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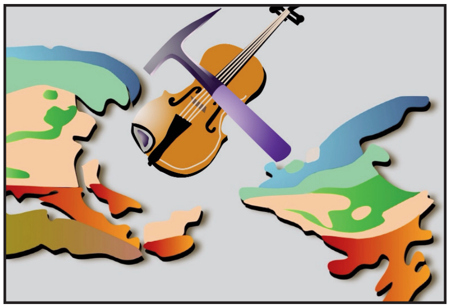

Tectonic Setting and Evolution of the Grenville Orogen: An Assessment of Progress Over the Last 40 Years

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SUMMARY
The Grenville Province is known for its high grade of metamorphism, complex ductile gneissic structure, and polyphase reworking, features indicative of residence in the deep crust (orogenic infrastructure) that hamper recognition of protoliths and original relationships and render tectonic interpretations especially challenging. This paper charts the evolving understanding from the 'Grenville Problem' of the 1950s before the plate tectonic paradigm, through a speculative quasi-plate tectonic stage in the 1970s that effectively proved to be a dead end, and the first constrained plate tectonic models for pre-Grenvillian Laurentia in the 1980s, to the recent LHO (large hot orogen) and collapsed LHO models for the Grenville Orogen itself. The collapsed LHO model is based on the finding that significant amounts of the superstructure (upper orogenic crust) are preserved, and that the present crustal architecture can be explained by tectonic juxtaposition of infrastructure and superstructure in a late extensional event associated with crustal-scale collapse of a high-strain channel under an orogenic plateau. Conceptual breakthroughs and critical datasets assembled in the period 1980–2000 that were influential in guiding tectonic thinking are discussed and it is argued that present understanding was contingent on the results of 2-D numerical forward modelling of orogenesis, in particular the LHO experiments and the more recent models of orogenic collapse. As a result, for the first time a conceptual plate tectonic model for the convergence and collapse stages of the Grenville Orogen based on empirical field data (the inverse model) is broadly supported by numerical forward-modelling experiments constrained by physically plausible processes in a LHO – and both are available for future testing and refinement. Moreover, they may also have application to other enigmatic high-grade Proterozoic orogens that have resisted simple incorporation within the plate tectonic narrative.

SOMMAIRE
La Province de Grenville est bien connue pour le métamorphisme élevés de ses roches, leur structure ductile gneissique complexe et leur remaniement polyphasé, caractéristiques qui correspondent à un séjour dans la croûte profonde (infrastructure orogénique) ce qui gène la reconnaissance des roches d'origine et leurs relations, et rendent particulièrement difficile les interprétations tectoniques. Le présent article retrace l'évolution de la compréhension du « problème du Grenville », à partir des années 1950, avant l'avènement du paradigme de la tectonique de plaques, en passant par l'étape d'une interprétation quasi- tectonique de plaques des années 1970, laquelle s'est avérée une impasse, puis par les premiers modèles balisés de tectonique de plaques de la Laurentie pré-grenvillienne des années 1980, jusqu'aux modèles récents des grands orogènes chauds (LHO) et de LHO d'effondrement visant à expliquer l'orogène de Grenville lui-même. Le modèle de LHO d'effondrement repose sur le fait que des portions importantes de la superstructure (croûte orogénique supérieure) sont préservées, et que l'actuelle architecture crustale peut s'expliquer par la juxtaposition tectonique de l'infrastructure et de la superstructure lors d'une phase d'extension tardive associée à un effondrement à l'échelle de la croûte d'un canal de fortes contraintes sous un plateau orogénique. Nous présentons ici les percées conceptuelles ainsi que les bases de données essentielles constituées de 1980 à 2000 qui ont orienté la réflexion tectonique, et nous proposons que la compréhension actuelle découle des résultats de la modélisation prospective numérique 2-D de l'orogenèse, en particulier des expériences LHO et des modèles plus récents d'effondrement orogénique. Et donc, pour la première fois, nous disposons

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d'un concept de modèle de tectonique de plaques permettant d'expliquer les phases de convergence et d'effondrement de l'orogène de Grenville qui découle de données empiriques de terrain (modèle inverse), et qui correspond largement aux résultats de modélisations prospectives numériques balisées conformes aux processus physiques d'un LHO, les deux étant disponibles pour essais et affinement. En outre, ils peuvent aussi être appliqués à d'autres orogènes protérozoïques de nature semblable et qui n'ont pu s'expliquer par la logique de plaques tectoniques.

INTRODUCTION

In a classic monograph entitled "*The Structure of Scientific Revolutions*", Kuhn (1962) remarked on the step-like progress of scientific understanding in which infrequent, momentous paradigm shifts were followed by longer periods of 'normal science' in which the implications of the new paradigm were tested, adopted and refined by the scientific community. For the earth sciences, the plate tectonics hypothesis of the 1960s was an epic paradigm shift that was quickly adopted by the community, not only because of its ability to explain the workings of modern Earth, but also because poorly understood features in Phanerozoic orogens assumed a new significance in a plate tectonic context. An early example from the Appalachian Orogen in Newfoundland that portended the scope of the coming revolution was the identification by Williams (1964) of a 'two-sided symmetrical system' consisting of the margins of Laurentia (Humber Zone) and Gondwana (Avalon Zone), separated by a wide region dominated by mafic supracrustal rocks (the 'Central Mobile Belt' or Dunnage Zone). An explanation for the symmetry was to follow two years later when JT Wilson published his landmark paper entitled "*Did the Atlantic close and then re-open?*" (Wilson 1966), and the 'system' was reinterpreted as a collisional orogen with the central collage of mafic crust composing the remnants of former oceanic tracts (Iapetus and Rheic oceans). However the plate tectonic revolution did not stop with the Phanerozoic, and following the establishment of criteria to distinguish between collisional and accretionary orogens (e.g. Dewey and Bird 1970), the challenge to extend plate tectonic analysis back into the Precambrian began. In a simplified view of continental collision, closure of an ocean by subduction eventually leads to the juxtaposition of a passive margin against an active margin, and the search for relics of these features was initiated in Precambrian shields worldwide. Since passive margin sequences are large and distinctive, attention was initially focussed on them, and the search rapidly proved successful. The first unequivocal Paleoproterozoic passive margin, complete with overlying foredeep succession and inverted in a foreland fold thrust belt, was described a few years later (the Coronation Supergroup in Wopmay Orogen, NW Canada; Hoffman 1973). Other examples followed, collectively signifying that many Proterozoic orogens were amenable to plate tectonic analysis, and hence were fundamentally similar in most important respects to those formed in the Phanerozoic. This work continues to the present day with, for example, the recent publication of a synoptic plate tectonic model for the large Paleoproterozoic Trans-Hudson Orogen in northern Canada (Corrigan et al. 2009), in which a wide range of evidence is assembled to support a complete Wilson cycle, comprising the opening and closing of the Manikewan Ocean over a period of ~250 M.y.

Although not widely remarked at the time, it is now apparent that most of the early recognized examples of collisional Proterozoic orogens were, like the Wopmay Orogen, initially identified on the basis of passive margin sequences on the lower plate that were subsequently inverted in fold–thrust belts. Pre-collisional continental margin arc batholiths that formed on active margins on the upper plate were less commonly identified, in part perhaps because most field work at the time was focussed on regions with recognizable supracrustal sequences, and in part because of a lack of robust criteria to distinguish deformed continental arc rocks from older basement or syn-collisional granitoid plutons.

Thus, during the period when plate tectonic principles were being successfully applied to many Proterozoic orogens, there remained some that were not readily accommodated within this framework. Many such holdouts were largely composed of high-grade metamorphic rocks with widespread evidence for ductile deformation, implying they had been exhumed from mid or lower crustal depths. Moreover, they commonly contained an abundance of granitoid gneiss and a corresponding paucity of recognizable supracrustal sequences, including the absence of passive margin sequences of appropriate age and location that might define former plate margins. In many cases these factors, together with the assumption that high-grade terranes were not prospective for mineral resources, discouraged geological surveys from including them in their regional mapping programs, thereby perpetuating ignorance of them.

This paper is a review of about 40 years of research progress in one such orogenic tract, the fragment of the late Mesoproterozoic to early Neoproterozoic Grenville Orogen exposed in North America in the Grenville Province of the southeast Canadian Shield and in inliers surrounded by younger rocks in the southeast and southern USA (Fig. 1; see caption for an explanation of the distinction between Grenville Orogen and Grenville Province). This proved to be a particularly egregious holdout to plate tectonic interpretations because, in addition to the reasons noted above, no relict axial oceanic tract and associated suture zone were recognized, and the southeastern margin of the orogen was rifted from Laurentia during the opening of the Iapetus Ocean in the late Neoproterozoic, providing a further source of uncertainty about its scale, symmetry, and overall architecture. As a result, it was not until the mid to late 1980s, well after plate tectonic interpretations were established for many Proterozoic orogens, that a working model for the pre-Grenvillian evolution of SE Laurentia within a 'normal' plate tectonic framework began to emerge, and only within the last decade that a plausible plate tectonic model for the Grenville Province itself has been developed. This late entry into the plate tectonic narrative was not for want of trying, as

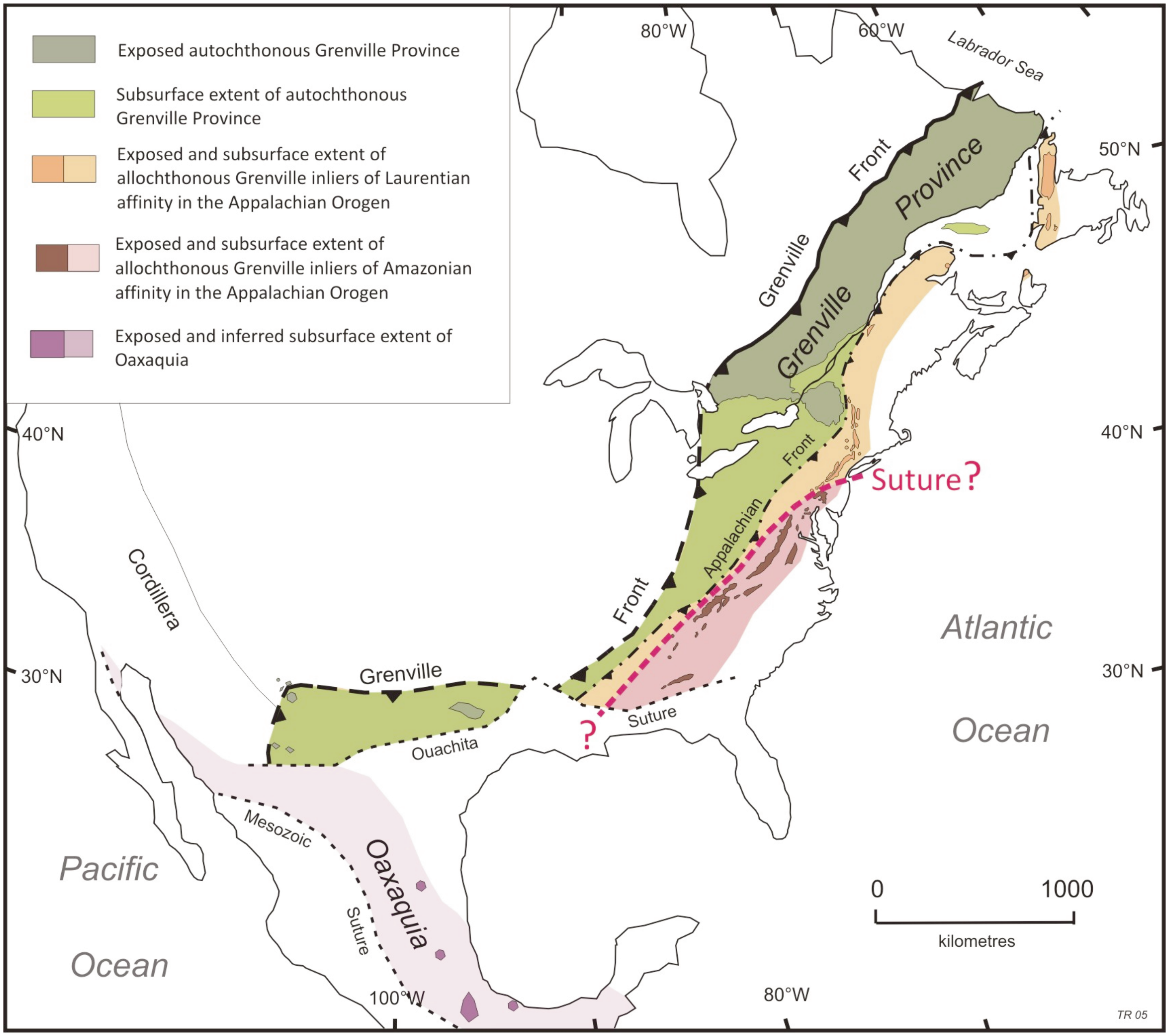


Figure 1. Map showing the extent of the Grenville Province and its continuation under younger cover and as inliers within the Appalachians, which collectively define the Grenville Orogen in North America. The dashed red line labelled 'Suture?' marks the inferred location of the orogenic suture zone between crust of Laurentian origin to the northwest and Amazonian origin to the southeast (see text for discussion). The limit of Grenvillian crust in the Appalachians corresponds approximately to the Paleozoic rifted margin of North America. Grenvillian inliers in the Appalachians were displaced during Paleozoic tectonism and are allochthonous. Crust south of the late Paleozoic Ouachita suture is exotic to North America, including the accreted microcontinent Oaxaquia, which has a 'Grenvillian' age of metamorphism and comprised part of the Grenville Orogen in Rodinia. Grenvillian crust detached from the re-entrant south of the Ouachita suture is located in the Precordillera terrane of western Argentina (see text for discussion). At the time of publication of *The Grenville Problem* in 1956 the extent of the autochthonous Grenville Province was poorly known, and other subdivisions shown were unknown. Figure modified from Rivers et al. (2012).

indicated by a 1974 conference workshop entitled: "*Is Grenvillian Geology Compatible with Plate Tectonics?*" In the conference report, Baer (1974) described a sense of optimism among the contributors that the question was answerable, but he also noted both the paucity of robust data on which to base any kind of tectonic interpretation, and the lack of agreement concerning critical features that were relevant to the question.

Groundwork for the current understanding of the Grenville Province began with the definition of the tectonic provinces of the Canadian Shield on the basis of their K/Ar ages (Harper 1967; Douglas 1972). However due to the reconnaissance scale of much of the early geological mapping, it wasn't until the burgeoning of new studies in the 1980s and 1990s, including 1:100,000 scale regional mapping programs undertaken by the geological surveys of Ontario, Québec, Newfoundland and Labrador, and Canada, and the stimulus of the LITHOPROBE program, that the breadth and depth of data necessary to achieve real progress were attained. With the recent publication of a post-LITHOPROBE review of the Grenville Province in North America (Rivers et al. 2012), and the fortieth anniversary in 2012 of the landmark first synthesis of the orogen by Wynne-Edwards (1972), it is appropriate to look back at the achievements of the last 40 years, identify the critical advances that have brought us to the present understanding, and assess the outlook for future progress. It is no surprise that several of the recent advances relate to the much larger 'geological toolkit' available to researchers today, but other advances are at least in part due to conceptually different ways of viewing and extracting information from what are now referred to as mid- to lower-crustal gneiss complexes.

As discussed later, there is a broad consensus in the current geological literature that the Grenville Province can be interpreted within the framework of a *large hot orogen (LHO)*, a plate tectonic concept proposed by Beaumont et al. (2001) and first applied to the Grenville Province by Jamieson et al. (2002). In the following sections, the progress from the 'Grenville Problem' identified in the mid 1950s, well before the plate tectonic revolution, to the current manifestation of the LHO paradigm, the *Collapsed LHO Model*, is charted by documenting critical conceptual breakthroughs that have proven particularly influential in shaping our current vision of the orogen. The paper concludes with an assessment of the outstanding first-order challenges facing researchers as viewed from the present perspective, and some suggestions for the way forward in the short term.

HISTORICAL DEVELOPMENT OF IDEAS

The Grenville Problem – A Stratigraphic Mindset

In 1955, the Royal Society of Canada (Section IV: Geology and Allied Sciences) convened a meeting of geologists with experience in the Grenville Province to discuss the progress of their work, address current issues, and evaluate the way forward. The resulting volume, edited by J.E. Thompson (1956), was entitled "*The Grenville Problem*". It presents a historical snapshot of the thinking at the time, and as is suggested by the title, several of the contributors were at an intellectual crossroads. Mineral identification and petrographic description were well developed disciplines, and regional mapping in low-grade areas of the Grenville Province, such as the 'Hastings Basin' in Ontario (Fig. 2; from Hewitt 1956), was quite advanced and included such refinements as the definition of isograds locally. However in the majority of the Grenville Province, where granitoid and gneissic rocks predominate and protoliths are less readily identified, mapping and interpretation had essentially stalled (e.g. the 'Highlands' in Fig. 2). Attempts to establish relationships among the various components of gneiss complexes were limited, and as a result they remained largely unsubdivided. Apparently in the absence of any other strategy, the approach to geological mapping at the time was to adopt the terminology, and implicitly the mind-set, of the pioneers. The terms Laurentian and Grenville had been introduced rather casually into the nascent geological literature on the Grenville Province by William Logan in the mid-19th century to distinguish metasedimentary packages mapped in western Québec that were inferred to be of different age (Logan 1863, in Osborne 1956). These terms later morphed into Laurentian Series (or System) and Grenville Series, with Laurentian assuming the role of basement and Grenville that of a cover sequence. Gneissic rocks, including granitoid intrusions, were generally included in the Laurentian System, and Osborne (1956, p. 10) noted that in the 1920s the presence of garnet was considered

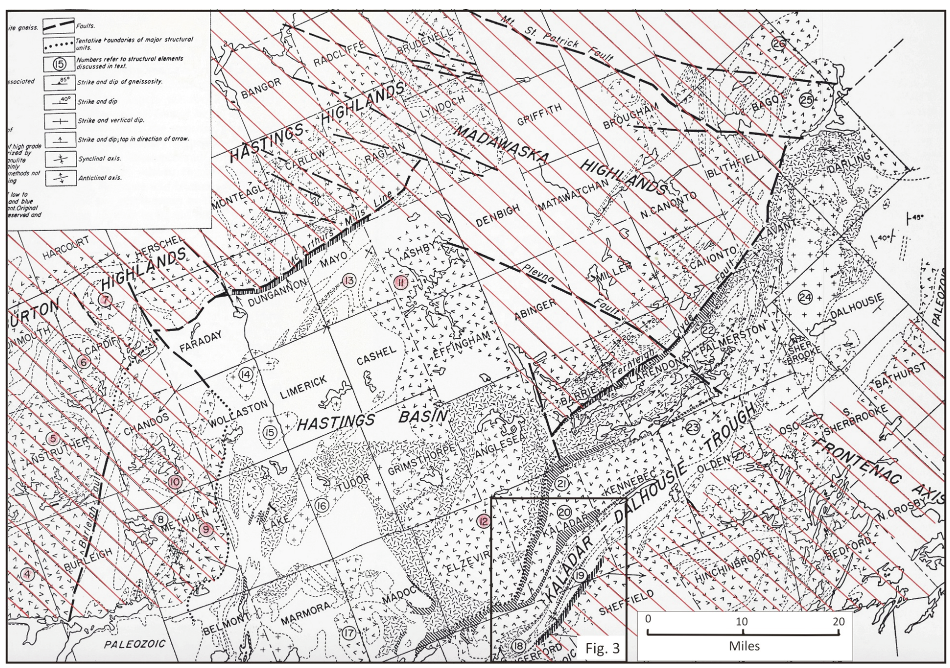


Figure 2. Part of a geological map of the southwestern Grenville Province in Ontario (slightly modified from Hewitt 1956). Areas shown by the red diagonal hachure were considered to be unsuitable for the 'normal stratigraphic mapping methods employed'. Note the identification of large-scale tectonic features, such as the Hastings Basin, Kaladar–Dalhousie Trough, and Madawaska Highlands, which were defined using a combination of structural and metamorphic criteria. For additional details, please consult original source.

by some as an indicator of affiliation with the Grenville Series. Detailed mapping and study was mostly focussed in those areas underlain by low-grade layered sequences composed of lithologies such as marble, metapelite, quartzite and amphibolite that were clearly derived from supracrustal protoliths. In southern Ontario and southwestern Québec, these were mostly assigned to the Grenville, Hastings and Morin series. In effect, these were the only areas amenable to the stratigraphic mapping techniques employed. The result was that the majority of rocks were assigned to an unsubdivided Laurentian basement. The 'problem' is made explicit in the legend accompanying the map reproduced in Figure 2, in which the areas with diagonal hatching are described as "…*terrane of high-grade metamorphic gneisses characterized by rocks of amphibolite and granulite metamorphic facies. Intrusives* [sic] *mainly concordant. Normal stratigraphic methods inapplicable".* In contrast, areas without hatching are described as "…*terrane of low to intermediate metamorphic grade, including schists, argillites, and blue 'Hastings' limestones. Intrusives* [sic] *may be discordant. Original sedimentary and volcanic structures often well preserved and normal stratigraphic methods apply in part*" (both quotes from Hewitt 1956).

Another aspect of the 'problem' was that as the information base grew and new cover series were defined, establishing viable criteria to discriminate among them became problematic. For instance, Hewitt (1956) described the 'general usage' in the Ontario Geological Survey at the time was to place the higher grade metasedimentary rocks into the Grenville Series, and the lower grade ones in which relict sedimentary structures were still visible into the Hastings Series (p. 22). However, he was aware the criterion was not robust, and acknowledged that it had been challenged. Moreover, he also noted that no unconformity had been observed at the base of the Grenville Series, and that "*so-called Laurentian granites and granite gneisses invade and replace the Grenville Series, and also invade and replace Hastings-type sediments*" (p. 23).

A separate, but related issue can be identified from the word 'replace' in the quote from Hewitt (1956) above. It concerns the apparently widespread acceptance of the process of granitization, whereby layered supracrustal rocks were inferred to have been converted to granite and other lithologies in the deep crust by substantial additions of K_2O, Na_2O, Al_2O_3 etc., and depletions of FeO and MgO. Related processes, such as syenitization, nephelinitization, and formation of metasomatic amphibolite and pyroxenite, were explicitly named by some of the contributors to the Grenville volume. In the minds of these authors the precursors of the granitized lithologies, particularly those with gneissic layering, were inferred to be stratified sedimentary rocks, and clearly a *stratigraphic mindset* was hampering intellectual progress for some. For instance, Ambrose and Burns (1956), in discussing the upper amphibolite-facies Clare River synform in the southwestern Grenville Province (Fig. 3), concluded: "*The situation seems perfectly clear. The sedimentary layers on either side of these limestone* [i.e. marble and calc-silicate] *layers, composed mostly of mixtures of biotite, amphibole, oligoclase, quartz and accessories, have been selectively replaced by rocks of granitic texture and granodioritic to quartz-monzonitic compositions*" (p. 50). As intended by the authors (see the title of their paper), this is an unequivocal statement in support of an origin by regional granitization. However, all minds were apparently not in agreement on this issue and there are signs the tide may have been turning. In discussion, Ambrose and Burns were challenged on their interpretation, and in a separate contribution Hewitt (1956, p. 40) stated: "*It appears certain that granites formed both by intrusion and replacement are present in the Grenville area*" (see also Hewitt 1960). Moreover others at the time interpreted metamorphosed granite, syenite, monzonite, anorthosite, mangerite, etc., elsewhere as orthogneisses, envisaging the concordant bodies to be sills, sheets or phacoliths emplaced within a folded metasedimentary succession (e.g. Buddington 1939, 1956; Wynne-Edwards 1957). In fairness, it should be noted that there is field evidence for Na metasomatism locally in the southwestern Grenville Province, for instance in some nepheline-bearing gneisses, that may have been influential in interpretations (see Hewitt 1960; Easton 1992). However, it is interesting to note that the now common term migmatite, introduced into the geological lexicon by J.J. Sederholm in the early twentieth century to describe "*a rock group* [that] *occupies in a sense a transitional position between the granites and the crystalline schists … and has no sharp boundary with any of them*" (from Dietrich 1979, p. 52), is not used by any of the authors in the Grenville volume.

All contributors to the Grenville volume recognized that the mineral assemblages in gneissic rocks implied a high grade of metamorphism, which was described in modern terms as upper amphibolite to granulite facies. From the present perspective, the disconnect between this description of metamorphic facies and the dated belief in the granitization hypothesis suggests a lack of understanding of the interface between metamorphic and igneous processes. For example, an issue raised by Hewitt was whether the high-grade metamorphism was a result of intrusion of granitic magma on a regional scale, but he concluded that "*they* [high-grade metamorphic rocks and granitic intrusions] *were not* […] *cause and effect, but rather* […] *both* [were] *results of P–T conditions of metamorphism in* [the] *deep zone* [of] *regional metamorphism*" (Hewitt 1956, p.33).

There is a single paper in the Grenville volume on isotopic dating (Shillibeer and Cumming 1956), which was in its infancy. According to the table in this paper, which lists all published radiometric determinations in the Grenville Province, the principal methods available at the time were $^{207}Pb/^{206}Pb$ analyses of Pb-bearing phases such as galena and pitchblende, and K/Ar analyses of micas. Analytical uncertainties for both methods, if quoted at all, were in the range of ± 30 to 200 Ma. A conclusion of Shillibeer and Cumming's paper, which is prescient given the large analytical uncertainties, was that no ages greater than 1350 Ma had been measured in the southwest Grenville Province.

Perhaps the greatest surprise for those reading the papers in the Grenville volume from the present perspective is the paucity of discussion

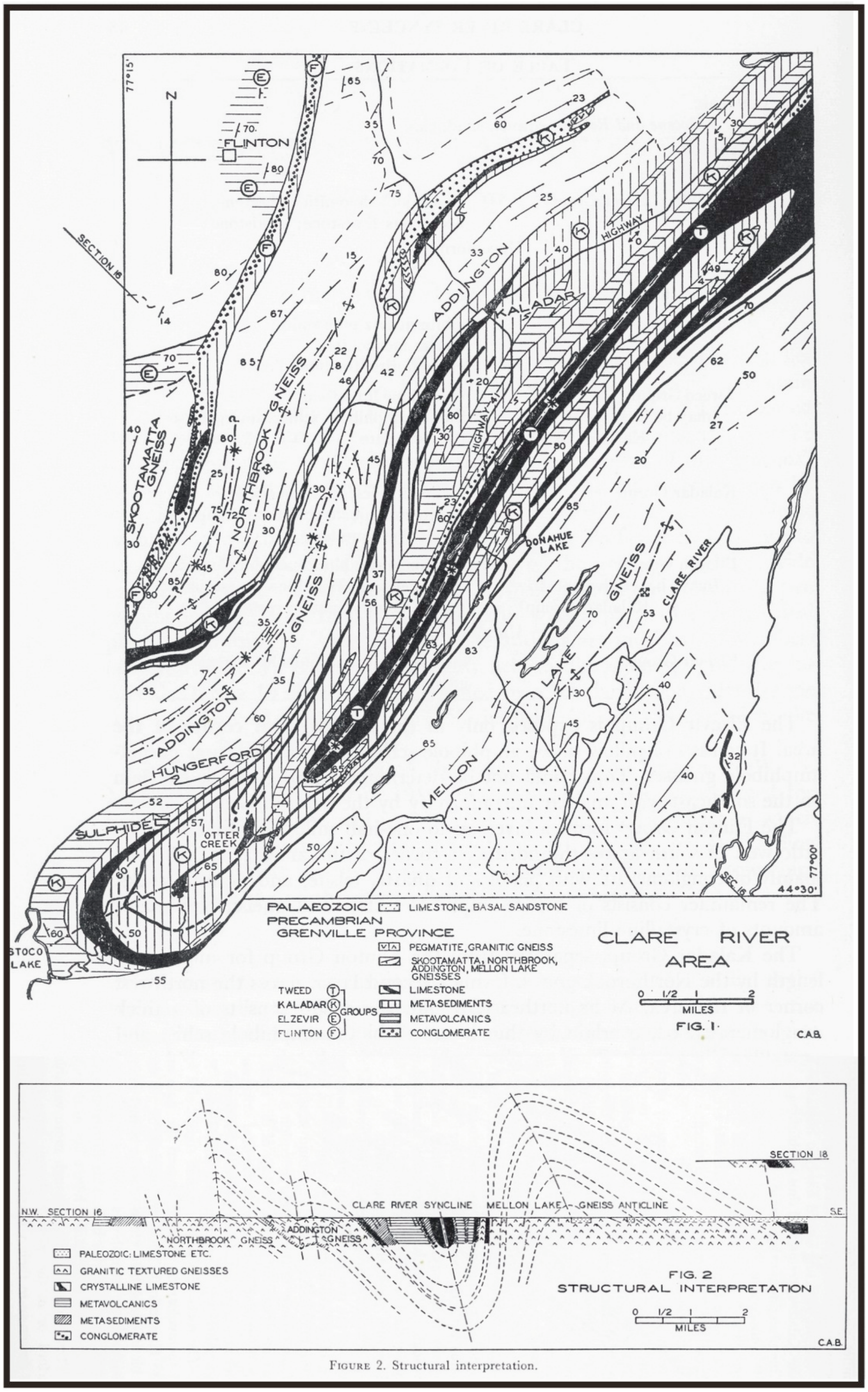


Figure 3. Geological map and NW–SE cross-section of the 'Clare River Syncline', Grenville Province of southwest Ontario (from Ambrose and Burns 1956; for location of map, see Fig. 2). Note the detail of the mapping, the subdivision of supracrustal rocks into four stratigraphic successions (Tweed, Kaladar, Elzevir, and Flinton groups), and the cross-section showing the large-scale structures. The granodioritic to quartz-monzonitic compositions and crystalline textures of the metasedimentary and metavolcanic rocks were inferred to be a result of granitization.

about the structural evolution. Although foliation traces are shown on maps and large-scale structures such as domes, basins, and 'synclines' are interpreted on maps and cross-sections (e.g. Figs. 2 and 3), in the majority of papers (with the notable exception of that of Buddington 1956) there is little mention of fabric elements, shear zones, faults, structural repetition, structural thickening or thinning of units etc., and only very limited discussion of small-scale folds which most authors, as field geologists, could not have failed to observe. It appears that the structures were observed and measured, but then ignored. Taken together with the stratigraphic approach noted above, this leaves the impression that for most authors the effects of deformation were perceived to involve a phase of folding, but otherwise to be essentially static, and that regional metamorphism was associated with widespread metasomatism that profoundly altered the compositions of units. It is easy to be wise in hindsight of course, but it is clear that the *stratigraphic mindset* and associated issues related to the origin of igneous and metamorphic units, and the lack of understanding of the effects and scale of ductile deformation, were proving significant barriers to progress, thereby stifling creative interpretations and serving as the defining attributes of the 'Grenville Problem'.

The Great Leap Forward: The First Pan-Grenville Synthesis

The first synthesis of the Grenville Province as a whole, by Wynne-Edwards (1972), was published only 16 years after the Grenville Problem, but it represented a sea of change in vision and understanding. It comprised a chapter in a book entitled "*Variations in Tectonic Styles in Canada*" (Price and Douglas, editors, 1972), which was destined to become a benchmark in Canadian geoscience. At the time it was written, the plate tectonic revolution was sweeping through the earth sciences, regional geological map coverage of the Grenville Province had significantly increased, and the granitization theory was passé. Moreover K/Ar determinations of basement cores from boreholes through the Paleozoic cover southwest of the exposed

Grenville Province had revealed the extent of the Grenville Orogen along the SE margin of Proterozoic Laurentia (Muehlberger et al. 1967; see Fig. 1). These were heady times for geologists and Wynne-Edwards, like many of his peers, was riding the mobilist wave and contemplating the relationships between geological structures observed in the field and inferred from maps, and the emerging subject of tectonics. Having been involved in a leadership role in the 'Grenville Project / Projet Grenville', a decade and a half of pioneering reconnaissance mapping and research studies in the Grenville Province under the auspices of the Geological Survey of Canada and the Ministère des Richesses naturelles du Québec, he had had the opportunity to see a lot of the Province first-hand. By the time he composed his synthesis, Wynne-Edwards had led regional reconnaissance mapping programs at 1 in = 4 miles (approximately 1: 250,000) scale in widely dispersed areas of the Grenville Province, including western Labrador (Ossokmanuan Lake area; Wynne-Edwards 1961), southwestern Québec (Mont Laurier and Kempt Lake areas; Wynne-Edwards et al. 1966), and southern Ontario (Westport area; Wynne-Edwards et al. 1967). To increase the rate of map coverage, he pioneered a new style of reconnaissance field mapping at the Geological Survey of Canada using large parties that enabled extensive areas to be covered astonishingly quickly – for instance, he noted that in 1964 his GSC field party covered "*13,000 square miles* [in the Mont Laurier and Kempt Lake areas] *to uniform standards in one field season*" (Wynne-Edwards 1972, p. 267). As a direct result of this output, he was influential in the design of a large regional reconnaissance mapping project carried out in the eastern Grenville Province in Québec by the Ministère des Richesses naturelles du Québec in the late 1960s (Franconi et al. 1975; Sharma and Franconi 1975), including its innovative adoption of computer-readable field notes to ensure internal consistency amongst field geologists (Wynne-Edwards et al. 1970).

In addition to his experience in the Grenville Province, Wynne-Edwards' vision also benefited from familiarity with advances in high-grade gneiss terranes elsewhere, such as the Archean complexes in NW Scotland, West Greenland, Australia and South Africa, Proterozoic complexes in Sri Lanka, and the Paleozoic Variscan Belt in central Europe. In 1967, he organized an international symposium on the deep crust, and the proceedings were published under the title *Age Relations in High-Grade Metamorphic Terrains* (Wynne-Edwards 1969). In this way, he was instrumental in bringing new approaches and ideas to test in the Grenville Province. Wynne-Edwards also organized field trips through recently mapped areas, thereby reducing the isolation of many Grenville field geologists. The informal 'Friends of the Grenville – Amis du Grenville' annual field trip, which continues to this day, originated from this time (see www.friendsofthegrenville.org). All in all, it is clear from Wynne-Edwards' maps, reports, and journal papers, as well as those of others at the time, that a profoundly new and more modern perspective was being brought to bear on the interpretation of high-grade gneiss terranes in the Grenville Province. As a metamorphic petrologist by training, Wynne-Edwards was particularly interested in mineral assemblages in granulite-facies rocks (e.g. garnet-cordierite-K feldspar ± sillimanite ± orthopyroxene gneisses; Wynne-Edwards and Hay 1963), but of perhaps wider import from a tectonic perspective was the inference from his 'stratigraphic analysis' that gneissic parts of the province consisted of exhumed remnants of an old basement terrane of Archean age that had been through several episodes of structural–metamorphic reworking, and from which successive supracrustal cover sequences had been largely removed by erosion (Fig. 4). Unravelling basement–cover relations had emerged as a productive way of analyzing metamorphic terranes in Phanerozoic orogens in the 1960s, and Wynne-Edwards was one of the first to apply the principles to a high-grade Proterozoic orogen. That there was old basement underlying the Grenville Province was not a new idea – a similar concept underlay the Laurentian system of Logan. The novelty was in its progressive growth by incorporation of supracrustal and intrusive units over time and the idea that, despite its potentially complex derivation from several types and ages of protolith, evidence for multiple episodes of reworking was preserved within it – and the evidence was potentially accessible to the geologist who knew what to look for.

For Wynne-Edwards, what to look for began with a structural analysis, and he produced some of the first regional structural maps of lineations, axial plane foliations, and folds of the Grenville Province in Canada (Fig. 5A, B) (such maps had been made earlier in the Adirondack segment of the Grenville Province, e.g. Buddington 1956). Wynne-Edwards (1972) appears to have been the first to use the concept of vergence to infer the regional direction of tectonic transport in the Grenville Province, and he recognized the significance of refolding before the systematic descriptions of superposed fold patterns were described in a geological textbook (by Ramsay 1967). He was also among the first to explicitly address the ductile nature of deformation in much of the Grenville Province, a feature characteristic of high-grade gneiss terranes worldwide. Using Grenvillian examples, he argued that the presence on all scales of folds with similar style (i.e. thick hinges and thin limbs), coupled with coaxial refolding, were signals of extreme ductility during deformation. He inferred that these units had deformed by a process he termed 'flow folding', wherein the integrated effects of solid state, ductile creep over long timescales could be likened to laminar flow of a viscous fluid (Carey 1953; Wynne-Edwards 1963). Although the concept was subsequently challenged and is no longer believed to be correct, the focus on large-scale structure and the insight into the extreme ductility of gneiss complexes was ahead of its time, and laid the groundwork for his regional tectonic interpretations and subsequent detailed studies by others. Moreover, it incidentally brought with it the implication that the 'stratigraphy' in supracrustal sequences was also affected by polyphase folding and faulting, and hence not readily amenable to stratigraphic mapping techniques, thereby providing another philosophical break with earlier work. On the other hand, it

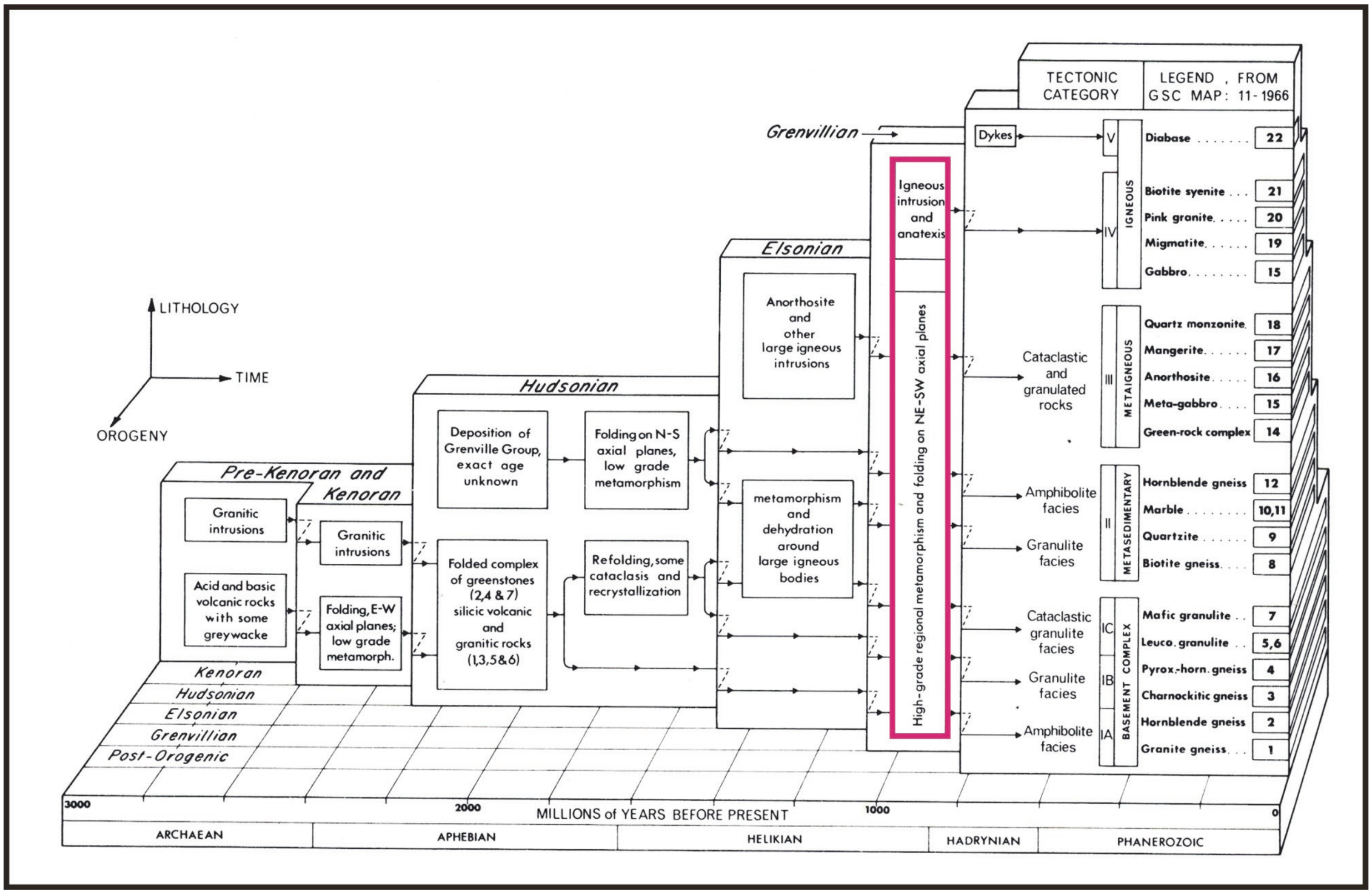


Figure 4. Stratigraphic analysis of the Grenville Province represented in a novel three-dimensional block diagram, with time and orogeny as horizontal axes and mapped lithologies as the vertical axis (from Wynne-Edwards 1969). The figure shows the Archean basement (back left) on which Paleo- and Mesoproterozoic successions (adjacent to right) were deposited and deformed, prior to anorthosite intrusion in the Mesoproterozoic and the Grenvillian Orogeny (red box). The right-hand columns of the figure group the inferred origins of map units into Archean basement, Paleoproterozoic sedimentary cover, and Mesoproterozoic intrusive rocks.

is apparent that the break was not complete, as it is also a sign of those times that he could write "*Varieties* [of gneiss] *with more or less continuous stratiform layering are commonly classified as metasedimentary, and those with gneissic foliation rather than layering are often described as igneous or meta-igneous*" (Wynne-Edwards 1972, p. 283).

Today, Wynne-Edwards is best known for his tectonic subdivision of the Grenville Province (Figure 6). This was a ground-breaking analysis based on an assemblage of criteria, including a 'stratigraphic analysis' of supracrustal sequences, structural trends, age of rocks, K–Ar signature, regional metamorphic grade, gravity and magnetic signature, and the distribution of anorthosite–mangerite–charnockite–granite (AMCG) complexes. AMCG complexes were singled out for special attention because they were thought to be anorogenic and hence serve as time markers, and also because the intrusions were postulated to reach their level of isostatic compensation at the putative basement–cover unconformity, where they spread out as phacoliths or sheets. The comprehensive and in many respects rigorous foundations of Wynne-Edwards' tectonic subdivision, especially in the southwestern part of the province where there were more data, positioned it ahead of its time and it became the point of reference for a generation of students of the Grenville Province. For instance, the tectonic subdivision of the western Grenville Province into a Grenville Front Tectonic Zone, Central Gneiss Belt, Central Metasedimentary Belt, and a Central Granulite Terrain has stood the test of time (although some of the names have been revised). In addition, he defined a foreland zone to the northwest of the Grenville Front thereby explicitly denoting the regional northwest vergence of this boundary for the first time (Fig. 6). In contrast, in the central and eastern parts of the province where geological knowledge was at a reconnaissance level and his tectonic divisions were largely based on aeromagnetic trends, they have mostly been superseded.

Wynne-Edwards (1972) also took the bold step of drawing the first orogen-scale cross-sections of the Grenville Province (Fig. 7.) Although conceptual, these clearly showed the northwest vergence of the orogen, the first figures to explicitly illustrate this

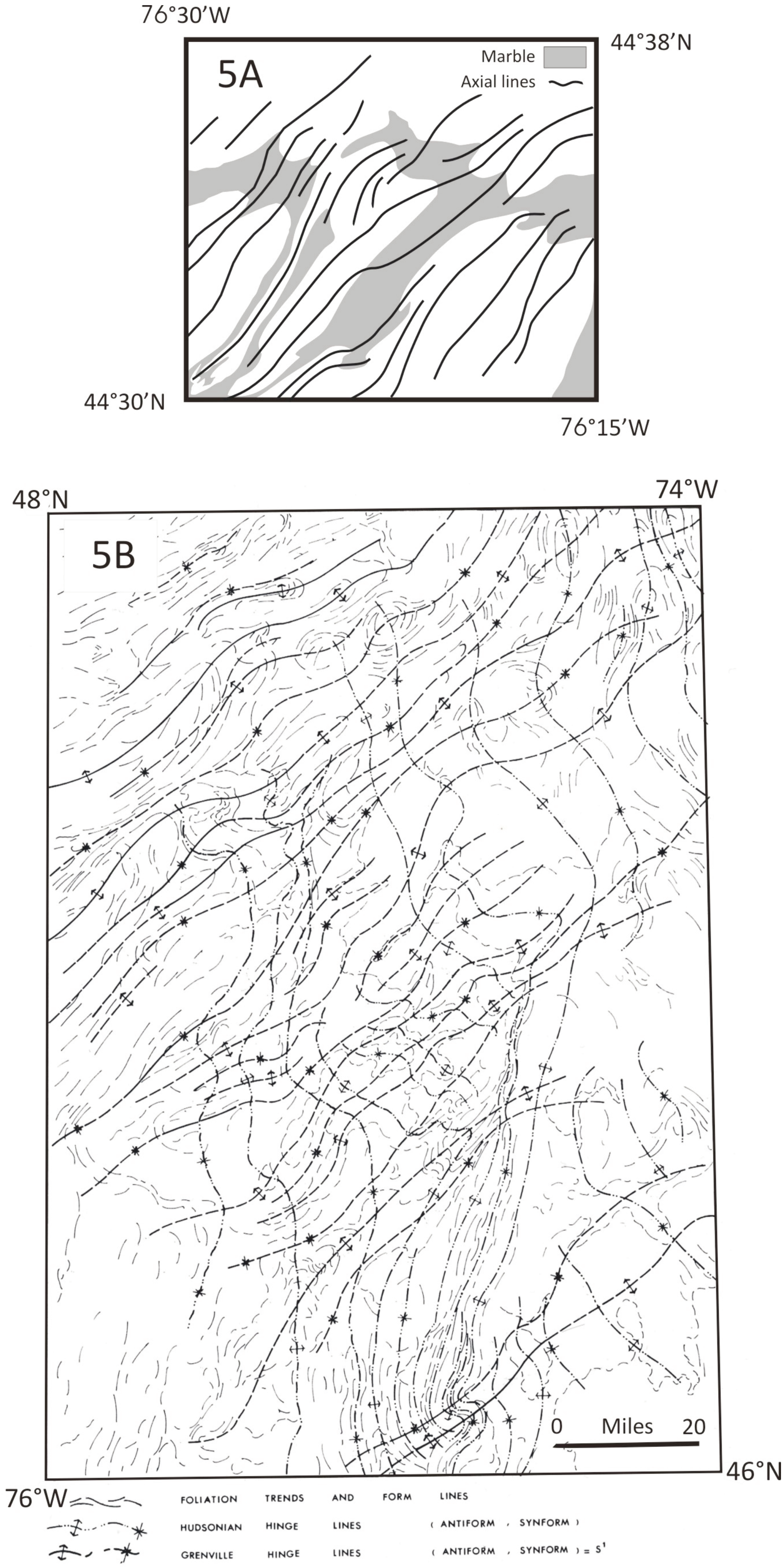


Figure 5. Structural maps produced by Wynne-Edwards; A. Map showing outcrop pattern of marble (grey) and the inferred traces of axial lines (fold axes), Westport map sheet, Frontenac Axis, southwestern Ontario (redrawn from Wynne-Edwards 1963); B. Structural trends of overprinting fold axes, Mont Laurier–Kempt Lake areas, western Québec (from Wynne-Edwards 1969). In A, the outcrop pattern of marble was recognized to be a result of superposed folding and was interpreted as evidence for 'flow folding'; in B, folds with NW–SE trends were interpreted to be Hudsonian, and to have been refolded by Grenvillian folds with NE–SW trends.

on a regional scale. The cross-sections and supporting text indicate that he envisaged a long-lived passive margin (geosyncline in his terminology) overlying an Archean basement on the SE margin of Laurentia that lasted some 600 M.y. from the Paleoproterozoic until the initiation of the Grenvillian Orogeny. Figure 7 shows several supracrustal successions of Paleoproterozoic to late Mesoproterozoic age, of which the youngest was termed the Grenville Supergroup, the collective successor to the Grenville and Hastings series and including the unconformably overlying Flinton Group (defined by Moore and Thompson 1972, 1980), all of which were inferred to have been deformed and metamorphosed during the terminal Grenvillian orogeny. In summary, Wynne-Edwards' (1972) paper provided the first coherent synthesis of the orogen, but the underlying assumption of a long-lived passive margin that underpinned the analysis is now known to be incorrect, as are inferences concerning the extent of Archean basement and continuity of Proterozoic cover sequences.

In his discussion of regional metamorphism, Wynne-Edwards (1972) pointed out the contrast in metamorphic signature between the Grenville Front Tectonic Zone (GFTZ) in the northern Grenville Province, in which kyanite is the dominant aluminum silicate, and the interior

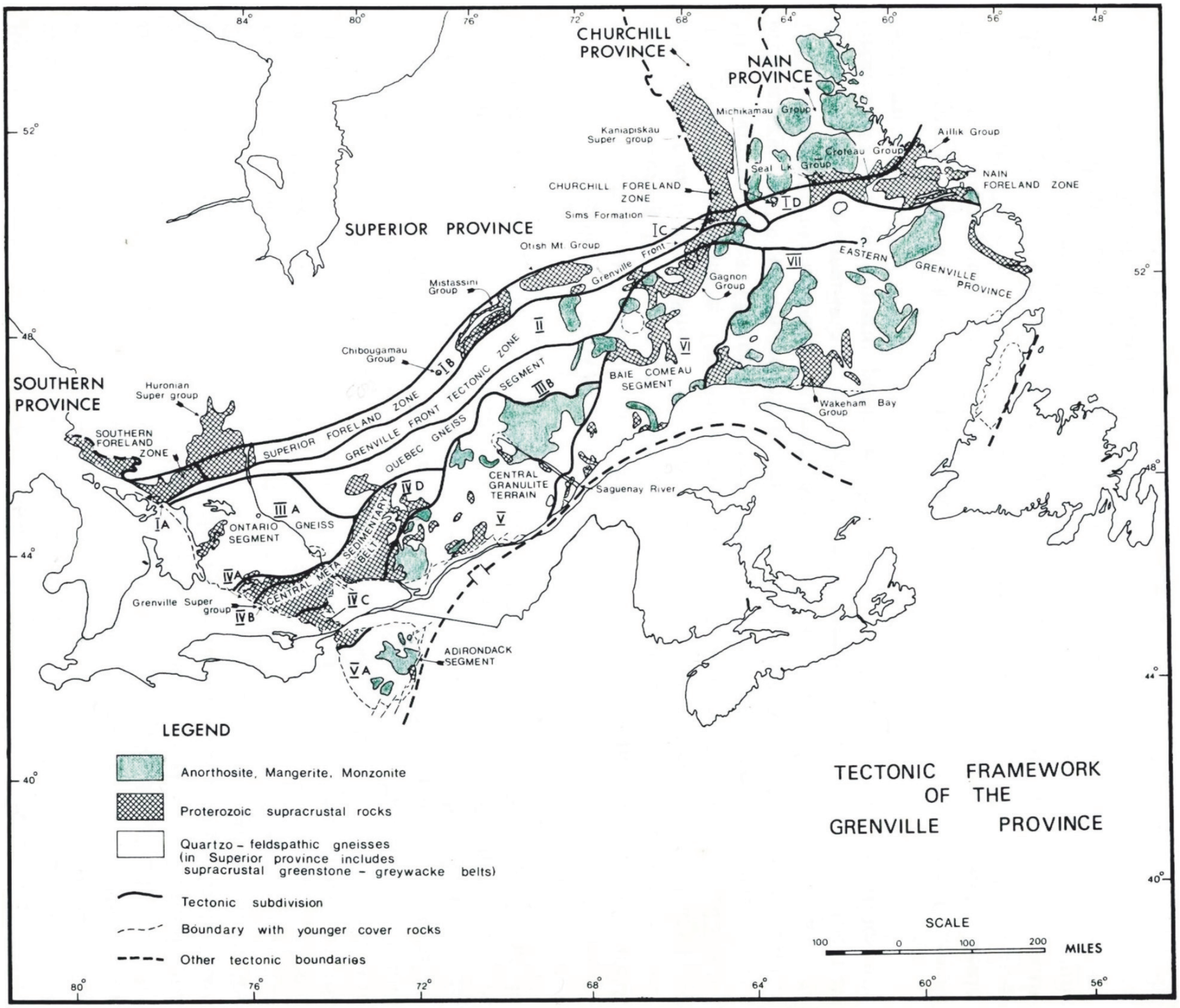


Figure 6. Wynne-Edwards' tectonic framework of the Grenville Province (from Wynne-Edwards 1972). This was the first tectonic subdivision to cover all parts of the Grenville Province. The figure highlights the locations of Proterozoic supracrustal sequences (grey shading) and AMCG complexes (green) within the 'sea' of quartzofeldspathic gneiss (white). This was the first figure to explicitly identify the Grenville Front Tectonic Zone (GFTZ) immediately southeast of the Grenville Front (GF), and a foreland zone to the northwest of the Grenville Province. Note that several Proterozoic sequences in the foreland are truncated at the GF, whereas the Kaniapiskau Supergroup extends from the foreland across the GF into the GFTZ, interpretations supported by more recent work. On the other hand, some areas identified as supracrustal sequences in the interior of the province are now known to be largely underlain by high-strain orthogneiss. The location of the GF in eastern Labrador has been revised and is now placed significantly farther north than shown. Several tectonic subdivisions for the western Grenville Province that are still used, despite name changes, include the Central Gneiss Belt (Ontario and Québec segments), Central Metasedimentary Belt, and Central Granulite terrain (Adirondack and Québec segments).

Grenville Province in which sillimanite is stable. This was a perceptive observation that he explained by the novel concept of 'fossil isograds' immediately south of the Grenville Front (Fig. 8), whereby pre-Grenvillian kyanite-bearing metamorphic rocks in the northern Grenville Province were exhumed and experienced only a low-grade thermal Grenvillian overprint and minor recrystallization. In support of this interpretation, he pointed to the determination of Archean Rb–Sr ages and Grenvillian K–Ar ages in rocks south of the Grenville Front adjacent to the Superior Province near Val d'Or. The explicit geochronological demonstration of the effects of metamorphism of more than one age within the Grenville Province was influential for a generation of students. As a result, it has

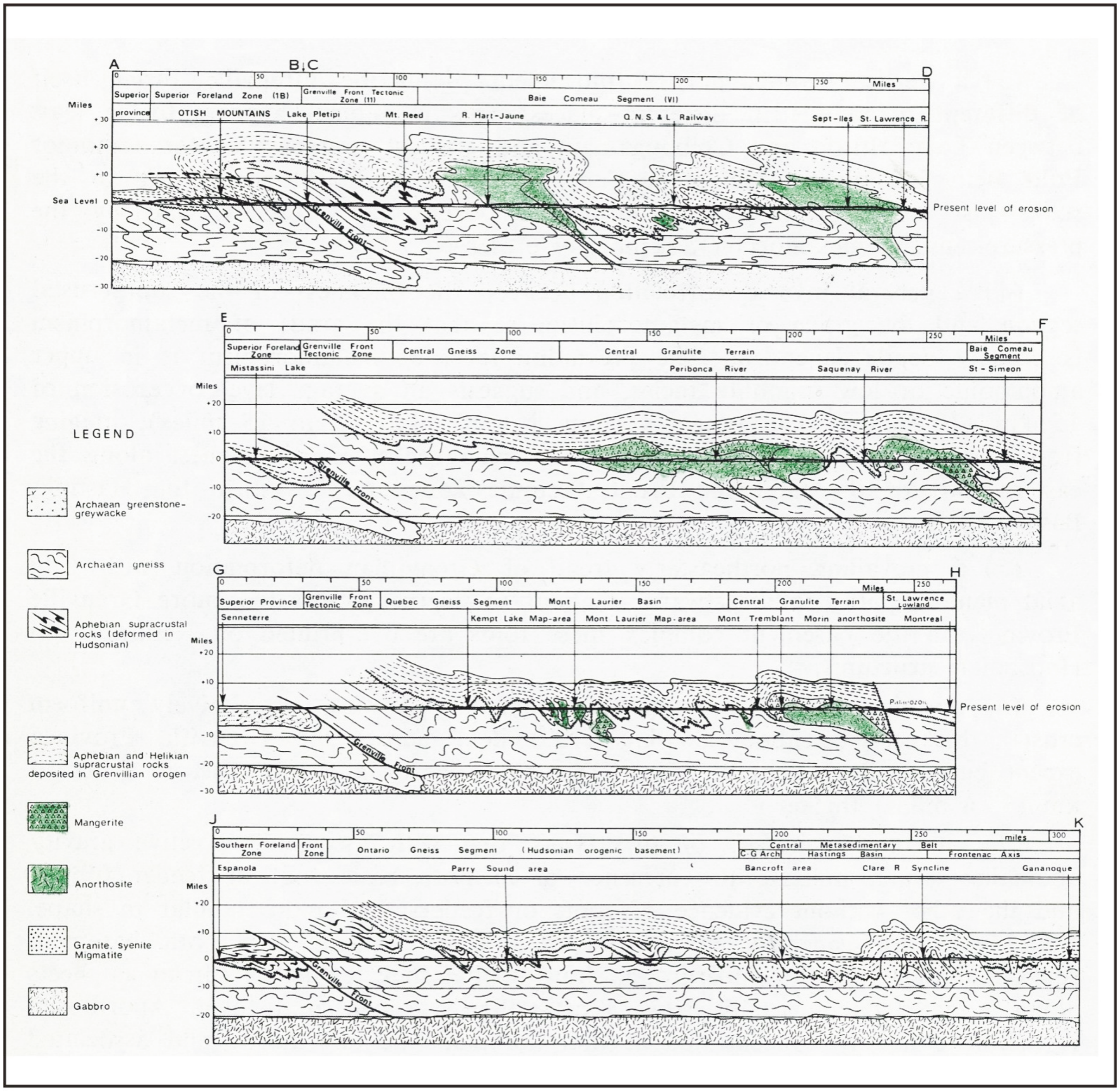


Figure 7. Schematic orogen-scale cross-sections through the Grenville Orogen (from Wynne-Edwards 1972). A–D Eastern Québec; E–F Central Québec; G–H western Québec; J–K southern Ontario. Note the recognition of NW vergence and inferred crustal scale of the Grenville Front. A feature of all the cross-sections is the inferred presence of Archean basement overlain by remnants of Proterozoic passive margin supracrustal sequences of various ages (the basement–cover hypothesis).

been extensively tested and is now known to be correct in principle. However, the hypothesis of 'fossil isograds' near the Grenville Front has not been upheld, the kyanite-bearing assemblages having subsequently been determined to be Grenvillian.

Although many of his ideas were original and provocative, the interpretation of a long-lived passive margin on SE Laurentia from the Paleoproterozoic and throughout the Mesoproterozoic shows that Wynne-Edwards had not completely shed the stratigraphic outlook of the previous generation. Today we understand that much of what Wynne-Edwards (1972) considered to be an Archean and Paleoproterozoic basement complex in the southeastern Grenville Province is orthogneiss derived from Paleoproterozoic and Mesoproterozoic intrusions emplaced in a long-lived continental margin (Andean) arc, reflecting

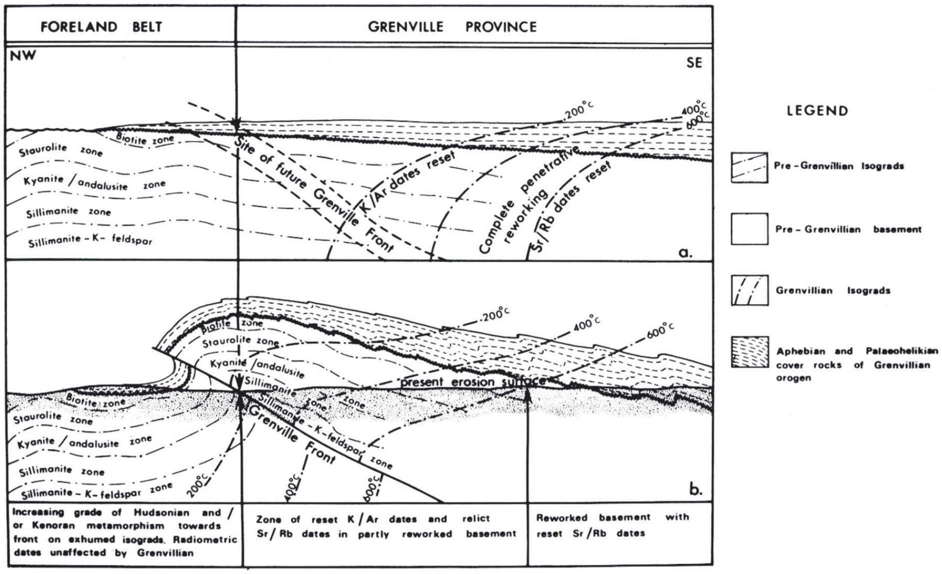


Figure 8. Exhumation of pre-Grenvillian metamorphic rocks at the Grenville Front, giving rise to 'fossil isograds', Wynne-Edwards' novel explanation for the observation that kyanite is the most abundant Al silicate adjacent to the Grenville Front, in contrast to sillimanite farther south in the interior Grenville Province (from Wynne-Edwards 1972).

the difference between passive margin and active margin settings discussed previously. Hence the framework of his stratigraphic analysis and structural overprinting model (Figs. 4 and 5B), no doubt influenced by the popularity of the reworked basement–cover paradigm at the time, is no longer considered viable. Moreover, the Central Metasedimentary Belt is now subdivided into several domains interpreted to represent accreted terranes (Easton 1992), a concept that is incompatible with the supracrustal rocks belonging to a single widespread supergroup (the Grenville Supergroup) and with formation in a passive margin setting. An early indication that his interpretation would require revision was the identification of metamorphosed pillow lavas and calc-alkaline volcanic rocks in the Central Metasedimentary Belt (e.g. Brown et al. 1975). In hindsight, it is interesting to note that although clearly a highly innovative scientist capable of composing provocative new hypotheses, Wynne-Edwards' (1972) adopted the conventional 'status quo' model of a long-lived geosyncline (passive margin) on SE Laurentia from ~1.8 to 1.1 Ga, which is thus perhaps the aspect of his synthesis that appears most dated today.

Plate Tectonic and Quasi-Plate Tectonic Models of the 1970s

As was alluded to in the Introduction, the early 1970s was an exciting time for Precambrian geologists as tentative attempts were made to extend the application of plate tectonic principles back in geological time. In the case of the Grenville Province, an important theme was the tectonic setting of what are now referred to as mid-crustal gneiss complexes. These were widely viewed as a granitoid 'basement' terrane that had undergone ductile reactivation under upper amphibolite- to granulite-facies conditions. Another theme involved the search for relics of ancient oceanic terranes within the high-grade rocks that would allow definition of a 'symmetrical orogenic system', and yet another line of investigation was based on a paleomagnetic definition of collisional orogeny using apparent polar wander curves for the two colliding cratons. At the time the Grenville Province was not well mapped and the gneiss complexes were largely unstudied, leaving room for imaginative interpretations that were only loosely constrained by limited data. In this section, five examples with very contrasting conclusions are briefly reviewed in the chronological order in which they appeared.

Basement Reactivation during Continental Collision

Incorporation of the Himalaya–Tibet orogen into a plate tectonic framework (e.g. Dewey and Bird 1970) implied a duality in Phanerozoic collisional orogens: short duration collisions that led to narrow mountain belts like the Alpine Orogen, and longer duration collisions that resulted in mountain chains at the margins of wide orogenic plateaux underlain by double thickness crust, such as the Himalaya–Tibet Orogen. This followed from buoyancy considerations, from which it was assumed at the time that continental crust could not be subducted *en masse* and hence that prolonged collision was accommodated by thickening and widening of the collision zone. This insight not only showed that modern lithospheric plates were not as uniformly rigid as originally postulated; it also opened the door to the hypothesis of reactivation of thick hot basement under an orogenic plateau, simultaneously providing a plate tectonic framework in which it could take place. This concept was developed by Dewey and Burke (1973) to provide a model for the formation of Phanerozoic high-grade gneiss terranes such as the Bohemian Massif in the Variscan Orogen of central Europe, and also as a more generic template for high-grade Proterozoic belts such as that exposed in the Grenville Province, to which part of their paper was explicitly directed. A cross-sectional view of their tectonic model is reproduced in Figure 9, from which it is apparent that they were the first to propose, albeit in an indirect and generic manner, that SE Laurentia was an active margin and the site of a continental margin arc prior to the Grenvillian Orogeny. However, since there was no known geological evidence for either NW-directed subduction or the remnants of a Mesoproterozoic continental margin arc in the Grenville Province at the time, their model was essentially based on an assumption that the wide belt of high-grade rocks preserved at the erosion surface had formed in a setting analogous to the Tibetan Plateau. Other aspects of their model were also less than compelling with regard to their application to the Grenville Province. For instance, foreland basins

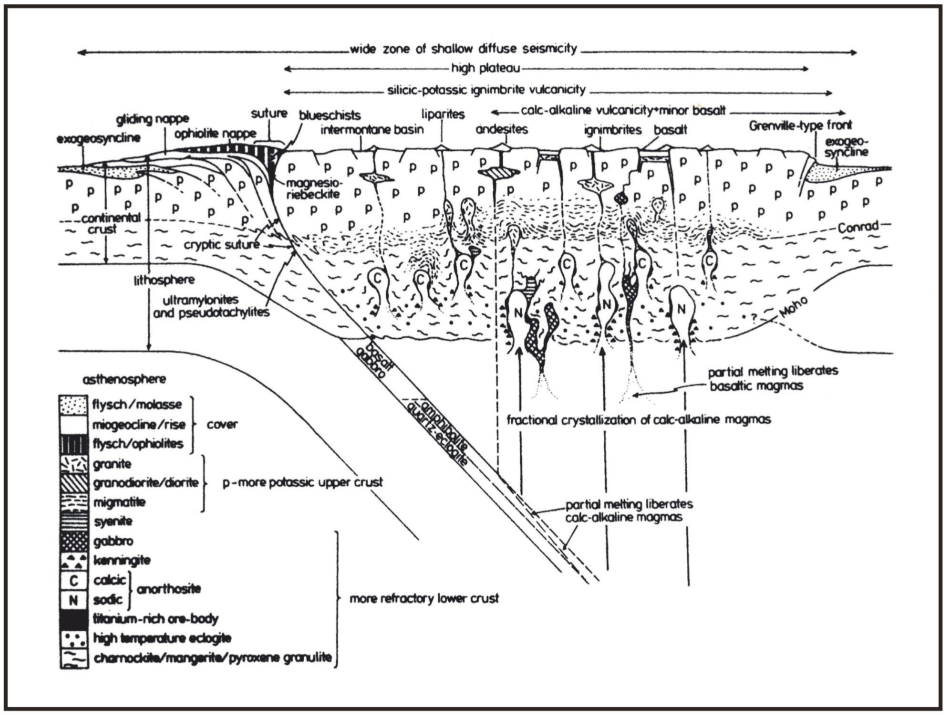


Figure 9. Tectonic model of basement reactivation during continental collision (from Dewey and Burke 1973). The model was based on the understanding of the Himalaya–Tibet Orogen at the time. Although the overall collisional tectonic setting proposed by the model is now widely accepted for the Grenville Province, the many details shown in the figure and discussed in the accompanying text were not easily tested at the time, and some are now considered to be incorrect. Moreover, there is as yet no robust argument concerning subduction polarity in the Grenville Orogen. See text for discussion.

filled with orogenic sedimentary rocks shown adjacent to the 'Grenville-type front' in Figure 9 (where they are labelled as 'exogeosynclines'), are conspicuous by their absence adjacent to the exposed Grenville Province in Canada; and their model does not provide a mechanism for the preservation of low-grade rocks such as the Hastings Basin adjacent to granulite-facies gneiss complexes, as shown for instance in the map of Hewitt (Fig. 2). Disregarding these issues, however, and considering the model from the present perspective, it is clear that in a broad sense this was a prescient interpretation that has stood the test of time. Nevertheless, for the most part its adoption by the Grenville community was slow to take hold. This was partly because of the lack of evidence for many of the features illustrated and discussed, and partly because the generic formulation of basement reactivation was difficult to test and did not preclude other tectonic settings. From today's viewpoint, there are several problems with details in their model and its application to the Grenville Province. These include both generic features in Figure 9, such as the lack of imbrication of crust under the plateau and the petrogenetic setting and timing of AMCG magmatism, and specific features such as the lack of accreted terranes. Moreover, the location of the orogenic suture in the Grenville Province was unknown, there is no major internal tectonic boundary comparable to the Allochthon Boundary Thrust (see below), and it was difficult to reconcile the high-level, rather superficial Grenville Front with adjacent foreland basin deposits in Figure 9 with the real thing. Nevertheless, with the publication of this paper, a potentially viable plate tectonic framework for understanding the Grenville Province was on the table for testing and refining and it has remained a point of reference for many authors ever since.

A Paleomagnetic Solution?

In the early 1970s, there was widespread hope that paleomagnetism would be the Rosetta Stone, providing the key to understanding ancient collisional orogens that had developed by plate tectonic processes. Specifically it was argued that it should be possible to determine the collisional history of an orogen by fingerprinting the separate pre-collisional apparent polar wander paths (APWPs) of the two continents involved in the collision, and documenting their convergence and subsequent wander as a single entity. The logic was impeccable, but the method gradually lost its gloss with respect to Precambrian orogens as practical problems were recognized. The most significant of these were the discovery of thermal resetting of the paleomagnetic poles, which implied that primary paleomagnetic information was not preserved in high-grade terranes, and a second practical issue was the accurate dating of the poles themselves, as opposed to the rocks in which they occurred (a non-trivial issue given the widespread use of Rb/Sr geochronology at the time, with its attendant large uncertainties). Given favourable settings, these problems can now be largely overcome, leading to a much more cautious application of the principles, but in the interval before they were understood and resolved several speculative paleomagnetic solutions were published, one of which focussed specifically on the Grenville Province (Irving et al. 1974).

The critical APWP data are summarized in Fig. 10A, which shows the tracks of the Grenville APWP (defined by poles in the hinterland of the Grenville Province representing a putative continent named Grenvillia) and the Mid to Late Keweenawan APWP (that defines the track for Interior Laurentia) for the interval ~1300–700 Ma. Note that the tracks of the two APWPs are quite distinct for the first part of this period before merging at ~1000 Ma, and following a common path thereafter. The preferred interpretation of the data (Irving et al. 1974) was: (i) Grenvillia and Interior Laurentia were initially part of a single continent, (ii) Grenvillia rifted from Laurentia at ~1300 Ma and proceeded to define its own APWP (the hairpin-

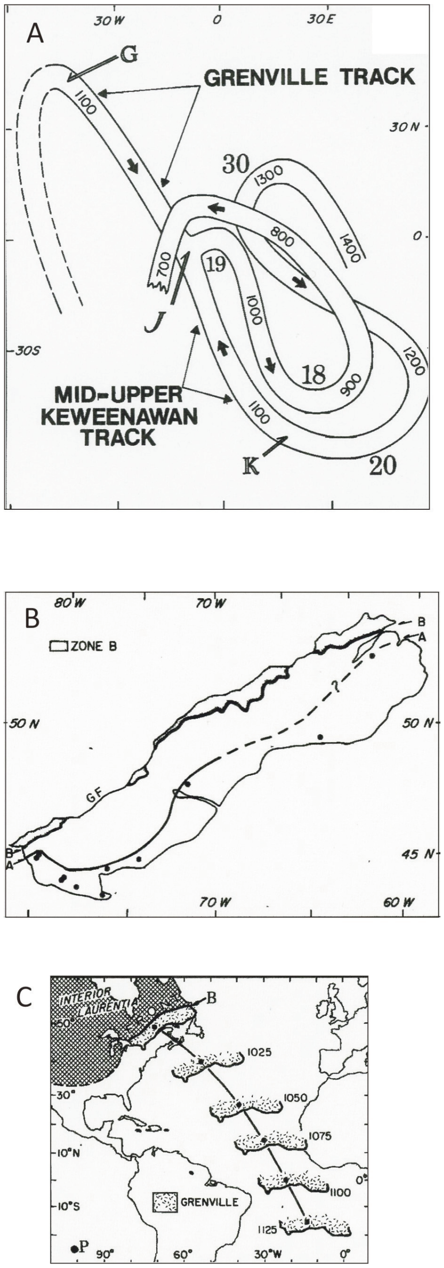


Figure 10. A: Apparent polar wander paths (APWPs) for Grenvillia and Interior Laurentia (from Irving et al. 1974). Note that the APWP for Grenvillia (Grenville track) and Interior Laurentia (Mid–Upper Keweenawan track) are different before 1000 Ma, at which time they merge and follow a common track thereafter. B: Suggested location of the Grenvillian collisional suture, shown by solid and dashed line; black dots are locations of analysed paleomagnetic poles for Grenvillia. C: Relative APWP for Grenvillia with inferred ages, holding Interior Laurentia stationary. Inferred pivot point is indicated by P in bottom left-hand corner.

shaped 'Grenville Loop'), (iii) Grenvillia and Laurentia collided at ~1000 Ma, after which (iv) they formed a single continent and shared a common APWP. Irving et al. (1974) were aware that the Grenville Front was not a suture, so they postulated that the suture must be situated farther to the south in the hinterland of the Grenville Province (Fig. 10B) where mapping constraints were conveniently lacking at the time. Finally, for illustrative purposes they calculated the relative APWP for Grenvillia holding Interior Laurentia stationary, from which they were able to determine the location of the fictive pivot point (P) required to bring Grenvillia into collision with Interior Laurentia at 1000 Ma (Fig. 10C). All in all, this was an elaborate construct based on a large number of individual paleopole determinations made by many authors, and for a few years it held some sway among members of the paleomagnetic community. Summarizing the model, Irving et al. (1974) stated (p. 5501): "*This scenario is obviously very speculative, but it does make quantitative predictions about the nature and timing of Grenvillian motions, the position of the suture, and the kinematic setting of adjacent igneous events, notably in the Keweenawan and Seal* [Lake] *Group.*"

Mesoproterozoic Aulacogen Model

Dewey and Burke's (1973) collisional model of basement reactivation proposed that the AMCG complexes that are so abundant in the Grenville Province were syn-orogenic magmatic complexes of Grenvillian age (see Fig. 9). However, as pointed out by Baer (1976), some of the first dated AMCG complexes in the Grenville Province turned out to be ~1.5–1.4 Ga, implying that they must have been part of the 'basement' during the Grenvillian Orogeny. In the same paper, Baer (1976) also drew attention to a NNE-trending aeromagnetic lineament in the Grenville province that he inferred separated the distributions of the ~1.5–1.4 Ga (mid Mesoproterozoic) anorthosite complexes to the east from the ≤1.3 Ga (late Mesoproterozoic) Grenville Supergroup to the west. He proposed that this magnetic feature, which he named the Chibougamau–Gatineau lineament, was an oblique, NNE-trending shear zone that separated deeply exhumed gneissic crust with pre-Grenvillian AMCG complexes in the east from the high-level Grenville Supergroup in the west. Further, he inferred that this distribution was inherited from the depositional setting of the Grenville Supergroup in an aulacogen or failed rift that had opened at approximately 1.3 Ga, and was later partly closed during the Grenvillian Orogeny. This was a modification of the passive margin (geosynclinal) setting proposed by Wynne-Edwards (1972), but not a radical one in that it still clung to an overall passive margin setting for southeast Laurentia during the Mesoproterozoic. In concluding, Baer (1976) surmised that the aulacogen was the "*earliest manifestation of a Wilson cycle in the North Atlantic, which has therefore opened three times, around 1300 Ma, 700 Ma and 200 Ma*" (p. 513).

Millipede Model of Ensialic Orogenesis

Wynne-Edwards published his millipede model of ensialic orogenesis in 1976, by which time he had relocated to western Canada and was no longer doing field work in the Grenville Province. However, he had visited other high-grade orogens and he proposed that the model was applicable in a generic way to Proterozoic orogens worldwide. The millipede model was predicated on two inferences, both of which were formulated during his work in the Grenville Province: (i) that many Proterozoic orogens are largely underlain by granitoid gneiss complexes that represent ductile, remobilized polymetamorphic basement on which thin layers of several supracrustal cover sequences had been deposited; and (ii) that there was no (or minimal) evidence for preservation of oceanic crust in Proterozoic orogens, and hence that orogenesis was ensialic. Inference (i) concerns basement reactivation, the same issue underlying the model of Dewey and Burke (1973), but posited a passive margin setting with one or more overlying cover sequences rather than an active margin setting. Inference (ii) also took the opposite tack to Dewey and Burke by inferring that the scarcity of relict oceanic crust implied a fundamentally different tectonic process compared to modern orogens. The ensialic tectonic evolution was envisaged to have occurred by slow (millipede) movement of the orogenic crust over a hot upwelling mantle spreading centre that heated the overlying continental crust, causing it to undergo ductile thinning by gravity-driven 'extending flow', a process that in turn led to foreland-vergent folding and thrusting of the thin supracrustal cover by 'compressive flow' at the orogen margins (Fig. 11A).

A third element of the model of particular relevance to the Grenville Province involved the formation of the large anorthosite and associated mafic complexes, their inferred linear arrangement at high angle to the orogenic front being posited to track the migration of continental crust over the mantle spreading centres where these complexes were inferred to originate (stars in Fig. 11B). Acknowledging that his model of Proterozoic ensialic orogenesis did not fit within the modern plate tectonic framework, Wynne-Edwards (1976) proposed that it represented an intermediate stage between Archean tectonics driven primarily by diapirism, and Phanerozoic plate tectonics in which ocean basins developed by rifting of continental crust (Fig. 11C).

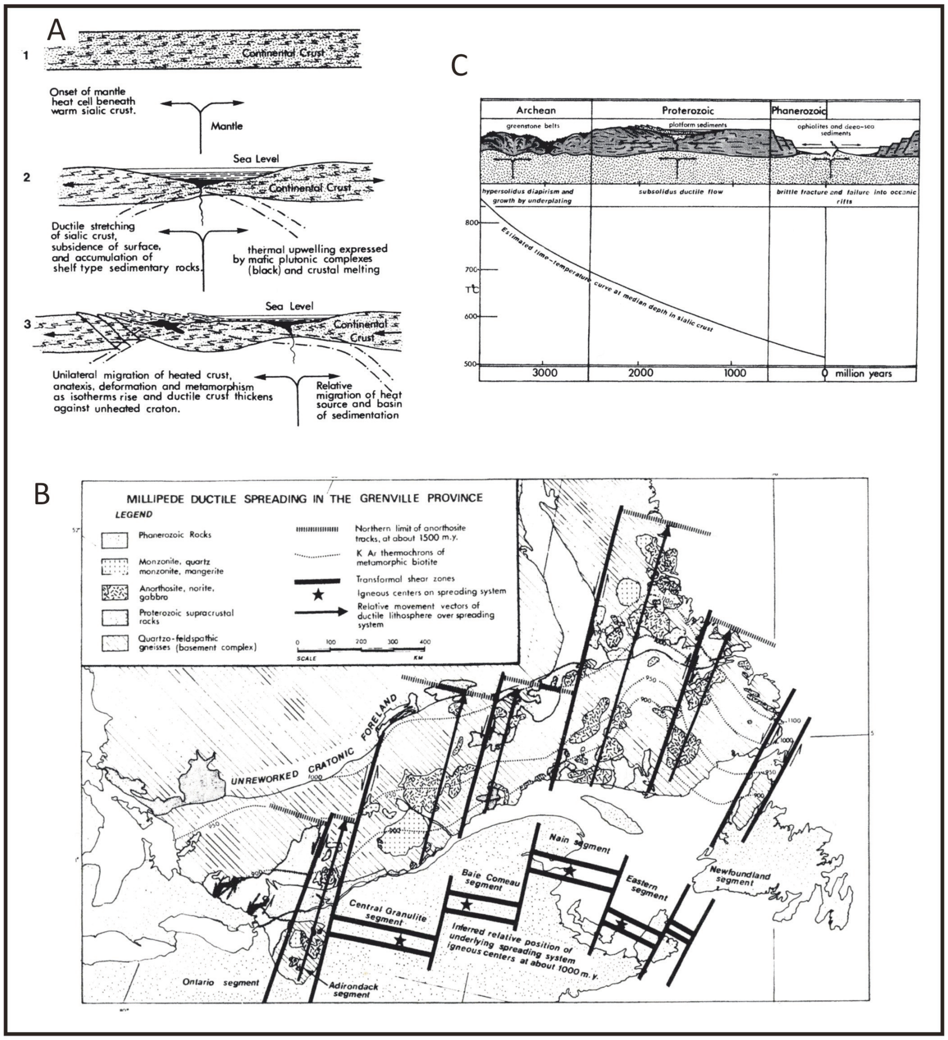


Figure 11. Millipede model for ensialic orogenesis (from Wynne-Edwards 1976). A: Movement of a continent over a zone of upwelling mantle leading to thermal softening and ductile stretching of continental crust by extending flow, and shortening by compressional flow near the orogen margin. Extensional deformation tracked the upwelling mantle source under the orogen. B: Proposed application to the Grenville Province; note the tectonic subdivision of the orogen into segments at high angles to the orogen margin, the prominent role of AMCG suites in the model, and the inferred locations of mantle spreading centres (stars). C: Proposed scheme of secular tectonic evolution, from diapirism in the Archean, through millipede orogenesis in the Proterozoic, to plate tectonics in the Phanerozoic. For additional details, please consult original source.

Shear Zone Model for the Grenville Province

In the following year, Baer (1977) proposed his second tectonic model that can perhaps be considered as a 'friendly amendment' to Dewey and Burke's (1973) Tibetan Plateau analogue of basement reactivation. In it, he suggested that the Chibougamau–Gatineau lineament, defined in his previous paper (Baer 1976), was but one of a series of oblique magnetic lineaments that subdivided the crust in the Grenville Province into approximately N–S-trending sigmoidal segments 200–400 km wide. He inferred that the lineaments were shear zones, and that their anastomosing orogen-scale pattern was a signal of oblique collision in a transpressional regime (Fig. 12). Apart from identification of the magnetic lineaments as shear zones, the model was principally predicated on three lines of evidence: (i) the absence of a collisional suture within the exposed Grenville Province; (ii) the interpretation that Grenvillian deformation was partitioned into 'severely deformed zones' of high shear strain, commonly underlain by supracrustal rocks, and 'moderately deformed blocks' composed of more rigid plutons or basement rocks that had escaped the brunt of Grenvillian deformation; and (iii) paleomagnetic data defining the 'Grenville loop' in the APW path between ca. 1050 and 950 Ma that was clearly different from the path for North America over the same period (see Fig. 10A). The geological evidence for the absence of a suture, which implied all the exposed Grenville Province was derived from Laurentian crust, and the paleomagnetic evidence for a distinct Grenville APW path, which implied formation on a separate continent, were incompatible and constituted a paradox. In seeking a solution to this paradox, Baer (1977) noted that paleomagnetic data for samples from near the Grenville Front or from 'moderately deformed blocks' yielded single poles close to those determined for North America

Figure 12. Shear zone model for the Grenville Province (from Baer 1977). Model based on identification of the Chibougamau–Gatineau aeromagnetic lineament (C–G) and its interpretation as a major shear zone. Dashed lines in figure represent regional structural trends; black and cross-hatched bodies are AMCG complexes. Model implies substantial strike-slip displacement along both the Grenville Front, and along approximately N-trending shear zones at high angle to the Front, for which no evidence has been found.

at ca. 1000 Ma, whereas samples from 'severely deformed' high-strain zones commonly yielded two directions of magnetization separated by large angular distances. He inferred the separation between the two poles was a signal of up to 60° counterclockwise rotation by dextral simple shear during the Grenvillian Orogeny, which he calculated would have been associated with relative displacement of ca. 200–300 km at the margins of the shear zones.

Summary: Parting Shots

Although they proposed very different tectonic regimes for the Grenville Province, the five 1970s plate tectonic models had several features in common. All were elaborate constructs conceived in the fertile minds of creative earth scientists (four geologists and one geophysicist) who were motivated by the search for novel plate tectonic-related explanations for the Grenville Orogen. Three of the four proposed by geologists envisaged some form of basement reactivation at depth and were framed in the context of the then-topical subjects of basement–cover relationships of passive margin sequences and aulacogens. Moreover, from the perspective of the Grenville Province, all three were based on limited data: either the wholesale application of work largely carried out elsewhere, or using limited or generic data for the Grenville Province that were subject to more than one interpretation. The paleomagnetic interpretation, on the other hand, was based on a lot of data, but it later became apparent that they were not robust. All five models were results of creative big picture thinking in a plate tectonic context, but as several of the authors openly admitted they were speculative and lacked solid supporting evidence in the form of robust unequivocal field and analytical data. Moreover, for the student at the time, all were ultimately unconvincing because few specific criteria were advanced to test them, and as a result none was consistently followed up or developed, or eventually laid the groundwork to subsequent understanding in a direct way. Verification of extensional flow in the orogenic hinterland and compressional flow near the orogen margins predicted by Wynne-Edwards' (1976) millipede model required criteria to characterize the two processes and kinematic analyses to determine flow directions, neither of which had been developed. Problems of dating paleomagnetic poles and thermal resetting were recognized in the late 1970s, thus rendering the principal sources of data in the models of Irving et al. (1974) and Baer (1977) suspect; and the inferred strike-slip character of the Grenville Front in Baer's (1977) shear zone model was not supported by later studies. Although a rift setting for rocks composing the Grenville Supergroup has been supported by later work, Baer's (1976) fixist aulacogen model bears only passing resemblance to the current inverted back-arc basin model, and it failed to gain traction because it was unable to provide a context for either the widespread volcanic units in the Grenville Supergroup, or for the subsequent subdivision of the Central Metasedimentary Belt into fault-bounded domains with distinct stratigraphy (Easton 1992). From the present vantage point, the generic LHO model of Dewey and Burke (1973) was closest to the mark, but the paucity of features that could be related to observations in the Grenville Province, and the speculative nature of both the crustal structure underlying the Tibetan Plateau and the petrogenetic processes operating within it made it difficult to apply in detail.

In summary, the fact that in the different models the pre-Grenvillian evolution of SE Laurentia was inferred to represent both passive and active margin settings, and that almost the whole gamut of possible bulk stress regimes was envisaged to explain the crustal structure formed during the Grenvillian Orogeny (i.e. predominantly compressional, transpressional, and extensional), emphasizes the low level of robust knowledge at the time and the speculative basis of all of the interpretations. This is underlined by the fact that each model was developed independently and bore little relationship to the others, and that none could be readily tested or written off without additional information. Collectively they are perhaps of most interest today as witnesses to a brief exploratory period in the application of plate tectonic principles to high-grade Precambrian terranes in which it was possible for creative individuals to publish hypotheses based on very limited information and an inversely large amount of speculation unsupported by robust constraints. In drawing this discussion to a close, it is pointed out that none of the conceptual models is believed to be correct in its entirety today, and that they were all 'parting shots', the last words their authors published about the evolution of the Grenville Province.

1980s and 1990s – The LITHOPROBE Years

The late 1970s ushered in what eventually turned out to be almost two decades of enhanced regional geological mapping, data collection and analysis by geological surveys in many parts of Canada, including the Grenville Province. Moreover, in the early 1980s, negotiations were completed for a novel collaborative program involving geoscientists in government and universities to undertake a program of deep crustal seismic reflection and refraction studies to image representative sections of the crust in the third dimension. Integral to the program were geological and geophysical (potential field) studies of bedrock in the vicinity of the seismic experiments to establish linkages between the imaged deep crust and the surface geology and produce an enhanced database to constrain interpretations.

In many ways, the timing of the LITHOPROBE program, the offspring of the negotiations, could not have been better. By the late 1970s, the non-destructive, high-resolution, multichannel vibroseis technology was well established for shallow targets, and its extension to the deep crust was ready for extensive field testing. The required computational capacity to handle large datasets was available off-the-shelf for the first time, simultaneously permitting enhanced analysis of the seismic data and manipulation of other existing geophysical datasets (e.g. magnetic and gravity). In addition, in several sub-disciplines of earth sciences relevant to crustal studies, including structural geology, metamorphic petrology, geochronology, geochemistry, and tracer isotope studies, theory, databases and instrumentation had advanced to a stage that they could contribute quantitative information on geological processes for the first time. This significantly enlarged geological toolbox resulted in the production of many more constraints on which to base tectonic models. In the following sections, some of the major advances from this period of intense data-gathering are summarized.

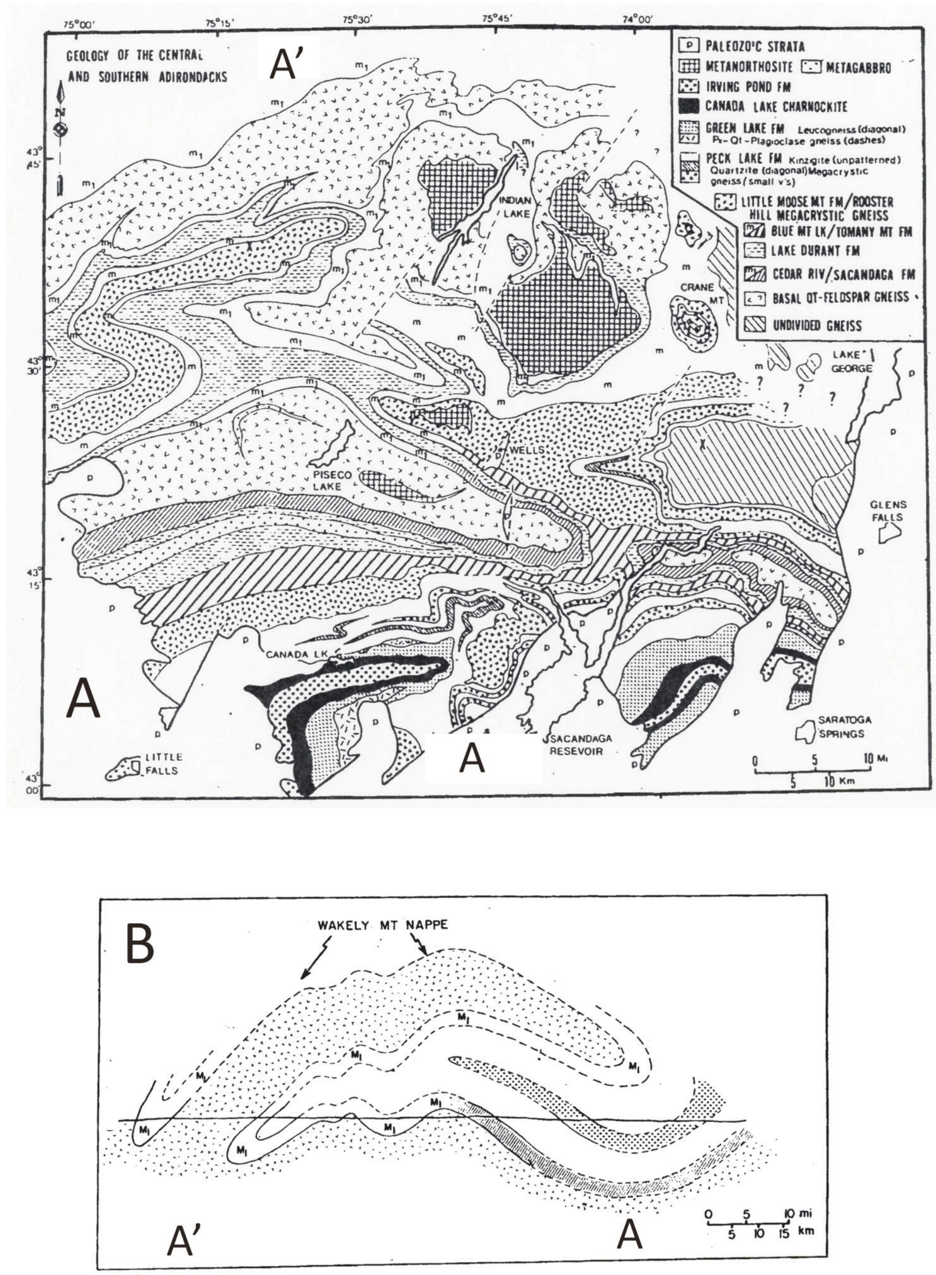
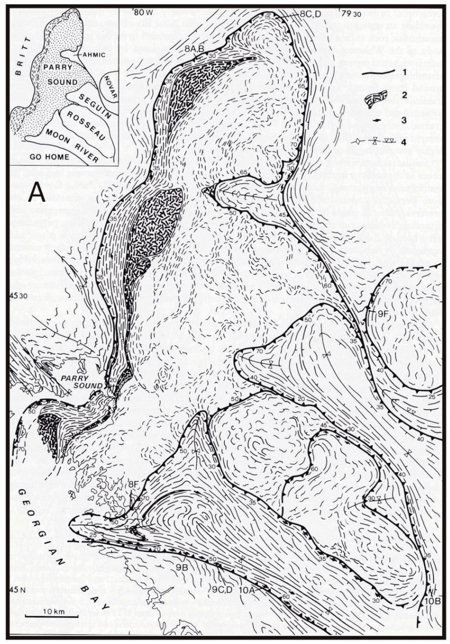


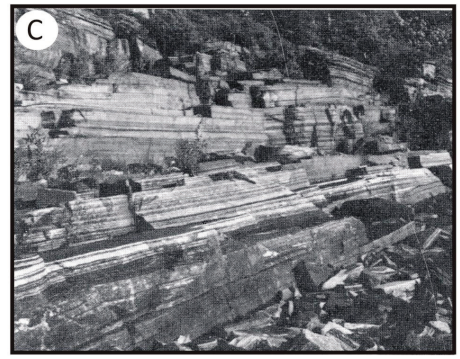
Figure 13. Map and generalized N–S cross-section of the southern Adirondack Highlands showing the pattern of fold interference and the interpretation of an E–W-trending, recumbent nappe composed of crystalline para- and orthogneisses of various compositions (from McLelland and Isachsen 1980). The gneisses were originally interpreted to comprise a supracrustal sequence above older basement. The grade of metamorphism is granulite to upper amphibolite facies, the nappe has an amplitude and wavelength of 10s of km and has been refolded by later upright structures.

Structural Mapping, Recognition of Terranes and Domains

As investigations of ductile structures in gneiss complexes became more extensive, the scale and extent of polyphase folding of gneissic layering became apparent. The first report of a regional-scale nappe in the Grenville Province was from the Adirondack Highlands (McLelland and Isachsen 1980; Fig. 13). The ~50 km amplitude of this granulite-facies structure provided an indication of the scale of deformation in the orogenic hinterland. Initially, following the lead of Buddington (1939, 1956), the folded units, although gneissic, were interpreted in stratigraphic terms as a conformable supracrustal succession overlying basement (see formation nomenclature in map legend). The tectonic significance of the structure was only understood later, following recognition that: (i) contacts between the 'supracrustal' units were tectonic and the 'stratigraphy' was in fact a thrust stack assembled during the pre-Grenvillian Shawinigan Orogeny; (ii) the 'basement' ('basal quartz-feldspar gneiss' in Fig. 13) in the antiformal core of the nappe was a syn-Shawinigan intrusion that promoted granulite-facies metamorphism and pervasive anatexis; and (iii) subsequently both the intrusion and its host rocks were deformed together during the high-grade Grenvillian Orogeny, leading to the regional nappe and associated mylonitization and formation of the well layered gneiss complex ('straight gneiss', see below) that had been misidentified as metasedimentary rocks. For most authors this profound reinterpretation, involving the superposition of two high-strain events under granulite-facies conditions, represented the final demise of stratigraphic reasoning and the basement–cover concept as appropriate paradigms for unravelling gneiss terranes. A modern tectonic interpretation of the map shown in Figure 13 can be seen in McLelland et al. (2013).

In this context, one of the seminal achievements of the 1980s was the development of new techniques for mapping the high-grade Grenvillian gneiss terranes, such that by the end of the decade, formerly intractable gneiss complexes were being subdivided into mappable units, their structure interpreted in three dimensions, and their value as information repositories exploited. Another example of this progress comes from the southwestern Grenville Province in Ontario, the area that had caused contributors to 'The Grenville Problem' so much grief thirty years previously. Using foliation trend maps, the 'sea of gneiss' was first subdivided into large stacked imbricate panels (domains and subdomains) on the regional scale (Davidson 1984; Fig. 14A), and the domains themselves were then subdivided internally into mappable tectonic units termed 'gneiss associations' up to a few kilometres thick (Culshaw et al. 1997; Fig. 14B). Definition of the gneiss associations involved integration of a range of criteria, including age and tectonic character of rocks, structural and metamorphic history, and the presence of cross-cutting dykes. Using a comparable approach, although covering a much larger area and based on less detailed mapping, Gower (1996) subdivided the extensive high-grade gneiss complex in the Grenville Province of eastern Labrador (Fig. 15), and similar work was also done in adjacent eastern





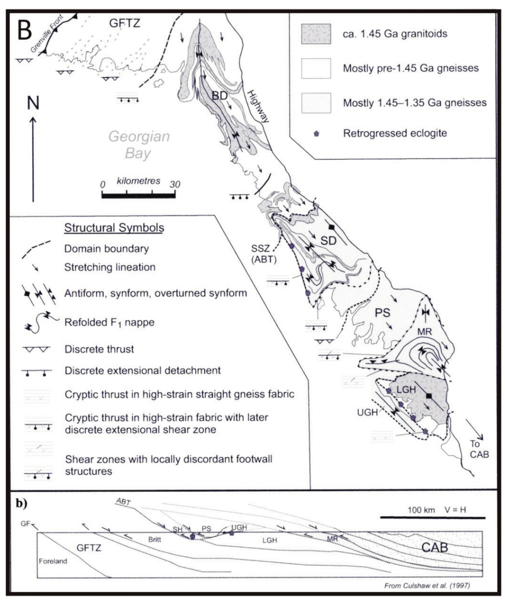


Figure 14. A: Foliation trend map for part of the Central Gneiss Belt (CGB) in the southwestern Grenville Province near Georgian Bay showing domains and subdomains outlined by shear zones (from Davidson 1984); B: Geological sketch map and NW–SE crustal-scale cross-section integrated with LITHOPROBE seismic data for the CGB along the Georgian Bay shoreline, showing major shear zones and the outcrop patterns of arc-related pre-Grenvillian granitoid units (from Culshaw et al. 1997); C: Field photograph of straight gneiss in the Parry Sound shear zone, originally interpreted as metasedimentary rocks (from Davidson 1984).

Québec (e.g. Gobeil et al. 2003). A key to all these studies was the recognition that the margins of domains and gneiss associations were zones of ductile 'straight gneiss' (Fig. 14C; Davidson 1984), tectonically layered gneiss formed by metamorphic differentiation at high grade in a regime of simple +/– pure shear and ductile recrystallization during the transport of mid and lower crustal domains and their assembly in a crustal-scale stack. Further, it was also recognized that in many cases attenuated mafic layers in the straight gneiss constituted the reflectors visible on deep crustal seismic reflection experiments, thereby providing a crucial key to interpreting the architecture of gneiss complexes in 3 dimensions. Although the concept of formation of tectonic layering by metamorphic differentiation on a cm scale was not new, recognition of its operation on a regional scale was transformational, especially given the history of the 'stratigraphic mindset' in which straight gneiss was commonly mapped as a supracrustal lithology, its well layered character being mistaken for relict bedding.

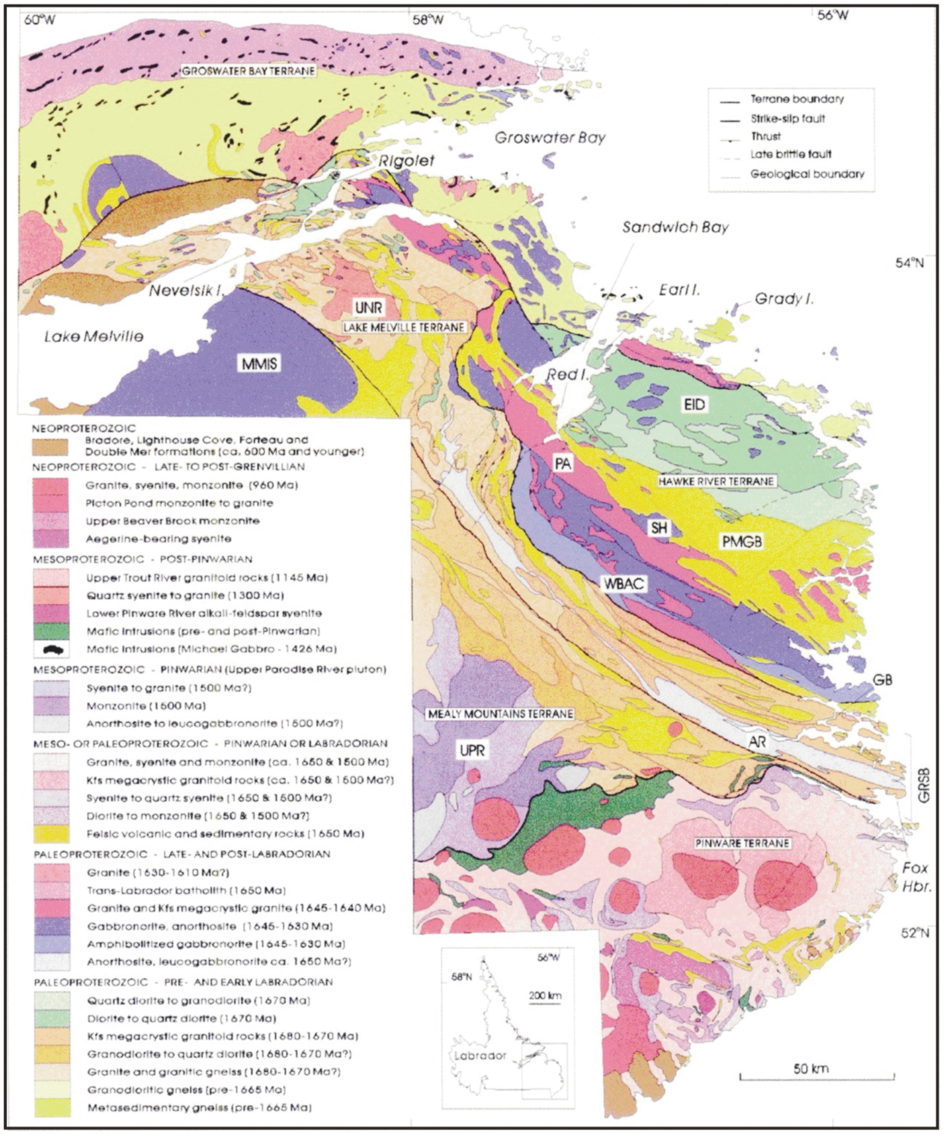


Figure 15. Geological map of the Grenville Province of eastern Labrador (from Gower 1996), showing the subdivision of the gneiss complex into many map units and their grouping into lithologically distinctive terranes separated by major high-strain zones. Most gneisses of Paleoproterozoic age were first deformed in the late Paleoproterozoic Labradorian Orogeny, a previously unknown orogenic belt almost completely included within the Grenville Province. Mesoproterozoic rocks in southeast Labrador interpreted to have formed in a Mesoproterozoic continental margin arc setting are referred to as Pinwarian. For additional details of lithologies characteristic of each terrane, see original source.

Recognition of the tectonic origin of layering in high-strain gneisses, and the common presence of asymmetric tectonic inclusions indicating very high strain, was accompanied by the systematic identification of kinematic indicators, an exercise that led to some seminal publications using Grenvillian examples (e.g. Davidson 1984; Hanmer 1988; Hanmer and Passchier 1991). Early studies of asymmetric kinematic indicators in the Grenville Province suggested that the shear zone boundaries between most domains were thrusts, supporting seismic evidence that the Grenvillian crust constituted a stack. However, in the more nuanced analyses that followed it became apparent that evidence for both thrust sense and normal sense displacement was present within many shear zones (e.g. a shear zone carried eclogite-facies rocks in its hanging wall, but exhibited kinematic evidence for extension; Culshaw et al. 1994, 1997), thereby providing the first evidence for reworking of thrust sense shear zones as normal faults and for post-thickening extensional spreading of the thickened crust.

Foreland and Hinterland

One major ductile shear zone, commonly defined by flaggy straight gneiss, was shown to be continuous along the length of the interior Grenville Province by Rivers et al. (1989). Named the Allochthon Boundary thrust (ABT), this upper amphibolite-facies structure is at least a kilometre wide in true thickness, dips gently southeast into the lower crust, and separates distinctly different lithotectonic packages in its hanging wall and footwall, implying it is the site of major transport. Recognition of the ABT provided the basis for a fundamentally new tectonic subdivision of the orogen into a Parautochthonous Belt adjacent to the orogenic foreland and overlying Allochthonous Belts in the hinterland (Fig. 16). The inferred long distance tectonic transport of 'allochthons' on the gently dipping ABT was contrasted with the stacking of more proximal units on the shear zone marking the Grenville Front (GF), and it was later shown that metamorphism in the hanging wall of the ABT was older than that in the hanging wall of the GF. This new interpretation of the crustal structure implied that the NNE-trending aeromagnetic lineaments in the shear zone model of Baer (1977), which occur on both sides of the ABT, were unlikely to be tectonically significant features. Another important feature of the ABT, discovered later, was that it also carried kinematic evidence for normal sense as well as reverse sense of motion (Culshaw et al. 1994; Ketchum et al. 1998), implying that it too had been reworked in extension after its formation.

Grenville Front and Parautochthonous Belt

During the same period, studies in several locations in the northwest Grenville Province confirmed the regional northwest vergence of the Parautochthonous Belt, revealed the lithological continuity of some units across the Grenville Front, and quanti-

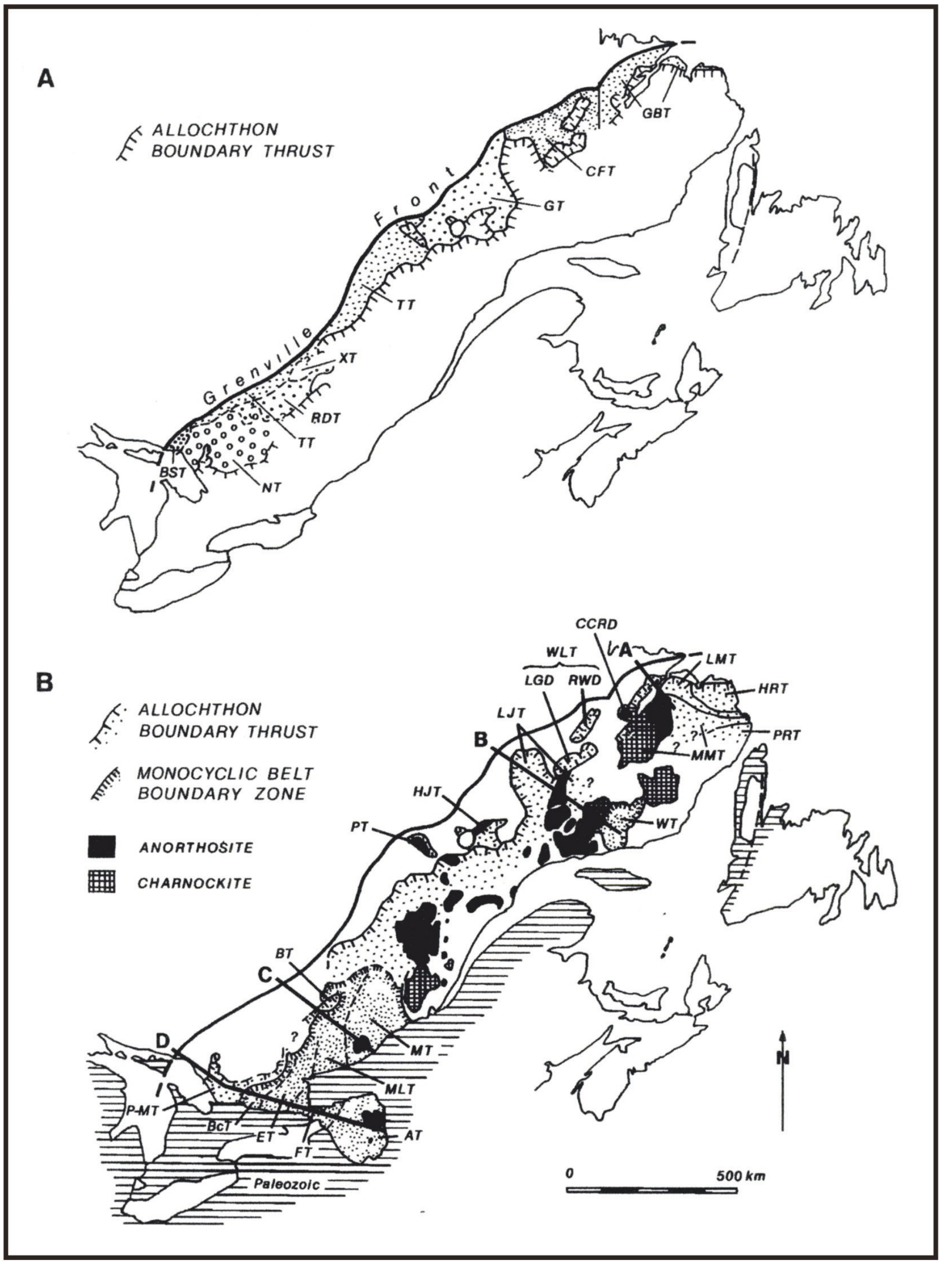


Figure 16. Tectonic subdivision of the Grenville Province into a parautochthonous belt structurally above the Grenville Front (shown in A), and a hinterland region composed of far-travelled allochthonous rocks structurally above the Allochthon Boundary Thrust (shown in B) (from Rivers et al. 1989). The subdivision was reinforced by later work that demonstrated the contrasting age and *P–T* character of the metamorphisms in the allochthonous and parautochthonous belts.

fied the increase in the pressure and temperature of Grenvillian metamorphism on its southeast side (e.g. Rivers 1983a, b; Owen et al. 1986; Daigneault and Allard 1994; Bethune 1997; Bethune and Davidson 1997). These data confirmed the lithological link with pre-Grenvillian Laurentia proposed by Wynne-Edwards (1972) and provided robust support for his contention that this part of the orogen represented a section of exhumed Laurentian crust, although with a strong Grenvillian overprint. Collectively these studies also defined the diverse structural manifestations of NW vergence in the Parautochthonous Belt, from crustal-scale shear zone (the GFTZ) to metamorphic fold and thrust belt. Moreover, evidence for significant strike-slip displacement was not found, thereby providing another line of evidence negating the shear zone model of Baer (1977).

Although the location of the ABT has been slightly revised since the initial proposal, subdivision of the orogen into parautochthonous and allochthonous belts remains a feature of all recent tectonic interpretations. In summary, it is not an exaggeration to state that the development and application of modern field mapping techniques and their integration with kinematic analysis in the 1980s and 1990s provided critical new insight into the crustal architecture and assembly of the Grenville Orogen.

Reflection Seismic Results

During the course of the LITHOPROBE program, four land-based deep seismic reflection experiments were conducted in the Grenville Province at high angles to the regional ENE structural grain, and two experiments involving marine seismic methods were shot over water at the western and eastern continuations of the province (in Lake Huron and the Labrador Sea). After processing, all transects yielded images of gently SE-dipping reflector packages in the upper and mid crust, some of which penetrated the full thickness of the crust, thereby reinforcing interpretations from surface mapping and illustrating more clearly than any previous dataset that the Grenville Orogen was composed of a stack of imbricate sheets. In several cases, reflectors could be connected to major shear zones at the surface, providing both confidence in the interpretations and information on the nature of the seismic reflectors themselves. In most transects a well-defined seismic Moho was imaged at about 40–45 km depth, but the underlying mantle generally lacked coherent reflections. One of the early transects from the foreland into the orogen (marine seismic line in Lake Huron; Green et al. 1988) provided a clear image of the Grenville Front (Fig. 17A), which was shown to be a crustal-scale structure underlying the 30 km thick Grenville Front Tectonic Zone defined by Wynne-Edwards (1972). The crustal structure of the orogenic hinterland is exemplified by a seismic line in western Québec (Fig. 17B), which illustrates internally imbricated, stacked packages of Proterozoic crust over 5 km thick transported up a crustal-scale ramp on the ABT; and the underlying parautochthonous Archean basement in the northwest of the orogen. Again, linkage of reflections with surface mapping provided confidence in the interpretations. This transect also shows a rise of the Moho at its northwest end, the first seismic evidence for late orogenic extensional thinning and crustal-scale collapse. The clear demonstration of the imbricate nature of the crystalline Grenville basement and the transported overlying sequences, although already suspected from surface mapping, implied that the deep orogenic structure was unlike that envisaged by Wynne-Edwards (1972, 1976), Dewey and Burke (1973), or Baer (1976, 1977). In summary, integration of surface mapping and seismic data provided the first constrained 3-D images of the architecture and assembly of the Grenville Province that underpins present understanding, and moreover some of the first images of the deep crust beneath an ancient LHO anywhere on Earth. Equally importantly, it provided a spatial context for sampling and analysis by other methods, as discussed in the following section.

Analytical Tools

Several analytical methods now taken for granted as part of the geologists' toolkit, including geochronology, thermobarometry, and various types of geochemical and isotopic analysis, first became widely available in the late 1970s and 1980s. All have undergone significant refinement subsequently, but the focus here is on the impact of their introduction to understanding of the Grenville Province.

Geochronology

The arrival of practical U–Pb geochronology of zircon, monazite, and titanite had an enormous influence on regional geological studies worldwide and an immediate impact on understanding in the Grenville Province. In Canada, the trigger for this development was the establishment of a thermal ionization mass spectrometry (TIMS) laboratory at the Royal Ontario Museum in Toronto under the leadership of Tom Krogh following his decade-long apprenticeship refining the analytical protocol at the Carnegie Institute in Washington. By collaborating closely with field geologists in the Grenville Province and elsewhere, Krogh and a stable of graduate students and PDFs produced a tidal wave of age determinations of unprecedented precision for the crystallization of igneous units and the timing of high-grade metamorphism. For the first time, and in a manner impossible with the earlier Rb/Sr method, cryptic temporal relationships among units in gneiss complexes could be unravelled with considerable confidence. There is a case to be made that the impact of modern U–Pb geochronology was greater in the Grenville Province than in other orogens in Canada, in part because of the low level of prior knowledge and the cryptic nature of many units due to polyphase deformation and high grade metamorphism, but also because sampling was carefully integrated with the ongoing new mapping throughout the orogen, enhancing the impacts of both. In any event, in a relatively short time some key features of the lithologic make-up of the orogen came into focus, including the extent of reworked Archean crust, the existence of a previously unknown late Paleoproterozoic orogeny within the eastern Grenville Province (the ~1660–1610 Ma

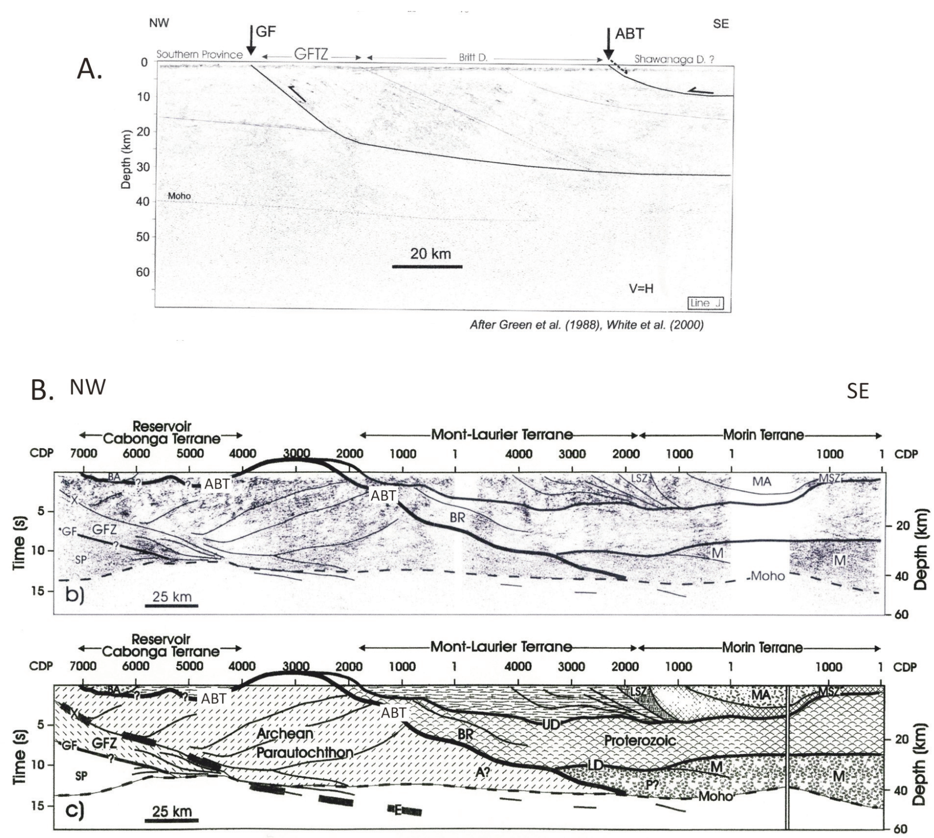


Figure 17. Examples of the results of deep seismic experiments in the Grenville Province undertaken during the LITHOPROBE program. A: GLIMPCE J profile across the Grenville Front and northern Grenville Province in southwest Ontario (after Green et al. 1988, White et al. 2000). B: Lines 52–54 in western Québec (after Martignole and Calvert 1996; Martignole et al. 2000). In A, the seismic responses of the Grenville Front (GF) and straight gneiss in the Grenville Front Tectonic Zone (GFTZ) are clearly imaged. In B, the southeast extent of Archean crust and the location of the Allochthon Boundary Thrust (ABT) in this part of the orogen are defined, and the scales of imbricated packages of the structurally overlying Proterozoic crust are delineated. Rise of the Moho near the northwest end of the seismic line (where intersected by thick dashed line) was interpreted as evidence for late-orogenic, crustal-scale extension. BR – Baskatong ramp; LD and UD – lower and upper detachments.

Labradorian orogeny; e.g. Gower 1996), the Paleoproterozoic to Mesoproterozoic (~1650–1400 Ma) age of many granitoid gneiss complexes in the hinterland of the orogen that formed in an arc setting (see later), and the <1400 Ma age of 'accreted terranes' in the southwestern hinterland (e.g. Easton 1992; Corrigan et al. 1994; Carr et al. 2000; McLelland et al. 2010, 2013). Map and cross-sectional views illustrating present understanding of the age distribution of crust in the Grenville Province that resulted from these studies are shown in Figure 18 (from Rivers et al. 2012; after Ludden and Hynes 2000). Cumulatively these data rendered all previous tectonic interpretations of the Grenville Province untenable. Moreover, in addition to the protolith ages of its component parts, the ~1090–980 Ma age range of peak Grenvillian metamorphism was revealed, implying the ~110 M.y. duration of the Grenvillian Orogeny.

At the same time, another geochronological technique, $^{40}Ar/^{39}Ar$ analyses of hornblende, muscovite and biotite, was providing a database of 'apparent ages' relating to the time of cooling through ~500°C, 350°C and 300°C respectively (e.g. Cosca et al. 1991, 1992). Overall, when excess argon ages were discounted, these supported the preliminary conclusions of Harper (1967) based on the K/Ar method that post-orogenic cooling was fast in the foreland near the Grenville Front, but anomalously slow in the hinterland where isotopic closure in some areas did not occur until 950 Ma, some 80–100 Ma after the metamorphic peak. However, some anomalies to this regional pattern were discovered in the hinterland, e.g. hornblende ages of ~1215 Ma in the eastern Grenville Province (Reynolds 1989) and clusters of hornblende ages of >1100 Ma in the southwest (Cosca et al. 1992). Since these apparent ages predated the Grenvillian Orogeny, they implied that parts of the orogen had not been heated above ~500°C in that event. The significance of this finding was not readily understood at the time, leading some to question the data and others the very existence of the Grenvillian Orogeny, but the data proved to be robust and in the longer run they paved the way for the identification of the orogenic lid (see later).

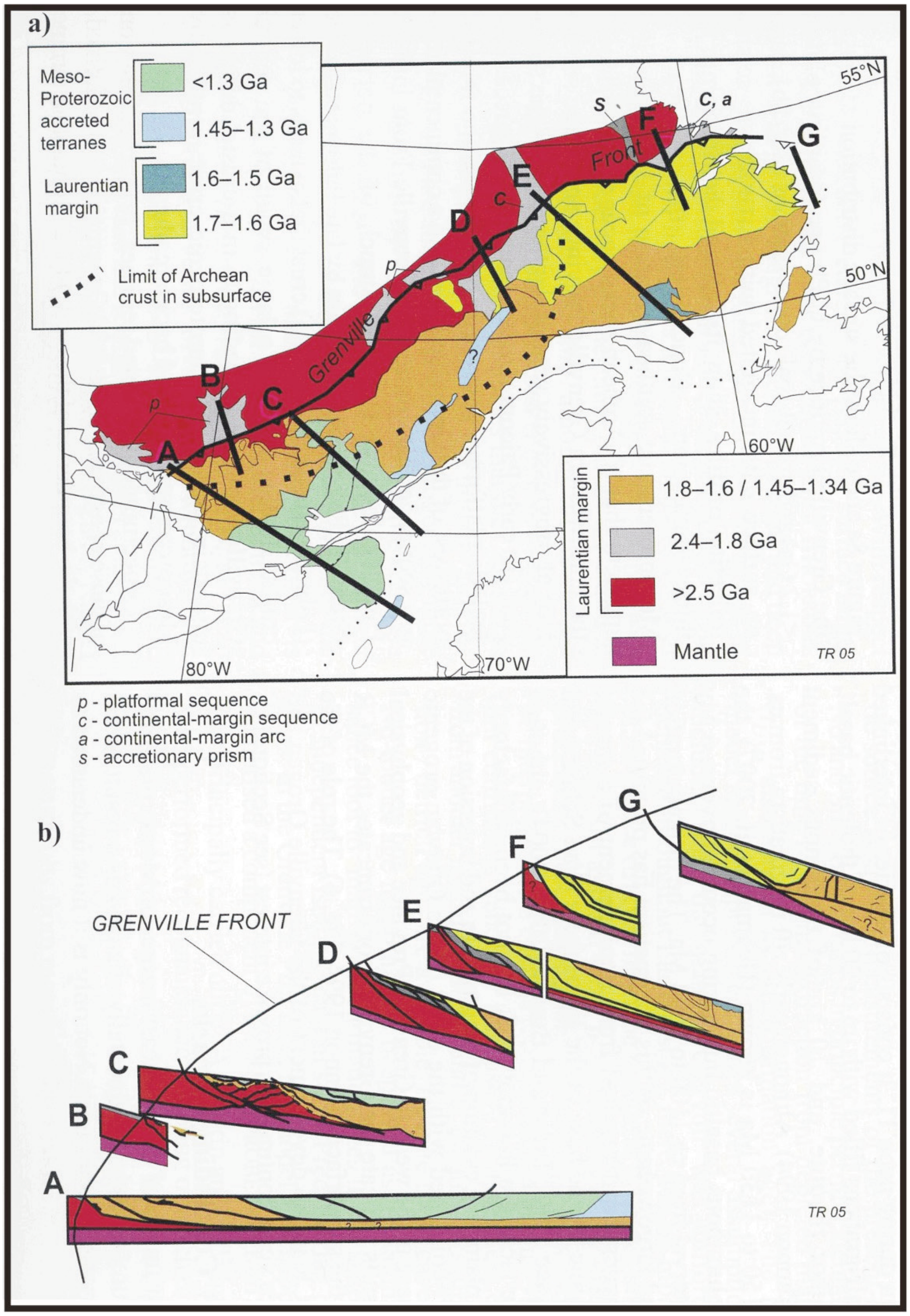


Figure 18. Schematic map and cross-sections showing distribution of rocks by age: (a) at the surface, and (b) projected / inferred at depth on LITHOPROBE and other deep-crustal seismic sections (from Rivers et al. 2012). Note that Archean crust (red) is only present at depth beneath the central Grenville Province and thins markedly towards the southeast. Yellow represents Labradorian crust reworked within the Grenville Province. Orange represents rocks formed within or associated with the Mesoproterozoic continental margin arc, light blue represents accreted Mesoproterozoic island arc terranes, and light green is the <1.4 Ga back-arc terranes that formed behind the continental margin arc and were subsequently re-accreted to Laurentia prior to the Grenvillian Orogeny.

Geothermobarometry

By the late 1970s thermodynamic data sets for the end-members of many common rock-forming minerals and the parameters for mixing models in solid solution phases had been estimated, making the quantitative *P*–*T* determination of metamorphic conditions a much more accessible undertaking. Moreover, it quickly became apparent that the high-grade rocks of the Grenville Province provided an ideal location in which to field-test calibrations. Those who both calibrated thermometers and barometers and tested them in the Grenville Province included Eric Essene and his many co-workers (e.g. Bohlen and Essene 1977, 1980; Essene 1982; Perkins et al. 1982; Bohlen et al. 1985; Anovitz and Essene 1990; Tuccillo et al. 1990), and Indares and Martignole (1984, 1985). Geothermometry on upper amphibolite- and granulite-facies gneisses in the Grenville hinterland revealed temperatures in the range 700 ± 50°C or higher, a not unexpected result although subsequently shown to commonly underestimate peak *T* due to post-peak resetting (the granulite uncertainty principle; Frost and Chacko 1989). However peak pressures were less readily predicted from mineral assemblages and determinations of 1000 ± 100 MPa for many samples in the gneiss complexes implied formation depths of ~25–30 km. Some early interpretations of the *P* and *T* data were carried out by regional contouring (e.g. Fig. 19), an approach that was quickly abandoned following recognition that it was incompatible with the stacked crustal architecture and ignored the age of the metamorphism. Relict eclogite was first recognized in the western Grenville Province by Davidson (1990) and the first thermobarometric studies of eclogite and associated high-pressure granulite, from a thrust sheet stack in the central Grenville Province, revealed peak *P*–*T* around 1800 MPa and 800°C (Indares 1993). This was the first quantitative *P*–*T* evidence for the former existence of double thickness crust (≥50–60 km) in the orogen. Moreover, the signal of high *T* (≥800°C) at these depths is distinct from that of eclogite formed in a subduction zone setting, the data thereby defining a previously unsuspected setting for eclogite formation at the base of double thickness crust under an orogenic plateau.

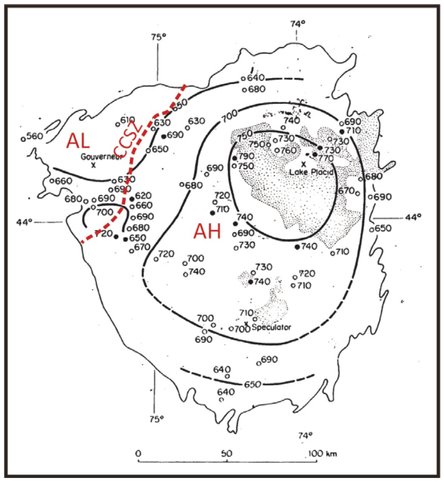


Figure 19. Contoured peak metamorphic temperatures in the Adirondacks estimated by various geothermometers (modified after Bohlen and Essene 1980). AH – Adirondack Highlands terrane, AL – Adirondack Lowlands terrane, CCSZ – Carthage–Colton shear zone. A first attempt at data presentation, the contouring ignored the stacked nature of the crust and the presence of the CCSZ, a major tectonic boundary. In addition, more recent work has shown that metamorphism in AH is Ottawan, whereas that in AL, part of the Ottawan Orogenic Lid, is pre-Grenvillian (Shawinigan).

Geochemical and Isotopic Petrology

Several geochemical, petrogenetic and isotopic techniques were also first widely used in the Grenville Province during this period. These studies were to some extent experimental, as it was unclear at the time whether igneous petrogenetic signatures could survive the effects of regional metamorphism. Early examples included the application of whole rock major and later trace element geochemical analysis to greenschist- and amphibolite-facies mafic rocks in the Central Metasedimentary Belt (e.g. Holm et al. 1985, 1986; Davis and Bartlett 1988; Smith and Holm 1990a, b), which showed that the primary geochemical signatures were preserved and led to recognition of tholeiitic and calc-alkaline magmas. These results, when combined with map distributions and geochronological data, provided the evidence to define the opening and closing stages of a short-lived back-arc basin. Comparable geochemical studies in the high-grade gneiss complexes led to recognition of the calc-alkaline character of widespread 'grey gneiss' (tonalitic, dioritic and granodioritic gneiss, commonly with amphibolite dykes and mafic enclaves), and the A-type character of associated 'pink gneiss' (granitic to monzonitic gneiss) (e.g. Dickin and Higgins 1992; McLelland et al. 1993; Corrigan and Hanmer 1995, 1997; Slagstad et al. 2004). Again, when integrated with geochronological data, these provided the basis for interpretation of a long-lived continental margin arc and associated back-arc (i.e. active margin) on southeast Laurentia from the late Paleoproterozoic and throughout much of the Mesoproterozoic.

Whole rock isotopic analysis of Nd in the Grenville Province was pioneered by Alan Dickin. As a result of a data collection program throughout the province spanning more than two decades, Dickin and co-workers have shown that grey orthogneiss can be 'mapped' into domains of different depleted mantle (T_{DM}) model age inferred to represent discrete times of magma extraction from the mantle (e.g. Martin and Dickin 2005; Dickin et al. 2010; Fig. 20). The data were interpreted to indicate periodic juvenile crustal additions in a continental margin arc through either arc magmatism or tectonic accretion.

Thus both geochemical and isotopic techniques, and their integration with the results of U–Pb geochronology and regional mapping, supported the interpretation of an active margin on SE Laurentia during the Mesoproterozoic. This result was a major conceptual breakthrough, permitting not only tectonic linkage with Paleo- and Mesoproterozoic active margin tectonics elsewhere in southeast Laurentia, but also finally severing the hold of the basement–cover / passive margin mindset that had persisted for so long.

AMCG Complexes

Igneous massifs consisting of anorthosite, mangerite, charnockite, and granite form intrusive complexes that are a signature element of Mesoproterozoic crust and particularly abundant in and adjacent to the Grenville Province. Some are enor-

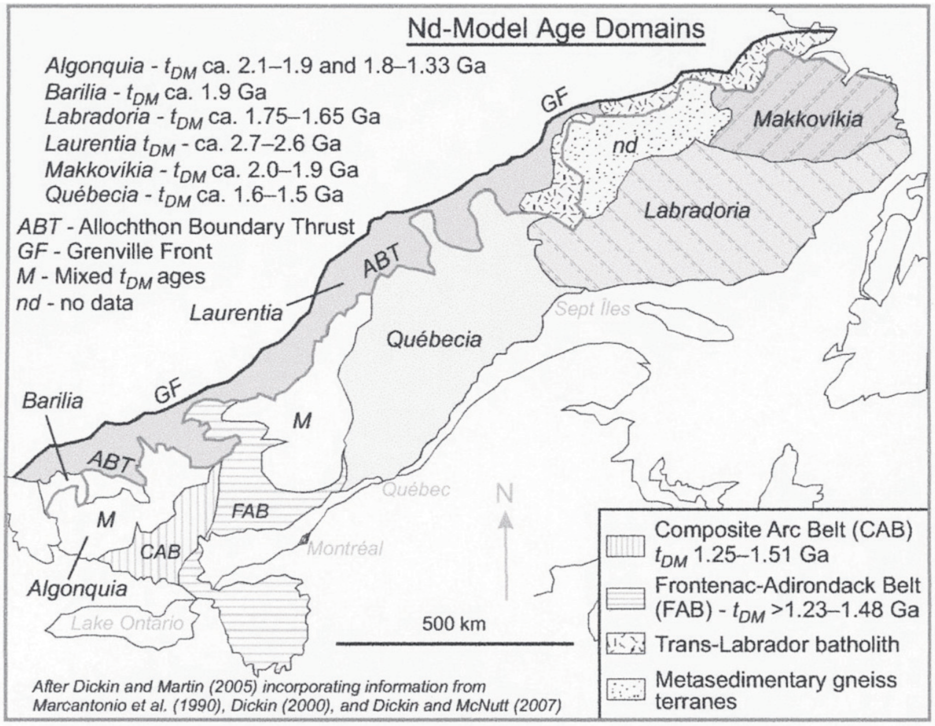


Figure 20. Nd model age map showing limits of model age domains for the Grenville Province (redrawn from Martin and Dickin 2005). The different model age ranges of the domains are compatible with crustal growth and accretion of juvenile crust in an active margin setting.

mous, with surface areas of the anorthosite component alone exceeding 10,000 km^2 at the current level of erosion. Critical insight into the petrogenetic origin of this volumetrically important, but enigmatic association of mantle- and crust-derived magmas, essential to understanding the pre-Grenvillian history of SE Laurentia, was achieved by Ron Emslie as a result of studies of AMCG massifs both in and adjacent to the Grenville Province. In a seminal paper that integrated field mapping, geochemistry and isotopic analysis, Emslie (1978) not only contributed to the definition of the AMCG lithological association and recognized the link with rapakivi granite suites, but also proposed a novel petrogenetic hypothesis for its formation. His proposal that the anorthosite components of the complexes originated by fractional crystallization of large, mantle-derived mafic magma bodies at the base of the crust that were subsequently injected as a crystal mush into the mid-crust, and that the associated granitoid rocks were crustal melts, has stood the test of time (e.g. Ashwal 1993). Recent debate has shifted to the tectonic setting in which AMCG complexes formed, geochemical arguments concerning the degree of involvement of continental crust and hydrous fluid in the magma chamber that fractionated anorthosite, and the significance of a compositional duality between labradorite anorthosite and andesine anorthosite complexes (e.g. Owens and Dymek 2001; Bédard 2010; Vander Auwera et al. 2011). Dating of AMCG complexes in and adjacent to the Grenville Province has shown that they crystallized over a period of >600 M.y. (from ~1620–980 Ma), thereby invalidating key aspects of the collision model of Dewey and Burke (1973) and the millipede model of Wynne-Edwards (1976). Consistent with this and overturning some previous interpretations, pre-Grenvillian anorthosite bodies are strongly, but heterogeneously, deformed (e.g. Martignole 1969; Martignole and Schriver 1970; McLelland and Isachsen 1980; Gobeil et al. 2003; Hébert et al. 2005). Moreover, the >600 M.y. age span for the crystallization of AMCG complexes implies that they were likely emplaced in more than one tectonic setting (e.g. back-arc rift and late- to post-orogenic settings; Corrigan and Hanmer 1997; McLelland et al. 2010; Rivers et al. 2012), the critical common factor inferred to be the arrival of a large volume of asthenospheric magma at the base of the continental crust where it can undergo the deep-seated fractionation envisaged by Emslie (1978). McLelland et al. (2013) have emphasized that emplacement of several AMCG massifs followed shortly after crustal thickening and the peak of metamorphism, leading them to suggest that delamination of an overthickened crustal root and associated decompression melting of rising asthenosphere were important mechanisms in the emplacement process.

Achievements of the LITHOPROBE Years – A Retrospective Summary

The three decades after 1970 were a time of intensive primary data gathering throughout the Grenville Province, much of which was mapped at 100,000 scale or greater for the first time, and by the end a new 1: 2,000,000 scale map showing the distribution and ages of Grenvillian gneiss complexes throughout the province was compiled (Davidson 1998). A major outcome of this work was the recognition that the Province contains a record of voluminous Paleo- and Mesoproterozoic continental margin arc and associated back-arc magmatism, thereby prompting a fundamental revision of the earlier passive margin hypotheses. Of equal significance, the revised interpretation of a long-lived continental margin arc and associated back-arc settings on SE Laurentia was readily correlated with new data emanating from central and western Laurentia (Hoffman 1989). For instance, the ~1650 Ma accretionary Labrador Orogen in the eastern Grenville Province has a counterpart of similar age and tectonic style in the Mazatzal Orogen of the SW USA (Gower et al. 2008), and the chemistry and age of the 1.5–1.34 Ga gneisses in the Grenville Province have been correlated with arc and back-arc rocks in the Granite–Rhyolite Province, SE USA (Tucker and Gower 1994; Slagstad et al. 2009; Fig. 21). These correlations supported evidence for the reworking of older Laurentian crust in the southeast Grenville Province during the Grenvillian Orogeny, thereby

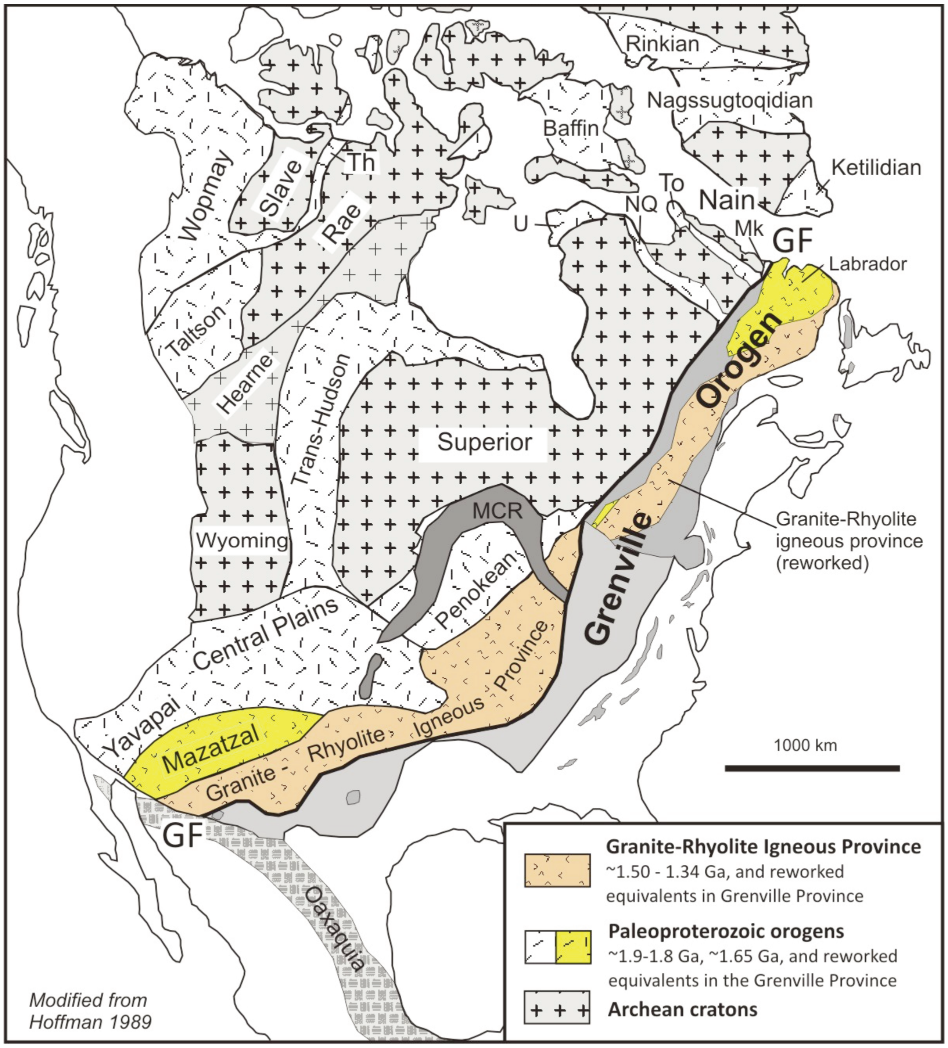


Figure 21. Proterozoic tectonic provinces of North America beneath Phanerozoic cover (from Rivers et al. 2012, after Hoffman 1989). Recognition that much of the Grenville hinterland consisted of reworked rocks of the Mesoproterozoic Granite-Rhyolite Igneous Province permitted the establishment of a robust linkage with Precambrian units in the central and southwest of the continent. Note also that the accretionary late Paleoproterozoic Labrador Orogen, which was almost entirely reworked within the eastern Grenville Province, is of similar age to the accretionary Mazatzal Orogen in the SW USA.

negating the paleomagnetic model of Irving et al. (1974).

Commensurate with this new understanding of an active margin was the identification of an accreted Mesoproterozoic island arc within the Grenville Province (the 1.45 Ga Montauban terrane; Bernier and MacLean 1993; Corrigan and van Breemen 1997; Sappin et al. 2009), and the re-interpretation of the northern Central Metasedimentary Belt of Wynne-Edwards (1972) from a passive margin setting to a collage of several accreted arc and back-arc terranes (Easton 1992), including the recently recognized remnants of an ophiolite complex (Chiarenzelli et al. 2010). This re-evaluation, which suggests a tectonic setting comparable to the modern Japan Sea (Easton 1992), led to its renaming as the Composite Arc Belt (CAB) by Carr et al. (2000). In addition, the discovery of metavolcanic rocks that formed in the upper parts of the Mesoproterozoic continental margin arc (Ratcliffe et al. 1991; Wodicka et al. 2004; Corriveau and Bonnet 2005) implies that both shallow and deep levels of the arc are preserved. These interpretations exemplify the profound changes in perception of both the pre-Grenvillian history of SE Laurentia and the origin of the arc-derived Grenvillian gneiss complexes, formerly regarded as 'basement'. A schematic plate tectonic model of pre-Grenvillian active margin tectonics based on these interpretations and incorporating extensive geochronological and geochemical data, is shown in cross-section and map views in Figure 22A–B (from Wasteneys et al. 1999; McLelland et al. 2010).

Two other new sources of information became available during this period. Re-mapping and associated geochemical and geochronological analyses of several Grenvillian inliers in the southern Appalachians and Texas was advanced to the stage that comparisons could be made with data from the Grenville Province. These results suggested a high degree of continuity of major tectonic features, such as the ages of the pre-Grenvillian accretion and the timing of the Grenvillian Orogeny, along the 5000 km of exposure in North America (e.g. Mosher et al. 2004, 2008; Tollo et al. 2004; McLelland et al. 2010, 2013; Rivers et al. 2012), and hence that it comprised a single orogen.

A second new source of information that was becoming increasingly robust was the combination of dated paleomagnetic poles and geodynamic modelling for Mesoproterozoic units from around the world that suggested the Grenville Orogen formed at the centre of a late Mesoproterozoic to early Neoproterozoic supercontinent, named Rodinia. The hypothesis emerged in several independent proposals in the early 1990s (McMenamin and Schulte-McMenamin 1990; Hoffman 1991; Moores 1991; Dalziel 1992), and has been extensively tested by paleomagnetic methods. Although the precise configuration of Rodinia remains uncertain, its existence is now widely considered plausible (e.g. Evans 2013). The outcome of an international effort to produce a robust paleomagnetic reconstruction of Rodinia, elaborated in a UNESCO– IGCP Project, placed the Amazon, Rio de la Plata, and Kalahari cratons opposite the 5000 km length of Laurentia (Fig. 23; after Li et al. 2008), with the Sunsás Orogen being the counterpart to the Grenville Orogen in northeast Laurentia.

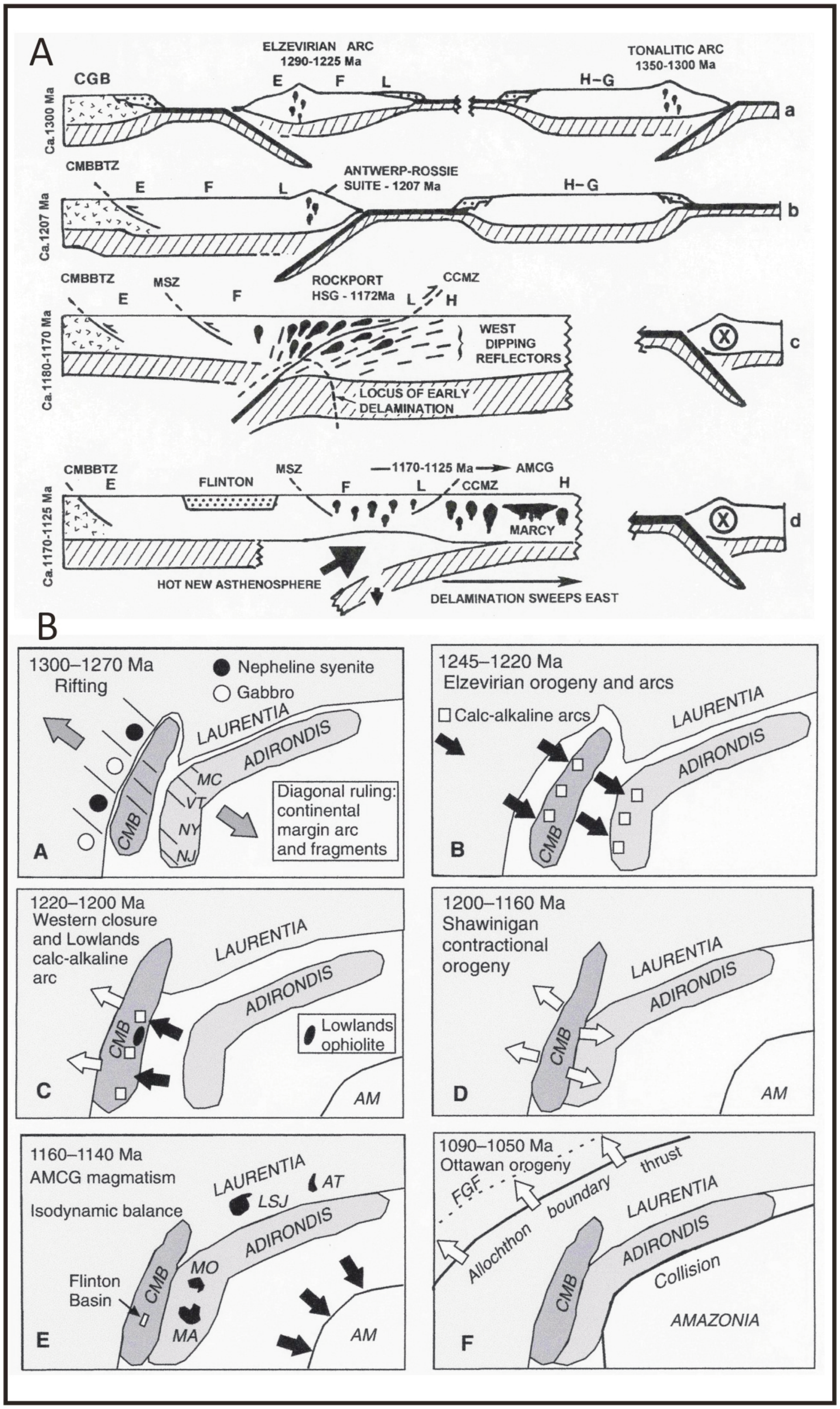


Figure 22. Plate tectonic models for the pre-Grenvillian and Grenvillian evolution of the SE margin of Laurentia, A: Cross-sectional view (from Wasteneys et al. 1999); B: Map view (from McLelland et al. 2010). The proposed pre-Grenvillian tectonic evolution involves back-arc rifting, followed by back-arc closure and re-accretion to Laurentia with associated ophiolite obduction, and later emplacement of large AMCG complexes. The proposed Grenvillian evolution involves collision leading to orogen widening, and possibly delamination of a thick lithospheric root.

By the year 2000 the data-gathering phase of the LITHOPROBE program was winding down, setting the stage for a comprehensive synthesis of the large volume of available data. At about the same time two new independent sources of information became available, the tentative location of the cryptic suture in the orogen, and numerical forward modelling of orogenesis. These, both individually and collectively, have provided great insight into the development of the Grenville Orogen and are discussed in the next section.

Progress in the 21st Century

The Cryptic Grenvillian Suture

Geological evidence that rocks of Laurentian affinity occur on both sides of the Grenville Front and the Allochthon Boundary Thrust, the two major crustal scale shear zones in the Grenville Province, implies that all exposed crust in the province developed on or close to Laurentia. This conclusion is also supported by Nd and Pb isotopic studies, and indicates the orogen was very wide. Thus the lack of a collisional suture within the contiguous Grenville Province, first inferred by Wynne-Edwards (1972) and a feature in the model of Baer (1977), has been upheld by subsequent work. A recent breakthrough has been the tentative identification of the collisional suture in the Grenvillian inliers in the southern Appalachians using whole rock Pb isotopic data. Following earlier work (Sinha et al. 1996; Tosdal 1996; Sinha and McLelland 1999), Loewy et al. (2003) showed that the whole rock lead signature of Laurentian crust from Labrador to Texas, including the ≤1.3 Ga accreted terranes of the CAB, defines an array on an uranogenic lead plot that lies below the average crustal evolution curve defined by Stacey and Kramers (1975) (Fig. 24). On the other hand, samples from Grenvillian inliers in the SE Appalachians define a more ^{207}Pb-rich array that overlaps with Stacey and Kramers' (1975) crustal evolution line. Samples from Amazonia, which as noted above is the probable conjugate to Laurentia in the continent–continent collision (Fig. 23), also fall on this line, compatible with a common source. The tentative location

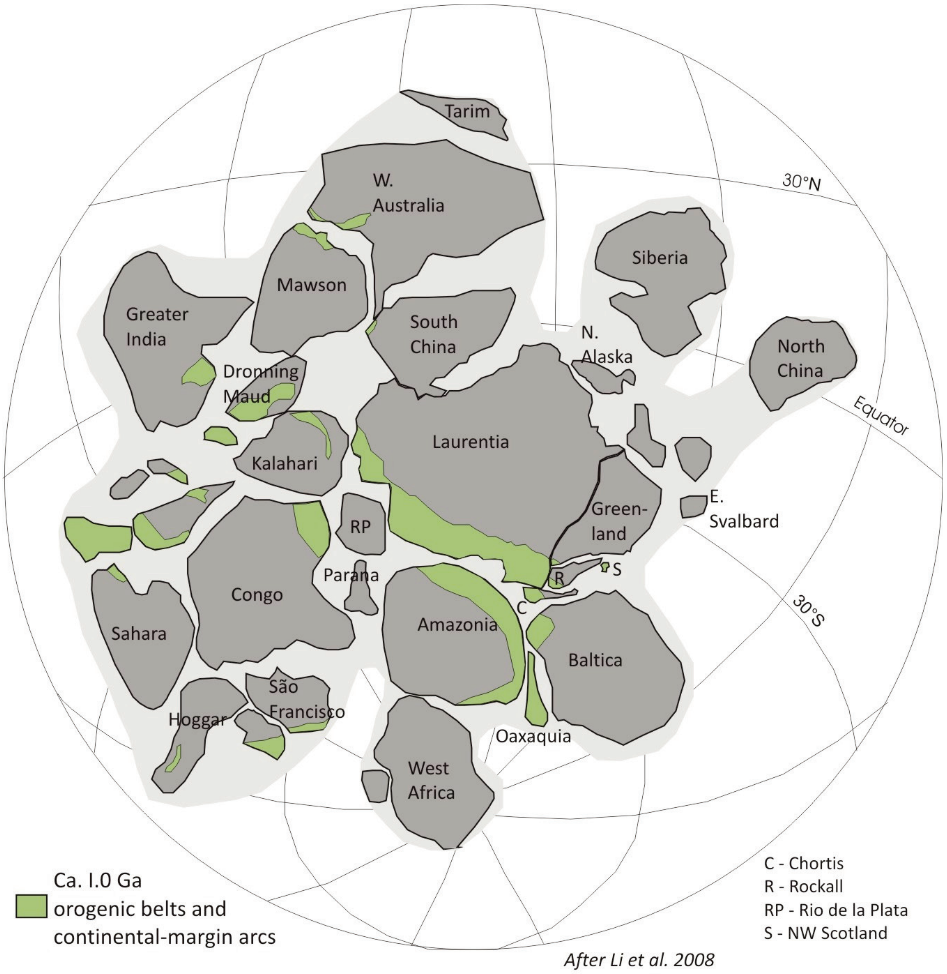


Figure 23. Rodinia supercontinent reconstruction, showing the ~1 Ga orogenic belts and continental margin arcs (green), with the Grenville Province at its centre (after Li et al. 2008, redrawn by Rivers et al. 2012). Note the interpretation that Laurentia and Amazonia were on opposite sides of the Grenville Orogen.

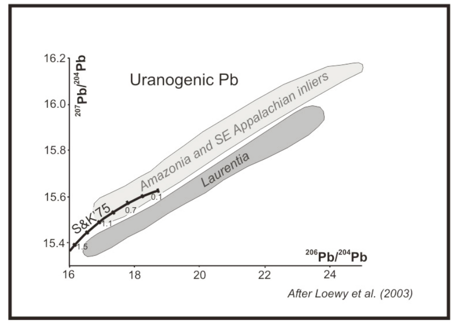


Figure 24. Uranogenic lead plot, $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$, showing fields with data for Laurentia (dark grey) and Amazonia (light grey) recalculated to an age of 1200 Ma (after Loewy et al. 2003). Samples from the Grenville inliers in the SE Appalachians overlap with the Amazonia field.

of the suture, based on the change in Pb isotopic signature, is shown in Figure 1 (from Hynes and Rivers 2010; see also McLelland et al. 2010, 2013; Rivers et al. 2012). This is an important result, providing the first quantitative evidence for a 'two-sided system' and hence that the Grenville Orogen developed in a collisional orogenic setting, a conclusion recently disputed on paleomagnetic grounds (Evans 2009). It reinforces previous interpretations that the orogen was very wide, being composed of ≥1000 km of Laurentian and peri-Laurentian crust alone at the southwest end of the Grenville Province, and thus compatible with a LHO. This preliminary result is also supported by data from South America. For instance, gneisses with 'Grenvillian' ages of peak metamorphism in the Precordillera terrane of western Argentina have a whole rock uranogenic Pb signature similar to Laurentia, leading to the interpretation that they represent the 'missing' piece of Grenvillian crust from south of the Ouachita Suture (see Fig. 1; Ramos et al. 1986; Dalziel et al. 1994; Tosdal 1996). Further, the Precordillera terrane is attached to the Arequipa–Antofalla terrane in Peru which has an uranogenic Pb signature similar to Amazonia (Tosdal 1996), providing independent evidence for the Amazonia – Laurentia collision in South America.

Model Orogens – The LHO Hot Nappe Model for the Grenville Province

The new millennium ushered in a new analytical tool – scaled 2-D thermal-mechanical forward modelling of crustal processes such as rifting and orogenesis. 1-D numerical models of heat conduction and fluid advection in a static crustal column were first published in the 1970s, and by the late 1990s the massively increased computing power made possible the construction of scaled 2-D models that employed a finite element grid to monitor the ductile strain, displacement and temperature of deformed crust in a rift or collision zone. In essence, the input parameters for the models are crust with specified physical properties, and the rate of plate convergence (crustal shortening), with the subsequent mechanical (i.e. structural) response of the crust being determined by its evolving rheological properties. The numerical code for these experiments typically incorporates the effects of changing *P*–*T* conditions on the bulk rock physical properties (i.e. rheology) over the temperature and pressure range of interest, and includes equations of state describing rock deformation using power law creep flow laws as a function of composition, temperature (geothermal gradient, internal radioactive heating), pressure (depth, fluid pressure), heat capacity, thermal conductivity, deformation mechanism, strain rate, etc. Later versions also allowed simulation of non-linear rheological weakening (e.g. initiation of partial melting, injection of melt), crucial in some orogens, and permitted the monitoring of *P*–*T*–*t* paths of individual crustal segments. In Canada, this research was led by Chris Beaumont with applications to the Grenville Province by Becky Jamieson, and these authors have recently published a summary of the current state of the science, including assumptions, limitations and ongoing issues (Jamieson and Beaumont 2013). By considering the physics of the orogenic process and analyzing orogens in terms of their evolving temperature and mass, the roles of individual variables could be evaluated, providing profound insight into the fundamental controls on orogenesis and to the general question of how orogens work. An early result was the recognition of two end-member types of orogen, referred to as small cold and large hot orogens (SCOs and LHOs; Beaumont et al. 2006; Jamieson and Beaumont 2013), the latter being characterized by a wide plateau in the orogenic hinterland underlain by double thickness crust. With respect to LHOs, which are not only large and hot, but also typically of long duration (Rivers 2008), quantitative estimation of the immense amount of crustal shortening–in the range of ~1000–2000 km–during the long collisional stage was transformational, offering a diametrically opposed interpretation to the earlier fixist view of orogeny. Moreover, the models led to much improved understanding of the contrasting evolution of different levels of orogenic crust, promoting the revival and redefinition of the 19th century terms 'infrastructure' and 'superstructure' (Culshaw et al. 2006). In addition, the proposal by Beaumont et al. (2001) with respect to the Himalaya–Tibet Orogen (HTO), the prototype LHO, that melting in the mid crust under the Tibetan Plateau coupled with rapid, monsoon-driven erosion at the Himalayan thrust front promoted gravity-driven, mid-crustal deformation by channel flow stimulated an intense re-evaluation of the active tectonics of the HTO, and possible implications for the Grenville Orogen were discussed by Jamieson et al. (2002, 2007, 2010). A numerical LHO experiment with relevance to the Grenville Province, known as the *LHO hot nappe model*, is shown in Figure 25 (after Jamieson et al. 2007). It is a modification of the LHO channel flow experiment for the HTO in that extrusion of mid-crustal material (simulating hot ductile crystalline nappes) is tectonically driven (piston analogy), in contrast to the gravity-driven flow of melt-saturated crust in the Himalaya–Tibet channel flow model, a consequence of the higher mean viscosity of the mid crust. However, in both experiments deformation is concentrated within the weak mid crust, which constitutes a 20–30 km wide high-strain 'channel' in which hot crustal segments from deep under the plateau undergo long-distance transport before exhumation at the orogenic front. Of particular significance to the Grenville Orogen regarding the experiment shown in Figure 25 are the long duration of the model collision (97.5 M.y.), the large amount of crustal shortening (1950 km), the simulated melt-weakening in the mid crust producing a non-linear reduction in viscosity, the entry of progressively stronger crust into the orogen that provides the tectonic driver (piston), and the formation and long distance transport of large, gently dipping crustal slices (hot nappes) from the mid and lower crust that are exhumed at the orogenic front, all features that resonate with observations in the Grenville Province.

More recently, numerical experiments have been carried out to simulate orogenic collapse (also referred to as gravitational collapse, extensional collapse, and gravitational spreading), the process that occurs when thick hot crust under the plateau in a LHO undergoes extension and thinning due to either gravitational potential energy or tensional plate tectonic forces (e.g. Rey et al. 2001, 2009; Vanderhaeghe and Teyssier 2001). An example is shown in Figure 26 (after Rey et al. 2009), in which the roles of extension rate and the degree of partial melting in the mid crust are evaluated. The larger scale of these latter models (compare Figs. 25 and 26) facilitates comparison with mapped crustal structures. Of particular relevance to the Grenville Province, as discussed in more detail below, are the necking (boudinage) of the brittle upper crust and the upward flow of ductile lower and mid crust into the boudin neck regions in these models.

In order to evaluate the significance of numerical experiments such as these for a particular orogen, it is necessary to have robust data with which to test them. Figure 25e (from Jamieson et al. 2007) shows that there is an acceptable first-order physical match of the crustal architecture of the western Grenville Province with the model orogen after 97.5 m.y. of elapsed model time. However, the number of variables in these models is large, rendering individual solutions non-unique. Hence each experiment should be extensively tested against natural data before being elevated to the status of a realistic approximation of reality. As discussed by Gervais and Brown (2011), the first steps in such testing require knowledge of the crustal architecture, the timing of peak metamorphism, the peak pressure (depth) and temperature at which crustal segments formed within the orogen, and their post-peak P–T–t evolution, as discussed further below. This comparative approach between *physical experiments of model orogens* constrained by numerical modelling and *conceptual models of orogens* constrained by empirical geological observations represents a new and increasingly informative way of tectonic analysis that is greatly improving insight and understanding.

Setting the Scene – Regional Syntheses

By the turn of the millennium, several syntheses had been published that provided quantitative information for the task of assembling a new conceptual tectonic model for the Grenville Orogen that could be tested against numerical experiments. These included interpretations of all the LITHOPROBE deep crustal seismic transects (Green et al. 1988; Forsyth et al. 1994a, b; Kellett et al. 1994; White et al. 1994, 2000; Eaton et al. 1995; Martignole and Calvert 1996; Gower et al. 1997; Hynes et al. 2000; Martignole et al. 2000), and a fence diagram with all the transects assembled in a single figure (Ludden and Hynes 2000), which provided the first constrained image of the crustal structure along the length of the province. In addition, regional syntheses that collectively covered most parts of the province had been published, i.e. for Ontario (Easton 1992), Québec (Hocq 1994),

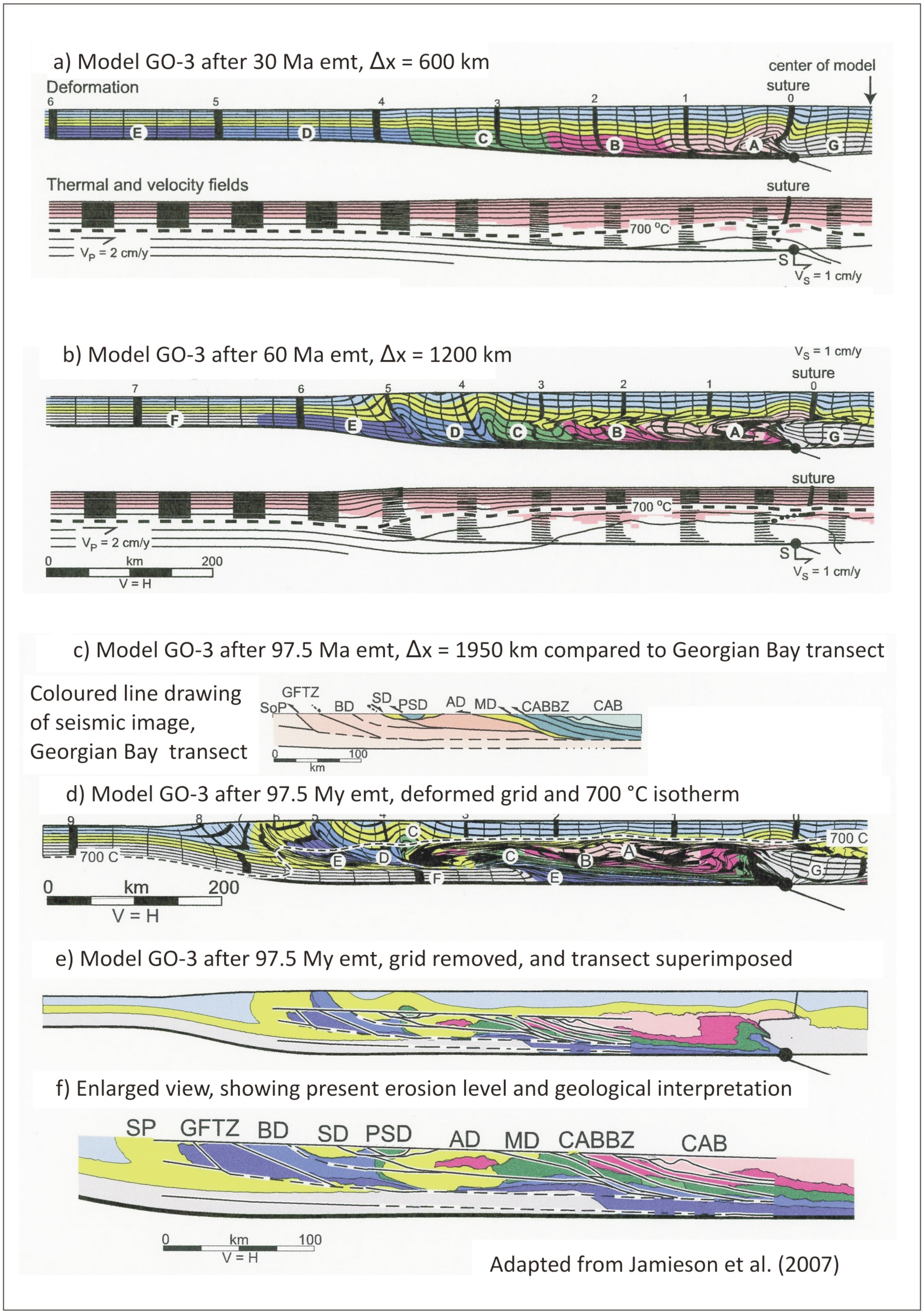


Figure 25. Crustal-scale numerical thermal-mechanical experiment of orogenesis in a LHO (model GO-3; adapted from two figures in Jamieson et al. 2007). (a-b) Crustal strain and isotherms after 30 and 60 M.y. elapsed model time (emt) and crustal shortening (Δx) of 600 and 1200 km respectively; (c) Crustal strain and isotherms after 97.5 M.y. emt (Δx = 1950 km); (d-e) Comparison of experiment after 97.5 M.y. emt with crustal structure imaged in the Georgian Bay seismic transect, southwest Grenville Province.

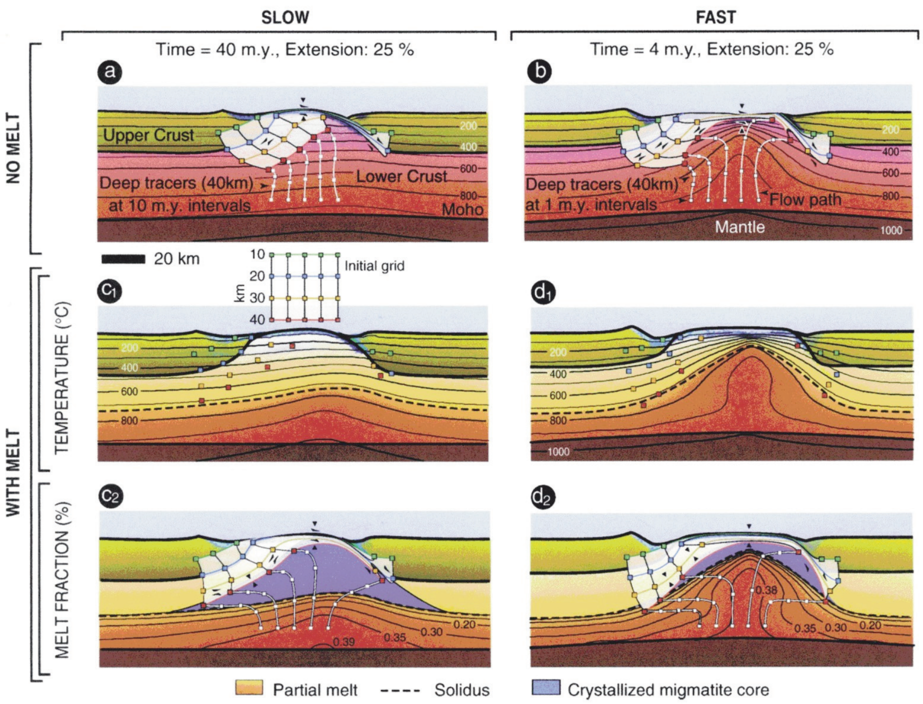


Figure 26. Crustal-scale numerical thermal-mechanical experiments of extensional collapse of LHOs (from Rey et al. 2009). All experiments show crust after 25% extension. The rate of extension varies from slow (over 40 M.y. emt) on left, to fast (over 4 M.y. emt) on right. Top row of figures is with no melt, bottom rows are with melt. Strain of initially rectangular grid, isotherms, and melt fraction are shown. In all experiments, the strong upper crust undergoes boudinage, and the ductile mid and lower crust flows upward into the boudin neck region, generating a crustal architecture resembling a core complex.

Labrador (Gower 1996), and the Adirondacks (McLelland et al. 1996), as were interpretations of the pre-Grenvillian tectonic evolution of SE Laurentia in the context of a continental margin arc and associated back-arc basins (Corrigan et al. 1994; Gower and Tucker 1994; McLelland et al. 1996; Corrigan and Hanmer 1997; Rivers 1997; Wasteneys et al. 1999; Rivers and Corrigan 2000). Other important syntheses included integrations of diverse datasets throughout the province in which the pre-Grenvillian history, Grenvillian stacking sequence, and *P–T–t* evolution were elucidated (e.g. Culshaw et al. 1997 and Carr et al. 2000 for SE Ontario; Corrigan and van Breemen 1997 and Martignole et al. 2000 for SW Québec; Indares et al. 2000 for central Québec; Gower and Krogh 2002, and van Gool et al. 2008 for Labrador); and a study of the distribution and tectonic significance of eclogite- and high-pressure granulite-facies rocks that were inferred to have developed at the base of double thickness crust (Rivers et al. 2002). Several of these studies explicitly noted the implied very large tectonic transport distances of lower and mid crustal rocks in the hanging wall of the Allochthon Boundary Thrust, supporting some form of LHO tectonic model.

Definition of the Grenvillian Orogeny

By the 1990s, it had become clear that the term Grenvillian Orogeny was being used in several mutually incompatible ways by different authors, creating the need for lengthy explanations to avoid confusion. Thus one of the aims of the LITHOPROBE synthesis was to provide a workable definition of the term. From a tectonic perspective it was deemed desirable to separate local pre-collisional accretionary events from the collisional Grenvillian Orogeny, despite the short time-gaps separating some of them. On the basis of the ages of metamorphic minerals, the Grenvillian Orogeny so defined has a span of ~110 M.y. (from ~1090–980 Ma; Rivers et al. 2012), compatible with a LHO. However, since the date of its initiation (1090 Ma) is based on the onset of high-grade metamorphism, the actual continent–continent collision must have started earlier, and followed almost directly on the heels of the accretionary Shawinigan Orogeny in the SW Grenville Province. A second issue, the recognition of systematic spatial and temporal variations in the effects of the Grenvillian Orogeny, led to its subdivision into two orogenic phases: the Ottawan phase principally restricted to the allochthonous terranes and domains in the hanging wall of the Allochthon Boundary Thrust, and the Rigolet phase in the parautochthonous terranes and domains in the hanging wall of the Grenville Front. A time chart with current usage is shown (Fig. 27; after Rivers et al. 2012). Both the ~70 M.y. duration of the Ottawan phase and the widespread distribution of Ottawan granulite-facies rocks in the orogenic hinterland are compatible with a LHO.

P–T Conditions of Grenvillian Metamorphism, Baric Subdivision of the Orogen, Post-Peak Extension, and Definition of the Ottawan Orogenic Lid

Although long known for its high-grade metamorphic signature, it was not until 2000 that a substantial *P–T* and associated geochronological database had been assembled throughout the Grenville Province. The high metamorphic grade attained during both the Ottawan and Rigolet orogenic phases, after integration with other data, implied the orogen had undergone a two-stage tectonic evolution involving crustal thickening and formation of an orogenic plateau in the hinterland during the long Ottawan phase, followed by outward growth into the foreland during the much shorter Rigolet phase. Figure 28 (from Rivers et al. 2012) shows that *P–T* estimates for Ottawan mid-crustal rocks (~800–1100 MPa) are in the sillimanite field, whereas those for the Rigolet metamorphism are in the kyanite field, consistent with field observations of mineral assemblages in metapelitic rocks. This supports the observation of Wynne-

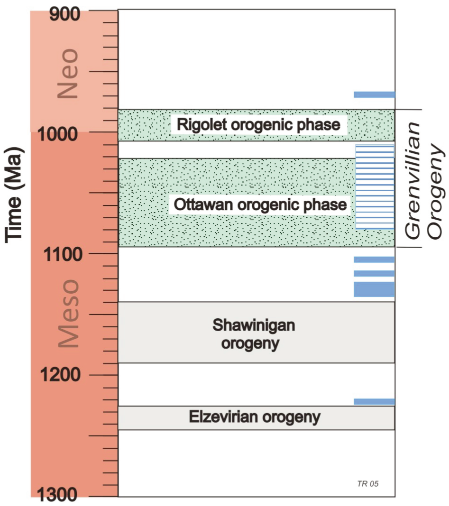


Figure 27. Time scale for the late Mesoproterozoic and early Neoproterozoic showing the ages of pre-Grenvillian accretionary events (Elzevirian and Shawinigan orogenies) and the Ottawan and Rigolet phases of the Grenvillian Orogeny (modified from Rivers et al. 2012). Note the long duration (~70 M.y.) of the Ottawan orogenic phase, making it a candidate for a LHO. Solid blue boxes indicate the ages of large labradorite anorthosite AMCG complexes in the Grenville Province; blue ruled box indicates age range of 7 smaller andesine anorthosite AMCG complexes in the central Grenville Province (see text for discussion).

Edwards (1972) noted previously, and suggests the geothermal gradient was significantly higher during the Ottawan than the Rigolet phase. Subdivision of the *P* data into natural baric groupings of *high pressure* (H*P:* >1400 MPa; >40 km depth), *medium pressure* (M*P:* 1000 ± 200 MPa; 25–35 km depth), and *low pressure* (L*P:* <800 MPa; <25 km depth) led to the definition of crustal levels for both orogenic phases (Fig. 28). When transferred to a map, the distribution of baric groups provided insight into orogenic crustal levels at the erosion surface for the first time (Fig. 29). In this figure it is apparent that the widespread Ottawan M*P* Belt is largely underlain by granulite-facies rocks that formed at 25–35 km depth, i.e. in the middle of a double thickness crust. Figure 29 also permitted insight into the crustal architecture, identifying the Ottawan crust in the hanging wall of the Allochthon Boundary Thrust as

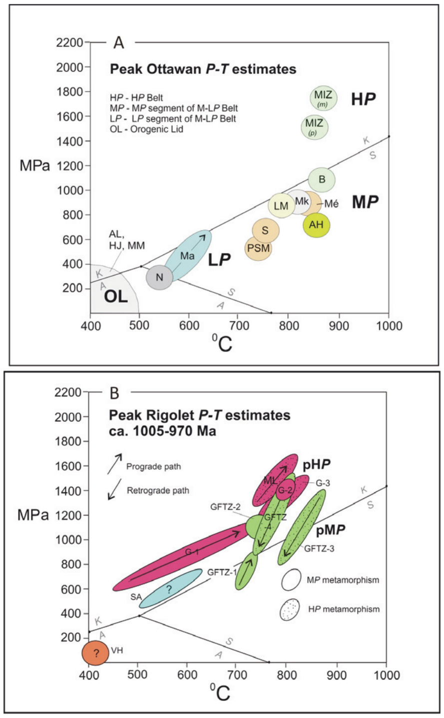


Figure 28. Peak *P–T* estimates for Grenvillian metamorphism, with prograde and retrograde paths where determined (from Rivers et al. 2012); A: Peak Ottawan metamorphism in the Allochthonous Belt; B: Peak Rigolet metamorphism in the Parautochthonous Belt. In A, peak metamorphism in the H*P* and M*P* belts was from ~1090–1060 Ma, whereas that in the L*P* Belt was from ~1050–1020 Ma. In B, metamorphism at all structural levels took place at ~1005–980 Ma.

a collage of imbricated metamorphic domains that formed at different crustal depths. In contrast, the domains comprising the Rigolet crust in the hanging wall of the Grenville Front are more laterally continuous along the orogen. An unanticipated result was that the high-pressure domains of Ottawan and Rigolet age, although temporally separated by >60 M.y., occur back-to-back on opposite sides of the Allochthon Boundary Thrust, an arrangement suggesting this boundary acted as a material focal plane in the orogen, and implying different stacking sequences on either side (Fig: 30; from Rivers 2008).

Evidence in the southwest Grenville Province for widespread ductile extensional deformation after the peak of Ottawan metamorphism was first documented by Culshaw et al. (1994, 1997), and was followed by direct dating of the extensional reworking of the Allochthon Boundary Thrust (ABT) at ~1020 Ma (Ketchum et al. 1998). Comparable evidence was gradually accumulated elsewhere in the province, leading to the recognition that post-peak extension in the hinterland was widespread and pervasive. This is shown schematically in Figure 30, where Ottawan crustal slices in the hanging wall of the ABT are separated by normal sense shear zones that were collectively interpreted as a signal of gravitationally driven extensional collapse on a crustal scale. Compatible with this interpretation was the identification of an *orogenic lid* (Rivers 2008) in the interior Grenville Province, composed of the uppermost orogenic crust (superstructure) characterized by ^{40}Ar/^{39}Ar hornblende ages of >1100–1040 Ma, the age range implying it had remained cool (≤500°C) throughout the high-grade Ottawan orogenic phase, or cooled through 500°C during that event. Recognition of the orogenic lid and its tectonic juxtaposition with exhumed mid crust along normal sense shear zones provided evidence for the crustal scale of orogenic collapse and permitted integration of the robust, but previously stranded 'old' ^{40}Ar/^{39}Ar data (e.g. Reynolds 1989; Cosca et al. 1991, 1992, 1995; Corrigan and van Breemen 1997; Streepey et al. 2004; Selleck et al. 2005) into a coherent tectonic model. The lid was subsequently named the Ottawan Orogenic Lid (OOL) by Rivers (2012).

Orogen-Scale Cross-Sections

Orogen-scale cross-sections displaying the inferred distribution of metamorphic rocks at depth are shown in Figure 31 (after Rivers et al. 2012). These highlight the post-peak juxtaposition of crustal levels, a feature missed in the early round of seismic interpretations. The scale and extent of the Ottawan Orogenic Lid and its juxtaposition against the M*P* Belt are evident, compatible with the interpretation that the orogenic architecture was profoundly modified after the metamorphic peak, as discussed further in the next section. Comparing these cross-sections with those in Figure 7, and considering the

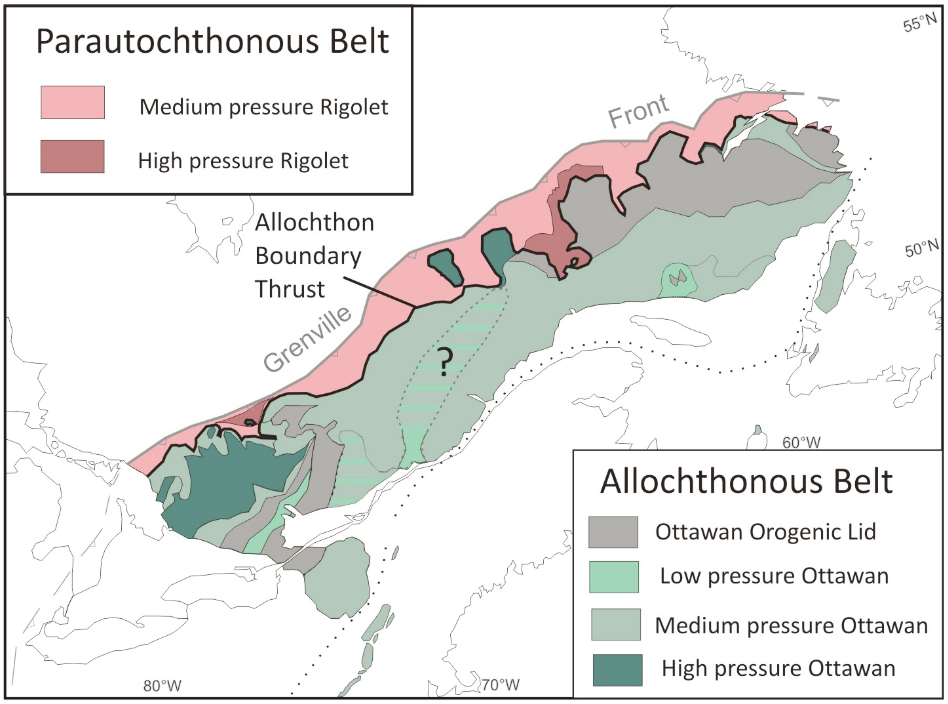


Figure 29. Sketch map of the Grenville Province showing the distribution of metamorphic rocks based on a baric subdivision of peak Ottawan metamorphism in the Allochthonous Belt and peak Rigolet metamorphism in the Parautochthonous Belt (modified after Rivers et al. 2012). *P–T* estimates are shown in Figure 28A–B. Extent of Ottawan low pressure metamorphism in the central Grenville Province is poorly defined. Age of metamorphism in the Ottawan Orogenic Lid is pre-Ottawan.

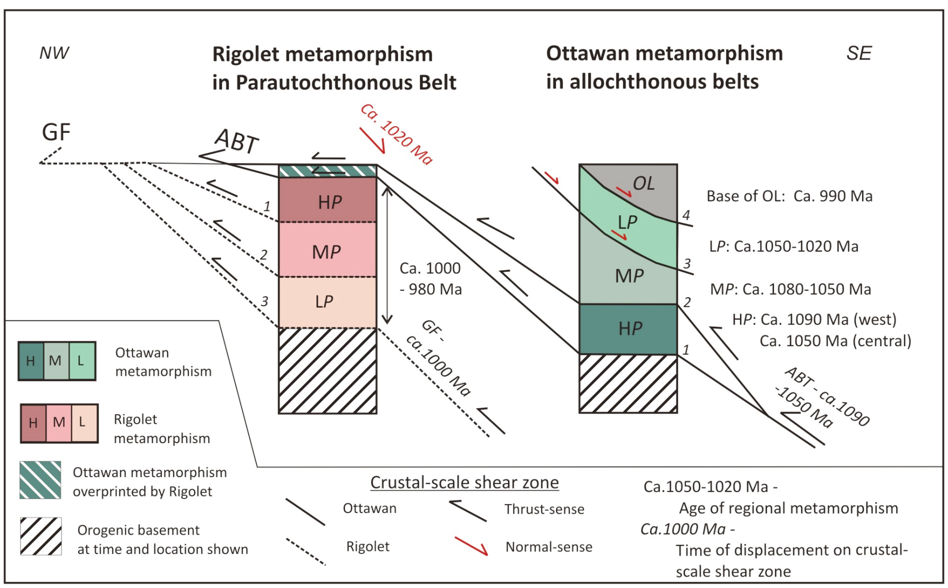


Figure 30. Inferred stacking sequences of metamorphic rocks in the Grenville Province; Ottawan metamorphism in Allochthonous Belts on right, Rigolet metamorphism in Parautochthonous Belt on left (modified from Rivers 2008). Relative sequence of displacement in each stacking sequence is shown by italic numbers at side of columns. Note out-of-sequence stacking in Ottawan crust above Allochthon Boundary Thrust (ABT), and in-sequence stacking in Rigolet crust above Grenville Front (GF). *HP*, *MP*, and *LP* are high, medium and low pressure metamorphism, OL – Orogenic Lid (see Fig. 29). Note that normal sense displacement on the ABT at ~1020 Ma preceded thrusting on the GF at ~1000 Ma.

embodied inferences of major tectonic transport of crystalline nappes during shortening and the juxtaposition of different crustal levels during extension in the former, it is evident that they represent a profoundly different perception of the Grenvillian orogenic architecture from that posited by Wynne-Edwards (1972).

Mid-Crustal Core Complexes, the Ottawan Orogenic Lid, and the Collapsed LHO Model for the Grenville Province

Figures 30 and 31 show that Ottawan crust in the *MP* Belt, metamorphosed at 1000 ± 200 MPa (~25–35 km depth) and ~800–850°C, is locally juxtaposed against the OOL in which the temperature of Ottawan metamorphism was ≤500°C and the estimated pressure was ≤ 400 MPa (≤12 km depth). In addition, there are now abundant data showing that the granulite-facies rocks in the *MP* Belt have sub-horizontal Ottawan gneissic fabrics, whereas rocks in the OOL exhibit sub-vertical *pre-Grenvillian* fabrics. This is illustrated schematically in Figure 32 (after Rivers 2012), which shows orogen-perpendicular and orogen-parallel cross-sections for the southwestern Grenville Province. The mid-crustal rocks (orogenic infrastructure) occur in domes that were compared to core complexes by Rivers (2012), with the intervening basin-shaped segments of the OOL inferred to have formed by extension and brittle–ductile faulting (in effect boudinage) of the upper crust (orogenic superstructure). First order similarity to the extensional collapse models of Rey et al. (2009; Fig. 26) is apparent.

Additional support for the interpretation of contrasting styles of Ottawan deformation at different crustal levels comes from the histories of small-scale, geon-11 (i.e. pre-Ottawan) intrusions shown schematically in Figure 32, which occur in both the mid crust and the OOL. In the mid crust, these bodies were ductilely deformed under granulite-facies conditions and overprinted by amphibolite-facies retrogression and boudinage, whereas in the OOL they are unmetamorphosed and undeformed and cross-cut the regional fabric. This contrast was interpreted by Rivers

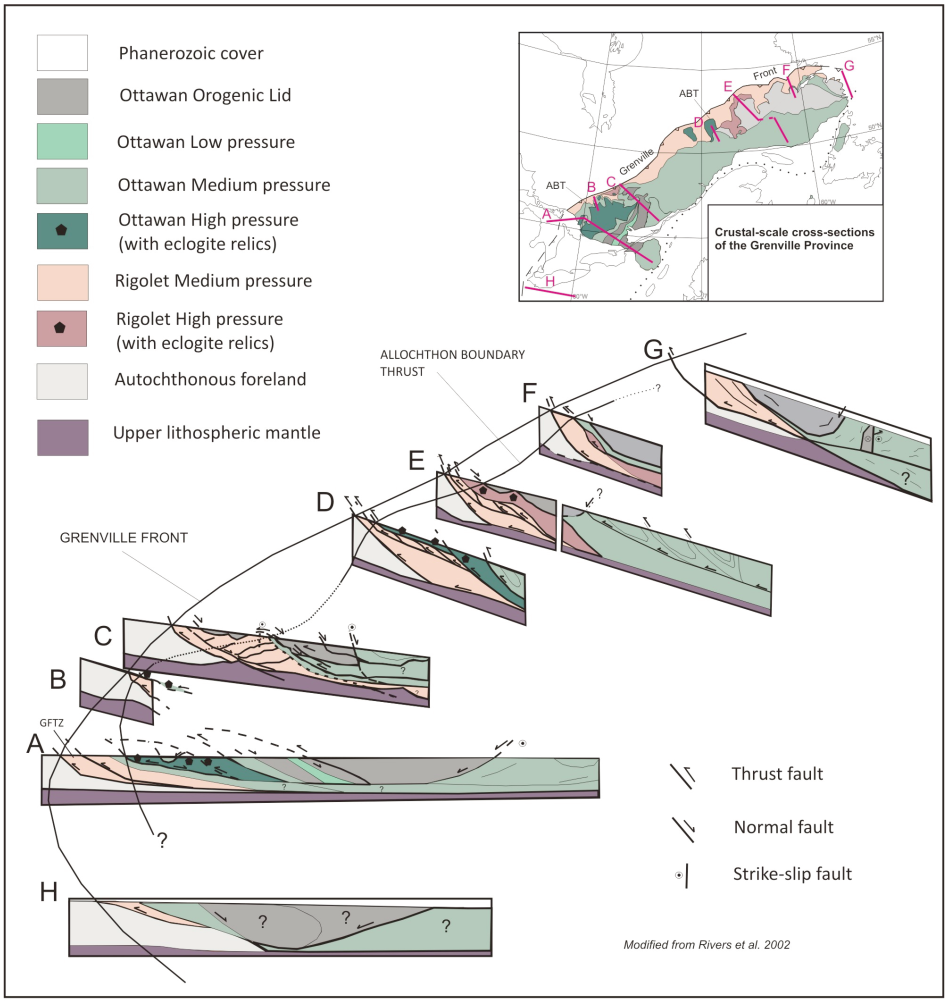


Figure 31. Crustal-scale cross-sections of the Grenville Province coloured according to inferred age and pressure of metamorphism at depth (modified from Rivers et al. 2002, 2012). Ottawan metamorphism in hanging wall of the Allochthon Boundary Thrust shown in shades of green, orogenic lid shown in grey, Rigolet metamorphism in hanging wall of the Grenville Front shown in shades of red. Sources of data for crustal-scale cross-sections: A, B, C, D, G based on LITHOPROBE seismic data, H based on COCORP seismic data, E, F extrapolated from surface structures (see Rivers et al. 2012 for details).

(2012) to signify that the Ottawan mid crust beneath the orogenic plateau was ductile and deformed by sub-horizontal flow in a 'channel' during crustal shortening and thickening under granulite-facies conditions while the overlying brittle upper crust was not penetratively deformed or metamorphosed; and that mid-crustal shortening/thickening was followed by extension/thinning under amphibolite-facies conditions, eventually resulting in juxtaposition of the two crustal levels. Extension was accompanied by magmatism locally, which may have facilitated collapse. For instance, the margins of the granulite-facies Adirondack Highlands terrane, which exhibits a domal shape, are the sites of deformed and recrystallized sheets of syn-extensional leucogranite (Fig. 31; Selleck et al. 2005; McLelland et al. 2010, 2013; McLelland and Selleck 2011; Wong et al. 2012). To a first approximation, such an evolution is compatible with numerical models of gravitational collapse of double thickness crust under an orogenic plateau, leading to thinning and sub-horizontal flow of the weak mid crust in the channel as the overlying strong upper crust extends by large-scale boudinage (e.g. Fig. 26). A schematic illustration of the proposed process, referred to as the *collapsed LHO model* for the Grenville Province, is shown in Figure 33 (after Rivers 2012).

Current Limitations of Modelling

It is widely acknowledged on physical grounds that rheological weakening of the mid crust beneath an orogenic plateau, due to heating and partial melting, will inevitably lead to orogenic collapse once the gravitational forces acting on the plateau are no longer balanced by tectonic forces. However the complete evolution of a LHO, from formation to collapse, has yet to be satisfactorily reproduced in a single numerical model. This suggests that the remarkable visual similarity between the orogenic architecture developed after 97.5 M.y. of convergence in the hot nappe LHO model (model GO-3, Fig. 25d; Jamieson et al. 2007) and the actual crustal architecture of the southwestern Grenville Province shown in Figure 25e is, in and of itself, an insufficient criterion for adoption of the model. Firstly, it is apparent that the comparison of crustal architecture in Figure 25e is between the *uncollapsed* crust in the tectonic model and *collapsed* crust in the Grenville Orogen. Subsequent numerical experiments at the same scale allowing for collapse by stopping convergence successfully reproduced crustal thinning in the hinterland by gravitational spreading and drove thrusting at the orogen margin (Jamieson et al. 2010, Jamieson and Beaumont 2011), but a core complex crustal architecture in which parts of the orogenic superstructure were juxtaposed against exhumed hot mid crust (infrastructure) was not developed. This may be because the models do not have the necessary resolution, or because discrete zones of weakness are needed to seed collapse. Thus, at present in order to examine processes that result in post-peak orogenic collapse structures such as those in the Grenville Province, it is necessary to use numerical models with boundary conditions specifically designed for this purpose, such as those in Figure 26 (Rey et al. 2009), which also may incorporate different material properties to those used for the development of the orogenic plateau. Secondly, the possibility that collapse of an orogenic

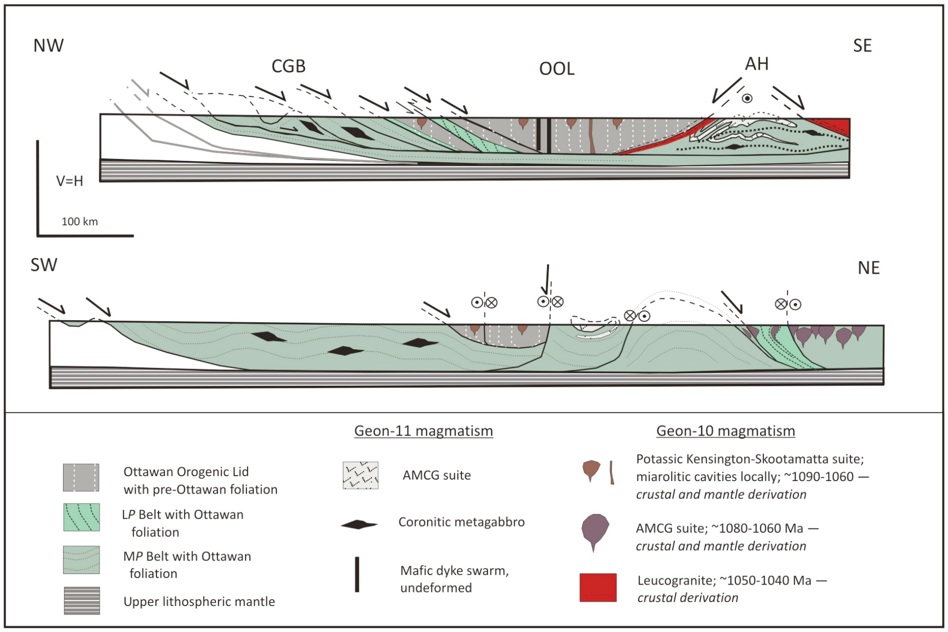


Figure 32. Orogen-perpendicular (NW–SE) and orogen-parallel (SW–NE) crustal-scale sections of the Grenville hinterland in the hanging wall of the Allochthon Boundary Thrust, western Grenville Province (modified from Rivers 2012). Orogen-perpendicular section (top) constrained by seismic data (enlarged version of A in Fig. 31); Orogen-parallel section (bottom) constrained by surface data and two seismic cross-lines. Line ornaments show contrasting fabric orientations in mid crust (sub-horizontal) and orogenic lid (sub-vertical). Contrasting histories of geon 11 mafic intrusions shown are discussed in text. AH – Adirondack Highlands terrane; CGB – Central Gneiss Belt; OOL – Ottawan Orogenic Lid.

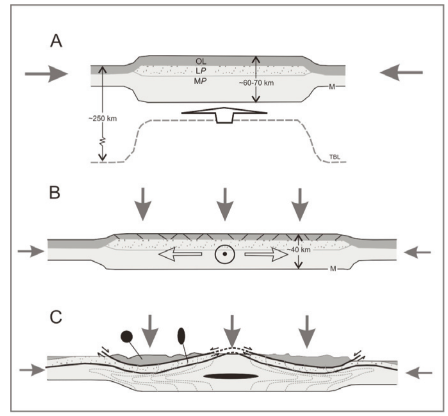


Figure 33. Conceptual 2-D cross-sectional model for the collapse of the Grenville Orogen (modified from Rivers 2012; based on Dewey 1988; Rey et al. 2001, 2009; Vanderhaeghe and Teyssier 2001; Vanderhaeghe 2009). A: Double thickness crust under orogenic plateau, with orogenic infrastructure (light grey) and superstructure (dark grey), and locations of future medium pressure belt (*MP*), low pressure belt (*LP*), and orogenic lid (OL). Delamination of the lithospheric root under the orogenic plateau is inferred to cause rise of the asthenospheric thermal boundary layer (TBL) leading to heating of the lower and mid crust (associated magmatism not shown). B: Thermal and melt weakening of the lower-mid crust cause it to flow laterally under gravity; horizontal extension may be in any direction (shown schematically as perpendicular and parallel to the orogen). C. Resulting structural regimes at different structural levels: extensional flow (flattening) of lower-mid crust causes boudinage of overlying strong upper crust and rise of ductile mid crust into boudin necks forming crustal-scale core complexes. Schematic orientations and magnitudes of the bulk ductile strain ellipse (black) at different crustal levels are shown.

plateau may be driven by detachment of its lithospheric root, with attendant thermal and isostatic effects on the crust, originally proposed by Bird (1979) for the Basin and Range Province, is not evaluated in crustal models such as that shown in Figure 25. Even in models that include the upper mantle, however, this mechanism is not considered to be important by modellers (R.A. Jamieson personal communication 2014). Nonetheless, in the opinion of the author it remains conceptually attractive for the Grenville Province to explain not only the orogenic architecture, but also the occurrence of mantle-derived syn-Ottawan magmatism (see below). Thirdly, unless physically constrained to two dimensions, gravitational collapse is a 3-D phenomenon that cannot be adequately represented in 2-D models. The 2-D limitation prescribes deformation to be plane strain, which is not in accord with general observation. Finally, the long tectonic transport distances of the ductile mid and lower crust in LHO hot nappe models suggest that viscous (frictional) heating may be important (e.g. Burg and Gerya 2005), although Jamieson and Beaumont (2013) concluded that its effects may be self-limiting because the heat generated acts to reduce viscosity, limiting the temperature rise to ≤50°C. Collectively these are significant considerations and they imply that 3-D, coupled crust–mantle models are needed to adequately simulate the complete tectonic evolution of collapsed LHOs. Such models, which are ongoing in several laboratories, require inclusion of additional variables to describe mantle behaviour and massive computational resources.

DISCUSSION

In reviewing progress in deciphering the tectonic evolution of the Grenville Province over the last 60 years, we have identified several stages: (i) a stage dominated by a fixist, stratigraphic mindset that characterized the Grenville Problem; (ii) the rigorous approach of the first Grenville synthesis, which despite limited data outlined some major tectonic features of the orogen, but was followed by a stage characterized by innovative, poorly constrained, quasi-plate tectonic models; (iii) an intense data-gathering stage during the LITHOPROBE era that led to the first constrained plate tectonic models for pre-Grenvillian Laurentia, separation of late Mesoproterozoic accretionary events from the collisional Grenvillian Orogeny, and tentative identification of the Grenvillian collisional suture; (iv) also during this stage, recognition of and linkage among: the great width of the Grenville Orogen, crustal imbrication and attainment of double crustal thickness crust, the widespread high temperature and ductile rheology of the mid crust, the long duration of the Ottawan orogenic phase, and the presence of an orogenic lid, all of which are compatible with a LHO; and finally (v) the integration of local tectonic evolutions throughout the Grenville Province in the context of the LHO paradigm into a single narrative, leading to the collapsed LHO model.

Extraction of these stages from the continuum of data collection, interpretation and understanding is to some extent an artefact and other divisions could probably have been chosen. However, regardless of the way the narrative is parsed, from an epistemological perspective the fundamental role of a tectonic paradigm in which to frame interpretations is evident. The lack of a practical paradigm was the defining factor of the stratigraphic mindset and the 'Grenville Problem'. Following the paradigm shift of plate tectonics there was a general paradigm, but a lack of the basic data necessary to make an informed decision about how to apply it, defining the quasi-plate tectonic stage. Moreover, this stage was characterized by the fixation of several influential authors on basement–cover relations in a long-lived passive margin setting, a counter-productive paradigm inherited from the pre-plate tectonic, stratigraphic mindset, which had the effect of diverting attention from alternative scenarios. Subsequently, the LITHOPROBE years were characterized by the production of robust field-based data by multiple techniques from an enlarged toolbox, leading to both the proposal of an active margin plate tectonic paradigm for pre-Grenvillian Laurentia and its testing by several independent methods. And finally, in the post-LITHOPROBE years, much research relating to the tectonic evolution of the Grenville Province has been driven by the application of the LHO concept, now recognized as a special case of the plate tectonic paradigm. From this perspective, the progress in understanding has followed the predictable path of 'normal science' after a fundamental paradigm shift. As Kuhn (1962) envisaged, the paradigm shift – the plate tectonics hypothesis in this case – provided a new framework in which to view the 'problem', define the important questions, and generate data to test it – and in the process the new paradigm was itself refined.

However, as noted in the Introduction, there were significant differences in the manner and timing of adoption of the plate tectonic paradigm. In places that were in the vanguard of the plate tectonics revolution, such as the Appalachian Orogen in Newfoundland in the 1960s, some of the field evidence to test the new paradigm was already in hand, and other critical interpretations followed quickly (e.g. the significance of ophiolite bodies and flysch sediment; Dewey 1969; Stevens 1970), with the result that adoption by the community was swift (e.g. Williams et al. 1972; Williams 1979). Similarly, in the Wopmay Orogen, although the primary field evidence was not acquired until a few years later (e.g. Hoffman 1973), the superb preservation and low metamorphic grade of the inverted continental margin sequence ensured that the plate tectonics paradigm was quickly adopted, thereby extending the application of plate tectonics back to the Paleoproterozoic.

In contrast, in the Grenville Orogen in the 1970s meaningful progress in geological mapping was restricted to small areas with recognizable supracrustal sequences, and an overall tectonic framework was not discernible. Many protoliths were not readily recognized because of the high grade of metamorphism, the crustal scale of deformation and the exposure of different levels of orogenic crust were not appreciated, and the types of data necessary to test the plate tectonic paradigm were not only lacking but not readily identified, opening the window on a period of unconstrained tectonic speculation that did not occur elsewhere. Moreover, although systematic data collection during the LITHOPROBE years subsequently led to the formulation of plate tectonic models for pre-Grenvillian Laurentia, it did not immediately lead to improved understanding of the Grenville Orogen itself. The case is made here that it was the publication of the LHO numerical models (e.g. Beaumont et al. 2001), a secondary paradigm shift within the broader plate tectonic framework, and their application to the Grenville Orogen (e.g. Jamieson et al. 2007) that provided the impetus for recent understanding. In some respects, we have at last reached a position comparable to that of Appalachian geologists in the mid-1960s, inasmuch as we now have testable models and a tectonic framework based on quantitative physical processes in which to situate new data and simultaneously evaluate the models and framework themselves. For instance, criteria have been published to distinguish among three plausible models for the evolution of large hot orogens (i.e. orogenic wedge, channel flow, and gravitational collapse; Gervais and Brown 2011), and recent work has suggested that such models are not mutually exclusive (Corrie et al. 2012; Rivers 2012; Jamieson and Beaumont 2013). It remains to be seen whether the collapsed LHO model will provide a suitable tectonic framework to interpret other Proterozoic orogens that have so far resisted easy incorporation into the plate tectonic narrative.

It has been observed many times in the literature, to the extent that it is almost a truism, that the Grenville Province can usefully serve as a natural field laboratory for the investigation of deep-crustal processes. Indeed as noted previously, this purpose has been fulfilled in some respects, for instance in terms of the definition of meaningful tectonic units such as domain and gneiss association for field mapping, the definition and evaluation of kinematic criteria in high-grade ductile shear zones, the testing of geothermobarometric calibrations, and the recognition of P–T conditions of eclogite formation at the base of an orogenic plateau. However from a practical perspective, the lack of understanding of both the internal crustal architecture of the Grenville Province and its overall tectonic context have rendered wider application of this ideal problematic in the past. With the publication of the collapsed LHO model, the role of the Grenville

Province as a natural laboratory should be significantly enhanced insofar as there is now a testable orogen-scale tectonic framework and the crustal architecture can be directly related to that of orogens in which collapse has not occurred. In this context, it is paradoxical that in an orogen known for its high grade of metamorphism and ductile gneiss complexes, features characteristic of the orogenic infrastructure, we now recognize that large parts of it represent the foundered upper crust (orogenic superstructure) that remained cool and was not penetratively deformed during the Grenvillian Orogeny. This mode of preservation of upper crust in an orogenic setting may constitute a signal for the former existence of an orogenic plateau.

The collapsed LHO model is the latest way of viewing the Grenville Province and, as the name implies, it incorporates two related concepts: that the orogen developed as a LHO with a mid-crustal channel in which some form of long distance tectonic transport of hot ductile rocks occurred above a major thrust-sense shear zone (the Allochthon Boundary Thrust in this case; Jamieson et al. 2007, 2010; Chardon et al. 2009); *and* that the architecture of ancient LHOs cannot be understood solely in terms of their constructive history, but must also take account the effects of subsequent profound collapse (e.g. Rey et al. 2001, 2009; Vanderhaeghe and Teyssier 2001; Gapais et al. 2009; Vanderhaeghe 2009; Jamieson and Beaumont 2013). Neither of these concepts was common currency in the tectonic literature as recently as a decade ago, and the linkage between them is even more recent. Clearly, given the limited time since its introduction, the ramifications of this new way of interpreting the Grenville Province have not been completely worked through, and there is much more normal science to be done to test and refine the model.

Implications for Future Research

During the last 15 years or so, several major conceptual advances in the tectonics of orogenic systems have been driven by numerical forward-modelling studies, of which the LHO paradigm is an example. On the one hand, this is producing a fundamental change in the way research in tectonics is carried out, on the other as discussed herein it reinforces the need for traditional field-based research (the inverse model) to test, validate and refine the predictions of the forward modelling. This suggests that field studies may become more focussed on evaluating model predictions rather than simply recording and interpreting nature as it is found.

Another aspect of research in tectonics that is assuming an increasingly prominent role is the integration of diverse data sets, as was attempted in both Grenville syntheses. In this context, an emerging field of investigation concerns the linkages and feedbacks among processes that were previously considered in isolation, such as the role of heat transport on crustal-scale faulting and folding and vice versa, thermal controls on rheology, advection and strain localization, and denudation rates on the thermal structure of orogens. Presently unsuspected or little studied linkages between such topics may reveal fruitful new lines of research. As noted in the Introduction, although many recent advances have been enabled by the much larger toolkit available today, others were achieved by breaking with the status quo and examining existing data and relationships in conceptually new ways, a process that has been dramatically accelerated by numerical forward modelling.

Some Future Research Directions

With this in mind, it is appropriate to end this section with a consideration of short- and longer-term research issues and directions. The list below includes topics for which investigations will likely be driven primarily by field-based research (the inverse model), those for which numerical experiments will likely provide first-order input (the forward model), and some general questions of tectonic significance.

Principally Field-Based Topics

1. Additional field testing of the tentative location of the collisional orogenic suture in the Grenville inliers in the Appalachians (Fig. 1) is required. Such work may also cast light on the orogenic polarity, which is cryptic in LHOs because of prolonged collision, possible loss of basal traction due to weakening of the lower crust and/or detachment of the sub-continental lithospheric root. In the Grenville Province, the pre-Grenvillian history in which southeast Laurentia comprised the upper plate in a long-lived Mesoproterozoic continental margin arc could imply that Laurentia was in an upper plate setting during the Grenvillian Orogeny, as proposed by Dewey and Burke (1973). However, the accretion of back-arc terranes in the late Mesoproterozoic presents the possibility for subduction reversal during back-arc closure prior to final collision. Robust evidence concerning this issue is difficult to come by. McLelland et al. (1996) and Culshaw et al. (1997) both proposed a lower plate setting on the basis of the high-grade of Grenvillian metamorphism, the latter authors inferring that eclogite in the hanging wall of the ABT implied development in a subduction setting. However as noted, the high-*T* conditions of eclogite- and H*P*-granulite-facies rocks in the central Grenville Province (≥800°C; Indares 1993) are more compatible with formation at the base of double thickness crust (Fig. 25), perhaps rendering this argument moot. Similarly, the numerical LHO models of Jamieson et al. (2007, 2010) inferred a lower plate setting for Laurentia, although the authors noted the subduction polarity was not critical to the outcome. Hynes and Rivers (2010) also argued for a lower plate setting for Laurentia, in this case on the basis of the high grade of metamorphism of the remnants of the continental margin arc. However, none of these arguments is completely watertight, and an upper plate origin cannot be definitively precluded by existing data. It would be compatible with the deep crustal structure of long-lived, continental margin arcs that have undergone an important compressional stage, such as parts of the Cordillera of the Americas (e.g. Charrier et al. 2007; Cook et al. 2012), which may

be relevant if the pre-collisional architecture controlled that of the subsequent continent–continent collision.

2. It has been inferred that the Allochthon Boundary Thrust (ABT) corresponds to the lower (initially thrust sense) boundary of a mid-crustal channel along which hot nappes were transported beneath an orogenic plateau during the Ottawan orogenic phase. However, the location of the upper boundary of the channel remains undefined. According to numerical modelling experiments, the upper boundary should be a normal sense shear zone that separates high-strain rocks in the channel from lower strain rocks in its immediate hanging wall – and the timing of normal sense displacement on the shear zone should be coeval with thrust sense displacement on the ABT (i.e. ~1090–1060 Ma in this case). Definition of the upper boundary of the channel remains a first-order issue to test and/or validate the collapsed LHO model. Some recent information that may have a bearing on this question comes from the hinterland in south-central Québec, where an extensive area of Ottawan low-*P* granulite-facies rocks in which primary igneous textures and structures are preserved has been described (Dunning and Indares 2010). Their data suggest the rocks were heated to ≥800°C, presumably from below, in a static, low strain setting. It is tentatively suggested that the L*P*–H*T* metamorphism and lack of penetrative strain may be a signature of development in the hanging wall above a mid-crustal channel. A test for compatibility with this suggestion would be the delineation of a normal sense shear zone marking the upper boundary of the mid-crustal channel, which from numerical experiments should separate strongly deformed granulite-facies rocks (i.e. high strain gneisses) in the channel from less deformed equivalents in its hanging wall (e.g. Jamieson et al. 2007). If this scenario is verified, it would provide an alternative to the commonly advocated 'regional contact metamorphism' setting for granulite facies terranes based on advected magmatic heat.

3. The metric for the definition of the Ottawan Orogenic Lid, the rheological entity representing the remains of the cool strong uppermost orogenic crust (superstructure) with brittle–ductile rheology in the Grenville hinterland, is in need of re-evaluation. The OOL was originally defined on the basis of $^{40}Ar/^{39}Ar$ apparent ages in hornblende (Rivers 2008, 2012), which implicitly assumes that the cool (≤500°C) *thermal* boundary of the lid corresponded to its *rheological* boundary. However, Schneider et al. (2013) described evidence from the hinterland in southwestern Québec that the area of the rheological lid defined by its lack of penetrative Ottawan deformation is larger than that of the thermal lid defined by its hornblende Ar signature, thereby introducing the concept of a 'hot lid' (>500°C). More data are required to evaluate this phenomenon, but it is tentatively suggested that the hot lid may be a result of conductive heating following collapse of the channel and juxtaposition of the orogenic superstructure against the exhumed hot mid crust.

4. With regard to metamorphic and geochronologic issues, there is a need for improved documentation of the *P*–*T*–*t* evolution of the exhumed mid crust in gneiss complexes such as those illustrated in cross-section in Figure 32, in order to tease out the details of their prolonged tectonic evolution. At the time of writing, most *P*–*T* estimates for the Grenville Province are based on classical geothermobarometry (the inverse model) and most *t* estimates are based on U–Pb TIMS geochronology on mineral separates. There is an obvious opportunity for application of forward modelling methods of thermobarometry (e.g. Thermocalc, Theriak-Domino, PerpleX) that take account of the full bulk composition and permit integration of mineralogical, modal and textural features in interpretations of the *P*–*T* path. Moreover, considering the evidence for prolonged metamorphism over several 10s of M.y., there is a need for better integration of geochronology with the *P*–*T* estimates in order to separate the timing of the prograde/burial history from the retrograde/decompression history. In this respect, there is also scope for enhanced application of *in situ* geochronological and geochemical methods (e.g. SHRIMP, LA–ICP–MS) that integrate the trace element chemistry of the accessory phases that serve as geochronometers with that of the major and minor phases used for thermobarometry, thereby improving linkage between the *P*–*T* and *t* determinations. Moreover, in addition to their use in a local context, the linked *P*–*T*–*t* data can be compared with theoretical *P*–*T*–*t* paths derived by numerical modelling to distinguish among competing tectonic hypotheses (e.g. Jamieson et al. 2007; Gapais et al. 2009; Gervais and Brown 2011). For instance, the suggestion of Rivers (2012) that metamorphism in the Ottawan upper crust (L*P* Belt; Fig. 32) developed as a result of conductive heating following juxtaposition with the exhumed hot mid crust (M*P* Belt) during extensional collapse is testable with integrated *P*–*T* and *t* studies of L*P* and M*P* domains.

5. The composite character of the gneissic fabric in exhumed gneiss complexes, incorporating both compressional and extensional strain components, requires further investigation. Quantitative fabric analysis by electron backscatter diffraction (EBSD), a technique that has not yet been used in the Grenville Province, may permit discrimination of compressional and extensional fabrics, determination of bulk deformation styles, identification of mineral-scale deformation mechanisms (inter- and intra-crystalline slip systems), and related estimates of the *P*–*T* conditions of fabric formation. Such information is relevant to the magnitude and distribution of

strain during collapse, and to the issue of whether extension was driven principally by gravity or a plate tectonic mechanism such as lithospheric delamination or slab roll-back.

6. Recent work has documented the widespread development of extensional fault propagation folds (FPFs) in exhumed granulite-facies gneisses in the southwestern Grenville Province (Schwerdtner et al. 2014). These are late, monoclinal, high-level structures that individually record limited extension, but their collective effects have not been assessed. Moreover, many host granitic pegmatite dykes implying a role for magmatic dilation of the crust during their emplacement. More information on these high-level features and their relationship to ductile extensional structures formed at deeper levels is needed to enhance understanding of the complete extensional collapse process.
7. In the 1980s to 1990s, lithospheric delamination was widely cited as a plausible process for the initiation of extensional collapse, driving uplift of the remaining thin lithosphere and leading to thermal weakening of the mid crust, which as a result underwent vertical flattening and rheological separation from the cooler stronger upper crust (e.g. Bird 1979; Dewey 1988; England and Houseman 1988; Dewey et al. 1993). However as noted above, this interpretation has not been supported by the current generation of numerical models, where the transition from crustal thickening to collapse is attributed to loss of basal traction between crust and mantle when convergence ceases (R.A. Jamieson, personal communication 2014). From the perspective of the author, lithospheric delamination remains attractive, however, as it involves rising asthenosphere, thereby providing a setting for decompression melting and the formation of synorogenic mantle-derived magmas (which in turn serve as a proxy for the delamination process). In the Grenville Province, there are now several reports of small syn- to late orogenic mafic intrusions, including an AMCG complex, ultrapotassic intrusions and lamprophyre dykes that are interpreted to have originated by partial melting of variably enriched lithosphere (e.g. Corriveau and Gorton 1993; Owens and Tomascak 2002; Gower and Krogh 2002; Valverde Cardenas et al. 2012). There is a need to augment these data and integrate them into a province-wide picture, both to test the possible tectonic linkage with delamination and to constrain the timing and location. A plausibly related topic concerns the absence of mantle reflections in the LITHOPROBE deep seismic experiments in the Grenville Province. It is possible that this may not be a failure of the seismic imaging protocol employed, as was tacitly assumed at the time, but rather evidence that the original sub-continental lithospheric mantle delaminated and was replaced by homogeneous asthenosphere. Such an interpretation would be compatible with the inference of a re-equilibrated Moho under the Grenville hinterland (Eaton 2006).
8. Although the petrology and genesis of Proterozoic AMCG complexes are subjects of active research (e.g. Bédard 2010; Vander Auwera et al. 2011), understanding of the tectonic setting(s) in which they developed and their role(s) in both the pre-Grenvillian evolution of SE Laurentia and the Grenvillian Orogeny remains poorly constrained. The data for crystallization ages of AMCG complexes, summarized in Figure 27, suggest that the large pre-Grenvillian complexes were characterized by labradorite anorthosite, whereas the smaller post-peak, syn-Grenvillian bodies were characterized by andesine anorthosite. Moreover, in places where the two types occur together there is evidence for inclusions of labradorite anorthosite in the younger andesine anorthosite intrusion, suggesting an origin by cannibalization, although this remains untested. Given the size and abundance of AMCG complexes in the Grenville Province and their significance for the Proterozoic in general, this is a topic that requires additional study.

Issues Requiring First-Order Input from Numerical Modelling

9. The tectonic subdivision of the Grenville Province into a collage of allochthonous hinterland terranes affected by the early long duration Ottawan metamorphism in the hanging wall of the Allochthon Boundary Thrust, and a more structurally continuous parautochthonous terrane in the foreland affected by the later short duration Rigolet metamorphism in the hanging wall of the Grenville Front has been described. Although a superficially comparable architecture has been reproduced by numerical models that allow the collapse of a LHO by gravitational spreading after convergence stops (GO-ST experiments; Jamieson et al. 2010), such models do not explain the presence of eclogite-facies rocks of Rigolet age in the Parautochthonous Belt (Martignole and Martelat 2005; van Gool et al. 2008). In the author's opinion, it is questionable whether the formation and exhumation of eclogite-facies rocks, and the coeval development of a crustal-scale shear zone (in the GFTZ) and metamorphic foreland-directed fold and thrust belt (in the Gagnon terrane) during the Rigolet phase, are results of post-Ottawan gravitational spreading [and hence an example of coupled extending and compressional flow, similar to that proposed in the millipede model of Wynne-Edwards (1976)]. Alternatively, it has been suggested that the Rigolet phase may represent a second period of convergence and crustal shortening following collapse of the plateau in the hinterland (Rivers 2008). Additional modelling studies could contribute to a resolution of this issue.
10. With respect to the structural evolution of thick hot crust during compression, numerical modelling studies have shown that dominant folds can develop despite a narrow range of viscosities, that they may

cause structural (as opposed to material) weakening (Schmalholz et al. 2005), and that as a result of thermal-mechanical feedback they advect viscous heat faster than it is conducted away (Hobbs et al. 2007), thereby influencing both the structural style and regional temperature distribution. Implications of these findings have yet to be applied to LHO numerical models, but they may be germane to interpreting the contrasting structural styles between the Adirondack Highland terrane and the Central Gneiss Belt in the Grenville Province (compare Figs. 13 and 14).

11. Another outstanding issue is the amount and direction of extension during orogenic collapse. In the exhumed mid crust, reliable estimates of the amount of extensional strain are probably not feasible from measurements of outcrop-scale structures, which may record only a finite increment of the total strain. Use of larger strain markers such as plutons, crustal-scale boudins, and entire domains should help (Schwerdtner et al. 2014), but the ultimate aim should be strain determinations using an external reference frame. Moreover, all such estimates need to be linked to the amount of extension in the orogenic superstructure. There is clearly a role for the creative interplay between field observation and numerical modelling here.

Issues of General Tectonic Significance

12. Murphy and Nance (2005) and Silver and Behn (2008) drew a distinction between short-lived *internal* oceans (also called Atlantic-type) with a clearly defined rifting stage that open and close on similar lines thereby defining a Wilson cycle, and long-lived *external* (Pacific-type) oceans that do not have a well-defined rifting stage and whose closure is postulated to lead to a dramatic reduction in subduction flux. Closure of either type of ocean may lead to the formation of a supercontinent. Signals for the closure of internal and external oceans should be distinctive, however, with that of internal oceans being marked by the juxtaposition of a passive margin against an active margin, and that of external oceans being marked by the juxtaposition of two active margins. On the basis of these criteria, the ocean to the southeast (present co-ordinates) of Laurentia whose closure led to the Grenvillian Orogeny and the formation of Rodinia was an external ocean (see also Dalziel et al. 2000). Additionally, because of the long duration of external oceans (several hundred m.y.), their closures are by definition rare events in Earth history and they are likely to give rise to LHOs due to the extensive thermal pre-conditioning of the active margin crust on both sides of the collision zone. There is an opportunity to build on the numerical modelling of Jamieson et al. (2007) and model the juxtaposition of two thermally pre-conditioned active margins with thick lithospheres to investigate the internal rheology and architecture of the resultant ultra-large, ultra-hot orogen.

13. Finally, a question of tectonic significance worth posing is whether the Grenville Orogen at the centre of the Rodinia supercontinent was the first LHO to have developed on Earth. Although there is increasingly robust evidence for the operation of some form of plate tectonics as far back as the Neoarchean (e.g. Brown 2008), and for the formation of a supercontinent in the late Paleoproterozoic (Nuna), high-grade gneiss complexes in Archean and Paleoproterozoic orogens are typically of low-P–high-T character, and lack evidence for the formation of a thick thrust sheet stack under an extensive orogenic plateau and its subsequent extensional collapse (e.g. the Paleoproterozoic Trans-Hudson Orogen at the centre of Nuna; Corrigan et al. 2009). This raises the possibility that prior to the Mesoproterozoic, the geothermal gradient was too high and the lithosphere too weak to permit the development of an orogenic plateau. If this is the case, the Grenville Orogen could be considered the type example of a LHO and its subsequent demise as a collapsed LHO.

CONCLUSIONS

This paper charts the progress of understanding from the definition of *The Grenville Problem* to the emergence of a testable solution that is referred to as the *Collapsed LHO model*. In so doing, it shows that our understanding of high-grade orogens has been profoundly deepened as light has been shed on different aspects of their constitution. It is evident that the path followed has been non-linear, and that the critical issues that have challenged workers to come up with innovative interpretations have changed over time, as understanding evolved and new analytical techniques and sources of data became available. There were also several false steps, including innovative conceptual models, some quite elaborate, that turned out to be dead ends. According to Kuhn (1962), such an apparently random walk is typical of the early stages of research on a complex topic for which there is no established conceptual framework, and prefigures the emergence of a new paradigm consistent with all available sources of information at the time. Once an appropriate paradigm becomes established, its predictive attributes lead to a narrowing of the range of solutions consistent with robust data and an improved understanding of the fundamental driving forces and predominant processes. Furthermore, trust in the paradigm is increased if it is able to explain linkages among independent and formerly unrelated data sets in a relatively simple physical model.

In this context, this paper also describes a progression in terms of what may be described as scientific beauty and creativity. In discussing these terms, Kieffer (2006) proposed that beauty in science is commonly equated with simplicity, and involves "*the proper conformity of the parts to one another and to the whole*", and that scientific creativity is "*the ability to form or formulate something that no one else has done before, and that feels as if it has the proper conformity of the parts to the whole*, […] *i.e.,* [creativity is] *the ability to formulate something that feels beautiful*' (p. 6). Using this definition, few would dispute that the Tectonic Lithofacies Map of the Appalachians for instance, produced by Hank Williams (Williams 1978), is a thing of beauty and the result of a great deal of scientific creativity (not to mention long hours of work!). In convening their meeting on The Grenville Problem, the participants were acknowledging that they were running low on scientific creativity, that many of their results were not beautiful (i.e. logical, internally consistent etc.), and that they needed a new paradigm to make progress. As we now know, this involved shedding some long-held preconceptions and the adoption of a new paradigm, which collectively proved more conducive to creative thinking. Wynne-Edwards' (1972) synthesis brought a measure of beauty to the understanding of the Grenville Province that endured for a generation. However, with the accumulation of diverse datasets and new conceptual models in the thirty years following its publication, eventually it too was shown to involve systematic errors and logical inconsistencies. Assembling a radically different model to replace it has taken much creativity from many people with a wide range of expertise, as summarized in this paper. This is the progress of 'normal science'. From the perspective of the author, there is considerable beauty in the Collapsed LHO Model, not only in its simple physical basis and because the parts appear to conform to current understanding of the whole, but also because unlike the quasi-plate tectonic models of the 1970s, it has a logical, predictive quality and is readily testable. It demands that we look at the Grenville Province differently, as did Wynne-Edwards' (1972) model in its time. However, it undoubtedly contains elements within it that are simplistic and naïve, not to mention incorrect, and its utility will be measured by how much and for how long it stimulates the direction of new research.

In this context, it goes without saying that much testing of the Collapsed LHO Model for the Grenville Province remains to be done before it can be considered robust – indeed a list of issues that require additional study has been included. As noted, it will also be a test of the model to determine whether it promotes useful insight and feedback into studies of the deep crust elsewhere, such as in other high-grade Proterozoic orogens that composed Rodinia, younger LHOs such as the Himalaya–Tibet Orogen, and in orogens with well developed core complex architecture in which collapse has occurred but some topographic relief remains (e.g. the Basin and Range Province, Aegean Sea). With regard to the exhumed high-grade terrane of the Variscan Bohemian Massif, with which the Grenville Province was compared by Dewey and Burke (1973), the recently proposed tectonic evolution involving horizontal channel flow and vertical extrusion of the lower crust (Schulmann et al. 2008) contrasts in several respects to that inferred for the Grenville Province, suggesting perhaps not surprisingly that there may be no one-size-fits-all model for the origin and evolution of high-grade gneiss terranes in hot orogens.

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