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**STRUCTURE AND U-PB GEOCHRONOLOGY
OF THE
PEMBROKE THRUST STACK,
CENTRAL METASEDIMENTARY BELT
BOUNDARY THRUST ZONE**

by

Sally J. McEachern, B.Sc.

**A thesis submitted to the Faculty of
Graduate Studies and Research in partial fulfillment
of the requirements for the degree of
Master of Science**

Carleton University

Ottawa, Ontario

November, 1990

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**STRUCTURE AND GEOCHRONOLOGY OF THE PEMBROKE
THRUST STACK, CENTRAL METASEDIMENTARY BELT
BOUNDARY THRUST ZONE**

submitted by Sally J. McEachern, B.Sc. in partial fulfilment of the requirements
for the degree of Master of Science.

Chairman, Department of Earth Sciences

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ABSTRACT

Structural study of the Pembroke area Central Metasedimentary Belt Boundary Thrust Zone (CMBBTZ) of the Grenville Province has identified an assemblage of ductile thrust bounded sheets termed the Pembroke thrust stack. It is comprised of 3 thrust sheets bounded by upper amphibolite facies quartzofeldspathic and carbonate tectonites. The thrust sheets were transported northwestward with a subordinate, northeast directed shear .

Comparison of the Pembroke area structural characteristics with those of the Haliburton area to the southwest reveals that the Ontario CMBBTZ is a remarkably uniform crustal scale shear zone with dominant structural characteristics traceable throughout its length.

U-Pb zircon geochronology has established that thrusting on the Pembroke thrust stack occurred in 3 main phases, ca 1180 Ma, 1060 Ma, and 1000 Ma. The 1180 Ma and 1060 Ma thrust events can be linked to collision of the Central Metasedimentary Belt with the North American margin and terminal collision of the hinterland Grenville continent with the margin.

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ORIGINAL CONTRIBUTION

Data were collected over a period of 2 months of field work during the fall of 1988 and the summer of 1989. I completed 1:250,000 scale mapping of the Central Metasedimentary Belt boundary which comprises the Pembroke NTS 31F map sheet.

I separated zircons and sphenes from 5 samples collected by me for U-Pb geochronology. I completed all stages of rock crushing, grinding, mineral separation and hand picking from all samples. I made 10 polished and etched SEM mounts containing 10 to 20 zircon grains each. I performed chemistry in the G.S.C. clean lab on zircons from sample K1. The remaining chemistry and all mass spectrometry was performed by technicians at the G.S.C. geochronology laboratory.

1.0 INTRODUCTION

1.1 PREFACE

A new attitude towards the peculiarities of the Canadian Grenville Province is currently invigorating the study of this ancient and deeply eroded orogenic belt. This has not always been the case however, as the Grenville once had, perhaps unfairly, the reputation of being undecipherable. Precise U-Pb geochronology, so important to outlining tectonic events in the highly deformed and stratigraphically ambiguous Grenville, was unavailable to earlier workers. Despite this limitation they were somewhat successful in recognizing geological relations in the Pembroke, Ontario area, the focus of this study. Frank Adams, working in this area, rather elegantly summarized the perspective necessary to unravelling the tectonic history of the Grenville. It is as appropriate today, in this time of newly awakened enthusiasm, as it was nearly a century ago.

'That was indeed a fair and sunlit earth which our predecessors,...had presented to them for study...We, their successors, in pursuing our studies are obliged to descend into the deeper parts of the earth where the light begins to fail and when once we pass through the last portal into the Pre-Cambrian world, we enter what these earlier geologists regarded as a hopeless chaos. At first we could dimly descry but the outlines of the vast indeterminate ruins of former worlds, but as our eyes become accustomed to the darkness these become somewhat more distinct and we recognise succession even in this ruined waste.'

F.D. Adams (1910)

1.2 GEOLOGIC SETTING

The study area is centred in the Pembroke, Ontario area at the northwestern boundary of the Central Metasedimentary Belt (CMB), a subprovince of the Grenville Province of the Canadian Shield (Fig.1).

The Grenville Province lies along the southwest margin of the Canadian Shield. It is a belt approximately 1900 km long and 400 km wide. It encompasses the reworked margin of North America and younger, possibly accreted, terranes which were involved in the 1.3-1.0 Ga Grenvillian Orogenic cycle (Wynne-Edwards, 1972; Moore, 1986; Easton, 1986). This cycle involved thrust imbrication, shortening and high grade metamorphism spanning some 250 Ma. Deformed rocks of "Grenvillian" age are known to extend through the eastern and southern U.S. into northern Mexico (Patchett and Ruiz, 1988; Bickford et al, 1986). High grade gneisses correlative with rocks of the northwestern Grenville in Labrador have been identified in Scandinavia (Gower, 1985).

There is growing evidence that the Grenville Province includes material metamorphosed and deformed during a series of orogenic events ranging in age from early middle to late Proterozoic (Rivers et al, 1989; Wardle et al, 1986; Baer, 1981; Moore and Thompson, 1980). In this study the term "Grenville Orogeny" will be limited to the northwest directed thrusting and/or high grade regional metamorphism prevalent throughout the Grenville Province at 1.18-1.00 Ga.

The CMB in Ontario is dominantly composed of large expanses of marble

Figure 1: Subdivisions of the Grenville Province after Wynne Edwards (1972). I=Grenville Front Tectonic Zone, II=Central Gneiss Belt, III=Central Metasedimentary Belt, IV=Central Granulite Terrane, V=Baie Comeau Segment, VI=Eastern Grenville Subprovince. Box outlines the area of Figure 2. Modified after Davidson, 1984.

interleaved with metavolcanics and other metasediments. This 1.3 Ga supracrustal succession is known as the Grenville Supergroup (Moore and Thompson, 1980).

The CMB is divided into three lithotectonic terranes (Fig.2) (Rivers et al, 1989; Wynne-Edwards, 1972).

1) Bancroft terrane: The Bancroft terrane contains the northwest limit of the main Grenville Supergroup marbles. These supracrustal rocks are associated with nepheline gneisses, syenites and orthogneisses. The metamorphic grade is mid to upper amphibolite facies, although there is evidence of retrogression from granulite facies at the northwestern boundary (Hanmer, 1988). Foliation and gneissic layering are generally parallel to the western boundary and dip gently to the southeast.

2) Elzevir terrane: The Elzevir terrane is dominated by metavolcanic rocks interlayered with marbles and clastic metasediments. Tonalitic and granitic batholiths of 1250-1290 Ma age intrude the supracrustal rocks, as do a series of younger plutons of gabbroic, syenitic and peralkaline composition (Davidson, 1984; Corriveau, 1990). The Elzevir is noted for the presence of "metamorphic lows" of greenschist to lower amphibolite facies.

3) Frontenac terrane: The Frontenac terrane to the southeast is dominated by marble, metapelites and quartzites. The metamorphic grade is mainly granulite and uppermost amphibolite facies. The foliation and structural trends gradually progress from southeast dipping at the northwest boundary with the Elzevir

Figure 2: Map showing the subdivisions of the Central Metasedimentary Belt (CMB) and their characteristic lithologies and approximate metamorphic grades (after Carlson et al, 1990). The CMB Boundary Zone is denoted by wavy lines. The box outlines the area of Figure 4, the thesis study area.

terrane, through the vertical to northwest dipping near the New York Lowlands.

The CMB is bordered to the east by the Central Granulite terrane, a zone characterized by granulite facies metamorphism and large anorthosite massifs. It is bordered to the west by the Central Gneiss Belt (Fig.1). The CGB is comprised of quartzofeldspathic gneisses of both plutonic and supracrustal origin. It has recently been recognized as a composite of 1.7-1.6 Ga. and 1.5-1.4 Ga. plutonic terranes imbricated and thrust northwestward (Nadeau, 1990).

The boundary of the CMB and the underlying CGB is the focus of this study. Different ages of crustal formation as determined from Pb and Nd isotopic ratios (1.3-1.2 Ga CMB crust versus 1.45 to 1.65 Ga crust in the CGB (Fletcher and Farquhar, 1982; Dickin et al, 1988) suggest that the CGB/CMB boundary marks the pre-Grenville cratonic margin of North America. The boundary locally truncates gneissosity and structures in the CGB. Foliation and gneissosity in the boundary zone are parallel to the northeast trend of the boundary. Exposure of the boundary is very poor in the eastern portion of the study area where it is transected by the Ottawa-Bonnechere Graben (OBG).

The northwest trending OBG extends from near Ottawa, Ontario along the Ottawa and Mattawa River valleys, north to Lake Temiskaming (Fig.2). Four large faulted outliers of lower-mid Ordovician rocks are found within the graben. Downfaulting of the outliers, related to graben development, has covered large portions of the study area (Kay, 1942). The shield gneisses are further obscured by large Pleistocene deposits of marine clay and sand. These were laid

down by the Champlain Sea which flooded the Ottawa Valley as far north as Pembroke (Lumbers, 1982; Gadd, 1987)

1.3 PREVIOUS WORK

The study area covers most of the Pembroke 1:250,000 map sheet. Many workers have examined parts of this area, commencing as early as 1899 (Barlow, 1899; Adams and Barlow, 1910; Quinn, 1952; Hewitt, 1954; Hewitt and James, 1955; Themistocleous, 1978, 1979; Lumbers, 1982).

The quartzofeldspathic gneisses and marbles of the area have been assigned to the Grenville Supergroup (Moore and Thompson, 1980). However, even at the turn of the century the influence of tectonic processes on the present aspect of the marbles was recognised. Barlow (1899) identified the tectonic nature of the marble melange, stating that the marble was a "dynamic breccia" which resulted from "complex folding and stretching occasioned by the operation of the strong orogenic forces prevailing". Similarly Adams and Barlow (1910) recognised that the boundary of the Grenville marbles was a zone of tectonism. Davidson in his 1984 reinterpretation of the nature of tectonic boundaries in the southern Ontario Grenville was the first to explicitly outline a tectonic boundary zone between the CMB and the CGB.

A more focused examination of the nature of the CMB Boundary Zone in the Pembroke area was made by Hanmer and Ciesielski (1984), as part of a reconnaissance of the boundary in Quebec and Ontario. They identified that the

boundary is a crustal scale shear zone resulting from the overthrusting of the CMB onto the CGB.

The only regionally comprehensive work of the area was published by Lumbers in 1982. He interpreted quartzofeldspathic tectonites of the boundary zone as metasedimentary rocks, and identified a basal "coarse clastic sequence" unconformably overlying a large diapir; the Algonquin Batholith. A model for the development of structures in the area suggested that regional metamorphism diapirically reactivated the Algonquin batholith (Schwerdtner and Lumbers, 1980). High strains observed in the supracrustal rocks and basal conglomerate were postulated to be due to the ballooning upward of the diapir. Field observations discount this theory on two major points. First, the basal conglomerate of the coarse clastic sequence does not contain the sedimentary cobbles or pebbles identified as the result of an erosional unconformity (Lumbers, 1982). The clasts are relict feldspar augen derived from the mechanical disaggregation of pegmatites. Secondly, kinematic indicators show the sense of movement in the "basal sequence" to be topside to the northwest, antithetic to the extension expected on the southeast side of a rising diapir. Despite differences of interpretation, Lumbers' work remains the only comprehensive study of the Pembroke area CMB boundary outside of this thesis, and was invaluable in extrapolating the study area outside the bounds of directly observed field exposures (see Fig 5).

1.4 OBJECTIVES AND NATURE OF STUDY

An examination of portions of the study area was included in a reconnaissance scale study of the CMB Boundary Zone (BZ) in Ontario and Quebec (Hanmer and Ciezielski, 1984). This preliminary study found that the Ontario and Quebec BZs were distinct from one another structurally. The reconnaissance determined that the Ontario boundary zone of the CMB is a southeast dipping crustal scale thrust zone juxtaposing the CMB with the CGB. The Quebec boundary zone is predominantly a lithologic boundary, marking the western limit of the Grenville Supergroup marbles. Irregular gneisses occur at its western margin but do not appear to be involved in discrete imbricated sheets as in Ontario (Hanmer and Ciezielski, 1984). While high strain tectonites are present in both the Ontario and Quebec boundary zones, they are not found as a distinct zone subjacent to the marbles in Quebec, a feature characteristic of the Ontario BZ (Hanmer and Ciezielski, 1984; Indares and Martignole, 1990). The foliation and extension lineation in the Quebec section are highly variable and are commonly steeply dipping. The Ontario BZ has a consistent shallow southeast dipping foliation and lineation. Movement on the Quebec boundary zone appears to have been dextral transpression while in Ontario it is dominantly northwestward overthrusting (Indares and Martignole, 1990).

More detailed study of the Ontario BZ centred on the Haliburton region (Fig. 3) where access and exposure were most favourable (Hanmer et al, 1988; Culshaw et al, 1983). This study showed the BZ to be comprised of crystalline

Figure 3: Map of the Haliburton area CMB Boundary Zone (CMBBZ), illustrating the principal thrust sheets of the Haliburton thrust stack and underlying thrust domains of the Central Gneiss Belt (CGB). (after Hammer, 1988).
 I = Redstone, II = Dysart, III = Glamorgan, IV = Grace thrust sheets, PC = Paleozoic cover.
 Dashed rectangle outlines the western end of the study area for reference.

thrust sheets transported northwestwards on upper amphibolite facies ductile thrust zones. Consequently the Ontario CMB Boundary Zone is referred to as the CMB Boundary Thrust Zone (CMBBTZ). The ductile thrust zone tectonites are quartzofeldspathic rocks and carbonates, the latter being a marble tectonic melange. Northeast directed shearing was coeval with, but subordinate to, the main northwestward movement. The base of the boundary thrust zone was apparently localized by highly aluminous paragneiss and cordierite-gedrite gneiss.

The objectives of this study of the Pembroke area boundary thrust zone (Pembroke CMBBTZ) were:

- 1) to determine where the base of the boundary thrust zone is situated.
- 2) to determine if the structural characteristics of the CMBBTZ in the Haliburton area continued along strike to the northeast.
- 3) to determine if any structures characteristic of the Quebec CMBBTZ were present at Pembroke.
- 4) to determine the timing of thrusting on the Pembroke boundary thrust zone.
- 5) to compare the timing of thrusting at Pembroke with available data along strike to the southwest.

Two main methods of study were employed to address these objectives; field observation and U-Pb geochronology.

As was noted in 1.2, with the exception of excellent road-cut exposures, exposure of the deformed Grenville gneisses is somewhat limited in large portions of the study area. This difficulty was exacerbated by a previously supposed lack

of correspondence between lithology and structure. Consequently it was necessary to determine the distribution of ductile thrust zones bounding possible thrust sheets in order to investigate thrust imbrication.

A series of tectonite mapping units (Hanmer, 1988, 1990) were used to differentiate between highly strained ductile thrust zone tectonites and moderately strained thrust sheet gneisses. It is essential to observe both the X/Z and Y/Z ($X > Y > Z$) sections of the finite strain ellipsoid to employ this classification scheme. Accordingly, field observations were made principally at roadcuts and outcrops where the required sections were visible.

Demarcation of the ductile thrust zones in the field has identified the distribution of the locus of the last increment of significant finite strain. This allowed selection of syntectonically deformed sheets and pegmatites involved in the thrusting for geochronologic study. Further details of the nature of this study are given in section 3.0.

2.0 STRUCTURE

2.1 TECTONITE MAPPING UNITS

The formation of straight banded silicate tectonites by progressive deformation of igneous rocks has been documented by Myers (1978). For the specific case of the Grenville Province workers including Davidson, (1984), and Nadeau (1984), have documented the development of rectilinear gneissic tectonites in the Central Gneiss Belt. As noted by Myers the high strain nature of these gneisses is illustrated by the progressive transposition of early cross-cutting structures. Other high strain features include the presence of sheath folds, isoclinal intrafolial folds, strong syntectonic grain size reduction and large separations between entrained boudins of exotic lithology (Davidson, 1984; Hanmer, 1988)

Although a limited correspondence between lithology and structure was found during mapping of the Pembroke CMBBTZ (see section 2.4) poor exposure made documentation of the detailed geology of the interior of thrust sheets difficult. Consequently, the best method for identification of thrust sheets was to determine the distribution of high strain ductile thrust zone tectonites bounding them. Two types of tectonites are found in the CMBBTZ; the first type is quartzofeldspathic.

The quartzofeldspathic gneisses have been divided into four structural mapping units on the basis of the observed geometry of gneissic banding.

These are:

1) Straight gneiss: An extremely rectilinear layered gneiss whose Y-Z section (perpendicular to the foliation and lineation) and X-Z section both display features resulting from accommodation of significant strain ($X \geq Y \geq Z$) (Plate 1a, Fig.4). These features include a) attenuation of irregularities (blocks, inclusions and lithologic boundaries), transposition of cross-cutting structures (dykes, veins, pre-existing folds) into parallelism with the shear plane (defined by strain gradients and parallel with the foliation and compositional layering); b) extreme attenuation and/or disaggregation of layers; c) development of well defined compositional layers with extremely sharp interfaces. Straight gneiss is usually comprised of mafic and leucocratic bands layered on a 1-10 cm scale. Individual compositional layers, sometimes no more than 1 cm thick, can be traced continuously for more than 2 metres. The gneiss is well annealed, resulting in a granoblastic texture (Plate 1b).

2) Porphyroclastic gneiss: An often straight gneiss characterized by the presence of volumetrically significant quantities of feldspar porphyroclasts (grain size ranges from 1-5 cm diameter). The porphyroclasts occur in a range of situations, from isolated augen, within trains connected by attenuated bands of recrystallized feldspar (parallel to the foliation), to spatially associated barely boudinaged pegmatitic layers (Plate 1c). Quartz ribbons are commonly developed. The large grain size of the feldspars is typical of growth in a volatile rich material such as a pegmatite.

Plate 1: High strain tectonites

1a: Quartzofeldspathic straight gneiss viewed looking on the XZ strain section. Note the extreme uniformity and transposition of layering and its rectilinear nature, both in the XZ section and the red weathered perpendicular ZY section.

1b: Photomicrograph of straight gneiss illustrating its granoblastic recrystallized texture. Note the prevalence of 120° junctions between equant grains. Crossed nicols, 10x.

1c: Typical aspect of porphyroclastic gneiss. Note lens cap (2 inch diameter) for scale. Coarse feldspar porphyroclasts occur as isolated augen and within disaggregated bands defining a foliation. These features illustrate the heterogeneity of strain distribution in this material.

1d: Porphyroclastic gneiss band within straight gneiss. The presence of discrete porphyroclastic gneiss bands parallel to straight gneiss foliation illustrates that the porphyroclastic gneiss is derived from the disaggregation of pegmatite intruded into the straight gneiss.

STRAIGHT GNEISS

REGULAR GNEISS

Figure 4: Comparison of XZ and YZ sections of straight gneiss (above) and regular gneiss (below). ($X > Y > Z$). Note transposition and rectilinear layering in both sections of straight gneiss (compare with Plate 1a), and irregularities in YZ section of regular gneiss (compare with Plates 2a,b) which serve to differentiate it from straight gneiss. Lines on XY section are extension lineation.

The observation of barely boudinaged pegmatite and attenuated trains of porphyroclasts within the same material and the presence of narrow discrete bands of porphyroclastic gneiss parallel to the foliation in straight gneiss leads to the conclusion that the porphyroclastic gneiss is developed from the disaggregation of pegmatite intruded along the foliation in straight gneiss (Plate 1d). The heterogeneous nature of the deforming porphyroclastic gneiss is illustrated by the presence of isolated feldspars and barely boudinaged pegmatite within the same layer. This heterogeneity is a function of the contrasting strength of coarse newly injected material and already deformed fine grained matrix.

The injection of pegmatite into the high strain tectonite introduces new coarse unstrained grains, which are stronger and more difficult to deform than an existing matrix aggregate. The finer grained matrix is weaker because its smaller grain size leads to more effective operation of processes such as grain boundary sliding, grain boundary diffusion and diffusion creep and their enhancement by hydrolytic weakening. These processes are precluded in larger grains whose greater radii inhibit efficient OH^- diffusion. Some new coarse grains will be more resistant and remain as isolated porphyroclasts, while other smaller grains will be subject to grain size reduction and deformation. Once the introduction of new unstrained pegmatite ceases the material will tend to deform in a more homogeneous manner.

The degree of disaggregation of the pegmatite and development of quartz ribbons attest to the high degree of strain accommodated by the porphyroclastic

gneiss.

3) **Regular gneiss**: A well layered gneiss whose Y-Z section commonly contains irregularities, inclusions and low angle cross-cutting features which are attenuated in the X-Z section (Plate 2a,b). The gneissic aspect observed in the X-Z section varies from diffusely layered to more highly strained rectilinear, consequently examination of the gneiss in three dimensions is required to differentiate between a straight gneiss and a particularly well layered regular gneiss (Fig.4). The lower strain regular gneiss passes visibly into straight gneiss with increasing attenuation and transposition in all sections.

4) **Irregular gneiss**: A gneiss characterized by cross-cutting structures and irregularities in all sections. Often irregular gneiss is complexly folded, displaying folds with axial planes in many different orientations (Plate 2c). The foliation in this gneiss anastomoses around large blocks and boudins. Folds are often nucleated at the margins of these blocks, an occurrence typical of anastomosing mylonitic foliation (Bell and Hammond, 1984). The inclusions and boudins vary from 10 cm diameter to tens of meters, and commonly preserve older finite increments of strain. In some instances the inclusions are blocks of straight or porphyroclastic gneiss. The preservation of large lower strain pods in an anastomosing strain pattern indicates that strain distribution is heterogeneous (Plate 2d). The irregular gneiss passes laterally into regular or straight gneiss if the heterogeneity of strain distribution is strong enough.

Regular and irregular gneisses are the lower strain gneisses which comprise

Plate 2: Thrust sheet gneisses

2a: Aspect of regular gneiss in the XZ strain section. Low angle cross cutting features are somewhat transposed and layered is largely parallel, giving the gneiss an apparently "straight" aspect.

2b: Aspect of regular gneiss in the ZY strain section perpendicular to 2a, same outcrop. Note the irregularity of pods and high angle cross-cutting veins. Observation of this section in outcrop allows differentiation between straight and regular gneiss.

2c: Irregular gneiss illustrating pods, cross-cutting elements and extreme variation in foliation and fold aspect.

2d: Straight gneiss pods entrained within irregular gneiss from the basal thrust zone. The preservation of once highly strained material in what is effectively now the thrust sheet illustrates that the locus of high strain shifts with time, and that the map of high strain distribution is indeed a "snapshot" of the last finite increment of strain.

the crystalline thrust sheets.

The second tectonite type is carbonate tectonite, referred to as a marble tectonic melange by Hanmer and Ciezielski (1984). A tectonic genesis for this melange is justified by the presence of features considered characteristic of tectonically derived melanges; a consistent foliation in map pattern, tight clustering of clast long-axis lineations throughout the outcrop and lineations parallel to the transport direction (Orange, 1990).

The melange matrix is a very coarse marble containing phlogopite, diopside, graphite and pyrite. Entrained within the marble are scattered misoriented inclusions of varying composition. The preservation of pre-incorporation textures and structures (such as 90° corners on a boudinaged mafic gneiss block, Plate 3a) attests to the high degree of ductility of the marble, as does its ability to intrude along foliation planes and spall off pieces of host gneiss.

The flowing marble absorbed significantly high strain, as evidenced by the large separations (pull-aparts) between inclusions of exotic lithology, and the isoclinal folding of long aspect ratio inclusions (Plate 3b-d). The size of inclusions carried is extremely variable, from cm long pieces and slivers to km long sheets.

Blocks of near isotropic granitoid have been interpreted as having an intrusive relationship with the marble (Lumbers, 1982). However, the lack of development of a skarn or chilled margin adjacent to these blocks argues for a tectonic contact with the marble (compare Lumbers, 1982 with Barlow, 1899).

Variation in the proportions of phlogopite, graphite and other minerals

Plate 3: Marble tectonic melange

- 3a: Mafic boudin inclusion within marble tectonic melange. Note the preservation of 90° corners on the boudin and wrapping of graphite/phlogopite layering around inclusions.
- 3b: Variably sized inclusions within marble melange. Note spalling off of pieces of the mafic block by the extremely mobile marble (above hammer).
- 3c,d: Isoclinally folded long aspect ratio inclusions within the marble melange. Note closure of fold to the right in 3d.

within the marble outlines a banding previously interpreted as relict sedimentary layering (Lumbers, 1982; Hewitt, 1954). The observation that the banding anastomoses around entrained inclusions illustrates that the layering results from ductile flow. This flow banding outlines a subtle fabric which is parallel to the alignment of long aspect ratio inclusions. The apparent dip of the banding is very shallow (often $< 20^\circ$), similar to the syntectonic foliation in the quartzofeldspathic tectonites. The distribution of inclusions varies from outcrop to outcrop but they are most commonly aligned in trains parallel to the flow banding within individual exposures. This indicates that the flow was at least locally laminar.

It must be stressed that this classification of tectonite types is based on their present geometry, and that the present geometry is a function of the last significant finite increment of strain, not the total accumulated finite strain. A straight gneiss which is no longer at the locus of high finite strain during the next increment of progressive deformation can become an irregular or regular gneiss if disrupted by intrusion of high angle structures or boudinage and folding of its layering. Consequently, the map of the distribution of high strain zones produced by employing these tectonite mapping units is a "snapshot" of the strain distribution arising from the last significant increment of high strain.

2.2 Ductile Thrust Zones

Delineation of the ductile thrust zones and thrust sheets of the Pembroke CMBBTZ has been made on the basis of high strain tectonite distribution as outlined in section 2.3. The quartzofeldspathic tectonites and marble melange define ductile thrust zones which outline at least three thrust sheets (Fig.5) which are here collectively termed the Pembroke thrust stack. The principal thrust zones are shallowly dipping (Fig. 6) and typically between 250 and 1300 m thick, the wider zones being those developed in marble tectonic melange.

A basal ductile thrust zone to the Pembroke thrust stack can be defined between the lowest thrust sheets and the granulite grade gneisses of the CGB. This basal ductile thrust zone is comprised of straight and porphyroclastic gneisses. The foliation within this thrust zone is very shallowly dipping, commonly less than 15°. The strike of the zone is approximately northeast-southwest. Within the zone, however, the strike of the local foliation can vary from that of the dominant trend by as much as 30° as the result of warping of such a shallow shear plane.

In the northeastern portion of the basal thrust zone a straight gneiss of similar composition to the overlying mafic Stafford thrust sheet is demonstrably derived from it. A traverse from the less deformed thrust sheet into the underlying straight gneiss reveals that the compositional layering of the straight gneiss results from progressive transposition of granitic veins and pegmatites intruded into amphibolite host gneiss (Plate 4a,b). Portions of the mafic straight

Figure 5: Map of the distribution of ductile thrust zone tectonites and thrust sheets of the Pembroke area Central Metasedimentary Belt Boundary Thrust Zone (CMBBTZ). Tectonites include silicate and carbonate tectonites. Thrust sheets are named. All contacts are inferred to approximate. Geology by the author, except for upper bound of the Opeongo thrust sheet, modified from Lunabers, 1982. CGB=Central Gneiss Belt, R=Rockingham, F=Foymount, P=Palmer's Rapids,

Figure 6: Equal area stereonet of poles to foliation from the Pembroke area CMBBTZ, illustrating the consistent NE-SW strike and shallow dip of the foliation.

gneiss underlying the Stafford thrust sheet at Killaloe are garnet bearing. They are compositionally similar to garnet bearing mafic gneisses found in the immediate footwall (CGB). The Killaloe straight gneisses may therefore be derived from both the hangingwall and footwall lithologies.

In the central portion of the basal ductile thrust zone (Rockingham area) determination of the location of the thrust zone was made on the basis of "paired" strain gradients. True straight or porphyroclastic gneisses were not exposed in the area but regular gneisses were observed to grade from moderate strain regular gneisses into gneisses with increasingly "straight" characteristics both southeastward from within the footwall and northwestward from within the west wing of the Stafford thrust sheet. Thus the continuation of the basal thrust zone was carried through the area between the two strain gradients.

The western portion of the basal thrust zone is outlined by particularly well developed porphyroclastic gneisses (Plate 4c). These underlie the Papineau thrust sheet, but are not demonstrably derived from it.

Structurally above the basal ductile thrust zone is the Opeongo thrust zone. It contains both quartzofeldspathic tectonites and marble tectonic melange. The gneissic tectonites include syenitic straight gneiss and porphyroclastic gneiss, which contains sillimanite and is possibly pelitic in origin. The syenitic straight gneiss contains bands of alkali granite, clinopyroxene syenite gneiss and amphibolite and was probably derived from the overlying, similarly alkalic, Opeongo thrust sheet (Plate 4d). Syenitic tectonite attached to the thrust sheet occurs at the southwest

Plate 4: Ductile thrust zone tectonites

- 4a: Ellipsoidal pod of amphibolite surrounded by anastomosing higher strain gneisses and syntectonic granites, Stafford thrust sheet interior. High strain tectonites of the basal ductile thrust zone below the Stafford thrust sheet are derived from this material.
- 4b: Straight gneiss tectonite of Stafford basal thrust zone derived from 4a. The compositional layering results from the transposition of amphibolite pods, syntectonic granites and biotite regular gneiss. Note the rectilinear nature of the layering in the bottom half of the picture.
- 4c: Porphyroclastic gneiss of the basal ductile thrust zone to the Papineau thrust sheet. Note the coarseness of the feldspars and disaggregation into connected trains of porphyroclasts.
- 4d: Syenitic straight gneiss of the Opeongo ductile thrust zone between the Opeongo thrust sheet and the underlying east wing of the Papineau sheet. Rectilinear layering results from metamorphic segregation between the felsic and mafic phases of the protolith augite syenite, as well as possible transposition of mafic veins intruded into the syenite.

end of the Opeongo sheet near Palmers Rapids (see Fig.5) and to the northeast at Foymount. Inclusions interpreted to be derived from the syenitic straight gneiss occur in the marble along strike from the attached material. This distribution of straight gneiss below the thrust sheet suggests that a more continuous zone of silicate tectonite may have been developed between the Opeongo sheet and the underlying thrust sheets, but was dismembered by accommodation of movement within the marble melange.

The "snapshot" nature of the distribution of the ductile thrust zones is illustrated by the presence of boudins of straight gneiss in irregular gneisses of the footwall adjacent to the basal thrust zone (Plate 2d). Regular gneiss adjacent to the straight gneiss inclusions has an extremely well developed stretching lineation and foliation parallel to that of the thrust zone itself. The regular gneiss has markedly fewer low angle cross-cutting features in its Y-Z section than regular gneisses in the interior of the thrust sheets. The interfaces between compositional layers are nearly rectilinear, as they are in straight gneisses, but are less sharp. The presence of straight gneiss inclusions in the irregular gneiss and nearly "straight" aspect of the regular gneiss suggests that this zone immediately below the present ductile thrust zone was at one time a straight gneiss zone. The zone described was probably the locus for high strain deformation during a preceding increment of high strain and may have been the basal ductile thrust zone at that time.

Marble melange outlines the ductile thrust zones overlying the Opeongo

and Papineau thrust sheets. However, not all bodies bounded by the melange are thrust sheets. In places the marble has forced its way into the thrust sheets and isolated large portions, creating km size inclusions. For example the southwest end of the Opeongo thrust sheet is divided into large bodies completely surrounded by marble melange. A similar feature is observed at Haliburton where the western wing of the Grace thrust sheet is separated from the main body by marble melange (Hanmer, 1988). These map scale inclusions should not be interpreted as individual thrust sheets, despite being bounded on all sides by ductile thrust zone material.

The extremely mobile marble has penetrated for several kms into the upper west portion of the Stafford thrust sheet, without reconnecting to the main thrust zone. Whether this is a failed thrust or disaggregation of the sheet (so as to create a very large tectonic inclusion) cannot be determined.

The rheology of the marble complicates interpretation of field relations. The melange is observed to cut the quartzofeldspathic ductile thrust zones in the lower part of the thrust stack, whereas in the upper part the marble melange entirely surrounds the thrust sheets and incorporates the gneiss tectonites as inclusions. While such an apparently intrusive relationship could be interpreted as the result of significant displacement in the marble melange postdating displacement and thrusting in the quartzofeldspathic ductile thrust zones, a rheologic explanation is likely the simplest one, as there are no features indicative of a temporal difference between movement on the silicate and carbonate

tectonites, other than their cross-cutting relationship. Both materials absorbed high strains, but the high degree of ductility and mobility of the "toothpaste"-like marble enabled it to intrude the coevally deforming straight gneiss.

The marble is able to spall off and tectonically erode the gneisses it intrudes. This may be the case for larger blocks of straight gneiss tectonite entrained within the marble, however, blocks with right angle corners appear to have been pulled apart. This strong competence contrast between the two ductile thrust zone materials is due to the greater thermal sensitivity of the rheology of the calcite comprising the melange matrix. At a given temperature the calcite is much weaker rheologically than the silicate minerals of the quartzofeldspathic tectonite (Rutter, 1976).

There is an apparent decrease in the proportions of quartzofeldspathic tectonite relative to marble melange upwards through the Pembroke thrust stack (also observed in the Haliburton area CMBBTZ, Hanmer, 1988). Where there is significant development of quartzofeldspathic tectonite there is little marble melange. Conversely where the ductile thrust zones are dominantly carbonate there is apparently less development of gneissic tectonite. The extreme mobility of the marble precludes determination of the amount of displacement on the ductile thrust zones.

2.3 Thrust Sheets

Three crystalline thrust sheets are outlined by the high strain tectonite zones (Fig.5). They are between 20 and 40 km in strike length and 3-4 km thick. They dip to the southeast at about 30°, somewhat more steeply than the ductile thrust zones. They are lens shaped with the long axis of the lens striking NE-SW parallel to the strike of the CMBBTZ. Two of the thrust sheets, the Stafford and the Opeongo, are lithologically uniform. Consequently there is some correspondence between lithology and thrust sheet structure in the Pembroke BTZ.

The Stafford thrust sheet occurs at the base of the Pembroke thrust stack in the NE corner of the study area. Internal deformation of the thrust sheet is extremely heterogeneous, resulting in the preservation of lower strain pods within a network of higher strain anastomosing shear zones. Extension lineations plunge down the dip of the shear plane. At the scale of tens of metres or more the foliation of the gneisses is approximately planar. These features associated with discrete zones of anastomosing shear are typical of deformation zones which have experienced a degree of bulk inhomogeneous shortening (Bell, 1981).

The degree of heterogeneity of strain distribution decreases progressively with increasing bulk strain. The interior of the thrust sheet is dominated by low strain pods tens of metres long by several metres wide (Plate 5a), while the margins of the thrust sheet contain a few relict low strain pods, rarely larger than a metre, enveloped within relatively wide and planar zones of regular gneiss

Plate 5: Stafford thrust sheet and basal thrust zone

5a: Low strain ellipsoidal pod of amphibolite typical of the thrust sheet interior. Note the anastomosing zones well layered regular gneiss occurring at the margins of the pod. This regular gneiss is biotite rich compared to the amphibolite pod.

5b: Well-layering, nearly straight, gneisses of the the Stafford lower margin. These gneisses are more highly strained than those of the thrust sheet interior. Anastomosing shears have coalesced to form broader high strain bands surrounding minor relict low strain pods. Cross-cutting granite veins, pegmatites and biotite hornblende gneiss are beginning to be transposed as the strain increases.

5c: Rectilinear high strain straight gneiss of the basal ductile thrust zone underlying the Stafford thrust sheet. Progressive strain has attenuated and transposed the thrust sheet structures. Mafic compositional layers are biotite-hornblende gneiss, and leucocratic layers are quartzofeldspathic.

5d: Detail of amphibolite low strain pod, illustrating the homogeneity of composition of the amphibolite, which is likely derived from a gabbro.

(Plate 5b). When one passes from the highly strained margin of the thrust sheet into the underlying ductile thrust zone itself the regular gneiss is transposed into a homogeneously strained straight gneiss.(Plate 5c).

The strain gradient within the Stafford thrust sheet has preserved its igneous protolith in the low strain pods and facilitated observation of the derivation of banded gneiss from an originally homogeneous mafic rock. The low strain pods are composed of amphibolite and highly deformed metagabbro (Plate 5d,6c). Syntectonic granite sheets crosscut the host foliation at a low angle and localize alteration of the amphiboles to biotite. Selvedges between the granite and amphibolite are locally nearly 70% biotite.

The higher strain zones anastomosing around the amphibolite pods have a higher percentage of biotite than the low strain pods, to the extent that in places mafic bands in the regular gneiss locally approach the appearance of a biotite schist. The leucocratic bands of the high strain zone gneisses are composed of quartz, microcline and plagioclase, the same assemblage found in the granite sheets. These observations suggest that the biotite-hornblende mafic layers are the result of metasomatic alteration of amphibolite by potassic fluids associated with the granite sheets. The regular gneiss of the thrust sheet margin is the result of attenuation of the granite sheets and the biotite-hornblende mafic layers. Plates 6b-d illustrate the change in composition of the mafic material from the low strain pods to the higher strain gneiss. In the relict pods the rock is composed of hornblende and oligoclase in a recrystallized texture that locally

Plate 6: Compositions of high and low strain zones, Stafford thrust sheet

6a: Minor unaligned biotite (Bi) overgrowing hornblende (Hb) and oligoclase (Ol) of a low strain pod amphibolite. Crossed nicols, 10x.

6b: Strongly aligned biotite within biotite-rich mafic band of higher strain regular gneiss, typical of that which anastomoses around amphibolite pods. Crossed nicols, 10x.

6c: Relict igneous clinopyroxene (Cpx) within hornblende, from a low strain pod of amphibolite. Crossed nicols, 10x.

preserves a relict igneous appearance. Biotite has overgrown the hornblende and plagioclase in random orientations (Plate 6a). The regular gneiss which anastomoses around the pods shows an increase in biotite content to a maximum of 25%. This biotite is aligned in the gneissic foliation (Plate 6b). The highest strained gneiss in the ductile thrust zone is comprised of transposed granitoid and mafic biotite rich layers. These layers have an even greater proportion of biotite, and a decrease in hornblende content. The biotites are strongly aligned parallel to the shear plane. The increase in biotite content of the mafic layers correlates with the increasing degree of strain of the material. The biotite is progressively oriented as the regular gneiss is more highly strained.

Structurally above the Stafford thrust sheet is the lithologically distinct Opeongo thrust sheet. It is bounded above by marble tectonic melange, and is underlain by syenitic straight gneiss and marble melange. The sheet is dominantly composed of an alkali syenite gneiss, whose mafic phase is mostly augite (Plate 7a). With an increase in quartz it grades into a pink alkali granite. A locally important nepheline syenite is found at the upper margins of the thrust sheet. The Opeongo sheet is variably strained, ranging from nearly isotropic syenite and alkali granite to a strongly foliated syenite regular gneiss, indicating that the strain distribution within the thrust sheet is heterogeneous as it is within the Stafford thrust sheet.

The thrust sheet and its lower boundary of syenitic straight gneiss is cross-cut by SE dipping late syntectonic pyroxene syenite veins. Alignment of augite

Plate 7: Composition of Opeongo and Papineau thrust sheets

7a: Syenitic gneiss typical of the more highly strained margins of the Opeongo thrust sheet.

7b: Photomicrograph of quartzofeldspathic composition typical of the Papineau thrust sheet. The Papineau gneiss is made up of varying proportions of the quartz, plagioclase, orthoclase and biotite seen here. More mafic portions contain much greater concentrations of hornblende and biotite. Crossed nicols, 10x.

crystals in the feldspar matrix defines a weak foliation. The veins vary in thickness from several cm thick to 1 metre or more and their composition is very similar to that of the thrust sheet.

The Papineau thrust sheet is located at the base of the Pembroke thrust stack in the SW corner of the study area, and is underlain by quartzofeldspathic straight and porphyroclastic gneisses of the basal ductile thrust zone. Lacking the coherence of the Stafford and Opeongo thrust sheets, it was outlined solely on the basis of bounding ductile thrust zone distribution. While portions of the thrust sheet are composed of plagioclase, hornblende mafic gneisses, locally of a dioritic composition, the bulk of the thrust sheet is composed of quartzofeldspathic gneiss (Plate 7b). The straight gneiss of the thrust zone below the Papineau thrust sheet is locally very mafic in composition. However, due to poor exposure, it cannot be demonstrated that the intercalated felsic and mafic layers are derived from transposed mafic host gneiss and syntectonic granites as can be done with the Stafford thrust sheet. Although some of the features suggest that the Papineau thrust sheet may have a mafic origin, derivation from a very impure supracrustal rock or mafic rich granitoid cannot be ruled out for some portions of the thrust sheet. Nevertheless, it is interesting to note that the Papineau thrust sheet, which occurs along strike from the Stafford and at the same structural level, may have the same protolith.

The upper bound of the Papineau thrust sheet is difficult to establish. It was not included in the study area, but examination of maps of the area by

other workers (Hewitt, 1954; Lumbers, 1982; Breaks and Thivierge, 1985) suggests that alkalic and syenitic gneisses (termed the New Carlow Syenite Complex by Breaks and Thivierge), similar to those of the more strained portions of the Opeongo thrust sheet, occur above it. These may be a southwestward continuation of the Opeongo sheet. Carbonates correlative elsewhere with the marble tectonic melange may define the ductile thrust zone overlying the Papineau thrust sheet, and underlying another syenitic thrust sheet.

2.4 Kinematics of Deformation

2.4.1 Shear-sense indicators

It was not the aim of this study to determine the sense of shear of the imbricated sheets within the Pembroke area of the Ontario CMBBTZ, as this had already been documented by Hanmer and Ciezielski (1984). However, the more detailed study of the Pembroke BTZ outlined here has found a population of mechanically independent shear-sense indicators which are consistent with those reported by Hanmer and Ciezielski, and which document movement on portions of the thrust stack not examined in the 1984 reconnaissance. This assemblage of shear-sense indicators will be outlined here.

A mineral stretching lineation is observed within the thrust zones and thrust sheets (Fig.7). It is defined by the alignment of quartz rods, stretched feldspar aggregates and micaceous aggregates on the shear plane parallel foliation surfaces, and by the bisectors of sheath folds (Cobbold and Quinquis, 1980) (Plate

Figure 7 : Equal area stereoplot of extension lineations from the Pembroke area CMBBTZ. The downdip lineation is shallowly plunging to the SE with an average trend of 155° .

8a,b). It is taken to be indicative of the bulk finite extension direction as asymmetric extensional shears cut the shear foliation at right-angles to the lineation (Platt and Vissers, 1980). The lineation is shallowly plunging to the southeast, consistent with that observed within the CMBBTZ to the southeast, and indicates that the shear direction was northeast-southwest.

The sense of shear along the shear direction is outlined by an assemblage of macroscopic shear-sense indicators. Given the strongly annealed aspect of the gneisses comprising the ductile thrust zones it is not unexpected that microscopic shear-sense indicators are comparatively rare (Hanmer, 1988). Microscopic asymmetric extensional shears (shear band foliation) were observed in the paragneisses within the basal ductile thrust zone. However, the paragneisses are inclusions suspended within the marble melange and are no longer oriented with respect to the strain ellipsoid of the deformation. Thus their asymmetric extensional shears cannot be considered indicative of the kinematics of regional deformation.

The shear-sense indicators which are indicative of the kinematics of deformation include rotated stiff inclusions, back rotated foliation segments, macroscopic asymmetric extensional shears, and extended competent veins.

Rotated stiff inclusions: An example of a rotated stiff inclusion, a feldspar porphyroclast, is presented in Plate 8b. The asymmetry of such an inclusion is the result of differential rigid body rotation between the stiff inclusion and its mantle within a softer, more ductile matrix (Ghosh and Ramberg, 1976; Passchier and

Plate 8: Strain and kinematic features

8a: Sheath fold developed in thrust sheet gneisses. Viewed looking southeast the fold axis is parallel to the stretching lineation, indicating that the lineation is parallel to the direction of maximum finite extension.

8b: Rotated porphyroclast from the basal ductile thrust zone below the Papineau thrust sheet. Note the extended in-plane tails to the porphyroclast. Viewed looking northeast the sense of drag of the tails gives a sinistral or top-side to the northwest sense of shear. Porphyroclast is 1.5 inches in diameter. Large and small arrows indicate instantaneous quadrants of extension and compression respectively. Half arrows indicate sense of bulk shear.

8c: Mineral stretching lineation on XY section parallel foliation surface. The lineation is outlined by stretched aggregates of quartz, feldspar and hornblende. Viewed looking northwest, the lineation is shallowing plunging to the southeast, the arrow outlines the trend.

Simpson, 1986; Hanmer and Passchier, in press). The relative rotation rates of the body and mantle are a function of the strain rate ratio (Sr) and the inclusion's aspect ratio (Gosh and Ramberg, 1976; Hanmer, 1990). The shear sense of the porphyroclast in Plate 8c is derived from the sense of drag of its mantle, deformed into long drawn out tails. The tails extend in-plane from the inclusion and are parallel to the shear plane away from the inclusion. The deflection of the tails adjacent to the porphyroclast reflects the rotation of the porphyroclast, which in turn is a direct response to the vorticity of the shear (Hanmer, 1990). Plate 8c, oriented looking northeast, gives a topside to the northwest, sense of shear.

Back-rotated foliation segments: Back-rotated foliation segments or "foliation fish" were found within the basal thrust zone. They are elliptical in cross-section, contain internal foliation parallel to the long axis of the segment, and are consistently 5-10 degrees antithetically oblique to the shear plane of the deformation. Viewed looking northeast, the segments are back-rotated to the southeast. The back-rotation of a segment is the result of the amplification of an initially minor misorientation of the segments' anisotropy with respect to the shear plane (Hanmer, 1986). The population of foliation segments of above aspect observed in the area are consistently back rotated to the southeast indicating a sinistral sense of shear.

Asymmetric extensional shears: Asymmetric extensional shears (or shear band foliation) are observed within the porphyroclastic gneisses of the basal thrust

zone at the west end of the study area (Papineau Lake). Asymmetric extensional shears are a consequence of non-ideal shear along the plane of anisotropy. The shears are commonly oriented at about 20 degrees to the shear plane, and have a sense of slip consistent with that of the bulk shear plane (Platt and Vissers, 1980), although conjugate sets of shear do occur (Harris and Cobbold, 1985). The shears observed at Papineau Lake are oriented such that their sense of slip indicates that shear in the matrix is consistent with northwestward overthrusting.

Extended competent veins: Extension or boudinage of competent veins can be used to outline the direction of maximum finite extension (x) provided the vein has only just started to lose its rheological integrity. At this juncture the strain experienced by the necks of the boudins reflects the bulk flow within the matrix (Hanmer, 1984; Hanmer and Passchier, in prep). As the vein continues to extend "in-plane" its orientation then reflects the orientation of the direction of maximum instantaneous extension and consequently the sense of shear. Extended competent veins have been observed within the Opeongo thrust zone separating the Stafford and Papineau thrust sheets. Plate 9a is an example of an extended syenite pegmatite. Its orientation, dipping to the southeast (viewed looking northeast), indicates that the sense of shear of the bulk deformation in the surrounding matrix is topside to the northwest.

The examples from the assemblage of independent shear-sense indicators presented above all indicate that the westernmost and easternmost sections of the basal thrust zone (Papineau Lake and Pembroke), and the structurally higher

Plate 9: Thrust and extension kinematics

9a: Extended syenite pegmatite vein from the Opeongo ductile thrust zone. As the vein has just started to lose its competency it reflects the bulk shear within the surrounding matrix. Viewed looking northeast, the back-rotation of the boudin segment indicates a sinistral or topside to the northwest sense of shear. Large and small arrows indicate instantaneous quadrants of extension and compression respectively. Half arrows indicate sense of bulk shear.

9b: Extensional shear zone cross-cutting the thrust shear foliation at a high angle. A narrow pegmatite vein is intruded along the shear plane of the extensional shear. Viewed looking to the northeast the deflection and slight attenuation of the foliation as it enters the shear zone indicates a topside down to the southeast sense of shear. Basal ductile thrust zone, Killaloe.

9c: Granoblastic extensional shear cutting the basal ductile thrust zone below the Stafford thrust sheet. Viewed looking west the deflection and attenuation of the foliation into the shear zone gives a topside down sense of shear. The granoblastic nature of the shear and lack of retrogression of metamorphic facies adjacent to the shear zone indicate that it is late-syntectonic with respect to the upper amphibolite facies thrust deformation.

C

A

B

Opeongo thrust zone record northwestward overthrusting. These observations, combined with those made by Hanmer and Ciezielski (1984) illustrate that the Pembroke Thrust Stack was assembled as a consequence of northwest directed thrusting.

2.4.2 Asymmetric Folds

An ubiquitous population of asymmetric folds within the study area occurs with fold axes parallel to the SE plunging stretching lineation, and bearing a consistent "S" sense of asymmetry (Plate 10a-c). The orientation is constant regardless of the interlimb angle, be it open to nearly isoclinal. These folds deform the shear plane of the high strain zones and the "S" sense of asymmetry is the only type developed in the ductile thrust zones. I distinguish here between folds of the shear plane parallel foliation and those of discrete veins or dykes, commonly observed within the thrust sheets. The latter folds, of both "S" and 'Z' asymmetry, are not strictly indicative of the sense of shear associated with their deformation, as their present asymmetry and aspect may also be a function of the initial orientation of the folded veins and/or dykes with respect to the principle strain axes (Hanmer and Passchier, in press). However, the regionally consistent "S" folds of the high strain zones fold the shear plane (X-Y plane) parallel foliation, and can be considered to be directly indicative of the kinematics of the deformation.

Folds of mylonitic foliation whose fold axes are parallel to the stretching lineation have been documented in many shear zones. Bell and Hammond (1984)

Plate 10: Ductile thrust zone lineation parallel folds

10a-c: Folds of the shear plane parallel foliation. The fold axes are nearly parallel to the southeast plunging extension lineation, with a consistent "S" asymmetry viewed down the lineation. Viewed looking east or east-south-east in each case.

10a: Tight to isoclinal folds, basal ductile thrust zone Pembroke.

10b: Fold of moderate tightness, basal ductile thrust zone, south of Killaloe.

10c: Fold of moderate to open tightness, basal ductile thrust zone, west of Pembroke.

model their development as the result of anastomosing foliation adjacent to ellipsoidal pods folding under a new increment of strain (Fig.8). While this may be a satisfactory explanation for some folds which are adjacent to such pods within the thrust sheets, it does not apply to the folds of the shear plane parallel foliation and does not account for the single sense of asymmetry occurring in these folds.

Considering that linear elements rotate towards the finite extension direction with progressive strain, and that a fold axis is a linear element, it could be postulated that the present orientation of the asymmetric southeast plunging folds is the result of progressive deformation (Skjernaa, 1979). However, this model of development for the folds does not account for the orientation of the open folds, as the strain required to rotate a fold axis initially at a high angle to the lineation into the plane of the shear zone would tend to make the fold isoclinal (Sanderson, 1973; Cobbold and Quinquis, 1980).

The "S" folds could be the result of two shear couples acting nearly orthogonal to each other (a situation not unique to this study, see Coward and Kim, 1981; Coward and Potts, 1983; Ridley, 1986).

Coward and Potts (1983) have presented a model for the development of two synchronous shear couples oriented at a high angle to each other, which involves combined thrust and wrench shear adjacent to a lateral ramp (Fig.9). Their modelling, along with that of Ridley and Casey (1990), suggests that asymmetric folds with fold axes parallel to the stretching lineation will be

Figure 8: a. Diagram of an ellipsoidal pod surrounded by anastomosing mylonitic foliation. b. Diagram of sheath fold produced by imposing new zone of inhomogeneous shear on the pod. Note that the fold has a sheath geometry *without significant rotation of the fold axis*. The X-axis of the strain ellipsoid is approximately parallel to the long axis of the pod, accordingly the relatively *open* folds at the margins of the pod have fold axes parallel to the X-axis. c. Attenuation and tightening of the sheath fold occurs, similarly tightening the aspect of the X-axis (= extension lineation) parallel folds. See text for discussion.

Extension lineation

d. Sketch of an open fold, such as that formed on the flank of the ellipsoidal pod in b. Note the parallelism of the fold axis with the extension lineation on the folded mylonitic foliation. Figures a-d modified after Bell and Hammond, 1984.

Figure 9: a) Diagram of a thrust plane illustrating the relative finite strains (schematic strain ellipses) developed between the slipped and unslipped regions in zones of combined thrust and wrench shear. Modified after Ridley, 1986. b) Schematic diagram of folds with hinges parallel to the stretching lineation, developed as a result of combined layer parallel (thrust) shear and wrench shear. These could be expected to form in the zones of sinistral and dextral wrench shear outlined in a). Modified after Coward and Potts, 1983.

produced. At Haliburton, where a significant change in trend of the boundary could indicate the presence of a lateral ramp to the southeast, the model fails as a southwest side ramp would produce "Z" folds looking down the extension lineation. All the lineation parallel folds at Haliburton are "S" sense.

Several problems are encountered when trying to apply this model to the Pembroke CMBBTZ. 1) There are no structural features at Pembroke to suggest the presence of a lateral ramp on either side of the thrust stack, a necessary condition for combined thrust-wrench shear. 2) The Ridley-Casey model of fold development in this regime implies rotation of the fold axes into parallelism with the lineation, after a high degree of strain has been experienced. The open interlimb angles of the "S" folds preclude this as outlined previously, and consequently this regional fold set could not be the result of a combined wrench/thrust shear.

An alternative model (Hanmer, 1988) relates the regional orientation of the fold axes and consistent fold asymmetry to a component of northeastward thrusting superimposed on the main northwestward movement (due to the influence of boundary conditions outside the area of consideration). This northeastward shear couple is most probably a movement subordinate to the the main northwestward motion. The occurrence of near isoclinal and open "S" folds and the absence of deflection of the stretching lineation would seem to favour nearly coeval movement of the two thrust regimes.

2.4.3 Extensional shearing

Within the immediate footwall to the basal thrust zone and the lower levels of the Pembroke thrust stack minor zones of shear occur, often with pegmatite intruded along the shear plane. These granoblastic shears dip to the southeast and transect the foliation of the footwall and thrust zone gneisses at greater than 30°. They are, however, at upper amphibolite facies metamorphic grade similar to the gneisses they cross and are granoblastic in texture. These features indicate that they are not post-tectonic structures, but are late syntectonic. The deflection of the foliation into the shear plane gives a topside to the southeast or extensional sense of shear (Plate 9c,d). These late syntectonic extensional shears have been attributed to orogenic collapse resulting from overthickening (Nadeau, 1984). They may be a result of extension in the Pembroke Thrust Stack and its footwall due to thrusting and continued loading of the hangingwall.

2.5 Metamorphic Conditions of Thrusting

The metamorphic grade of rocks in the Pembroke region CMBBTZ is upper amphibolite facies. This is determined from the mineral assemblages observed in the following lithologies;

Quartzofeldspathic rocks:

biotite-hornblende- 2 feldspars-quartz +/- almandine +/- diopside

Mafic rocks:

epidote-titanite-oligoclase-hornblende +/- almandine (Plate 11a)

Metapelites:

quartz-2 feldspars-almandine-biotite- sillimanite +/- cordierite +/- kyanite

(Plate 11b)

Marbles:

quartz-diopside-calcite

Upper amphibolite facies overthrusting is observed throughout the CMBBTZ. However, at the basal ductile thrust zone the mafic horizons are locally greasy-green in colour, a characteristic cast seen in granulite grade rocks. Thin section examination of material from within the basal thrust failed to find orthopyroxene, a key mineral of granulite grade rocks. Samples from the footwall immediately below the basal thrust zone contain relict hypersthene, indicating that these rocks have undergone retrograde metamorphism from granulite to upper amphibolite grade. This is interpreted to be the result of upper amphibolite grade thrusting on the basal thrust zone.

A particularly ferroaluminous supracrustal rock is found in the western section of the study area near Centreview, Ontario. This rock contains cordierite-gedrite-orthopyroxene-sillimanite-quartz-plagioclase-biotite, with the gedrite-cordierite and hypersthene occurring within discrete bands (Plate 11c,d). Metastable sillimanite, and spinel have been reported to occur in this rock within the cordierite (Miller, 1984; Breaks and Thivierge, 1985). Sapphirine after kyanite is reported to occur within some garnets. Upper amphibolite facies

cordierite-almandine-kyanite bearing metapelites, correlative with this rock, are found along strike within the basal thrust zone (Fig.20). The orthopyroxene bearing Centreview assemblage, apparently indicative of granulite facies conditions, was probably controlled by a local bulk composition, and is not in itself considered indicative of the regional metamorphic grade.

These highly aluminous and locally ferro-aluminous supracrustal rocks are lithologically correlative with a cordierite-gedrite rock found in the Haliburton-Bancroft area of the CMBBTZ (Hanmer, 1988; Lal and Moorehouse, 1969). The Haliburton supracrustal rock contains the synfoliation assemblage sillimanite-garnet-cordierite-biotite-2 feldspars-quartz and a postfoliation assemblage gedrite-cordierite-kyanite-biotite-chlorite-garnet. Hanmer interpreted this assemblage as representing minimum conditions of 650°C at 6 kbars. The regional upper amphibolite facies assemblage in the Pembroke area metapelites is therefore consistent with the P-T conditions cited for the lithologically correlative Haliburton metapelites.

Plate 11: Metamorphic assemblages of the Pembroke CMBBTZ

- 11a: Photomicrograph of recrystallized amphibolite, Stafford thrust sheet. Assemblage is hornblende (Hb)-oligoclase (Ol)-titanite (Ti) +/- epidote (not shown). Titanite rims iron oxide (black). Plane polarized light, 10x.
- 11b: Photomicrograph of metapelite, illustrating common pelitic synfoliation metamorphic assemblage, sillimanite (Si)-almandine (A)-biotite (Bi)- 2 feldspar - quartz (white matrix). Plane polarized light, 10x.
- 11cd: Photomicrograph of cordierite-gedrite rock, illustrating its metamorphic assemblage. 11c: Postfoliation assemblage includes cordierite (Co)- gedrite (Ge)- and garnet (Ga). Crossed nicols, 25x. 11d: Mafic portion of Centreview cordierite-gedrite rock illustrating hypersthene (H)-garnet -cordierite bands. Crossed nicols, 25x.

3.0 GEOCHRONOLOGY

3.1 Introduction

Recent tectonometamorphic studies have recognised imbricate thrust slices bounded by ductile shear zones within the strongly deformed southwest Grenville Province gneisses (Davidson, 1984; Hanmer, 1988; McEachern, 1990). As ductile deformation at the mid-crustal levels presently exposed rarely preserves recognisable stratigraphy, precise U-Pb dating of zircon and other accessory minerals is the tool best employed to decipher the tectonic history and timing of events which comprise the Grenville Orogenic Cycle. This paper reports on new U-Pb zircon dating from the Central Metasedimentary Belt Boundary Thrust Zone (CMBBTZ) which provides new constraints on the timing of tectonic evolution of the southwestern Ontario Grenville.

The CMBBTZ is a crustal scale shear zone separating the amphibolite to granulite grade gneisses of the Central Gneiss Belt (CGB) from the overlying Central Metasedimentary Belt (CMB) (Fig.10). The quartzofeldspathic gneisses of the CGB have been interpreted as an assemblage of thrust bounded domains (Davidson, 1986; Nadeau, 1988). These domains are comprised of reworked juvenile North American margin (Hoffman, 1989; Nadeau and Van Breemen, in press). Shear-sense indicators in the ductile thrust zones bounding the sheets indicate northwest directed overthrusting throughout the stack. U-Pb zircon dating has placed the earliest recorded movement on the lowest structural level at

Figure 10: Subdivisions of the Central Metasedimentary Belt (CMB) and structural setting of the CMB Boundary Thrust Zone (CMBBTZ). Box outlines the area of Figure 11. BT = Bancroft terrane, H = Haliburton thrust stack, P = Pembroke thrust stack, CGB = Central Gneiss Belt, BSZ = Bancroft shear zone, HCA = Harvey-Cardiff arch.

1160 Ma (Van Breemen et al, 1986) and defines a southeastward migration with time of the northwest limit of thrusting (Nadeau, 1990).

The CMB is lithologically variable and is comprised of 3 lithometamorphic terranes; the Bancroft, Elzevir and Frontenac terranes. The Bancroft terrane has been characterized by the association of middle-to upper-amphibolite orthogneisses with nepheline gneisses and marbles of the (1280-1250 Ma) Grenville Supergroup (Moore, 1986). The CMBBTZ is coincident with the Bancroft terrane throughout its length, and the boundary of the Elzevir and Bancroft terranes marks the upper limit of the CMBBTZ in its central and northeastern portions. The Elzevir terrane is noted for its lower metamorphic grade (lower-amphibolite to greenschist) and interlayered metavolcanics and supracrustals. Stratigraphic relationships preserved in the Elzevir terrane have led workers to divide the Grenville orogeny into two phases, a 1220-1250 Ma plutonic stage termed the Elzevirian orogeny (Moore and Thompson, 1980), and a 1090-1050 Ma culminating collisional event characterized by high-grade regional metamorphism and deformation. (Easton, 1986).

The CMBBTZ is comprised of upper-amphibolite grade crystalline thrust sheets separated by shallowly southeast dipping quartzofeldspathic and carbonate ductile thrust zones (Hanmer and Ciezielski, 1984; Hanmer, 1988; McEachern, 1990). The structural characteristics of the CMBBTZ are remarkably uniform throughout its exposure in Ontario. Shear-sense indicators within the CMBBTZ define northwest directed thrusting with a subordinate northeast shear couple.

The base of the CMBBTZ was apparently localized by highly aluminous supracrustal rocks (locally cordierite-gedrite bearing), discontinuously preserved along the base of the zone for over 250 km.

Previous U-Pb geochronologic study of the CMBBTZ found that movement within the thrust stack at Haliburton, Ontario (Fig.15) younged upwards in an apparent continuation of the sequence of thrusting within the CGB (Van Breemen and Hanmer, 1986). Field evidence indicates that northwest directed thrusting of the Haliburton thrust stack was out-of-sequence. The timing of thrusting at the base of the CMBBTZ at Haliburton was dated as approximately 1060 Ma (U-Pb on zircon). Movement on the highest structural levels near Bancroft occurred as late as 990 Ma.

This chapter presents U-Pb zircon geochronology data from the northeast region of the CMBBTZ near Pembroke, Ontario (Fig.11). A recent study in this region has delimited three thrust sheets bounded by quartzofeldspathic tectonites and marble tectonic melange (McEachern, 1990). At least two structural levels are recognized; the Stafford and Papineau thrust sheets are situated within the lowest structural level, while the Opeongo thrust sheet overrides them both. This assemblage of structures is herein termed the Pembroke thrust stack. Samples of syntectonic pegmatites and granitoid sheets have been collected from along the base of the Pembroke thrust stack and at higher structural levels to determine the timing of thrusting on the Pembroke area CMBBTZ. Comparison of the ages of movement on the Pembroke and Haliburton thrust stacks, as well as ages of

Figure 11: Map of the distribution of ductile thrust zone tectonites and thrust sheets of the Pembroke area Central Metasedimentary Belt Boundary Thrust Zone (CMBBTZ). Thrust sheets are named. All contacts are approximate to inferred. Stars mark sampling sites of numbered U-Pb geochronology samples. Geology by the author, except for the upper bound of the Opeongo thrust sheet, modified from Lumbers, 1982. CGB=Central Gneiss Belt, CMB=Central Metasedimentary Belt.

deformation in the CMB and CGB constrain a model for the development of the southwest Grenville orogenic cycle, presented in Chapter 4.

3.2 Sampling and Analytical Procedure

50 kg samples of fresh material were obtained through sampling from the interior of dykes and sheets, avoiding weathered faces and altered zones.

Heavy mineral separates of accessory minerals were prepared by use of a Roger's Table (Tm) and heavy liquid floatation. The accessory minerals were magnetically separated using a Frantz TM LB-1 separator.

To further minimize the effects of peripheral Pb loss all fractions (with the exception of sample J1-89) were strongly air abraded until terminations and sharp faces were removed (Krogh, 1982). Polished grain mounts were made for all samples, where possible. The polished mounts were etched in concentrated HF vapour to emphasize internal structure, and were examined with a scanning electron microscope.

Preparation and analytical techniques follow those outlined in Parrish et al. (1987). Mass spectrometry, data reduction and error propagation techniques are outlined in Roddick et al. (1987). Linear regression analysis followed a modified form of York (1969). Two sigma uncertainties in ratios $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ are 0.5% and 0.15% in $^{207}\text{Pb}/^{206}\text{Pb}$. The isotopic data are presented in Table 1, and plotted in Figures 12-14.

3.3 Age Determination of Syntectonic Pegmatites and Granite Sheets

Syntectonic pegmatites and granite sheets in varying states of strain are found throughout the Pembroke thrust stack. They are commonly small bodies no larger than one metre thick. As a group, the suite of granite pegmatites and sheets display features which characterize them as syntectonic. Pre-tectonic bodies are rotated toward the extension direction and transposed with the host gneisses. These are strongly sheared and disaggregated. Syntectonic bodies are demonstrably strained, with a strongly developed internal foliation and stretching lineation. They bear evidence of having been rotated toward the extension direction but remain discordant with respect to the host gneiss foliation. Late-syntectonic bodies bear less evidence of strain due to their shorter residence time within the deforming shear zone. They have weakly developed foliations and crosscut the host gneiss foliation. Nevertheless, their commonly boudinaged and/or folded aspect indicates that they are late-syntectonic. Individual examples of some or all of these strain states can be present within a single outcrop.

All representatives of the suite of syntectonic pegmatites and granite sheets are presently oriented such that they dip to the southeast. This ubiquitous orientation, combined with the observation of deflection of host gneiss foliation at the margins of the rotating bodies indicates that the suite was emplaced during conditions of regional northwestward overthrusting. Determination of the age of crystallization of the syntectonic bodies was undertaken to constrain the timing of northwestward thrusting within the Pembroke thrust stack. Individual dykes or

sheets selected for analysis were restricted to those within the bounding belts of highest strain tectonites, to ensure that the samples would be representative of conditions of thrusting during the last increment of finite high strain.

Four of the samples studied were selected from several localities along strike within the basal thrust zone tectonites. This lowest thrust zone underlies the Stafford and Papineau thrust sheets. Two of these samples are representative of syntectonic pegmatites and two are late-syntectonic granite sheets. The fifth sample was obtained from a late syntectonic pegmatite within the ductile thrust zone separating the Papineau and the overlying Opeongo thrust sheets in order to ascertain what variation there was in the timing of thrusting on higher structural levels.

(1) Syntectonic pegmatite, basal thrust zone, Killaloe, Ont. (K1-89)

This syntectonic pegmatite crosscuts southeast dipping straight gneisses of the basal ductile thrust zone underlying the Stafford thrust sheet at its eastern end (Fig.11). It is a hornblende granite pegmatite with a very well developed internal foliation and minor quartz ribbons (Plate 12a). Its discordancy with the straight gneiss tectonites and its own strong internal fabric attest to the syntectonic emplacement of this pegmatite dyke. Its age of crystallization constrains the timing of northwest directed thrusting at the base of the Pembroke thrust stack.

Nonmagnetic zircons from this sample are euhedral to subhedral. The

Figure 12a: Concordia plot of isotopic ratios of zircon fractions from sample K1. Upper and lower intercepts are indicated. See text for details.

Figure 12b: Concordia plot of isotopic ratios of zircon fractions from sample K2. Upper and lower intercepts are indicated. See text for details.

Plate 12: Geochronology sampling sites K1 and K2

12a: Sample K1 syntectonic granite pegmatite, basal ductile thrust zone, Killaloe. This strained, strongly foliated and lineated granite cross cuts darker red straight gneisses of the basal ductile thrust zone. Viewed looking southwest.

12b: Sample K2 syntectonic granite pegmatite, basal ductile thrust zone, Killaloe. The strongly foliated and lineated granite, similar in composition to sample K1, cross cuts the straight gneisses of the basal thrust zone. Note its transection of a fold in the straight gneiss, lower left, and the large angles between the main body and its intrusive apophyses, which would be transposed were the body pre-tectonic. Viewed looking east.

euohedral crystals have well developed bipyrarnid terminations and prism facets which are very slightly rounded in most cases. Two dominant morphologies are present, stubby flat prisms and thin tabular grains (aspect ratio 1:1:10). Synnuesis twins of both morphologies are found, but are most common among the tabular grains.

The stubby prisms are clear and colourless and lack strong internal zoning consistent with their low U content. The prism facets are commonly very slightly rounded. The thin tabular, needle-like grains constituted the smaller population by volume. They are commonly fractured, cloudy and orange coloured. These metamict zircons have very high U contents (1000 ppm U, + 149 μm), but were selected for one analysis as needle-shaped prisms were thought less likely to contain cores. 3 fractions of the stubby prisms were analyzed as 2 single grains and a grain pair. A fourth fraction of the damaged tabular grains consisted of a pair of grains.

The zircon data for this sample are plotted in Figure 12a. The strongly metamict tabular fraction is very strongly discordant, and accordingly was disregarded for the age determination. 2 of the 3 prism fractions are slightly discordant and plot close to concordia. A third is somewhat more discordant and plots farther down concordia. A Yorkfit linear regression through the 3 more concordant points yields an upper intercept of 1180 +60/-18 Ma and a lower intercept of 963 +/-130 Ma. Considering the slight rounding of the prism facets the discordance of the points is most probably the result of mixing between the

igneous crystallization age and a younger thin overgrowth. The large uncertainty on the lower intercept encompasses the timing of upper amphibolite facies metamorphism in the CMBBTZ (ca 1060 Ma, Metzger et al, 1990), consequently the slight rounding is most probably a metamorphic overgrowth. The upper intercept age of $1180 \pm 60/-11$ Ma is considered to be the age of igneous crystallization of this syntectonic pegmatite.

(2) Syntectonic pegmatite, basal thrust zone, Killaloe, Ont. (K2-89)

The second syntectonic granite pegmatite from the basal ductile thrust zone at Killaloe is also highly strained and sheared (Fig.11, Plate 12b). It has a strongly developed foliation and mineral stretching lineation nearly concordant with those of its host gneiss tectonites. Intrusive offshoots of the main body strongly crosscut the tectonite foliation but are themselves internally foliated. The pegmatite truncates folded gneissic layering. These features demonstrate its syntectonic intrusive relationship. The age of this body also constrains the time of early northwest directed thrusting.

Nonmagnetic zircons from this sample are euhedral stubby to elongate flat prisms with slightly rounded bipyramid terminations. Synnuesis twins of these grains were observed. The crystals are very clear, colourless and largely inclusion and fracture free. The most elongate and well terminated grains were selected for analysis. Polished and strongly etched mounts revealed no cores and showed regular igneous zonation in the higher U grains (Plate 13). A thin low U rim was

Plate 13: Scanning electron microscope images of K2 zircons

13a: SEM photograph of polished and strongly etched slightly elongate zircon with rounded terminations. Note euhedral igneous U zonation dominating the bulk of the grain, and the thin resorbed zones and rims at the grain margins.

13b: SEM photograph of a polished and strongly etched stubby slightly rounded zircon from K2. The well etched portion to the right reveals a very well developed igneous zonation over the bulk of the grain, with a thin low U (light coloured) rim truncating the zonation and rounding the tip. The rim is interpreted to be a metamorphic overgrowth on the original igneous crystallized grain.

Plate 14: Metamorphic rims on igneous K2 zircons

14a and b: SEM photographs of polished and etched K2 zircons illustrating the thin metamorphic low U rim mantling the grains.

14a: Igneous internal zonation of a stubby grain is transected by the overgrowth which also rounds the terminations.

14b: Elongate slightly tabular grains illustrating the bright low U overgrowth on the grain tips.

A

4400 2000 WE 20MM 00000 0 00004

B

4400 2000 WE 20MM 00000 0 00004

2 of/de 2

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

observed on the grains (Plate 14). The three fractions of single grains analyzed were abraded for 13 hours.

The data for the 3 fractions analyzed from this sample are plotted in Figure 12b. Two of the fractions meet concordia within analytical error, the third is slightly more discordant. A Yorkfit linear regression through these 3 fractions yields an upper intercept of $1189 \pm 35/-11$ Ma and a lower intercept of $1016 \pm 95/-116$ Ma (MSWD = 0.01). Given the presence of a low uranium rim on these grains the slight discordancy of the data is interpreted to be the result of mixing between the age of the upper intercept and a small amount of metamorphic overgrowth generated somewhere between 1100 and 1000 Ma. The upper intercept age of $1189 \pm 35/-11$ Ma is considered to be the age of crystallization of this syntectonic pegmatite.

(3) Late-syntectonic granite vein, basal thrust zone, Pembroke, Ont., (CR1-89)

This late biotite-hornblende granite vein cross-cuts southeast dipping straight gneiss tectonites underlying the Stafford thrust sheet on its eastern end (Fig.11). The vein is well foliated but parallel sided (Plate 15a). Other veins of the same composition and strain state are weakly boudinaged. These features indicate late-syntectonic emplacement of this granite vein. Its age of crystallization determines the timing of late-syntectonic northwestward thrusting on the basal thrust zone of the most easterly portion of the Ontario CMBBTZ.

Nonmagnetic zircons from this sample are markedly smaller than those of

the Killaloe pegmatites (-105 + 74 μm fraction is the largest). These small grains comprise two morphologies; euhedral tabular grains and a larger population of smaller subhedral to irregular grains. Synnuesis twins and multiple twins are very common (Plate 15b-d). Close examination of the multiple twins (under the scanning electron microscope) reveals that they are composed of individual grains of often subhedral to irregular shape which have been sutured together (Plate 16). The population of small subhedral and irregular grains is apparently made up of individual grains from multiple twins broken during crushing. The euhedral tabular grains are very clear, colourless, and inclusion and fracture free.

Etched mounts of the subhedral grains and the multiple and single twins showed inner regions of clear igneous zonation which pass outward into zones of similar but discordant zonation. This discordant zonation is characterized by repeated internal truncation of various zones (Plates 16,17). Zonation of this type has been observed in zircons from late-syntectonic veins in the CMBBTZ to the southwest, and has been interpreted to be the result of growth in a dynamic crystal mush (van Breemen and Hanmer, 1986). The apparent welded margins and truncation of facets of the multiple twins suggests that the discordant zonation in the crystals is the result of a resorption and/or pressure solution process which sutures individual grains together. The relatively fragile sutures are then easily broken, during movement in the granitic fluid, freeing the irregularly faceted grains to reweld to other aggregates. This process is repeated to produce the discordant internal zonation and subhedral morphology of the grains. The most

Plate 15: Geochronology sampling site for CR1

15a: Sample CR1 late syntectonic granite vein (red-brown) shallowly cross-cuts the basal ductile thrust zone foliation, Pembroke. The foliated vein is one of a set of identical composition which are slightly boudinaged and climb to the northwest. Viewed looking northeast.

15b: Sample CR1 zircon aggregates within the intact rock. Note triple junction of sutured aggregate. Plane polarized light, 10x.

15c,d: Separated multiple zircon aggregates which survived crushing. Note the fusing of individual grains not only along prism facets. Aggregates are comprised of up to 10 or more individual crystals. Plane polarized light, aggregates are 100-200 μm .

Plate 16: Scanning electron microscope images of CR1 zircons

16a: SEM photograph of polished and etched twin pair showing highly discordant U zonation, with truncations by successive layers. Note that there is no continuity between the zonation of the two grains indicating they evolved separately.

16b: SEM photograph of polished and etched zircon, separated from an aggregate. Note the outer discordant U zonation surrounding euhedral internal zonation. Successive discordant layers appear to partially resorb older zircon.

Plate 17: Scanning electron microscope images of CR1 twins

17a: Polished and etched zircon pair from an aggregate which did not completely survive polishing and grinding of the mount. Note the discordant truncations between U zonation surrounding a more euhedrally zoned interior. The contact between the two crystals truncates zonation in both grains, between which there is no common rim or zonation.

17b: Polished and etched zircon pair from a multigrain aggregate broken during polishing and grinding of the mount. As in 17a note the discordant and truncated U zonation surrounding an euhedrally zoned interior, and the mutual truncation of facets where the crystals are joined. Hazy trapezoidal zone on the lower left of the small grain is zircon from a third crystal removed during polishing. The truncation of the layering of the grains seen here and in 17a is interpreted to be the result of pressure solution and or resorption suturing the grains together to form the aggregate. During shearing, as the syntectonic body is intruded into the ductile thrust zone, these relatively weaker sutures break apart. When a new layer of zircon is precipitated on the grain successive discordant layering results

equidimensional grains with the highest aspect ratio were selected for analysis. Three fractions of multiple grains were analyzed.

The data points from the fractions analyzed are plotted in Figure 13a. They are clustered near concordia, all less than 1.5% discordant. Fraction A is concordant within analytical error, however the analytical error is unusually large owing to the small amount of sample analyzed. The slight discordance of the points is most likely the result of a small amount of recent lead loss. A Yorkfit linear regression through the points with a lower intercept of 200 Ma yields an upper intercept of $1053 \pm 1.9-1.9$ Ma (MSWD = 0.09). Increasing the lower intercept to 500 Ma does not significantly increase the upper intercept. An age of 1053 ± 3 Ma is considered to be the age of crystallization of this late syntectonic pegmatite.

(4) Late-syntectonic pegmatite dyke, basal thrust zone, Papineau Lake, Ontario, (P1-89)

This late granitoid dyke strongly transects porphyroclastic gneiss tectonites of the basal thrust zone at the western limit of the study area (Fig.11). The dyke is foliated but partially attenuated owing to its intrusion late in the deformation (Plate 18a). Its age of crystallization constrains timing of late syntectonic northwestward thrusting on the central portion of the Ontario CMBBTZ.

Nonmagnetic zircons from this sample comprised several morphologic populations, one of which had clear cores and rims and was accordingly avoided

Figure 13a: Concordia plot of isotopic ratios of zircon fractions from sample CR1. Upper and lower intercepts are indicated. See text for details.

Figure 13b: Concordia plot of isotopic ratios of zircon fractions from sample P1. Upper and lower intercepts are indicated. See text for details.

Plate 18: Geochronology sampling sites of samples P1/J1

a: Sampling site of sample P1 pink granite pegmatite, which crosscuts porphyroclastic gneiss tectonites of the basal ductile thrust zone, Papineau Lake. This late-syntectonic dyke is well foliated but parallel-sided.

b: Sampling site of sample J1 syenite pegmatite dyke, Opeongo ductile thrust zone. This coarse slightly foliated dyke crosscuts syenitic straight gneisses of an intermediate structural level thrust zone. Its boudinaged segments are slightly back-rotated down to the southeast, confirming its late-syntectonic intrusion during northwestward thrusting.

for analysis. The zircons chosen for analysis are large well terminated fragments of prismatic zircons. They are clear, inclusion-free and lack cores. 3 fractions were analyzed. One fraction constituted a single large fragment, while the other 2 fractions were made up of 2 smaller euhedral fragments.

The zircon data from this sample are plotted in Figure 13b. Two fractions, A and B, overlap. They are less than 0.7% discordant, while the third fraction C is very slightly more discordant. The best estimate for the age of this sample is found from a Yorkfit linear regression through the points. This yields an upper intercept of $1056 \pm 20/-3$ Ma and a lower intercept of 550 Ma. The relatively large uncertainty of the upper intercept is a function of the overlapping of two fractions. The upper intercept age of ca. 1056 Ma is interpreted to be the age of crystallization of this late-syntectonic pegmatite.

(5) Late-syntectonic syenite pegmatite, lower ductile thrust zone, Opeongo thrust sheet, (J1-89).

This late-syntectonic augite-syenite pegmatite vein transects syenitic straight gneiss of the ductile thrust zone at the base of the Opeongo thrust sheet (Fig.11). This vein is extended in-plane and boudinaged with a slight back rotation of the boudins (Plate 18b). It reflects the direction of maximum instantaneous extension in the surrounding tectonite and so indicates that northwest directed thrusting was taking place at the time of its emplacement. Its age of crystallization reflects the timing of latest syntectonic thrusting on a higher structural level of the Pembroke

thrust stack.

Very little zircon was recovered from this sample, however two morphologic populations were present in the non-magnetic fraction, large well-terminated stubby fragments, and much smaller rounded tabular grains. The fragments are colourless to pale orange coloured with no internal zonation and minor fractures. Two fractions of the fragmented grains and a third of the tabular grains were analyzed. The fractions were not air abraded in order to avoid losing material.

The zircon data for this sample, plotted in Figure 14, show two groups of considerably different ages. The two fractions of well faceted zircon fragments plot near concordia ca 1000 Ma, and are less than 1.5% discordant. The third fraction, consisting of the slightly rounded tabular grain plots much higher up concordia. It has a 207/206 age of 1083 Ma. Given the rounded nature of the tabular grains, their different morphology and much smaller size compared to the large prismatic fragments the third fraction is likely inherited zircon entrained within the syenite pegmatite. The two younger fractions of coarse zircon fragments are considered to be indicative of the age of the pegmatite itself. The slight discordance of these unabraded fractions is most probably due to a small amount of recent surface lead loss. A Yorkfit linear regression through the data points with a lower intercept of 200 Ma yields an upper intercept of 1002 ± 1 Ma (MSWD = 0.75). Increasing lower intercept to 500 Ma yields 1007 ± 2 Ma (MSWD = 0.14). If the 207/206 age of the fractions are taken as a minimum age

Figure 14: Concordia plot of isotopic ratios of zircon fractions from sample J1. Fraction B is inherited. Upper intercept through fractions A and C represents age of crystallization of the pegmatite. See text for details.

(998 Ma) and the maximum uncertainty on the 500 Ma regression is taken as the maximum age (1009 Ma) then the best estimate for the age of crystallization of this pegmatite is $1002 \pm 7/-4$ Ma.

3.4 Discussion of Geochronologic Results

The analytical data for samples 1-5 are summarized in Table 1, new age determinations are summarized in Table 2. A discussion of the implications of the ages of the syn- and late-syntectonic pegmatites is presented here.

Assembly of the Pembroke thrust stack and Ontario CMBBTZ

The data of samples 1 through 4 show clear evidence for two main phases of syntectonic thrusting on the basal thrust zone of the Pembroke thrust stack, an earlier phase ca. 1180 Ma, and a later event ca. 1055 Ma. The younger age correlates within error with ages of thrusting of 1060 ± 6 Ma and 1065 ± 15 Ma from syntectonic granite veins near the base of the Haliburton area CMBBTZ (Van Breemen and Hanmer, 1986).

Figure 15 shows the distribution of ca. 1060 Ma late-syntectonic samples obtained from the basal part of the CMBBTZ. Ages of ca. 1060 Ma syntectonic thrusting (including the ages obtained during this study) are dispersed from the easternmost margin of the CMBBTZ (sample 3) to the southwestern end near Haliburton (Hawk Lake granite veins, van Breemen and Hanmer, 1984). Thus an age of ca. 1060 Ma has been obtained from late-syntectonic veins along the entire

TABLE 1: U-Pb ANALYTICAL DATA

Fraction ¹	Wt. mg	U ppm	Pb ^a ppm	$\frac{206\text{Pb}}{204\text{Pb}}$ ^b	Pb ^c pg	^{208}Pb %	$\frac{206\text{Pb}}{238\text{U}}$ ^a	$\frac{207\text{Pb}}{235\text{U}}$ ^c	Corr. Coeff.	$\frac{207\text{Pb}}{206\text{Pb}}$ ^c	$^{207}\text{Pb}/^{206}\text{Pb}$ Age (Ma)
<u>SM-J1-89</u>											
A	0.014	747	122	5234	21	6.2	0.1664 ± 0.09%	1.664 ± 0.10%	0.95	0.07253 ± 0.03%	1000.8 ± 1.3
B	0.013	366	65	2689	20	5.5	0.1808 ± 0.09%	1.894 ± 0.10%	0.93	0.07555 ± 0.04%	1083.3 ± 1.6
C	0.018	694	113	3625	36	5.6	0.1661 ± 0.09%	1.661 ± 0.10%	0.94	0.07249 ± 0.04%	999.7 ± 1.5
<u>SM-K2-89</u>											
A	0.018	160	33	3677	10	10.2	0.200354 ± 0.09%	2.19015 ± 0.10%	0.91	0.07928 ± 0.04%	1179.2 ± 1.7
B	0.011	222	44	2863	10	8.4	0.196705 ± 0.09%	2.13253 ± 0.11%	0.95	0.07863 ± 0.04%	1162.8 ± 1.4
C	0.009	146	30	1258	13	9.4	0.199455 ± 0.10%	2.17633 ± 0.12%	0.90	0.07914 ± 0.05%	1175.6 ± 2.1
<u>SM-CR1-89</u>											
A	0.002	159	27	436	8	4.7	0.176486 ± 0.25%	1.81672 ± 0.44%	0.56	0.07466 ± 0.36%	1059.3 ± 14.6
B	0.003	604	101	1268	15	2.8	0.175856 ± 0.10%	1.80301 ± 0.12%	0.86	0.07436 ± 0.06%	1051.2 ± 2.5
C	0.003	1253	210	4168	11	3.4	0.175541 ± 0.09%	1.80002 ± 0.10%	0.89	0.07437 ± 0.05%	1051.5 ± 1.9
<u>SM-P1-89</u>											
A	0.009	1895	360	9764	20	13.8	0.176914 ± 0.09%	1.81613 ± 0.10%	0.96	0.07445 ± 0.03%	1053.8 ± 1.2
B	0.013	737	137	6127	18	11.9	0.176813 ± 0.08%	1.81443 ± 0.10%	0.95	0.07443 ± 0.03%	1053.0 ± 1.2
C	0.015	1072	196	8328	22	11.1	0.176067 ± 0.09%	1.80541 ± 0.10%	0.95	0.07437 ± 0.03%	1051.5 ± 1.3
<u>SM-K1-89</u>											
A	0.058	434	83	28700	11	6.8	0.1912 ± 0.09%	2.048 ± 0.10%	0.96	0.07769 ± 0.03%	1138.9 ± 1.3
B	0.028	282	57	10660	9	8.5	0.1976 ± 0.08%	2.148 ± 0.10%	0.95	0.07883 ± 0.03%	1164.3 ± 1.2
C	0.047	379	75	14260	15	8.5	0.1954 ± 0.09%	2.110 ± 0.10%	0.96	0.07833 ± 0.03%	1155.2 ± 1.1

¹ Letters are zircon fractions;^a Radiogenic Pb, corrected for spike, fractionation, blank and common Pb;^b Measured ratio, corrected for spike, fractionation, blank and common Pb;^c Total common Pb in analysis^a Radiogenic ^{208}Pb , expressed as % of total radiogenic Pb;[^] Uncertainties are 1-sigma %;^{^^} Uncertainties are 2-sigma %.

Table 2: New age results from the Central Metasedimentary Belt Boundary Thrust Zone

Sample 1: Syntectonic pegmatite K1, basal ductile thrust zone, Killaloe

1180 $\pm$ 60/-18 Ma igneous crystallization age
963 $\pm$ /- 130 Ma lower intercept age of metamorphic overgrowth

Sample 2: Syntectonic pegmatite K2, basal ductile thrust zone, Killaloe

1189 $\pm$ 35/- 11 Ma igneous crystallization age
1010 $\pm$ 95/-116 Ma lower intercept age of metamorphic overgrowth

Sample 3: Late-syntectonic granite vein CR1, basal ductile thrust zone, Pembroke

1053 $\pm$ /- 03 Ma igneous crystallization age

Sample 4: Late-syntectonic syenite pegmatite J1, ductile thrust zone, Opeongo thrust sheet

1056 $\pm$ 20/-3 Ma igneous crystallization age

Sample 5: Late-syntectonic syenite pegmatite J1, ductile thrust zone, Opeongo thrust sheet

1002 $\pm$ 7/-4 Ma igneous crystallization age
1083 Ma Pb 207/206 age inherited zircon

length of the CMBBTZ in Ontario , suggesting that it has moved as a uniform front.

Movement on the upper structural levels of the CMBBTZ is also nearly coeval. The maximum age of 1010 Ma for late syntectonic thrusting on the upper structural level of the Pembroke thrust stack (sample 5) indicates that movement on the higher levels occurred later than movement at the base. Similar results have been obtained from the Bancroft area CMBBTZ. A late-syntectonic pegmatite at the top of the thrust stack has an age of crystallization of 990 ± 21 Ma. On a smaller scale these data confirm that the "break-back thrusting", outlined by a southward migration with time of the northwest limit of thrusting (Nadeau, 1990), within the southwestern CGB continues within the CMBBTZ.

The complex detailed time relations of thrusting between successive CGB structural levels are also mirrored within the CMBBTZ. Ages of $1029 \pm 14/-4$ and ca. 1010 Ma were obtained from late pegmatites sampled from the basal ductile thrust zone at Killaloe (van Breemen and Hanmer, 1984). The age of 1030 Ma is from a boudinaged, folded and mildly foliated pegmatite. The age of 1010 Ma is from a parallel-sided cross-cutting and undeformed pegmatite, and is considered to be the maximum age of the pegmatite. These results suggest that later thrusting on the higher structural levels reactivated the apparently abandoned lower structural levels. This sequence of renewed thrusting after the main thrust imbrication event has also been documented in the underlying CGB thrust domains (Nadeau, 1990). Obviously in detail thrusting within the Grenville mid-

crust does not conform to a straightforward time sequence.

Despite an apparent complex interplay between thrusting on different structural levels the chronological development of the CMBBTZ thrust stacks along strike in Ontario are amazingly internally consistent. The whole of the Ontario Central Metasedimentary Belt Boundary Thrust Zone from Pembroke to Haliburton has been thrust coevally ca. 1060 Ma, along a strike length of some 250 kilometres. Similarly movement on the highest structural levels is consistently ca. 1000 Ma. These relatively small time windows for imbrication all along the CMBBTZ in Ontario indicate that this crustal scale shear zone has moved as a uniform front. This uniformity in chronological development along so long a boundary is theorized here to be the result of collision between major geologic edifices. High grade regional metamorphism within both the CGB and Adirondack terrane (Fig 10) occurred ca. 1055 Ma (Davidson and van Breemen, 1989; Nadeau 1988; McLelland, 1988), and has been ascribed to the culminating Ottawa phase of the Grenville Orogenic cycle (Moore, 1986). This metamorphic phase along with the major tectonic pulse ca 1060 Ma recorded within the CMBBTZ and its adjacent terranes potentially marks the terminal continent-continent collision as modeled by Windley, (1986, 1990).

Middle Proterozoic initiation of thrusting

The ca. 1180 Ma ages of crystallization of the Killaloe pegmatites are significantly older than that of the other samples in this study and are the oldest

recorded ages of northwest directed thrusting within the Ontario Grenville, with the exception of Grenville Front itself (Easton, 1986). Considering the strain state and field relations of these samples there can be little doubt that they were emplaced syntectonically with respect to northwest thrusting deformation.

While at present pre-1060 Ma thrusting has not been documented from the Haliburton thrust stack of the CMBBTZ, field evidence suggests that it also experienced thrusting prior to 1060 Ma. Field relationships and present stacking order within the Haliburton thrust stack indicate that it has been thrust out-of-sequence. The elements within the present thrust stack must initially have been assembled prior to 1060 Ma. I suggest here, in the absence of data to the contrary, that the Haliburton thrust stack was also initially assembled ca. 1180 Ma, and that thrusting at 1060 Ma re-imbricated stack, generating its present configuration.

An age of 1180 Ma for earliest thrusting on the Pembroke thrust stack has several important implications for the tectonic development of the CMBBTZ and the southwestern Grenville as a whole. 1) This data would suggest that the CMBBTZ is a long-lived crustal shear zone initially active ca 1180 Ma, but persistently active until 1000 Ma, a time span of over 150 Ma. The scarcity of U-Pb isotopic dating in this region precludes definite determination as to whether this activity was continuous or episodic. However, the reasonably continuous spread of ages among synthrusting pegmatites of the CGB footwall (1160-1030 Ma, Fig 15, highlights the possibility that the CMBBTZ remained active between

major pulses (1180, 1060, 1000 Ma) of thrust imbrication. 2) If the northwest directed thrusting within the CMBBTZ and underlying CGB is considered to be the result of the collision of large geologic edifices, the 1180 Ma Killaloe pegmatites indicate that the collision of the Elzevir terrane with the North American margin (southwest CGB) occurred over 100 Ma earlier than previously considered, and consequently provide the first geochronologic corroboration that the western CGB crust had reason to have been thickened prior to 1160 Ma. Pressure-temperature studies of the conditions during emplacement of coronitic olivine metagabbros of the CGB estimate pressures of 9-10 kb (Grant, 1987). These probable dykes were emplaced ca. 1170 Ma into associated 1320 Ma metasediments at a crustal depth of 35-40 km, requiring that the CGB had experienced substantial crustal thickening between 1320 and 1170 Ma. (Nadeau, 1990). The presence of sapphirine-bearing, relict eclogitic tectonic inclusions associated with metasediments in pre-1160 Ma ductile thrust zones of the CGB also indicates major crustal thickening was initiated before 1160 Ma (Grant, 1989; Nadeau, 1990). The 1180 Ma age for initial thrusting along the CGB/CMB boundary indicates that collision and its consequent imbrication, necessary for significant thickening of the CGB crust, were active prior to 1160 Ma as required by the presence of very high-pressure inclusions within the supracrustal rocks.

4.0 DISCUSSION

The following chapter examines the implications of features described in Chapters 2 and 3 with respect to A) deformation at mid-crustal levels (shear localization and processes of deformation); B) the nature of the Central Metasedimentary Belt Boundary Thrust Zone as a whole; C) the subdivision and lateral extension of the Central Metasedimentary Belt and D) the tectonic history and development of the southwest Ontario Grenville orogen.

4.1 Deformation at Mid-crustal Levels

Shear Zone Localization

Pelitic metasediments and cordierite-gedrite rock are common to the base of the Haliburton and Pembroke thrust stacks (Plate 11c,d). Figure 16 illustrates the distribution of pelitic metasediment and cordierite-gedrite rocks in the CMBBTZ. The spatial association between this unusual supracrustal package and the base of the CMBBTZ in Ontario suggests that there is a genetic relationship between them.

As fluids are known to be channelled by shear zones the specific mineralogy of these supracrustal rocks could be the result of metasomatism by fluids channelled within the basal ductile thrust zone (Carter and Dworkin, 1990; Kerrich, 1986). However, this particular mineral assemblage (section 2.7) has been theorized to be a restite after a metasediment (Breaks and Thivierge, 1985)

or a consequence of metamorphism of a paleosol (Dymek, 1988; Culshaw, 1983) and is unlikely to be solely the result of alteration by the influx of fluids.

The converse argument, that the shear zone was localized by the presence of this specific horizon, warrants consideration. This model, though hypothetical, gains strength from the increasing attention paid to the role of compositional boundaries in deformation of the lithosphere. Ranalli and Murphy (1987) have suggested that many important rheological contrasts in the lithosphere may occur at compositional boundaries. Such a compositional contrast is present at the base of the CMBBTZ. The supracrustal rocks are sandwiched between the dry stiff granulite facies CGB footwall and relatively stiff crystalline thrust sheets of the CMBBTZ.

Shear localization occurs when a smaller increment of applied stress is required to deform a specific zone at a given strain rate, than to initiate deformation elsewhere (Poirier, 1980). This depends on the conditions of strain and intrinsic properties of the material. The physical processes leading to plastic instability (and hence localization) include geometric and strain softening (Poirier, 1980; White et al, 1980).

Strain softening occurs through the action of dynamic recrystallization and some recovery processes. Grain size reduction, the product of dynamic recrystallization and end-product of subgrain development during recovery, will

Figure 16: Distribution of pelitic metasediments and cordierite-gedrite supracrustal rocks within the CMBBTZ (Black shading and dots). Major Pembroke area occurrences are named. Dashed line outlines Paleozoic cover. CGB=Central Gneiss Belt, CMB=Central Metasedimentary Belt, BTZ=CMB Boundary Thrust Zone. S=Stafford, O=Opeongo. P=Papineau, Gl=Glamorgan, Gr=Grace, D=Dysart, R=Redstone thrust sheets.

soften the material by enhancing diffusion-accommodated grain boundary sliding and other grain size dependant deformation mechanisms (see section 2.1) (Nicolas and Poirier, 1976; Brodie and Rutter, 1984). The new strain free grains created by dynamic recrystallization can be weaker than existing strain-hardened grains as they more easily permit movement of dislocations, being free of dislocation tangles and pileups. Diffusion, in existing grains which have strain hardened, can also contribute to softening by facilitating dislocation climb around tangles (White et al, 1980), thereby increasing mobility of dislocations.

Geometric softening occurs when an active slip plane rotates to a more favourable orientation, (commonly into parallelism with the edges of the shear zone), and the slip direction rotates into parallelism with the flow direction.

Strain softening can be expected to be active regardless of the composition of the deforming material. Geometric softening, however, would be strongly favoured within the supracrustal rocks. A metamorphosed biotite-sillimanite orthoamphibole rock will have a much greater population of possible easy slip planes (basal sections of phyllosilicates for example) than a coarse crystalline mafic gneiss (Robin, 1979). A proportion of these readily available active slip planes can rotate into orientations favourable to slip imposed by the stress field.

The phyllosilicate bearing supracrustal rock would thus have been easier to deform than the thrust sheets and underlying CGB rocks. Through the action of geometric softening it could have localized the distribution of strain in the initial stages of thrusting. Thus it may have played a key role in the localization of the

base of the CMBBTZ, and highlights the widely observed influence of rheological contrasts on the development of thrust zones in the ductile regime (Hanmer, 1988; Lucas and St. Onge, 1989).

Processes of Deformation

Exposure of mid-crustal ductile shear zones is sufficiently rare to warrant some consideration of the deformation processes active in this dynamic level of the lithosphere. In order for a shear zone to form, shear localization is required. In the ductile region shear zones are initially localized by strain concentrations arising from strain softening or material inhomogeneities (White et al, 1980). There is generally less pronounced strain localization in shear zones at higher temperatures. Accordingly mid-crustal shear zones are wider than those developed near the brittle-ductile transition zone (Bak et al, 1975; Sibson, 1977; Hanmer, 1988).

Several processes are theorized to be important to the development of strain localisation, some of which have been discussed in section 2.6. The dominant deformation mechanisms expected in the ductile region are dynamic recrystallization, grain size reduction and dislocation creep. Others include reaction softening, hydrolytic weakening and pore-fluid effects.

Reaction softening occurs when a metamorphic or other chemical reaction produces new strain free grains, produces rheologically weaker mineral phases, or releases fluids (White and Knipe, 1978). Metamorphic dehydration reactions, and

pore-fluid effects, produce softening through the action of the Rebinder effect, an increase in dislocation mobility adjacent to grain boundaries due to absorbed water (Rutter, 1972). Release of fluid also causes weakening by enhancing grain boundary sliding (White et al, 1980).

Hydrolytic weakening decreases the creep strength of a material and promotes an increase in the strain rate, enhancing strain localisation (Tullis and Yund, 1980; Blacic and Christie, 1984). This is theorized to occur because of the hydrolysis of Si-O bonds. These are replaced by weaker Si-OH---HO-Si bonds which enhance the mobility of dislocations (Blacic and Christie, 1984). The creep strength of the material decreases, causing enhanced strain localization at the sites of hydration.

Examination of the development of straight gneisses in the Stafford thrust sheet provided an opportunity to identify the processes involved in localizing the ductile thrust zone within a mafic thrust sheet. While dynamic recrystallization and grain size reduction were the dominant deformation mechanisms observed throughout the bulk of the thrust stack, observations suggest that reaction softening and hydrolytic weakening were the primary strain softening and localisation processes in the Stafford thrust sheet.

The mafic host gneisses of the Stafford thrust sheet are cut by abundant syntectonic granitoids (Plate 19a). At the sites of granitoid intrusion a more highly strained biotite rich gneiss is developed. This regular gneiss anastomoses around pods of lower strain amphibolite and is apparently derived from the mafic

Plate 19: Granite/Amphibolite contacts, Stafford thrust sheet

19a: Intrusive relationship between coarse microcline rich granite pegmatite sheet and host thrust sheet amphibolite from the less deformed interior of the thrust sheet

19b: Biotite selvage (bright steel grey) developed between the granite and the amphibolite as a result of K⁺ and H⁺ metasomatism of the amphibolite. Same locality as in 19a.

19c: Biotite hornblende anastomosing higher strain shear (black center) localized at the metasomatized contact between an amphibolite pod (upper left blue-grey) and granitic pegmatite (lower right).

material of the amphibolite pods and potassic-silicic material added by the granitoids (Plate 19b,c). As one approaches the more highly strained margin of the thrust sheet the relict amphibolite pods are replaced by strongly foliated biotite-hornblende regular gneiss. The ductile thrust zone tectonites underlying the thrust sheet are the high strain equivalents of the regular gneiss.

The formation of the regular gneiss and higher strain zones involves creation of biotite at the expense of hornblende, through the addition of potassium and hydrogen ions. The syntectonically intruded microcline rich granitoids are the probable source of potassic rich water which reacts with the amphibolite. This metasomatic reaction occurs throughout the mafic Stafford thrust sheet and the underlying ductile thrust zone. A model for the localization and initiation of shear zones within the thrust sheet based on these observations is presented here.

1) Intrusion of syntectonic granitoids into host amphibolite adds heat and potassium rich fluids (Fig.17a). As the potassium rich fluids diffuse into the host amphibolite two types of softening processes occur; reaction softening and hydrolytic weakening. The reaction softening is a consequence of metamorphic reactions involving the host gneiss. The water and potassium react with the hornblende of the gneiss to produce biotite and quartz. The chemical reaction is

The reaction products, biotite and quartz, are weaker than the hornblende

Figure 17: Schematic illustration of deformation model discussed in text.

A: Intrusion of syntectonic granite (cross pattern) into amphibolite (dark shading) adds water and potassium to the amphibolite, which reacts to form biotite and quartz. Reaction softening and hydrolytic weakening are initiated.

B: Biotite is produced at the granite/amphibolite contacts, armouring the amphibolite boudins from the reaction. Strain is localised in the biotite rich margins, generating a biotite-hornblende regular gneiss (light shading). Zone of higher shear strain anastomose around the amphibolite boudins.

C: The rheologic contrast between the stiff amphibolite boudins and weaker biotite regular gneiss causes the boudins to fracture. New granite and potassic fluids are drawn in, reaction softening and hydrolytic weakening are repeated. The intrusion/reaction process continues within a network of progressively smaller boudins, and high strain zones

A

B

C

D

Figure 17: D) Straight gneiss is developed from alternating layers of aligned biotite-hornblende and transposed granitic material. Only very small relict amphibolite boudins remain. Foliation softening helps to localize strain within the ductile thrust zone.

E

E) Within the thrust sheet itself chemical gradients between the boudins and surrounding gneiss enhance diffusion of K^+ and water into the amphibolite boudins, once the deformation has ceased. Biotite formed at the expense of hornblende in these boudins is unaligned in contrast with the biotite of the surrounding regular gneiss.

they are replacing, resulting in reaction softening which will localize strain distribution. Addition of water to the feldspar of the amphibolite hydrolytically weakens the rock, decreasing its strength and promoting an increase in the strain rate (Blacic and Christie, 1984; Tullis and Yund, 1980).

The biotite-hornblende reaction and hydrolytic weakening occur at the margins of amphibolite boudins fractured by granitoid intrusion. Production of biotite at the margins of the boudins acts as a physical buffer to diffusion of the potassium and fluid into the amphibolite boudins, armouring them from the effects of the metasomatism (Klein et al, 1985). The processes described localize the strain in the deforming thrust sheet at the margins of the amphibolite boudins (Fig.17b).

3) There is an increase in strain rate, due to softening at the initiation of deformation, which is naturally partitioned into the rheologically weaker biotite hornblende gneiss at the boudin margins. The variation of rheology between the deforming biotite rich gneiss and the amphibolite causes the mafic boudins to fracture, creating new zones to draw in the syntectonic granitoid and/or potassium rich fluids. The reaction softening and hydrolytic weakening can then continue within a network of smaller mafic boudins and anastomosing higher strain zones (Fig.17c).

There is a marked increase in volume of granitoid with progressive deformation. This relationship between volume of granitoid and strain state may either be the consequence of localisation of granite intrusion by the deformation

or vice versa, or most likely both.

4) Shear localization proceeds and a foliation is progressively developed, through transposition of the biotite gneiss, granitoid sheets and veins and reduction of the relict amphibolite boudins (Fig.17d). A compositional layering is formed, consisting of quartz-microcline-plagioclase layers (from the transposed granitoid material and pegmatites) alternating with mafic layers. When sufficiently continuous the compositional layering decreases the bulk strength of the material. Jordan (1987, 1988), in his experimental studies noted that there was a transition from work hardening in initially homogenous deformed material to work softening once a continuous compositional layering developed. This was a result of the change of the material bulk rheology from being determined by the strength of the load carrying framework, to being determined by the volume fraction of the coalesced weaker phase. This process of "foliation softening" localizes shear (Jordan, 1987; Bell, 1981). The high strain ductile thrust zone straight gneiss is the end member product of these deformation processes.

Heterogeneously sheared and metasomatized amphibolite is preserved within the thrust sheet. Once the deformation ceases the fluid and chemical gradients between the sheared zones and the boudins will cause migration of the chemical species, partially biotizing the relict pods (Fig.17e). Consequently the metasomatism and hydration occur over an area greater than the ductile thrust zone itself, as observed in other deformed mafic bodies (Beach, 1980).

At upper amphibolite facies (the metamorphic realm of mid-crustal shear

zones) recrystallization and recovery accommodated dislocation creep are the dominant deformation mechanisms (Tullis and Yund, 1984). Observations of the development of shear localization in the mafic Stafford thrust sheet indicate that, while these processes play a part in the localization, hydrolytic weakening and reaction softening were key processes in the development of the ductile thrust zone below the sheet.

The model for deformation presented here illustrates the importance of fluids to deformation at mid-crustal levels. It is reasonable to postulate that in regions where the metamorphic grade is upper amphibolite or higher reaction softening and hydrolytic weakening play a significant role in the deformation of mid-crustal lithosphere.

4.2 Nature of the Ontario CMBBTZ

Structural Characteristics

The structural characteristics of the Pembroke area CMBBTZ presented in this study are remarkably similar to those of the Haliburton area some 200 kms along strike to the southwest.

The major structural characteristics shared by the two regions are:

- 1) The Ontario CMBBTZ, as exposed in the region, is comprised of lens shaped crystalline thrust sheets of similar size (25-35 km strike length, 4-5 km thick), dipping to the southwest at around 20-25°(Fig. 18).

Figure 18: Diagram of the Ontario Central Metasedimentary Belt Boundary Thrust Zone (BTZ) illustrating the spatial distribution of the Haliburton and Pembroke thrust stacks and individual thrust sheets. Dashed line outlines Paleozoic cover. S=Stafford, O=Opeongo, P=Papineau, Gl=Glamorgan, Gr=Grace, D=Dysart and R=Redstone thrust sheets. CGB=Central Gneiss Belt, CMB=Central Metasedimentary Belt.

CGB

BTZ

**Haliburton
Thrust
Stack**

**Pembroke
Thrust
Stack**

CMB

- 2) The thrust sheets are separated by ductile thrust zones of quartzofeldspathic tectonites and or marble tectonic melange.
- 3) The synthrusting metamorphic grade is upper amphibolite.
- 4) The CMBBTZ, dominated by northwestward thrusting, experienced a subordinate but possibly coeval component of northeastward thrusting, as evidenced by an ubiquitous set of asymmetric folds.
- 5) The base of the CMBBTZ was localized by highly aluminous metasediment and cordierite-orthoamphibole rock.

The coincidence of the scope and range of structural characteristics throughout the Ontario CMBBTZ illustrates that it is a remarkably uniform structural entity. The assemblage of features characteristic of the Ontario CMBBTZ cannot be traced beyond the Ottawa River and is quite distinct from those of the Quebec CMB/CGB boundary. The different structural features between the Ontario and Quebec segments may possibly be the result of a change in orientation and kinematics of external boundary forces. Nevertheless, the CMBBTZ, as it is exposed in Ontario, is the single largest shear zone yet identified in the Ontario Grenville. The resolution of a significant step of the Moho coincident with the CMBBTZ in Ontario (Mereu et al, 1986) confirms that it is indeed a major crustal scale shear zone.

Timing of Assembly

As was discussed in Chapter 3, an age of 1060 Ma for syntectonic thrusting

of the Ontario CMBBTZ has been found throughout the 200 km long basal thrust zone. This suggests that the forces which coevally thrust the whole of the Ontario BTZ to the northwest at 1060 Ma were of large enough scope, uniformity and strength to displace a structural entity of that magnitude.

It is suggested here that the terminal continent-continent collision between the Laurentia margin and the outboard continent (be it Africa as suggested by Morel and Irving (1978) or South America as suggested by Bond et al (1984)) provided the boundary forces necessary for the 1060 Ma imbrication. Furthermore, the "break-back" thrusting which persisted on a smaller scale within the Ontario CMBBTZ thrust stacks was probably the result of forces arising from continued convergence and possibly indentation of the Laurentia margin by the hinterland continent.

The foregoing discussion illustrates that the Ontario CMBBTZ is a remarkably uniform crustal-scale shear zone which owes its consistent structural features and displacement as a discrete "front" to the action of large-scale boundary forces.

4.3 Subdivision and Lateral Extension of the CMB

A Revised Subdivision of the CMB

The Central Metasedimentary Belt (or southeastern (allochthonous monocyclic) zone of Rivers et al, 1989)) has been viewed as an assemblage of three terranes; the Bancroft; Elzevir; and Frontenac-Mont Laurier terranes

(Rivers et al, 1989; Davidson, 1986; Wynne-Edwards, 1972). The Bancroft terrane extends from the northwestern margin of the CMB to the northeast trending nepheline syenite and gneiss belt that marks its southwestern boundary with the Elzevir terrane (Fig.19a). The boundary zone of the CMB previously encompassed only the basal thrust zone of the Haliburton thrust stack and a projected narrow margin of high strain gneisses (Fig.2).

A comparison of Figures 19a and 19b illustrates that the Bancroft terrane and Ontario CMBBTZ are completely coincident. The nepheline gneiss and syenite belt which marks the Bancroft terrane's boundary with the Elzevir is situated at the upper boundary of the Haliburton thrust stack. At Pembroke the upper boundary of the CMBBTZ is here placed at the carbonate ductile thrust zone overlying the uppermost Opeongo thrust sheet and along the deformed marbles of the York River shear zone (Hanmer and Ciezielski, 1984), which overlies the New Carlow syenites, above the Papineau thrust sheet. The nepheline syenites and gneisses of the Bancroft terrane boundary are dispersed along the York River shear zone and within and adjacent to the thrust zone overlying the Opeongo sheet. Thus, delineation of the Pembroke thrust stack by this study has found that it is coincident with the northern part of the Bancroft terrane, in the same way that the Haliburton thrust stack is with the southern region.

Due to the coincidence of the CMBBTZ and the Bancroft terrane it is

Figure 19: Comparison of the spatial distribution of a) the Bancroft terrane and b) the CMBBTZ. Black dots are nepheline-alkalic gneiss bodies. Note the coincidence between the boundaries of the Bancroft terrane and the CMBBTZ. Ruled area = thrust sheets of CMBBTZ, H = Haliburton thrust stack, P = Pembroke thrust stack, ET = Elzevir terrane, FT = Frontenac terrane, BSZ = Bancroft shear zone. Base map after Carlson et al, 90.

Figure 20: Revised subdivisions of the Central Metasedimentary Belt (CMB). Light shaded region is the CMB, including the Elzevir and Frontenac terranes. CMBBTZ=CMB Boundary Thrust Zone, BSZ=Bancroft shear zone, HCA=Harvey-Cardiff Arch. Base map after Hoffman, 1990.

suggested here that in future the entire region previously termed the Bancroft terrane be renamed the Ontario Central Metasedimentary Belt Boundary Thrust Zone. The CMBBTZ includes the entire Haliburton and Pembroke thrust stacks, not just the basal ductile thrust zone. It is appropriate for it to be recognised as such.

A revised subdivision of the CMB proper, illustrated in Figure 20, characterizes it as being comprised of the Elzevir and Frontenac-Mont Laurier terranes. Between the CMB and the CGB lies the Central Metasedimentary Belt Boundary Thrust Zone.

The identification of the CMBBTZ in Ontario focuses attention on a belt of metagabbroic bodies which lie immediately above the upper bound of the zone (Fig.21). The belt has apparently been displaced as a coherent unit on the extensional Bancroft shear zone (Carlson et al, 1990). If this belt represents a coherent structural unit underlain by extensional mylonites this raises several questions: 1) Have the now isolated gabbros, given that they have behaved as a unit with respect to extension, behaved as a unit during earlier thrusting? and 2) Given that their field relations and textures suggest syntectonic igneous emplacement (Hanmer, pers. comm.), were they originally crystallized in a common tectonic environment? These questions and the significance of the spatial association of the belt with the CMBBTZ cannot be addressed without further study. This places a priority on geochemical characterization and isotopic

Figure 21: Distribution of syntectonic metagabbro bodies (ruled shading) adjacent to the Central Metasedimentary Belt Boundary Thrust Zone (BTZ) upper boundary. Stars indicate nepheline gneisses and nepheline syenites also adjacent to upper bound. Metagabbros are: 1.O'Brien's Hill, 2.Raglan-Mallard Lake, 3.Boulter, 4.Faraday, and 5. Hadleigh. CGB=Central Gneiss Belt, CMB=Central Metasedimentary Belt, Thrust sheets named as per Figure 18. Dashed lines outline Paleozoic cover.

age determinations of the individual bodies.

Southwestward Extension of the CMB and CMBBTZ

The southwestward continuation of the CMB is obscured by Paleozoic cover over southwestern Ontario and the mid-United States. Recent seismic reflection profiling in Ohio (Culotta et al, 1990; Beardsley and Cable, 1983) images southeast dipping reflectors which have been correlated with the CGB-CMB boundary (Fig.22a). Although this apparently confirms extension of a reflective CMB-CGB boundary into the U.S. subsurface, a comparison of the COCORP results with an earlier reflection and refraction study by Mereu et al, (1986) across the CMBBTZ in the Pembroke area reveals significant discrepancies between the crustal structure of the CMBBTZ in Ontario and Ohio. Mereu et al's study determined that there is a step on the Moho beneath the CMBBTZ at 36 km depth (Fig.22b). They concluded that the boundary of the CMB-CGB is a deep-seated crustal feature. COCORP's profile images the boundary as a band of shallow reflectors extending to a maximum depth of 20 km, where they are truncated by west-dipping reflectors of the Coshocton Zone (interpreted by Culotta et al (1990) to be a west-dipping suture). The depth to which the CMBBTZ of Ontario extends apparently changes along strike. The trend of Grenville linear features imaged by potential fields turns southward south of Lakes Ontario and Erie (Culotta et al, 1990). The convergence of the Coshocton Zone reflectors with those identified with the CMBBTZ may be a consequence

Figure 22 a: Line drawing of reflectors from shot line COCORP OH 1. Note the depth to which the reflectors interpreted to be the Central Metasedimentary Belt Boundary Thrust Zone (CMBBTZ) extend. Modified from Culotta et al, 1990. **b:** Composite record section from 1982 COCRUST experiment for line OA, shot B with traces plotted at reflection points. Main trace is that of the Moho. Approximate depth to reflectors is at left. Note the "step" on the Moho and greater depth of CMBBTZ reflectors as compared to 22a. Modified from Mereu et al, 1986.

of an overall change in trend of the orogenic belt with respect to the structure imaged by the Coshocton Zone reflectors.

4.4 Tectonic History of the Southwest Grenville Orogenic Cycle

The resolution of possible cryptic sutures in the Grenville highlights the possibility that the earlier age of thrusting identified in this thesis records initial docking of the CMB with the CGB after southeast-dipping subduction. The northwest-dipping reflectors of the Coshocton zone have been postulated to be the expression of a northwest-dipping subduction zone (Culotta and Oliver, 1990). Subduction of this polarity probably ceased ca. 1060 Ma as a result of collision between the hinterland continent and the earlier modified margin of Laurentia. The following outline of the development of the southwest Grenville Orogenic Cycle is intended primarily to focus future work but also puts into a more regional context the geochronologic results of this study. It is primarily a modification of the tectonic models of Windley (1986, 1990) and Corriveau (1990).

1) 1270-1225 Ma: Plutonism, arc volcanism and sedimentation within the Elzevir terrane (Condie and Moore, 1977; Easton, 1986). This is most probably a consequence of southeastward dipping subduction of material formed in an oceanic environment (Brown et al, 1975), perhaps that of a marginal basin (Holm et al, 1986; Smith and Holm, 1988) (Fig.23a).

2) 1180 Ma: Collision of CMB volcanic arc with the southeast margin of Laurentia. 1180 Ma marks the earliest recorded thrusting on the CMB-CGB boundary (this study). There is cessation of south-dipping subduction at this time. Collision of the arc with the continental margin initiates imbrication of the margin (1160 Ma thrusting on the Parry Sound shear zone of the CGB (van Breemen et al, 1986)) (Fig.23b).

3) 1180-1100 Ma: Deformation accompanied by a southward regression of the northwest limit of thrusting in the CGB ("break-back" thrusting of Nadeau, 1990) and generates deformation and regional metamorphism within the Elzevir-Frontenac terranes (Davis and Bartlett, 1988).

4) 1089-1076 Ma: Switch to northwest dipping subduction beneath the Elzevir-Frontenac edifice generates potassic plutonism within the CMB. As the timing of thrusting on the CMBBTZ (this study) indicates that the CMB had already collided with the margin of Laurentia by 1100 Ma, and the spread in ages of the potassic plutons does not indicate southwest dipping subduction as suggested by Corriveau (1990), northwest dipping subduction beneath the combined CGB-CMB is the most probable tectonic environment responsible for the 1089-1076 Ma plutonism. This polarity of subduction (supported by the resolution of a major north-dipping reflective zone southwest of the CMB and transecting it in the subsurface (Culotta and Oliver, 1990)) was due to closure of the intervening ocean between the southwestern margin of Laurentia and the hinterland continent (Fig.23c).

5) 1060 Ma: Terminal continent-continent collision occurs and there is cessation of north-dipping subduction. Metamorphism to upper-amphibolite grade within the CMBBTZ and adjoining terranes (Metzger, 1990). Major reactivation and out-of-sequence thrusting occurs within the suture between the allochthonous CMB terranes and the margin of Laurentia (this study). Renewed northwest-directed thrusting occurs within the CGB (Nadeau, 1990) (Fig.23d).

6) 1060-1000 Ma: Continued convergence maintains northwest directed thrusting to 1000 Ma within the CMBBTZ and to 1027 Ma within the CGB (this study; van Breemen and Hanmer, 1986; Nadeau, 1990). Thrusting and thickening of the lithosphere leads to amphibolite facies extensional collapse within the CGB ca. 1040 Ma (Nadeau, 1990). Minor extensional shearing occurs within the CMBBTZ itself.

7) Post 1000 Ma: Low grade extensional shearing occurs at the top of the CMBBTZ (Bancroft shear zone, Carlson et al, 1990), and the present structural level of the Elzevir terrane is emplaced. Cooling and uplift occur.

5.0 CONCLUSIONS

The following conclusions can be drawn regarding the structure and assembly of the Pembroke area CMBBTZ:

- 1) The Ontario CMBBTZ at Pembroke is comprised of at least three crystalline thrust sheets transported northwestward on upper amphibolite facies ductile thrust zones. These thrust sheets comprise the Pembroke Thrust Stack.
- 2) Two of the thrust sheets are lithologically coherent. These are the Stafford thrust sheet, derived from a mafic amphibolite and the Opeongo thrust sheet, derived from a syenite body.
- 3) Subordinate northeastward thrusting, outlined by a regionally consistent fold set, was possibly coeval with the main northwestward thrusting
- 4) The base of the CMBBTZ at Pembroke was localized by aluminous metasediment and cordierite-gedrite rock.
- 5) Reaction softening and hydrolytic weakening were key processes involved in the deformation of the mafic Stafford thrust sheet, and may play an important role in the deformation of mid-crustal lithosphere.
- 6) The Pembroke Thrust Stack has experienced three main phases of imbrication and deformation, as determined by U-Pb geochronology: ca. 1180 Ma, 1060 Ma, and 1000 Ma. Thrusting occurred later on the higher structural levels, and apparently reactivated the abandoned lower levels.

In view of the similarities between the structural characteristics and timing

of thrusting of the Pembroke thrust stack and the Haliburton thrust stack the following conclusions are drawn regarding the nature of the Ontario CMBBTZ:

- 1) The CMB Boundary Thrust Zone, as it is exposed in Ontario, is a uniform entity. It is a crustal scale shear zone with dominant structural characteristics which extend along its entire length from Pembroke in the northeast to Haliburton in the southwest. The Ontario CMBBTZ is structurally distinct from the CMBBTZ in Quebec.
- 2) The Ontario CMBBTZ was initiated by collisional thrusting ca 1180 Ma. Major reimbrication occurred ca 1060 Ma, at which time the entire Ontario CMBBTZ moved as a uniform front. Thrusting on the higher structural levels ca. 1000 Ma was also apparently coeval along the length of the CMBBTZ.
- 3) The Ontario CMBBTZ is a major tectonic feature with a protracted history of northwestward overthrusting spanning nearly 200 Ma.

In light of the conclusions drawn above the following constraints are placed on the evolution of the SW Ontario Grenville Orogenic Cycle

- 1) Earliest thrusting on the base of the Ontario CMBBTZ records the collision of the CMB with the underlying CGB. This initiated crustal shortening by imbrication and thickening within the continental margin of Laurentia.
- 2) Collision ca 1180 on the CMBBTZ initiated break-back thrusting in the southwestern CGB, a pattern of imbrication which persisted on a smaller scale within the CMBBTZ itself.
- 3) Major reimbrication and reactivation within the CMBBTZ ca 1060 Ma records

the terminal continent-continent collision of Laurentia with the hinterland continent.

APPENDIX

Sample Preparation and U-Pb Analysis

Abraded selected zircons are leached in warm 3N HNO₃ for about 20 minutes to remove any pyrite residue. Once transferred to the clean lab of the G.S.C. geochronology laboratory the zircons are given a final leaching in the HNO₃ and rinsed in high purity water and acetone.

The zircons are then weighed in aluminum boats on a microbalance and transferred to Teflon[™] micro-capsules. A tracer solution of ²⁰⁵Pb (Parrish and Krogh, 1987) is added to the capsules and weighed by difference. 0.1 to 0.3 ml of very pure 48% Hf and 0.01 of 70% HNO₃ are then added. The capsules are placed in Teflon[™] dissolution vessels, which are sealed and heated in an oven at 240°C for 30 hours to dissolve the zircons.

After dissolution, the samples are evaporated to fluoride salts. In order to dissolve the salts 0.3 ml of 3.1N HCl is added to the samples, which are then sealed and heated in a 210°C oven for 12 hours.

Separation of U and Pb from the spiked samples is achieved by ion-exchange elution chemistry in 1.25 ml anion exchange columns. This follows the procedure outlined in Parrish et al, 1987. The anion exchange resin added to the columns is washed and then the sample is loaded and washed. The U and Pb are eluted into separate beakers. One drop H₃PO₄ is added to each Pb and U collection beaker. In addition one drop of HNO₃ is added to each U beaker.

The contents are evaporated in preparation for mass spectrometry.

U-Pb Geochronology Sample Localities

UTM coordinates of samples for U-Pb dating are as follows:

SM-K1-89: West facing roadcut, 1 km south of Killaloe Station, Ontario.

UTM: 18T, 311500E-5045175N

SM-K2-89: Same locality as K1, sample from branching dyke 6m north of K1.

SM-P1-89: West facing roadcut, Papineau Lake east road.

UTM: 18T, 278500E-5026900N

SM-CR1-89: NW corner roadcut of 4 corner roadcut exposure at junction.

UTM: 18T, 339375E-5070000N

SM-J1-89: SW facing roadcut, 1.5 km south of Jewelville, Ontario.

UTM: 18T, 302825E-5022375N

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