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Résumé de l'article

Des travaux d'imagerie sismique et des forages profonds ont montré que la transition océan-continent (OCT) de marges continentales de divergence pauvre en magma exposée de nos jours, correspond à une zone d'hyperétirement tectonique caractérisée par un amincissement extrême de la croûte continentale, qui a exhumé sur le fond marin, jusqu'à la tranche la plus profonde de la croûte continentale, voire du manteau continental serpentinisé. Parce qu'on peut difficilement échantillonner l'OCT sur les marges actuelles, une grande partie de notre compréhension des détails de la nature de l'OCT provient d'ophiolites pauvres en magma d'une OCT obduite, comme celles préservées dans les portions supérieures de la bande plissée alpine. Des masses lenticulaires de roches ultramafiques allochtones sont communes dans de nombreuses autres bandes orogéniques anciennes, comme l'orogène Calédonienne-Appalaches, mais leur origine et signification tectonique reste incertaine. Nous présentons un sommaire des occurrences d'OCT potentielles anciennes de cet orogène, en commençant par des séquences de la marge laurentienne, où la présence d'OCT a déjà été déduites (le Supergroupe Dalradien d'Écosse et d'Irlande, et le complexe de Birchy de Terre-Neuve). Nous spéculons ensuite sur l'origine de cas isolés de péridotite de type alpin dans des séquences de marge des Laurentides du Québec-Vermont et de la Virginie-Caroline du Nord, en nous concentrant sur les unités de rift d'âge néoprotérozoïque tardif (pour éviter les ophiolites du Taconique). La conjonction d'affleurements de piètre qualité et de la déformation taconique omniprésente, signifie que l'origine et la mise en place de nombreuses masses ultramafiques dans les Appalaches demeureront incertaines. Néanmoins, la présence fréquente de roches de type OCT tout le long de la marge Calédonnienne- Appalaches de Laurentia suggère que l'ouverture de l'océan Iapetus peut avoir été accompagnée d'hyper-étirement et de la formation de marges pauvres en magma le long de nombreux segments.

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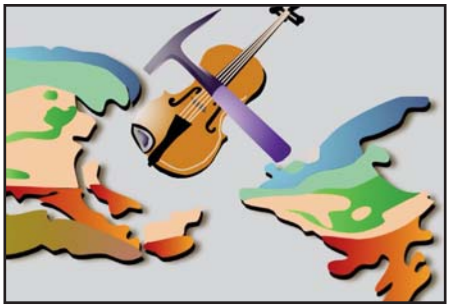

The Ocean – Continent Transition Zones Along the Appalachian – Caledonian Margin of Laurentia: Examples of Large-Scale Hyperextension During the Opening of the Iapetus Ocean

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SUMMARY
A combination of deep seismic imaging and drilling has demonstrated that the ocean-continent transition (OCT) of present-day, magma-poor, rifted continental margins is a zone of hyperextension characterized by extreme thinning of the continental crust that exhumed the lowermost crust and/or serpentinized continental mantle onto the seafloor. The OCT on present-day margins is difficult to sample, and so much of our knowledge on the detailed nature of OCT sequences comes from obducted, magma-poor OCT ophiolites such as those preserved in the upper portions of the Alpine fold-and-thrust belt. Allochthonous, lens-shaped bodies of ultramafic rock are common in many other ancient orogenic belts, such as the Caledonian – Appalachian orogen, yet their origin and tectonic significance remains uncertain. We summarize the occurrences of potential ancient OCTs within this orogen, commencing with Laurentian margin sequences where an OCT has previously been inferred (the Dalradian Supergroup of Scotland and Ireland and the Birchy Complex of Newfoundland). We then speculate on the origin of isolated occurrences of Alpine-type peridotite within Laurentian margin sequences in Quebec – Vermont and Virginia – North Carolina, focusing on rift-related units of Late Neoproterozoic age (so as to eliminate a Taconic ophiolite origin). A combination of poor exposure and pervasive Taconic deformation means that origin and emplacement of many ultramafic bodies in the Appalachians will remain uncertain. Nevertheless, the common occurrence of OCT-like rocks along the whole length of the Appalachian – Caledonian margin of Laurentia suggests that the opening of the Iapetus Ocean may have been accompanied by hyperextension and the formation of magma-poor margins along many segments.

SOMMAIRE
Des travaux d'imagerie sismique et des forages profonds ont montré que la transition océan-continent (*OCT*) de marges continentales de divergence pauvre en magma exposée de nos jours, correspond à une zone d'hyper-étirement tectonique caractérisée par un amincissement extrême de la croûte continentale, qui a exhumé sur le fond marin, jusqu'à la tranche la plus profonde de la croûte continentale, voire du manteau continental serpentinisé. Parce qu'on peut difficilement échantillonner l'*OCT* sur les marges actuelles, une grande partie de notre compréhension des détails de la nature de l'*OCT* provient d'ophiolites pauvres en magma d'une *OCT* obduite, comme celles préservées dans les portions supérieures de la bande plissée alpine. Des masses lenticulaires de roches ultramafiques allochtones sont communes dans de nombreuses autres bandes orogéniques anciennes, comme l'orogène Calédonienne-Appalaches, mais leur origine et signification tectonique reste incertaine. Nous présentons un sommaire des occurrences d'*OCT* potentielles anciennes de cet orogène, en commençant par des séquences de la marge laurentienne, où la présence d'*OCT* a déjà été déduites (le Supergroupe Dalradien d'Écosse et d'Irlande, et le complexe de Birchy de Terre-Neuve). Nous spéculons ensuite sur l'origine de cas isolés de péridotite de type alpin dans des séquences de marge des Laurentides du Québec-Vermont et de la Virginie-Caroline du Nord, en nous concentrant sur les unités de rift d'âge néoprotérozoïque tardif (pour éviter les ophiolites du Taconique). La conjonction d'affleure-

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ments de piètre qualité et de la déformation taconique omniprésente, signifie que l'origine et la mise en place de nombreuses masses ultramafiques dans les Appalaches demeureront incertaines. Néanmoins, la présence fréquente de roches de type *OCT* tout le long de la marge Calédonnienne-Appalaches de Laurentia suggère que l'ouverture de l'océan Iapetus peut avoir été accompagnée d'hyper-étirement et de la formation de marges pauvres en magma le long de nombreux segments.

INTRODUCTION

Our knowledge of the ocean-continent transition (OCT) of magma-poor passive margins has increased significantly since exhumed mantle rocks were first dredged and then drilled during ODP Leg 103 off the Western Iberian margin (Boillot et al. 1980, 1987). A combination of modern high-quality geophysical data, deep sea drilling and comparative studies of analogue areas onshore (e.g. Manatschal 2004; Péron-Pinvidic and Manatschal 2009) has shown that the OCT of magma-poor passive margins is a zone of hyperextension characterized by extreme thinning of parts of the continental crust, resulting in exhumation of the lowermost crust and/or serpentinized continental mantle onto the seafloor (e.g. Iberian margin, Tucholke et al. 2007; Sibuet and Tucholke 2013). Serpentinization is facilitated by the movement of large volumes of water from the surface down into the mantle along major extensional structures, the largest of which is typically a concave-downwards lithosphere-scale master detachment (e.g. Manatschal 2004; Manatschal et al. 2007, 2011; Sutra and Manatschal 2012).

Rifted continental margins have been divided into two types depending on the amount of rift-related magmatism. A 'volcanic' or magma-rich margin is characterized by seaward-dipping reflectors typical of subaerial lava flows which mask the rift-related extensional structures, whereas a 'non-volcanic' or 'magma-poor' rifted margin lacks these features (Louden and Chian 1999; Dean et al. 2000). Hyperextension has been viewed to be a characteristic of magma-poor margins. However it is now recognized that the degree and nature of magmatism associated with hyperextension varies (e.g. Müntener and Manatschal 2006) and hyperextension is not exclusive to magma-poor margins such as Iberia. For example the northeast Atlantic 'volcanic' margin was affected by hyperextension processes in the Late Jurassic – Early Cretaceous (Osmundsen and Ebbing 2008; Lundin and Doré 2011).

Allochthonous, lens-shaped bodies of ultramafic rock are common in many orogenic belts, particularly the Alps. Along the western boundary of the Austroalpine nappes in eastern Switzerland, podiform ultramafic bodies are found in close association with dolerite dykes and radiolarian chert, and have long been regarded to be characteristic of the deep ocean floor (Steinmann 1905). This rock association in the Alps, later referred to as the 'Steinmann Trinity', has traditionally been regarded to represent Tethyan oceanic mantle sequences that have been imbricated within ophiolite complexes. However, the discovery of distal margin sequences directly overlying subcontinental mantle in many places in the Alps (see Manatschal and Müntener 2009 for a historical review) supports the idea that at least some of the ophiolites in the Alps represent ancient OCTs, similar to the Western Iberian and Newfoundland margins. The Alpine Tethyan OCT ophiolites typically contain only minor amounts of mafic igneous rocks and are characterized by blocks of ancient subcontinental mantle exhumed by top-down basement detachment faults and overlain by extensional allochthons, tectono-sedimentary breccias and a post-rift sedimentary sequence similar to that of the adjacent distal continental margin (e.g. Manatschal 2004; Manatschal and Müntener 2009). Similar OCT sequences have been reported in the Pyrenees (Lagabrielle and Bodinier 2008; Lagabrielle et al. 2010) but the recognition of OCT ophiolites in older orogenic belts has received less attention.

This study investigates occurrences of Alpine-type ultramafic rocks of potential OCT affinity within the Caledonian – Appalachian orogen. Although it is a well-studied orogenic belt with a strike length of over 7500 km, OCT sequences have only recently been recognized (e.g. the Laurentian margin of Scotland and Ireland, Chew 2001; Henderson et al. 2009; Baltic margin of Norway, Andersen et al. 2012; Laurentian margin of Newfoundland, van Staal et al. 2013). Long linear belts of ultramafic rocks are common within the Caledonian – Appalachian orogen (e.g. the Appalachian serpentinite belts of Hess 1939, 1955) and the origin and tectonic significance of many of these isolated occurrences of Alpine-type peridotite remains uncertain.

CRITERIA FOR IDENTIFYING AN OCEAN-CONTINENT TRANSITION (OCT) IN THE GEOLOGICAL RECORD

The Field Relationships of OCT Rocks

On present-day rifted margins, the OCT is typically covered by a thick pile of sediments at abyssal depths; the Iberia–Newfoundland conjugate rifted margin (Fig. 1) is the only location where a 'complete' OCT sequence has been drill-intersected across a magma-poor rift system. Little is therefore known about the detailed nature of OCT rock types on present-day rifted margins, and the low resolution of deep seismic imaging techniques means that the structural and intrusive relationships of the various OCT components are difficult to ascertain (Manatschal and Müntener 2009). Hence, much of our knowledge about the structural, magmatic, hydrothermal and sedimentary record of continental breakup and early seafloor spreading comes from obducted OCT ophiolites, the best examples of which occur in the Alpine Tethyan domain such as the Platta, Tasna and Chenaillet ophiolite units (Manatschal and Müntener 2009). The Platta and Tasna units (Fig. 2a) are believed to represent the OCT of the former Adriatic and European/Briançonnais conjugate rifted margins, whereas the Chenaillet unit (Fig. 2b) has an affinity closer to that of true oceanic crust. All three units escaped deep Alpine subduction and critically preserve pre-Alpine contacts between the exhumed basement and a volcano-sedimentary cover sequence (Manatschal and Müntener 2009).

The following synthesis of the

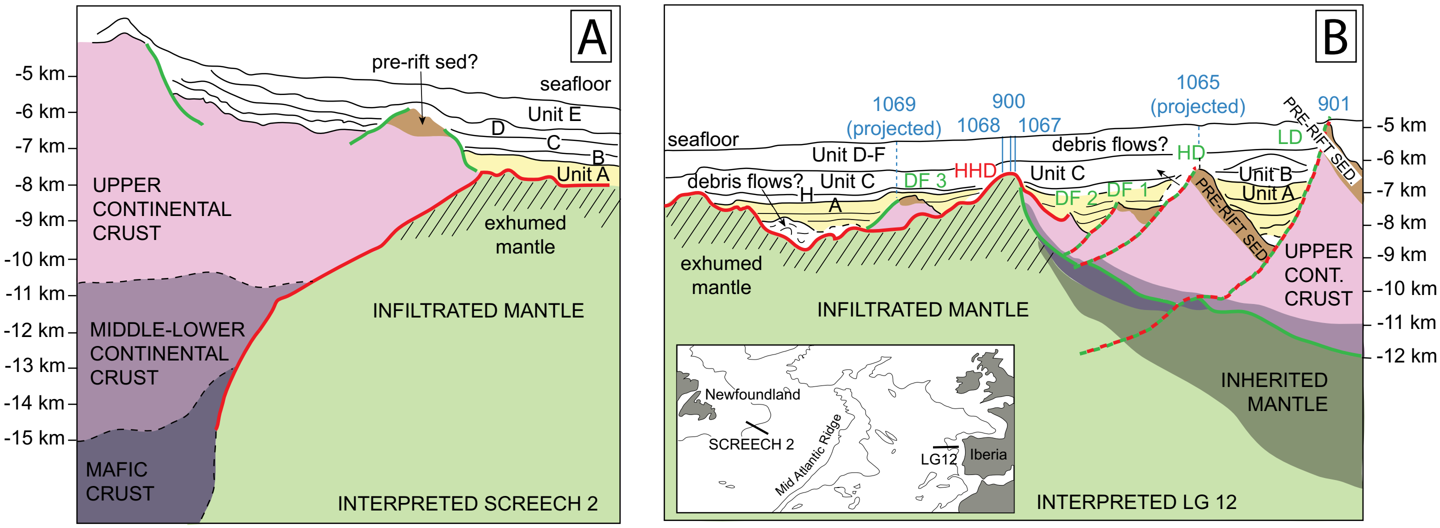

Figure 1. Cross section across the A) Newfoundland and B) Iberian rifted margins (modified after Péron-Pinvidic and Manatschal 2009). Unit correlations and borehole numbers are also taken from Péron-Pinvidic and Manatschal (2009).

chief characteristics of the Alpine Tethyan OCT units is summarized from Manatschal and Müntener (2009) unless otherwise stated. The most prominent structural features observed in these OCT ophiolite units are top-down basement detachment faults that are analogous to the extensional detachments in metamorphic core complexes. These detachment fault systems cannot be used to uniquely identify OCT ophiolites in the geological record as they may resemble oceanic detachment faults that develop on the flanks of slow-spreading ridges, and those fault systems at slow-spreading ridges may also exhume plutonic lower crust and mantle rocks (e.g. Cann et al. 1997; Reston and Ranero 2011).

The low-angle faults in OCT ophiolites are characterized by a series of cataclasites and gouges, are often ‘impregnated’ by calcite near the top of the basement (ophicalcite), and are overlain by tectono-sedimentary breccias that pass upwards into sedimentary breccias and post-rift sediments (Fig. 2a, b). Because these faults are low-angle structures that no longer carry their original hanging wall, they have historically been interpreted as either sedimentary or reactivated Alpine tectonic contacts. These detachment faults overprint earlier exhumation-related mylonitic shear zones in peridotites and gabbros in the footwall rocks and are overprinted further oceanwards by syn-magmatic high-angle normal faults that are parallel to basaltic dykes interpreted as feeder channels to the overlying volcanic rocks.

Below the top-basement detachment fault the most common rock type is foliated, massive serpentinized peridotite and/or gabbro. Serpentinization in Alpine-type mantle rocks is pervasive and commonly almost complete, and seismic velocities obtained from present-day OCT suggest that serpentinization can be complete as far down as 2 km (Chian et al. 1999). Olivine is rare, and clinopyroxene and orthopyroxene are only occasionally preserved. Passing upward towards the detachment fault, fractures and veins filled by chlorite and serpentine minerals mark the transition to serpentinite or gabbro cataclasites (Fig. 2a). The intensity of the brittle deformation increases even further up-section into a fault core zone of serpentinite gouges (Fig. 2a). Clasts of dolerite within the fault zone suggest that detachment faulting was accompanied by magmatic activity. The hanging wall above the top-basement detachment fault is formed by extensional allochthons of tectono-sedimentary breccias, post-rift sediments (Fig. 2a), and further oceanwards (Fig. 2b) by basalts. The extensional allochthons comprise continent-derived blocks, ranging in size from tens of metres to blocks kilometers in extent. The extensional allochthons and tectono-sedimentary breccias comprising both mantle- and continent-derived clasts help distinguish a magma-poor OCT sequence from a mid-ocean ridge setting, as the emplacement of continent-derived extensional allochthons is unlikely in the latter. The breccias in the Alpine OCT sequences are typically tectonized at their base and pass upwards into clast-supported, poorly organized sedimentary breccias dominated by clasts derived from the underlying footwall (cf., Robertson 2007). Basalts (typically pillow breccias) become more voluminous oceanwards and locally cover exhumed mantle rocks. The oldest sediments of the post-rift sequence are typically radiolarian cherts that drape over the underlying tectono-sedimentary breccias, extensional allochthons, or basalts.

The Alpine Tethyan OCT ophiolites described by Manatschal and Müntener (2009) and other workers clearly do not conform to the classical definition of a Penrose-type ophiolite (Penrose conference participants 1972), such as the Semail ophiolite in Oman (Nicolas et al. 1988), the Bay of Islands Complex in Newfoundland (Bird et al. 1971) and the Troodos ophiolite in Cyprus (Gass 1968). The Alpine Tethyan OCT ophiolites contain only minor amounts of mafic igneous rocks (basaltic lavas, sheeted dyke complexes and gabbros) and are instead characterized by blocks of ancient subcontinental mantle exhumed by top-basement detachment faults and overlain by extensional

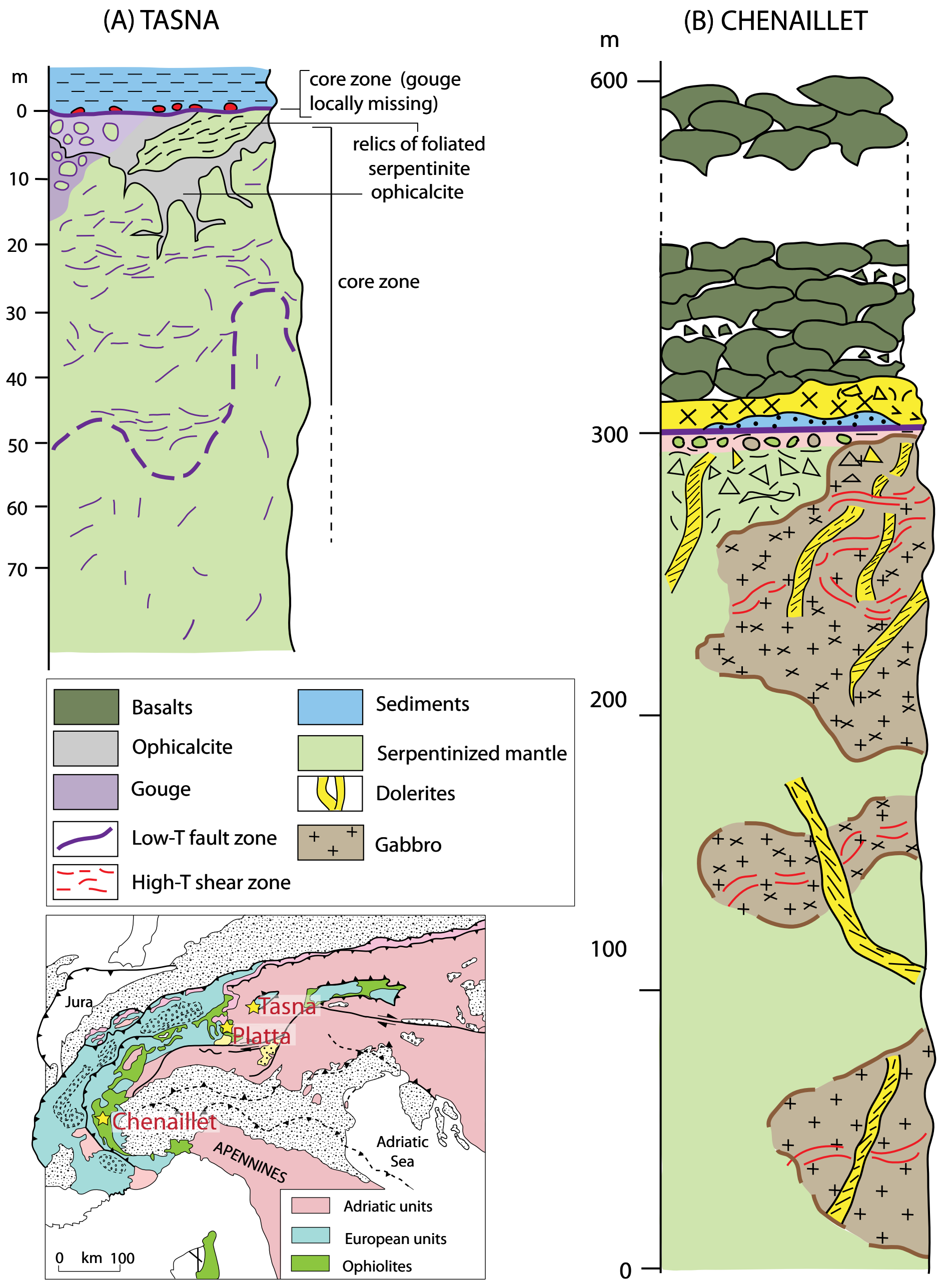

Figure 2. Representative vertical sections through an Alpine Tethys OCT adapted from Manatschal and Müntener (2009) illustrating (A) the Tasna section, which comprises predominantly exhumed subcontinental lithospheric mantle, and (B) embryonic oceanic crust of the Chenaillet section.

allochthons, tectono-sedimentary breccias and a post-rift sedimentary sequence similar to that of the adjacent distal continental margin. To avoid confusion when discussing the tectonic setting of allochthonous, lens-shaped bodies of ultramafic rock within the Appalachian – Caledonian orogenic belt, henceforth the term 'Alpine-type' is used when referring to potential OCT ophiolites. The term 'Penrose-type ophiolite' is used to describe the idealized ophiolite sequence complete with a sheeted dike complex as a result of seafloor spreading (Penrose Conference Participants 1972).

The Geochemistry of Ocean-Continent Transition Zone Rocks

Ultramafic Rocks

Studies of xenoliths suites derived from sub-continental lithospheric mantle show that it is dominated by peridotite, consisting of olivine, orthopyroxene, clinopyroxene, and an aluminous phase, typically spinel at low pressure and garnet at high pressure (Lee et al. 2011). Continental peridotites range in composition from fertile lithotypes (lherzolite with abundant clinopyroxene and high Al_2O_3, CaO, and Na_2O contents) to highly melt-depleted lithotypes (an olivine- and orthopyroxene-rich residue of harzburgite with low Al_2O_3, CaO, and Na_2O and high MgO content; Boyd 1989). Ancient cratons are underlain by a thick keel of highly depleted peridotite, whereas the sub-continental lithospheric mantle beneath Phanerozoic mobile belts is thinner and only mildly depleted relative to the underlying asthenosphere (Griffin et al. 2009). The Al_2O_3 and Na_2O content of Phanerozoic, Proterozoic, and Archean peridotites are negatively correlated with MgO because of progressive melt extraction and depletion of clinopyroxene and garnet with time (Lee et al. 2011). However, many sub-continental lithospheric mantle peridotites display geochemical evidence of refertilization (i.e. being re-enriched in basaltic melt components) and therefore continental mantle is the product of at least two major processes: melt depletion followed by refertilization or other major metasomatic enrichment processes such as Si enrichment (Lee et al. 2011).

Sub-continental lithospheric mantle exhumed at OCTs on present-day passive margins is dominated by moderate (50%) to highly (95–100%) serpentinized peridotites (Kodolányi et al. 2012). Serpentinized peridotite in Deep Sea Drilling Project (DSDP) and Ocean Drilling Project (ODP) drill cores from the Iberia and Newfoundland passive margins have higher incompatible trace element contents and relatively flat chondrite-normalized rare-earth element (REE) and primitive mantle-normalized trace element patterns when compared to serpentinites from mid-ocean ridge (Mid-Atlantic Ridge and Hess Ridge) and fore-arc (Mariana and Guatemala) tectonic settings (Kodolányi et al. 2012). The higher incompatible trace element contents are attributed to smaller degrees of partial melting and/or strong refertilization by metasomatizing melts prior to serpentinization; hence, the subcontinental lithospheric protolith is considered to have a less depleted chemical composition compared to other mantle settings (Kodolányi et al. 2012). However, Müntener and Manatschal (2006) document the presence (on the Newfoundland passive margin, ODP site 1277) of highly depleted harzburgite (up to 25% melting) that is inferred to represent inherited Caledonian sub-arc mantle exhumed close to the ocean floor during the rifting of the North Atlantic, which attests to the role that local inheritance may play in the composition of exhumed mantle at OCTs.

Mafic Rocks

In addition to the occurrence of exhumed, ancient subcontinental mantle, most OCTs are characterized by a scarcity of mafic plutonic rocks and the absence of sheeted dike complexes (Manatschal and Müntener 2009). Synrift magmatism at these magma-poor OCTs is typically of mid-ocean ridge basalt (MORB) affinity. Basalt, dolerite and gabbro recovered from the Iberian and Newfoundland passive margins typically have compositions spanning normal- through transitional- to enriched-MORB (e.g. Seifert et al. 1997; Müntener and Manatschal 2006). The geochemical features of basaltic and gabbroic rocks in ancient OCTs in the geological record, such as the Jurassic External Liguride units (Montaninia et al. 2008) or the Platta unit in the Eastern Central Alps (Desmurs et al. 2002), is typically of a transitional- to normal-MORB-type composition.

Identifying OCT Rocks in Polyphase-Deformed Orogenic Belts

The OCT rocks of modern-day rifted continental margins are usually found at abyssal depths and are unlikely to be encountered in the geological record unless they are imbricated onto the continental margin by later collisional orogenesis. Although the western Alpine Tethys OCT ophiolites (the Platta, Tasna and Chenaillet units) described by Manatschal and Müntener (2009) are preserved within thrust nappes, they were not overprinted by pervasive Alpine deformation or metamorphism. Hence they preserve pre-Alpine structures and basement – cover relationships and their paleogeographic position relative to the former rifted margin can also be established. However, many of the Alpine Tethys OCT ophiolites (particularly those that have undergone deep subduction) have experienced pervasive Alpine deformation that at best hinders pre-Alpine paleogeographic reconstructions and at worst obscures the internal relationships between the OCT rocks within individual nappes.

This situation is common in many ancient orogenic belts, which typically have experienced significantly more internal strain than the upper portions of the Alpine fold-and-thrust belt where the type Alpine OCT units are preserved. Examples include internal segments of the Laurentian margin of the Caledonian – Appalachian orogenic belt, which form the majority of the case studies presented herein. The outboard-positioned parts of the Laurentian margin typically have undergone amphibolite-facies metamorphism and polyphase deformation related to collision with an intra-oceanic arc terrane during the Early to Middle Ordovician Grampian – Taconic orogeny. Potential OCT occurrences in the polyphase-deformed Laurentian margin are therefore commonly tectonically juxtaposed against or overlain by Penrose-type ophiolite sequences associated with the colliding oceanic arc terrane. Conclusively identifying an OCT sequence in such tectonic settings is therefore difficult, as serpentinite mélanges incorporated within ancient orogenic belts are commonly interpreted as evidence for obduction of a Penrose-type ophiolite during collisional orogeny. The possibility that some of the occurrences of serpentinite mélange and associated rocks within the Caledonian – Appalachian orogenic belt may have been produced during an earlier phase of crustal hyperextension is now investigated.

EXAMPLES FROM THE CALEDONIAN – APPALACHIAN OROGENIC BELT

In this contribution we summarize the occurrences of potential ancient OCTs within the Caledonian – Appalachian orogenic belt, starting with regions on the rifted Laurentian margin where we have worked and an OCT has been inferred (e.g. the Dalradian Supergroup of Scotland and Ireland, Chew 2001; Henderson et al. 2009; and the Birchy Complex of the Fleur de Lys Supergroup of Newfoundland, van Staal et al. 2013). We then speculate on the origin of isolated occurrences of ultramafic rocks within the Laurentian margin of the Appalachians in Quebec – Vermont and Virginia – North Carolina, before considering the occurrence of a geographically widespread mélange of variably altered lenses of mantle peridotite separating the Lower Allochthon and Middle Allochthons in the Caledonides of Southern Norway, for which an OCT origin has also been inferred (Andersen et al. 2012).

Laurentian Margin

Scotland and Ireland

The Dalradian Supergroup of Scotland and Ireland (Fig. 3) is a metasedimentary succession that was deposited on the eastern margin of Laurentia during the late Neoproterozoic and Early Cambrian. Existing constraints imply that the base is younger than 800 Ma and that the age ranges to at least 510 Ma (Smith et al. 1999; Tanner and Sutherland 2007). It comprises a thick sequence of lithologically diverse metasedimentary and mafic volcanic rocks, along with three distinct glacigenic units that are correlated with widespread Neoproterozoic glaciations (McCay et al. 2006). Lithostratigraphic correlation is hampered by the almost complete absence of stratigraphically useful fossils, complex polyphase deformation and rapid lateral facies changes. Despite these difficulties, a coherent lithostratigraphy has been established from western Ireland through mainland Scotland to the Shetland Islands (Harris et al. 1994), comprising four groups – Grampian, Appin, Argyll and Southern Highland. The Dalradian Supergroup was deformed during the Grampian Orogeny (ca. 475 – 465 Ma), which was caused by the collision of the Laurentian continental margin of Scotland and northwest Ireland with an oceanic arc terrane. The boundary between the deformed Laurentian margin and the oceanic arc terrane to the southeast is marked by the Highland Border – Fair Head – Clew Bay line (Fig. 3), which is equivalent to the Baie Verte – Bromp-

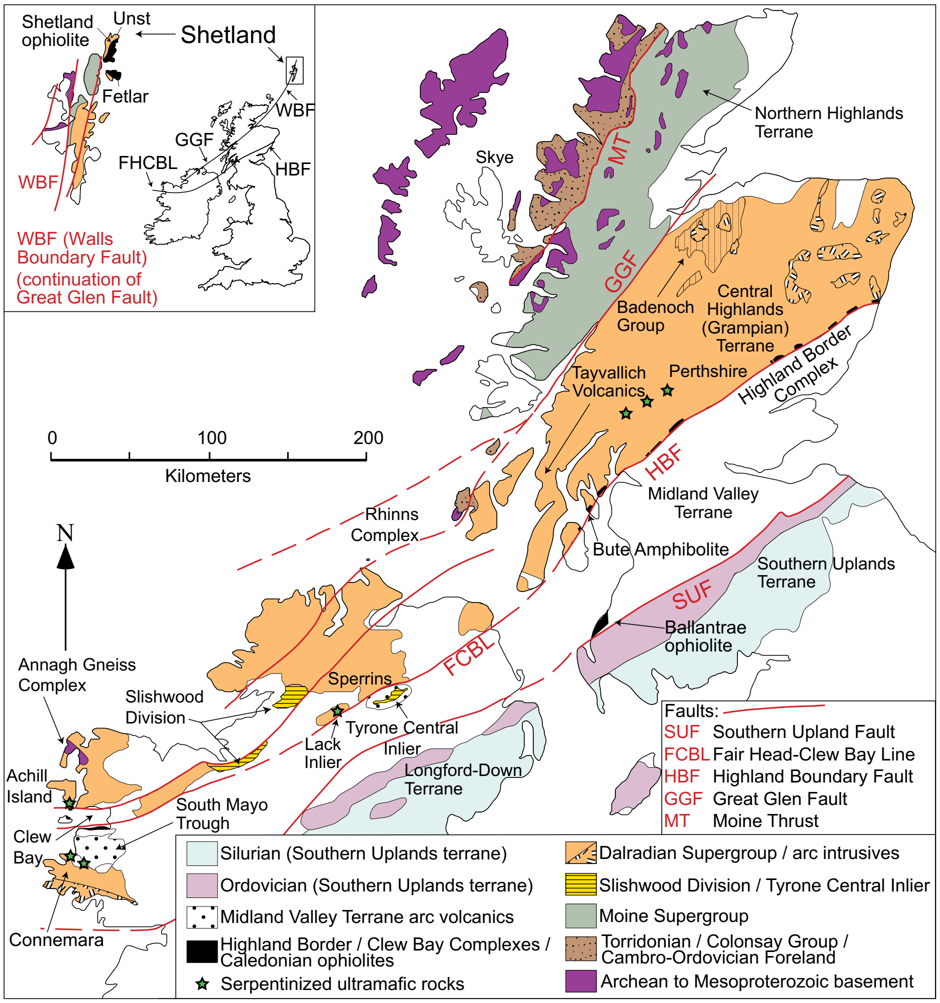

Figure 3. Geological map of the Caledonides of Scotland and northwestern Ireland, highlighting Caledonian ophiolites and rocks of potential OCT affinity.

ton line in the Canadian Appalachians. Early Ordovician accretionary complexes (the Highland Border Complex in Scotland and the Clew Bay Complex in western Ireland; Fig. 3) crop out along this fault zone.

On the Scottish – Irish sector of the Laurentian margin, mafic volcanic activity in the Dalradian Supergroup occurred throughout deposition of the Argyll Group and the lower part of the Southern Highland Group, reaching its greatest development in the Easdale and Tayvallich subgroups of the Argyll Group (Fettes et al. 2011). Absolute age constraints on the timing of volcanic activity are poor, with the only reliable geochronology being the U–Pb zircon dates of 595 ± 4 Ma on a keratophyre intrusion (Halliday et al. 1989), and of 601 ± 4 Ma on a felsic tuff (Dempster et al. 2002) from within the Tayvallich Volcanic Formation of the upper Argyll Group. Easdale Subgroup volcanism has been suggested to have occurred at around ~630 – 620 Ma (Fettes et al. 2011).

On southern Achill Island in western Ireland, a stratigraphic horizon with abundant serpentinite olistoliths embedded in a graphitic pelite matrix (Fig. 4a) is spatially associated with volcanic rocks of the Easdale Subgroup (Kennedy 1980; Chew 2001). In addition to the presence of large serpentinite olistoliths, small flakes of fuchsite, a bright-green chromian muscovite, are found embedded within black graphitic pelite throughout the sequence. The contacts between the large serpentinite blocks and the enclosing graphitic pelites reveals that the pelites have been injected into the serpentinite olistoliths, and small fragments of serpentinite are commonly found to be completely enclosed and injected by the pelitic matrix (Fig. 4b). In addition, small clasts of (meta-) sedimentary rocks that resemble the local country rocks are found embedded in the matrix. The serpentinite mélange is soft-sedimentary in origin and is pre-tectonic with respect to the regional ductile fabrics (Fig. 4c, Kennedy 1980; Chew 2001). Serpentinite bodies (indicated by green stars on Fig. 3) are also found within the upper Argyll Group of the north Connemara Dalradian. Although originally assumed to represent serpentinized peridotite bodies associated with the nearby ca. 475 Ma Dawros – Currywongaun ultramafic intrusive suite in north Connemara (Friedrich et al. 1999), graphitic pelites are locally observed to penetrate serpentinite olistoliths up to 150 m long (Chew 2001) on coastal sections. Serpentinite olistoliths embedded in black graphitic pelites along with fuchsite has also been recorded in stream sections in the isolated Lack Inlier in Northern Ireland (Fig. 3; Chew 2001; McFarlane et al. 2009).

In Scotland a remarkably persistent horizon of ultramafic material has been identified at the base of the Ben Lui Schist of the upper Argyll Group (Graham and Bradbury 1981; Hawson and Hall 1987). It extends for over 20 km along strike from Tyndrum northeast to Loch Tay/Glen Lyon in Perthshire (extent denoted by the three green stars on Fig. 3) and consists of chromite, chromian magnetite and fuchsite, along with concordant bands of small talcose pods (Fortey and Smith 1987). Detrital fuchsite clasts up to 1 cm in size have also been recorded in turbiditic grit channels at the base of the Ben Lui Schist 4 km south of Killin at the western end of Loch Tay (Chew 2001; westernmost of the three green stars on Fig. 3). In addition, irregularly spaced larger serpentinite bodies occur along this horizon in Perthshire and northeast Scotland (Garson and Plant 1973; Hawson and Hall 1987) and these are also regarded as potential serpentinite olistoliths by Chew (2001). The serpentinite olistoliths occur at a similar stratigraphic level (Upper Easdale – Tayvallich Subgroup) for over 500 km along strike in the Dalradian of Ireland and Scotland and are associated with a change from shallow- to deep-water sedimentary

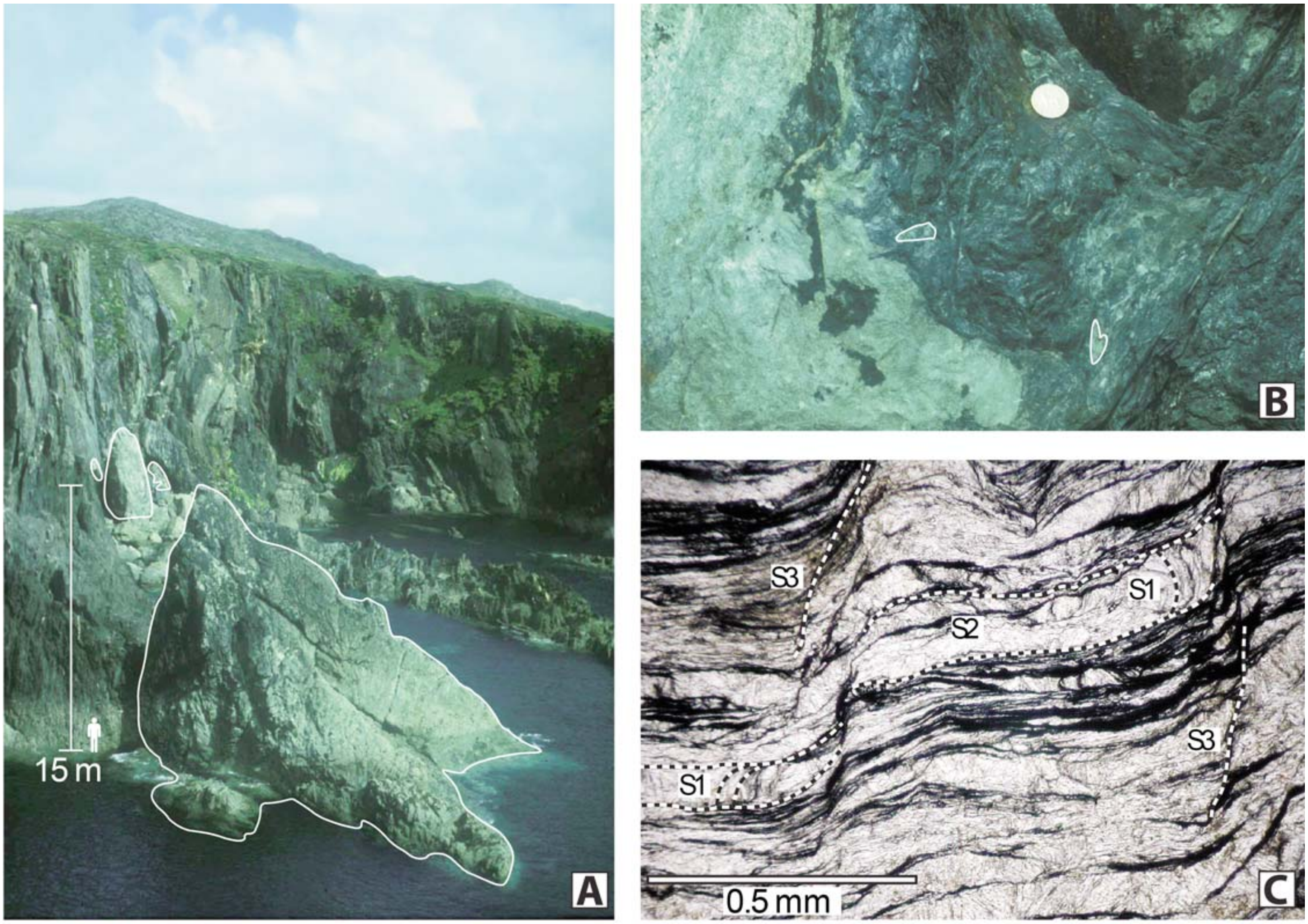

Figure 4. (A) The serpentinite mélange on south Achill, western Ireland. (B) Black graphitic pelites intruding the margins of a pale serpentinite clast on south Achill. (C) Photomicrograph of a talcose graphitic pelite demonstrating the pre-tectonic nature of the ultramafic detritus.

strata and the first major sequence of rift-related basaltic volcanic rocks. This evidence was interpreted by Chew (2001) to suggest that the serpentinite olistoliths represented protrusions of serpentinized mantle onto the seafloor that were generated in Easdale Subgroup times during a phase of major crustal extension leading to the formation of an OCT.

A series of poorly exposed fault-bound slivers of ophiolitic rocks (termed the Highland Border Ophiolite [HBO] in Scotland; Tanner and Sutherland 2007) crop out within the Highland Boundary – Fair Head – Clew Bay fault zone in Scotland and western Ireland. These rocks have traditionally been regarded as Late Cambrian – Early Ordovician Penrose-type ophiolite complexes that were dismembered following obduction during the early stages of the Grampian Orogeny. The affinity of this suite of supposed Penrose-type ophiolitic rocks has also been called into question by Tanner (2007), who suggests that they represent exhumed serpentinized sub-continental lithospheric mantle, similar to the Alpine-type OCT ophiolites of the Liguria region in northern Italy.

Field observations from the HBO (Leslie 2009; Henderson et al. 2009) broadly support a model in which the widespread occurrence of sheared and fragmental ophicarbonate and associated sedimentary rocks of the HBO originated in a stretching OCT setting, now preserved as a fragment of Alpine-type OCT ophiolite on the southeastern margin of the Grampian orogenic belt. The discontinuous horizon of serpentinite bodies in the Easdale Subgroup rocks of the Dalradian Supergroup of Ireland and Scotland (Fig. 3) described by Chew (2001) are likely intimately associated with the HBO, with both units representing small slices of exhumed serpentinized sub-continental mantle that originally lay beneath an extending Dalradian basin during the opening of the Iapetus Ocean. However, not all exposures of mafic and ultramafic rocks within the HBO represent exhumed serpentinized sub-continental lithospheric mantle. For example, the geochronology and *P-T* work of Chew et al. (2010) demonstrates that the Bute Amphibolite (Fig. 3) represents a fragment of a Grampian supra-subduction zone ophiolite that was obducted at ca. 490 Ma. The fragmentary and challenging nature of the geological record within the Highland Boundary fault zone means that the tectonic affinity of

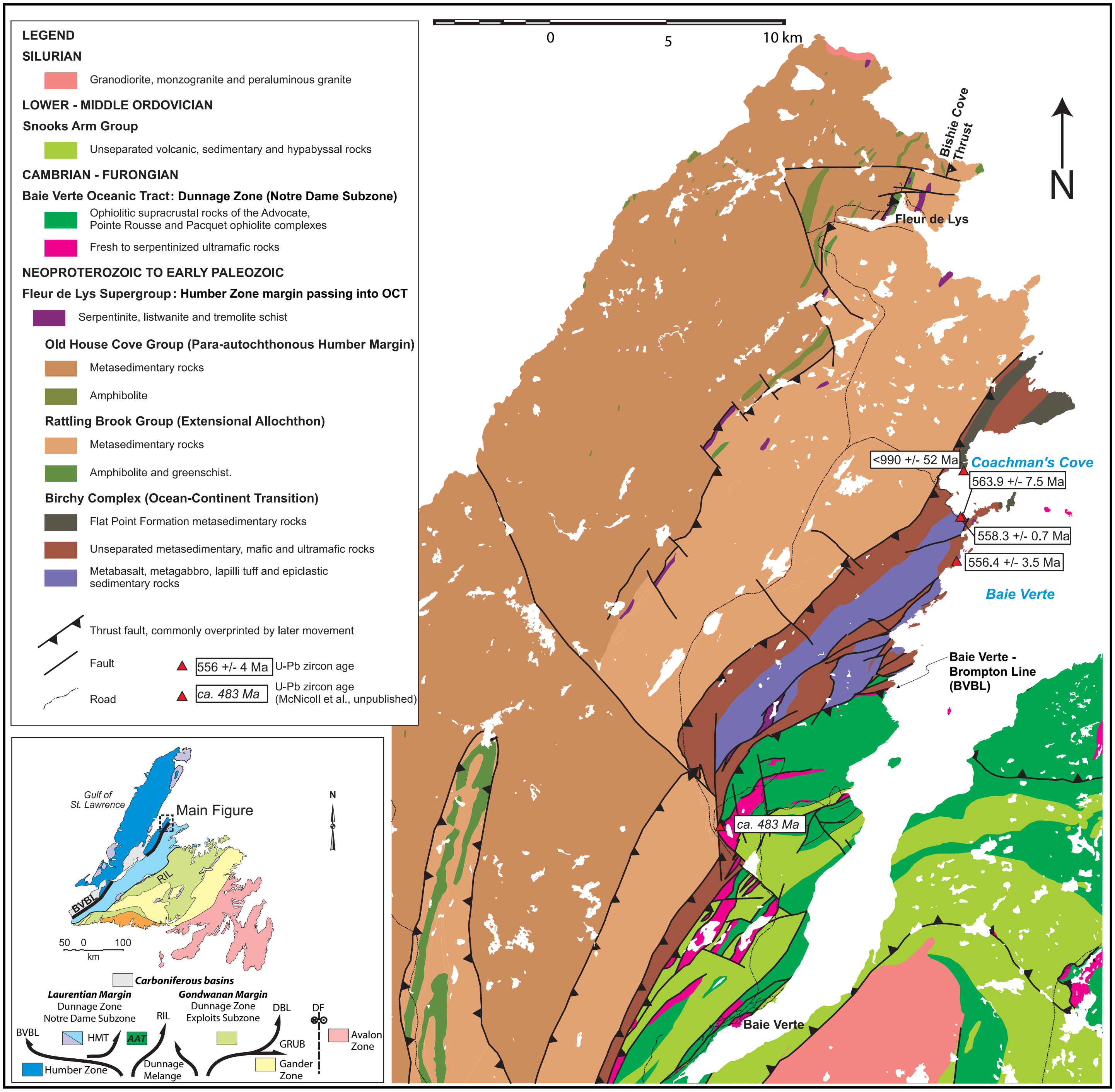

Figure 5. Geology of the OCT rocks of the Birchy Complex and adjacent units near the town of Baie Verte (from van Staal et al. 2013). AAT: Annieopsquotch Accretionary Tract; BVBL: Baie Verte – Brompton Line; DBL: Dog Bay Line; DF: Dover Fault; GRUB: Gander River Ultramafic Belt; HMT: Hungry Mountain Thrust; RIL: Red Indian Line.

many slivers of mafic and ultramafic rock within the HBO will remain unknown.

Newfoundland

The Laurentian continental margin in Newfoundland, also known as the Humber Zone (Williams 1979) is divided into a weakly deformed and metamorphosed western external zone and an eastern internal zone that has undergone polyphase metamorphism and deformation during the Taconic (mid-Ordovician) and Salinic (Silurian) orogenic events (Cawood et al. 1994; Lin et al. 2013). It is separated from the diverse package of oceanic rocks that formed within the Iapetus Ocean proximal to Laurentia (the Notre Dame Subzone of the Dunnage zone, Fig. 5 inset) by a narrow, but complex zone of long-lived shear zones and faults termed the Baie Verte – Brompton line (Fig. 5).

The Fleur de Lys Supergroup on the western Baie Verte peninsula is thought to represent the internal,

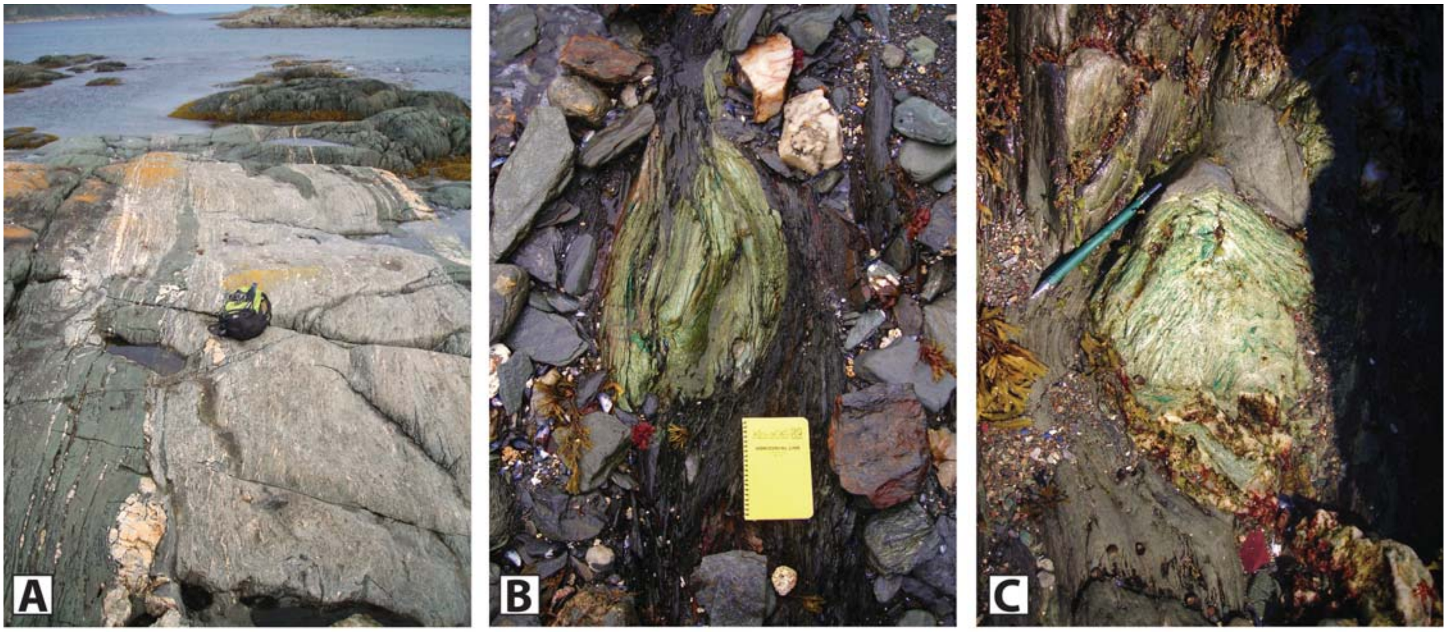

Figure 6. (A) Isoclinal fold closures within interlayered mafic schist and psammitic wackes in the Birchy Complex, western Newfoundland. Small podiform serpentinite clasts enclosed by B) graphitic pelite, and C) mafic schist, in the Birchy Complex.

polyphase-deformed and distal (i.e. more oceanward) portion of the Humber margin, based on lithological linkages (e.g. the presence of marble and marble breccia derived from the Humber platform) with the autochthonous, external parts of this margin (Bursnall and de Wit 1975; Williams 1977; Hibbard 1983; Hibbard et al. 1995; Cawood et al. 2001). The Fleur de Lys Supergroup comprises several groups of dominantly clastic psammitic and pelitic schist, some of which may be correlatives (Hibbard 1983; Hibbard et al. 1995), and some units dominated by mafic schist. It is thought to be Ediacaran to Early Ordovician in age and may be correlative with the upper part of the Dalradian Supergroup (Kennedy 1975).

The two easternmost units within the Fleur de Lys Supergroup, the Rattling Brook Group and the Birchy Complex (Fig. 5), both contain slivers of ultramafic rock. Isolated blocks of soapstone, carbonate-bearing serpentinite and talc-tremolite-carbonate-bearing ultramafic schists (possibly suggesting a lherzolite protolith, van Staal et al. 2013) are tectonically interleaved within psammites and pelites in the western part of the Rattling Brook Group. They are particularly prominent within a narrow, discontinuous shear zone (the D_1 Bishie Cove slide of Kennedy 1971) that is interpreted by van Staal et al. (2013) as an early thrust that emplaced the Rattling Brook Group above correlative rocks of the Old House Cove Group to the west.

The Birchy Complex (Hibbard 1983) lies east of and structurally overlies the Rattling Brook Group (Fig. 5); it comprises highly strained and metamorphosed, polyphase-folded mafic schists (Fig. 6a) that are locally interlayered with psammite, graphitic pelite, calc-silicate, coticule, jasper and ultramafic rocks. The Birchy Complex forms a steeply dipping, thin structural footwall (1 – ca. 2.5 km outcrop width) to the ca. 490 Ma supra-subduction zone ophiolites (Hibbard 1983; Dunning and Krogh 1985; Cawood et al. 1996; Skulski et al. 2010) of the Baie Verte oceanic tract (Notre Dame subzone) across the Baie Verte – Brompton line to the east (Fig. 5; van Staal et al. 2007). The ultramafic rocks in the Birchy Complex vary from brecciated talc- and/or tremolite-bearing serpentinite to listwanite and bright green fuchsite-actinolite/tremolite schist. They principally occur in highly deformed graphite-bearing mica schist as metre-to decimetre-scale lenses (Fig. 6b), in other metasedimentary rocks, and also in metavolcanic rocks (Fig. 6c). The metasedimentary rocks locally contain detrital chromite, suggesting that they were in part derived from the ultramafic rocks. They therefore closely resemble the occurrences of ultramafic rocks within the Dalradian Supergroup of southern Achill Island, western Ireland (van Staal et al. 2013).

The protoliths of the Birchy Complex mafic schists include metagabbro, lava, pyroclastic and/or epiclastic rocks (Hibbard 1983). No pillow structures have been identified, but the mafic schists, in places, probably represent highly deformed and metamorphosed submarine flows and/or high-level sills. Hibbard (1983) and van Staal et al. (2013) have determined that the mafic rocks of the Birchy Complex are tholeiitic in composition and have a strong affinity with MORB. A gabbro from the Birchy Complex has yielded a Late Ediacaran U–Pb zircon ID–TIMS age of 558 ± 1 Ma (van Staal et al. 2013), while LA–ICPMS U–Pb concordia zircon ages from a gabbro and an intermediate tuffaceous schist have yielded ages of 564 ± 7.5 Ma and 556 ± 4 Ma, respectively (van Staal et al. 2013). These ages overlap with the last phase (565–550 Ma) of rift-related magmatism observed along the Humber margin of the northern Appalachians (Cawood et al. 2001).

The Birchy Complex has traditionally been considered to represent a tectonic mélange associated with the initial stages of the Early to Middle Ordovician obduction of the Penrose-type ophiolites of the Baie Verte oceanic tract onto the Humber margin (Bursnall 1975; Williams 1977; Hibbard et al. 1995). This tectonic setting was inferred based on its association of interleaved ultramafic and sedimentary rocks, its highly dismembered character and its location immediately adjacent to the Penrose-type ophiolites of the Baie Verte oceanic tract across the Baie Verte – Brompton line (Fig. 5). van Staal et al. (2013) infer that the age relationships and characteristics of the Birchy Complex and adjacent Rattling Brook Group suggest that the ultramafic rocks represent slices of continental lithospheric mantle exhumed onto the seafloor with magmatic accretion of MORB-like mafic rocks. The Rattling Brook block is regarded as a major extensional allochthon that was separated from the para-authochthonous Humber margin along an extensional detachment lubricated by exhumed mantle, while the Birchy Complex represents the remnants of an OCT zone formed during hyperextension of the Humber margin prior to establishment of the Iapetus mid-ocean ridge further outboard (van Staal et al. 2013).

Quebec – Vermont

Potential ancient OCT rocks associated with hyper-extension of the Laurentian margin occur southwest of Newfoundland in the Northern Appalachians of northern Vermont and southern Quebec (van Staal et al. 2013). These rocks (the Vermont – Quebec serpentine belt of Doolan et al. 1982) have been considered to represent remnants of tectonically emplaced slivers of Taconic Penrose-type ophiolites (Stanley et al. 1984), although nowhere do they constitute a typical Penrose-type ophiolite stratigraphy.

In common with the Birchy Complex rocks of Newfoundland and the isolated occurrences of ultramafic rocks along the Laurentian margin of Scotland and Ireland, one of the chief difficulties in recognizing sequences produced during hyper-extension is distinguishing continental margin rocks from those of oceanic (including supra-subduction zone) affinity. In many cases this can be a circular argument, as the suture zone in the Canadian Appalachians (the Baie Verte – Brompton line) that separates continental margin rocks to the northwest (Humber zone of Williams 1979) from the Penrose-type ophiolites, arc volcanic rocks, mélanges, and syn-orogenic deposits to the southeast (Dunnage zone of Williams 1979) is defined principally by the outcrop pattern of the putative Penrose-type ophiolitic rocks (e.g. Williams and St.-Julien 1982). The best evidence for ultramafic rocks potentially associated with hyper-extension of the Laurentian margin therefore would come from occurrences within unequivocal Iapetan rift-related sequences of the Humber zone.

In the internal Humber zone of the southern Quebec Appalachians (Fig. 7), three metamorphosed lithologic units (correlative with formal units of the external Humber zone) are recognized within a series of anticlinoria and structural windows: the Oak Hill, Caldwell, and Rosaire groups (latest Neoproterozoic to Early Ordovician; St.-Julien and Hubert 1975). These units were formerly referred to as the Sutton Schists in the Sutton Mountains anticlinorium and the Bennett Schists in the Notre Dame Mountains anticlinorium (Fig. 7). In the external Humber zone, the Oak Hill Group comprises mafic volcanic rocks overlain by quartzites, dolostones, and phyllites, and represents a rift-drift transition. The Late Ediacaran (ca. 565 Ma) Caldwell Group (Bédard and Stephenson 1999; Villeneuve and Bédard, personal communication) is characterized by quartzofeldspathic sandstone with subordinate mafic volcanic rocks, green and red slates, and phyllites, whereas the Rosaire Group consists of quartzite, black slates, and phyllites (Castonguay and Tremblay 2003).

Within the Rosaire and Caldwell groups in the Notre Dame Mountains anticlinorium, a series of discontinuous serpentinite slivers occurs along a complex $D_1 – D_2$ shear zone (Tremblay and Pinet 1994). This series of tectonized and brecciated serpentinites is collectively termed the Pennington Sheet (Fig. 7), which was subsequently deformed by later $D_3 – D_4$ folds (Tremblay and Pinet 1994). Although it was previously thought to represent a sliver of the Thetford Mines ophiolitic complex (of Penrose-type affinity) that crops out in the Dunnage zone immediately to the southeast (Fig. 7), the correlation of the Pennington Sheet with the Thetford Mines ophiolitic complex is not clearly established (Tremblay and Castonguay 1999) and is not supported by the available geochronologial data. The Pennington sheet has yielded a $^{40}Ar – ^{39}Ar$ metamorphic hornblende age of 491 ± 11 Ma (Whitehead et al. 1996), whereas the Thetford Mines ophiolite has yielded a U–Pb zircon crystallization age of 479.2 ± 1.6 Ma (Tremblay et al. 2011). The Pennington sheet age correlates better with the ophiolitic Belvidere Mountain complex in adjacent Vermont, which has yielded a metamorphic hornblende $^{40}Ar – ^{39}Ar$ plateau age of 505 ± 2 Ma (Laird et al. 1993), and is closely associated with rift clastics and slope-rise deposits of the Humber zone (Hazens Notch Formation, see below). van Staal et al. (2013) suggested that the slivers of mantle interleaved with strongly tectonized metasedimentary rocks of the Pennington Sheet are better interpreted as a segment of the hyper-extended Appalachian margin of Laurentia.

The Dunnage zone and part of the easternmost Humber zone of southern Quebec continue south along strike into northern Vermont (Fig. 8), although in Vermont this belt has not been formally subdivided into the Humber (continental) and Dunnage (oceanic) terranes as in southern Quebec. A sequence of rift-related clastic rocks of Late Proterozoic to Early Paleozoic age is preserved in a group of thrust sheets called the Green Mountain slices, whereas oceanic and supra-subduction zone rocks occur in the Rowe, Moretown and Hawley slices (Fig. 8), known collectively as the Rowe – Hawley belt (Kim et al. 2003). The Vermont Appalachians lack well-developed ophiolite sequences but slivers of highly serpentinized peridotite occur in the Green Mountain, Rowe, Moretown, and Hawley slices (Fig. 8) and have been interpreted as Penrose-type ophiolitic remnants (Doolan et al. 1982; Stanley et al. 1984).

The peridotites within the Moretown and Hawley slices (Fig. 8) most likely represent tectonically

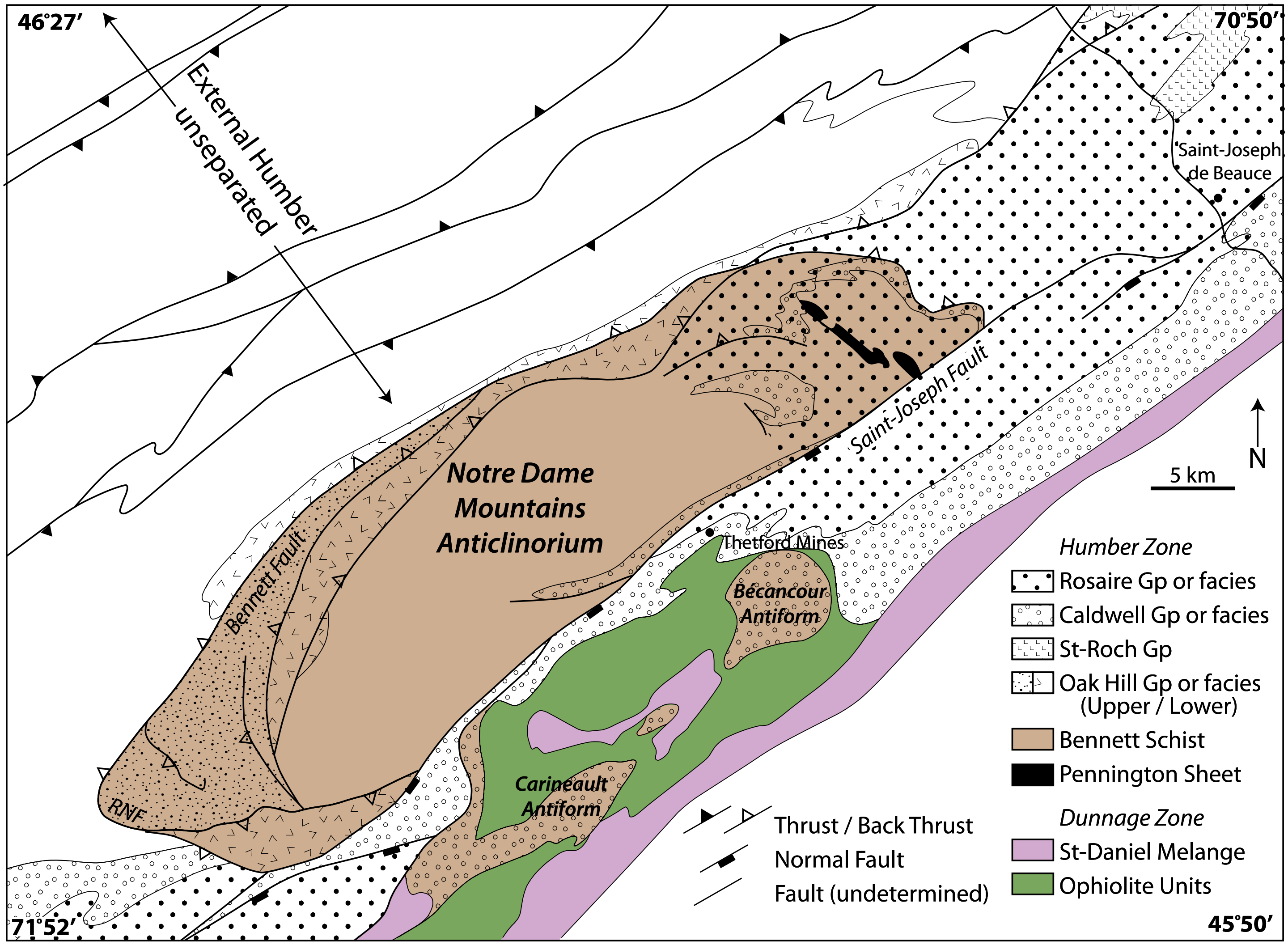

Figure 7. Simplified geologic map centered on the Notre Dame Mountains anticlinorium (NDMA) of southern Quebec (from Castonguay and Tremblay 2003). A patterned ornament is added where the original facies of the Bennett Schist has been recognized.

emplaced slivers of Penrose-type ophiolites associated with the closure of the Iapetus ocean (Coish and Gardner 2004). Detrital zircon data imply that the host sedimentary rocks (the Moretown Formation of presumed arc affinity) must be Early Ordovician or younger in age (Ryan-Davis et al. 2013). The peridotite mineral assemblage (serpentine, talc, small amounts of magnesite, tremolite and magnetite, and local relict olivine, pyroxene and chromite), high MgO, and low TiO_2 and Al_2O_3 whole-rock compositions suggest a dunite protolith, whereas the compositions of remnant olivine (high Mg#) and chromite (high Cr#) indicate that the peridotites formed as highly-depleted mantle residues, probably in a forearc, supra-subduction zone setting (Coish and Gardner 2004).

The rocks of the Green Mountain and Prospect Rock slices (Fig. 8) are composed of albite-bearing schists (e.g. the non-graphitic Fayston Formation and the graphitic Hazens Notch Formation) and rare greenstone horizons (Thompson and Thompson 2003). The Hazens Notch and Ottauquechee formations also contain serpentinized ultramafic and talc – carbonate bodies. The Fayston, Hazens Notch and Ottauquechee formations are interpreted by Thompson and Thompson (2003) and Kim et al. (2003) to represent metamorphosed rift clastics and slope-rise deposits spanning the Late Neoproterozoic to Cambrian Iapetan rift – drift transition, and are likely correlatives of the rift – drift facies exposed within the Sutton Mountains (Colpron et al. 1994) and Notre Dame Mountains anticlinoria in southern Quebec. The geochemistry of the greenstones within the Green Mountain Slice and the Sutton Mountains anticlinorium suggest that they formed during rifting (Coish et al. 1985; Colpron et al. 1994). The slivers of mantle interleaved with strongly tectonized metasedimentary rocks in the rift-related Laurentian margin sequences of southern Quebec (Sutton Mountains anticlinorium; the Pennington Sheet in the Notre Dame Mountains anticlinorium) and northern Vermont (e.g. Belvidere Mountain Complex) may therefore represent sequences formed during hyperextension of the Laurentian margin.

Virginia – Carolina

The Blue Ridge province of Virginia

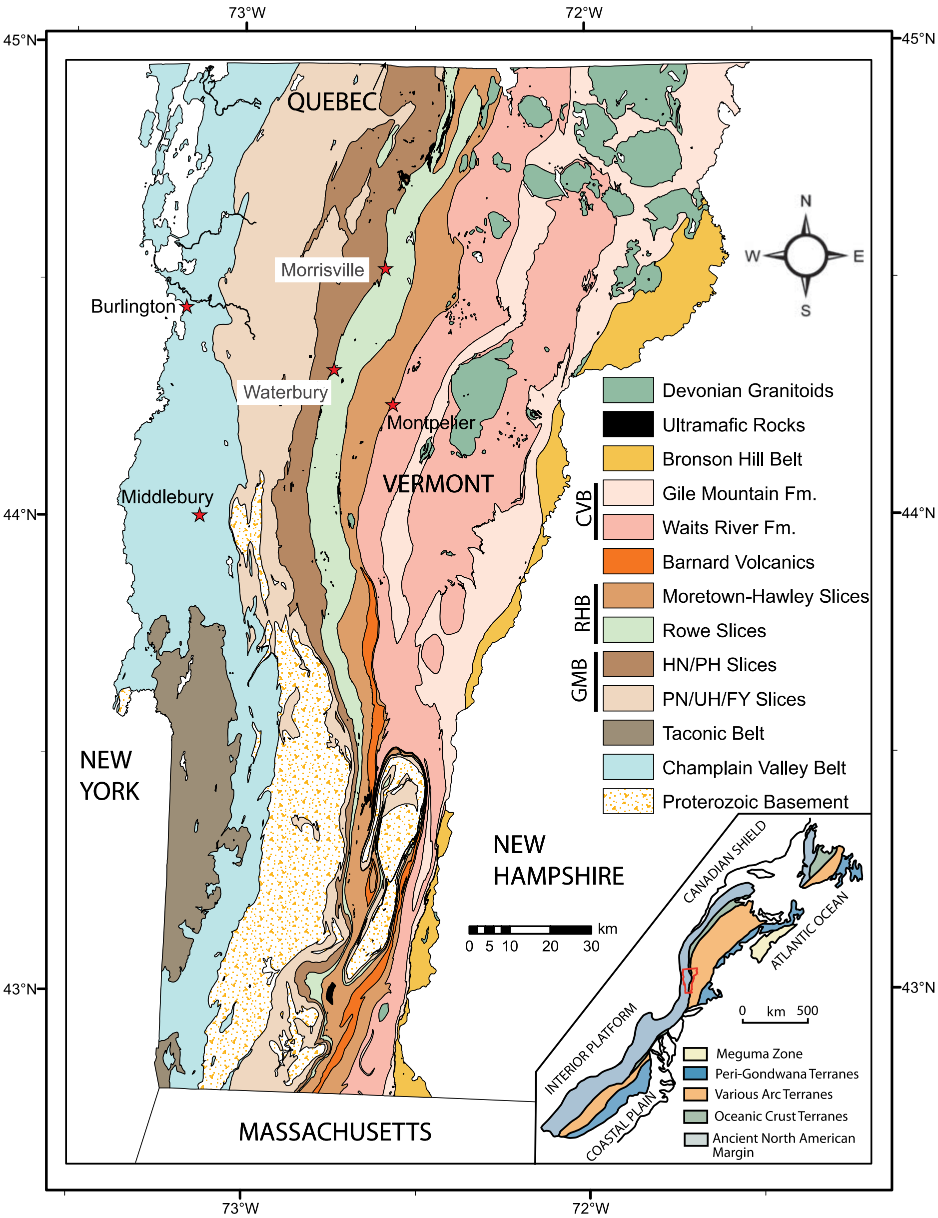

Figure 8. Geological map of Vermont (from Coish et al. 2012). GMB: Green Mountain Belt; PN: Pinnacle; UH: Underhill; HN: Hazens Notch; FY: Fayston; PH: Pinney Hollow; RHB: Rowe – Hawley Belt; CVB: Connecticut Valley Belt. The occurrences of ultramafic rocks are marked in black. Inset map shows terranes in the northern Appalachians (from Hibbard et al. 2006).

and North Carolina largely comprises a crystalline basement massif of Mesoproterozoic (1.2 – 1.0 Ga) age that is flanked by Late Neoproterozoic to Early Paleozoic cover. It contains the largest region of Mesoproterozoic rocks within the Appalachian orogen and is an assumed correlative of the Grenville province of Canada (Rivers 1997) and the Adirondacks (McLelland et al. 2010). The Late Neoproterozoic to Early Paleozoic cover records the transition from deep to shallow-water deposition along the Laurentian margin and is linked to two periods of crustal extension at 760 – 680 Ma and ca. 565 Ma (Southworth et al. 2009), with the latter resulting in the opening of the Iapetus Ocean (Aleinikoff et al. 1995). The Late Neoproterozoic sequences include the Lynchburg Group of Virginia, which is broadly correlative with the Mount Rogers Formation of Virginia – North Carolina (felsic volcanic rocks within this formation are dated at ca. 760 Ma; Aleinikoff et al. 1995), the Ashe Formation in North Carolina, and the Tallulah Falls, Sandy Springs and New Georgia formations in Georgia (e.g. Rankin et al. 1973; Hatcher 1987).

Ever since Hess (1955) recognized two parallel belts of ultramafic rocks in the Appalachians, the origin and tectonic significance of these serpentinite belts has been the subject of controversy. The westernmost serpentinite belt of Hess (1955) occurs west of a zone of intense deformation in the eastern Blue Ridge Province (i.e. within rocks of Laurentian affinity), whereas the other serpentinite belt occurs east of an axis of intense deformation in the Piedmont Province (i.e. part of the Iapetan realm; Hibbard et al. 2006). A distinctive feature of the Late Neoproterozoic cover of the eastern Blue Ridge Province relative to temporally correlative cover sequences of the western part of the province is the abundance of mafic and ultramafic rocks (Misra and Conte 1991).

Typically, Blue Ridge ultramafic rocks (and those of the southern Appalachians in general) occur as abundant, small isolated pods of metadunite and subordinate metaharzburgite surrounded by metasedimentary rocks, enclosed within the regional foliation, and having no evidence of intrusive contacts, contact metamorphism or chilled margins (Misra and Keller 1978; Raymond et al. 2003). The clastic metasedimentary rocks surrounding these bodies commonly display a continuous, undisrupted stratigraphy (Wang and Glover 1997; Kasselas and Glover 1997). In the literature, they have been described as mélanges (e.g. Abbott and Raymond 1984) or Alpine-type ultramafic rocks, and they contrast markedly with the large, nearly complete Penrose-type ophiolite sections of the northern Appalachians that formed in a suprasubduction zone setting. They are pretectonic with respect to the pervasive Taconic deformation, and few primary textural and structural features have survived amphibolite to granulite-grade regional metamorphism, although compositional layering is locally preserved in some ultramafic rocks (Swanson et al. 2005). Most of the larger Blue Ridge ultramafic bodies are associated with mafic rocks (e.g. the Buck

Creek mafic – ultramafic suite; Peterson and Ryan 2009), but the smaller bodies are not and this may in part be a result of deformation and disaggregation during emplacement (Swanson et al. 2005). It is possible that the ultramafic rocks were emplaced into intercalated volcanic and sedimentary rocks and are not genetically related (Rankin et al. 1973). However, the proximity of the mafic rocks to some of the Blue Ridge ultramafic bodies has been used to infer a petrogenetic relationship (Wang and Glover 1997).

A variety of tectonic models has been put forward to account for the origin and emplacement of ultramafic bodies in the Blue Ridge and elsewhere in the southern Appalachians. These models include tectonically dismembered Penrose-type ophiolites (e.g. Misra and Keller 1978; McElhaney and McSween 1983; Hatcher et al. 1984; Raymond et al. 2003; Swanson et al. 2005; Peterson and Ryan 2009), fragments in tectonic mélange complexes (e.g. Abbot and Raymond 1984; Lacazette and Rast 1989), and a rift-related intrusion origin (i.e. the ultramafic rocks are consanguineous with the mafic rocks and represent sill and dike emplacement of fractional crystallization products from a picritic-basaltic magma; Wang and Glover 1997). Reaching a definitive interpretation on the origin and emplacement of ultramafic bodies in the southern Appalachians is unlikely, as is suggested by the large disparity in the existing tectonic models, and by the intensity of the overprinting Taconic deformation. We feel that an OCT origin may explain many of the enigmatic features of the Blue Ridge serpentinite belt, and in particular may be applicable to some of the occurrences of ultramafic rocks in the Late Neoproterozoic rift-related sequence of the Lynchburg Group of Virginia and the Ashe Formation in North Carolina.

Baltic Margin of Norway

The Caledonides of Scandinavia and East Greenland were formed by the closure of the Iapetus Ocean in the Middle Silurian (ca. 430 Ma), and the ensuing continent-continent collision continued for 30 Ma into the Early Devonian. The Scandinavian Caledonides are divided into an Autochthon, Parautochthon, and Lower, Middle, Upper and Uppermost Allochthons (Sturt and Austrheim 1985). The Lower and Middle Allochthons are believed to represent shelf and continental slope units deposited on the Baltoscandian margin (e.g. Roberts 2003). The Upper Allochthon is interpreted as a series of magmatic arc, oceanic and marginal basin deposits from locations within and peripheral to the Iapetus Ocean (e.g. Pedersen et al. 1991), although certain units within this assemblage predate the opening of Iapetus and are likely exotic to Baltica (e.g. the Kalak Nappe Complex in Finnmark; Kirkland et al. 2008). The Uppermost Allochthon is considered to have Laurentian affinities (e.g. Stephens and Gee 1985).

The basement-cover nappes of the Lower and Middle Allochthons in southern Scandinavia are commonly interpreted to have originated from the margin of Baltica because their Proterozoic history is similar to that of the autochthonous local basement (e.g. Lundmark et al. 2007). Andersen et al. (2012) highlighted the presence of a mélange hosting solitary mantle peridotites (Qvale and Stigh 1985) in southern Norway (Fig. 9) that occurs structurally above the Western Gneiss Region and structurally below the large crystalline Proterozoic nappe complexes of the Middle Allochthon (the Jotun, Upper Bergsdalen and Lindås nappes; Fig. 9). The mélange is found at the same structural level along a distance of more than ca. 400 km from the Bergen Arcs northeastwards across southern Norway, and comprises numerous lenses of variably altered mantle peridotite and minor mafic meta-igneous rocks (Andersen et al. 2012). Until the study of Andersen et al. (2012), the mélange had either been largely disregarded in regional tectonostratigraphic syntheses (e.g. Roberts and Gee 1985) or was believed to represent a dismembered Penrose-type ophiolite. The mélange may have had a much wider geographical distribution (Andersen et al. 2012), as regional mapping shows that a mélange with abundant mantle peridotites of detrital origin continues into the Gula, Seve and equivalent 'suspect' nappe complexes in the central Scandinavian Caledonides (Stigh 1979).

In common with most of the other occurrences of potential OCT ophiolites within the Appalachian – Caledonian orogen that are discussed in this study, the mantle peridotite-bearing mélange has undergone intense polyphase Caledonian (Scandian) deformation and metamorphism. However, there is no evidence to suggest an intrusive relationship between the ultramafic rocks and the host sedimentary rocks (Andersen et al. 2012). Interpretation of the unit is also hampered by a lack of firm age constraints on the timing of mélange formation, as the associated gabbros and basalts are undated and the sedimentary matrix of the mélange has no preserved fossils except those found in the Middle Ordovician (Llanvirn; 470 – 464 Ma) monomict serpentinite conglomerate east of Vågå (Bruton and Harper 1981; Fig. 9). Andersen et al. (2012) infer that the association of solitary mantle peridotites, detrital ultramafic rocks and siliciclastic- and carbonate-rich sedimentary rocks (with limited volumes of associated gabbros and basalts) implies formation in deep basins formed by large-magnitude extension rather than in a magma-dominated spreading-ridge environment.

The thin sheets of highly attenuated continental crystalline basement and associated metasedimentary rocks in the Middle Allochthon, structurally overlying the mantle peridotite-bearing mélange, are interpreted by Andersen et al. (2012) as extensional allochthons juxtaposed onto continental mantle lithosphere by large-magnitude extensional detachments similar to those in present-day continental margins and in the Alps (e.g. Manatschal 2004). In such a model, the regional mélange unit found between the Lower and Middle Allochthons in the southwestern Scandinavian Caledonides would therefore represent the vestiges of a hyperextended pre-Caledonian continental margin of Baltica, while the Lindås, Upper Bergsdalen and Jotun crystalline nappe complexes (Fig. 9) would represent ancient outboard ribbon continents. The tectonic configuration of the pre-Caledonian margin of Baltica in the model of Andersen et al. (2012) is significantly more compli-

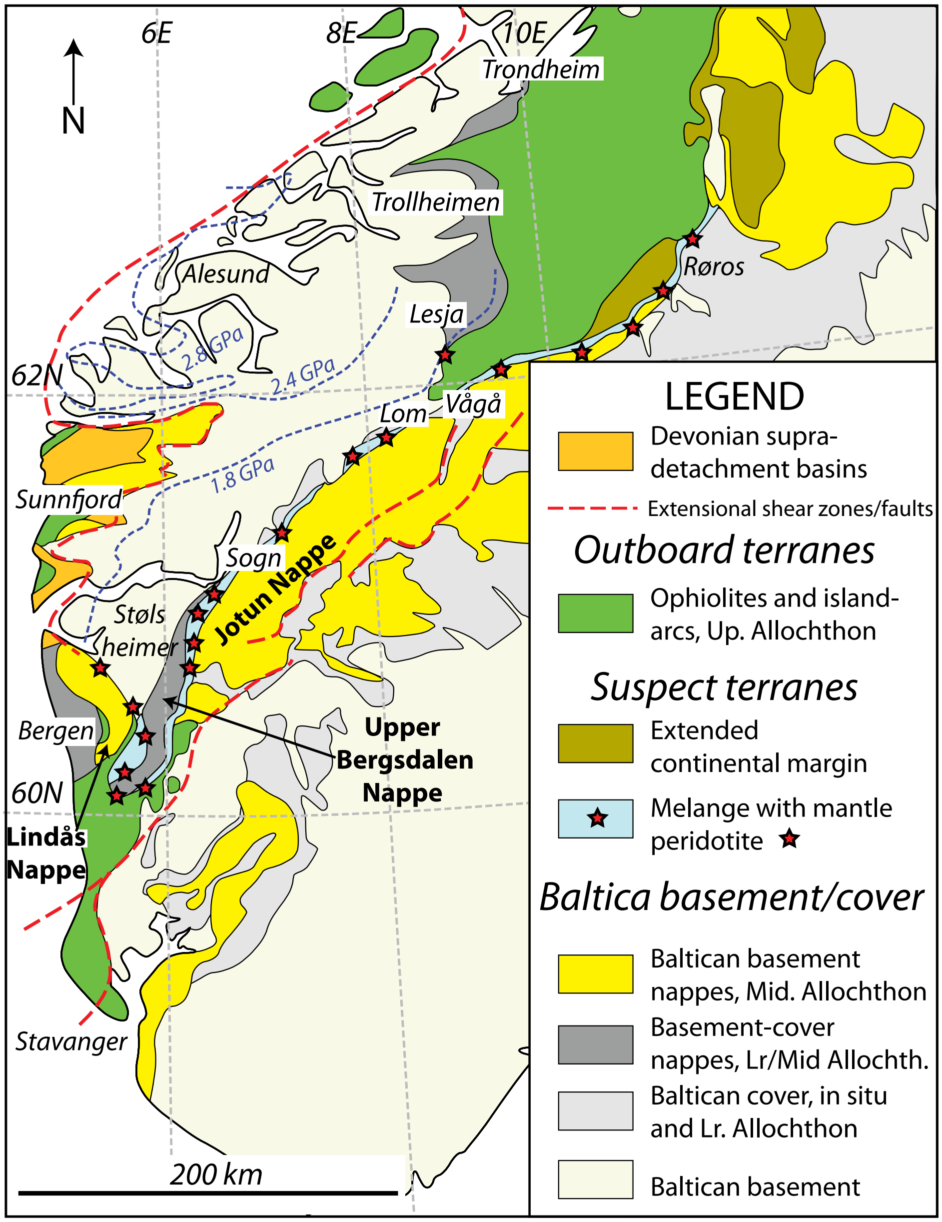

Figure 9. Tectonostratigraphic map of the South Norwegian Caledonides (from Andersen et al. 2012), highlighting the regional distribution of the hyper-extended mélange assemblages structurally below the large crystalline nappes (such as the Lindås, Upper Bergsdalen and Jotun Nappes) of the Middle Allochthon.

cated than that traditionally conceived. In particular, the presence of an OCT domain (now represented by the mantle peridotite-bearing mélange below the major crystalline continental nappes) has been largely disregarded in previous tectonic reconstructions. Given that the width of an OCT domain (passing from highly attenuated extensional allochthons of continental crust through transitional crust into unambiguous oceanic crust) can be upwards of 100 km (e.g. Péron-Pinvidic and Manatschal 2010), failing to recognize the presence of OCT domains in orogenic belts can result in significantly underestimated crustal shortening estimates.

CONCLUSIONS

Recognition of OCT Sequences in the Caledonian – Appalachian Orogenic Belt

Conclusively identifying OCT sequences within the Caledonian – Appalachian orogenic belt has proved challenging and this problem is particularly acute for the polyphase-deformed rocks originally formed near or on the Laurentian margin. On the Laurentian margin, potential OCT sequences are commonly tectonically juxtaposed against Penrose-type ophiolite sequences of the colliding Grampian – Taconic oceanic arc, and the inferred OCT rocks (typically isolated occurrences of Alpine-type ultramafic rocks) do not preserve the pre-orogenic extensional structures and basement – cover relationships as seen in the type Alpine OCT units (Manatschal and Müntener 2009). It is probably no coincidence that the two best documented occurrences of OCT sequences on the Laurentian margin (the Dalradian Supergroup in western Ireland; Chew 2001, and the Birchy Complex of the Fleur de Lys Supergroup of Newfoundland; van Staal et al. 2013) are superbly exposed. The wave-polished Atlantic coastal outcrops in both units enable the field relationships of the isolated serpentinite occurrences to be established, and it can be demonstrated that they are at least in part detrital and embedded in a matrix of graphitic pelite. Both sequences are associated with MORB-like rift-related basaltic volcanic rocks linked to the opening of the Iapetus Ocean, and hence clearly pre-date the formation of the Grampian – Taconic oceanic arc. In summarizing the isolated occurrences of ultramafic rocks within the Laurentian margin of the Appalachians in Quebec – Vermont and Virginia – North Carolina, we have attempted to restrict the discussion to sequences in which the host rocks are associated with the break-up of the Laurentian continent leading to the formation of the Iapetus Ocean (i.e. the matrix to the Alpine-type ultramafic rocks is Late Neoproterozoic in age). However, because of poor exposure and the intensity of the overprinting Taconic deformation, the origin and emplacement of many ultramafic bodies in the Appalachians will remain uncertain. Nevertheless, the common occurrence of OCT-like rocks along the whole length of the Appalachian – Caledonian margin of Laurentia suggests that the opening of the Iapetus Ocean may have been accompanied by hyperextension and formation of magma-poor margins along many segments.

Implications of Hyper-Extended Margins within the Caledonian – Appalachian Orogen

Hyperextension During Break-up

van Staal et al. (2013) explored the implications of hyperextension along segments of the Laurentian margin during the opening of the Iapetus Ocean, including the delaying of the onset of thermal subsidence and the formation of ribbon-continents. The last major magmatic pulse on the Appalachian Humber margin took place from 615 to 570 Ma and is thought to be related to the opening of the Iapetus Ocean (Kamo et al. 1989; Cawood et al. 2001), consistent with paleomagnetic evidence that eastern Laurentia had separated from its conjugate margin(s) during the Late Ediacaran (McCausland et al. 2007). However, thermal subsidence analysis suggests that the rift-drift event took place during the late Early Cambrian, at least 30 – 40 my later, along the length of the Appalachian margin (Bond et al. 1984; Williams and Hiscott 1987; Cawood et al. 2001; Waldron and van Staal 2001), which is supported by a small, latest Ediacaran rift-related pulse of predominantly MORB magmatism between 565 and 550 Ma along the Appalachian Humber margin (Cawood et al. 2001, Hodych and Cox 2007, van Staal et al. 2013). To explain this apparent paradox, Cawood et al. (2001) and Waldron and van Staal (2001) invoked a multistage rift history that involved an initial separation of Laurentia from the west Gondwanan cratons at ca. 570 Ma, followed by rifting of another block or blocks from Laurentia (e.g. the Dashwoods ribbon-continent) at ca. 540 – 535 Ma into an already open Iapetus Ocean, thus establishing the main passive margin sequence in eastern Laurentia. van Staal et al. (2013) speculate that rift-related thermal subsidence (and the resultant transgression) at ca. 540 – 535 Ma may have been significantly delayed by a number of factors, and hence the end of rift-related magmatism at ca. 550 Ma is the best proxy for the final break-up and the onset of spreading in the Iapetus Ocean along the northern Appalachian margin of Laurentia. The factors that were inferred to have inhibited thermal subsidence include the insulating effects of a thick sedimentary blanket on the Laurentian margin, anomalous slow cooling and prolonged rift-margin uplift and emplacement of hot mantle under the hyperextending crust along this segment of the Laurentian margin (van Staal et al. 2013). Potential Dashwoods equivalents occur in the Southern Appalachians (van Staal and Hatcher 2010) and in the Irish Caledonides, which if correct provides further support for extensive hyperextension during opening of the Iapetus Ocean. The ribbon continents that were rifted from the Irish sector of the Laurentian margin (the Slishwood Division; Flowerdew and Daly 2005, and the Tyrone Central Inlier; Chew et al. 2008; Fig. 3) are discussed further below.

Hyperextension During Ocean Closure

The presence of a collage of ribbon continents outboard of the Laurentian margin formed during hyperextension has significant implications for the evolution of the Grampian – Taconic orogeny during the closure of the Iapetus Ocean. These include the preservation of different structural and metamorphic histories within the ribbon continents compared to each other and particularly to autochthonous rocks of the adjacent margin (van Staal et al. 2013). For example, the Grampian – Taconic tract is characterized by several poorly understood structural and metamorphic events that took place between 515 and 455 Ma (Laird et al. 1993; van Staal et al. 2007, 2009b; Chew et al. 2010; Castonguay et al. 2010). A complex margin as described above allows for incomplete suturing and entrapment of small oceanic basins, similar to the present-day Caspian and Black seas, between part of the autochthonous margin and adjacent orogen. Such basins could have closed later during the Appalachian – Caledonian cycle, creating small orogens that are younger than deformation in their neighbouring rocks. The prevalence of Silurian Salinic metamorphic ages along some segments of the Humber margin (Lin et al. 2013) may, in part, be due to such a process.

Both the OCT sequences of the Dalradian Supergroup in western Ireland (Fig. 3) and Birchy Complex in the Fleur de Lys Supergroup of Newfoundland (Fig. 5) were subjected to high-pressure (> 10 kbar) Grampian – Taconic metamorphism (Chew et al. 2003; Willner et al. 2012) evidenced by preservation of Grampian – Taconic ^{40}Ar – ^{39}Ar white mica ages (Chew et al. 2003; van Staal et al. 2009a; Castonguay et al. 2010) in contrast to the autochthonous Laurentian margin rocks sitting further inboard which yielded mainly Silurian or Devonian ages (Hibbard 1983; Cawood et al.1994; Lin et al. 2013). Both Chew et al. (2003) and van Staal et al. (2013) attributed the formation and preservation of high pressure – low temperature metamorphic assemblages to subduction of the leading edge of the hyper-extended Laurentian margin beneath the Grampian – Taconic arc system before it returned along the same subduction channel because of its buoyancy. OCT rocks are able to reach and preserve (ultra)high-pressure conditions as they tend to follow dense oceanic lithosphere deep into subduction zones prior to the arrival of more buoyant continental lithosphere that resists subduction (e.g. Beltrando et al. 2010). van Staal et al. (2013) surmise that this process could have translated the Birchy Complex and spatially associated rocks to a high structural level during the Taconic orogeny (470 – 460 Ma). This may explain preservation of evidence for pervasive Taconic tectono-metamorphism in these rocks compared to its apparent non-preservation in other, more inboard parts that have undergone a Salinic overprint (Cawood et al. 1994 and van Staal et al. 2009a, b).

In northwestern Ireland, two high-grade basement paragneiss terranes, the Tyrone Central Inlier and the Slishwood Division (Fig. 3), crop out immediately to the southeast of the Laurentian margin. Their metamorphic and magmatic evolution is substantially different from that of the lower-grade Dalradian Supergroup rocks adjacent to the northwest, and this led to speculation that they represent exotic terranes (e.g. Max and Long 1985; Sanders et al. 1987), but more recent research (e.g. Daly et al. 2004; Chew et al. 2008) suggests that both terranes have a Laurentian affinity. The Tyrone Central Inlier has experienced upper amphibolite-facies metamorphism during the Grampian Orogeny whereas the Slishwood Division has experienced eclogite- and granulite-facies metamorphism prior to suturing with the Laurentian margin (Sanders et al. 1987; Flowerdew and Daly 2005). It is believed that the Tyrone Central Inlier and the Slishwood Division represent crustal fragments that detached from the Laurentian margin during the opening of the Iapetus Ocean (e.g. Chew et al. 2008). Consequently, they were able to evolve independently of the autochthonous Laurentian margin during the early stages of the Grampian Orogeny; the Tyrone Central Inlier experienced high-grade metamorphism, possibly in the roots of a deforming Grampian arc, whereas the Slishwood Division may have been subducted beneath this same arc system. Both units were finally juxtaposed with the Laurentian margin during regional southeast-directed Grampian D_3 thrusting (e.g. Alsop and Hutton 1993).

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