U–Pb zircon geochronology and implications of Cambrian plutonism in the Ellsworth belt, Maine

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ABSTRACT

The Ellsworth belt is one of several fault-bounded blocks exposed along the southeastern coast of Maine that formed within Ganderia. New ID-TIMS U–Pb geochronological data integrated with field relationships provide additional insights into the timing of magmatism and deformation in the Ellsworth belt. The deformed Lamoine Granite was selected for U–Pb zircon analysis in order to: *i*) establish the protolith age; *ii*) provide direct temporal constraints on regional low-grade metamorphism and deformation; and *iii*) elucidate relationships between the Ellsworth belt and coeval rocks elsewhere in the Appalachian orogen. The Lamoine Granite was emplaced within the Ellsworth Schist at 492 ± 1.7 Ma; this is the first unequivocal evidence for a Furongian magmatic event in the Ellsworth belt. The schistosity in the Lamoine Granite is parallel to the main fabric of the host Ellsworth Schist and provides a maximum estimate for timing of the regional metamorphic overprint. Widespread deformation in the Ellsworth belt where kinematic indicators indicate a top-to-northwest sense of shear is attributed to thrusting during which progressive horizontal shortening, caused crustal thickening and peak greenschist facies metamorphism. The Cambrian U–Pb age permits correlation of the Lamoine Granite with the Cameron Road Granite in the Annidale belt of New Brunswick where subduction-related magmas intruded the Penobscot arc–back-arc and were subsequently deformed during the Penobscot Orogeny.

Keywords: Appalachians, Ganderia, geochronology, granites, Maine, Cambrian

PREAMBLE

The Cambrian Ellsworth belt occupies the eastern portion of the Penobscot Bay inlier, coastal Maine (Fig. 1; Reusch et al. 2018). It remains an inadequately documented yet highly significant part of Ganderia, the leading tectonic element in the peri-Gondwanan realm of the Appalachian orogen (Hibbard et al. 2007). Bimodal volcanic rocks of the Ellsworth belt and a slice of mantle peridotite have been interpreted to record rifting of Ganderia from Gondwana between 510 and 500 Ma (Schulz et al. 2008; van Staal et al. 2012). Its complex, heterogeneous deformation suggests a protracted but still poorly understood accretionary history. While Ganderia's Paleozoic tectonic evolution is well established in other parts of the Appalachian orogen (e.g., Rogers et al. 2006; Johnson et al. 2012; Pollock et al. 2012), a detailed understanding of the Ellsworth belt's role in this evolution has been hampered by a dearth of high-precision isotopic age determinations.

Plutonic rocks are abundant throughout the Penobscot Bay inlier. The anomalous pre-Silurian deformed Lamoine Granite in the Ellsworth belt is of special interest because it contrasts with the majority of Silurian to Devonian massive plutons (e.g., Stewart 1998; Tucker et al. 2001). However, rather little is known of the age, character, and significance of this penetratively deformed and metamorphosed unit—specifically whether it represents basement, synrift magmatism, or post-rift subduction-related magmatism. Detailed bedrock mapping (Reusch and Hogan 2002; Reusch 2003a; Pollock 2008) suggested that it may be coeval with, or pre-date, adjacent Cambrian volcanic rocks.

In the Ellsworth belt, a major unanswered question concerns the regional tectonic significance of an angular unconformity between the Ellsworth Schist and overlying Castine Volcanics. The Lamoine Granite was speculated to contain the same foliation as within pebbles of presumed Ellsworth Schist in the basal conglomerate of the Castine Volcanics. Other reasons for selecting the Lamoine Granite for U–Pb zircon geochronology were to: i) test whether these outcrops represent isolated exposures of Ganderian basement; ii) provide a maximum age for regional greenschist metamorphism and northwest-vergent deformation; and iii) compare its age with previously published ages from the region (e.g., Tucker et al. 2001; Schulz et al. 2008).

In this study, we present a new high precision U–Pb zircon age by ID-TIMS on the deformed and metamorphosed Lamoine Granite that may bear on the nature of the Ellsworth-Castine unconformity. Implications of the new U–Pb age are used in conjunction with data from regional field investigations (Reusch 2003b; Pollock 2008) to compare the history of granitic magmatism, deformation and regional metamorphism in the Ellsworth belt with the interpreted tectonic evolution of Ganderia elsewhere in New England (e.g., Putnam-Nashoba belt) and Atlantic Canada (e.g., Annidale belt and Exploits subzone).

GEOLOGICAL SETTING

The Penobscot Bay inlier, ca. 4500 km^2 in area, extends from the Sennebec Pond Fault west of the Camden Hills on the west shore of Penobscot Bay to the east shore of Frenchman Bay and beyond. It hosts one of the most complete pre-Silurian sequences in Ganderia of the Appalachian peri-Gondwanan realm (Hibbard et al. 2007). The inlier comprises the dominantly continental St. Croix and Islesboro belts (Reusch et al. 2018) and, to the east, the Ellsworth belt of contrasting oceanic affinity (Schulz et al. 2008). The Islesboro belt contains the oldest known Gondwanan Proterozoic basement in Maine. The Penobscot

Bay inlier is juxtaposed with strata of the Fredericton Trough along the Sennebec Pond Fault to the northwest. Silurian strata of the Coastal Volcanic belt unconformably overlie the inlier to the southeast.

The Ellsworth belt extends for over 250 km along the south coast of Maine-New Brunswick and is interpreted from seismic data (Stewart 1998) to be several kilometres thick. It comprises a structurally complex supracrustal assemblage of mainly low-metamorphic grade. Rocks include polydeformed quartz-feldspar-chlorite-mica schists (Ellsworth Schist) and Miaolingian bimodal volcanic rocks of marine origin. Minor occurrences of pelagic chert, limestone, and black shale are present on North Haven Island; serpentinized peridotite is present on Deer Isle (Reusch et al. 2018). The Ellsworth Schist, dominant component of the belt in the study area between Penobscot Bay and Frenchman Bay (Fig. 2), is juxtaposed northwestward against sedimentary rocks of the St. Croix belt along the steeply dipping Turtle Head fault. Westward, ca. 3 km northeast of Castine, the Ellsworth belt structurally overlies younger Penobscot Formation metamorphosed black shales of the St. Croix belt. Basement of the Ellsworth belt is nowhere exposed, however, Nd- and Pb-isotopic data (Schulz et al. 2008) suggest it resembles Neoproterozoic Ganderian basement in Atlantic Canada.

Lamoine Granite

Within the Ellsworth belt, the Lamoine Granite is a 1500 m long, east-west striking sill that crops out along the north shore of Mount Desert Narrows (Fig. 3A). The unit dips moderately to the south and has a maximum width of ca. 100 m. It is a white to pale-grey-weathered granite composed of medium-grained, equigranular anhedral quartz and feldspar; the assemblage is metamorphosed to lower greenschist (chlorite-muscovite) facies. Fracture surfaces are commonly hematite coated. The granite is flanked by the Ellsworth Schist on its north side but an unequivocal intrusive contact with the schist is nowhere exposed. Both McGregor (1964) and Reusch (2003a) interpreted the Lamoine Granite to have been emplaced in the Ellsworth Schist as a hypabyssal pluton related to the Rhyolite of Goose Cove. The schistosity (Fig. 3B) in the Lamoine Granite is defined by strongly aligned muscovite and chlorite that parallel the regional schistosity in the Ellsworth Schist. The granite, therefore, pre-dates the main episode of deformation in the Ellsworth belt.

Additional relative age constraints are provided by an undeformed, massive flow-laminated rhyolite dyke (Reusch 2003b) that extends from Lamoine Beach to Racoon Cove (Fig. 2). This intrusion clearly crosscuts the penetrative D_2 fabric present in the Lamoine Granite and Ellsworth Schist. The dyke is interpreted as a feeder to the nearby Silurian (424 ± 2 Ma) Cadillac Mountain intrusive complex (Seaman et al. 1995).

Ellsworth Schist

The Ellsworth Schist (Smith et al. 1907; Schulz et al. 2008) of the Ellsworth belt comprises a structural assemblage of polydeformed and metamorphosed bimodal volcanic and sedimentary rocks. The unit is dominated by a white-weathering, dark green quartz-feldspar-muscovite-chlorite rock—a phyllite to schist consisting of alternating laminae of quartz-feldspar and chlorite-rich mafic material. Stewart (1998) described bimodal marine volcanic rocks in 10–100 m thick units. Basalt flows and pillows typically contain chlorite, actinolite, and minor epidote and mm-size feldspars. Rhyolite layers, which range in thickness from several cm to 1 m thick and more, are typically grey and weather cream to white; some are interpreted as quartz and/or feldspar crystal tuffs. The Egypt member of the Ellsworth Schist is a ca. 1 km thick assemblage of metamorphic rocks exposed in the core of a late (D_3) synform. It consists of feldspar-porphyroblastic schists, amphibolites, and greenstones. The Morgan Bay member of the Ellsworth Schist, which crops out on the west shore of Union River Bay, comprises medium-bedded pelitic schists, impure quartzites, and minor conglomerate. The age of the Ellsworth Schist is constrained by a U–Pb zircon age of 508.6 ± 0.8 Ma from quartz-phyric felsic tuffs at a location ca. 25 km to the southwest of the Lamoine Granite (Schulz et al. 2008).

Metamorphism

The Ellsworth Schist is regionally metamorphosed to greenschist facies. Mineral assemblages throughout the unit are characterized by quartz and albite, with abundant chlorite ± epidote, and the replacement of plagioclase and K-feldspar by muscovite. Most quartzo-feldspathic layers are bounded by layers of biotite-muscovite-chlorite. The highest-grade metamorphic rocks (M_3) occur in the distinctly younger contact aureoles of Silurian and younger plutons, where pelitic layers of the Ellsworth Schist contain appreciable andalusite, cordierite, and tourmaline (Reusch 2003a).

Deformation

Several phases of deformation are identified in the Ellsworth Schist. Outside of the Morgan Bay member, unequivocal sedimentary bedding is nowhere readily discernible. The oldest fabric preserved within the Ellsworth Schist is a well-developed, thin segregation of green chlorite and white sericite. The dominant foliation is a composite schistosity, S_2, which was formed by transposition of the earlier S_1 schistosity (Fig. 3C). This main D_2 fabric along Mount Desert Narrows is subhorizontal to moderately dipping across the open F_3 Hancock-Trenton antiform; farther north, it is moderately developed to locally intense and becomes steep close to the Turtle Head fault. Ductile deformation associated with D_2 is evident from tight to isoclinal asymmetric folds developed in thin quartz laminations, sigmoid quartz veins, and S–C foliations in shear bands (Fig. 4). These kinematic indicators associated with the D_2 fabric indicate a predominant top-to-northwest sense of shear. Associated with the S_2 foliation is a well-developed lineation (L_2), outlined by the preferred orientation of syn-kinematic quartz crystals and pyrite aggregates. Most of the elongation lineations measured on S_2 display a (pre-F_3) preferred gentle plunge to the southeast (Fig. 5). Minor late phase folds are present locally. The D_3 deformation—e.g., Hancock-Trenton antiform ca. 2 km north of the Lamoine Granite—consists of large-scale asymmetric, open to tight folds (F_3) with subvertical axial surfaces and subhorizontal east-west-trending fold axes that are distinct from the orientation of F_2 fold axes. A younger S_3 crenulation cleavage developed in phyllosilicate layers overprints the main S_2 schistosity and is coplanar with D_3 fold axial surfaces. D_3 is attributed to the latest Silurian–Devonian Acadian Orogeny.

Contact relationships

The stratigraphic base of the Ellsworth Schist is not exposed; however, it structurally overlies metamorphosed black shales of the Cambrian–Ordovician Penobscot Formation (Osberg et al. 1985; Reusch 2003a). The Ellsworth Schist is overlain by volcanic rocks of the Castine Volcanics in eastern Penobscot Bay and along the Bagaduce River east of Castine. The Castine Volcanics comprise a 2 km thick sequence of subaqueous rhyolite and basalt, locally pillowed; interbedded marine volcaniclastic sedimentary rocks; sparse impure carbonate beds; layers of iron- and manganese-rich marine chemical precipitates; and a major volcanic-hosted massive sulphide deposit (Schulz et al. 2008). Rocks of the Castine Volcanics are metamorphosed to sub-greenschist (chlorite) facies and generally lack a penetrative foliation. The rocks are folded into a series of open folds that have long wavelengths and small amplitudes with northeasterly trends (Stewart 1998). Eruption of the Castine Volcanics during the Drumian is established by overlapping zircon ages of 503.5 ± 2.5 Ma from fine-grained felsic tuff (Schulz et al. 2008) and 503 ± 4 Ma from massive rhyolite (Ruitenberg et al. 1993). A thin basal conglomerate marks the Ellsworth-Castine contact (Fig. 3D). The conglomerate contains matrix-supported angular to subrounded pebbles of green silicic metamorphic rock (Stewart 1998) that are interpreted as clasts of the underlying Ellsworth Schist implying a basal angular unconformity/nonconformity.

U–Pb GEOCHRONOLOGY

A sample of Lamoine Granite was collected from the southwest edge of Lamoine Beach on the north shore of Mount Desert Narrows, Hancock County, Maine (UTM: 19N 555854, 4921932, NAD 27). Sample preparation and analyses were performed at the Radiogenic Isotope Laboratory, Memorial University of Newfoundland utilizing isotope dilution-thermal ionization mass spectrometry. Zircons were isolated from ca. 30 kg of unweathered rock using a jaw crusher and Bico disc mill, and concentrated using a Wilfley table, diiodomethane (CH_2I_2), and a Frantz isodynamic separator. Individual zircon crystals were individually hand selected from the least magnetic fraction using a binocular stereomicroscope. All zircons were air abraded (Krogh 1982) to remove the metamict outer surfaces in order to reduce the effects of radiogenic Pb loss and age discordance. Zircon dissolution was carried out with HF and HNO_3 in Teflon bombs and mixed with a $^{205}Pb/^{235}U$ isotope tracer. U and Pb were separated by anion exchange chromatography and loaded on a Re filament for analysis using a Finnigan MAT 262V thermal ionization-mass spectrometer following the procedures of Sánchez-García et al. (2008). Atomic ratios were corrected for fractionation, spike, and laboratory blank of 1 pg of common lead at the age of crystallization calculated from the model of Stacey and Kramers (1975), and 1 pg U blank. Analytical uncertainties are cited at the 95 per cent confidence interval. Age calculations and U–Pb data were plotted using the Isoplot program of Ludwig (2012) with the ^{238}U (1.55125×10^{-10} a^{-1}) and ^{235}U (9.8485×10^{-10} a^{-1}) decay constants and present day $^{238}U/^{235}U$ ratio of 137.88 determined by Jaffey et al. (1971).

The Lamoine Granite yielded abundant, predominantly clear, euhedral prismatic crystals that vary in length between 50 μm and 150 μm on the long axis (Fig. 6). Three fractions of four or five zircon crystals were analyzed and produced mutually overlapping and concordant points (Fig. 7). The fractions have low uranium contents and $^{206}Pb/^{238}U$ ages between 490 ± 4.0 and 494 ± 4.6 Ma. (Table 1). The weighted average of all three analyses is 492 ± 1.7 Ma (95 per cent confidence interval, MSWD = 0.73), which is the emplacement age of the Lamoine Granite.

DISCUSSION

Ellsworth deformation and metamorphism

Our U–Pb data from the Ellsworth belt provide new constraints on granitic magmatism with implications for Paleozoic tectonothermal events elsewhere in Ganderia. The 492 ± 1.7 Ma age of the Lamoine Granite records Cambrian magmatism within the Ellsworth belt, and is the youngest pre-metamorphic age. This precludes the Lamoine Granite from representing crustal basement to the Ellsworth belt.

On the basis of field relationships, McGregor (1964) and Reusch (2003a) interpreted the Lamoine Granite as a high-level intrusion that is comagmatic with the Goose Cove rhyolite of the Ellsworth Schist (Fig. 2). The age obtained in this study, however, demonstrates that the pluton is ca. 16 million years younger than the Miaolingian (508.6 ± 0.8 Ma) volcanic rocks from Sand Point (South Blue Hill) 22 km to the southwest (Schulz et al. 2008). Thus, the Lamoine Granite represents a hitherto unrecognized Furongian magmatic event in the Ellsworth belt.

The age of the Lamoine Granite constrains the timing of polyphase deformation and metamorphism in the Ellsworth belt. The Lamoine Granite was emplaced ca. 16 million years after deposition of the protolith of the sample of Ellsworth Schist collected from South Blue Hill (Schulz et al. 2008), and the granite has the same D_2 fabric as the enclosing schist. The schistosity in the Lamoine Granite, defined by chlorite and muscovite, is parallel to the schistosity (S_2) in the Ellsworth Schist, suggesting that both units were simultaneously metamorphosed to greenschist facies. Complicating matters, the S_2 fabric in the Ellsworth Schist transposes the S_1 (metamorphic) compositional layering.

Specifically, the Lamoine Granite is reported to cut the earlier metamorphic foliation (S_1) in the Ellsworth Schist (J.P. Hibbard, personal communication, 2007). Stewart et al. (1995) interpreted penetrative deformation and greenschist-facies metamorphism in the Ellsworth Schist to have occurred prior to deposition of the overlying ca. 503 Ma Castine Volcanics. However, if the schistosity in the Lamoine Granite and main fabric in the Ellsworth Schist are contemporaneous, it indicates that development of the regional metamorphic foliation (S_2) must post-date emplacement of the 492 Ma granite intrusion. Therefore, the Furongian age of the Lamoine Granite provides a minimum age for S_1 and a maximum age for the D_2 structural-metamorphic (M_2) overprint.

Emplacement of the Lamoine Granite was succeeded by a regional shortening event and development of the main fabric of the Ellsworth Schist. The penetrative asymmetry of small-scale folds and S–C shear bands—showing overall top-to-northwest kinematics (Reusch 2003a)—indicates progressive horizontal shortening and crustal thickening attributed to thrust faulting (Hibbard 1995). The L_2 lineation occurs on the main foliation plane which is parallel to the plane of best cylindrical fit of strongly non-cylindrical D_2 fold hinges (Fig. 5). We interpret the elongate L_2 mineral lineation to have formed synchronously with tight to isoclinal folds of quartz layers in the S_2 fabric. Regionally, except where the mineral lineation is steeply plunging along faults, most of the L_2 stretching lineations measured on S_2 display a preferred northwest-southeast plunging orientation at shallow angles. This indicates a northwest-southeast oriented sense of shearing and thrusting. The typically southeast-plunging L_2 mineral stretching lineation is consistent with overall top-to-northwest transport.

Regional shortening of the Ellsworth belt was a tectonometamorphic event that post-dates emplacement of the Lamoine Granite and formed under greenschist facies conditions in the mid-crust. Abundant microfractures along fold hinges, and presence of deformed extensional quartz veins associated with the S_2 foliation (Fig. 4B), are consistent with a brittle strain pattern of deformation under conditions of low deviatoric stress at a relatively high structural level in the lithosphere. However, the L_2 stretching lineation associated with the primary S_2 foliation, and intrafolial folds, are semi-ductile structures. Their co-existence implies deformation across the brittle-ductile transition.

In the Ellsworth belt, the minimum age of thrusting and associated metamorphism is constrained by relatively unstrained fossiliferous rocks of the Silurian Ames Knob Formation. A specimen of *Pentamerus* collected from near the base of the formation on North Haven Island is interpreted to be late Llandovery (Brookins et al. 1973; Berry and Boucot 1970) which suggests that juxtaposition of the Ellsworth belt with the St. Croix belt occurred prior to the Telychian. These relationships preclude correlation of D_2 in the Ellsworth belt with the Acadian orogeny; rather, D_3 is the local manifestation of the Acadian Orogeny.

Implications for Cambrian unconformity

A maximum 492 Ma age for regional metamorphism (M_2) indicates that an earlier thermal event produced the S_1 fabric present in the Ellsworth Schist. Burial of the protolith, uplift and erosion of the schist would need to have occurred in the short time span between the 509 Ma eruption of tuff in the Ellsworth Schist and deposition of the Castine Volcanics ca. 503 Ma. Stewart and Wones (1974) interpreted the penetrative deformation in the Ellsworth Schist to be absent in the Castine Volcanics. The lack of refolded D_1 structures in the Ellsworth Schist is consistent with interpretation of S_1 as a gravity-driven viscous compaction foliation. We suggest that S_1/M_1 may simply reflect compaction of hot volcanogenic sediments.

Clasts of strained Ellsworth Schist that occur at the base of the Castine Volcanics, however, indicate that the schist was deformed prior to incorporation into conglomerate beds and therefore must record a deformation event prior to erosion from their source rocks. The unconformity at the base of the Castine Volcanics occurred after D_1 in the Ellsworth Schist, but before D_2 responsible for the regional greenschist facies metamorphism throughout the Ellsworth belt.

Age constraints and structural evidence suggest that both the Ellsworth Schist and Castine Volcanics were metamorphosed in a single regional thermal event. The Castine Volcanics evidently escaped the effects of the regional D_2 shortening event that are prominent in the Ellsworth Schist. Inhomogeneous deformation during thrusting, therefore, may be the primary control on contrasts in the magnitude and nature of deformation in the Ellsworth belt.

Regional correlations in Ganderia

The new date for the Lamoine Granite allows comparison with the timing of similar magmatic rocks elsewhere in the Appalachian orogen (Fig. 8). Metavolcanic rocks of the Gushee member of the Penobscot Formation in the St. Croix belt yield less precise average U–Pb zircon ages (ca. 490–487 Ma, Berry et al. 2016) that are slightly younger than the 492 Ma age of intrusive magmatism in the Ellsworth belt. This correlation is significant, as structures and foliated metamorphic rocks in the St. Croix belt may help to constrain when the Ellsworth and St. Croix belts were juxtaposed. Asymmetric low-angle folds and old-over-young relationships indicate northwest-directed thrusting of the Rockport Group over the Benner Hill Formation along the Clam Cove fault (Osberg and Berry 2020). Emplacement and deformation must post-date rocks of the Benner Hill Formation that contain deformed Sandbian–Katian brachiopods (Berry et al. 2016). The minimum age of juxtaposition is provided by metamorphism under low-pressure amphibolite-facies conditions related to intrusion of high-level plutons in the Přídolí (West et al. 1995). It is possible, considering the common polarity of structures, that the D_2 deformation in the Ellsworth belt and deformation in the St. Croix belt are related and coeval. This interpretation would imply a maximum Katian age for northwest-directed thrusting and peak metamorphism in the Penobscot Bay inlier.

Subvolcanic and intrusive rocks of the Annidale belt of southern New Brunswick are obvious correlatives of the Lamoine Granite. The 493 ± 2 Ma (McLeod et al. 1992) subvolcanic rhyolite and felsic breccia of the Lawson Brook Formation and penetratively deformed 490 ± 2 Ma Cameron Road Granite have LREE-enriched geochemical signatures (Johnson et al. 2012) consistent with magmatism influenced by subducting oceanic lithosphere in a back-arc setting. The age of the Cameron Road Granite, its composition, hypabyssal textural features, and post-emplacement schistosity—all support the assertion that the Lamoine Granite is consanguineous.

Temporally equivalent volcanic and plutonic rocks resembling those of the Ellsworth belt are common in the central Newfoundland type area of Ganderia. The Lamoine Granite is coincident with the 493.9 +2.5/−1.9 Ma Pipestone Pond and Coy Pond ophiolite complexes (Dunning and Krogh 1985) of the Exploits subzone in Newfoundland. The latter are interpreted to represent remnants of an ophiolite belt generated in a back-arc setting (Jenner and Swinden 1993). Furongian plutonic and volcanic elements of both the Annidale belt and Exploits subzone are inferred to represent a magmatic arc system (Penobscot arc–backarc), formed upon Neoproterozoic basement along the margin of Ganderia. In contrast, the Miaolingian volcanic rocks of the Ellsworth belt are viewed as an oceanic rift that developed inboard (southeast, present day coordinates) of the ocean-facing margin of the active Penobscot arc (Schulz et al. 2008).

Similar rock types and relationships are also preserved in southeast New England. Kay et al. (2017) correlated metavolcanic and sedimentary rocks in the high-grade Putnam-Nashoba belt with bimodal volcanic and sedimentary sequences in the Annidale belt. Lithological, structural geochemical and geochronological data support a model of these terranes representing the back-arc component of the Furongian–Early Ordovician Penobscot arc–back-arc system. This same interpretation is implied by Kuiper (2016). They consider the Ellsworth belt to have occupied a more proximal (southeast) location with respect to Gondwana, consistent with its interpretation as an oceanic rift (Schulz et al. 2008) that led to separation of Ganderia from Gondwana.

Tectonic interpretation

The 492 Ma Lamoine Granite strongly resembles the 490 Ma Cameron Road Granite of the Annidale belt, 250 km distant in New Brunswick. In addition to similar age and lithology, both display a strongly northwest-vergent fabric. The latter is associated with supra-subduction zone volcanism in the back-arc region of the Penobscot arc (Johnson et al. 2012). In Maine, within the adjacent St. Croix belt, metavolcanic rocks of the 490–487 Ma Gushee member ca. 50 km to the west, have island arc geochemical signatures (Berry et al. 2016). Based on the close similarity in age, rock type, and deformation style between the 492 Ma Lamoine Granite and volcanic and plutonic rocks in the Annidale and St. Croix belts, we suggest the Lamoine Granite was erupted in a supra-subduction zone setting (Fig. 9) superimposed on the older oceanic rift setting inferred by Schulz et al. (2008). A progression of younger ages to the west is consistent with slab rollback in that direction, which has been proposed for Penobscot arc magmatism in Newfoundland (Zagorevski et al. 2010).

Post-Furongian deformation documented in the Ellsworth belt may be equivalent to Early Ordovician regional deformation, referred to as Penobscottian, elsewhere in the orogen. In the central Newfoundland type area of Ganderia, a major tectonic event during the Tremadocian–Floian is characterized by penetrative deformation and low-grade metamorphism in a high-level fold-and-thrust belt associated with ophiolite obduction onto the Gander margin and closure of the Penobscot back-arc basin (Williams and Piasecki 1990; Zagorevski and van Staal 2011). Polarity of structures related to Penobscottian orogenesis in Newfoundland (van Staal and Barr 2012) is generally assumed to be southeast-directed. The 474 +6/−3 Ma Partridgeberry Hills Granite (Colman-Sadd et al. 1992) postdates Early Ordovician obduction of Penobscot oceanic crust, stitches the Coy Pond ophiolite complex on the Ganderian continental margin, and indicates that Penobscottian obduction and deformation was complete by the Floian.

A minimum age for northwest-vergent deformation in New Brunswick is constrained by the 479 Ma Stewarton Gabbro, which stitches the terrane boundary between the Annidale belt and southeasterly New River belt. This post-490/pre-479 Ma deformation is referred to as the Penobscot Orogeny (Fyffe et al. 2011). No Penobscot stitching plutons have been identified in the Penobscot Bay inlier, however, based on comparison with New Brunswick, we consider it most likely that Ellsworth D_2 deformation is Penobscottian. We also stress that it is not currently possible to rule out a younger maximum age for D_2 deformation based on similar northwest-vergent structures of Late Ordovician–Silurian age present in the St. Croix belt (West et al. 1995). But D_2 is unlikely to be Acadian, as D_2 structures are pre-Ludlow and probably pre-Wenlock.

Two mechanisms have been proposed to explain the Penobscot event. Zagorevski et al. (2010) invoked a collision between the west-facing Penobscot arc and a seamount. Waldron et al. (2015b) invoked collision between a west-facing Penobscot arc, which originated east of Gondwana, and first a Cayman-trough-like ophiolite (Ellsworth) then an east-facing promontory of Gondwana (St. Croix). These end member scenarios are currently both viable, and their further evaluation constitutes a top priority in Appalachian tectonics. We suggest a variation on the Zagorevski et al. (2010) scenario in which, rather than a seamount, the west-facing arc collided with the main Iapetus spreading center. Such a ridge-arc collision must have occurred along the periphery of Gondwana, and it would explain the observed sequence of Miaolingian rifting, Furongian arc and back-arc magmatism, Early Ordovician northwest-vergent deformation, syn/post-collision gabbroic plutonism, and renewed Middle Ordovician arc and back arc magmatism.

CONCLUSIONS

This U–Pb geochronological study of deformed granite from the Ellsworth belt in coastal Maine indicates that the deformed leucocratic granite exposed at Lamoine Beach crystallized at 492 ± 1.7 Ma. This age is the first unequivocal evidence for a Furongian intrusive event in the Ellsworth belt and precludes the Lamoine Granite from representing basement to the Ellsworth Schist. The schistosity in the granite is parallel to main fabric in the enclosing schist and provides a maximum estimate for age of regional deformation and associated metamorphic overprint. We attribute the main deformation to thrusting of the Ellsworth belt over the St. Croix belt adjacent to the northwest. Kinematic indicators indicate a top-to-northwest sense of shear that resulted from progressive horizontal shortening, causing crustal thickening and peak greenschist-facies metamorphism. The age of this orogenic event is constrained to be younger than 492 Ma.

A Furongian age for the Lamoine Granite requires that the unconformity between the Ellsworth Schist and Castine Volcanics predates the regional D_2 deformation, and is therefore unrelated to juxtaposition of the Ellsworth and St. Croix belts. Polarities of structures, degree of metamorphism, and style of plutonism of the Ellsworth belt resemble Cambrian–Ordovician rocks and structures in the Gander domain in New England and Atlantic Canada. Specifically, the Lamoine Granite correlates with the Cameron Road Granite in the Annidale belt of New Brunswick which suggests that both are products of subduction-related magmatism in the Penobscot arc and back-arc. Deformation in the Ellsworth belt has similarities with the Penobscot Orogeny in New Brunswick. A ridge-arc collision model explains Ellsworth, St. Croix, and Annidale belt relationships by relating structural styles, metamorphism, and plutonism to collision between a west-facing Penobscot arc and the main spreading centre in the Iapetus Ocean.

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Figure 1. Geology of the Penobscot Bay inlier. Abbreviations, DI: Deer Island; FB: Frenchman Bay; NHI: North Haven Island; THF: Turtle Head Fault. Base map from Hibbard et al. (2006)

Figure 2. Simplified geological map of the Mount Desert Narrows area, Maine. Base map from Reusch (2003a).

Figure 3. Representative photos of outcrop field relationships: (A) Deformed medium-grained granite that contains L_2 lineation, indicating that its emplacement pre-dated the D_2 deformation; (B) Lamoine Granite selected for U–Pb analysis that contains the penetrative S_2 foliation parallel to the host Ellsworth Schist; (C) Foliated (S_2) muscovite-chlorite schist; (D) Conglomerate bed at the base of the Castine

Volcanics that contains pebbles of vein quartz and a cobble of strained green silicic metamorphic rock similar to the underlying Ellsworth Schist implying a basal angular unconformity.

Figure 4. Representative structures displaying top-to-northwest sense-of-shear within albite-quartz-chlorite-muscovite rocks of the Ellsworth Schist, Newbury Neck and Ellsworth quadrangles: (A) S–C shear bands (penny for scale); (B) Asymmetrically deformed quartz vein (pen for scale); (C) Asymmetrically folded quartz veins (notebook for scale); (D) S–C shear bands (chl: chorite, alb: albite); (E) mica fish; (F) Asymmetrically boudinaged quartz vein.

Figure 5. Equal-area lower-hemisphere projection of bedding (n=81, blue, contour interval [CI]=5%); S_2 foliation (n=201, red, CI=5%); L_2 lineations (N=86; green; CI=10%). Individual D_2 fold hinges (●, n=56), lie along a best-fit great circle (021/20), the pole (P_f=70$^{o}\rightarrow$291) to which is coaxial to the pole to foliation. Although S_2 was refolded during D_3 (Acadian Orogeny), L_2 stretching lineations display the preferred northwest-southeast orientation.

Figure 6. Representative photomicrograph of zircons separated from the least magnetic fraction.

Figure 7. U–Pb ages and Concordia diagram for Lamoine Granite.

Figure 8. Tectonostratigraphic evolution of the Ganderian margin of the Appalachian orogen in Maine, New Brunswick, and Newfoundland. Modified from van Staal and Barr (2012). Ages of units are U–Pb zircon and cited in the text; and from Dunning et al. (1990) and Colman-Sadd et al. (1992). Abbreviation, CRG: Cameron Road Granite

Figure 9. Schematic Early Palaeozoic evolution of Ganderia. (A) Oldest part of the Penobscot arc is ca. 514 Ma. Ellsworth bimodal volcanic rocks and serpentinized mantle suggest departure of Ganderia from Amazonia in Miaolingian (509–504 Ma). (B) Continued extension of Penobscot arc, presumably due to slab rollback, opens the back-arc (e.g., ophiolite in Newfoundland); Lamoine Granite intruded in the back-arc; increasing buoyancy of eastern Iapetan lithosphere suggests mechanism for decrease in dip angle. (C) Mid-Iapetan ridge collides with Penobscot arc, closing the back arc basin affording a mechanism for top-to-northwest sense of shear and subsequent intrusion of mafic stitching plutons (e.g., Stewarton Gabbro). Upper plate regime becomes extensional again post-ridge collision as the relative plate velocity decreases.

Table 1. U–Pb data for Lamoine Granite.

Figure 1

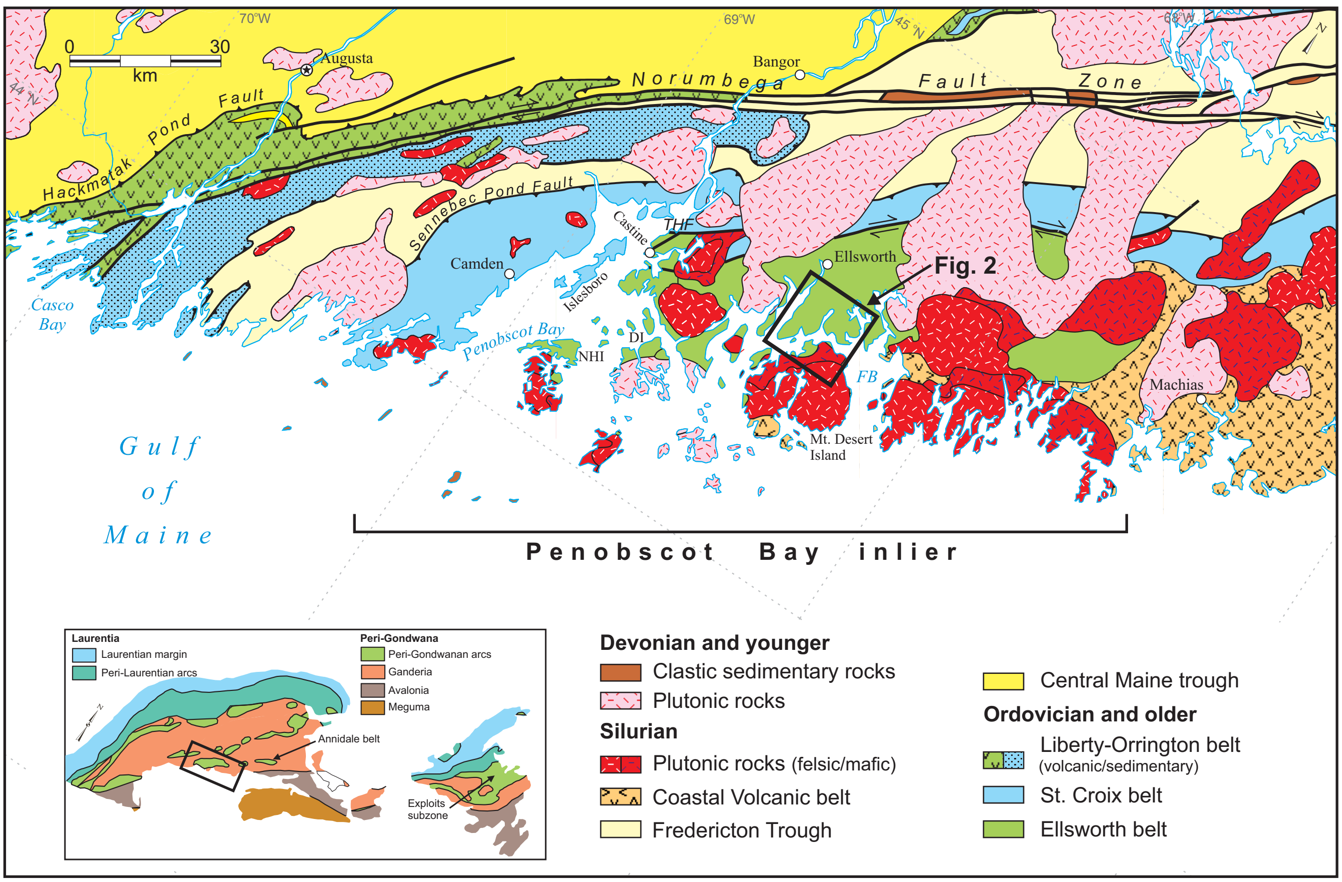

70°W
69°W
68°W
45°N
44°N
0 30
km
Augusta
Bangor
Norumbega Fault Zone
Hackmatak Pond Fault
Sennebec Pond Fault
THF
Castine
Camden
Islesboro
Ellsworth
Fig. 2
Casco Bay
Penobscot Bay
NHI
DI
FB
Mt. Desert Island
Machias
Gulf of Maine
Penobscot Bay inlier
Laurentia
Laurentian margin
Peri-Laurentian arcs
Peri-Gondwana
Peri-Gondwanan arcs
Ganderia
Avalonia
Meguma
Annidale belt
Exploits subzone
Devonian and younger
Clastic sedimentary rocks
Plutonic rocks
Silurian
Plutonic rocks (felsic/mafic)
Coastal Volcanic belt
Fredericton Trough
Central Maine trough
Ordovician and older
Liberty-Orrington belt (volcanic/sedimentary)
St. Croix belt
Ellsworth belt

Figure 2

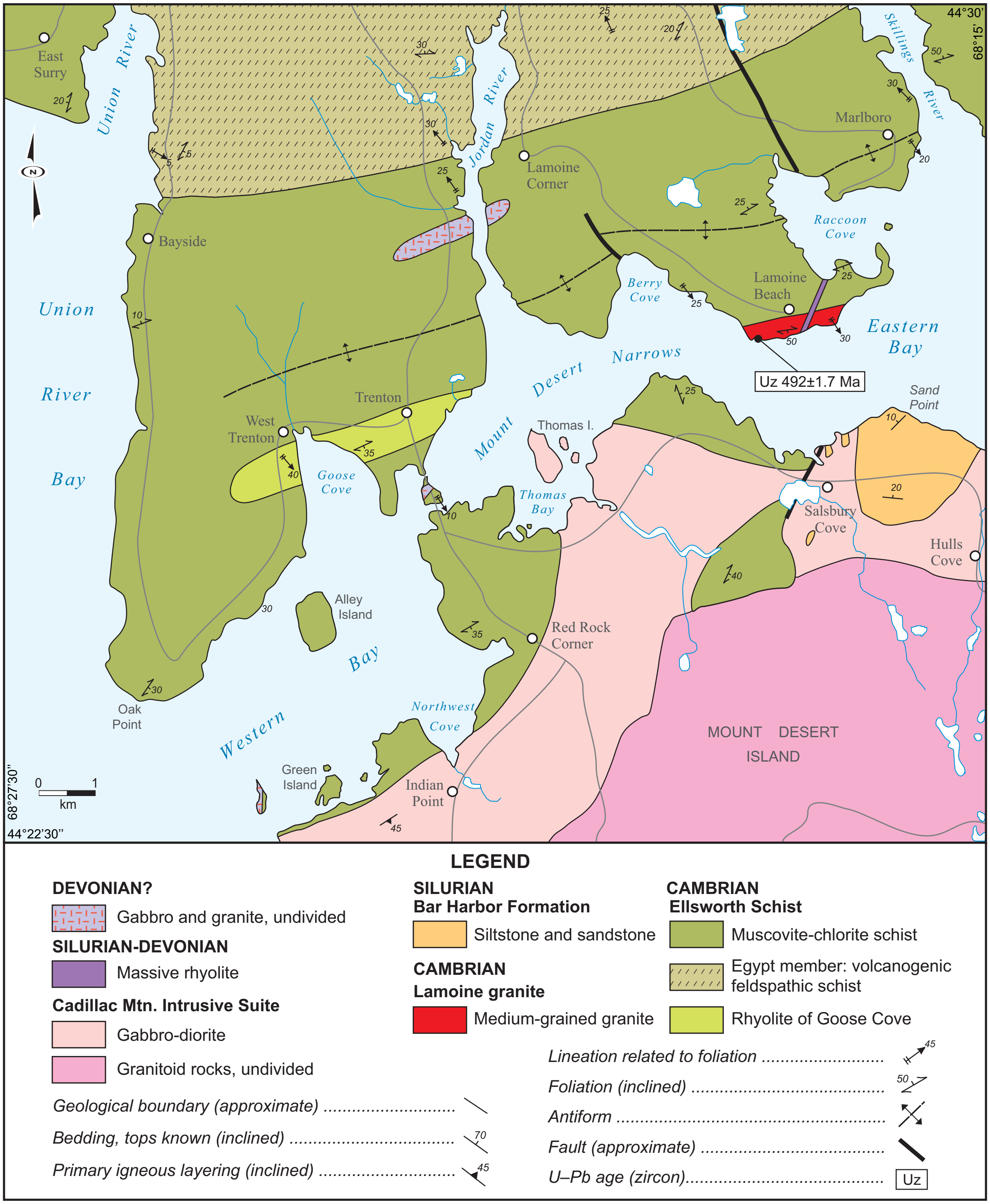

East Surry
Union River
Jordan River
Skillings River
Marlboro
Lamoine Corner
Bayside
Raccoon Cove
Berry Cove
Lamoine Beach
Eastern Bay
Union River Bay
Mount Desert Narrows
Uz 492±1.7 Ma
Sand Point
Trenton
West Trenton
Thomas I.
Goose Cove
Thomas Bay
Salsbury Cove
Hulls Cove
Alley Island
Red Rock Corner
Western Bay
Oak Point
Northwest Cove
MOUNT DESERT ISLAND
Green Island
Indian Point
44°30'
68°15'
68°27'30"
44°22'30"
0 1 km
LEGEND
DEVONIAN?
Gabbro and granite, undivided
SILURIAN-DEVONIAN
Massive rhyolite
Cadillac Mtn. Intrusive Suite
Gabbro-diorite
Granitoid rocks, undivided
SILURIAN
Bar Harbor Formation
Siltstone and sandstone
CAMBRIAN
Lamoine granite
Medium-grained granite
CAMBRIAN
Ellsworth Schist
Muscovite-chlorite schist
Egypt member: volcanogenic feldspathic schist
Rhyolite of Goose Cove
Geological boundary (approximate)
Bedding, tops known (inclined)
Primary igneous layering (inclined)
Lineation related to foliation
Foliation (inclined)
Antiform
Fault (approximate)
U–Pb age (zircon)
Uz

Figure 3

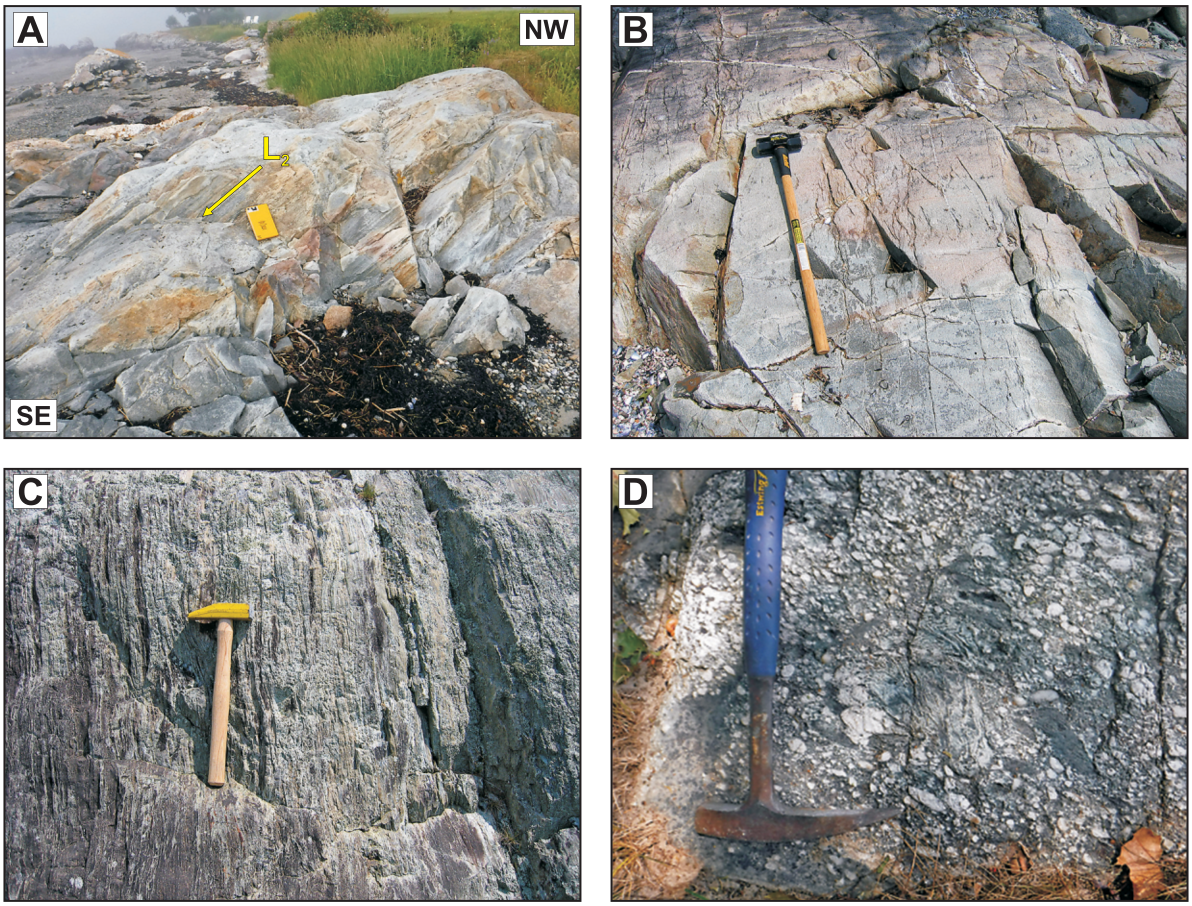


Figure 4

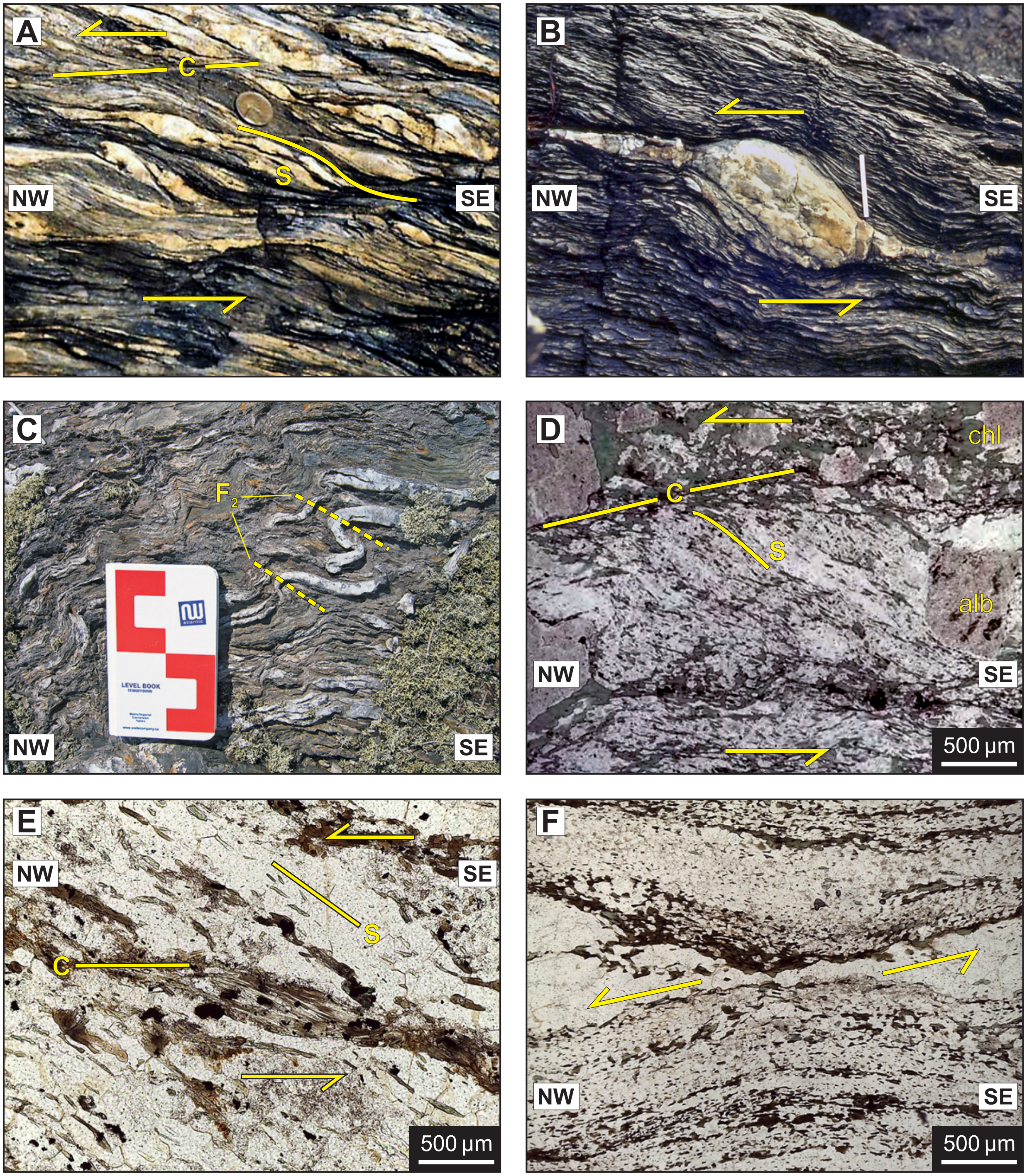

A
C
S
NW
SE
B
NW
SE
C
F_2
LEVEL BOOK
NW
SE
D
chl
C
S
alb
NW
SE
500 µm
E
NW
SE
S
C
500 µm
F
NW
SE
500 µm

Figure 5

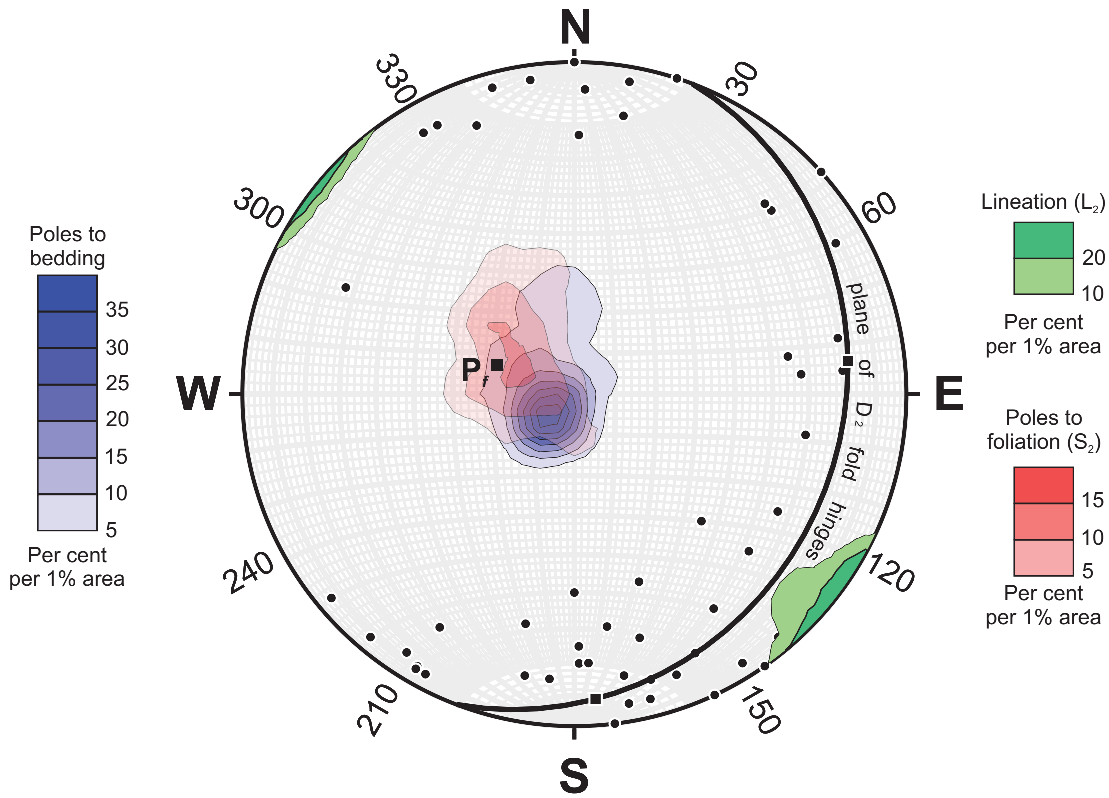

Poles to bedding
35
30
25
20
15
10
5
Per cent per 1% area
N
E
S
W
30
60
120
150
210
240
300
330
P_f
plane of D_2 fold hinges
Lineation (L_2)
20
10
Per cent per 1% area
Poles to foliation (S_2)
15
10
5
Per cent per 1% area

Figure 6

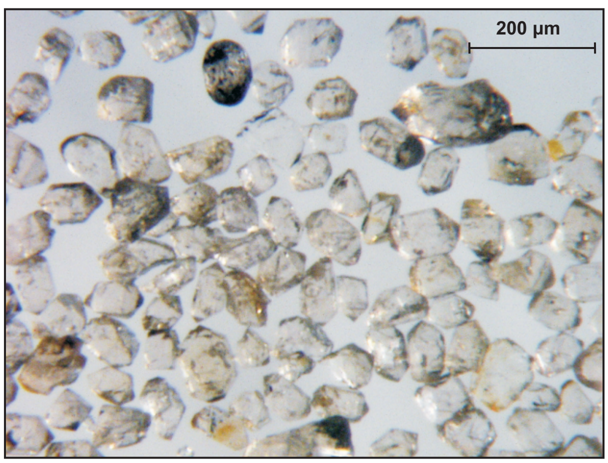
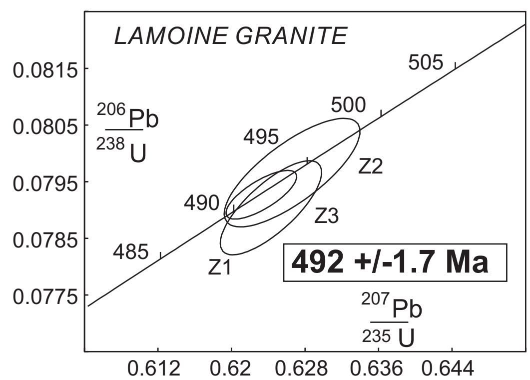


Figure 7


LAMOINE GRANITE
0.0815
0.0805
0.0795
0.0785
0.0775
206Pb/238U
505
500
495
490
485
Z1
Z2
Z3
492 +/-1.7 Ma
207Pb/235U
0.612
0.62
0.628
0.636
0.644

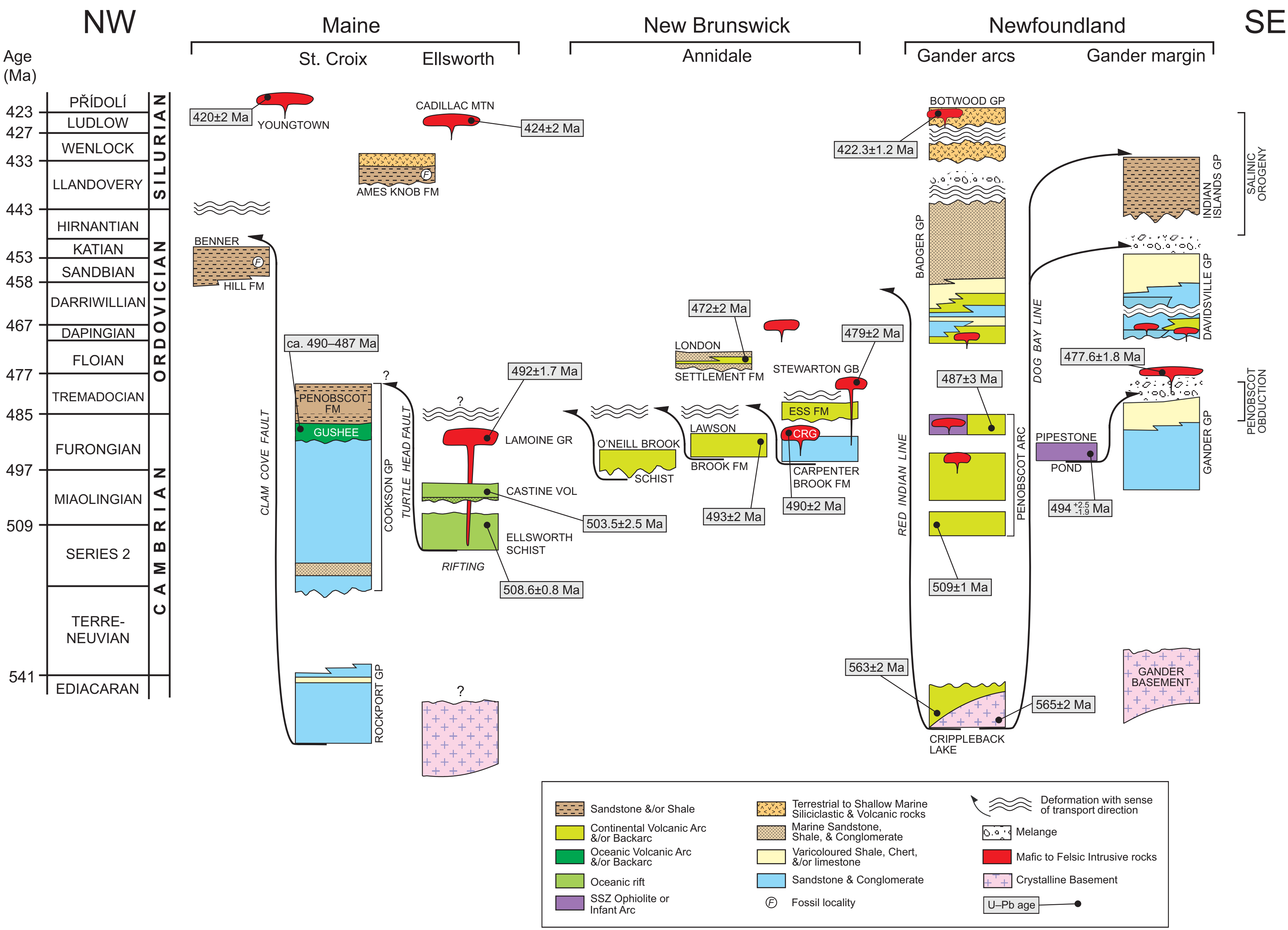

NW
SE
Maine
St. Croix
Ellsworth
New Brunswick
Annidale
Newfoundland
Gander arcs
Gander margin
Age (Ma)
423
427
433
443
453
458
467
477
485
497
509
541
PŘÍDOLÍ
LUDLOW
WENLOCK
LLANDOVERY
HIRNANTIAN
KATIAN
SANDBIAN
DARRIWILLIAN
DAPINGIAN
FLOIAN
TREMADOCIAN
FURONGIAN
MIAOLINGIAN
SERIES 2
TERRE-NEUVIAN
EDIACARAN
SILURIAN
ORDOVICIAN
CAMBRIAN
420±2 Ma
YOUNGTOWN
CADILLAC MTN
424±2 Ma
AMES KNOB FM
BENNER
HILL FM
CLAM COVE FAULT
ca. 490–487 Ma
PENOBSCOT FM
GUSHEE
COOKSON GP
ROCKPORT GP
TURTLE HEAD FAULT
492±1.7 Ma
LAMOINE GR
CASTINE VOL
503.5±2.5 Ma
ELLSWORTH SCHIST
RIFTING
508.6±0.8 Ma
O'NEILL BROOK
SCHIST
472±2 Ma
LONDON
SETTLEMENT FM
LAWSON
BROOK FM
493±2 Ma
STEWARTON GB
479±2 Ma
ESS FM
CRG
CARPENTER BROOK FM
490±2 Ma
BOTWOOD GP
422.3±1.2 Ma
BADGER GP
RED INDIAN LINE
487±3 Ma
PENOBSCOT ARC
509±1 Ma
563±2 Ma
565±2 Ma
CRIPPLEBACK LAKE
DOG BAY LINE
INDIAN ISLANDS GP
SALINIC OROGENY
DAVIDSVILLE GP
477.6±1.8 Ma
PENOBSCOT OBDUCTION
PIPESTONE POND
494 +2.5 -1.9 Ma
GANDER GP
GANDER BASEMENT
Sandstone &/or Shale
Continental Volcanic Arc &/or Backarc
Oceanic Volcanic Arc &/or Backarc
Oceanic rift
SSZ Ophiolite or Infant Arc
Terrestrial to Shallow Marine Siliciclastic & Volcanic rocks
Marine Sandstone, Shale, & Conglomerate
Varicoloured Shale, Chert, &/or limestone
Sandstone & Conglomerate
Fossil locality
Deformation with sense of transport direction
Melange
Mafic to Felsic Intrusive rocks
Crystalline Basement
U–Pb age

Figure 9

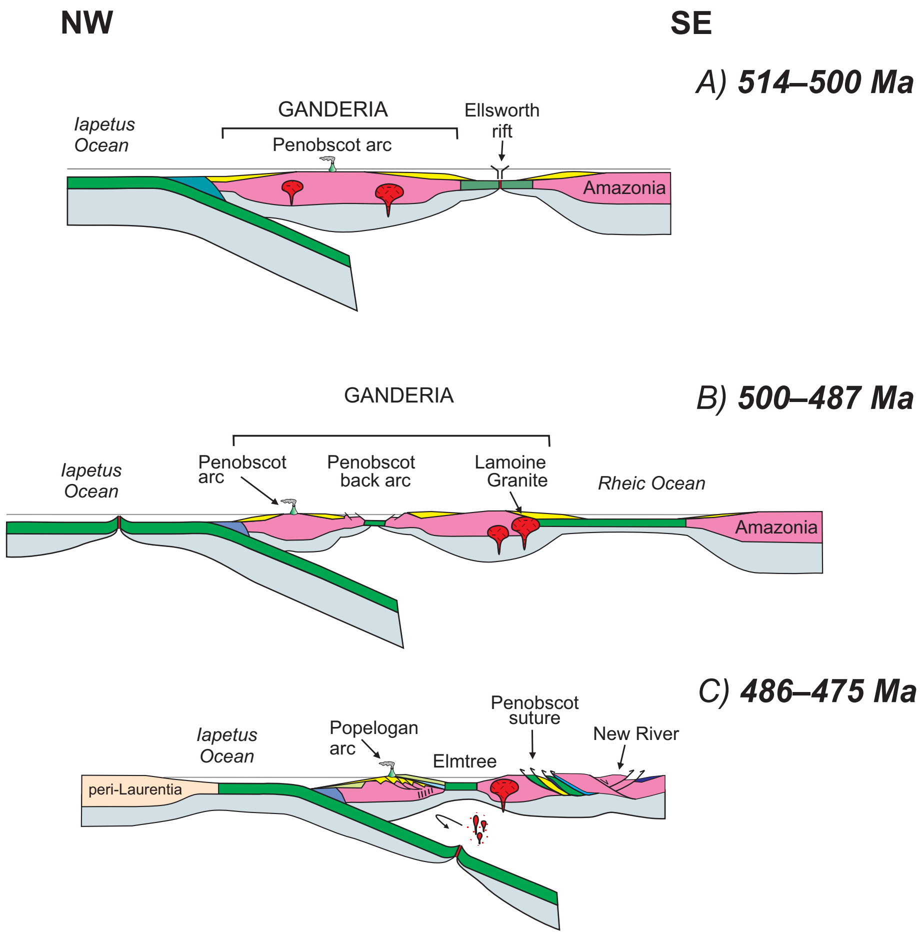

NW
SE
A) 514–500 Ma
Iapetus Ocean
GANDERIA
Penobscot arc
Ellsworth rift
Amazonia
B) 500–487 Ma
GANDERIA
Iapetus Ocean
Penobscot arc
Penobscot back arc
Lamoine Granite
Rheic Ocean
Amazonia
C) 486–475 Ma
Iapetus Ocean
Popelogan arc
Elmtree
Penobscot suture
New River
peri-Laurentia

Table 1. U-Pb data for the Lamoine Granite

JP41407: UTM (19N 0555854, 4921932 NAD 27)

Fraction	Weight	Concentration		Measured		Corrected Atomic Ratios							Age (Ma)		
	(µg)	U (ppm)	Pb rad (ppm)	TCPb (pg)	206Pb/204Pb	208Pb/206Pb	206Pb/238U	±	207Pb/235U	±	207Pb/206Pb	±	206Pb/238U	207Pb/235U	207Pb/206Pb
Z1 5 sml equant clr	0.007	135	11.9	1.1	4647	0.2348	0.07904	68	0.6243	46	0.05729	32	490.4 ± 4.0	493	503
Z2 5 sml equant clr	0.007	66	6	1.1	2359	0.2612	0.07966	78	0.6266	60	0.05705	38	494.1 ± 4.6	494	493
Z3 4 sml equant clr	0.006	92	8.2	0.93	2965	0.2526	0.07927	36	0.6232	32	0.05702	20	491.8 ± 2.1	492	492

Notes: Z=zircon, sml=small, clr=clear, All zircons were abraded (cf. Krogh, 1982). pg=picogram, mg=milligram.
* atomic ratios corrected for fractionation, spike, laboratory blank of 1 pg of common lead at the age of the sample calculated from the model of Stacey and Kramers (1975), and 1 pg U blank. Two sigma uncertainties calculated with an unpublished error propagation procedure are reported after the ratios and refer to the final digits.