ISSUES IN CANADIAN GEOSCIENCE

Taking the Pulse of Planet Earth: A Proposal for a New Multi-disciplinary Flagship Project in Canadian Solid Earth Sciences

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SUMMARY

Herein I propose a vision for a new multidisciplinary “big science” project for Canada’s solid earth sciences. I call this proposed project: “Taking the Pulse of Planet Earth”. At a modest cost, and over a 5 to 10 year life-span, it would aim at providing the most comprehensive and multidisciplinary knowledge base of the complete record of mafic magmatism in and around Canada, and through stimulating international cooperation, around the world.

A complete record of mafic magmatism (spatial distribution, ages, periodicities, rates, volume estimates, estimated geochemical fluxes to atmosphere and hydrosphere, tectonic settings, structural trends, sequence stratigraphic framework, evolving major and trace element compositions, evolving isotopic ratios, paleomagnetic information, paleo-intensities, associated ore deposits, etc.) constitutes critical input data for numerous first-order questions about the past and present evolution of our planet. Many of such questions relate to issues that are currently a focus of attention: global change, past climate extremes, complex Earth systems, planetary evolution, extinction events, flood volcanism, potential relationships with large impact events, and the discovery of new ore resources.

The proposed project is a focused, “smart”, and highly efficient approach to solve a large number of these seemingly unrelated but first-order questions in contemporary earth science. At its core, it would have a large dating program, aiming to provide approximately 200 new, high-precision ages of mafic magmatic events across Canada and adjacent regions. A Supporting Geoscience grant system would ensure that other aspects of the magmatic record receive equal attention. Finally, I illustrate the impact this project would have on paleo-continental reconstructions. As part of this illustration, I synthesize existing data on two dyke swarms, the ca. 2.45 Ga Matachewan and Kaminak swarms, respectively, and propose a novel Superior-Hearne reconstruction within supercraton Superia.

SOMMAIRE

Je propose ci-contre l’idée d’un nouveau projet multidisciplinaire de grande envergure dans le domaine des sciences des roches solides au Canada. J’ai nommé ce projet « Prendre le pouls de la planète Terre ». D’un coût modeste et s’échelonnant sur cinq à dix ans, ce projet constituerait la base de connaissances multidisciplinaire la plus complète de tout le répertoire des événements magmatiques mafiques au Canada et à son pourtour, cela, en profitant des effets stimulant de la coopération internationale.

Un répertoire complet des événements magmatiques mafiques (distribution spatiale, âges, périodicités, taux, estimations des volumes, estimations géochimiques des flux dans l’atmosphère et l’hydrosphère, cadres tectoniques, styles structuraux, cadres stratigraphiques des séquences, compositions des suites évolutives des éléments majeurs et en trace, évolution des ratios isotopiques, données paléomagnétiques, paléo-intensités, gisements associés, etc.) constitue un registre de données de base cruciales pour nombres de grandes questions sur l’évolution passée et actuelle de notre planète. Plusieurs de ces grandes questions sont liées à des problèmes actuels qui mobilisent l’attention, tels : les changements à l’échelle planétaire, les événements climatiques extrêmes du passé, les systèmes planétaires complexes, l’évolution de la planète, les grandes extinctions biotiques, les grands épanchements volcaniques, les liens éventuels avec de grands impacts météoritiques, ainsi que la découverte de nouvelles sources de minerai.

Le projet proposé constitue une approche ciblée, « habile », et très efficace permettant de solutionner un grand nombre de ces grands problèmes, sans liens apparents, des géosciences contemporaines. Au cœur du projet on retrouve un grand programme de datation visant à établir quelques 200 nouvelles datations de grande précision d’événements magmatiques au Canada et dans les régions périphériques. Un système de subvention d’appoint permettrait d’assurer que d’autres aspects de la problématique magmatique reçoivent autant d’attention. Finalement, à titre d’illustration, je décris les répercussions escomptées d’un tel projet sur les reconstitutions paléo-continentales. Dans le cadre de cette illustration, je présente une synthèse des données disponibles concernant deux réseaux de dykes, soit les réseaux de Matachewan et de Kaminak de 2,45 Ga, respectivement, et propose une nouvelle reconstitution Supérieur-Hearne dans le super-craton Supéria.

INTRODUCTION

LITHOPROBE, for more than two decades the premier flagship project of Canada's solid earth sciences, is winding down. Lithosphere-scale cross-sections have been gathered across the Canadian landmass and final syntheses are now being prepared (e.g., Percival et al., 2004). The inevitable ending of this project, on the heels of its success, will leave a growing vacuum across the Canadian earth science community at a time when competition for significant science funding is stronger than ever. Much of this competition revolves around highly visible "big science" projects in such fields as physics, astronomy, biochemistry and material science. Hence, we need to position ourselves to compete in this arena—we need a new flagship project. Here I will outline my vision for such a project, which I call "Taking the Pulse of Planet Earth" and which has at its core a large multidisciplinary study of all mafic magmatism through time. I use "mafic magmatism" as a shorthand here, but mean to include all mantle-derived magmatic activity other than steady-state arc magmatism; that is, all basalt (±komatiite)-dominated and (or) bimodal magmatism associated with divergent margins, or more generally extensional regimes, intraplate magmatic provinces, mantle plumes, anorogenic provinces, kimberlite and alkaline provinces.

Before describing this vision in some detail, it is important to understand the key reasons why LITHOPROBE was successful as a "big science" project, so that we may emulate some of the same proven formulae in any future project. First of all, proponents of LITHOPROBE had a grand vision (e.g., Keen, 1981; Clowes et al., 1984)—to understand the fundamental architecture of the Canadian crust and lithosphere from coast to coast, in the third dimension, and through time. Second, rapid advances in seismic reflection and deep probing electromagnetic techniques, largely made possible by rapid growth in modern electronics and computing power, opened an entirely new observational window into the crystalline crust and, increasingly over the last decade, into the lithospheric mantle (e.g., Calvert et al., 1995; Cook et al., 1999). Third, the transect approach divided the overall project up into manageable chunks, linking regional expertise pertinent to particular transects with thematic expertise from across the country. Fourth, the Supporting Geoscience grant system assured "buy-in" from a multi-disciplinary science community, bringing together the best minds from different disciplines and organizations to work together on cross-sections through the Canadian lithosphere. And finally, competent leadership and management made it all happen. Of course, favourable timing of these and other factors (e.g., funding sources and cycles, willingness of the Geological Survey of Canada to be a significant partner, industry interest), all coming together at the right time, was equally critical.

Although all of the reasons above are necessary for a successful "big science" project, the first two - a grand vision, and a powerful new observational window - are undoubtedly the most important at a conceptual stage of any new project, and hence I will focus on those. The "vision" I propose is to understand the first-order pulse of the Earth, as reflected in its record of mafic magmatic events, at a global scale and over 4.5 billion years of Earth history. The "new observational window" is provided by ever increasing precision, accuracy, and resolving power in a broad range of disciplines and techniques: geochronology, isotope and trace element geochemistry, paleomagnetism, sequence stratigraphy, and geophysical approaches such as tomography, receiver function analysis, and geodynamic modeling.

THE PULSE OF PLANET EARTH

Silicate planets regulate their internal thermal state through melting events in their mantles; through transport of these melts and entrained heat to their surfaces; through creation of new lithosphere; and through recycling of cold crust and lithosphere back into their hot convective interiors (e.g., Davies, 1999). Today, on Earth, plate tectonics is the dominant process and is driven to a large extent by the negative buoyancy of aged, and therefore cool, rigid, and relatively dense slabs of oceanic lithosphere (i.e., the upper thermal boundary layer of the convective mantle). Mantle plumes (e.g., Morgan, 1971; Ritsema and Allen, 2003; Montelli et al., 2004), originating from instabilities at deeper thermal boundary layers (i.e., the core-mantle boundary in whole-mantle convection, e.g., Campbell, 2001), are thought to contribute about 10% of the global heat loss (Davies, 1999). Plate tectonics and mantle plumes are two independent manifestations of mantle convection, one strongly controlled by the mechanical behaviour of the cold upper boundary layer (e.g., Anderson, 2002a), the other by the fluid dynamics of a hot deep boundary layer. Each process produces voluminous mafic magmas, but on different and independent time scales and with different characteristic plan forms.

At longer time-scales, plate tectonic activity appears quasi-periodic and self-organizes into the supercontinent cycle (e.g., Schuiling, 1973; Anderson, 1982; Gurnis, 1988). There are subtle indications that the periodicity between successive supercontinent cycles is getting shorter (Fig. 1), perhaps primarily because the average size of continental plates has increased, allowing less time lag between break-up and subsequent aggregation events (Bleeker, 2003; see also Hoffman, 1997).

Running time forward into the future, average plate size may grow further while the overall vigour of mantle convection will decrease as a result of secular heat loss and exponential decay of heat-producing elements. At some point in the future, plates will seize up (e.g., Anderson, 2002b) and ultimately planet Earth will die a "thermal death", a state long reached by our much smaller neighbouring planet, Mars. There will

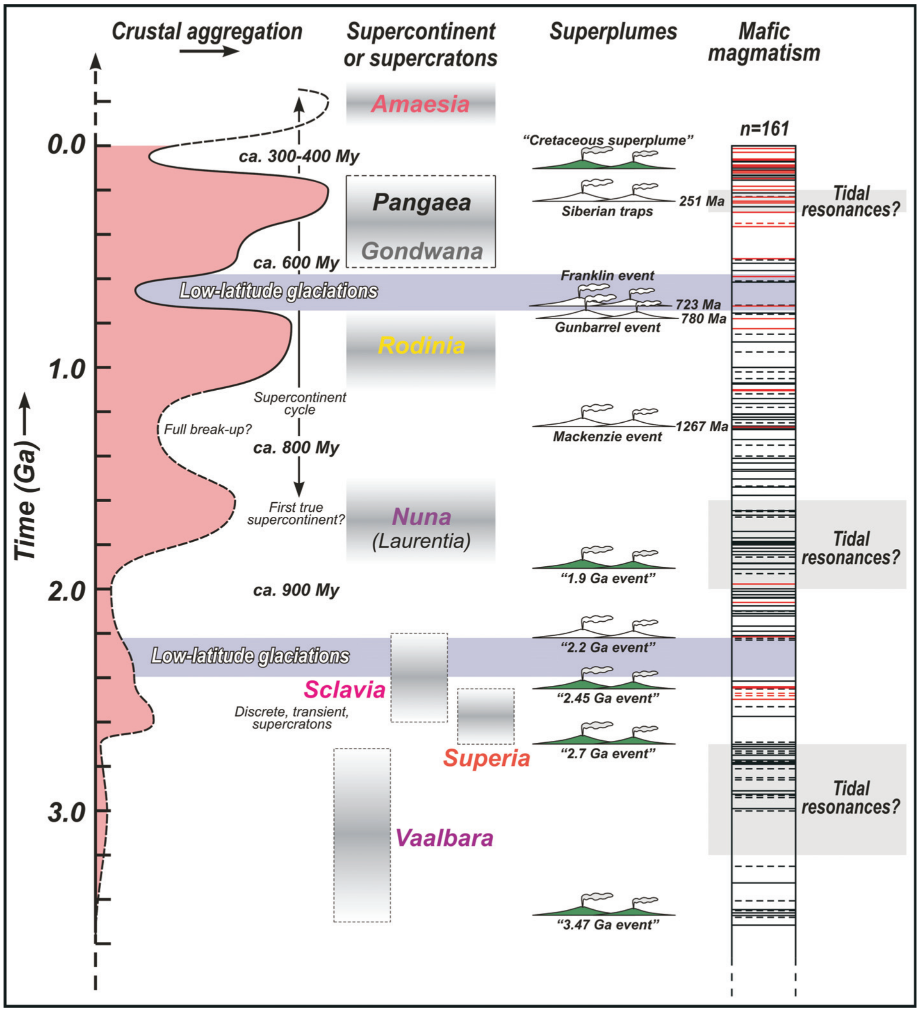


Figure 1 Crustal aggregation states (supercratons, supercontinents) through time (after Bleeker, 2003). The diagram shows several first-order events in Earth evolution that may relate, directly or indirectly, to the crustal aggregation cycle: superplume events (e.g., Condie, 2001), a compilation of mafic magmatic events (Ernst and Buchan, 2001), and the two Proterozoic time intervals during which low-latitude (global?) glaciations may have prevailed (e.g., Evans et al., 1997; Hoffman et al., 1998; Evans, 2000). Also shown are approximate intervals during which the fluid outer core may have experienced tidal resonances (Greff-Lefftz and Legros, 1999). Mid-Proterozoic Nuna was probably the first true supercontinent, whereas the late Archean may have been characterized by several discrete, transient, aggregations referred to here as supercratons: Vaalbara, Superia, Sclavia and possibly others. The diachronous breakup of these supercratons, during the Paleoproterozoic, spawned the present ensemble of approximately 35 Archean cratons, which now are variably incorporated into younger crustal assemblies. Since the assembly of Nuna, the time gaps between successive crustal aggregation maxima appear to have become shorter (Hoffman, 1997; Bleeker, 2003). Note the correlation of intervals of global glaciation with periods of continental breakup and dispersal, and with apparent minima in the frequency of mafic magmatic events in the continental record (legend for the latter: red line, well-established mantle plume event; black line, other mafic magmatic event; dashed line, poorly dated event; see Ernst and Buchan, 2001).

be a transient era, in which heat production will still exceed conductive heat loss so that the mantle underneath the seized-up lithosphere will heat up, and transient plume activity or mantle overturn events may temporarily bring back mobility to the lithosphere, resulting in significant resurfacing. This is the probable state of our closest sister planet, Venus. Smaller neighbouring planets, although each having unique attributes, provide to some extent future snapshots of planet Earth as the rate of thermal evolution scales inversely with planetary radius (but, see also Stevenson, 2003). In this sense, Venus, with a radius 0.95 that of Earth, is marginally ahead of us, whereas our much smaller Moon, after initial cooling of its magma ocean, may never have had a mobile lithosphere, although the 3.9–3.1 Ga mare basalts suggest significant transient heating and possibly one or more mantle overturn events (e.g., Hess and Parmentier, 1995; Stegman et al., 2003).

Going back in time, it is possible that mantle plumes may have played a more significant role, although this remains uncertain. Perhaps plume activity was highly episodic, in response to strong spikes in heat flow across the core-mantle boundary due to tidal resonances in the fluid outer core (Greff-Lefftz and Legros, 1999; see Fig. 1). Increased core heat flow would have temporarily destabilized the boundary layer (D") at the base of the mantle and sharply increased plume activity. Because past rates of deceleration of the Earth's spin (due to tidal drag) are variable and not very well known (e.g., Denis et al., 2002, and references therein), the absolute timing of these resonances are poorly constrained but are estimated at ca. 3.0±0.2 Ga and 1.8±0.2 Ga (Greff-Lefftz and Legros, 1999). Could this explain the post-Archean spike in komatiite magmatism at ca. 1.9 Ga, as observed in circum-Superior belts?

In the past, plate tectonic recycling must have operated faster (e.g., Burke et al., 1976; Hargraves, 1986) to keep pace with significantly higher heat production and a still significantly higher primordial heat budget retained from the era of accretion and internal differentiation (e.g., Richter, 1988; Pollack, 1997; Davies, 1999). Thermal arguments suggest that at some point in the distant past, plate tectonics may not have been able to keep pace with the required rate of heat loss (e.g., Davies, 1992, 1999) for the simple reason that oceanic lithosphere, on reaching a nearby trench, was on average too young (hence too buoyant to subduct), and too thin (and hence less capable of cooling the mantle). Therefore, other and less familiar geodynamic processes must have mediated the required heat loss, perhaps involving 1) catastrophic mantle overturn and melting events (Davies, 1995; Condie, 1998; e.g., the 2.72–2.70 Ga basalt-komatiite-rhyolite magmatism documented in virtually every fragment of Archean crust around the world?); and 2) a less organized return flow of lithospheric material into the deep mantle in the form of delamination or “drip” (e.g., Davies, 1992) of subcreted mafic and ultramafic material after its partial transformation into dense, refractory eclogite. As part of the transformation into dense eclogite, aqueous fluids and fusible tonalite-trondjhemite-granodiorite (TTG) components were extracted from the subcreted mafic-ultramafic material and ascended into the overlying crust to contribute to the formation of granite-greenstone terrains. Numerous questions remain, but these less familiar, non-uniformitarian processes explain in part why Archean cratons do not look like modern continental plates, even though many of the second-order processes were similar (e.g., Vlaar, 1986; Zegers and van Keken, 2001; Bleeker, 2002; Hamilton, 2003). Certainly there was great mobility, involving both horizontal and vertical tectonics, but not necessarily in the form of plate tectonics *sensu stricto,* driven by strongly asymmetrical subduction of rigid, negatively buoyant slabs.

Most importantly for the present purpose, all these processes of first-order geodynamic interaction between core, mantle, and lithosphere, and of planetary evolution in general, leave a record in the form of mafic magmatic events. The products of these mafic magmatic events are preserved in the continental geological record through time, and for the last 180 million years also in the oceanic record. With increasing precision and accuracy these mafic magmatic events can be dated (e.g., Krogh et al., 1987; Harlan et al., 2003), while at the same time the mafic magmas provide chemical probes into the evolution of the lithosphere and convective mantle (e.g., Sylvester et al., 1997; Campbell, 2003). Some of them entrain deep crustal and mantle xenoliths to the surface, providing the only direct rock samples of the lithosphere available to us. Remanent magnetism of mafic magmatic rocks, if primary, can provide paleo-intensities of the geomagnetic field at the time of crystallization (e.g., Macouin et al., 2003), thus providing constraints on processes in the liquid outer core. When did the inner core start to form (e.g., Labrosse et al., 2001)? And when did the geodynamo ignite?

The very presence of these mafic magmatic events signifies extension, rifting and break-up, and arrival of mantle plumes or asthenospheric upwellings. Some of the largest mafic magmatic events may be related to catastrophic mantle overturn events or slab avalanches. Basalt flows, dykes, and sills signify critical events on rifted margins and in the evolution of many sedimentary basins and, where they can be dated, allow time calibration of basin evolution. Some of the largest events are capable of venting enough CO_2, other volcanic gases, and (or) ash into the atmosphere to result in major environmental deterioration and upsets of the greenhouse balance. Although ultimate causes are still being debated (e.g., Courtillot and Renne, 2003), the two largest Phanerozoic extinction events, the Permo-Triassic and K-T boundaries, overlap in time or immediately follow the extrusion of some of the largest continental flood basalt sequences, the Siberian (e.g., Kamo et al., 2003) and Deccan (Hofmann et al., 2000) traps, respectively. Collectively, mafic magmatic events provide perhaps the most important record of “the pulse of the Earth” (e.g., Larson, 1991) in its overall thermal evolution from a hot, young planet to a cold, dead planet.

DATING ALL MAFIC MAGMATIC EVENTS THROUGH TIME

Many mafic magmatic events have been precisely dated (e.g., see Ernst and Buchan, 2001 for a recent compilation; see also Ernst and Buchan, 2004); however, many others remain undated or have yielded imprecise, less robust, or questionable ages (e.g., many old K-Ar ages). A few mafic magmatic events may not be datable directly, although with continuing advances in U-Pb and ^{40}Ar-^{39}Ar dating, their number is shrinking. Hence, given the significance of mafic magmatic events to nearly all first-order geodynamic processes, either as direct manifestations of these processes, or as time calibrators, it is surprising that no concerted national or international effort has yet been made to date all such events and obtain a complete time series of mafic magmatism and its critical attributes. Perhaps this deficiency is more conspicuous now then ever, at a time when highly capable robotic rovers are investigating the surface of a neighbouring planet, yet key elements of the much more readily available terrestrial record remain poorly known.

Significant interest in a complete record of all terrestrial mafic magmatism exists in Canada and, indeed, Canadian geochronologists have been leading efforts to date such rocks. There is equal interest in this around the world, and a Canadian initiative may be the critical impetus for a global initiative (e.g., see plans for an international dating campaign on pre-Mesozoic large igneous provinces being developed by the Large Igneous Provinces Commission, at www.largeigneousprovinces.org). A comprehensive study of all mafic magmatism on Earth would have major impacts across numerous earth science disciplines, ranging from the study of ancient tectonic regimes, and the chemical and dynamic evolution of the core and mantle, to testing putative links between major flood volcanism, impacts, and extinctions, and the study of what triggers major climatic excursions. It is beyond the scope of this paper to do equal justice to all these disciplines and questions; below, I will merely illustrate potential impacts on two related fields: Precambrian evolution and paleo-continental reconstructions.

PALEO-CONTINENTAL RECONSTRUCTIONS

Let us examine plate tectonic reconstructions of various times in the past and the impact a global dating program would have on such reconstructions.

The extant record of Archean crust is highly fragmented and scattered around the globe in about 35 significant pieces, the “Archean cratons” (Bleeker, 2003). Each of these cratons is crosscut by numerous mafic dykes swarms, the precise ages of which provide a “bar code” (Fig. 2) that identifies that piece of crust and which can be expected to match, at least in part, the “bar code” from a distant craton that has since rifted off and been dispersed around the globe. For example, from the time of its formation in an ancestral landmass (Kenorland or Superia? see Bleeker, 2003), up to its incorporation into the Laurentian collage (Hoffman, 1988, 1989), the Superior craton was cut by as many as 20 mafic dyke swarms and intrusive events (Buchan and Ernst, 2004). To date, only about half of these events have been dated precisely. In contrast, the Slave craton in northwestern Canada was intruded, over a similar time interval, by about 10 dyke swarms, few if any of which match those in the Superior. Hence, these two distinct pieces of Archean crust were never close neighbours and likely originated from different ancestral supercratons (Bleeker, 2003). Only by 1.9–1.8 Ga were these crustal fragments brought into relative proximity during their amalgamation into Laurentia (Hoffman, 1988).

Subsequently, both cratons were cut by radiating dykes of the giant Mackenzie swarm at 1267 Ma (LeCheminant and Heaman, 1989), which fan out from a focal point along the northern edge of the Slave craton to the southeast, as far as the northwestern Superior craton (e.g., Ernst and Baragar, 1992; Baragar et al., 1996). Were Laurentia to break up, it would be the shared record of the Mackenzie swarm dykes, and their inherent paleomagnetic record, that would allow reconstruction of Laurentia and reveal, most conclusively, a shared, transient, residence of the Slave and Superior cratons in this continent from some time prior to 1267 Ma to the time of breakup.

Although correlation of platformal sequences on dispersed cratons is one of the more definitive tools to track initially adjacent pieces of crust (e.g., the sequence stratigraphic correlation of the Transvaal Supergroup, overlying the Kaapvaal craton, with that of the Mount Bruce Supergroup, overlying the Pilbara craton; e.g., Cheney, 1996), it is not the most generally applicable tool, because it relies on good preservation. During collision and orogenesis, platformal sequences may be entirely removed by uplift and erosion. Even where platformal sequences are preserved and potential sequence stratigraphic correlations can be made, they may not provide the detailed spatial and directional information to tightly constrain past configurations.

Mafic dyke swarms, on the other hand, have a significant aerial and depth extent and commonly survive significant uplift. Equally important, they provide a trend and thus directional information, as well as potentially precise piercing points (Park et al., 1995; Buchan and Ernst, 1997). In theory, an analysis of flow direction (e.g., from magnetic fabrics or imbrication of tabular plagioclase phenocrysts in the laminar flow regime near dyke margins) can provide unique azimuthal directions. Integrated mapping, high-precision age dating, fabric studies, and paleomagnetism of mafic magmatic events and their dyke swarms thus allow continental fragments to be placed:

1) at a specific latitude;
2) at a specific time;
3) with a known orientation;
4) in an position that optimizes geological continuity prior to break up and dispersal; and
5) that satisfies the specific requirements of precise piercing points.

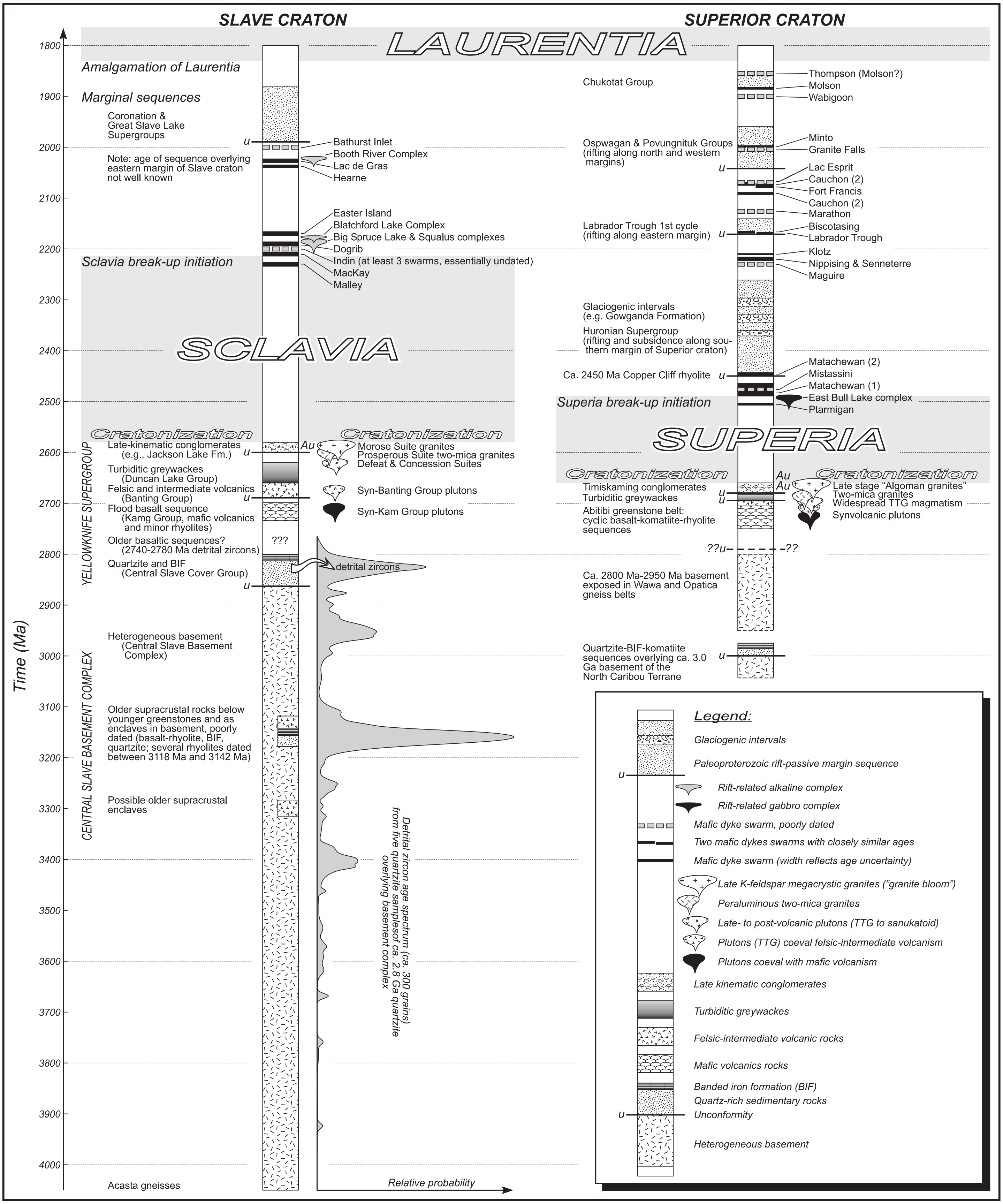
In an ideal case, information from multiple dyke swarms (e.g., all dyke swarms of the Superior, precisely dated) would allow definition of improved apparent polar wander paths, providing additional information on how a certain continental fragment arrived at a specific location and which other blocks were fellow travelers. When a supercraton breaks up, apparent polar wander paths bifurcate; when two cratons are joined by collision, two previously independent paths merge into a common path. Better-defined and more densely populated polar wander paths can greatly reduce or even eliminate the ambiguities due to polarity. They may also contribute to the understanding of true polar wander events (e.g., Evans, 2003).

None of these various approaches is strictly new and various pioneers have applied them successfully, particularly over the last two decades. However, their scale of application and integration, under the proposed project, would be new. As recent examples, Wingate et al. (2002) have shown the power of every new precisely dated mafic event and associated paleopole in testing the putative Laurentia-Australia connection in the mid-Proteozoic, whereas Buchan et al. (2000) have applied similar tests to Laurentia-Baltica connections. However, no comprehensive effort has been made to address these questions for all mafic magmatic events across Canada. For instance, about half of the mafic magmatic events in the Slave and Superior, two of the best-studied cratons worldwide, remain to be dated precisely. Worse, few if any mafic dyke swarms have been dated from the Rae craton and, hence, the ancestry of this second-largest building block of Laurentia remains entirely unknown.

Given the improved precision in many of the underlying techniques, and the growing awareness that mafic magmatic events and their inherent information (precise age, composition, causative tectonic event, orientation, paleolatitude and polar wander path) provide the most efficient, robust, and generally applicable tools to unravel past plate configurations, the time seems right for a national and international effort.

AN EXAMPLE: A SUGGESTED SUPERIOR-HEARNE CORRELATION AT 2.45 GA

As one further illustration of the power of this approach, I will present a possible reconstruction of the Hearne and Superior cratons prior to their breakup and dispersal sometime before 2.0 Ga. The Superior craton is cut by the large Matachewan dyke swarm


SLAVE CRATON
SUPERIOR CRATON
LAURENTIA
1800
1900
2000
2100
2200
2300
2400
2500
2600
2700
2800
2900
3000
3100
3200
3300
3400
3500
3600
3700
3800
3900
4000
Time (Ma)
Amalgamation of Laurentia
Marginal sequences
Coronation & Great Slave Lake Supergroups
Note: age of sequence overlying eastern margin of Slave craton not well known
u
Bathurst Inlet
Booth River Complex
Lac de Gras
Hearne
Easter Island
Blatchford Lake Complex
Big Spruce Lake & Squalus complexes
Dogrib
Indin (at least 3 swarms, essentially undated)
MacKay
Malley
Sclavia break-up initiation
SCLAVIA
Cratonization
Cratonization
YELLOWKNIFE SUPERGROUP
Late-kinematic conglomerates (e.g., Jackson Lake Fm.)
Au
u
Morose Suite granites
Prosperous Suite two-mica granites
Defeat & Concession Suites
Turbiditic greywackes (Duncan Lake Group)
Felsic and intermediate volcanics (Banting Group)
u
Syn-Banting Group plutons
Flood basalt sequence (Kamg Group, mafic volcanics and minor rhyolites)
Syn-Kam Group plutons
Older basaltic sequences? (2740-2780 Ma detrital zircons)
???
Quartzite and BIF (Central Slave Cover Group)
u
detrital zircons
CENTRAL SLAVE BASEMENT COMPLEX
Heterogeneous basement (Central Slave Basement Complex)
Older supracrustal rocks below younger greenstones and as enclaves in basement, poorly dated (basalt-rhyolite, BIF, quartzite; several rhyolites dated between 3118 Ma and 3142 Ma)
Possible older supracrustal enclaves
Detrital zircon age spectrum (ca. 300 grains) from five quartzite samplesof ca. 2.8 Ga quartzite overlying basement complex
Acasta gneisses
Relative probability
Chukotat Group
Thompson (Molson?)
Molson
Wabigoon
Ospwagan & Povungnituk Groups (rifting along north and western margins)
Minto
Granite Falls
u
Lac Esprit
Cauchon (2)
Fort Francis
Cauchon (2)
Marathon
Labrador Trough 1st cycle (rifting along eastern margin)
u
Biscotasing
Labrador Trough
Klotz
Nippising & Senneterre
Maguire
Glaciogenic intervals (e.g. Gowganda Formation)
Huronian Supergroup (rifting and subsidence along southern margin of Superior craton)
Ca. 2450 Ma Copper Cliff rhyolite
u
Matachewan (2)
Mistassini
Matachewan (1)
East Bull Lake complex
Ptarmigan
Superia break-up initiation
SUPERIA
Cratonization
Cratonization
Timiskaming conglomerates
Turbiditic greywackes
u
u
Au
Au
Late stage "Algoman granites"
Two-mica granites
Widespread TTG magmatism
Synvolcanic plutons
Abitibi greenstone belt: cyclic basalt-komatiite-rhyolite sequences
??u
??
Ca. 2800 Ma-2950 Ma basement exposed in Wawa and Opatica gneiss belts
Quartzite-BIF-komatiite sequences overlying ca. 3.0 Ga basement of the North Caribou Terrane
u
Legend:
Glaciogenic intervals
Paleoproterozoic rift-passive margin sequence
u
Rift-related alkaline complex
Rift-related gabbro complex
Mafic dyke swarm, poorly dated
Two mafic dykes swarms with closely similar ages
Mafic dyke swarm (width reflects age uncertainty)
Late K-feldspar megacrystic granites ("granite bloom")
Peraluminous two-mica granites
Late- to post-volcanic plutons (TTG to sanukatoid)
Plutons (TTG) coeval felsic-intermediate volcanism
Plutons coeval with mafic volcanism
Late kinematic conglomerates
Turbiditic greywackes
Felsic-intermediate volcanic rocks
Mafic volcanics rocks
Banded iron formation (BIF)
Quartz-rich sedimentary rocks
u
Unconformity
Heterogeneous basement

(e.g., Halls and Zhang 1998, and references therein), which radiates from an apparent focal point along its Huronian margin—a probable break-up margin that was later obscured by younger Grenvillian overthrusts. Although complicated by the presence of two age populations, the younger Matachewan dykes have been dated precisely at 2446 Ma (e.g., Heaman, 1997). Many of these dykes contain abundant, large plagioclase megacrysts (Fig. 3a, b, c), which set these dykes apart petrographically from many other dyke swarms. I estimate that such an abundance of large plagioclase megacrysts occurs in fewer than 10% of mafic dyke swarms worldwide. Following up on earlier suggestions of similar dykes in the Kaminak area of the Hearne craton (Christie et al., 1975), Heaman (1994) showed that these dykes, characterized by a similar abundance of large plagioclase megacrysts (Fig. 3d, e), are essentially identical in age (ca. 2.45 Ga, Heaman, 1994). Remarkably, both dyke swarms trend in a northerly direction, at high angles to dominant late Archean tectonic trends in each craton.

Existing paleomagnetic data (Christie et al., 1975) allow the Hearne craton to be placed, at ca. 2.45 Ga, just to the south of the Huronian margin of the Superior craton (Fig. 4a, b, c) - a position that could equate the Kaminak dykes with a southern continuation of the younger age population of the Matachewan dykes, perhaps as another branch of a giant radiating dyke swarm associated with a triple junction along the Huronian margin (Fig. 4d). This configuration (Fig. 4d) suggests that dyke intrusion, rifting, and eventual break-up of supercraton Superia may have occurred in response to the arrival of a mantle plume head—the Matachewan plume of Heaman (1994). The proposed reconstruction would suggest a more or less direct correlation between the partly glaciogenic Huronian Supergroup (e.g., Young et al., 2001) and Hurwitz Group (e.g., Young, 1973, 1975), perhaps on either side of a large continental rift (Fig. 5). By 2218 Ma, the age of the Nipissing diabase sills in the Huronian Supergroup (Corfu and Andrews, 1986; Krogh et al., 1987), this rift was evidently wide enough to impede southward propagation of Nipissing magmas across the rift into the Hurwitz basin. Nipissing sill magmas are thought to be derived, via a radiating swarm of feeder dykes, from a focal point northeast of the Superior craton (Buchan et al., 1998).

This Superior-Hearne

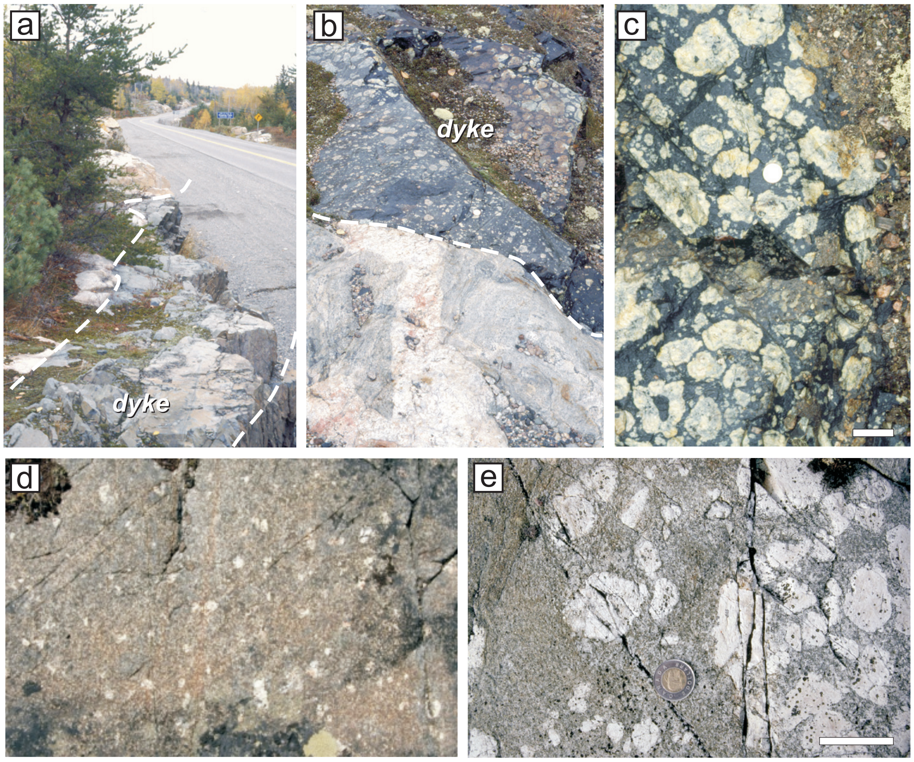


Figure 3 Field photographs of the Matachewan (a,b,c) and Kaminak (d,e) mafic dyke swarms. Both dyke swarms have been dated at ca. 2.45 Ga (Heaman, 1994, 1997). **a.** North-trending Matachewan swarm cutting southern Superior Province granitoids, along highway 144 from Sudbury to Timmins. **b.** Margin of typical Matachewan dyke, with abundant 1–5 cm plagioclase megacrysts. **c.** Close-up of photo b; scale bar: 5 cm. **d.** Typical Kaminak dyke with moderately sized plagioclase phenocrysts. e. As photo d, but with larger and more abundant plagioclase megacrysts; scale bar: 5 cm.

Figure 2 Comparison of the partial “bar codes” of the two best-known Archean cratons in Laurentia, the Slave and Superior cratons. Because of lateral heterogeneity of the Superior craton, the older record is not easily generalized and may be less relevant to craton correlations. Younger Archean stratigraphy of the Superior craton is based on the Abitibi greenstone belt and surrounding granitoid terrains (e.g., Card, 1990; Corfu, 1993; Bleeker, 1999; Ayer et al., 2002). Ages of dyke swarms are from compilation by Ernst and Buchan (2001). Detrital zircon record from ca. 2.8 Ga quartzites (Sircombe et al., 2001) used as a proxy for basement ages in the Slave craton (see also Bleeker and Davis, 1999). Except for widespread basalt-komatiite volcanism between 2730 Ma and 2700 Ma in both cratons, there are no significant age matches. Cratonization of the Superior craton preceded that of the Slave by at least 50 to 70 million years. Following cratonization, the Slave and Superior cratons were part of different supercratons, Sclavia and Superia. Breakup of Superia was initiated at ca. 2.45 Ga (e.g., Heaman, 1997), whereas Sclavia did not break up before 2.23 Ga. Breakup of each supercraton must have spawned several independent Archean cratons some of which must have been “nearest neighbours” to either the Slave or the Superior in these ancestral landmasses. Finally, from about 2.0 Ga to 1.8 Ga, the Slave and Superior, and several other cratonic fragments, were incorporated in the crustal collage of Laurentia.

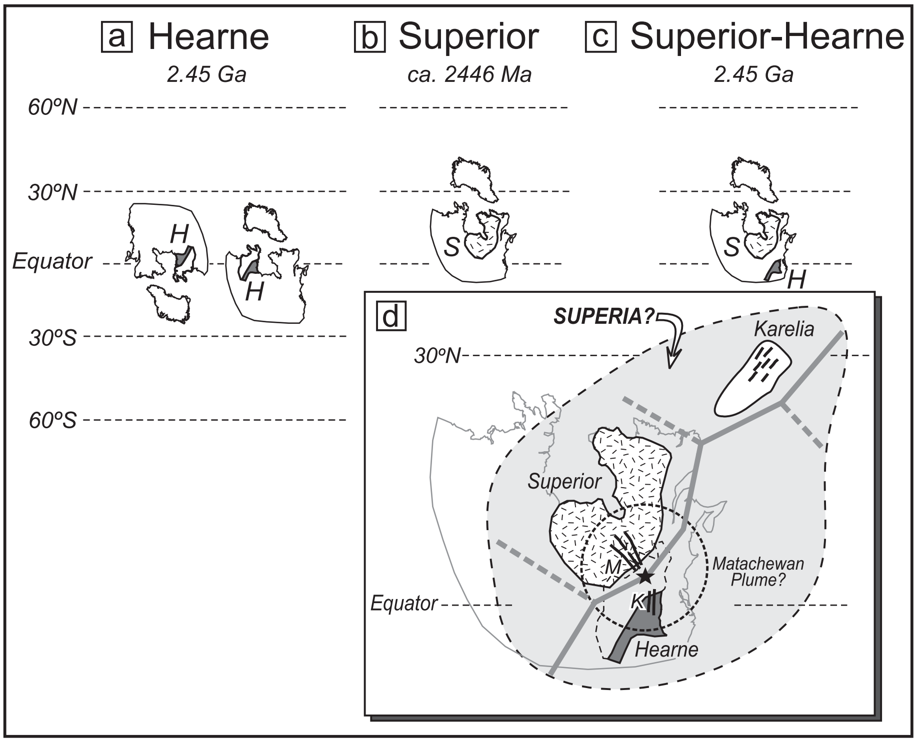


Figure 4 Inferences from paleomagnetic data for the ca. 2.45 Ga Kaminak (Hearne craton (H), Fig. a) and Matachewan dykes (Superior craton (S), Fig. b). Kaminak paleopole based on three sampling sites and data of Christie et al. (1975); Matachewan paleopole based on 36 sampling sites data of Bates and Halls (1990). Outline of Laurentia shown for reference only. Hemispherical ambiguity allows two orientations of the Hearne craton relative to the Superior. Because of a near-equatorial position, both orientations would permit the Hearne craton to have originated south of the Huronian margin of the Superior craton (e.g., see Fig. c for a "normal" orientation of Hearne, which allows for a better geological fit). Inset (d) shows enlargement of the proposed Superior-Hearne configuration in supercraton Superia, at 2.45 Ga, with locations and approximate orientations of Matachewan (M) and Kaminak (K) dykes. Dashed, 2000 km-diameter circle, is the putative "Matachewan plume" head (Heaman, 1994) centered on the Huronian margin. The Karelian craton is also shown, in a position suggested by Mertanen et al. (1999), as is a hypothetical rift topology.

reconstruction (Fig. 4d), prior to Paleoproterozoic break-up and dispersal of these cratonic fragments, is arguably one of the most specific, and testable, pre-2.0 Ga plate reconstructions proposed to date, although the Kaminak swarm paleomagnetic pole (Christie et al., 1975) and age need to be improved. An immediate and straightforward test would be to investigate the flow direction in Kaminak dykes, as the reconstruction of Figure 4 would predict a north-to-south magma flow in these dykes, away from a northerly plume source.

If correct, the new reconstruction would further suggest that Hearne crust and its large, juvenile Kaminak greenstone belt represent a continuum of the belt-like crustal growth observed in the southern Superior craton. Alternatively, if refined 2.45 Ga paleopoles for both the Kaminak and Matachewan swarms would prove to be statistically identical (i.e., the original interpretation of Christie et al., 1975), it would place both cratons in approximately their current relative position at ca. 2.45 Ga. This alternate result may require a radical re-interpretation of Trans-Hudson Orogen in terms of being the product of opening and closure of a narrow "intra-cratonic" ocean rather than the prevailing view of a wide Manikewan ocean (Stauffer, 1984; see also Symons, 1998; Halls and Hanes, 1999). These first-order questions about the fundamental architecture and evolution of Laurentia have presented themselves loud and clear since the 1975 paper of Christie et al., yet they remain unresolved. A related question is the identity and significance of the two or more age populations among the dykes of the composite Matachewan swarm.

PALEOGEOGRAPHY AT CA. 1883 MA: WHERE ARE THE CONJUGATE MARGINS OF THE SUPERIOR?

Although possibly distracting the discussion from the specific late Archean Superior-Hearne reconstruction proposed above, it is worth pointing out that very similar paleogeographic questions present themselves again when we consider the distribution of ca. 1883 Ma mafic-ultramafic magmatism around the margins of the Superior craton (e.g., Molson dykes, Fox River Sill). If this widespread magmatism is related to rifting and break-up of the Superior craton, perhaps related to arrival of a mantle plume underneath the western part of this craton, why do we find mafic sills of identical age (1883±5 Ma; R. Parrish, unpublished date; mentioned in Van Kranendonk et al., 1993) in the Piling Group on the southern flank of the Rae craton? Are these identical ages mere coincidence, or a product of insufficient age accuracy? Or do they suggest proximity of the Piling Group basin, and by inference the Rae margin, to the Superior craton and the Molson plume centered on this latter craton?

In general, which margins were conjugate to the circum-Superior margin at ca. 1.88 Ga and where are they now? Given the presence of world-class mineral deposits along the western and northern Superior margin (e.g, Thompson, at 80 Mtonnes the largest komatiite-associated Ni-Cu-PGE deposit in the world), this question is of more than scientific interest. Again, all these questions are most clearly and critically addressed by a comprehensive survey of the record of ca. 1.88 Ga mafic magmatism around the Superior and other cratons and the information inherent therein: spatial distribution, sequence stratigraphic framework, high-resolution age data, and paleomagnetic information.

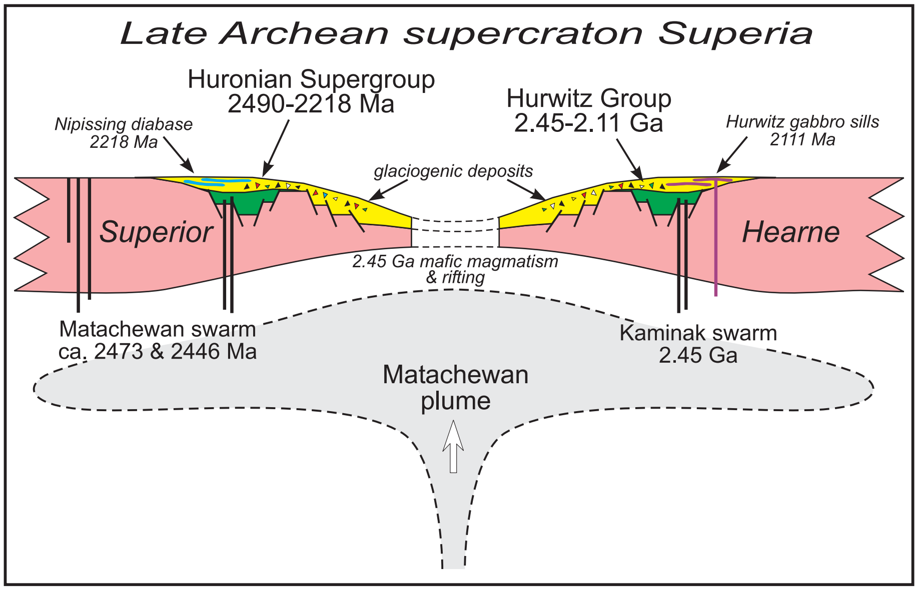


Figure 5 Schematic cross-section through Superior-Hearne prior to their Paleoproterozoic break-up and dispersal, based on matching age, petrographic character, and paleopole information of Matachewan and Kaminak dykes. This configuration suggests direct correlation of the Huronian Supergroup and Hurwitz Group, both of which contain glaciogenic intervals (e.g., Young, 1973, 1975; Ojakangas, 1988). Nipissing diabase dykes and sills, which are thought to have invaded the Huronian basin from a northerly source (Buchan et al., 1998), apparently failed to cross the widening rift at 2218 Ma. Alternatively, break-up had already occurred by 2218 Ma.

DISCUSSION

The time is right for a comprehensive, multidisciplinary, Canada-wide study of all mafic and intraplate magmatic events through time, their precise ages, their tectonic settings, and other inherent information, which not only addresses critical paleogeographic questions but has the potential to illuminate secular evolution of the mantle and the core.

Results from such a project would produce a quantum leap in the understanding of Precambrian terrains, younger break-up margins, and past plate configurations such as the Superior-Hearne reconstruction proposed herein, particularly if a Canadian project would help stimulate similar initiatives on other continents (e.g., Australia, southern Africa, Europe, Russia and China). More complete "bar codes" for a significant number of Precambrian crustal fragments would immediately lead to more robust reconstructions of past crustal aggregations, including that of Rodinia (e.g., Hoffman, 1991) and Nuna, as well as the first outlines of Archean supercratons. Equally important, with a complete time series of mafic magmatic events, we can investigate apparent periodicities (e.g., Prokoph et al., 2004), pulses and gaps, and their ultimate causes—i.e. the pulse of planet Earth. With volume estimates, we can address production rates over time. Is there a connection with climate and extinctions (e.g., Courtillot and Renne, 2003)? Is there a connection with large impacts (Abbott and Isley, 2002; Glikson, 2003; Becker et al., 2004)?

The overall price tag of the proposed project would be substantial but modest compared to that of LITHOPROBE. Funding on the order of 10 M$ over 10 years would allow many of the goals to be achieved, including approximately 200 new high-precision ages. Of course, increased funding would allow more supporting geoscience and hence assure broader buy-in from a wider spectrum of disciplines.

Naturally, high-precision geochronology would be a lead discipline, as precise ages are critical to the ordering of events in their correct sequence, the unraveling of cause and effect, and the determination of rates. However, the following disciplines would all be natural and equal partners in this potential "big science" project: major and trace element geochemistry, isotope geochemistry, paleomagnetism, paleo-intensity studies and insights into core dynamics, structural geology and tectonics, regional mapping, sequence stratigraphy and basin analysis, petrology and xenolith studies, geophysics, geodynamic modeling, economic geology (Ni-Cu-PGEs, Cr, diamonds), Earth systems science and the study of extinction events.

A strategic link with the Integrated Oceanic Drilling Program (IODP; http://www.iodp.org) would extend the scope into the marine and oceanic realm. Finally, this project would aim to understand the evolution of planet Earth in its true natural context - the dynamic evolution of the Solar System. Hence it would seek close links with the planetary science community. Perhaps more so than for LITHOPROBE, international participation should be encouraged, to benefit from expertise not currently resident within Canada.

Major industry players around the world are spending considerable time and money on the understanding and exploration of mafic magmatic provinces, with the potential rewards of world-class mineral deposits such as those of Norilsk, Thompson, or a Merensky Reef. Even other deposit types, not traditionally related to mafic magmatic events (VMS, SEDEX), may owe their ultimate origin to mafic or ultramafic intrusions, i.e. as the heat engines that drove hydrothermal circulation (e.g., Pirajno, 2000). Key examples would be the 2716–2710 Ma, giant Kidd Creek Cu-Zn-Ag deposit, closely associated with ultramafic flows and intrusions (Bleeker, 1999; Hannington and Barrie, 1999), or the Sullivan Pb-Zn deposit in the Belt-Purcell basin, closely associated with the 1468 Ma Moyie sills (e.g., Anderson and Davis, 1995). Hence, there is no doubt that industry would be a supportive partner, allowing significant opportunities for matching funding.

Finally, the same tectonic questions that control mafic magmatic events are also relevant to the triggering and emplacement of kimberlite provinces. Indeed, as emphasized in the introduction, this project should include all intra-plate magmatic events as they reflect equally on the tectonic pulse of the Earth. This project will clearly look into the mantle, and in some ways even into the core. In this sense it is a logical follow-up on LITHOPROBE, which had a definite crustal and lithospheric perspective. Through its mantle perspective there is potential for synergies with the POLARIS project already underway in the geophysical community.

CONCLUSIONS

"Taking the Pulse of Planet Earth", by means of a comprehensive multidisciplinary study of the complete record of mafic magmatism, including a large dating program, is a "smart" and highly efficient approach to address a number of first-order questions in contemporary Earth science over the next 5 to 10 years.

A complete record of mafic magmatism (ages, periodicities, rates, volume estimates, geochemical fluxes, spatial distribution, structural trends, evolving isotope and trace element ratios, paleomagnetic information, associated ore deposits, etc.) will provide critical constraints on issues as diverse as paleogeographic reconstructions and the supercontinent cycle; the triggers of past climate extremes; complex Earth systems through time; crustal growth, core and mantle evolution; evolution of the core dynamo; causes of flood volcanism, and the potential relationships with extinction events; the hypothesized relationship between flood volcanism and large impact events; and, last but not least, the discovery of new ore deposits of strategic minerals.

The proposed project is certain to stimulate a quantum leap in the understanding of Precambrian terrains and their paleogeographic distribution through time. More importantly, a more complete understanding of mafic magmatism through time will provide new insights into the evolution of planet Earth. Finally, this project would promote, at a modest cost, new links between numerous earth science disciplines and facilitate further integration between earth and planetary sciences.

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