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Geological Association of Canada Newfoundland Section

A B S T R A C T S

2007 Spring Technical Meeting February 19–21, 2007

JOHNSON GEO CENTRE, SIGNAL HILL, ST. JOHN'S NEWFOUNDLAND

The technical meeting featured a symposium entitled *The Map that Moved Mountains*, marking the 30th anniversary of the ground-breaking "*Tectonic-lithofacies map of the Appalachian Orogen*", developed by Dr. Harold (Hank) Williams in 1977. This remarkable piece of work was the first to depict orogen-scale tectonic elements in terms of their original settings and locations, and its influence has pervaded all subsequent studies of the Appalachians and influenced those in other ancient orogens. The symposium featured contributions related to the Appalachian-Caledonian Orogen, especially those with broad and provocative ideas, contributions related to the evolution of mountain belts in general, and also contributions related to the evolution of geological maps and how they have influenced our thinking. The symposium also honoured Hank's long and distinguished career, and his huge contributions to our geological knowledge of Newfoundland, North America, and western Europe.

In addition to the symposium, a general session included papers on an eclectic range of topics. The Spring Technical Session also featured the third of the "Topical Geoscience Lecture" series, co-sponsored by the Professional Engineers and Geoscientists of Newfoundland and Labrador (PEG-NL). This year's lecture was delivered by Dr. Paul F. Hoffman of Harvard University, Cambridge, MA, and was entitled: "*The Snowball Earth: An ancient catastrophic event with relevance to modern times*." This topic was an appropriate choice given the snow storm that crippled the city during the meeting!

TECHNICAL PROGRAM CHAIR
ANDREW KERR

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The Master Of Iapetus –
A Poem For Hank Williams

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'…we find no vestige of a beginning,
no prospect of an end…'
James Hutton 1726–1797

That noted gentleman farmer
found granite penetrating
He said so himself,
humming tunes as he walked
the sedimentary rock at Salisbury Crags,
his grey shales tilted between Dunbar and Eyemouth.

Would he have the same turn of tune
if he saw your rocks, Hank?
Would Hutton's heart beat the same rhythm
for Newfoundland as it did his Scotland?
He'd walk your Tablelands
humming Harry Hibbs' tunes just for effect,
we know that now…
he would see why we call this home
he would understand our love of rock and water
know why we caress each stone
each pounding wave,
know why we are who we are…
like Robbie Burns who was 'bred to the plow'
we are born of this place,
of this relentless coastline
and this heroic sea…

So now, over 200 years later,
The gentlemen fiddler from the Southside
Calls out to the world, calls out across Iapetus
Echoing off Hutton's Unconformity,
booming off his granite grave
"Get up, Jim, and get over here…
I got somethin' to show ya' and
Yer' not gonna' believe it!"

The peri-Gondwanan realm in Cape Breton Island and southern New Brunswick

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The current division of the peri-Gondwanan realm of the northern Appalachian orogen into Avalonian and Ganderian components resolves some of the long-standing problems in reconciling terrane models in New Brunswick and Cape Breton Island with those in New England and Newfoundland. The similarity in Neoproterozoic history between Ganderia and Avalonia makes resolution of those components particularly challenging, especially because the Neoproterozoic components of Ganderia are so little exposed in Newfoundland and Maine. Complexity within each of Ganderia and Avalonia also contributes to the problem, as both consist of multiple Neoproterozoic terranes. The previously well-documented geological contrasts between Ganderia and Avalonia are supported further by recognition that Avalonia experienced systematic and pervasive ^{18}O-depletion that did not affect Ganderia. This depletion may have been linked to hydrothermal alteration during rifting at ca. 560–550 Ma as Avalonia separated from Gondwana.

U-Pb dating has shown that Neoproterozoic rocks are more widespread in both western Cape Breton Island and in the New River belt of southern New Brunswick than was previously recognized. From mainland southern New Brunswick, they appear to be offset to Grand Manan Island and the central Gulf of Maine. These Neoproterozoic Ganderian belts are separated from the also Neoproterozoic Ganderian Brookville-Bras d'Or terrane of southern New Brunswick and Cape Breton Island by the Silurian Kingston-Aspy arc. Geophysical studies suggest that the basements are different under these Ganderian Neoproterozoic belts, although all these areas produced granitoid rocks with negative epsilon Nd values, in contrast to the positive values characteristic of Avalonia.

The original positions of Ganderia and Avalonia around Gondwana, the nature of their pre-Neoproterozoic basements, and their relationship to the now-adjacent Meguma remain major uncertainties. Geochemical, isotopic, and detrital zircon data from sedimentary and metasedimentary sequences in Avalonia suggest that older stratigraphic units of Avalonia had different and more continental and mature sources than the Upper Neoproterozoic and Lower Paleozoic cover. Those sources were not identical to those which provided similarly continental and mature sediment to Ganderia. Links between sources and basements in Ganderia and Meguma seem more likely than links between those areas and Avalonia.

Post-Taconic carbonate ramp development: the Late Ordovician Lourdes Formation, Port au Port Peninsula, Newfoundland

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The Caradocian Lourdes Formation, outcropping continuously along 18 km of coastline on the Port au Port Peninsula, constitutes the only post-Taconic Ordovician carbonate succession in Newfoundland. This ~75 m-thick succession represents a prolonged period of carbonate ramp development, punctuated by unconformities that bound the formation and each of its three depositional members. The nature and significance of the base of the formation are obscured in its only onshore exposure; on the Port au Port Peninsula, the Lourdes Formation has been recently re-interpreted to form the hanging wall of a regional thrust fault which displaced the succession to its current position, directly overlying the Humber Arm Allochthon. Deposition began with the Shore Point Member, possibly coeval with Caradocian sea level rise. It comprises peritidal siliciclastic and carbonate cycles, and is capped by a paleokarst unconformity. Renewed transgression following subaerial exposure led to deposition of deeper subtidal, predominantly carbonate sediments of the Black Duck Member. This member marks a peak in biological activity on the ramp, with an abundant and diverse shelly fauna, intense bioturbation, and most notably, the occurrence of a large number of coral bioherms in the uppermost 15 m. A prominent paleokarst surface forms the top of the Black Duck Member, and is overlain by sandstone and cobble conglomerate representing exposure, differential erosion, reworking of fossil elements, and seaward transport of siliciclastic detritus during relative sea-level lowstand. A third and final phase of carbonate ramp development followed with deposition of the Beach Point Member, an argillaceous, shallow-marine carbonate unit containing metre-scale shallowing upward units and unusual in-situ brecciated grainstone beds. Pyrite-coated and bored hardgrounds and related intraclasts suggest slow sedimentation and near-surface to seafloor diagenesis and reworking. The proportion of siliciclastic silt and clay increases upward throughout the Beach Point Member, culminating with the overlying shales and sandstones of the Winterhouse Formation. As there is no evidence for a significant rise in sea level, the final demise of the carbonate ramp was likely caused by changing circulation patterns and increased siliciclastic input marking a new stage of basin development.

Trilobites on the block: a Middle Cambrian mass-kill in the Penguin Cove Formation, Northern Brook Anticline, western Newfoundland

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A loose block of Penguin Cove Formation in the Northern Brook Anticline of western Newfoundland is host to an unusual layer crowded with abundant complete specimens of the Middle Cambrian corynexochid trilobite *Kootenia*. At least forty individuals occur in a 32 × 19 cm area on the block; most of these range in length from 3.6 to 4.2 cm. The trilobites are deformed, however, in a textbook example of coaxial (irrotational) strain, *i.e.*, pure shear. The principal strain Y'/X' ratio is between 0.67 and 0.68.

Because trilobite remains typically are preserved as incomplete, disarticulated molts or fragments, it is probable that these complete, articulated trilobites represent a death assemblage. This mass mortality could have been caused by oxygen deprivation, possibly caused by a catastrophic release of CO_2 from the seafloor. Mass mortality following mating may be another interpretation, but this is regarded as unlikely, because a second block from the same locality contains larger cranidia and pygidia, indicating that, normally, the *Kootenia* had a longer lifespan.

Most of the *Kootenia* on the first block are of similar size. This indicates that they probably were of about the same age. This suggests that—like some modern day shrimp—certain trilobites may have lived in "schools".

The Reid Brook zone: new insights into the Voisey's Bay Ni-Cu-Co deposit

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The Voisey's Bay Ni-Cu-Co sulphide deposit occurs within troctolites and olivine gabbros of the 1.34 Ga. Voisey's Bay Intrusion. The Voisey's Bay Intrusion is a member of the Nain Plutonic Suite and straddles the ca. 1.85 Ga. suture between Archean orthogneisses of the Nain Province to the east and Paleoproterozoic paragneisses of the Churchill Province to the west. The Voisey's Bay intrusion consists of troctolite to olivine gabbro in two large magma chambers connected by an east-west trending dyke.

The Discovery Hill, Mini-Ovoid, and Ovoid sulphide deposits occur within the sub-vertical dyke system. The distribution of sulphide minerals appear to be controlled by conduit morphology, sulphide traps occur where the dike has a flexure or change in width. These morphological changes appear to be controlled by the interaction of multiple structural elements including vertical E-W fractures and s-c fabrics within the gneiss.

The Eastern Deeps sulphide deposit is located within the base of a magma chamber where sub-horizontal sill-like intrusions branch from the sub-vertical dyke and enter the chamber. The geometry of the sill-like intrusions and the distribution of sulphide minerals appear to be controlled by structural weaknesses produced through intersecting sub-vertical faults.

The Reid Brook zone is located adjacent to, and west of the Discovery Hill deposit. Unlike the other known sulphide deposits contained within the dyke, massive sulphide minerals in the Reid Brook deposit occur not only within the dyke, but proximal to and within the adjacent paragneiss country rocks. The massive sulphide deposit appear to ascend through the dyke as the last stage of a major mineralizing event. Mineralization propagates up through the dyke along a trajectory defined and constrained by pre to syn-tectonic faults. During the last stage of mineralization, massive sulphide minerals are injected into the country rocks along open-space, sub-horizontal fractures. The open-space fractures appear to be produced by the intersection of multiple syn-tectonic brittle faults. The massive sulphide body located within the paragneiss in the Reid Brook zone represent a unique mineral domain not yet observed within other Voisey's Bay deposits. However, analogous structural relationships have been observed elsewhere along the mineralized trend and will be re-examined in light of the discovery of massive sulphide deposits along them at Reid Brook.

Appalachian tectonic maps

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Tectonic maps have been employed to portray the relationships between large and small tectonic units for many decades. A 1961 USGS-AAPG tectonic map of the U.S. portrayed the Appalachians in a pre-plate tectonics context. P. B. King's 1969 North American tectonic map was produced at the dawn of widespread infusion of plate tectonics theory into geoscience, but at a time when we were on the threshold of extensive detailed geologic mapping in the internides of the Appalachians. Because of this, while most major boundaries on King's map in western North America survived into W. R. Muehlberger's 1996 AAPG "Tectonic map of North America," those in the Appalachians internides mostly did not. King's 1970 tectonic map of the southern and central Appalachians was an improvement on the 1961 and 1969 tectonic maps, but it also suffered from a lack of new data on the internides.

Harold Williams' monumental 1978 "Tectonic-Lithofacies Map of the Appalachians" produced the first modern tec-

tonic map covering the entire orogen and portrayed the entire Appalachians at a convenient scale (1:1 000 000 and 1:2 000 000), where state-of-the-art details could be shown, and the differences between the northern and southern-central Appalachians were more apparent. Throughgoing elements also became more obvious. It became the basis for the first application of the suspect terranes concept to the whole orogen in the early 1980s, and is still a useful compilation. The 2006 Hibbard, van Staal, Rankin, and Williams lithotectonic map updates the 1978 map and attempts to interpret the components of the Appalachians in terms of tectonic kindred, to apply a modified version of Williams' 1970s Newfoundland model throughout the orogen and to accurately depict the shapes of plutons and other elements.

J.D. Keppie's 1982 map of the New England and Canadian Maritime Appalachians delineated most of the tectonostratigraphic terranes and plutons that we still recognize, except for those added recently in Newfoundland. The Hatcher, Osberg, Drake, Robinson, and Thomas 1989 DNAG "Tectonic map of the U.S. Appalachians" attempted to integrate the terranes concept and accurately depict the shapes of plutons and known tectonic units.

Prior to the 1989 Thomas, Chowns, Daniels, Neathery, Glover, and Gleason paleogeologic map of the subsurface Appalachians beneath the Coastal Plain and the 1991 Horton, Drake, Rankin, and Dallmeyer terrane map of the southern and central Appalachians, few attempts had been made to portray and compile the geology beneath the Gulf and Atlantic Coastal Plains in a modern context. Today it is possible to produce a tectonic map of the southern and central Appalachians that includes interpretation of subsurface geology from modern compilations of potential field and drill data. For example, these data reveal the much greater extent of the Alleghanian eastern Piedmont fault system, internal structure of the Inner Piedmont, the possible Carolinian affinity of the Brunswick terrane, and much better resolution of the Wiggins-Suwannee suture and failed rift.

Doubtlessly, future tectonic maps will greatly improve these maps as new techniques are invented, new data become available, and more of the internides are mapped in detail.

Comparative analysis of pre-Silurian crustal blocks of the northern and southern Appalachians

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The New York promontory serves as the divide between the northern and southern segments of the Appalachians. Antiquated subdivisions, distinct for each segment, implied that they had independent lithotectonic histories. Using new lithotectonic subdivisions we compare first order features of the pre-Silurian orogenic crustal 'building blocks' in order to test the validity of the implication of independent lithotectonic histories for the two segments.

Three lithotectonic divisions characterize the entire orogen, including the Laurentian, Iapetan, and the peri-Gondwanan realms. The Laurentian realm, composed of native North American rocks, is remarkably uniform for the length of the orogen. It records the multistage Neoproterozoic-early Paleozoic rift-drift history of the Appalachian passive margin, formation of a Taconic Seaway, and the ultimate demise of both in the Middle Ordovician. The Iapetan realm encompasses mainly oceanic and magmatic arc tracts that once lay within the Iapetus Ocean, between Laurentia and Gondwana. In the northern segment, the realm is divisible on the basis of stratigraphy and faunal provinciality into peri-Laurentian and peri-Gondwanan tracts that were amalgamated in the Late Ordovician. South of New York, stratigraphic and faunal controls decrease markedly; rock associations here are consistent with those of the northern Appalachians, although second order differences exist. Exotic crustal blocks of the peri-Gondwanan realm include Ganderia, Avalonia, and Meguma in the north, and Carolinia in the south. Carolinia most closely resembles Ganderia, both in early evolution and Late Ordovician-Silurian docking to Laurentia. Southern equivalents of Avalonia and Meguma have yet to be recognized.

Our comparison indicates that, to a first order, the pre-Silurian Appalachians developed uniformly, starting with complex rifting and a subsequent drift phase to form the Appalachian margin, followed by the consolidation of Iapetan components and ending with accretion of the peri-Gonwanan Ganderia and Carolinia. This deduction implies that any first order differences between northern and southern segments post-date Late Ordovician consolidation of a large portion of the orogen.

Makkovik bedrock mapping project – implementing a map-based digital GIS data capture system

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The 2006 field season marked the first year of a multi-year, 1:50 000-scale, bedrock mapping project with the goals of interpreting the geology of the Aillik domain of the Makkovik Province and of producing regional geological maps. The first field season covered all of the Makkovik map area (NTS map sheet 13O/03). The outcome of this project will be a detailed, comprehensive, GIS-integrated geological map and associated database, which will also be a valuable tool for mineral exploration and for land-use planning. To achieve this goal in

a timely fashion, a map-based digital GIS data capture system was implemented. The hardware and software components of the system used in the field are briefly summarized. The hardware device, the HP IPAQ 6510, is a Pocket PC with a built-in internal GPS, thereby requiring one less piece of equipment. This device is a durable handheld computer with an external keyboard. At base camp, a tablet PC (Compaq tc4200) was used to draw contacts as the data was collected and to create a preliminary geological map. The software utilized was ArcPad 6.0.3 (ESRI) which enabled both the visualization of field data and the capture of data into a database structure at the outcrop. Field data was captured using an ArcPad add-in program called Ganfeld, developed by the Geological Survey of Canada, which creates a series of shape files for point data. The project geologist is capable of customizing the files and associated look-up-tables to suit individual project requirements. These files can then be compiled for creation of the digital maps. Maps can be published as a GIS-integrated geological map, where the user can select station locations and download the actual field notes of the geologist, in addition to other geological data collected, including any photos of the outcrop. The resulting end-product is a map that provides more useful information for digital applications, as well as a map that can easily be printed in hard-copy form.

Was a long-lived mantle plume associated with Iapetus opening in Laurentia?

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Harold Williams and co-workers showed that the Humber Zone of western Newfoundland preserved vestiges of the Laurentian margin of the Iapetus Ocean and traced these southward in their highly influential Tectonic-Lithofacies Map of the Appalachian Orogen. Meanwhile, Burke and Dewey 1973 (Journal of Geology, 81: 406–433) had suggested that Iapetus opening began with a mantle plume centred near Quebec's Sutton Mountains causing a three-pronged rift whose failed arm lay along the Ottawa Graben. This was supported by Kumarapeli 1993 (Tectonophysics, 219: 47–55) and then by Puffer 2002 (American Journal of Science, 302: 1–27) who suggested that the plume was long-lived with basaltic magmatism that was dominantly tholeiitic from ~615 to ~565 Ma and then dominantly alkalic until ~550 Ma with seafloor spreading beginning soon after. Hodych and Cox 2007 (Canadian Journal of Earth Sciences, in press) supported this long-lived plume hypothesis by providing U-Pb zircon dates for basalts from the Humber Zone in Quebec that closed a possible gap of ~10 Ma between the end of tholeiitic magmatism and the beginning of alkalic magmatism. This long-lived Sutton Mountains plume hypothesis implies that Laurentia was slow-moving from ~615 to ~550 Ma which is consistent with paleomagnetic evidence, although very rapid true polar wander at ~590 Ma may need to be invoked.

Looking for the oases of Snowball Earth in the East Greenland Caledonides

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Many lines of evidence support a theory that the entire Earth was ice-covered for long periods 600–700 million years ago. Each glacial period lasted for millions of years and ended violently under extreme greenhouse conditions. These climate shocks triggered the evolution of multicellular animal life, and challenge long-held assumptions regarding the limits of global change. Perhaps Robert Frost foresaw this in his poem, "Fire and Ice":

Some say the world will end in fire,
Some say in ice.
From what I've tasted of desire,
I hold with those who favour fire.
But if it had to perish twice,
I think I know enough of hate
To say that for destruction ice
Is also great
And would suffice.

A search for oases (holes of open water) in the 640 Ma Snowball Earth in the central East Greenland Caledonides led instead to an isotopic harbinger for both the 720 Ma and 640 Ma Snowball Earth episodes.

The plutonic map of the Newfoundland Appalachians: a two-sided asymmetrical system

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Newfoundland geology has influenced models for the evolution of the Appalachian- Caledonian Orogenic Belt for many years, and it continues to do so. Our extensive record of magmatism in both ensimatic and ensialic settings demonstrates that the familiar tectonic zones established by Hank Williams in the 1970's each contain distinct sequences of plutonic rocks. Although the orogen in Newfoundland has a broadly symmetrical pattern, its plutonic map pattern is asymmetrical, in that there is both temporal and compositional polarity.

"Early sequence" plutonism (essentially Cambro–Ordovician) is largely restricted to the Dunnage Zone. In the west, there are both trondhjemites (intraoceanic arcs?), and calc-alkaline suites (mature or continental arcs?). In contrast, equivalent Ordovician suites in the east record anatexis of the Gander Zone metasediments following juxtaposition of the Gander and Dunnage zones, likely by obduction of the latter. There is a prominent gap in the plutonic record in the latter part of the Ordovician (460–440 Ma), the significance of which remains unclear.

"Middle sequence" plutonism (mostly Silurian) expanded well beyond the Dunnage Zone, notably to the east, and affected all areas except the Avalon Zone (sensu stricto). Its onset in the Humber and Gander zones most likely indicates the closure of the main Iapetus basin. The Dunnage Zone plutonic suites are bimodal, and have an alkali-calcic, "A-type" geochemistry, in sharp contrast to spatially associated Ordovician suites. This compositional shift may record a transition from compressional to extensional tectonic environments. Compositional commonality amongst these suites across the Dunnage Zone does not support wide separation of the western and eastern parts during most of the Silurian. The Humber and Gander zones, on opposite sides of the orogen, are both dominated by peraluminous, "I-type" granite suites (commonly K-feldspar megacrystic), with subordinate "S-type" muscovite-biotite granites. In the east, these form a continuum, and were derived from diverse supracrustal, infracrustal, and subcrustal sources. The Gander Zone Middle Sequence suites could represent distal arc-related magmas, generated via subduction of oceanic crust originally located between the Gander and Avalon zones, but the primitive arc-type rocks expected in such settings are absent. The granitoid rocks could equally represent a late-orogenic, post-closure assemblage, within which spatial compositional and temporal variations reflect the nature of lower crustal blocks, coupled with the eastward propagation of some mysterious "lithospheric delamination" process.

During "late Sequence" plutonism (mostly Devonian), magmatic activity shifted eastward once more, because younger post-orogenic granites appear to be most abundant in the Gander-Avalon boundary boundary region. These suites are typically more compositionally evolved than their Middle Sequence counterparts, and their highly variable isotopic compositions indicate that the Gander-Avalon zonal boundary is a crustal-scale structure separating discrete basement terranes. They are also the group of plutonic rocks with the greatest potential for economic deposits of fluorite, molybdenum, tungsten, uranium and other commodities.

Underground electrostatics

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Electrostatic charge separations in the subsurface are generated by natural, although sometimes mysterious, physical, and electrochemical processes. Measuring electric potentials related to these charge separations is cheap and easy using a high impedance voltmeter and two specialized electrodes, and forms the basis of the 'self potential' (SP) geophysical technique, which has been used since the 1920's for finding ore bodies and in groundwater and geothermal investigations. Interpreting SP anomalies can be challenging, since charge separation can arise in various ways. Depending on their origin they are described as mineral, diffusion, streaming or bio-electrical potentials. Mineral potentials generated by graphite and massive to disseminated ore bodies are electrochemical in nature, can be as high as 2V, are almost always negative, and are remarkably steady over time. (Geophysicists more familiar with other electrical methods sometimes assume that there are currents associated with mineral potentials, and this idea is perpetrated in recent text books—to the frustration and fury of those in the know.) Other SP potentials are associated with changes in lithology, movement of ions or groundwater, or (a particularly under-investigated field) the behaviour of plants. These potentials are more transient, on a range of timescales.

In a recent study, a well characterized area on the campus of Memorial University was repeatedly surveyed in order to determine which natural and anthropogenic features generated SP anomalies, and whether these anomalies were steady or transient. We found anomalies associated with a building, a buried metallic pipe, trees, and subtler ground variations. The locations of anomalies, both large and small, were remarkably unvarying over a period of days and weeks. The building always generated a significant negative anomaly similar in origin, we think, to mineral potentials, but the sign of other anomalies (including that associated with the pipe) and the magnitude of all anomalies varied with time. In a second area dominated by a shallow sewer pipe, SP data allowed modeling of the burial depth and charge distribution of the pipe. Our results show that SP can be a useful and reliable method for shallow ground surveys, but that the time varying nature of both sign and magnitude of small to moderate anomalies should be taken into account in data collection and interpretation.

Where was the Iapetus Ocean born ? Tectonics and paleogeography of the Precambrian-Cambrian transition in Laurentia *

** 2007 Atlantic Geoscience Society—APICS Geoscience Lecture*

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During late Neoproterozoic, eastern Laurentia experienced widespread rift magmatism and clastic rift sedimentation that was succeeded in Early Cambrian by marine sedimentation which heralded the birth of Laurentia's Iapetan margin. Do these rift- to-drift events, however, mark the separation of continents and the birth of the Iapetus Ocean? Paleomagnetic evidence from Laurentia and the West Gondwana cratons in-

dicates that Amazonia, the oft-proposed conjugate margin to Laurentia, could not have been adjacent to eastern Laurentia during the margin's rift-drift transition at 550 to 535 Ma. Either another continent was the conjugate margin to Laurentia, or Laurentia already faced an open Iapetus Ocean at the time, with the ca. 550 Ma rifting marking the separation of one or several basement terranes. Some "peri-Laurentian" terranes have been identified, such as the Argentine Precordilleran terrane, which was derived from the Ouachita margin of Laurentia in the Early Cambrian, and the Dashwoods block in western Newfoundland, which may have separated from Laurentia only to have been re-accreted during the closure of the Iapetus Ocean. If late Neoproterozoic rifting represents the separation of basement terranes from Laurentia, then the timing, paleogeography, and even definition of the birth of the Iapetus Ocean is an open question. Assuming that the ca. 1000 Ma Grenvillian collisional relationship between Amazonia and eastern Laurentia is correct, the opening of the Iapetus Ocean between Laurentia and West Gondwana is only constrained to have happened between ca. 920 Ma post-Grenville extension and the onset of ca. 570 Ma voluminous rift magmatism. It is possible that the Iapetus Ocean dates from earlier, ca. 750 Ma rift magmatism in eastern Laurentia, and that its early history may now be recorded in terranes rather than in its presumed bordering continents.

Protection and promotion of "Earth's Geological Showcase" in Newfoundland and Labrador

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A diverse and protracted geological history, spectacularly revealed along 30 000 km of glacially scoured, wave-beaten coastline, has rewarded Newfoundland and Labrador with the enviable status of one of Earth's great geological showcases. The international geoscience community has long recognized our geology as a global resource with outstanding value for understanding the tectonics of ancient mountain building. The two-sided symmetry of the Appalachian orogen in northeastern Newfoundland gave rise to Wilson's paradigm of ancient ocean opening and closing. Later mapping in eastern Newfoundland uncovered a spectacular record of early life's evolution, in the form of Ediacaran biota and diverse ichnofauna that inhabited Precambrian seas adjacent to volcanic arcs once sited peripheral to Gondwana. Systematic surveys of Labrador uncovered some of the Earth's oldest rocks and greatest mineral deposits.

The global scientific significance of this geology is reflected, foremost, by the selection of IUGS global stratotypes for the Precambrian–Cambrian and Cambrian–Ordovician boundaries (Fortune Head and Green Point, respectively), by UNESCO World Heritage (UWH) designation of Gros Morne National Park for its ancient ocean crust and mantle upon a contemporary continental margin, and by pending UWH designation of Ediacaran fossils at Mistaken Point. Our geological heritage also captures the interest and imagination of municipalities and private foundations, who work with geoscientists across Canada to preserve, protect, and promote this resource for geo-tourism and educational purposes. A prominent example is the Johnson GEO CENTRE: Earth's Geological Showcase©, a world-class geological interpretation centre dedicated to fostering public awareness of Earth Science; other venues include Gros Morne's Discovery Centre and the newly-minted Rooms. Smaller, municipal-based developments celebrate minerals and mining, plate tectonics and terrane boundaries, ancient life and geological time, landscapes and glaciation.

Increasing worldwide scientific and public attention requires matching effort to safeguard this invaluable geological heritage. Currently, legislative protection is provided under the Wilderness and Ecological Reserves Act, the Historic Resources Act and the Canada National Parks Act, and related regulations. The most effective guardian of the resource, however, is an informed and concerned population in Newfoundland and Labrador.

A maritime perspective on Maine's Gander Zone, including a few thoughts on tectonic-climate linkages

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Maine's Gander Zone extends from the foothills of the Boundary Mountains to the coast. Lower Paleozoic quartz-rich strata of the Lunksoos, Liberty-Orrington, and St. Croix inliers share common detrital zircon populations. They represent a passive continental margin that, according to shelf quartzites with bipolar cross beds (St. Croix) and deepwater *Oldhamia* trace fossils (Lunksoos), faced northwest. In Penobscot Bay, the Ellsworth terrane, composed of marine volcanic sequences and minor tectonized harzburgite, sits structurally above Early Ordovician black shales of the St. Croix. It is an obvious candidate for GRUB equivalency. Late in the Ordovician, the attenuated leading fringe of Ganderia accreted to Laurentia along the Red Indian Line, which most likely lies along the northwestern margin of the Hurricane Mountain mélange. In this view, the overlying Dead River Formation to the southeast is a structural lid rather than post-mélange cover. Lower Silurian strata of the Central Maine (CM) and Fredericton troughs (FT) record a forearc through foredeep system. The intervening Liberty-Orrington inlier exposes a southwestward extension of the Brunswick subduction complex (BSC), with the Dog Bay Line juxtaposing the BSC and FT. The BSC was raised when the main

Gander block (St. Croix) docked, causing proximal turbidite deposition (Vassalboro, southeastern margin of CM) and distal anoxia (Smalls Falls) in the former forearc. Slab break-off triggered minor within-plate volcanism. The Acadian foreland system, prominent in Maine, propagated northwestward following the docking of Avalon.

Two examples from Maine illustrate how Appalachian tectonics may contribute to a general understanding of tectonic-climate linkages. First, Penobscot orogeny and the emergence of the New Caledonian ophiolite share much in common. The latter event coincided with the onset of Antarctic glaciation at 34 Ma. In both cases, the exhumation of soluble basic and ultrabasic rocks caused sequestering of atmospheric carbon dioxide through silicate weathering and organic carbon burial. For the 34 Ma event, a rapid trigger is needed to explain the climatic overshoot, and slab breakoff seems a plausible candidate. Second, near Farmington, a recently discovered slumped horizon rests directly on black shales, suggesting a methane release trigger for the slump. This relationship resembles the mechanism invoked for terminal Paleocene extinction, the best ancient analog for the worst-case future global warming scenario.

Two high-pressure belts in the Grenville Province? Tectonic setting of the Ottawan and Rigolet orogenic phases of the Grenvillian Orogeny and the role of the Allochthon Boundary Thrust

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Recent recognition of high pressure (ca. 1400–1500 MPa) metamorphism at ca. 1000 Ma in the Parautochthonous Belt, together with earlier reports of ca. 1700–1800 MPa metamorphism at ca. 1090–1060 Ma in allochthonous terranes structurally above the Parautochthonous Belt, implies that there are two high pressure belts in the Grenville Province. These belts occur back-to-back across the Allochthon Boundary Thrust, a major ductile shear zone that separates parautochthonous terranes in the northwestern Grenville Province from structurally overlying allochthonous terranes to the southeast. A tectonic model for the evolution of these two high pressure belts in the Grenville Orogen during the 110 My of convergence comprising the ca. 1090–980 Ma Grenvillian Orogeny is described. Early tectonic burial during the Ottawan orogenic phase (ca. 1090–1020 Ma) involved formation of eclogite in lower crustal rocks in the orogenic hinterland. The eclogite was exhumed to mid-crustal depths and transported as large nappes towards the erosion front on the Allochthon Boundary Thrust. Subsequent formation of eclogite during the Rigolet orogenic phase (ca. 1005–970 Ma) involved deep burial of rocks derived from the former orogenic foreland and their exhumation beneath the Allochthon Boundary Thrust, which thus acted as a material focal plane across which high-pressure rocks from the hinterland and the foreland, initially separated by several hundred km, converged and were exhumed. This model is consistent with the results of numerical modelling of large, hot, long-duration orogens, and supports other independent evidence that the hinterland of the Grenville Orogen was the site of an orogenic plateau.

Recognition of the fundamental spatial and temporal asymmetry of the Allochthon Boundary Thrust and its pivotal role in focusing exhumation provides the basis for the first unified tectonic model to link the Ottawan and Rigolet orogenic phases in a single long-lived convergent orogen.

Monazite U-Th-Pb dating by electron microprobe: a powerful new tool for constraining tectonothermal models

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The relatively new technique of "chemical" (non-isotopic) dating of monazite (REE phosphate) by electron microprobe (EMP) has been demonstrated to produce geochronologic results with precision comparable to U-Pb and Th-Pb isotopic techniques, but with advantages of superior spatial resolution and capability to date individual thermal and deformational episodes within a metamorphic continuum. Under appropriate circumstances, monazite partially re-crystallizes and undergoes partial age resetting, potentially providing a near-complete "tape recording" of the chronology of an orogenic event. Spatial resolution of less than 3 µm has an advantage over SHRIMP and ion microprobe analyses (minimum of about 15 The relatively new technique of "chemical" (non-isotopic) dating of monazite (REE phosphate) by electron microprobe (EMP) has been demonstrated to produce geochronologic results with precision comparable to U-Pb and Th-Pb isotopic techniques, but with advantages of superior spatial resolution and capability to date individual thermal and deformational episodes within a metamorphic continuum. Under appropriate circumstances, monazite partially re-crystallizes and undergoes partial age resetting, potentially providing a near-complete "tape recording" of the chronology of an orogenic event. Spatial resolution of less than 3 µm has an advantage over SHRIMP and ion microprobe analyses (minimum of about 15We have done much monazite dating in the Appalachians, but will focus in this presentation on two case studies from New England that illustrate the value of EMP dating: Acadian (broadly defined) to Alleghanian metamorphism from central Massachusetts and northeastern Connecticut, and Taconic, Acadian and Alleghanian metamorphism in western Connecticut and adjacent New York and Massachusetts. In both examples, patterns of ages from monazite EMP analysis indicate that the standard accepted tectonic models have significant problems, and may point the direction toward new models based on reinterpretation of structural and stratigraphic observations. We emphasize that these new dates are mainly of use in interpreting ambiguous field data and regional correlations.

In central Massachusetts and adjacent areas (from the Bronson Hill arc eastward to the high-grade zones of the Sturbridge area), the conventional view has been of a principal Acadian tectonothermal event at ca. 400 Ma (Robinson's "classic Acadian") with a successor event at ca. 360 Ma (his "neo-Acadian"). Targeted monazite dating indicates highest-grade (near-granulite) metamorphism at ca. 435 Ma, with additional events at 400 Ma and 360 Ma. Abrupt age breaks across strike suggest major regional east-west shortening with cryptic major faults. To the west, approaching the Bronson Hill arc, a major belt of late recrystallization at 330 Ma indicates early onset of Alleghanian effects, and post-300 age resetting is seen as main-phase Alleghanian.

In western Connecticut (west of the Mesozoic basin), the conventional model is of a Taconic fore-arc allochthonous on Laurentian margin (Grenville) with *in situ* post-Taconic sedimentary basins, all metamorphosed to kyanite-sillimanite grade in the Acadian, and with minor Alleghanian overprint to the south near Long Island Sound. Our dating shows a complex pattern of intermixed Taconic ages (ca. 520, 470–480 and 445–450 Ma) with multi-stage Acadian ages (> 420, 385–390 and 355–360 Ma), but some locations in older rocks within the supposed Acadian belt show no evidence of preceding Taconic metamorphism. Cameron's Line, a notable tectonic break highlighted by Rodgers on his 1985 Connecticut geologic map, has been interpreted as the western limit of imbricated Taconic thrust slices containing deep-water rocks. Our dating shows that numerous locations in assumed Cambro–Ordovician rocks east of Cameron's line did not experience Taconic metamorphism at all, and thus these rocks may have originated east of the Bronson Hill arc prior to the Acadian (broadly defined). This would basically require that Cameron's line marks the western limit of a major detachment zone rather than the western limit of far-travelled Taconic thrusts.

The Taconic orogeny in Newfoundland: a three-stage process

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Hank Williams spent a large part of his geological career on the remnants of the Taconic orogeny in western Newfoundland. In particular, his outstanding work concerning the emplacement of ophiolites is known worldwide. The generally established tectonic model in those days was one of a collision between the Appalachian margin and a forearc/arc terrane during the Ordovician. Subsequent work, particularly geochronology and isotope geology, indicated that this model was incomplete. We will present new evidence that the Taconic orogeny comprises three separate accretionary events starting in the Late Cambrian and finishing in the Late Ordovician. Taconic 1 is represented by ca. 495 Ma west-directed obduction of the ca. 510 Ma Lushs Bight oceanic Tract onto the peri-Laurentian Dashwoods microcontinent. Subduction is inferred to have initiated at a spreading centre abandoned during an inboard ridge jump responsible for separation of Dashwoods from Laurentia. Partial subduction of the buoyant Dashwoods forced subduction to step back into the Humber seaway, which led to formation of the ca. 490 Ma Baie Verte oceanic tract (BVOT). Dextral oblique closure of the Humber seaway first formed the Notre Dame arc (489–477 Ma) built on Dashwoods and the coeval Snooks Arm arc built on the BVOT, followed by their collision with Laurentia (Taconic 2) and each other. The obliquity of convergence induced large-scale translations of continental ribbons of the Laurentian margin from the latitude of Labrador to central Newfoundland. After a magmatic gap of c. 7–10 my, the Notre Dame arc records a voluminous flare-up of predominantly tonalite magmatism (464–459 Ma) during the waning stages of Taconic 2. Magmatism overlaps with strong deformation and comprises both arc and non-arc-like tonalite. We relate this flare-up to break-off of the oceanic lithosphere of the downgoing Laurentian slab. Taconic 3 is represented by 455–450 Ma collision between a peri-Laurentian arc terrane and the peri-Gondwanan Popelogan-Exploits arc and their composite accretion to Laurentia.

Ancient Laurentian Detrital Zircon in Ordovician Sediments from the Closing Iapetus Ocean

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The Southern Uplands is a belt dominated by Ordovician–Silurian turbidites in the British Caledonides, roughly equivalent to parts of the Dunnage Zone of the Newfoundland Appalachians. Lying between Laurentian rocks of the Scottish Highlands, and Ganderian/Avalonian rocks of England and Wales, the Southern Uplands are interpreted as representing deposition in the closing Iapetus Ocean. Suggested depositional settings include an accretionary fore-arc, and a back-arc environment attached to Laurentia. Deformation in the terrane records convergence, with significant sinistral transpression, and is likely to have been diachronous; deformation in the north was initiated while deposition was still taking place in the south. The belt is divided into a series of NE-SW fault-bounded tracts, distinguished by different sedimentary successions. In most, the stratigraphically lowest sediments are black, graptolitic shales, which pass northward and stratigraphically upward into lithic wackes; the time of transition is successively younger to the southeast. In some tracts, different compositions can be distinguished; quartzose, continentally-derived wackes interdigitate with units derived from andesitic volcanic sources.

Zircons were extracted from quartzose wackes from several tracts in the northern part of the terrane, deposited in late Ordovician. U-Pb analyses were carried out on 60–80 grains by multicollector ICPMS using laser ablation with a beam diameter of 40–60 micrometres. Zircons from a sample deposited early in the depositional history (Kirkcolm Fm.) display a range of U-Pb ages from Paleoarchean to late Ordovician, including the oldest such grain yet recorded from the British Isles. Neoarchean (2.8–2.5 Ga), Paleoproterozoic (2.0–1.7 Ga), and Mesoproterozoic (1.5–1.0 Ga) age populations suggest sources in Laurentia, such as the Grenville and Trans-Hudson orogens. The overall age distribution is comparable to metasedimentary rocks of the Laurentian margin of Iapetus in the Taconian orogen of western Newfoundland. Samples with younger depositional ages show increasing amounts of Grenville-age zircon (ca. 1.0 Ga) and a general trend of reduced Archean input. Several analyses from the Glenlee Fm. plot on a discordia line suggesting overprinting of Archean zircon in the early Paleozoic, consistent with tectonothermal reworking of Laurentian detritus in the Grampian orogen.

The Meguma Supergroup of southern Nova Scotia: new insights on stratigraphy, tectonic setting, and provenance

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The easternmost tectonic element of the northern Appalachian orogen, the Meguma terrane, traditionally includes the Cambrian–Ordovician Goldenville and Halifax formations (Meguma Group) and the younger White Rock and Torbrook formations, intruded by mainly Devonian plutonic units and overlain by Carboniferous and younger rocks. Recent mapping in the Meguma Group, combined with petrographic and chemical studies, has resulted in re-evaluation of its stratigraphy, tectonic setting, and provenance. As previously proposed, the lower metasandstone-dominated Goldenville Formation and upper slate-dominated Halifax Formation should be formally elevated to "group" status, because the new mapping has demonstrated that both formations can themselves be subdivided into formations and members. Thus, the Meguma Group will be elevated to a "supergroup". The redefined Goldenville Group consists of massive metasandstone with minor interbeds of metasiltstone and slate (Church Point, Green Harbour, Tangier, and Taylor Head formations), and grades upwards into thinly bedded metasandstone, metasiltstone, and silty slate (Government Point Formation). The uppermost unit (Moshers Island and Beaverbank formations) is characterized by numerous Mn-rich calcareous concretions. Units in the overlying slate-rich Halifax Group include the lower Acacia Brook/Cunard formations and the upper Bear River/Feltzen/Glen Brook formations.

The Church Point Formation of the Goldenville Group contains a distinctive metasiltstone unit (High Head member) with abundant trace fossils, including the early Cambrian deep-water ichnofossil *Oldhamia*. The stratigraphically lowermost exposed unit in the Goldenville Group is located 3 km in stratigraphic thickness below the High Head member. This metasandstone unit yielded 555 Ma detrital zircon, providing a maximum depositional age for the exposed part of the Goldenville Group. The upper part (Tancook member) of the Government Point Formation of the Goldenville Group has yielded an early Middle Cambrian shelf-lithofacies trilobite faunule of Acado-Baltic affinity. In the overlying Halifax Group, the upper part of the Bear River Formation locally contains the graptolite *Rhabdinopora flabelliformis* and acritarch species that are Early Ordovician. The gap in age between this formation and the overlying late Ordovician–Early Silurian White Rock Formation indicates that a significant unconformity exists between the Halifax Group and White Rock Formation.

Protoliths of the metasandstone units in the Goldenville and Halifax groups were predominantly feldspathic wacke to arenite. Preliminary whole-rock geochemical data from this clastic material suggest that the Meguma Supergroup was deposited near an active or recently active continental margin, and not at an Atlantic-style passive continental margin as previously assumed. This interpretation is further supported by the presence of numerous syn-depositional mafic sills of within-plate chemical character along the northwestern section of the Meguma Supergroup, suggesting that deposition was in a rift environment, possibly related to Late Neoproterozoic to early Paleozoic separation of the Meguma terrane from Gondwana. The lowest exposed metasandstone bed contains a detrital zircon population that is almost exclusively Late Neoproterozoic, indicating an age-homogeneous source area. In contrast, a sample from the Tancook member yielded a broad spectrum of detrital zircon ages extending back into the Archean, suggesting that the source area had changed significantly by the time (Middle Cambrian) when that member was being deposited.

Appalachian reminiscenses

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The Appalachian Orogen is the North American type example of a collisional geologic mountain belt. It has a long history of ideas and resulting models. Most were attempts to rationalize the formation of geologic mountains from a preceding special depositional regime or geosyncline. All were contrived to comply with a world of fixed continents and permanent oceans. With the advent of plate tectonics, a realization that continents drift and that oceans open and close to form geologic mountain belts is about as profound as geology gets.

The opening and closing of an ancient Iapetus Ocean is the model for the 1978 Tectonic Lithofacies Map of the Appalachian Orogen, originally developed in 1977. It evolved as a teaching aid, which explains its size and format. The map attempts to identify and delineate ancient continental margins, vestiges of oceans, and suspect terranes. These are early Paleozoic Zones whose outline is the map's first order message. For example, the ancient continental margin of eastern North America, or the local Humber Zone, has all the features of a rifted margin, from rifting, passive development, and finally destruction. The opposing continental margin and other outboard suspect terranes are less well known. The present North Atlantic Ocean is a model for Iapetus, although some would consider the modern North Atlantic as kinder, gentler, and probably less full of guile.

The 1978 Appalachian Map is now updated by a 2006 digital version that allows future modifications and mixing and matching of other data sets. For the most part, the new map follows the model of the former map. It has the latest subdivisions of early Paleozoic rocks, with much more emphasis on middle Paleozoic and later Paleozoic rocks. It also distinguishes plutonic rocks by age, as well as other useful features.

Maps are beautiful, fun, and informative. They represent the level of understanding at the time they are made. Maps are the way in which geologists communicate best and are therefore the dynamic force in the science. But unlike most maps and scientific publications that are heavily subsidized, the bottom line on the 1978 Tectonic Lithofacies Map of the Appalachian Orogen is that it made money.

The habitat of gold in a possible Carlin-type deposit near Jackson's Arm, White Bay, western Newfoundland: evidence from LAM-ICP-MS and SEM-MLA studies

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Gold mineralization is developed within Paleozoic carbonate rocks at Jackson's Arm. These occurrences have been modeled by some as analogues of Carlin-type gold deposits. Arsenian pyrite is a diagnostic feature of Carlin-type gold occurrences, where it commonly forms overgrowths and rims on earlier formed pyrite.

We undertook petrographic, Scanning Electron Microscope (SEM) with MLA, and Laser Ablation–Inductively Coupled Plasma–Mass Spectrometer (LAM-ICP-MS) analysis on a series of polished thin sections from the Jackson's Arm occurrences to examine Au and As distributions. The sulphide minerals consist of massive to semi-massive layers of equant cubiform pyrite (py) grains that are locally colloformal. Arsenopyrite (apy) is intergrown with the py masses as needles and diamond-shaped crystals. The host rock to the mineralization ranges from massive carbonate to laminated carbonate with quartzite, sandstone and/or "dirty carbonate" (*i.e.*, contains significant silicate/oxide component) interlaminae. The sulphide minerals are restricted to carbonate layers and locally the quartzite or sandstone laminae appear to have acted as aquacludes restricting fluid flow and attendant sulphide precipitation to permeable carbonate laminae. In some "dirty carbonate" laminae, primary(?) magnetite is overgrown and replaced by py and apy.

Back Scatter Electron (BSE) imaging by SEM indicates that the equant py grains contain internal concentric zones with different compositions. Arsenic is the most commonly zoned element, although Pb likewise exhibits zonation, as detected by the SEM analyses. LAM-ICP-MS analyses were conducted on the samples to determine Au and "toxic element" contents and distributions in py and apy. Apy grains contain between 0.48 and 133 ppm Au, 1 to 177 ppm Co, and 0.72 to 220 ppm Sb; no other elements exhibited significant concentrations or variations in concentrations. Py grains contain 569 ppm to 5.75% As, 0.9 to 52 ppm Au, 0-207 ppm Pb, 0.19-50 ppm Sb and 1.86-994 ppm Co. In apy, Au negatively correlates with Sb and has slight positive correlations with Se and Te. In the py, Au exhibits excellent positive correlations with As, slightly positive correlations with Te and Se, and negative correlations with Sb; Bi, Cd, Pb SO_4, Ag and Co contents are independent of Au contents. No zonation was detected in apy, but some py grains exhibited widespread, concentric zonation, most especially in As contents. There is no consistent pattern exhibited, however, such as low (or high) As rims compared to cores, suggesting that the elemental zonations reflect variable conditions extant during pyrite precipitation (*i.e.*, alternations in fluid content, temperatures and/or other physiochemical parameters).

Tectonic architecture of an arc-arc collision zone, Newfoundland Appalachians

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The Appalachian-Caledonian orogen records a complex history of the closure of the Cambro-Ordovician Iapetus Ocean. The Dunnage Zone of Newfoundland preserves evidence of an Ordovician arc-arc collision between the Red Indian Lake Arc, which forms part of the peri-Laurentian Annieopsquotch accretionary tract (ca. 480–460 Ma), and the peri-Gondwanan Victoria Arc (ca. 473–453 Ma). Despite the similarity in age, the coeval arc systems can be differentiated on the basis of the contrasts that are apparent across the Red Indian Line suture zone. These contrasts include structural and tectonic history, stratigraphy, basement characteristics, radiogenic lead in mineral deposits and fauna. The arc-arc collision is considered in terms of modern analogues (Molucca and Solomon seas) in the southwest Pacific and the timing is constrained by stratigraphic relations in the two arc systems. The Victoria Arc occupied a lower-plate setting during the collision and underwent subsidence during the collision, similar to the Australian active margin and Halmahera arcs in the southwest Pacific. The timing of the subsidence is constrained by three new ages of volcanic rocks in the Victoria Arc (457 ± 2; 456.8 ± 3.1; 457 ± 3.6 Ma) which immediately predate or are coeval with deposition of the Caradoc black shale. In contrast the Red Indian Lake Arc contains a sub-Silurian unconformity and distinct lack of Caradoc black shale suggesting uplift during the collision. The emergent peri-Laurentian terranes provided detritus into the newly created basin above the Victoria Arc. The evidence of this basin is preserved in the Badger Group, which stratigraphically overlies the peri-Gondwanan Victoria Arc but incorporated peri-Laurentian detritus. Thus the Badger Group forms a successor basin(s) over the Red Indian Line. Following the collision, subduction stepped back into an outboard basin, the Exploits-Tetagouche backarc, closing the Iapetus Ocean along the Dog Bay Line in the Silurian. Correlative tracts in the Northern Appalachians and British Caledonides support the Ordovician arc-arc collision; however, the evidence is less obvious than in Newfoundland.

Investigation of silicic segregations in the Ferrar Dolerite sills, Antarctica, using fluid dynamic experiments

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The Ferrar Dolerite sills are a series of 100–350 m thick Jurassic sills which are exposed over an area of ~10^5 km² in Antarctica. Coarse-grained leucocratic segregations in the upper parts of these sills form anastomosing sub-horizontal lenses 0.1–3 metre thick and extending tens of metres along strike. All segregations have sharp upper contacts and some have sharp lower contacts with the host rock, while in others the lower contact is diffuse. Segregations are temporally, spatially and chemically related to the Ferrar Dolerites and range in composition from diorite to granodiorites. They have geochemical trends that are compatible with residual liquids after crystallization of pyroxene and plagioclase from the parent dolerite. Segregations are thought to form by an imperfect filter pressing mechanism that forms in response to gravitational instability, such as: tearing of the crystallizing pyroxene-plagioclase mush when its weight exceeds its strength; compaction and dilation of the mush (Philpotts, et al., 1996); or by compaction of large mushes.

One issue in the formation of segregations concerns the amount of mixing experienced by liquids entering the porous network, since some segregations appear homogeneous and others show stratification. Preliminary experiments investigated mixing between two homogeneous liquids with differing viscosities (n_1, n_2) and densities (r_1, r_2). A porous disk, representing the mush, was dropped through a stratified liquid, and the mixing observed between overlying liquid and liquid injected through the pores. Controlling parameters are dimensionless numbers describing the balance of processes within the system: the Reynolds number ($Re = r_1UL/n_1$), the Froude number ($Fr = U/[g(r_2\text{-}r_1)/r_2L]^{1/2}$ and the viscosity ratio (n_2/n_1) of the two liquids. U is the velocity of injecting liquid through the mush, and L is the size of the pore space. Complete mixing occurs at relatively high Re and Fr numbers with small viscosity contrast, while no-mixing occurs at relatively low Re and Fr numbers. At intermediate Re and Fr numbers an incomplete mixing pattern occurs. These and other results suggest that segregations with internal stratification and diffuse contacts form as a result of high viscosity contrast between the interstitial liquid in the mush and the infilling liquid. Homogeneous segregations may form at relatively high Re and Fr flow regimes.

