop 10 m high.

dimensional. Four discrete thrust sheets of tonalitic or syenitic orthogneiss outcrop in the Haliburton area (Figs. 2 and 3). They are lens shaped, 25 km in strike length and up to 4 km thick. They dip towards the southeast at about 20° and separate the underlying Central Gneiss Belt from the Harvey-Cardiff Arch (Fig. 1). Each thrust sheet is bounded by belts of high-strain tectonite. For example, the lowermost thrust sheet (Redstone) is floored and, for the most part, roofed by straight and porphyroclastic gneiss; the overlying thrust sheets (Dysart, Grace, and Glamorgan) are separated by thick (500 +m) belts of marble tectonic mélange, the lowest of which contains thick zones of metapelite(?). Whether the orthogneisses were once intrusive into their present supracrustal neighbours can no longer be ascertained given the tectonic nature of their contacts (see below). Three of the thrust sheets (Redstone, Dysart, and Glamorgan) are predominantly tonalitic in composition. However, there is a gradual increase in compositional complexity from north to south. The Redstone thrust sheet is entirely tonalitic. The Dysart is predominantly tonalitic with a minor granitic component. The Glamorgan thrust sheet is predominantly tonalitic, but with a significant (25+ %) granitic component. I suggest that all three thrust sheets were derived from a single body.

Redstone thrust sheet—The lowermost thrust sheet comprises a compositionally homogeneous, coarse-grained, biotite–hornblende tonalitic orthogneiss with coarse, aligned, clotty biotite aggregates of centimetre size. Rare, relic, strongly pleichroic, metamorphic orthopyroxene is indicative of an early granulite facies metamorphism. Foliation is everywhere parallel to compositional layering. The lower part of the thrust sheet consists of a straight gneiss variant of the tonalitic gneiss, remarkable for the absence of isoclinal or rootless fold

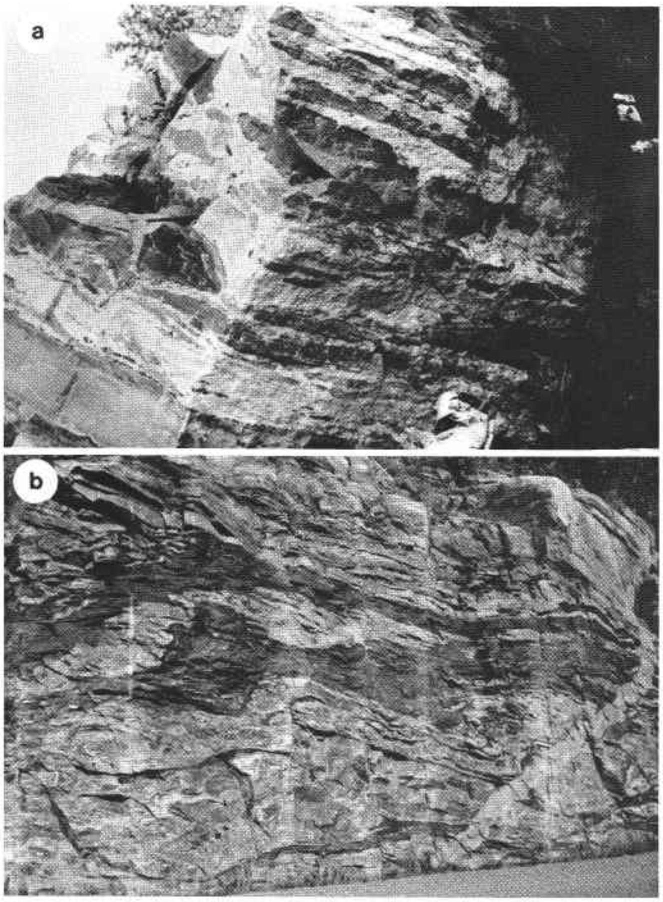

FIG. 5. (*a*) Mobile marble is capable of tectonically eroding silicate inclusions as seen here (centre left). This small-scale example is illustrative of identical structures that are observed at outcrop scale. (*b*) ''Regular'' gneiss observed obliquely to the extension lineation. Subhorizontal biotite-rich ''tectonic-schist'' (dark) in the centre has isolated a lens of gneiss from its wall rocks. Interpreted as a discrete ductile tectonic slide (see text).

closures (Fig. 2). The straight gneiss is medium to fine grained with evenly dispersed fine-grained (2 mm) biotite laths. The straight layering comprises alternating 2–5 cm bands of tonalitic to granitic gneiss, with distinct amphibolite bands, all of which may show variation in colour index according to the proportion of dispersed fine-grained mafic phases in the matrix. This layering is in stark contrast to that in the uniform ''clotty biotite'' variety.

Dysart thrust sheet—This is a thrust sheet of coarse homogeneous tonalitic orthogneiss strongly resembling the ''clotty biotite'' variety of the underlying Redstone thrust sheet. A particular feature of the Dysart thrust sheet, though also common in the Redstone, is the occurrence of local swarms of continuous, foliation-parallel amphibolite sheets, up to 1 m thick. They show no isoclinal or rootless fold closures, that is, there is no evidence of transposition. They show little or no evidence of branching, no cross-linking, and no en échelon apophyses (Nicholson and Pollard 1985); rare, small apophyses that branch off from amphibolite sheets and make a high angle with the foliation are taken to indicate a relatively low strain state, implying that the sheets are intrusive mafic sills, as opposed to rotated dykes or supracrustal inclusions. The point being made here is that not all continuously layered gneisses in the Haliburton area are ''straight gneisses'' in the sense defined above. With care it is a simple matter to distinguish concordant mafic sills from the amphibolite layers of ''straight gneiss.'' The former are associated with a coarse ''clotty'' tonalitic gneiss host, whereas the latter are associated with the fine- to medium-grained, layered quartzo-feldspathic component of the tonalitic straight gneiss, similar to that described from the Redstone thrust sheet. In fact, the association of tonalitic straight gneiss with amphibolite sheets suggests that the mafic sill swarms represent rheological heterogeneities that localized ductile high-strain zones within the softer tonalitic gneiss. At its southwestern end, the Dysart thrust sheet becomes more granitic in composition. Contact relations with the tonalitic gneiss remain unclear, but the granitic component represents an important lithological link with the overlying Glamorgan thrust sheet.

Glamorgan thrust sheet—This is the largest and compositionally most variable of the thrust sheets in the Haliburton area. It consists predominantly of coarse homogeneous tonalitic orthogneiss with a variable, but important, proportion of concordant intrusive granitic sheets, 10's of metres in thickness, that are most impressively developed in the northeastern part of the thrust sheet. They are also present along its upper and lower boundaries to the southwest (Easton and Van Kranendonk 1987). The granitic component, together with local occurrences of compositionally variable, irregularly folded quartzo-feldspathic gneiss cut by postfolding amphibolite veins, renders the Glamorgan lithologically and structurally more complex than either the Redstone or the Dysart thrust sheets (see Bright, 1980; Easton 1985 for detailed lithological descriptions).

Grace thrust sheet—A thrust sheet of generally homogeneous, coarse-grained leucocratic syenitic orthogneiss lies to the northeast along strike from the Dysart and Glamorgan tonalitic thrust sheets. Towards the southwest the syenitic thrust sheet thins, contains highly variable proportions of clinopyroxene and amphibole (see Culshaw 1986 for petrographical details), and is structurally intercalated between the Dysart and Glamorgan thrust sheets. Both straight gneiss and simple gneissic varieties are cross-cut by isotropic syenite veins ranging from 1 to 10 m in thickness. In its northeastern part, the syenitic gneiss is structurally overlain by tonalitic gneiss, metagabbro, and pyroxenite preserved in the core of an open northwest–southeast-trending synform. The Grace thrust sheet is bounded above and below by a very coarse marble tectonic mélange. Most of the misoriented inclusions in the mélange are syenitic and were tectonically eroded from the thin western wing of the Grace thrust sheet by the forcible intrusion of highly mobile marble along planes of weakness in the syenitic gneiss (see Hanmer and Ciesielski 1984). Indeed, the 25 km long west wing of the Grace thrust sheet is itself a large tectonic inclusion, separated from the main body of the thrust sheet. Outcrop-scale tectonic inclusions show that syenitic gneiss, locally rectilinear, was cross-cut by discrete metre wide veins of isotropic, medium-grained syenite, prior to incorporation in the mélange.

Ductile shear zones

The interpretation of the tonalitic and syenitic gneiss bodies as thrust sheets stems from observations made within the bounding tectonites, especially the kinematically informative straight and porphyroclastic gneisses. The Redstone thrust sheet is bounded on both sides by concordant belts of straight and porphyroclastic gneiss (Fig. 2). An extension lineation is developed in the foliation (Fig. 3) as a mineral alignment or as elongate mineral aggregates (streaks and rods). It is also marked by the bisectors of sheath folds (Cobbold and Quinquis 1980) and by simple tight to isoclinal fold axes. Extensional structures (shear band foliation of White *et al.* 1980) intersect the main foliation at approximately 90° to the lineation. These observations serve to demonstrate that the lineation is indeed parallel to the bulk finite extension direction. Foliation is, with only local exceptions, parallel to map-scale compositional layering. The widespread occurrence of rotated winged feldspars and polymineralic tectonic inclusions (e.g., Hanmer 1984; Passchier and Simpson 1986), shear band foliation, asymmetrical boudinage, and back-rotated foliation fish (Hanmer 1986), and oblique foliation within late syntectonic layer-parallel pegmatites, all indicate a consistent top-side northwestward sense of differential movement along the lineation direction (see Hanmer and Ciesielski 1984; Hanmer 1984 for illustrations). Given the constant mean orientation of foliation and lineation across the 250 km northwest–southeast width of the Central Gneiss Belt, and the clear evidence therein for northwestward overthrusting outlined above, these observations serve to demonstrate that the Redstone thrust sheet is a large elliptical allochthonous thrust sheet or "horse" (Boyer and Elliot 1982), entirely bounded by ductile thrust zones.

In contrast to Redstone, the Dysart, Glamorgan, and Grace thrust sheets are bounded by metasedimentary rocks (Fig. 2). The metasediments are not a good source of kinematic observations, but are very informative with regard to their syntectonic rheological state. Interpretation of the Dysart, Glamorgan, and Grace gneiss sheets as thrust sheets is therefore based upon their containment within marble tectonic mélange and their association with the Redstone thrust sheet.

A commonly occurring set of asymmetrical folds suggests a kinematic framework somewhat more complex than pure northwestward thrusting. Centimetre to metre amplitude folds are widespread in all layered lithologies. They often occur singly, are open to tight, and, with very few exceptions, show an "S" asymmetry when viewed down the extension lineation. These observations suggest a complex kinematic picture, perhaps combining two contemporaneous shear couples oriented at a high angle to each other (e.g., Coward and Kim 1981; Brun and Burg 1982; Coward and Potts 1983; Ridley 1986), or a late rotation of the thrust direction (e.g., Merle and Brun 1984; Harris 1985; Dieterich and Durney 1986) where the later fold axis orientation was influenced by the earlier linear fabric elements (e.g., Hanmer 1979; Cobbold and Watkinson 1981). A common model situation for two synchronous shear couples in a thrusting environment involves combined thrust and wrench strains in the vicinity of a lateral ramp (Coward and Potts 1983). Although the western terminations of the Redstone and Dysart thrust sheets (Fig. 2) lie along the general direction of thrust transport, there is no indication anywhere in the map area of sinistral shear along steeply dipping northwest–southeast-striking planes. Furthermore, a sinistral lateral ramp model would predict fold asymmetry opposite to that observed (e.g., Ridley 1986). The alternative model involves a component of northeastward-directed thrusting, related to boundary conditions at a scale greater than that of the present study area, combined with the dominant northwestward thrusting. The fact that the coaxial asymmetrical folds preserve measurable interlimb angles either suggests that the northeastward thrusting was late, or indicates the difficulty of establishing asymmetry in the associated isoclinal folds. In the latter case, there would be no reason to separate the northwestward- and northeastward-thrusting components in time.

Footwall

The base of the lowest thrust sheet, the Redstone, is marked by a particularly well developed porphyroclastic gneiss. In the footwall the granitic gneisses of the Central Gneiss Belt are, for the most part, "irregular." There is a marked structural discordance in the east of the study area between the east-northeast-striking, southeast-dipping basal tectonite in the hanging wall and the vertical north–south layering of the underlying anorthosite and granitic "regular gneiss" (Fig. 2). The hanging wall structure clearly truncates that in the footwall. Elsewhere, the hanging wall and footwall structures are approximately concordant. Much of the footwall is invaded by discrete sheets of medium-grained leucogranite, 1–10 m thick, which cut across the host gneiss layering at a low angle. Thicker (< 150 m) sheets of the granite are shown in Fig. 2. Sheets of the granite also occur within the lower part of the basal porphyroclastic gneiss beneath the Redstone thrust sheet. The granite sheets vary from isotropic to foliated. This characteristic, together with the internal truncations observed in strongly zoned mantles of zircon crystals (van Breemen and Hanmer 1986), demonstrates that the swarm of granite sheets was emplaced late syntectonically with respect to the ductile emplacement of the Redstone thrust sheet.

Conditions of thrusting

Metapelite(?) occurs adjacent to the tonalitic Redstone and Dysart thrust sheets. The mineralogy of the metapelite(?) is complex, comprising both a mimetically annealed synfoliation assemblage and a postfoliation assemblage. The former consists of sillimanite – garnet – cordierite – biotite – 2 feldspars – quartz, aligned and enclosed in the foliation and (or) the lineation, broadly indicative of the upper amphibolite facies. Particularly ferroaluminous (Lal and Moorhouse 1969) horizons contain the postfoliation assemblage gedrite–cordierite–kyanite–biotite–chlorite–garnet(?). Relics of staurolite associated with sapphirine occur within cordierite, and minor sillimanite replaces kyanite. In the absence of partial melt, this assemblage suggests minimum conditions of 650°C at 6 kbars (1 kbar = 100 MPa) (Fig. 6).

Geochronology

The U–Pb data pertinent to the Haliburton area have been published elsewhere (van Breemen and Hanmer 1986) together with full descriptions of the zircons analysed. It suffices here to indicate the structural context of that study. Two samples of syntectonic granitic rock were analysed: (1) a very strongly flattened array of branching, folded granite veins intruded into already well-foliated amphibolitic gneiss at the margin of the straight gneiss overlying the Redstone thrust sheet; (2) an isotropic to poorly foliated granitoid sheet emplaced into porphyroclastic gneiss below the Redstone thrust sheet. The first yielded an age of 1065 ± 15 Ma and is interpreted as syntectonic with respect to the ductile thrusting represented by the straight gneiss. The second yielded an age of 1060 ± 6 Ma and is interpreted as very late syntectonic with respect to the thrusting represented by the porphyroclastic gneiss. These two dates are indistinguishable, leading to the conclusion that the present thrust stack in the boundary zone

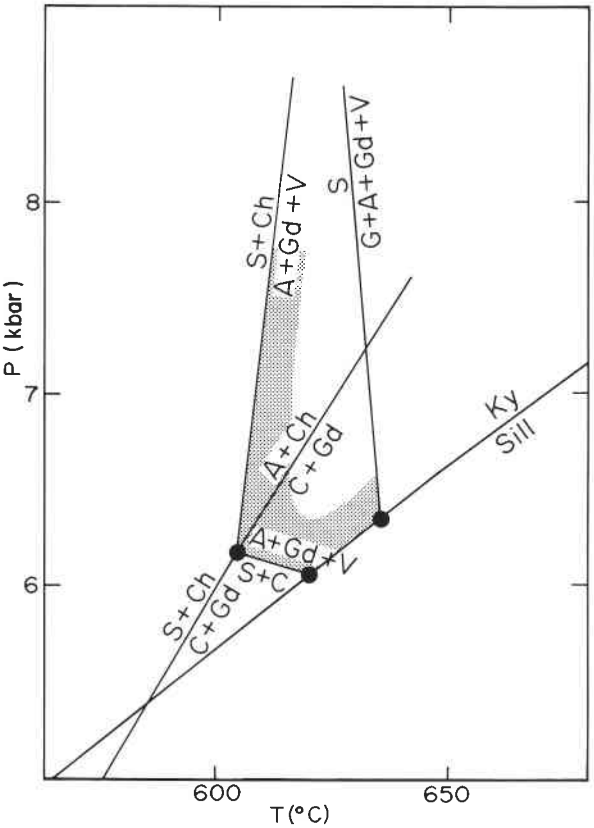

FIG. 6. Mineral equilibria in $P-T$ space assuming biotite, plagioclase, and quartz are present. Stippled area represents metamorphic conditions determined from the preserved assemblage in metapelites(?) in the Haliburton area of the Central Metasedimentary Belt boundary zone. Kyanite (Ky); sillimanite (Sill); aluminosilicate (A); cordierite (C); chlorite (Ch); garnet (G); gedrite (Gd); staurolite (S); vapour (V). After Carmichael in Bailes (1980). 1 kbar = 100 MPa.

of the Central Metasedimentary Belt in the Haliburton area was assembled at about 1060 Ma. This conclusion is supported by other age data from other parts of the boundary zone along strike to the northeast (van Breemen and Hanmer 1986).

Stacking order

Slices of syenitic gneiss occur between all three tonalitic thrust sheets (Redstone, Dysart, and Glamorgan; Fig. 2). The syenitic gneiss between the Dysart and Glamorgan thrust sheets is the southwestward extension of the Grace thrust sheet. To the east of the Dysart thrust sheet, kilometre-size slivers of anorthosite enclosed in marble appear to be detached from the overlying Grace thrust sheet. Even larger slices of very similar anorthosite, also enclosed in marble, occur at the same structural level, along strike from the syenite gneiss southwest of Haliburton (Hanmer and Ciesielski 1984). The kilometre- to centimetre-scale misoriented inclusions in the surrounding marble mélange suggest that this southwestern extension of the thrust sheet has been severely disrupted tectonically. This is especially evident beneath the syenite thrust sheet south and west of Haliburton where syenite inclusions, 10's to 100's of metres in size, are very abundant. In contrast, the syenitic straight gneiss between the Redstone and Dysart thrust sheets is completely surrounded by nonsyenitic rocks (e.g., marble, tonalite, metapelite(?), ''beaded'' gneiss; Fig. 2). It is not an inclusion within the marble mélange, but appears to be tectonically ''attached'' to the metapelite(?) and ''beaded gneiss'' (see below) beneath it.

Given the extreme syntectonic mobility of the marble and the absence of either stratigraphy or known lithological sequence, it is impossible to be certain of the prestacking geometry of the various lithological elements of the boundary zone of the Central Metasedimentary Belt in the Haliburton area. However, the following observations and inferences may be made concerning the stacking of the thrust sheets.

(1) As indicated by the truncation of footwall structure and geochronology, the Redstone thrust sheet was emplaced over an already deformed Central Gneiss Belt (see above).

(2) If the suggestion that the tonalitic thrust sheets were once part of a continuous body is valid, then the intercalation of thrust sheets of syenitic and tonalitic gneiss strongly suggests that the present thrust stack results from the imbrication of an initially layered configuration. Since syenitic gneiss was cross-cut by discrete veins of isotropic, medium-grained syenite prior to incorporation in the marble mélange, and tonalitic gneiss shows local relics of granulite facies metamorphism, both lithologies were gneissic prior to incorporation in the present amphibolite facies thrust stack. This, coupled with the general, though incomplete (see east side Fig. 2), separation of tonalitic and syenitic gneiss, allows one to consider a prestacking sandwich configuration of the two subhorizontal crystalline gneiss sheets separated by marble and metapelite(?). Given that the underlying Central Gneiss Belt was deformed by thrusting prior to the construction of the thrust stack in the boundary zone of the Central Metasedimentary Belt, such a sandwich configuration, while admittedly speculative, is suggestive of prestack thrusting. If such speculation is valid, it implies that the presently mappable ductile thrust zones are out-of-sequence thrusts. Determination of which of the two lithologies, tonalite or syenite, made up the upper and lower levels of the sandwich depends on where one chooses to place the locus of greatest differential movement within the shear zones between the thrust sheets. Such a choice remains totally unconstrained. Note that restacking of earlier ductile thrusts by later, laterally discontinuous, anastomosing ductile thrusts has also been described from the Alps (De Roo and Lister 1987).

(3) A set of late synmetamorphic extensional shears is developed in thrust sheets and ductile thrust zones throughout the Haliburton area as well as in the underlying Central Gneiss Belt (see also Nadeau in Davidson *et al.* 1985). They are bands of granoblastic straight gneiss, up to 10 m thick, which, with few exceptions, dip to the southeast about 10–15° more steeply than the foliation or layering that they cut. They show no sign of metamorphic retrogression. The sense of deflection of the host gneiss layering, as it passes with material continuity into the shears, consistently indicates top-side down to the southeast movement. The few exceptions alluded to are geometrically and kinematically conjugate to the southeast-dipping shears. These synmetamorphic extensional shears represent a finite increment of strain whose maximum extension is aligned with the direction of the thrust-related lineation. Since they cut the ductile thrust zones, they imply a relatively late extension of the assembled, or assembling, thrust stack in a manner analogous to similar stack-collapse structures in the Himalayas or the Alps (Burchfiel and Royden 1985; Krohe 1987).

(4) Thin, discrete, carbonate- or biotite-rich, ductile shear zones occur throughout the Haliburton area. A layer-parallel

carbonate ductile shear zone, up to 25 m thick, lies within the footwall about 500 m below the basal porphyroclastic gneiss (Fig. 2). It contains misoriented broken fragments of wall rock. Both fragments and marble layering are folded with "S"-shape profiles (looking northeast) and strongly curvilinear axes. Asymmetrical shear band foliation and rotated winged inclusions indicate top-side to the northwest sense of movement. The rocks of the shear zone footwall are identical to those of its hanging wall, perhaps suggesting only minor displacement. Coarse, platy, highly micaceous biotite–feldspar "tectonic schist" zones (Davidson 1984) occur sporadically throughout both the stack and its footwall. They comprise flat-lying to gently southeast-dipping schistose zones, up to several metres thick, which cut across and produce minor offsets of gneissic banding, veining, and folding (Fig. 5*b*). In some examples, amphibolite inclusions, presumably relics of the precursor lithology, point to possible formation of the schistose zones by synkinematic K-metasomatism of mafic sills. The discrete nature, retrograde mineralogy, and wide distribution of the carbonate and micaceous shear zones suggest that they are younger than both the main ductile thrusting and the extensional shears. Since they occur both within and below the boundary zone of the Central Metasedimentary Belt, they appear to represent a set of late, postmetamorphic peak, out-of-sequence thrusts of minor consequence.

Thrust localization

A field-based discussion of the rheological behaviour of two of the principal lithologies in the Haliburton area, tonalitic gneiss and Grenville Supergroup metapelite(?), is warranted with regard to the localization of ductile thrust zones. The rheological behaviour of the marble mélange and its potential for extreme flow have been briefly discussed above. Its role in the transport of the thrust sheets can be reasonably inferred, but remains unconstrained.

The lower side of the Dysart thrust sheet is lined along much of its strike length by a narrow belt of metapelite(?). This belt is particularly ferroaluminous at its eastern end. It is separated from a structurally lower metapelite(?) belt by serpentine-bearing marble tectonic mélange (Fig. 2). Nowhere do the two metapelite(?) belts link and there is no evidence to show that they are parts of the same layer or that they form the limbs of a marble-cored fold. However, even though a progressive transition has not been observed, both metapelite(?) belts are succeeded to the east by a coarse, sombre, biotite-rich gneiss of beaded aspect ("beaded gneiss"), of uncertain origin. The beading is due to the presence of clusters of coarse (centimetre scale) feldspar porphyroblasts, either scattered evenly throughout the gneiss or concentrated in isotropic quartzo-feldspathic pegmatitic layers. Red garnets are locally present in the "beaded" gneiss, but no aluminosilicates have yet been found. Thinner, less continuous belts of metapelite(?) occur at the western and southern boundaries of the Dysart thrust sheet. On account of the ferroaluminous composition of the gedrite-bearing component, Culshaw (1983) suggested that the metapelite(?) represents a weathering horizon, derived from the tonalitic basement (Lal and Moorhouse 1969). There is, however, no direct indication as to the origin of these aluminous rocks. Culshaw (1983) further proposed that, since both sides of the Dysart thrust sheet would represent the same tectonic horizon, the Dysart thrust sheet should be a fold, that is, a fold nappe. However, there is no evidence for a fold closure within the Dysart thrust sheet, nor does the fold nappe model account for the body of metapelite(?) within the thrust sheet, northwest of Haliburton.

There are alternative interpretations. For example, the tonalitic gneiss might be intrusive into the metapelite(?). Assuming that the metapelite(?) is part of the Grenville Supergroup (see, however, Culshaw 1983, 1986), this is unlikely, since U–Pb dating of the tonalite (1450–1300 Ma; van Breemen and Hanmer 1986) suggests that it is older than the Grenville Supergroup (1300–1250 Ma; Easton 1986). Alternatively, the tonalite–metapelite(?) contact may be tectonic. If the coarse tonalitic gneiss and the metapelite(?) were juxtaposed across an irregular boundary and subsequently deformed, then relatively thick, continuous belts of the latter would be softer than the tonalitic gneiss and could act as strain sinks, thus localizing the ductile shear zones that form the boundaries of the thrust sheets. Accordingly, the hook-shaped apophysis at the western end of the Dysart thrust sheet, bounded on its upper side by metapelite(?) and lying southwest of the isolated body of metapelite(?) within the thrust sheet, might represent a failed thrust, localized by two discontinuous bodies of metapelite(?). If valid, this model could have important consequences for the localization of the boundary zone of the Central Metasedimentary Belt throughout the Ontario segment, since similar ferroaluminous metapelite(?) occurs discontinuously within the boundary zone for several hundred kilometres to the northeast (R. H. Thivierge, personal communication 1984) yet is not reported from within the belt.

Tectonic implications

Allochthonous domains in the Grenville Province of Ontario can now be shown to fall into three broad size classes. The largest is represented by the Central Metasedimentary Belt, the allochthonous northwestern margin of which has a strike length of approximately 300 km (Hanmer and Ciesielski 1984); the smallest is represented by the gneissic "horses" described in this study. Domains of intermediate size occur within the Central Gneiss Belt (Fig. 1). Their size is difficult to specify on account of their overlapping and laterally discontinuous nature. Some form elongate spoon-shaped structures, 25+ km across the "bowl" in a northeast–southwest direction, but well in excess of 50 km along the narrow northwest–southeast-oriented "handle" (Fig. 1). Indeed, from Fig. 1, it appears that these elongate structures may be promontories attached to thrust sheets 100+ km in northeast–southwest strike length. In other words, thrusting in the southwestern Grenville Province spans the range from large thrust sheets to, at least locally, pervasive imbrication (considered at the broad scale). The Haliburton "horses" are easily identified owing to the correspondence between structure and lithology. Are others elsewhere masked by lithological monotony? How generally penetrative is thrust imbrication in the southwestern Grenville Province?

An obvious consequence of crustal shortening by thrusting is crustal thickening due to the imbrication of thrust sheets. The potential contribution of pervasive thrust imbrication to Dewey and Burke's (1973) now classical schematic cross section of the dynamically thickened Grenville crust, which they compare to the Tibetan Plateau, warrants consideration. This may also apply to other areas of significantly thickened continental crust associated with crustal shortening, for example, within the subducted Indian subcontinent south of the Himalayan suture zone, or the Pennine Nappes of the western Alps (e.g., Burg and Chen 1984; Butler 1986 and references therein). Interestingly, Bohlen (1987) suggests that crustal thickening by thrusting will not of itself produce the apparent metamorphic sequence described in this study: early sillimanite – field (granulite facies?) metamorphism followed by a later, perhaps postthrusting, kyanite-bearing assemblage. He considers that such an anticlockwise pressure–temperature–time path implies initial magmatic underplating followed by isobaric cooling. Resolution of this apparent paradox awaits further metamorphic study.

Conclusions

(1) The boundary zone of the Central Metasedimentary Belt in the Haliburton area is a stack of alternating tonalitic and syenitic, laterally discontinuous, crystalline thrust sheets (horses), transported toward the northwest on upper amphibolite facies ductile shear zones during the Grenvillian Orogeny, at 1060 Ma. At the regional scale they represent a penetrative development of thrust imbrication.

(2) The thrust stacking order is not a simple "piggyback" sequence. Out-of-sequence shear zones bounding the present thrust sheets probably cut through an older "sandwich" of two crystalline thrust sheets separated by metasediments.

(3) Kinematics of the deformation are complex. Dominant northwestward thrusting was, at least partly, coeval with subordinate northeastward thrusting. Late synmetamorphic extensional shears cut all layered tectonites in the stack. Minor late thrusting on discrete shear zones apparently postdates the extensional structures.

(4) Pelite(?) and marble played a mechanically significant role during localization and transport of the thrust sheets. Belts of mechanically weak pelite(?) appear to have localized the thrust sheets, while highly mobile marble behaved as a relatively low-viscosity fluid during transport, able to intrude and erode more competent wall rock.

(5) Structural studies in the deeply excavated Grenville Province highlight potential analogues of the architecture and processes pertaining to the deeper levels of modern mountain belts.

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