Short-lived mantle generated magmatic events and their dyke swarms: The key unlocking Earth's paleogeographic record back to 2.6 Ga

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In: Dyke Swarms—Time Markers of Crustal Evolution, edited by E. Hanski, S. Mertanen, T. Rämö and J. Vuollo, A.A. Balkema Publishers, Rotterdam, 2006.

ABSTRACT

The continents preserve a rich record of short-lived mantle-generated magmatic events through time and space. Many of these events can now be dated routinely and precisely, with a resolution of a couple of million years or better. The spatial and temporal association of such events with rifting and continental break-up leads to remnants being preserved on originally adjacent (conjugate) margins and their respective hinterlands. Originally adjacent but now distant pieces of crust are thus likely to share remnants of one, if not several, short-lived magmatic events. The overall record of short-lived magmatic events ("magma bursts") in a particular fragment of continental crust defines, in essence, a high-resolution "barcode" that characterizes the ancestry of that piece of crust. Originally adjacent pieces of crust ("nearest neighbours") are thus likely to share part of their barcodes. Even though break-up margins may be severely modified and reworked during subsequent events, and many of the break-up related volcanic rocks may have long been eroded, associated dyke swarms have high preservation potential and are likely to preserve within them the high-resolution spatial and temporal information needed to allow successful paleogeographic reconstructions. Other independent, but generally more fuzzy data can then be used to test specific reconstructions based on the precise "piercing points" provided by coeval dyke swarms. In this paper we illustrate the general methodology and propose a new and detailed Superior-Hearne-Karelia reconstruction forming the core of 2.7-2.1 Ga supercraton Superia. In general, a complete characterization of all fragments of continental crust in terms of their magmatic event barcodes would be the most efficient way to solve Earth's pre-Pangaea paleogeographic evolution, as far back as 2.6 Ga. High-resolution ages are the most efficient early filter to focus further work (e.g. paleomagnetism, geochemistry) on globally significant events. Only several hundred new ages would be required to catalyze a quantum leap of progress in this overall field. To store and efficiently disseminate all relevant data on short-lived magmatic events, we urgently need a peer-reviewed global database, similar to other formal databases in related fields that deal with globally significant datasets. To stimulate the creation of such an international database we herein propose datasheets that list the kind of information required for each short-lived magmatic event.

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INTRODUCTION

Among the most fundamental contributions of the geological sciences to the overall body of scientific knowledge are: 1) the concept of deep time; 2) an increasingly detailed record of biotic evolution, as preserved in the fossil record; 3) a detailed and mobilistic view of the dynamics of planet Earth, e.g. mantle convection, plate tectonics, and mantle plumes; and 4) a record of its evolving paleogeography through time. In recent years, the ongoing geological and geophysical exploration of amazingly diverse planetary bodies across the Solar System is quickly shaping up as another such fundamental contribution.

The fourth entry in this short list is very much a work in progress, known in detail only back to ca. 250 Ma, the time of "maximum packing" of supercontinent Pangaea. Prior to 250 Ma, the paleogeographic record of Earth's continental crust becomes increasingly speculative, although there is growing optimism that this problem may be tractable, in principle, back to ~2.6 Ga, the age of "cratonization" of a considerable fraction of continental crust extant today (e.g. Bleeker 2003). Crustal fragments significantly older than this age of cratonization are either too few in number or too reworked to ever allow a meaningful pre-2.6 Ga global paleogeographic synthesis, although isolated reconstructions may be attempted for some of the better preserved crustal fragments (e.g. an ancient Pilbara-Kaapvaal connection; Cheney et al. 1988, Trendall et al. 1990, Cheney 1996, Wingate 1998, Zegers et al. 1998, Nelson et al. 1999, Strik et al. 2001, Byerly et al. 2002). And, within the realm of individual Archean cratons, qualitative docking histories of terranes can be established at ca. 2.7 Ga, for instance the apparent crustal growth within the Superior craton (Percival et al. 2004, Percival & Williams 1989).

Going back in time beyond Pangaea, an increasing number of "pieces of the puzzle" may be missing or their diagnostic information so thoroughly degraded that any reconstruction suffers, inevitably, from increasing degrees of freedom. Continuing attempts to reconstruct ca. 0.9 Ga supercontinent, Rodinia, reflect this uncertainty (e.g. Jefferson 1978, Sears & Price 1978, 2003, Gower et al. 1990, MacMenamin & McMenamin 1990, Dalziel 1991, Hoffman 1991, Moores 1991, Buchan et al. 2001, Karlstrom et al. 1999, 2001, Wingate et al. 2002, Pisarevsky et al. 2003, Li et al. 2005, Fioretti et al. 2005). Furthermore, in the Precambrian, with at best an incipient fossil record and with paleomagnetic datasets that are commonly complicated by overprinting, our toolkit is severely limited. In the pre-Pangaea world, there is no preserved record of ocean floor spreading to help guide paleogeographic reconstructions. Such reconstructions thus rely on matching details in continental geology from one craton to the next (e.g. Gower et al. 1990, Karlstrom et al. 2001, Thorkelson et al. 2001). Many such details are 1) inherently fuzzy (e.g. ages of granitoid belts and metamorphism), 2) variable or diachronous along strike (e.g. orogenic belts and their structural trends, ages of structural events), or 3) highly susceptible to modification (e.g. the outlines of sedimentary basin and the "piercing points" they provide). This renders many of the reconstructions based on such data uncertain, allowing multiple solutions that require further critical data for ultimate confirmation.

In the last two decades, however, our increasing ability to date many short-lived mafic magmatic events (e.g. Krogh et al. 1987, Heaman & LeCheminant 1993), commonly with a precision of ±2 Ma or better, has paved the way for perhaps the most robust tool in reconstructing ancient continental paleogeographies: integrated mapping, high-precision age dating, and paleomagnetism of short-lived mafic magmatic events and their dyke swarms (e.g. Halls 1982, Fahrig 1987, Buchan et al. 2000, Wingate & Giddings 2000, Ernst et al. 2005, Vuollo & Huhma 2005). Data thus gathered allow continental fragments to be placed:

1. at a specific latitude;
2. at a specific time;
3. with known orientation;
4. such that the precise piercing points provided by the dyke swarms are satisfied; and
5. in a position that optimizes general geological continuity prior to break-up and dispersal.

As will be demonstrated below, successful matching of more than one dyke swarm across two cratons has the ability to provide unique and robust solutions, even in the absence of high-quality paleomagnetic data.

Precise age matches among short-lived mafic magmatic events are a first and highly efficient filter to alert us to the possibility that two cratons, now distant, may have been adjacent pieces of crust in an ancestral landmass, i.e. "nearest neighbours" (Bleeker 2003). As explained below, this realization leads to the simple but powerful concept of "barcodes" (Bleeker 2004) to uniquely identify the ancestry of crustal fragments. Obtaining well-populated barcodes for all ca. 35 Archean cratons would be, in our view, the quickest and most efficient way to robust paleogeographic reconstructions. This would require a systematic global dating program of several hundred new and refined high-precision ages (e.g. Bleeker 2004; Ernst et al. 2005). The ultimate goal of such a program should be to have precise ages for every short-lived magmatic event in the geological record. Besides complete and precise age data, it is equally important, of course, that each event is carefully characterized in terms of other key attributes: geological setting, areal distribution, paleomagnetism, geochemistry, etc. There is no doubt that collectively such data would catalyze a quantum leap in understanding not only of pre-Pangaea paleogeography but also of the evolving Earth system as a whole (Bleeker 2004).

Finally, we suggest that the scientific discipline concerned with the study of mafic dyke swarms, large igneous provinces, and other short-lived mantle generated magmatic events would be well served by a formal global database, similar to those used by mineralogists and palaeontologists to store formal mineral and fossil data, or astronomers and planetary scientists to store and track data on celestial bodies and objects. Each entry to such a database of short-lived magmatic events should come complete with all essential data (e.g. name of event, age, location, character, areal extent, and volume estimate) and be reviewed by an international committee overseeing the global database. To assist in the launching of such a global database, we herein propose tentative data sheets that highlight the kind of information required. Scientific gatherings like the International Dyke Conferences could stimulate and accelerate development of a high-quality and well-populated global database by requesting that all events discussed at such meetings come with completed data sheets.

THE IMPORTANCE OF GLOBAL RECONSTRUCTIONS

Continental geology consists of a collage of crustal fragments of different ages. The overall architecture can be compared to the nested structure of "Russian dolls" and is fractal in nature (Bleeker 2005): ancient fragments of crust are embedded in younger, larger, fragments, which are themselves embedded in yet younger fragments of later supercontinental aggregations. At the largest scale, this geological record of repeated fragmentation is embedded in the present ensemble of large continents, which themselves are fragments of the most recent supercontinent in the evolution of planet Earth, "Pangaea" (Wegener 1915).

Because the scale of fragmentation, particularly for the older record, is generally smaller (<1000 km) than the scale of typical tectonic systems (≥1000 km, e.g. orogenic belts and their associated basins, arc-trench systems, mantle plume heads), accurate paleogeographic reconstructions are essential to appreciate the full tectonic context in which a particular piece of crust formed or was reworked. In other words, due to plate tectonic break up and dispersal, the critical tectonic elements that can explain the geology in one craton may now be preserved within another, distant, craton. A complete time series of paleogeographic maps, at least back to ~2.6 Ga, would provide a full context for much of the extant continental crust and lithosphere, and the ultimate ground truth for global tectonic models. It would be a crowning achievement of the plate tectonic revolution and allow us to answer questions such as: Where is the conjugate of the ca. 1.9-2.0 Ga western margin of the Superior craton, with its fabulous endowment of magmatic nickel sulphide deposits? Or, where is the other half of the gold-rich Abitibi greenstone belt? And if diamondiferous roots below Archean cratons are largely Archean, where is the rest of the root that underlies the Slave craton and contributed to the formation of highly profitable diamond deposits? Equally important, it would allow an enormous body of regional geological research, now distributed and partitioned among different cratons and continents, scattered among numerous journals, in many different languages, and captured in innumerable regional maps and reports, to be synthesized in its natural context. Hence, the stakes are considerable.

FUZZY DATA, FUZZY RECONSTRUCTIONS

Pre-Pangaea reconstructions generally rely on matching details of continental geology, with or without paleomagnetic constraints. No record of ocean floor spreading remains to restore cratons to their original position and most craton margin geometries are either non-distinct or too modified to allow robust fits based on the external geometry of crustal fragments alone (Fig. 1). In a few rare cases, interpreted rift margin geometries of promontories and re-entrants have been used as an additional constraint, e.g. the tentative mid-Proterozoic fit of Australia-Antarctica with southwestern Laurentia (the "AUSWUS" fit, Karlstrom et al. 1999, 2001). Despite this extra constraint, this fit remains controversial and is one of several proposed Australia-Laurentia reconstructions (Hoffman 1991, Dalziel 1997, Weil et al. 1998, Buchan et al. 2001, Thorkelsen et al. 2001, Wingate et al. 2002, Fioretti et al. 2005) including some with South China inserted between (Li et al. 1999, 2005).

Figure 1

Many proposed reconstructions rely on matching "piercing points": i.e. the point where a linear boundary within a craton, for instance a major structural lineament, intersects a rifted margin (Figs. 1a, b). Obviously, each well-defined, high-angle, piercing point must have a conjugate along the margin of another craton. Although a simple and powerful concept, there are many complications. Break-up margins commonly follow older sutures or crustal boundaries, thus minimizing the number of well-defined, high-angle piercing points. Others such piercing points are inherently fuzzy, either geometrically (e.g. an orogenic front) or in terms of age (e.g. anatectic granitoid belts).Yet others are highly susceptible to the degree of uplift and exhumation of the respective margins (e.g. the outline of a shallow, pre-rift, sedimentary basin; Figs. 1b, c). Any piercing point based on intersection of a shallow or moderately dipping structural feature will shift significantly with differential uplift or will be completely erased from one or both margins, leaving few clues about an ancient connection.

Other tools commonly employed to compare or contrast distant margins are statistical patterns of zircon data, either in the form of 1) a variety of somewhat imprecise basement ages, or 2) the peaks in detrital zircon "spectra" obtained from cover sequences (e.g. Fitzsimons & Hulscher 2005). Although in some cases this can lead to compelling correlations, the age peaks are commonly too broad, non-unique or, alternatively, too unique (i.e. spatially too restricted, no distant match), to allow unambiguous paleogreographic solutions. Of course, all these approaches based on variably fuzzy data are useful and collectively may build a case for a specific paleogeographic correlation, but rarely do they allow an unequivocal "true or false" test of such a correlation.

SHORT-LIVED MAGMATIC EVENTS AND BARCODES

In contrast to many of the fuzzy constraints discussed above, the rich record of short-lived mantle generated magmatic events preserved within the continents allows more precise, testable, solutions. Several key attributes of the short-lived magmatic record are important in this context:

1. Mantle-generated magmatic events are typically short-lived ("burps from the mantle"), often less than a million year and thus within the resolution of our most precise dating methods (e.g. Marzoli et al. 1999, Kamo et al. 2003, but see Jourdan et al. 2005).
2. Even where an overall event may be longer lived (e.g. 10-30 million year for all components of a large igneous province), they tend to consist of several discrete magma pulses that individually were short-lived.
3. Short-lived magmatic events are commonly associated with continental break-up, thus leaving remnants of the event on the conjugate margins (e.g. Hill 1991).
4. They are spatially extensive, especially their dyke swarms, thus providing a large footprint extending away from craton margins (e.g. Halls 1982). This is important because craton margins are likely to be severely modified in a subsequent collision. Precise age data, and especially paleomagnetic data, thus can be obtained from better preserved distal portions of the events.
5. Because of their shape and attitude, individual dykes, or (sub)swarms of related dykes, provide precise piercing points (Fig. 1) (Buchan & Ernst, 1997).

6. And because the dyke swarms are generally vertical and have significant depth extent in the crust, the precise piercing points they provide are essentially insensitive to uplift.
7. Mantle-generated magmatic rocks commonly have a distinct geophysical expression, thus allowing them to be traced aeromagnetically through areas of poor outcrop or below cover rocks.
8. And, finally, the mafic magmatic rocks may have distinctive chemistry and isotopic compositions that may strengthen or weaken a specific correlation.

Because of advances in U-Pb (baddeleyite, zircon) and Ar-Ar (various igneous minerals, whole rock) geochronology, many of these events can now be dated precisely. Any tentative age match warrants further investigation, ideally involving maximum age refinement and comparison of potentially coeval primary paleomagnetic poles ("key poles"; Buchan et al. 2000). If the age match persists at the highest level of precision (e.g. ±1 Ma), a direct correlation becomes likely and the paleomagnetic and geometrical information inherent in the dykes may be sufficient to allow a unique solution (but see Ernst & Buchan 2002, Hanson et al. 2004, for examples of synchronized but distant magmatic events). Even at this point, not all information inherent in the dykes is exhausted. The overall reconstruction should yield a rational dyke swarm pattern (e.g. Fig. 1d), with, for instance, fanning sub-swarms pointing to magmatic centres ("hotspots"). Textural or magnetic anisotropy data may test for a flow direction predominantly away from this centre. Finally, once all the information content of the short-lived mafic magmatic event is exhausted and provides tight constraints on the correlation, one can further test the proposed correlation by comparing other regional geological elements. There is little doubt that this general methodology, if applied systematically and globally, is the most efficient route towards more robust paleogeographic reconstructions.

A critical step in the overall methodology is obtaining precise ages for as many short-lived mafic magmatic events as possible, and from as many as possible crustal fragments and cratons around the world. Precise ages allow the various events to be ordered in time while immediately drawing attention to potential matches, thus highlighting those events that have the most potential for correlation and deserve further work. A number of precisely dated mafic magmatic events within an individual craton provide age bars on a time line, i.e. a "barcode" that provides a quick graphical representation of the short-lived magmatic events within that fragment of crust. Figure 2 shows hypothetical barcodes for five cratons. Although all have some unique (endemic) bars, there are two precise age matches between craton A and D, at times T_4 and T_6, respectively, and potentially a third at T_2. Hence, it is exceedingly likely that cratons A and D were adjacent pieces of crust ("nearest neighbours") in an ancestral supercraton, at least between times T_4 and T_6, and possibly from before T_2 if a refined age of the oldest dykes in craton D would converge on the precise age in A. One can also surmise from the barcodes that cratons A and D likely broke up shortly after T_7, as subsequent events in both cratons are distinct. Furthermore, cratons C and E may be nearest-neighbour fragments of another supercraton that existed between T_5 and T_8. However, at least two of the ages need to be refined. Finally, craton B, despite a reasonably well-populated barcode, does not share any match with any of the other cratons and therefore likely represents a distant, if not unrelated, fragment of crust.

Figure 2

Given three successive age matches between the barcodes of cratons A and D, the geometrical and paleomagnetic information inherent in the dyke swarms should allow a unique fit. As explained below, if the paleomagnetic information proves compromised by overprinting, the dyke patterns alone may still carry sufficient information for a unique fit. All this is possible because of the superior, non-fuzzy, information content inherent in short-lived magmatic events and their dykes swarms.

AN EXAMPLE: MATCHING BARCODES BETWEEN SUPERIOR AND KARELIA

The Superior craton of the Canadian Shield has the most detailed record of Paleoproterozoic mafic magmatic events (Buchan & Ernst 2004, Ernst & Buchan 2004). This is partly a function of location, in a well-exposed and well-studied shield area, but also one of size and tectonic evolution. Acting as a lower plate in most of the marginal Proterozoic belts, reworking of the craton is limited to its outer margins and large portions preserve an essentially primary record of Proterozoic dyke intrusion events and partial remnants of large igneous provinces.

The Paleoproterozoic barcode of the Superior craton comprises numerous precisely dated events and is unparalleled in the world. Conspicuous first-order characteristics of this barcode are (Fig. 3):

- At least two centres of voluminous 2505-2445 Ma magmatism, comprising the Mistassini radiating dyke swarm in Quebec and the giant Matachewan radiating dyke swarm, associated intrusions, and volcanic rocks in Ontario (Fahrig 1987, Heaman 1997, Halls & Zhang 1998, Ernst & Buchan 2002).
- Several 2230-2200 Ma dyke swarms and a voluminous sill province of the same age (Buchan et al. 1998, Buchan & Ernst 2004, Corfu & Andrews 1986, Krogh et al. 1987, Noble & Lightfoot 1992). The dyke swarms may define a radiating pattern with a focal point to the east of the craton, from where they are thought to have fed the Nipissing sills intruding in the Huronian Supergroup on the southern flank of the craton (Buchan et al. 1998, Palmer et al., submitted).
- A prominent dyke swarm at 2125-2100 Ma, the Marathon dykes (Buchan et al. 1996, Hamilton et al. 2002). New work on these dykes has both improved the precision of their ages and demonstrated a radiating pattern with a focal point to the south of Lake Superior (Halls et al. 2005).
- Craton encircling rift/passive margin sequences of the “Circum-Superior belt” (Baragar & Scoates 1981), with mafic/ultramafic volcanic rocks, sills, and dykes ranging in age from ca. 2170 Ma, the first cycle of volcanism in the Labrador Trough (Le Gallais & Lavoie 1982, Skulski et al. 1993, Clark & Wares 2004) to 2048-1860 Ma (see Ernst & Buchan 2004, for various events; see also the “LIP of the Month” feature for May 2004 at http://www.largeigneousprovinces.org/). Some of the major dykes swarms coeval with these events are the 2167 Ma Biscotasing dykes of Ontario, the 2000 Ma Minto dykes of northern Quebec, and the 1883 Molson dykes of northern Manitoba.

Figure 3

To illustrate the effectiveness of the barcode methodology, we include in Figure 3 similar data for the smaller Slave, Hearne, and Karelia cratons. Both the Slave and Karelia cratons now have reasonably well-populated barcodes, although much work remains to be done. The Slave craton, with approximately ten well-dated events, provides an example of a craton that shares few similarities with the Superior craton barcode. Hence, it clearly was not a “nearest neighbour” of the Superior craton in a Paleoproterozic supercontinent and, in fact, may represent a fragment of unrelated, exotic, crust prior to both cratons becoming incorporated into 1.8 Ga Laurentia. Bleeker (2003) suggested that while the Superior craton is an internal fragment of one large Paleoproterozoic “supercraton”, Superia, the Slave is a fragment of another such supercraton, Sclavia. These two supercratonic landmasses (latest Archean to earliest Paleoproterozoic continents) may never have been connected in a single supercontinent. The Slave craton barcode is presented here as a contrast, but will not be discussed in detail any further.

The Karelia barcode is quickly becoming better defined (Vuollo & Huhma 2005), and although age precision needs to be improved, it now matches many of the critical age bars of the Superior barcode (see above, and Fig. 3). Given these multiple age matches, within the precision of currently available data, there can be little doubt that Karelia and Superior cratons represent crustal fragments that were nearest neighbours in Paleoproterozoic supercraton Superia (Bleeker 2003). One more inference can be made without considering further data: Karelia likely originated from along the southern margin of the Superior craton (see also Heaman 1997), as it is here that we find the focal points for 2505-2445 Ma and 2125-2100 Ma magmatism, as well as the voluminous 2217 Ma Nipissing sills in the Huronian Supergroup. The latter likely have their equivalent in the Karjalitic sills of Karelia (Vuollo & Huhma 2005). Interestingly, no basement-cutting feeder dykes to these sills have been found in Karelia, suggesting far-travelled transport of magmas as sills within Paleoproterozoic cover or along the underlying unconformity. The key point here is that all these far-reaching and testable inferences are based, thus far, on nothing more than sets of ages and general field relationships. All the other inherent information can now be brought to bear on testing of these inferences. This is the power of systematic precise age dating and the barcode methodology.

UNIQUE GEOMETRICAL MATCHES BASED ON MULTIPLE DYKE SWARMS

As explained above, a single precise age match immediately should draw attention and focus further work. Obvious questions that should follow are:

- Does the age match survive age refinement?
- Does the age match involve just one event or can it be extended to multiple events through an interval of time, thus greatly strengthening the likelihood of a "nearest neighbours" type correlation"?
- And ultimately, is the suggested correlation supported by paleomagnetic, compositional, and other tests?

A single precise age match, by allowing temporal and possibly spatial matching of dyke swarms in two cratons, may quickly suggest a tentative paleocontinental reconstruction. However, the data will typically allow significant freedom in the reconstruction (e.g. detailed placing and orientation of one craton relative to the other), even if relevant paleomagnetic data are available. Errors in inclination and declination in primary paleopoles from both cratons may, collectively, amount to 10-20 degrees in latitude, and 10-20 degrees in relative orientation, even ignoring polarity ambiguity (Fig. 4a). However, once two dyke swarms can be matched, particularly if they show fanning in both cratons, the fit becomes fully constrained (Fig. 4b). Matching of further events, and/or other elements of the geology in both cratons can then raise the likelihood of a specific correlation beyond reasonable doubt (Fig. 4c). The example shown in Figure 4c is modeled on the Superior-Hearne correlation proposed by Bleeker (2004), although it should be mentioned that ca. 2110 Ma (Marathon) dykes have not (yet?) been found in the Hearne craton. Sills of exactly this age, the Hurwitz gabbros (Heaman & LeCheminant 1993), and a few dykes (e.g. Aspler et al. 2002), do occur however in the cratonic cover of the Hearne craton. Recently, Heaman (2004) suggested that the ca. 2500 Ma event of the Superior (Mistassini) is also present in the Hearne craton among mafic dykes in the Kaminak area, extending a southern Superior-Hearne link (Bleeker 2004) across three events and 400 million years.

Figure 4

Following this methodology, we now have sufficient data from both Superior and Karelia to extend this detailed correlation to the Karelia craton (Fig. 4d). We propose that Karelia was situated southeast of the southern Superior craton (present coordinates) and adjacent to the Hearne craton from the time of crust formation, accretion, and aggregation in the late Archean to the time of break-up (Fig. 4d). If correct, all three cratons thus trace their origins back to growth of ancestral supercraton Superia (Bleeker 2003, 2004) by rapid accretion of disparate crustal elements and juvenile crust between ca. 2720 Ma and ca. 2680 Ma. Both southern Superior and Karelian crust underwent high-grade metamorphism between about 2660 Ma and 2640 Ma (Fig. 3) and thereafter show a shared history of magmatic events and dyke swarm emplacement during the Paleoproterozoic (Fig. 3). Although incipient rifting and extension was locally initiated as early as 2500-2440 Ma, final break-up must have occurred much later, sometime after 2100 Ma.

The key to our reconstruction is the simultaneous and successful matching of ca. 2450 Ma and ca. 2100 Ma dykes to respective magmatic centres in the reference frame of the Superior craton, i.e. the Matachewan and Marathon plume centres or hotspots (Fig. 4d). It is possible that ca. 2500 Ma NE-trending dykes are present in Karelia, perhaps interspersed with known 2440 Ma NE-trending dykes, and line up towards the Mistassini centre. As magmatic activity of this age is present in Kola, it could be argued that the Kola craton should be an integral part of this reconstruction and part of a "greater Karelia" craton (see Fig. 4d). Although this needs to be tested by more specific data from the Kola Peninsula, it would argue for the ca. 1.9-2.0 Ga, high-grade, Belemoride mobile belt to be the product of intracratonic shortening and orogeny of stretched crust or the closure of only a narrow ocean basin that temporarily separated Kola from Karelia. Again, the answer to this long standing question of the relationship between Kola and Karelia is to be found in the Paleoproterozoic dyke swarms of both cratons, not in the complex high-grade metamorphic rocks of the Belemoride orogenic internides.

Our analysis further suggests a fairly direct correlation between the Huronian Supergroup overlying the southern Superior and the Sariolan-Jatulian sequences overlying Karelia. Both cover successions are heavily intruded by ca. 2220-2200 Ma sills (Figs. 3 and 4d), the Nipissing sills in Canada and Karjalitic sills in Finland, respectively. The Sariolan-Jatulian sequences should show an even stronger correlation with the Hurwitz Group of the Hearne craton. These similarities have been pointed out before (e.g. Ojakangas 1988) but never in the specific spatial context that we are now able to provide. Also, Heaman (1997), keenly aware of some of the emerging age matches, proposed a Superior-Karelia connection[1], but placed Karelia "up-side down", i.e. juxtaposing southern Karelia closest to the Huronian margin of the Superior. Both our reconstruction (this study) and that of Heaman (1997) require complex paleomagnetic constraints (Mertanen et al. 1999) to be relaxed. Placing Karelia well to the east of the Superior craton and at higher latitudes (Bleeker 2004) is preferred by the paleomagnetic data (Mertanen et al. 1999) but leads to much less compelling geological correlation. As the paleomagnetic data for Karelia are complex, with multiple components, and not necessarily fully primary (S. Mertanen, pers. comm. 2005), we argue that the remarkable geological fit of Figure 4d outweighs the uncertainty in the paleomagnetic data.

Other straightforward inferences and predictions that follow from our reconstruction are:

1. With further work, more matching events will be found. For instance, we predict that the 2220-2200 Ma event (Nipissing and Karjalitic sills) will extend into the Hearne craton[2].
2. Similarly, we expect that a ca. 2.3 Ga event, newly identified in Karelia (Vuollo & Huhma 2005), may well have counterparts in the Superior and (or) Hearne cratons.
3. As the Superior, Karelia, and Hearne cratons share multiple events up to at least 2100 Ma (see Fig. 3), final break-up must have occurred subsequent to this date but likely prior to 1980 Ma, since a prominent NW-trending 1980 Ma dyke swarm is present in Karelia (Vuollo & Huhma 2005) but without a counterpart in the southern Superior craton (Buchan & Ernst 2004; Ernst & Buchan 2004). This important observation implies that the Huronian (southern Superior), Sariolan-Jatulian (Karelia), and Hurwitz (Hearne) cover sequences formed in long-lived intracratonic rifts and extensional basins and, contrary to the generally held view, do not represent true passive margin prisms on rifted craton margins facing an open ocean.
4. The Superior-Karelia-Hearne reconstruction of Figure 4d obviously represents just the beginning of a full reconstruction of Superia. A marked re-entrant is present to the west of the Hearne craton and, following earlier suggestions by Roscoe & Card (1993), it seems likely that the Wyoming craton originated from this location. Better definition of dyke swarms, more precise age dating, and paleomagnetism of key events in the Wyoming craton (e.g. the ca. 2170 Ma dykes described by Harlan et al. 2003) will hopefully allow a final fit of the Wyoming craton in our reconstruction. On the east side of our reconstruction there is a long "unsatisfied" margin from where other Archean cratons must have originated. In our view, the Yilgarn craton of Western Australia is one of the likely candidates.

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[1] Prior to Heaman (1997) and our study, a number of authors have drawn attention to the general geological similarities between the Superior and Karelia cratons, either based on comparable stratigraphy of cratonic cover sequences (e.g. Ojakangas 1988), or the occurrence of similar ca. 2.45 Ga layered intrusions (e.g. Alapieti et al. 1990; Vuollo et al. 1995; and Vogel et al. 1998), but no specific correlations were presented.

[2] Due to its remoteness, few mafic magmatic events have yet been defined and dated in the Hearne craton. Furthermore, the craton has been strongly overprinted (reworked) during the Hudsonian orogeny (1.9-1.7 Ga). Therefore, field relationships are complex. We thus interpret the relatively poorly populated "barcode" of the Hearne craton to be a function of severe undersampling rather than intrinsically fewer events.

5. Ancient basement in Karelia, e.g. the 3.5 Ga Siurua gneiss (Mutanen & Huhma 2003; see small diamond symbol in Fig. 4d) likely correlates with ancient crust known in the southern Hearne craton (van Breemen et al. 2005, Loveridge et al. 1988).
6. Archean structural trends in Karelian basement are likely to have been at high angle to the strong NW-SE structural trends of the nearly penetrative Svecofennian overprint.
7. Similarly in the Hearne craton, original Archean basement structural trends were likely ENE-WSW, subparallel to the dominant structural grain of the southern Superior craton but at a high angle to the present NE-SW Paleoproterozoic structural overprint.
8. And finally, Karelian basement terranes, including Paleo- to Mesoarchean nuclei referred to above (and their analogues within the Hearne craton), represent the next crustal elements in the southward continuation of the Superior craton (within the context of a rapidly southward growing supercraton Superia). From a Superior craton perspective they represent the "missing terranes" that accreted and collided with other southern Superior terranes to cause the final stages of the Kenoran orogeny.

Now we have a spatially and geometrically correct reference frame for the various cratons in hand, there is little doubt that numerous other important insights will emerge from a detailed integration and synthesis of their respective geological databases. With knowledge of the initial relative positions of the cratons within supercraton Superia, and of their final positions within 1.8 Ga supercontinent Nuna, we can begin to constrain relative plate motions during the "Hudsonian-Svecofennian" orogenic cycle in detail.

DATA SHEETS AND A FORMAL GLOBAL DATABASE

To construct increasingly detailed barcodes for cratons from around the world, to help characterize these crustal fragments and draw attention to possible precise age matches, we urgently require a global database. Ultimately, such a database should contain all relevant data on every short-lived mantle generated magmatic event and large igneous province, through time and space. An initial version of such a database has been compiled by Ernst & Buchan (2001) and already has become an invaluable resource to all research related to mafic magmatic events and their direct or indirect consequences.

As new events are recognized around the world, or data on known events are improved, such data should be continually added to and updated in this global database. Just recently, at the Fifth International Dyke Conference[3] (this volume), a large number of magmatic events were discussed in varying detail. An effort to capture such data could quickly expand and improve the global database, particularly if attempts were made towards more uniform data coverage (e.g. name of event, age, location, aerial extent, volume estimate, structural characteristics, composition, etc.). Some fundamental attributes would be of great interest in the context of a complete global database (e.g. frequency of events, and volume estimates, both critical to questions of secular evolution), but are not always easily retrieved from the published literature. Nevertheless, such data, or crude estimates thereof, might well be available to individual researchers familiar with specific events.

We thus propose a model wherein individual researchers or research groups most familiar with individual events are encouraged to complete and submit relevant data on each event to the growing global database. The latter could be managed by the LIP Commission[4] or any other appropriate international body. Formal inclusion of events in the global database should require that a minimum set of fundamental attributes be provided and subjected to peer review. Of course, such a global database model would be similar to how mineralogists catalogue formal mineral species or how the astronomical community has long managed its data on a myriad of celestial objects, planets, asteroids, comets, etc. In that field, without an international database, confusion would reign. We argue that in the field of short-lived terrestrial magmatic events the time has come for a similarly systematic and global approach.

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[3] Held in Rovaniemi, Finland, July 31-August 3, 2005; see http://idc5.gsf.fi/.

[4] See http://www.largeigneousprovinces.org/.

As a first step in this direction, we here present tentative “data sheets” for short-lived mantle generated magmatic events (Tables 1a and b). These data sheets could help to structure the global database or serve merely as a checklist for the kind of data coverage required for each event. If our suggested approach is accepted by the international community, these data sheets should become part of a web-based interface to the global database, to which data on a particular event can be submitted. Below we provide a commentary on the data categories included on the data sheets.

Levels of events

We suggest that there are actually two different scales or “levels” of events:

1. Individual short-lived magmatic events at a structural or lithological “magmatic unit” level: for example, an individual dyke swarm with a specific orientation; an individual layered intrusion or a group of related intrusions; or a sequence of related basalt flows. The duration of these individual magma generation events (“magma bursts”) is typically less than a million years and, in the older record, within the resolution of most dating methods. An individual unit should be spatially contiguous, occurring or preserved on a single continent or tectonic plate. It is understood that other remnants of the event may be preserved elsewhere, but are likely known under different (local) names and would be best described as separate, but linked, entries into the database.

2. Several related structural and lithological units that collectively comprise a larger event or “igneous province”. A typical example would be the North Atlantic Igneous Province with its various lava sequences, related dykes swarms, layered intrusions, possible precursor events, and the somewhat later but still related pulses of (minor) magmatic activity after the main event. Crustal melts and underplating should also be considered part of these broad events. Although the main magma bursts are typically short lived, the overall events typically span 10-30 million years of related magmatic activity. Individual units and remnants of the overall event may be scattered across different plates or continents.

Obviously, these two levels of events, although closely related, require different but partially overlapping data and prompt different questions. We thus present two separate data sheets, one for “magmatic unit” level events (Table 1a), and another for “igneous province” level events (Table 1b). First we discuss the data sheet for individual “magmatic units”, with data for the ca. 2188 Ma Dogrib event from the Slave craton in the Canadian Shield serving as a specific example.

Required and optional data

The data sheets contain both required and optional entries. All required data should be submitted for an event to be formally listed in the global database. In the data sheets these required fields are preceded with an asterisk (*). This approach will promote uniform data coverage and prevent duplicate entries. To maintain data quality, we suggest that submitted events should be subjected to peer review, as is customary for many other formal global databases (e.g. minerals and their names, fossil taxa, celestial objects, etc.). At the level of an individual “magmatic unit”, required data are all the information to uniquely identify and characterize an event: formal name, approximate age, principal expression (e.g. dykes or flows), location, areal extent and volume estimate, structural data, and basic compositional data. If such data cannot be provided, the event is insufficiently characterized.

Data sheet for an individual “magmatic unit”

The data sheet for a “magmatic unit” level event comprises a single sheet with ten data categories (Table 1a). These are:

1. Magmatic event, main identifiers

A first category in Table 1a consists of six entries that are the basic identifiers of the event: name, alternate name(s) if any, approximate age, principal expression (e.g. dykes, and (or) layered intrusion), related units, and overall importance of the event. The approximate age (in Ma) should be a single number that best dates the event and allows it to be ordered in time.

2. Location data
A second category specifies location: which continent, latitude and longitude, type locality, and which crustal or tectonic domain.

3. General characteristics
This category captures critical data that characterize the event: e.g. principal expression, areal extent (km^2), a volume estimate (km^3) and how it was derived, the overall size of the event, interpreted tectonic setting and field characteristics. Volume estimates, although rarely straightforward, are critical for assessing the relative size of events and, ultimately, magma production rates through time. We suggest the following classification of event sizes, compatible with common usage in large igneous province terminology (e.g. Coffin & Eldholm 1994, 2001):

Giant (LIP):	$>10^7$ km^3
Major (LIP):	10^6 - 10^7 km^3
Substantial (LIP):	10^5 - 10^6 km^3
Moderate:	10^3 - 10^5 km^3
Small:	$\leq 10^3$ km^3

The first three categories (giant, major, and substantial) qualify the size of what are generally considered large igneous provinces (LIPs), with (eruptive) volume estimates on the order of one to several million cubic kilometres[5]. When intrusive and underplated volumes are considered as well, some of the largest LIPs would classify as true giants, e.g. the Ontong Java plateau at ca. 45x10^6 km^3. The two smaller categories (moderate to small) describe sub-LIP scale events.

As an example (see Table 1a), the size of the Dogrib event is estimated as "moderate" with an approximate volume of 1,200 km^3. This crude volume estimate is derived as follows:

- The Dogrib dyke swarm consists of at least two, if not several, large subparallel dykes and numerous minor dykes.
- The two larger dykes are up to 100 m wide, and collectively the swarm can be followed over at least 300 km across the southern Slave craton.
- Assuming that nearly all magma is contained in the two larger dykes, this leads to a surface area of 60 km^2 for just these two dykes.
- Furthermore, assuming ca. 5 km of erosion and ca. 15 km depth penetration below the present erosion level, hence 20 km of vertical extent, we arrive at a volume estimate of ca. 1,200 km^3.

Hence, our characterization of the Dogrib event as "moderate" in size, according to our classification above. As the dykes occur within the margin of a rifted Archean craton, the original magma volume of the Dogrib event may have been significantly larger with parts of it rifted away. Also the depth penetration through the crust could be larger, or there could be underplated basaltic material at the base of the crust. Finally, the dykes could have fed flood basalts that have since eroded. Most volume estimates will thus be minimum estimates that may increase over time as events become more completely documented.

4. Age data
This data category list all relevant age data, estimated errors, methods, etc. Key entries should be referenced. It would be useful to provide an indication whether the age might be improved and, if so, how?

5. Primary structural data

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[5] Coffin & Eldholm (1994, 2001) and others (e.g. Ernst et al. 2005) have generally used a surface area of $>10^5$ km^2, rather than volume estimates, to define LIPs.

This category provides all the primary structural date, e.g. morphology (shape), strike and dip of flows, the trend of dykes, whether they are fanning or radiating, etc.

6. Secondary structural data

This category should provide basic information on the present structural and metamorphic state of the units described. How deformed are they? What is their mineral assemblage, fresh and igneous or recrystallized and metamorphic? How deep is the present erosion level?

7. Compositional data

This category lists a number of typical compositional identifiers. The only required entry is that of approximate silica content, allowing general characterization as ultramafic (<45 wt% SiO2), mafic (45-52 wt%), intermediate (52-66 wt%), or felsic (>66 wt%). Obviously, complete chemical characterization would be desirable and may help in testing correlations. Furthermore, complete chemical data for most if not all events in the database would allow many interesting queries, investigation of secular trends, and related research. It should thus be encouraged that all event entries come with full chemical characterization.

8. Physical properties and paleomagnetism

This category allows capturing of physical property data (e.g. densities) and a discussion of paleomagnetic data.

9. Comments

This category allows any additional information or comments to be entered.

10. References

Finally, references should be listed at the bottom of the data sheet; e.g. the first paper(s) describing or defining the event and its name, those that detail the age dating of the event (if available), possible paleomagnetic studies, and papers on the geochemistry of the magmatic products, or the spatial distribution of the event as based on mapping or interpretation of aeromagnetic maps.

Data sheet for a larger "igneous province"

The data sheet for a larger igneous province (Table 1b) is similar but not identical to that of an individual magmatic unit. Obviously, at the larger scale of an entire igneous province, a number of additional questions become important. What is the overall age range of the event, relative to the main magmatic pulse? What are the component units that belong to the event? Apart from dykes, are there volcanic rocks, or perhaps large layered intrusions or sill provinces? Was there uplift just prior to or during the magmatic activity? Are there related rift basins or other sedimentary basins? And are there any ore deposits related to the overall event?

In general, the data sheet (Table 1b) is self-explanatory, requiring little additional discussion. The ca. 1267 Ma Mackenzie event of the Canadian Shield (Fahrig & Jones 1969, Fahrig 1987, LeCheminant & Heaman 1989, 1991, Heaman & LeCheminant 1993, Baragar et al. 1996) is listed as an example. The main point here is that the data sheet requests information on all the different components that collectively comprise a large igneous event. Ideally, each of the component magmatic units would be individual entries at the "magmatic unit" level.

CONCLUSIONS

Paleocontinental reconstructions are of critical importance to synthesizing the complex and fragmented record of continental geology. A relatively complete time series of such reconstructions back to ~2.6 Ga would be a crowning achievement of the plate tectonic revolution. Although much work remains to be done, and while some pieces of the puzzle may no longer exist, we think this goal is achievable. Presently, however, many proposed reconstructions remain underconstrained because of the complex and fuzzy nature of the data available for correlation.

Over the last two decades, short-lived mantle-generated magmatic events, and the information inherent therein, have emerged as the key to unravelling pre-Pangaea paleocontinental reconstructions. Multiple precisely dated events define "barcodes" for individual cratons or crustal fragments and provide an efficient representation of the short-lived magmatic events experienced by that piece of crust. Originally adjacent pieces of crust ("nearest neighbours") are likely to share at least part of their magmatic history, perhaps in the form of distant dykes, and thus will show a partial match between their barcodes. Multiple matches among the barcodes of now distant cratons almost certainly imply that the cratons were adjacent parts of an ancestral landmass. A global age dating program of all short-lived magmatic events is thus the most efficient route to more robust reconstructions, potentially as far back as 2.6 Ga.

Matching a single event across two cratons may result in a reasonable correlation but will typically remain underconstrained. Matching of two or more dyke swarm events has the potential to provide fully constrained geometrical solutions, which can be tested further with independent data (paleomagnetic data, details in basement geology). A robust ca. 2.6-2.1 Ga connection between the Superior, Hearne, and Karelia cratons is presented as an example of this approach. Three events (ca. 2500 Ma, ca. 2446 Ma, and ca. 2110 Ma) are now matched between the southern Superior and the Hearne craton. Hurwitz gabbro sills in the cover of the Hearne craton, dated at 2111 Ma, are likely part of the Marathon event. At least four key events can now be matched between the Superior and Karelia cratons, allowing a tightly constrained fit (Fig. 4d). Break-up of these cratons must have occurred sometime after 2100 Ma but before 1980 Ma, the date of an important magmatic event in Karelia (numerous dykes) that has no match in the southern Superior craton. This implies that the Huronian, Sariolan-Jatulian, and Hurwitz cover sequences formed in intracratonic rifts and extensional basins and do not represent true passive margin prisms on rifted craton margins facing an ocean basin.

Finally, all research on short-lived magmatic events and their consequences, including the field of paleocontinental reconstructions, would greatly benefit from an improved and expanded, formal, global database. Such a database should be maintained through an international body and all entries should be peer reviewed and comprise a minimum set of critical attributes. This approach would be similar to any other important global database. To promote development of such a global database, we propose basic data sheets that will help in capturing the critical data on short-lived magmatic events and promote uniformity in data coverage.

ACKNOWLEDGEMENTS

Jouni Vuollo and his Finnish colleagues are thanked for organizing the Fifth International Dyke Conference, in Rovaniemi, Lapland. The conference and its pre- and post-meeting field trips provided a stimulating environment for discussion of the ideas presented herein. We also acknowledge our Canadian colleagues, many of which have been pioneers in the study of mafic magmatic events and their precise dating. Ken Buchan provided insightful comments on a first draft of this paper. Geological Survey of Canada Contribution 2005505.

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Table 1a: Data sheet for short-lived magmatic event, individual “magmatic unit” level.

1. MAGMATIC EVENT		**DOGRIB**
	***Official name**	Dogrib Dykes [e.g. 1]
	Alternate name(s)	
	***Approximate age (Ma)**	2188
	***Principal expression**	Dykes
	Related units, larger event, or LIP?	Possibly the slightly younger Duck Lake sill
	Importance	High; for key pole comparison with similar age dykes in other cratons, e.g. Tulemalu-Macquoid dykes in Rae(?) craton
2. LOCATION		
	***Continent(s)**	North America
	***Latitude & longitude (degrees)**	62 degr 30' N, 114 degr 30' W
	***Type locality**	Along highway west of Yellowknife, Northwest Territories, Canada
	***Crustal or tectonic domain(s)**	Slave Province, Canadian Shield
	Craton	Slave craton (Archean)
3. GENERAL CHARACTERISTICS		
	***Principal expression: flows, dykes, sills, etc.**	Dyke swarm, no known associated flows [e.g. 1]
	***Areal extent (km2)**	100,000?
	***Volume estimate (km3)?**	1200?
	***Size of event?**	Moderate
	***Interpreted tectonic setting?**	Initial extension and attempted rifting of Slave craton crust (within Sclavia supercraton)
	***Field characteristics**	Brownish weathering, medium- to coarse-grained diabase, well developed chilled margins
	***Magnetic expression**	Moderately magnetic, well resolved on aeromagnetic maps
	Phenocrysts?	?
4. AGE DATA		
	Age and estimated error (Ma)	2188 +/-4 [2,3]
	Method (decay system)	U-Pb
	Mineral	Baddeleyite, unabraded
	Type	Upper intercept, regression through several discordant multigrain fractions
	Potential to improve age? How?	Yes; more concordant baddeleyite fractions
5. PRIMARY STRUCTURAL DATA		
	***Morphology**	Tabular dykes
	***Trend or strike azimuth (000 degrees)**	065
	***Dip, typical angle (00 degrees)**	(Sub)vertical
	***Fanning, radiating (for dykes)?**	Not apparent
	Dyke width (average, and maximum observed)	Ca. 100 m (max)
	Extension (%), over what width?	<1% over ca. 100 km
	Offsets or consistent stepping pattern?	
	Cuts what?	Late Archean granitoids and greenstones
	Orientation relative to local structural trends?	Perpendicular to regional late Archean cleavage; cuts Yellowknife greenstone belt trend at high angle, ~45-65 degrees
	Nearest margin?	Western and southern margin of Slave craton
	Textural studies? Phenocryst imbrication?	
	Magnetic fabric (AMS) studies?	
	Flow direction?	
6. SECONDARY STRUCTURAL DATA: STRUCTURAL-METAMORPHIC STATE		
	***Deformational state**	Fresh; locally offset by Paleoproterozoic brittle faults of the West Bay-Indin Lake fault system
	***Metamorphic state**	Fresh; low-T Paleoproterozoic overprint related to Wopmay orogen
	Estimated depth of exposure?	Ca. 5 km?
	Cut by?	Paleoproterozoic brittle faults of the West Bay-Indin Lake fault system
7. COMPOSITIONAL DATA		
	***(Ultra) mafic, intermediate, felsic, bimodal**	Mafic
	Magma type	Tholeiitic
	SiO2 (wt%, volatile free)	49.5-52.5
	Mg#	53-67
	TiO2 (wt%, volatile free)	0.7-1.1
	Ti/Zr	
	La/YbN	
	La/Nb	1.3-1.7
8. PHYSICAL PROPERTIES AND PALEOMAGNETISM		
	Density (g/cm3)	3.00; 2.96 for chilled margin
	Magnetic susceptibility (SI units)	
	Paleomagnetic data?	See references [3,4,5]
	Quality of data?	Probably primary
	Koenigsberger ratio (Q-value)	
9. COMMENTS		
	Any additional information or comments	Two large parallel dykes can be followed for >100 km in the Yellowknife area; a number of small parallel dykes.
10. REFERENCES		
	***Literature references, maps, etc.**	
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Table 1b: Data sheet for larger generated magmatic event, “igneous province” level.

1. LARGE IGNEOUS PROVINCE		**MACKENZIE**
	***Official name**	Mackenzie [1,2,3]
	Alternate name(s)	
	***Approximate age (Ma)**	1270 [4,5,6]
2. LOCATION		
	***Continent(s)**	North America
	***Latitude & longitude (degrees)**	67 degr 00' N, 115 degr 00' W
	***Type locality**	Nothern Canadian Shield, "District of Mackenzie"
	***Crustal or tectonic domain**	Archean and Proterozoic basement of Laurentia
	Craton(s)	Laurentia and rifted fragments thereof (Siberia?)
3. GENERAL CHARACTERISTICS		
	***Principal expression: flows, dykes, sills, etc.**	Giant radiating dyke swarm, basalt flows, sills, layered intrusions
	***Dominant magma type**	Tholeiitic
	***Areal extent (km2)**	>2,700,000 [2]
	***Volume estimate (km3)?**	1,000,000(?); 80,000 for dykes [2]
	Magmatic underplating? Included in volume estimate?	Near plume centre, probably; not included.
	***Size of event?**	Major
	***Interpreted tectonic setting?**	Plume head impacting on Mesoproterozoic supercontinent Nuna, possibly leading to break-up
4. AGE DATA		
	Age and age range (Ma)	1272-1265
	Early precursor events? Age (Ma)?	
	Age of main mafic magma pulse (Ma)?	1267+/-2
	Age of first felsic rocks (Ma)?	
5. COMPONENT MAGMATIC UNITS		
	Volcanics	Coppermine, Ekalulia, Nauyat, Hansen
	Dyke swarms (and geometry)	Mackenzie (radiating)
	Sill provinces	Christie Bay, Tremblay, Goding Bay
	Layered intrusions	Muskox Intrusion, a lopolithic (funnel-shaped) dyke; others probably marked by gravity anomalies in proximity to plume centre
	Magmatic underplating?	Probably, near plume centre
	Associated felsic magmatism?	
	Carbonatites?	
	Kimberlites?	
	Lamprophyres?	
6. OTHER CHARACTERISTICS		
	Uplift?	Regional domal uplift inferred from dyke swarm geometry
	Related rift basins?	Rift basins along Arctic coastline
	Relation to other sedimentary basins?	
	Break-up and ocean formation?	Poseidon ocean [2]
	Ore deposits?	Ni-Cu-PGE in Muskox intrusion
	Extinction event that may be related?	
7. COMMENTS		
	Any additional information or comments	Has largest radiating swarm known
8. REFERENCES		
	***Literature references, maps, etc.**	
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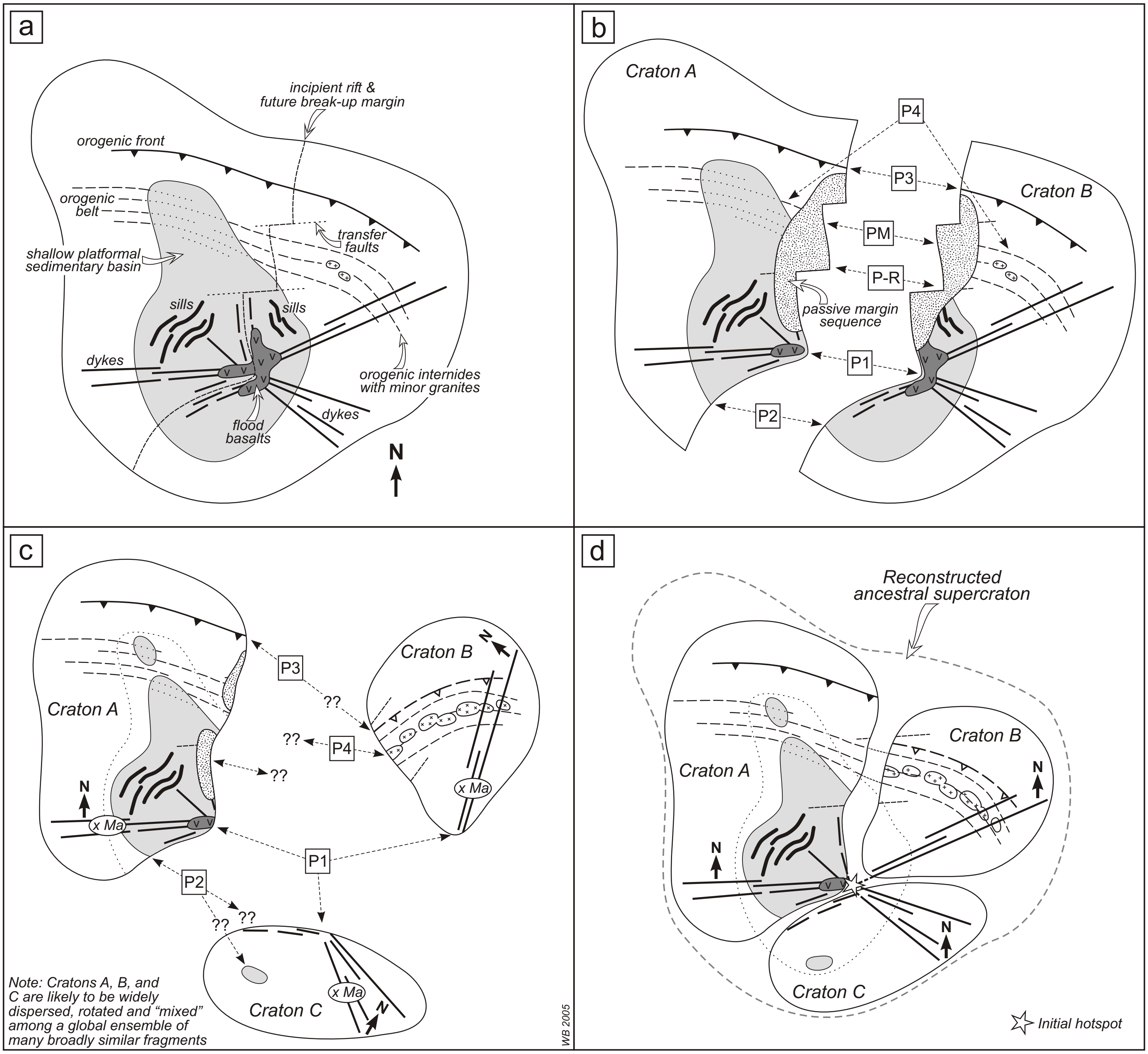
FIGURE CAPTIONS

Figure 1: Piercing points and craton reconstruction. a) A hypothetical (super)craton with various geological elements, just prior to break up. A large igneous province, with flood basalts and associated dykes and sills, is emplaced along the incipient rift. b) Break up of the supercraton has spawned to cratons (A and B). As long as both cratons are not too modified (e.g. South American and African conjugate margins), they are easily fitted together again using a variety of piercing points and other matching features: e.g. P-R, the fitting of promontories and re-entries along the rifted margins; PM, general correlation and fitting of the conjugate passive margins; P1, piercing points and reconstruction of the large igneous province; P2, piercing points provided by older sedimentary basins; P3, piercing points provided by an ancient orogenic front or fold-thrust belt; and P4, the non-precise piercing points provide by orogenic internides. c) The more general case where further break up has occurred (craton C) and craton margins have been abraded, modified, and differentially uplifted. Craton B was strongly uplifted and its sedimentary cover has been eroded. Piercing point P3, if still recognizable as such, has strongly shifted, and an exhumed granitoid belt is unmatched in craton A. Craton C was also uplifted, erasing piercing point P2. Dykes related to the large igneous province, however, remain on all three cratons and precise age dating (x Ma) yields a critical clue that they might be part of a single event. Primary paleomagnetic data may yield additional geometrical clues (North arrows), if not paleolatitudes. d) Reconstruction of the original supercraton, based only on the precise piercing points and other information derived from the dyke swarms.

Figure 2: Hypothetical "barcodes" for five cratons. Individual "bars" are the age range (of variable precision) of short-lived magmatic events on vertical time lines. Partially matching barcodes, e.g. between cratons A and D (from time T_4 to T_6, and possibly from as early as T_2), are a strong indication that the two cratons had a shared history in an ancestral supercraton, i.e. they were "nearest neighbours". Cratons C and E are unrelated to A and D, but may have shared a common history as part of another supercraton. However, more precise age data are required. Craton B, with no matches, must represent a distant, if not unrelated, fragment of crust.

Figure 3: Barcodes (2.72-1.80 Ga) for the Superior craton (centre), the Slave (left), and the Hearne and Karelia cratons (right). Note the relatively poor match between the Slave craton and the Superior, indicting that these cratons were distant areas of crust between 2.66 Ga and 1.9 Ga. On the other hand, Karelia, Hearne, and Superior show numerous matches between their barcodes and thus must have been adjacent pieces of crust within ancestral supercraton Superia, which existed from the late Archean across much of the Paleoproterozoic until break-up sometime after 2100 Ma.

Figure 4: a) "Fitting" of two cratons based on dykes (and paleopoles) from a single event. Note that significant freedom remains in the reconstruction due to insufficient constraints and cumulative errors in the paleopoles. b) A fully constrained fit due to matching dykes that radiate out from more than one magmatic "plume centre" (or hotspot). c) Strengthening of the suggested fit by matching cover sequence stratigraphy and elements of the basement geology, yielding a robust paleogeographic correlation. This diagram is modeled on the Superior-Hearne fit proposed by Bleeker (2004). d) Paleogeographic correlation of the Superior, Hearne, and Karelia cratons in 2.68-2.00 Ga supercraton Superia. The detailed fit is based on successful matching of several short-lived magmatic events, at ca. 2450 Ma (Matachewan), ca. 2217 Ma (Nipissing (N) and Karjalitic (K) sills), and ca. 2110 Ma (Marathon), as well as correlation of the cover sequences (see text). Kola is likely part of this correlation as part of a "greater Karelia" craton. The Wyoming craton likely originated from the re-entrant west of the Hearne craton. Note that our reconstruction successfully places the ca. 3.5 Ga Siurua gneiss of Karelia (diamond symbol; "Europe's oldest rocks") along strike of similar age crust in the Hearne craton. Black arrows indicate part of the long-distance transport of magma to feed the Nipissing and Karjalitic sills.



Note: Cratons A, B, and C are likely to be widely dispersed, rotated and "mixed" among a global ensemble of many broadly similar fragments

Figure 1
Bleeker & Ernst, 2006

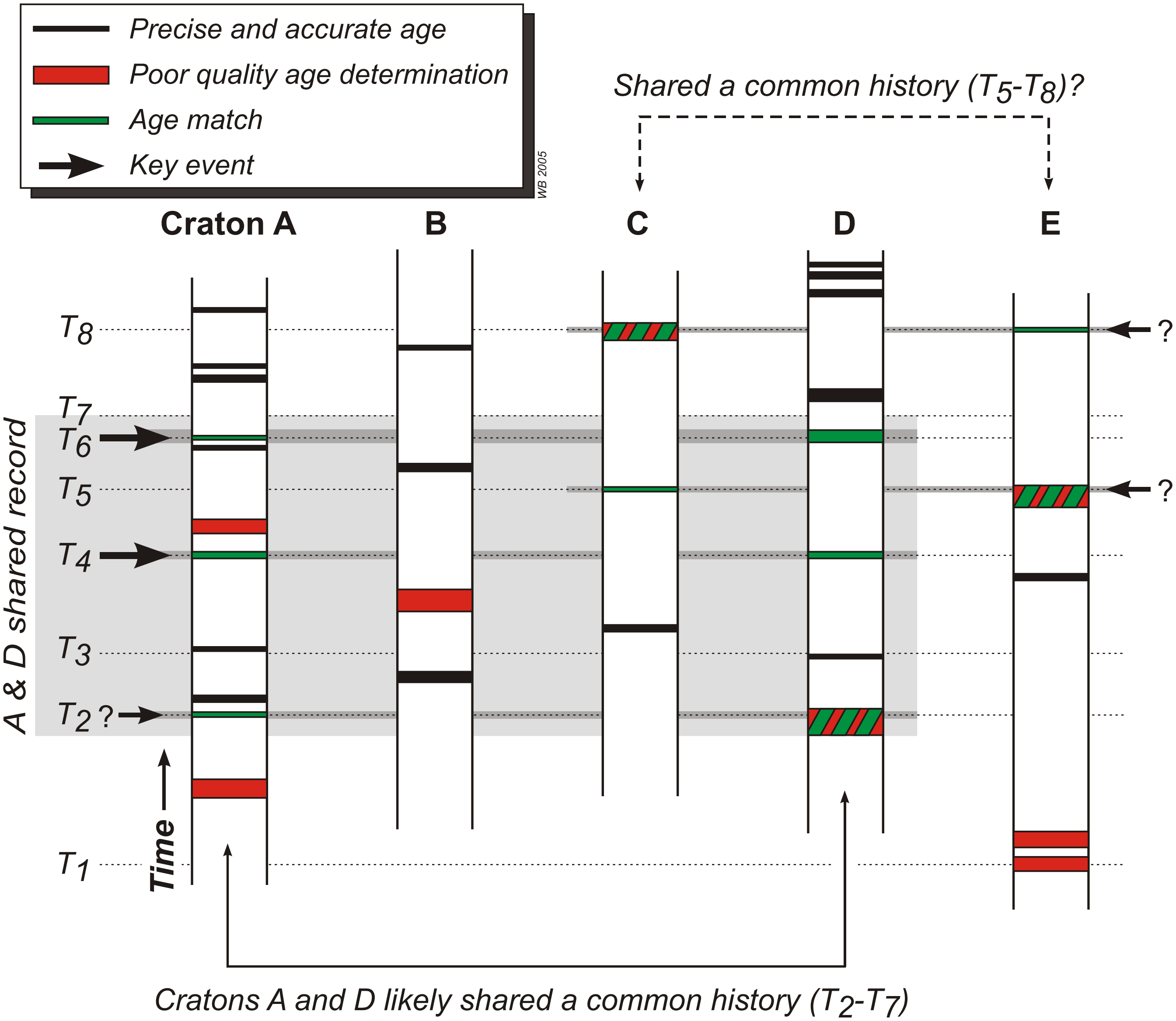


Figure 2
Bleeker & Ernst, 2006

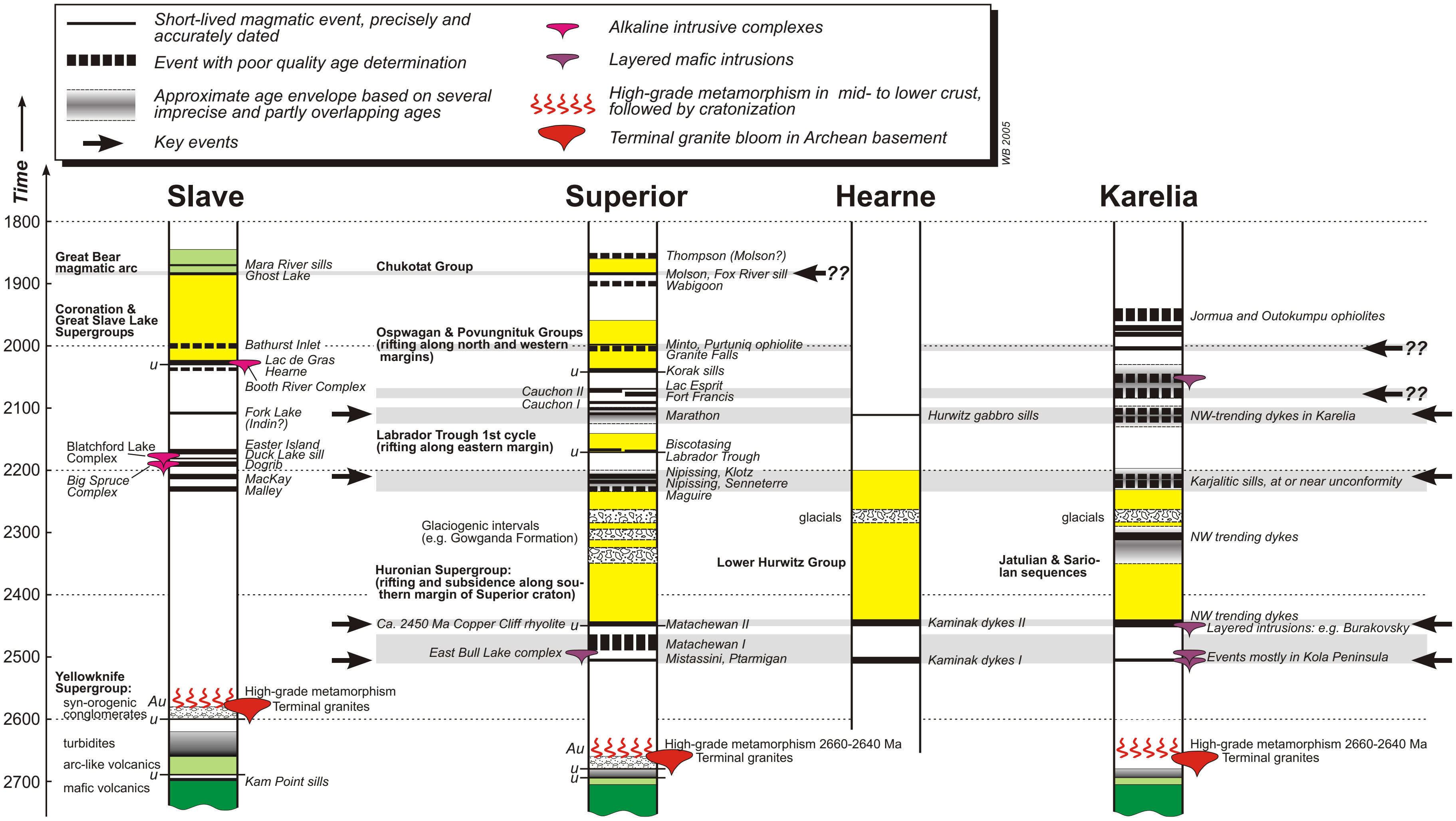


Figure 3
Bleeker & Ernst, 2006

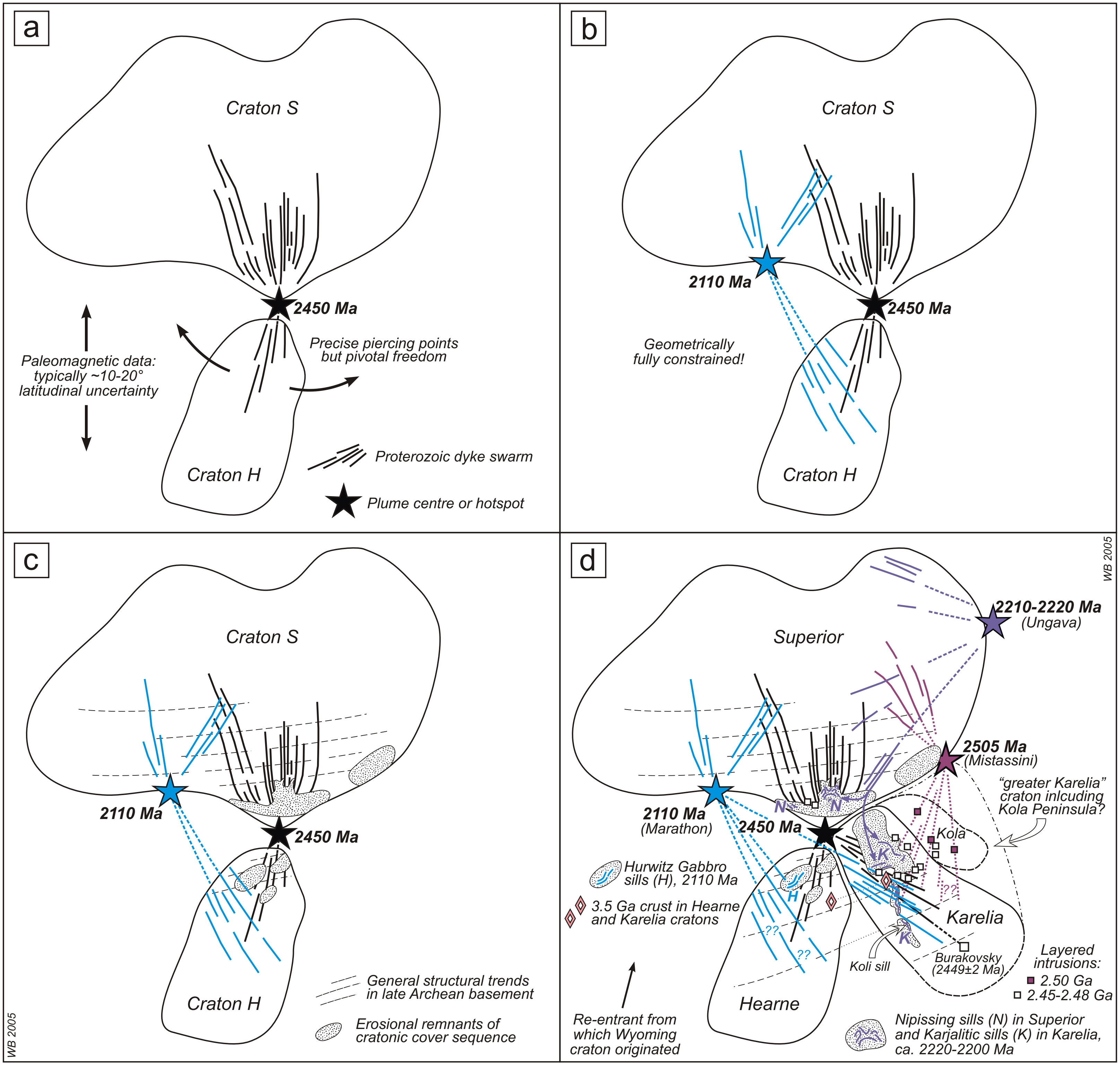


Figure 4
Bleeker & Ernst, 2006