Dating ductile deformation using U–Pb geochronology: examples from the Gilbert River Belt, Grenville Province, Labrador, Canada[1]

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The Gilbert River Belt, in the Grenville Province in southeastern Labrador, is a distinctive, west–northwest-trending zone of locally intense deformation and voluminous granitoid plutonism, up to 30 km in width. In an attempt to directly quantify the timing of deformation in ductile shear zones within the belt, rocks interpreted as having been intruded synchronously with ongoing deformation were sampled for U–Pb isotopic analysis. Three of these samples are <2 m wide granitic veins that have sharp intrusive contacts that truncate ductile deformation fabrics, but are themselves deformed at metamorphic conditions similar to their host rocks and are therefore interpreted as having intruded *after* the initiation of deformation and fabric development, but *prior* to cessation of this deformation. The first vein is syntectonic with respect to amphibolite-facies deformation and yielded a zircon age of 1664^{+14}_{-9} Ma. The second vein intruded synchronously with the development of a zone of amphibolite-facies straight gneisses, which defines the southern limit of the Gilbert River belt at 1509^{+11}_{-12} Ma. The third vein is syntectonic with respect to greenschist-facies deformation and yielded a zircon age of 1113^{+6}_{-5} Ma and a monazite age of 1078 ± 2 Ma. A sample of the K-feldspar megacrystic granite that underlies much of the belt and is interpreted as having intruded during ongoing amphibolite-facies deformation yielded a zircon age of 1644^{+8}_{-6} Ma; a mildly deformed granitic vein that crosscuts the megacrystic granite at the same location contained zircon that indicate a 1062^{+5}_{-6} Ma crystallization age. Monazite from a granodioritic gneiss yielded a concordant age of 1077 ± 3 Ma, interpreted as the time of final cooling during gneiss formation. These results indicate that much of the amphibolite-facies deformation (1664–1644 Ma) in the Gilbert River Belt is correlative with the regionally extensive Labradorian orogenic event, whereas greenschist-facies deformation (1113–1062 Ma) and monazite growth (1078 Ma) are the result of renewed tectonomagmatic activity during Grenvillian orogenesis.

La ceinture de Gilbert River est une zone orientée ouest–nord-ouest, pouvant atteindre une largeur de 30 km, caractérisée par une déformation localement intense et par de volumineuses intrusions de composition granitoïde. De façon à quantifier la chronologie de la déformation dans les zones de cisaillement ductile présentes dans la ceinture, des intrusions mises en place pendant les différentes phases de déformation ont été échantillonnées pour fins de datation par la méthode U–Pb. Trois de ces échantillons sont des filons granitiques d'une largeur <2 m, ayant des contacts intrusifs francs et recoupant les structures de déformation ductile. Toutefois, ces échantillons ont été déformés dans des conditions de métamorphisme semblables à celles de leur encaissant et ont donc été mis en place *après* le début de la période de déformation ductile, mais *avant* sa cessation. Le premier filon est syntectonique de la déformation au faciès amphibolite et a livré un âge de 1664^{+14}_{-9} Ma (zircon). Le second filon fut injecté à 1509^{+11}_{-12} Ma, pendant la formation d'une zone de gneiss rectiplanaires métamorphisés au faciès amphibolite qui définit la limite méridionale de la ceinture Gilbert River. Le troisième filon est syntectonique de la déformation au faciès des schistes verts et a livré un âge de 1113^{+6}_{-5} Ma (zircon), et de 1078 ± 2 Ma (monazite). Le granite à phénocristaux de feldspath-K couvrant une grande partie de la ceinture et mis en place pendant la déformation au faciès amphibolite a livré un âge de 1644^{+8}_{-6} Ma (zircon); au même site d'échantillonnage, un filon granitique peu déformé et recoupant le granite à phénocristaux de feldspath-K contient des zircons livrant une âge de cristallisation de 1062^{+5}_{-6} Ma. Des monazites extraites d'un gneiss granodioritique ont livré un âge concordant de 1077 ± 3 Ma qui est interprété comme représentant le stade final de refroidissement du gneiss. Ces résultats indiquent que la déformation au faciès amphibolite de la ceinture Gilbert River (1664–1644 Ma) peut être corrélée en grande partie à l'épisode orogénique labradorien, qui est d'extension régionale, alors que la déformation au faciès des schistes verts (1113–1062 Ma) et la formation de monazite (1078 Ma) sont liées à une reprise de l'activité tectonomagmatique pendant l'orogenèse grenvillienne.

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Introduction

Our understanding of the role of zones of highly deformed rocks is often hampered by limited knowledge of the absolute timing of their formation. Geologists have long been able to interpret the kinematic significance of such rocks, but a lack of precise age information has hindered attempts to understand crustal-scale deformation processes. It is often difficult to confidently correlate individual phases of deformation away from areas where they are in direct contact. In the following contribution, we present natural examples of how precise U–Pb geochronology, combined with detailed field observations, offers an additional tool that may be used to address these problems.

The Gilbert River Belt (GRB) is located in the eastern part of the Grenville structural province in southeastern Labrador, Canada (Fig. 1). It is a distinctive, west–northwest-trending zone of locally intense deformation and voluminous granitoid plutonism, up to 30 km in width (Gower et al. 1987, 1988; Hanmer and Scott 1990; Scott et al. 1992*a*, 1992*b*, 1992*c*). The belt coincides with a major Bouguer gravity anomaly (Gower et al. 1987) and distinctive regional aeromagnetic patterns (Geological Survey of Canada 1985). The inland, along-strike continuation of the GRB, based on this aeromagnetic signature and geological mapping, appears to be in excess of 300 km, suggesting that the belt is a crustal feature of fundamental importance (Gower et al. 1987; van Nostrand et al. 1992). The belt separates the lithotectonically distinct Hawke River terrane to the north from the Pinware and Mealy Mountains terranes to the south (Gower et al. 1987; Rivers et al. 1989), and is interpreted as the southeastern continuation of the Lake Melville terrane (Gower et al. 1987, 1988).

The GRB is a major structural element in the eastern Grenville Province; detailed knowledge of its evolution is important to our understanding of the geology of this part of eastern North America and to our attempt to correlate these rocks with their European counterparts (e.g., Gower 1992). It also provides an opportunity to explore the possibility of using U–Pb geochronology to directly determine the age of deformation within shear zones developed under a wide range of physical conditions. The timing of magmatism and deformation within the belt, and its overall structural history are discussed in the following sections.

Geological and kinematic framework of the Gilbert River Belt

Recent regional mapping (1 : 100 000 scale) in the Port Hope Simpson and St. Lewis River map areas (Gower et al. 1987, 1988) provides the foundation for the present topical study (Fig. 2). The GRB transects these two map areas and is composed of metasedimentary gneisses, variably foliated, commonly megacrystic granitoid plutons, and deformed anorthositic and related igneous rocks (Fig. 2). These rocks occur as elongate, interfingering map units that define the pronounced west–northwest structural grain of the belt. The southern margin of the GRB is delineated by a laterally continuous approximately 100 m wide zone of well-banded granoblastic straight gneiss, well exposed in the vicinity of Long Harbour (Fig. 2), which displays well-developed down-dip extension lineations and north-side-up kinematic indicators (Hanmer and Scott 1990). Rocks of the belt become less strongly deformed progressively northward; the northern limit of this deformation lies within the White Bear Arm anorthosite complex (Gower et al. 1987). The most northerly deformation examined in the present study is the greenschist-facies mylonite zone south of Occasional Harbour (Fig. 2).

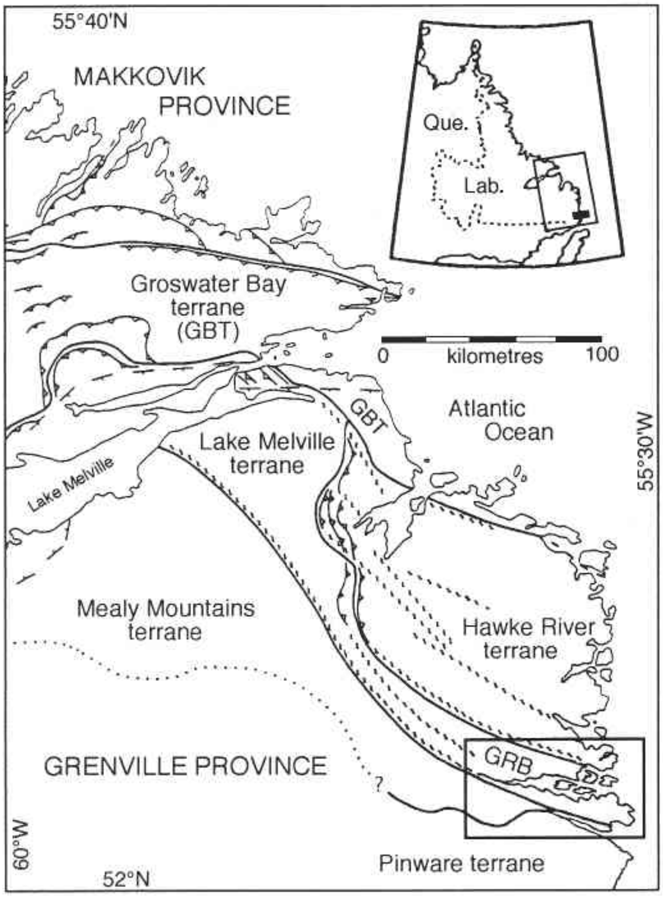

FIG. 1. Tectonic map of eastern Quebec and southeastern Labrador. Inset shows location of Fig. 1 in eastern Canada. Area shown in Fig. 2 is outlined. GRB, Gilbert River Belt. Modified from Gower et al. (1988).

Although the GRB is not well exposed along most of its strike length (e.g., van Nostrand et al. 1992), wave-washed exposures along the southern Labrador coastline provided an excellent opportunity to study a complete, across-strike section of the belt in detail (Hanmer and Scott 1990). This structural examination has revealed that within the GRB significant deformation is concentrated in six narrow corridors (< 1 km wide) containing discrete bands (< 10 m wide) of mylonite (Fig. 2). The mylonitic corridors are arranged in an anastamosing array (Fig. 2), whereas bands within individual corridors are arranged en echelon. Only three of the corridors, Long Harbour, Rexon's Cove, and Occasional Harbour (Fig. 2), presently show significant (> 200–300 m) along-strike continuity of individual bands.

Metamorphic conditions under which the mylonites of the GRB developed range from upper-amphibolite to greenschist facies. The mylonites have been subdivided into high-grade (mid to upper amphibolite facies) and low-grade (greenschist facies) types, and occur in all rock types observed in the GRB (Hanmer and Scott 1990). The amphibolite-facies mylonites that were examined are characterized by dominantly shallow to subhorizontal extension lineations and a dextral sense of displacement, as shown by the presence of rotated feldspar por-

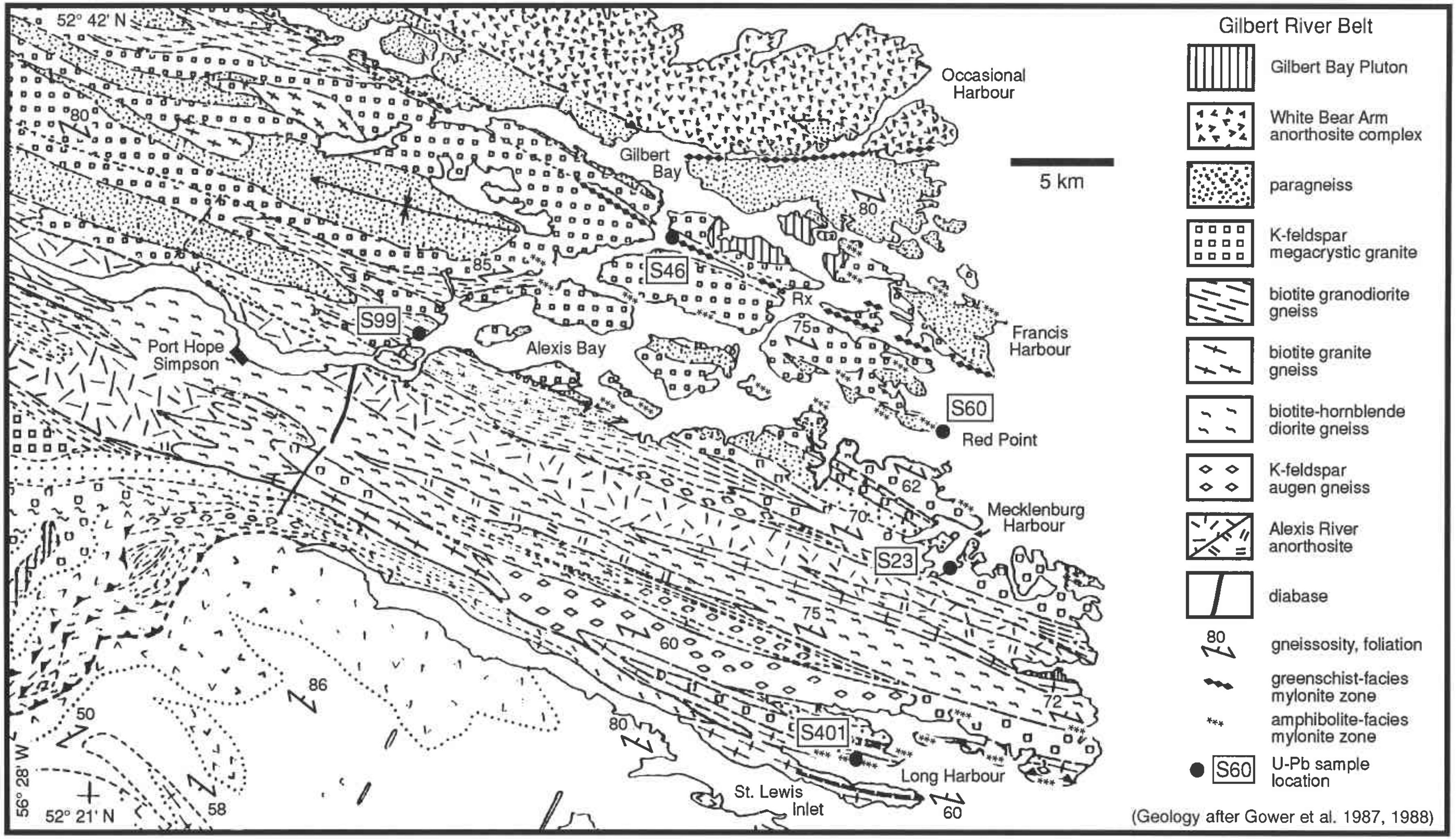

FIG. 2. Geological map of the easternmost part of the Gilbert River Belt, southeastern Labrador (after Gower et al. 1987, 1988) showing locations of samples described in text. Locations of mylonitic rocks from Hanmer and Scott (1990).

phyroclasts and extensional shear bands. Dip-lineated zones (north side up) and indications of sinistral movement are present but less common (Gower et al. 1987; Hanmer and Scott 1990). Greenschist-facies mylonites occur in two laterally continuous zones (Fig. 2), characterized by shallow to moderate east–southeast-plunging extension lineations. Composite C–S fabrics, commonly developed within these zones, consistently indicate a dextral sense of offset.

A relative chronology of deformational events has been established from relationships observed in the field (Hanmer and Scott 1990). Mineral assemblages within amphibolite-facies mylonite zones and in the foliated host rocks are identical, suggesting that much of the regional fabric development outside the zones and the mylonites themselves may have formed synchronously. Greenschist-facies mylonite zones occur within and rework amphibolite-facies host rocks, suggesting that they postdate the high-grade deformation. The low-grade zones are characteristically narrower than the amphibolite-facies mylonite zones. Greenschist-facies ultramylonites are locally cut by pseudotachylite veins, brittle fractures, and narrow zones of cataclastic rocks. This progression of deformation styles suggests that the history of the area is characterized by a sequence of deformation under conditions of decreasing temperature with time (Hanmer and Scott 1990). Whether this deformation is part of a single, continuous event, or is part of a punctuated multistage history characterized by subsequent reactivation and overprinting, will be addressed in the following quantitative geochronologic investigation.

Previous geochronology

Much geochronology has recently been undertaken in the Grenville Province of eastern Labrador and has led to the recognition of two periods of orogenic activity. The older event, referred to as Labradorian orogeny (Nunn et al. 1984), involves deformation, metamorphism, and dominantly felsic magmatism from 1.71 to 1.62 Ga, culminating between 1.68 and 1.64 Ga (Nunn et al. 1988; Gower et al. 1992 and references therein). Tectonomagmatic activity of Grenvillian age (1.15–0.95 Ga) is present to a limited extent in the eastern Grenville Province (Gower et al. 1991 and references therein). A more detailed discussion of these orogenic events follows presentation of the results of this study.

Prior to the present study, only one rock in the GRB had been dated by the U–Pb method. Zircon from a massive granite pluton that straddles Gilbert Bay in the northern part of the study area has been dated at 1132^{+7}_{-6} Ma (Gower et al. 1991) (Gilbert Bay Pluton, Fig. 2).

U–Pb results

Analytical methods

The analytical methods used are essentially those of Krogh (1973, 1982) as followed at the Centre de recherche en géochimie isotopique et en géochronologie (GEOTOP) U–Pb Laboratory at the Université du Québec à Montréal (Machado et al. 1990), involving magnetic sorting of the bulk heavy mineral concentrate using a Frantz isodynamic separator, handpicking of highest-quality grains, air abrasion (durations stated in text are at ~20 kPa (3 p.s.i.)), and sample dissolution in Teflon digestion vessels with addition of a mixed $^{205}Pb-^{233}U-^{235}U$ tracer solution. Analyses were carried out on a VG Instruments Sector mass spectrometer equipped with a Daly detector. Average 2σ analytical errors are 0.1% for $^{207}Pb/^{206}Pb$ and 0.5% for U–Pb determinations. All ages are quoted at the 95% confidence level.

The U–Pb results from six rocks analysed in this study are presented in Table 1 and as concordia diagrams in Fig. 3. The samples and their field settings are described from northeast to southwest, across the strike of the GRB, in the following section.

Granitic vein, Rexon's Cove (S46)

A considerable effort was made during field work to identify intrusive rocks that appear to have been intruded synchronously with ongoing deformation, and which might readily be dated using the U–Pb system in accessory minerals. The principal targets were <2 m wide granitic veins in wave-washed coastal exposures where crosscutting relationships with their deformed host rocks could be unequivocally observed. To determine the age at which greenschist-facies deformation occurred along the Rexon's Cove mylonite zone (Fig. 2), a granitic vein interpreted as having intruded syntectonically with these mylonites was sampled. The vein has sharp intrusive contacts (i.e., no strain gradient at its margins) that truncate greenschist-facies deformation fabrics, but is itself folded, boudined, and contains a chlorite-bearing foliation that is parallel to the mylonitic fabric in the host rock (Fig. 4). It is therefore thought to have been emplaced after the onset of greenschist-facies deformation, but prior to cessation of this event. Although it cannot be unequivocally demonstrated using field criteria that deformation of the vein did not occur until long after it was intruded during *renewed* deformation, the strong physical similarity of deformation fabrics and their orientations in both the host rocks and the vein is consistent with the interpretation that the vein was intruded relatively late into an actively deforming zone.

Both zircon and monazite were separated from the sample. Zircon in the diamagnetic fraction consisted of clear, colourless equant prisms euhedral in form. A selection of gem-quality grains was abraded for up to 42 h. Thin (<5 μm) colourless overgrowths were observed on a small proportion of the equant prisms and were removed by abrasion prior to analysis. The upper intercept of the discordia defined by analyses of three fractions indicates an age of 1113^{+6}_{-5} Ma (Fig. 3*a*), interpreted as the age of emplacement of the granitic vein. A single small fragment of a euhedral monazite grain (analysis 4) is concordant at 1078 ± 2 Ma. Whereas the rock may initially have crystallized at 1113 Ma, the 1078 Ma monazite age suggests that approximately 35 Ma may have elapsed prior to final cooling through 725 ± 25°C (Parrish 1990). Attempts to date individual zircon overgrowths were not successful, but we speculate they may be also be ca. 1078 Ma. Alternatively, the 1078 Ma monazite and the zircon overgrowths may represent the crystallization event, the 1113 Ma zircons may therefore be inherited. The Rexon's Cove greenschist-facies mylonites are at least 1113 Ma, and the zone may have been reactivated at, or remained active until, 1078 Ma. Additional samples with identical relationships to the deformation fabrics were collected elsewhere in this greenschist-facies zone, but trace minerals suitable for U–Pb dating were not recovered.

Granitic vein, Red Point (S60)

On Red Point (Fig. 2), a leucogranitic vein transects amphibolite-facies sinistral strike-slip mylonitic fabrics, but is itself deformed by ductile deformation (Fig. 5). The vein has

TABLE 1. U–Pb analytical results

Analysis No.	Mineral[a]	Sample: Magnetic properties[b]	Sample: No. of grains	Size (μm)	Mass (mg)	Concentrations: U (ppm)[c]	Concentrations: Pb (rad) (ppm)[c]	Concentrations: Pb (com) (pg)[d]	Atomic ratios: $\left(\frac{^{206}Pb}{^{204}Pb}\right)^e$	Atomic ratios: $\left(\frac{^{208}Pb}{^{206}Pb}\right)^f$	Atomic ratios: $\left(\frac{^{206}Pb}{^{238}U}\right)^f$	Atomic ratios: $\left(\frac{^{207}Pb}{^{235}U}\right)^f$	Atomic ratios: $\left(\frac{^{207}Pb}{^{206}Pb}\right)^f$	Apparent ages (Ma): $\left(\frac{^{206}Pb}{^{238}U}\right)$	Apparent ages (Ma): $\left(\frac{^{207}Pb}{^{235}U}\right)$	Apparent ages (Ma): $\left(\frac{^{207}Pb}{^{206}Pb}\right)$
(a) Rexon's Cove granitic vein (S46)																
1	z	dia	6	40–60	0.005	138	29	11	813	0.2660	0.18476	1.94680	0.07642	1093	1097	1106
2	z	dia	20	40–60	0.013	185	36	11	2 520	0.2122	0.17680	1.85006	0.07593	1049	1063	1093
3	z	dia	3	60–80	0.011	182	35	25	859	0.2221	0.17199	1.78925	0.07545	1023	1042	1081
4	m	IF	1	20–40	0.002	978	2662	30	864	16.2079	0.18103	1.88115	0.07537	1073	1074	1078
(b) Red Point granitic vein (S60)																
5	z	dia	7	40–60	0.028	94	30	17	2 842	0.1763	0.28743	3.99954	0.10092	1629	1634	1641
6	z	dia	20	40–60	0.066	88	28	78	1 353	0.1729	0.28544	3.95887	0.10059	1619	1626	1635
7	z	dia	9	40–60	0.030	101	32	49	1 091	0.1591	0.28194	3.88858	0.10003	1601	1611	1625
8	z	dia	8	40–60	0.036	111	32	26	2 596	0.1078	0.27480	3.73618	0.09861	1565	1579	1598
(c) Alexis Bay granodioritic gneiss (S99)																
9	m	IF	1	20–40	0.005	7645	4635	11	37 945	2.8071	0.18047	1.87575	0.07538	1070	1073	1079
10	m	IF	1	60–80	0.028	5735	5478	39	46 038	5.0266	0.18073	1.87454	0.07522	1071	1072	1074
(d) Mecklenburg Hr. megacrystic granite (S23A)																
11	z	dia	1	60–80	0.008	124	37	14	1 389	0.0901	0.28598	3.96572	0.10057	1621	1627	1635
12	z	dia	24	20–40	0.016	234	67	20	3 264	0.1363	0.27003	3.66857	0.09853	1541	1565	1597
13	z	dia	27	20–40	0.018	220	61	17	3 984	0.0992	0.26861	3.63999	0.09828	1534	1588	1592
14	z	dia	1	40–60	0.004	315	83	13	1 650	0.0836	0.25776	3.44364	0.09689	1478	1514	1565
(e) Mecklenburg Hr. granitic vein (S23D)																
15	z	dia	14	20–40	0.006	545	99	9	3 970	0.0595	0.18619	1.99654	0.07777	1101	1114	1141
16	z	dia	5	20–40	0.004	725	126	10	3 363	0.0346	0.18159	1.89680	0.07576	1076	1080	1089
17	z	dia	28	20–40	0.007	587	102	72	662	0.0455	0.18057	1.87893	0.07547	1070	1074	1081
(f) Long Harbour granitic vein (S401)																
18	z	M1	20	20–40	0.010	155	51	12	2 593	0.1107	0.31238	4.79571	0.11134	1752	1784	1821
19	z	M1	44	20–40	0.017	160	49	10	4 830	0.1493	0.28725	4.09253	0.10333	1628	1653	1685
20	z	M1	20	20–40	0.012	131	40	12	2 344	0.1648	0.27973	3.87415	0.10045	1590	1608	1632
21	z	M1	24	20–40	0.008	161	48	10	2 071	0.1549	0.27434	3.71523	0.09822	1563	1575	1591

[a] z, zircon; m, monazite.
[b] dia, diamagnetic at −0.5° tilt of Frantz magnetic separator at maximum current; M1, magnetic at 1° tilt; IF, nonmagnetic between 1.0 and 1.8 A at 10° side slope.
[c] Concentrations are known to 10–20% for sample weights below 20 μg. For sample weights less than 1 μg, the concentrations listed are maximum values.
[d] Total common Pb present corrected for common Pb in spike.
[e] Measured ratio, corrected for fractionation only.
[f] Ratios corrected for spike, fractionation, blank, and initial common Pb. Maximum total blanks for zircon analyses are 15 pg for Pb and 2 pg for U; for monazite analyses, they are 35 pg and 5 pg, respectively. The isotopic composition of initial common Pb was calculated with the two-stage model of Stacey and Kramers (1975). The decay constants are those recommended by the Subcommission on Geochronology of the International Union of Geological Sciences (Steiger and Jäger 1977).

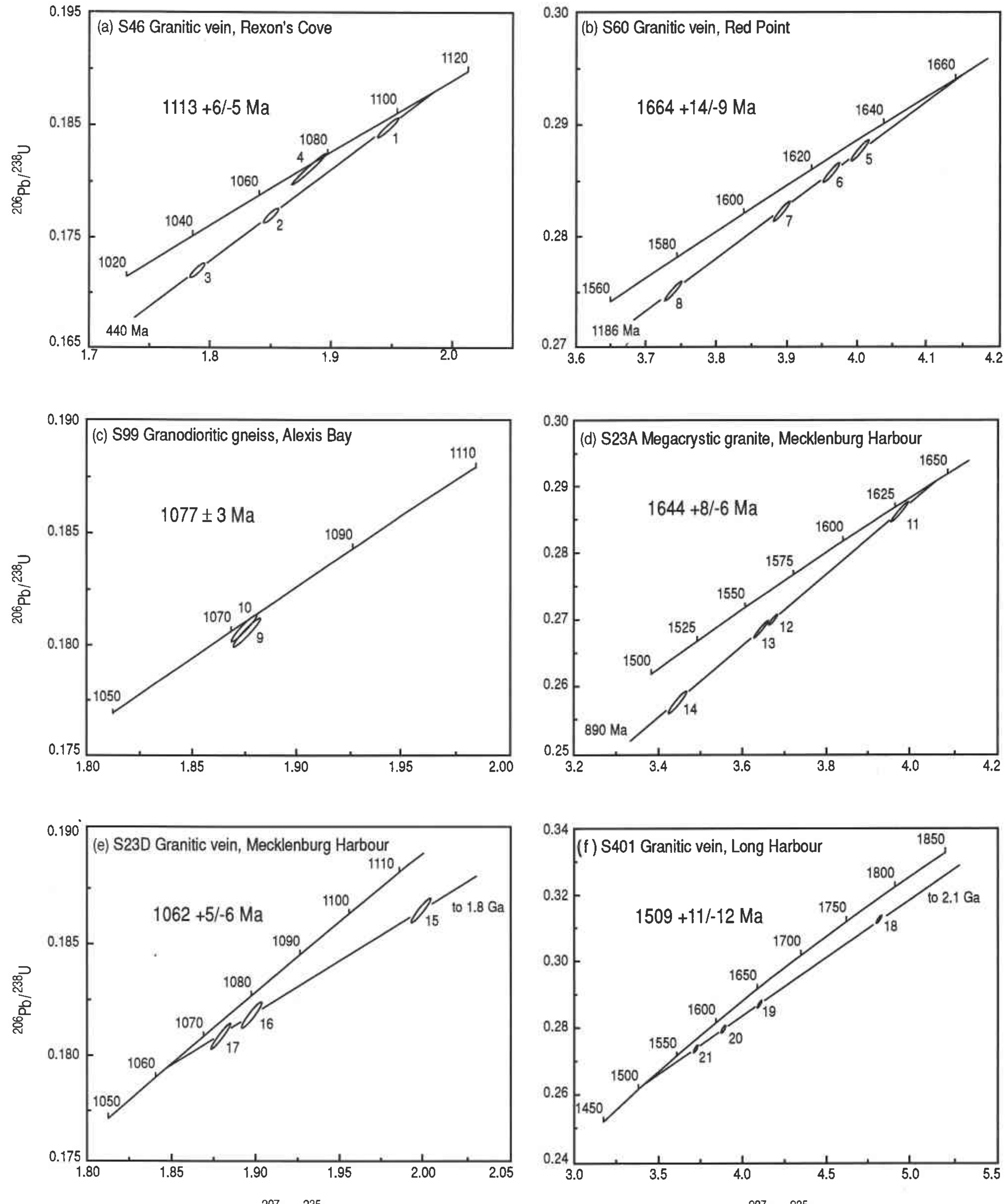

FIG. 3. Concordia diagrams for samples analysed in this study. Analytical data are listed in Table 1.

sharp intrusive contacts and planar and linear fabric elements in orientations identical to its deformed metasedimentary gneiss host rocks. This is thought to indicate that although the vein intruded *after* the amphibolite-facies deformation fabric had been developed in the host rocks, ongoing deformation imparted identical fabric elements to the leucogranitic vein, consistent with the interpretation that the vein was intruded relatively late into a continuously deforming zone. The crystallization age of the vein should therefore indicate a minimum age for this high-grade deformation.

Zircon separated from this sample included a variety of variably altered grains, but was dominated by a population of

FIG. 4. Folded and boudined granitic vein (sample S46) in Rexon's Cove greenschist-facies mylonite zone. Note that the vein truncates fabrics in the mylonitic rocks, but is itself deformed at greenschist facies and is therefore interpreted as having intruded synchronously with ongoing deformation in this zone. Pen (central foreground) is 15 cm long.

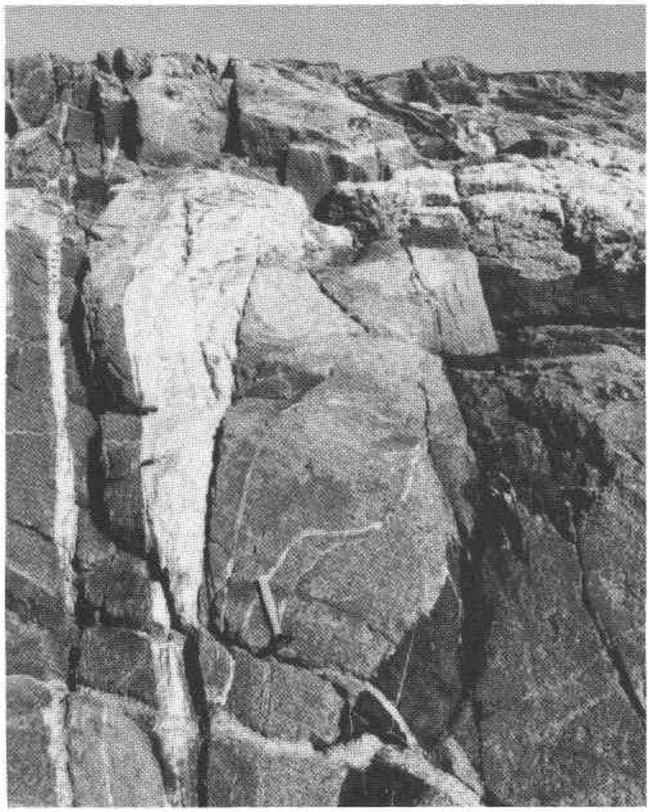

FIG. 5. Outcrop at Red Point, view toward west–northwest. Granitic vein (sample S60) truncates amphibolite-facies fabric in host paragneiss, but is itself affected by this deformation and is therefore interpreted as having intruded synchronously with movement within this zone. Hammer in central foreground is 35 cm long.

colourless, euhedral prisms with a stubby habit. As examined using a binocular microscope, these gem-quality grains showed no evidence of overgrowths or internal core structures. A population from the highest quality magnetic fraction, free of visible inclusions and cracks, was selected and given an extended abrasion treatment for up to 100 h. Four populations were analysed and showed a positive correlation between time of abrasion and $^{207}Pb/^{206}Pb$ age. The four analyses (Nos. 5–8) define a discordia line (Fig. 3*b*) with an upper intercept of 1664^{+14}_{-9} Ma, which is interpreted as the age of emplacement of the vein, and a lower intercept of 1186^{+82}_{-72} Ma, thought to be the result of Pb loss due to younger tectonothermal activity (discussed below). Although the total probability of fit of the four points is good (74%, Davis 1982), the shallow angle of intersection between the discordia line and concordia results in large uncertainties on the intercepts. As field relationships suggest that this vein was intuded into an *active* shear zone, 1664 Ma is a minimum age for this deformation.

Granodioritic gneiss, Alexis Bay (S99)

A map unit of polydeformed granodioritic gneiss, intruded by numerous granitic phases and mafic dykes, was recognized by Gower et al. (1987, 1988). In an attempt to characterize the age of this unit, a representative sample was selected from a locality at the west end of Alexis Bay (Fig. 2). The sample contained both zircon and monazite. A wide variety of zircon morphologies was present in each of the magnetically separated fractions. Grains were of low quality, and as a result zircon was not analysed. Two single grains of monazite, a smaller euhedral grain (Fig. 3*c*, analysis 9) and a larger fragment (analysis 10), were selected (Table 1); they are identical within analytical error. The average $^{207}Pb/^{206}Pb$ age of 1077 ± 3 Ma is interpreted as the best estimate for the age of the final tectonomagmatic episode experienced by the gneiss at the sample location.

Mecklenburg Harbour (S23)

The potassium feldspar megacrystic granite that underlies an important part of the GRB (Gower et al. 1987, 1988) is well-exposed on the shores of Mecklenburg Harbour in the southeast part of the area (Locality 4, Fig. 2). A representative sample of this magnetite-bearing granite was obtained from an outcrop where a number of crosscutting relationships with other rock types are apparent. A characteristic feature of this map unit is the ubiquitous presence of mafic dykes that are up to several metres wide. The dykes display evidence of two distinct phases of deformation. The dykes are boudined, indicating an initial period of extension. The dyke boudins are also folded, indicating subsequent compression, and display a distinctive "lobe-and-cusp" fold morphology (Fig. 6), with granitic material filling the rounded lobes or mullions, dyke material filling the tightly pinched cusps (see also Fig. 5 in Hanmer and Scott 1990). A moderate- to well-developed axial planar foliation associated with these folds, observed both in the dykes and the granitic rocks, is parallel to the west–northwest-trending foliation observed throughout the GRB.

The observed response of the dykes to the sequence of deformation (extension followed by compression) suggests that they behaved initially as relatively more competent than the enclosing granite (boudinage) and subsequently as relatively less competent (formation of fold cusps). This apparent reversal in rheological behavior can be explained in terms of strain rate variation and changing thermobarometric conditions associated with either cooling magmatic bodies or regional granulite-facies metamorphism (Hanmer and Scott 1990; Talbot and Sokoutis 1992). The absence of granulite-facies assemblages in these rocks suggests that much of the high-temperature shearing observed in the megacrystic granite may have occurred early in the cooling history of the rock and can essentially be considered as synmagmatic. This relationship implies that the granite and the dykes are comagmatic and that both are syntectonic with respect to the imposed foliation.

Four samples were collected at this location. The oldest magmatic phase in the outcrop is the megacrystic granite (S23A). A ~50 kg sample collected from a weakly foliated part of the outcrop that was free of visible xenoliths or mafic dykes yielded high-quality zircon sufficient for analysis. Two samples of the mafic dykes were collected; no U-bearing minerals suitable for U–Pb dating were recovered from either sample. A ~10 kg sample was collected from a 10–15 cm wide pink aplitic vein (S23D) that intrudes the megacrystic granite and crosscuts both dyke phases, but is itself mildly deformed and locally foliated. A trace amount of high-quality zircon was recovered from this sample.

Megacrystic granite (S23A)

Much of the zircon throughout the more magnetic fractions consisted of cloudy irregular, altered grains of probable xenocrystic origin, or coarse, cracked, faint-pink to colourless square-section prisms. Increasingly common in the less magnetic fractions were euhedral, stubby (~2:1) colourless prisms. In the diamagnetic fraction, the majority of euhedral gem-quality grains is of this type. Four populations of inclusion- and crack-free grains of varying size were selected for analysis (Nos. 11–14, Table 1); they define a discordia line with an upper intercept age of 1644^{+8}_{-6} Ma, interpreted as the age of granite emplacement, and a lower intercept age of 890^{+56}_{-50} Ma (Fig. 3*d*). Some of the larger grains in each of the magnetic fractions were overgrown by extremely thin, colourless overgrowths; attempts to analyze individual overgrowths were unsuccessful.

The predominance of the euhedral, stubby prisms in the higher quality magnetic fractions suggests that these are the most likely type to have crystallized magmatically, and 1644^{+8}_{-6} Ma can be reasonably interpreted as the age of crystallization of this sample. The lower intercept, and possibly the thin overgrowths, may be related to tectonothermal activity ca. 0.9 Ga. Although the four analyzed populations lie on a well-defined discordia (78% total probability of fit, Davis 1982), lead loss less than 800 Ma after initial crystallization has resulted in a shallow angle between concordia and the discordia line, leading to rather large uncertainty in the calculated upper intercept age. Based on the interpretation of the relative timing of deformation in the dykes and the megacrystic granite, the crystallization age of this unit is suggested as the age of the deformation fabrics in this sample, and indeed much of the amphibolite-facies shearing observed in the belt.

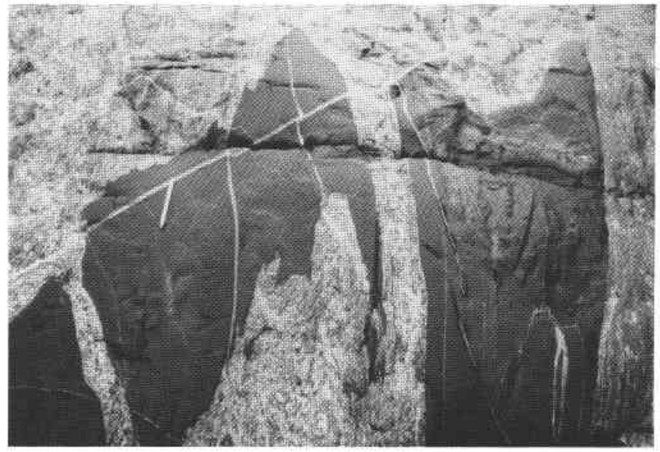

FIG. 6. Deformed megacrystic granite (sample S23A) and mafic dykes at Mecklenburg Harbour. Dykes were initially extended (boudinage) and then compressed to form a strong fabric parallel to the axial planes of the "lobe-and-cusp" folds (described in text). Narrow vein that cuts diagonally across megacrystic granite and dykes is similar to sample S23D. Pencil at left is 12 cm long.

Granitic vein (S23D)

Zircon separated from this sample consisted almost exclusively of colourless, 3:1 aspect square-section prisms in each of the magnetically separated fractions. Inclusion- and crack-free grains that showed no visible core-overgrowth relationships were selected from the diamagnetic fraction and abraded for up to 42 h. Three populations of these abraded grains were selected for analysis. They define a discordia line (Fig. 3*e*) with a lower intercept of 1062^{+5}_{-6} Ma and an upper intercept of 1790^{+142}_{-122} Ma. The three analyses lie near the lower intercept (95–98% discordant), and yield increasingly older $^{207}Pb/^{206}Pb$ ages with increasing total time of abrasion (Nos. 15–17, Table 1).

The alignment of the three points suggests that air abrasion has successfully removed any effects of recent lead loss (Krogh 1982). With increased abrasion and loss of material from the outer parts of grains, the populations yield increasingly older $^{207}Pb/^{206}Pb$ ages, suggesting that the zircon crystals contain a ca. 1.8 Ga old component of Pb, interpreted as originating from unobserved xenocrystic cores. The lower intercept, 1062^{+5}_{-6} Ma, may therefore correspond to the time of lead-loss and almost complete resetting of the U–Pb chronometer during emplacement of this vein. The analysed zircons have relatively high uranium contents (545–725 ppm) and could readily have lost radiogenic lead during a subsequent tectonothermal event. Alternatively, small amounts of core material may have been overgrown by new, magmatic zircon at 1062 Ma, varying proportions of core and overgrowth resulting in the range of observed $^{207}Pb/^{206}Pb$ ages in analyses Nos. 15–17.

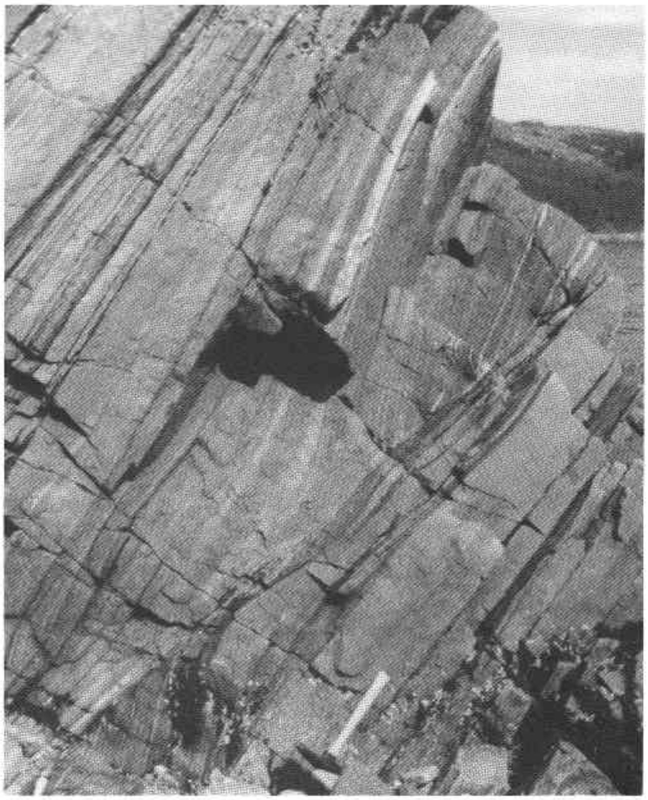

FIG. 7. Outcrop of straight gneisses at Long Harbour (S401), view toward east–southeast, with extensional megashear band indicating top side to the south sense of displacement. Hammer in central foreground is 35 cm long.

The age of the host rocks (S23A, 1644^{+8}_{-6} Ma) is at least 16 Ma younger (within analytical error) than the upper intercept age of the inherited grains (1790^{+142}_{-122} Ma), suggesting that the immediate host rocks may not have provided the xenocrysts. Magmatic rocks that are within the age range of the xenocrysts are known from this region and possibly underlie the Mecklenburg Harbour area (Gower et al. 1992 and references therein). However, the extremely long projection of the discordia line from the three analyses, and resultant large uncertainty in the upper intercept age, indicate that this interpretation must be regarded with caution.

Granitic vein, Long Harbour (S401)

A 100–150 m wide zone of granitic, granoblastic straight gneiss (Hanmer 1988) occurs along the southern margin of the GRB (Fig. 2). It is the widest continuous package of rocks observed that have been strongly deformed at high grade within the area (Hanmer and Scott 1990) and possibly represents the most important structural zone in the belt. A moderately foliated, pink-weathering aplitic vein crosscuts this strong fabric (Fig. 7), but can be traced across strike to where it becomes transposed and ultimately parallel to the layers in the straight gneiss. This relationship indicates that it was intruded after much of this deformation, but prior to the final stages of high-grade deformation.

High-quality zircon separated from this sample consists of small, colourless, elongate, square-section prisms. Core–overgrowth structures were not observed in any of these grains. An inclusion- and crack-free selection was abraded for 35–46 h. Four populations were analysed; they define a discordia line with an upper intercept age of 2067 ± 28 Ma and a lower intercept age of 1509^{+11}_{-12} Ma (Fig. 3*f*). A positive correlation exists between $^{207}Pb/^{206}Pb$ age and duration of abrasion, indicating that an older component of radiogenic lead is preserved in more internal parts of the grains selected, despite the absence of visible cores. These observations suggest that these grains contain zircon formed at ca. 2.07 Ga and that they experienced almost complete lead loss and resetting of the U–Pb chronometers at 1509 Ma. Alternatively, the lower intercept may represent the age of zircon overgrowths not recognized optically on the grains that were analysed. In either case, the analysed grains are interpreted as in part xenocrystic, and the lower intercept age is interpreted as the minimum age of emplacement of this vein into the actively deforming shear zone at Long Harbour.

Discussion

Labradorian events

Gower et al. (1992) have recognized three distinct early- to mid-Labradorian magmatic pulses in eastern Labrador, which occur broadly from oldest to youngest from southwest to northeast, across the structural grain of the eastern Grenville Province. The oldest, referred to as the Neveisik Island magmatic event, found in the central part of the Lake Melville terrane at ca. 1677 Ma, consists of granitoid plutons intruded by mafic dykes. The second is recognized in the Hawke River terrane at ca. 1670 Ma (Red Island magmatic event) and involves voluminous granitic magmatism and mafic dyke emplacement. Migmatization and deformation of these rocks must have occurred prior to 1663 Ma, the age of an undeformed discordant granite intrusion (Shoal Bay) that intrudes ca. 1671 Ma tonalitic gneisses of the Red Island magmatic event. The youngest pulse, in the Groswater Bay terrane, is the Double Island event, which consists of tonalite, quartz diorite, and granodiorite plutons that range in age from 1658 to 1649 Ma. These rocks are intruded by mafic dykes, which are deformed and metamorphosed prior to the intrusion of the Michael Gabbro at 1426 ± 6 Ma (Schärer et al. 1986). Titanite growth at ca. 1646 Ma observed in samples from the eastern part of the Hawke River terrane is thought to be linked with the second deformation event (Gower et al. 1992).

Extensive felsic magmatism has been identified throughout the northern part of the eastern Grenville Province and northward into the Makkovik Province at ca. 1650 Ma (Trans-Labrador Batholith of Wardle et al. 1986). A period of late-Labradorian granitic magmatism, from 1632 to 1622 Ma, is recognized in the Groswater Bay and Hawke River terranes (Schärer et al. 1986; Gower et al. 1992).

Intrusion of the leucogranite vein at Red Point (S60, Fig. 8) into ongoing sinistral strike-slip deformation at 1664 Ma is coeval with the earlier (pre-Shoal Bay pluton) phase of regionally recognized Labradorian deformation in the Hawke River and Lake Melville terranes (Gower et al. 1992). As Gower et al. (1992) point out, the extent of magmatic activity at 1663 Ma is not known; the Red Point syntectonic leucogranite vein, approximately 85 km due south of the Shoal Bay pluton, is only the second known example of igneous activity of this age in the eastern Grenville Province. It nonetheless offers direct evidence justifying correlation of deformation events from the north and west into the GRB at ca. 1664 Ma.

The 1644 Ma megacrystic granite at Mecklenburg Harbour (S23A, Fig. 8), which is interpreted as having intruded into

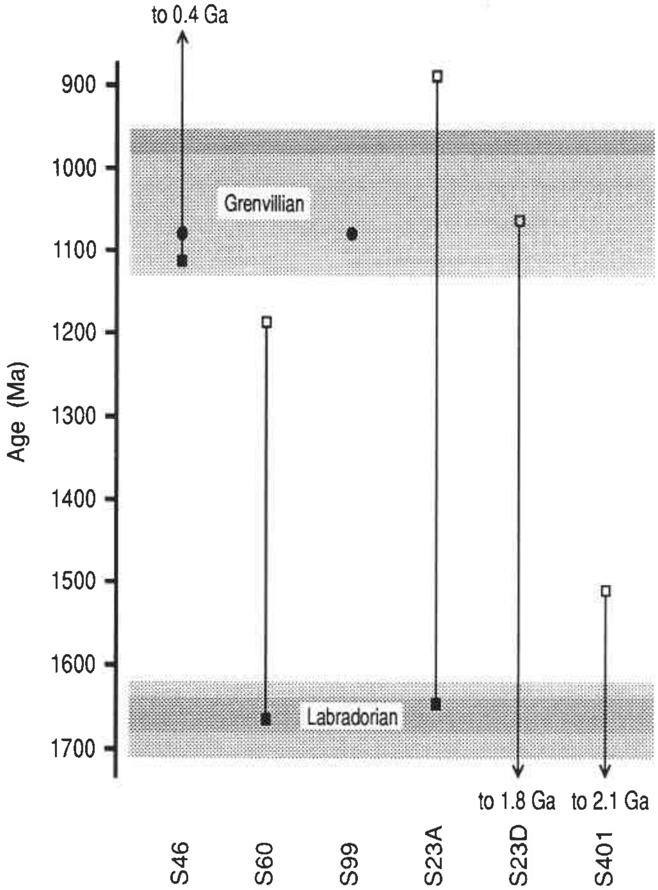

FIG. 8. Summary of U–Pb geochronological data for the eastern part of the Gilbert River Belt. Periods of regionally extensive Grenvillian (Gower et al. 1991) and Labradorian (Gower et al. 1992) magmatism are shown as shaded areas. Filled squares correspond to upper intercept ages, open squares to lower intercept ages, and filled circles to concordant monazite ages. Darker and lighter bands correspond to main and subordinate periods of orogenic activity, respectively.

ongoing dextral strike-slip deformation in the GRB, is coeval with the second period of Labradorian metamorphism and deformation (post-Double Island magmatic event) recognized by Gower et al. (1992). The field relationships observed at Mecklenburg Harbour are representative of much of the high-grade deformation in the GRB. We therefore suggest that the age of this unit, and corresponding synmagmatic deformation, support the interpretation that widespread deformation was occurring throughout the eastern Grenville Province during Labradorian orogeny. As much of this deformation is synmagmatic, we suggest that west–northwest-elongated forms of the megacrystic granite bodies are in fact primary, these rocks having been intruded as sheet-like bodies. Their magnetite-rich compositions and elongate map patterns contribute to the striking regional aeromagnetic features (Geological Survey of Canada 1985).

The age of the granitic dyke (S401) at Long Harbour (1509^{+11}_{-12} Ma, Fig. 8), interpreted as syntectonic with the formation of the straight gneiss, at first seems somewhat anomalous, as rocks of ca. 1.5 Ga age are not widely known in southeastern Labrador (Tucker and Gower 1990). Three Grenvillian granitic intrusions have yielded evidence of zircon growth of roughly this age. A garnet–biotite pegmatite on Double Island (Groswater Bay terrane) was emplaced at 1499^{+8}_{-7} Ma (Schärer et al. 1986) and is identical, within analytical uncertainty, to the emplacement age of the granitic dyke at Long Harbour. Zircons from the Rivière Bujeault headwaters syenite (Pinware terrane), emplaced at 964 ± 5 Ma, define an upper intercept of 1530 ± 30 Ma (Gower et al. 1991). The banded granodioritic Cuff Island gneiss (Groswater Bay terrane), metamorphosed at 968^{+7}_{-8} Ma, contains inherited zircons dated at 1587^{+60}_{-55} Ma (Schärer et al. 1986). A fourth sample, a 1029 ± 2 Ma microgranite dyke at Beaver Brook (Hawke River terrane) shows evidence of inheritance of 1566 ± 13 Ma zircons (Schärer et al. 1986). Thus, although ca. 1.5 Ga rocks are not common, there is significant evidence in favour of post-Labradorian, pre-Grenvillian magmatism and associated deformation. The 1509 Ma age of the granitic vein from the Long Harbour straight gneisses is thought to provide a reliable minimum age of deformation along the southern margin of the GRB.

Grenvillian events

Numerous discrete pulses of Grenvillian-aged tectonomagmatic activity have been identified in the eastern Grenville Province of southern Labrador and eastern Quebec (Gower et al. 1991 and references within). The volume of Grenvillian-aged rocks that have been identified to date increases across strike toward the southwest.

In the eastern Groswater Bay terrane, zircons from a 1649 Ma granitic intrusion define a lower discordia intercept of 980 Ma (Schärer and Gower 1988), and titanite ages between 978 and 968 Ma have been reported (Schärer et al. 1986). In the Hawke River terrane, a 1029 Ma monazite and a 977 Ma titanite age have been identified (Schärer et al. 1986; Schärer and Gower 1988). The Southwest Brook granite, along strike from the GRB in the Lake Melville terrane, contains zircons that define an upper intercept of 1079 ± 6 Ma (Schärer and Gower 1988). Discordant titanites with $^{207}Pb/^{206}Pb$ ages of ca. 1045 Ma and monazite with ages ca. 1030 Ma have been reported from the Lake Melville terrane (Schärer et al. 1986; Schärer and Gower 1988; Gower et al. 1991). Rocks of the Pinware and easternmost Mealy Mountains terranes have been intruded by a series of weakly deformed to nondeformed felsic intrusions (monzonite to granite), which form distinctive, equant plutons and range in age from 966 ± 3 Ma to 956 ± 1 Ma (Gower and Loveridge 1987; Gower et al. 1991).

The granitic vein that intruded the Rexon's Cove greenschist-facies mylonite zone at 1113^{+6}_{-5} (S46, Fig. 8) is less than 3 km from the western end of the Gilbert Bay Pluton, dated at 1132^{+7}_{-6} Ma (Gower et al. 1991). This supports the suggestion that the granitic vein, and indeed much of the discordant granitic veining observed in the northeastern part of the GRB, may be related to the Gilbert Bay Pluton (Gower et al. 1987; Hanmer and Scott 1990). The lower discordia intercept of the Red Point granitic vein (1186^{+82}_{-72} Ma, S60) is similar within error to both of these rocks. The 1078 Ma monazite age from the Rexon's Cove granitic vein and the 1077 Ma old monazite in the granodioritic gneiss from Alexis Bay (S99, Fig. 8) are identical to the age previously reported further along strike for the Southwest Brook granite (1079 Ma), possibly indicating a distinct tectonomagmatic event within the GRB – eastern Lake Melville terrane at this time. The granitic vein at Mecklenburg Harbour (S23D, 1062 Ma, Fig. 8) is significantly younger than, but possibly related to, the ca. 1078 Ma event. With the possible exception of the lower intercept of the megacrystic granite from Mecklenburg Harbour (890^{+56}_{-50} Ma, S23A, Fig. 8), evidence of thermal disturbance that might correspond to the late granitoid plutonic activity (ca. 966–956 Ma) to the south of the GRB was not observed. Thus, within the GRB, Grenvillian-aged igneous rocks are of limited extent only and Grenvillian deformation appears to locally overprint Labradorian structures.

Directly dating periods of deformation

Four of the samples for which results are presented here are interpreted as having been intruded into active zones of ductile deformation (S46, S60, S401, and S23A). The first three of these samples are narrow granitic veins, which truncate ductile deformation fabrics in the rocks that they intrude, but are themselves deformed by ductile deformation processes and have developed fabric elements in orientations identical to their host rocks, suggesting that they were intruded synchronously with ongoing ductile deformation. Zircon and monazite separated from samples of these veins provided useful information about the timing of emplacement of these rocks and consequently minimum age information on the timing of deformation at each sample location. In the fourth sample (S23A), it was demonstrated, based on mechanical (i.e., lobe-and-cusp) relationships in the outcrop (Hanmer and Scott 1990), that much of the penetrative deformation fabric was imparted during initial cooling of the rock, and thus the crystallization age of the sample provides a minimum age for this deformation. Two of these deformation ages (S60, 1664 Ma and S23A, 1644 Ma) are coeval with regionally recognized periods of deformation (Gower et al. 1992) indirectly supporting our outcrop-based interpretations. The ages of deformation determined in the Long Harbour area (S401) and Rexon's Cove greenschist mylonite zone (S46) have not been previously recognized in the eastern Grenville Province; in both cases the ages determined here are consistent with known field relationships and existing geochronological data.

Conclusions

The results presented here indicate that the Gilbert River Belt experienced two distinct episodes of tectonomagmatic activity, separated in time by 500–600 Ma. The older events (1664–1644 Ma) involved voluminous felsic plutonism and deformation at amphibolite-facies conditions that resulted in the formation of dominantly dextral and subordinate sinistral strike-slip mylonite zones and corresponds with Labradorian orogenesis recognized throughout the eastern Grenville Province. The spatial distribution of the majority of amphibolite-facies sheared rocks within the belt (Fig. 2) indicates that they can accommodate only a small amount of total displacement (Hanmer and Scott 1990). The zone of most significant displacement may be the zone of banded, straight gneiss at Long Harbour (Hanmer and Scott 1990). The Long Harbour straight gneiss zone appears to have been active at 1509 Ma, clearly much later than Labradorian events in the eastern Grenville Province. As this age represents a minimum (i.e., it postdates much of the strong deformation in this zone), we cannot determine here if the zone was initiated during the Labradorian or alternatively if it represents subsequent (postcollisional ?) readjustment while these rocks remained at mid-amphibolite facies conditions.

Narrow granitic veins have been identified at 1113 and 1062 Ma, confirming the presence of Grenvillian intrusions across the GRB. The older of these veins is interpreted as having intruded a zone of ongoing, greenschist-facies deformation, the extensive Rexon's Cove mylonite zone, indicating that this zone was active during Grenvillian time. The age of the Occasional Harbour zone of greenschist-facies mylonites (Fig. 2) was not determined, but based on its similar metamorphic grade and physical attributes, we speculate that it might also be a Grenvillian feature. We have not determined the age of the amphibolite-facies deformation in the host rocks of the Rexon's Cove and Occasional Harbour zones. Therefore, we are unable to directly determine if the greenschist-facies mylonites represent late reworking of Labradorian high-grade rocks, or if they were derived by continuous cooling of a high-grade Grenvillian deformation zone, although field relationships support the former interpretation. Two samples contained monazite, dated at 1078 Ma in both cases, indicating a late tectonothermal event within the GRB, coeval with the intrusion along strike of the Southwest Brook granite, collectively suggesting widespread tectonomagmatic activity at this time. Igneous activity coeval with late (966–956 Ma) magmatism identified to the southwest of the GRB by Gower et al. (1991 and references therein) was not identified in the present study. Whether this activity is absent in the GRB or was not sampled is not known.

Attempts to directly determine the age of ductile deformation appear to have been a first-order success. Although we were unable to date every one of the samples that were collected, the results are nonetheless encouraging. In several cases, the syntectonic material that was sampled did not contain high-quality U–Pb bearing minerals related to intrusion. In other cases, overgrowths on existing minerals were present but were too thin to analyse. Based on the present examples from the GRB, corroborated by the existing regional U–Pb geochronological framework, it is suggested that careful selection of rocks that have synkinematic crosscutting relationships with ductile deformation may allow direct dating of these tectonic events. The examples described here may serve as a model for workers in deformed terranes looking for a technique to quantify the evolution of deformation.

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