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The late Archean record: a puzzle in ca. 35 pieces

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Abstract

The global Archean record preserves ca. 35 large cratonic fragments and a less well defined number of smaller slivers. Most Archean cratons display rifted margins of Proterozoic age and therefore are mere fragments of supercratons, which are defined herein as large ancestral landmasses of Archean age with a stabilized core that on break-up spawned several independently drifting cratons. The tectonic evolution of individual Archean cratons, such as the Slave craton of North America or the Kaapvaal craton of southern Africa, should therefore always be considered in the context of their ancestral supercratons. This is particularly true for many of the smaller cratons, which are too limited in size to preserve the complete tectonic systems that led to their formation. These limitations not only apply to the crustal geology of Archean cratons but also to their underlying lithospheric mantle keels. If these keels are Archean in age, as their broad correlation with ancient surface rocks suggests, they also are rifted and drifted remains of larger keels that initially formed below ancestral supercratons. The study of Archean cratons and their lithospheric keels should thus be global in scope.

In the search for late Archean supercratons, a craton like the Slave, with three to four rifted margins, has a ca. 10% maximum probability of correlating with any of the ca. 35 remaining cratons around the globe, assuming wholesale recycling of Archean cratons has been limited since ca. 2.0 Ga. Alternatively, if the original number of independently drifting cratons was significantly larger, the probability of successful correlations is much less. Due to repeated cycles of break-up and plate tectonic dispersal since ca. 2.0 Ga, the probability of correlation is probably independent of present-day proximity, unless there is independent evidence that two neighbouring cratons were only separated by a narrow ocean. Nevertheless, most previously proposed craton correlations rely (erroneously?) on present-day proximity, implicitly extrapolating relatively recent paleogeography back to the Archean.

Considering the fundamental differences between some of the better known cratons such as the Slave, Superior, and Kaapvaal, it seems likely that these cratons originated from independent supercratons (Sclavia, Superia, Vaalbara) with distinct amalgamation and break-up histories. This is contrary to widely held opinion, based largely on an idealized view of the supercontinent cycle, that all cratons shared a common history in a single late Archean supercontinent.

In contrast to the Superior and Kaapvaal cratons, which are radically different from the Slave craton and each other, the Dharwar craton of peninsular India, the Zimbabwe craton of southern Africa, and the Wyoming craton of North America all show significant similarities to the Slave craton. It thus seems likely that at least some of these were nearest neighbours to the Slave craton in the ca. 2.6–2.2 Ga Sclavia supercraton.

Keywords: Slave craton; Supercontinent; Supercraton; Craton correlation; Archean

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1. Introduction

Despite rapid progress in recent years the study of Archean cratons commonly remains narrowly focussed, either by discipline or by geographic area. Although the reasons for such research biases are obvious this tends to impede a more complete understanding of the ancient cratons, their genesis, and the Archean Earth in general.

Archean cratons[1] are complex fragments of pre-2.5 Ga crust with, commonly, genetically linked upper mantle. Hence, their study requires a multidisciplinary approach at the lithospheric scale. Perhaps it is less obvious that this endeavor should be global in scope as most cratons show rifted or faulted margins and hence are merely fragments of larger ancestral landmasses (Williams et al., 1991). Individual cratons, now generally embedded as exotic bits in Proterozoic or younger collages (e.g., Laurentia, Hoffman, 1988, 1989), are in most cases too small to preserve the full complexity of the tectonic systems that led to their formation. Earth's major tectonic systems are typically developed at scales larger than 500 km or even 1000 km. Important examples are diffuse continental rift zones; complete subduction systems including an accretionary prism, arc, back-arc basin, and remnant arc; oceanic plateaus; collision zones with their associated sedimentary basins; and igneous provinces resulting from mantle plume impact or lithospheric delamination. The scale of these systems thus determines that our understanding of the tectonic settings in which individual cratons formed will remain underconstrained unless we are able to reconstruct the larger landmasses from which they originated. In other words, the diagnostic features that determined the tectonic evolution of one craton may no longer be preserved within its own realm, but could well be preserved within another craton that has since rifted off and drifted around the globe. This limitation is equally true for understanding the crustal geology of Archean cratons as it is for understanding the architecture of their lithospheric mantle keels.

The necessity for a global approach is readily apparent in the case of the Slave craton located in the northwestern Canadian Shield (Fig. 1). Although one of the better exposed cratons in the world, its limited size (ca. 500 by 700 km), and the presence of three, if not four, rifted margins predetermine it to be merely a small fragment from a much larger crust–mantle system—the supercraton "Sclavia"[2,3] (Bleeker, 2001a) that is postulated to have existed from its amalgamation at ca. 2.6 Ga to its progressive break-up at ca. 2.2–2.0 Ga. Very similar considerations apply to the Kaapvaal craton of southern Africa, which is bordered by rifted and collisional margins of different ages. In the case of the Kaapvaal craton, a specific correlation has indeed been proposed: that the Kaapvaal craton was formerly connected to the Pilbara of Western Australia in a "Vaalbara" supercraton (e.g., Cheney, 1996). Presently, this is one of the leading contenders for an Archean craton correlation although details on the timing of a shared history, if any, remain a matter of debate (Cheney et al., 1988; Trendall et al., 1990; Cheney, 1996; Zegers et al., 1998; Wingate, 1998; Nelson et al., 1999; Strik et al., 2001; Byerly et al., 2002).

Hence, developing a better understanding of the Archean record not only involves a more detailed documentation of individual cratons, but also comparing and contrasting their geological records and, ultimately, testing potential correlations to reconstruct the larger Archean landmasses from which the present ensemble of cratons originated. The present volume on the Slave and Kaapvaal cratons is therefore timely as it focuses on two very different fragments of Archean lithosphere, both of which have seen intense research efforts in recent years, much of it multidisciplinary in scope (e.g., Bostock, 1997; Griffin et al., 1999; Cook et al., 1999; Bleeker and Davis, 1999a; Grütter et al., 1999; Carlson et al.,

[1] Craton: a segment of continental crust that has attained and maintained long-term stability, with tectonic reworking being confined to its margins. Although there is no strict age connotation in this definition, e.g., some segment of crust could have attained "cratonic" stability during the Proterozoic, the term is most commonly applied to stable segments of Archean crust. Long-term stability is thought to be a function, in part, of thicker lithosphere involving a relatively cool but compositionally buoyant keel of Fe-depleted upper mantle (i.e., tectosphere; Jordan, 1978, 1988).

[2] Supercraton: a large ancestral landmass of Archean age with a stabilized core that on break-up spawned several independently drifting cratons.

[3] Sclavia is derived from the Greek word for "slave": sclavos.

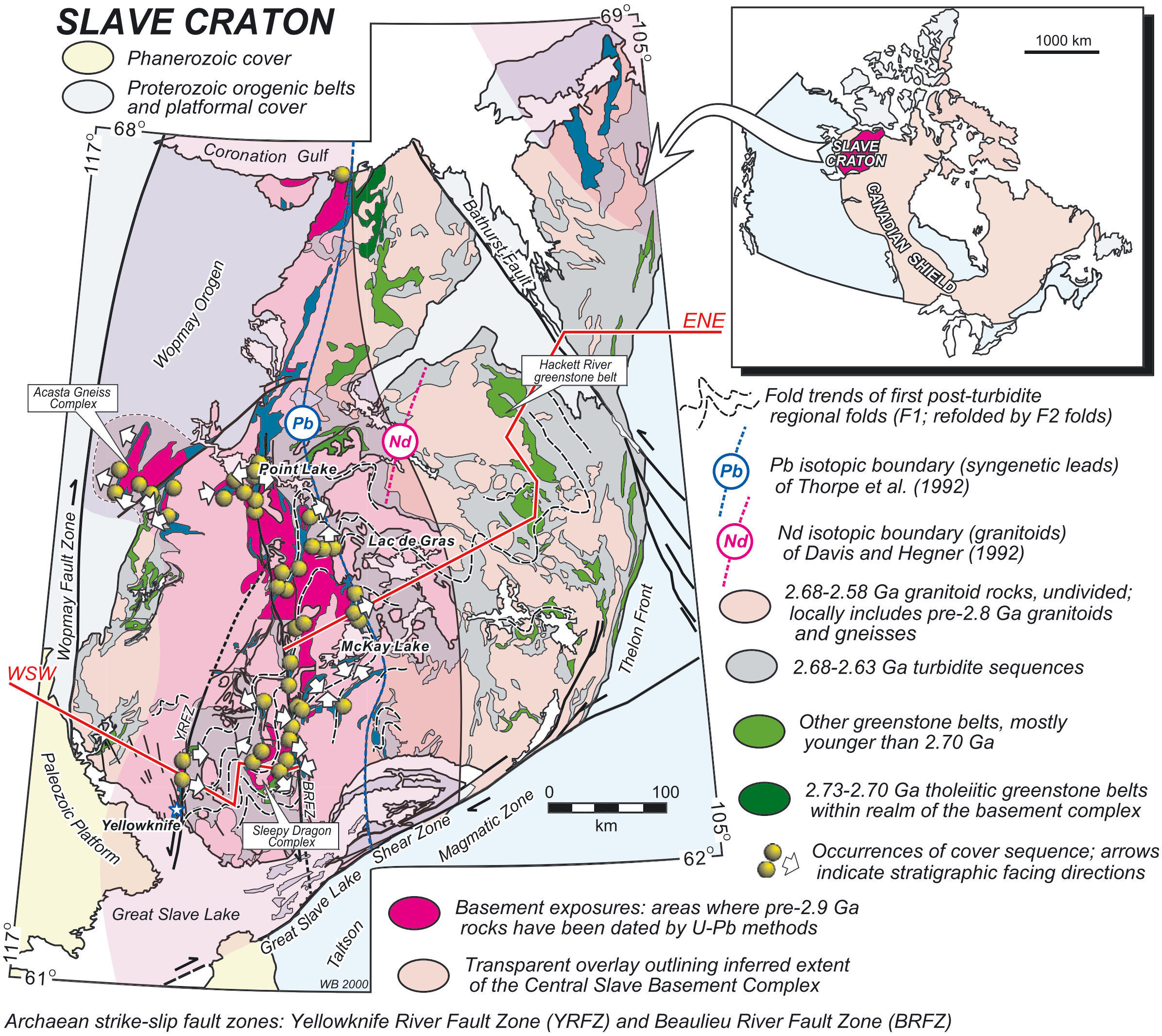


Fig. 1. Geology of the Slave craton. Transparent overlay outlines minimum extent of the Hadean to Mesoarchean basement complex underlying the central and western parts of the craton, the Central Slave Basement Complex of Bleeker et al. (1999a,b, 2000). Ancient basement may reappear in the northeastern part of the craton. WSW–ENE cross section is presented in Fig. 7. Pb isotopic boundary of Thorpe et al. (1992), Nd isotopic boundary of Davis and Hegner (1992).

2000; Kopylova and Russell, 2000; Irvine et al., 2001; Jones et al., 2001). In this contribution, I thus emphasize the need for a global approach in Archean studies and outline some of the basic logic that is relevant to craton correlations. I will introduce the Slave craton, particularly in terms of its first-order attributes that compare and contrast with those of other cratons. From this I conclude that the Slave craton is so different from another well-known craton in the Canadian Shield, the Superior, that these two cratons likely trace their ancestry to different supercratons, Sclavia and Superia (Bleeker, 2001a). In searching for possible correlations with the Slave craton, I identify the Dharwar, Zimbabwe, and Wyoming cratons as the most likely candidates. Perhaps one or more of these "Slave-like" cratons may have been a "nearest neighbour" to the Slave in the late Archean supercraton Sclavia.

2. Craton correlation and supercratons: why bother?

As introduced above and briefly expanded on here, important reasons for a global approach to the Archean are:

- to compare, contrast, and ultimately correlate Archean cratons into their ancestral supercratons,
- and thus overcome the scale limitation of individual cratons;
- to simplify the highly fragmented Archean record;
- to address the fundamental question whether late Archean crustal evolution is best described by several transient, more or less independent, supercratons (as proposed in this study) or by a single late Archean supercontinent (Williams et al., 1991);
- and hence, in what form can the supercontinent cycle be projected back into the Archean?
- to provide major constraints on the reconstruction of any younger supercontinental aggregations, e.g., Nuna, Rodinia, or Gondwana (and vice versa);
- in an applied sense, to identify the dispersed "missing fragments" of mineral-rich crustal domains;
- and, finally, to improve our understanding of the genesis of diamondiferous lithospheric keels.

These reasons are clear. Even a single successful craton correlation will greatly simplify the highly fragmented Archean record and likely prompt other unforeseen correlations. At the same time, it also will put major constraints on the aggregation history of younger supercontinents such as Rodinia (McMenamin and McMenamin, 1990; Dalziel, 1991; Hoffman, 1991). Craton correlation also addresses important questions such as: where are the missing pieces or continuation of the richly endowed Abitibi greenstone belt of the Superior craton, a large Neoarchean crustal domain that is clearly truncated by younger boundaries on several sides? Or, where is the conjugate margin of a specific, fabulously rich, Paleoproterozoic break-up margin such as the Thompson Nickel Belt of the western Superior craton (Bleeker, 1990a,b)? And if many diamonds are Archean, as has been proposed (e.g., Richardson et al., 1984, 2001), and linked to formation of Archean lithospheric mantle keels, could it be, for instance, that Slave diamonds and Indian diamonds (Dharwar craton) come from a once contiguous piece of mantle lithosphere?

3. The late Archean record: a puzzle in ca. 35 pieces

In the search for craton correlations, it is useful to start with the following question: how many Archean cratons are there? Or more specifically, in terms of reconstructing late Archean supercratons: how many independent fragments of Archean crust are preserved that experienced separate drift histories after the break-up of their ancestral late Archean supercratons but before their amalgamation in younger late Paleoproterozoic landmasses like Laurentia?

The Slave craton is clearly one of these independent fragments, as it appears to have broken out of its postulated ancestral supercraton Sclavia between 2.2 and 2.0 Ga based on the ages of marginal dyke swarms (LeCheminant et al., 1997) and marginal sedimentary sequences (Fig. 2). It probably drifted independently for ca. 200 million years prior to being amalgamated into the rapidly growing landmass of Laurentia (Hoffman, 1989) by 2.0–1.8 Ga, which forms the core to present-day North America. To answer the question posed above, today's highly fragmented state of the global Archean record (Fig. 3) is only a partial guide. Many additional fragments were created relatively recently by the break-up of the late Paleozoic supercontinent Pangaea. For instance, opening of the Atlantic Ocean separated the São Francisco craton in Brazil from Archean components in the Congo craton of central Africa (e.g., Hurley and Rand, 1969). Similarly, the Lewisian gneiss complex of western Scotland is merely an eastern fragment of the Nain craton, which underlies south–central Greenland (e.g., Park, 1995). Ancient gneisses in Labrador are a western fragment of the same craton left behind in North America with the aborted opening of the Labrador Sea. Hence, in any pre-Pangaea reconstructions these recently separated siblings should be combined and regarded as a single craton.

An accurate estimate of the number of independent cratons thus involves tracking the various bits and pieces of Archean crust back in time through previous

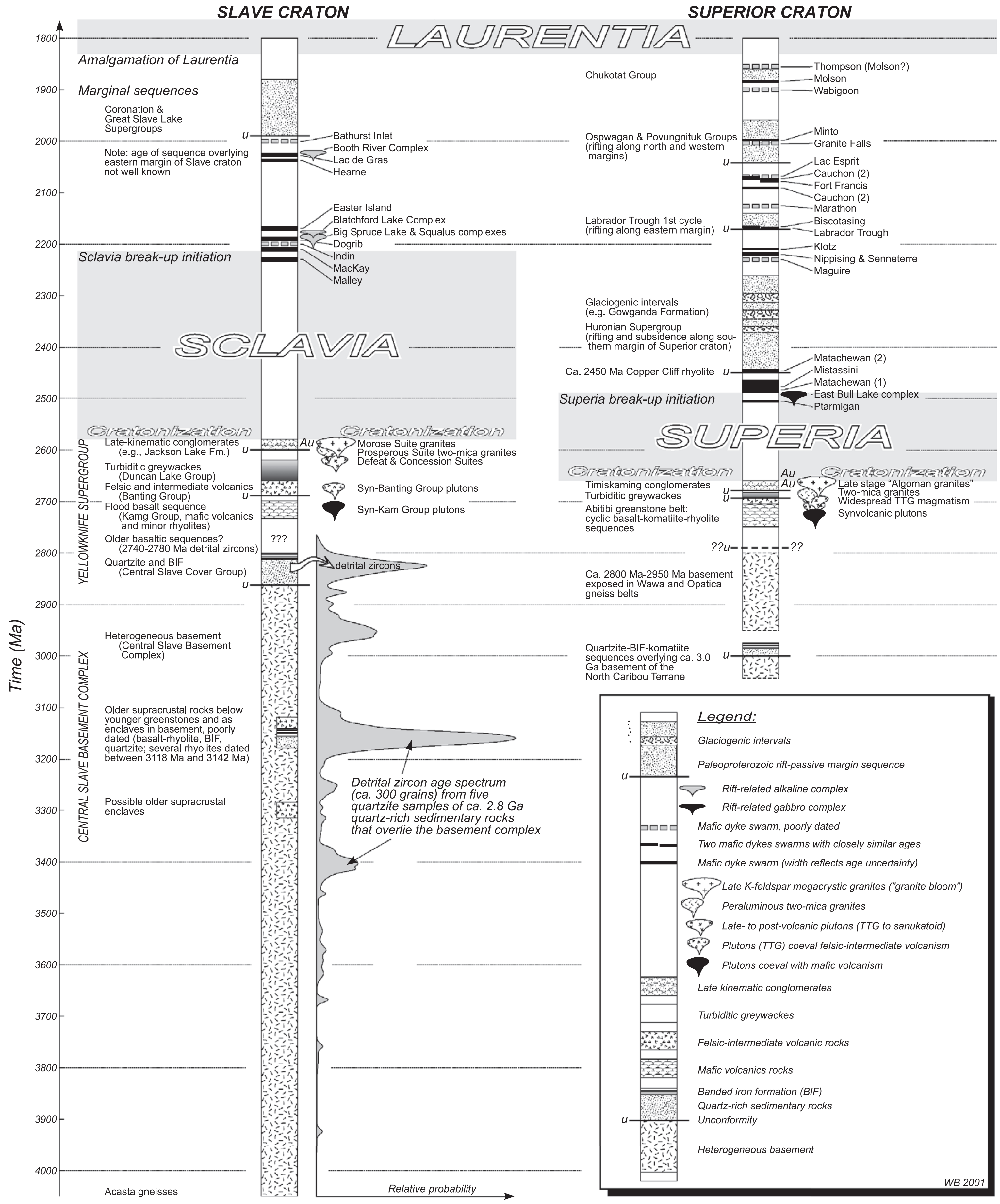


Fig. 2. Comparison of generalized chronostratigraphies of the two best known cratons in Laurentia, the Slave and Superior cratons. Due to lateral heterogeneity of the Superior craton, the older record is not easily generalized and may be less relevant to craton correlations. Younger Archean stratigraphy of the Superior craton is based on the Abitibi greenstone belt and surrounding granitoid terrains (Card, 1990; Corfu, 1993; Bleeker, 1999). Ages of dyke swarms 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, 1999b). Except for widespread basalt–komatiite volcanism between 2730 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 50–70 million years. The Slave and Superior cratons must have been part of different supercratons, Sclavia and Superia. Break-up of Superia was initiated at ca. 2.45 Ga, whereas Sclavia did not break-up before 2.23 Ga. Break-up of each supercraton must have spawned several independent Archean

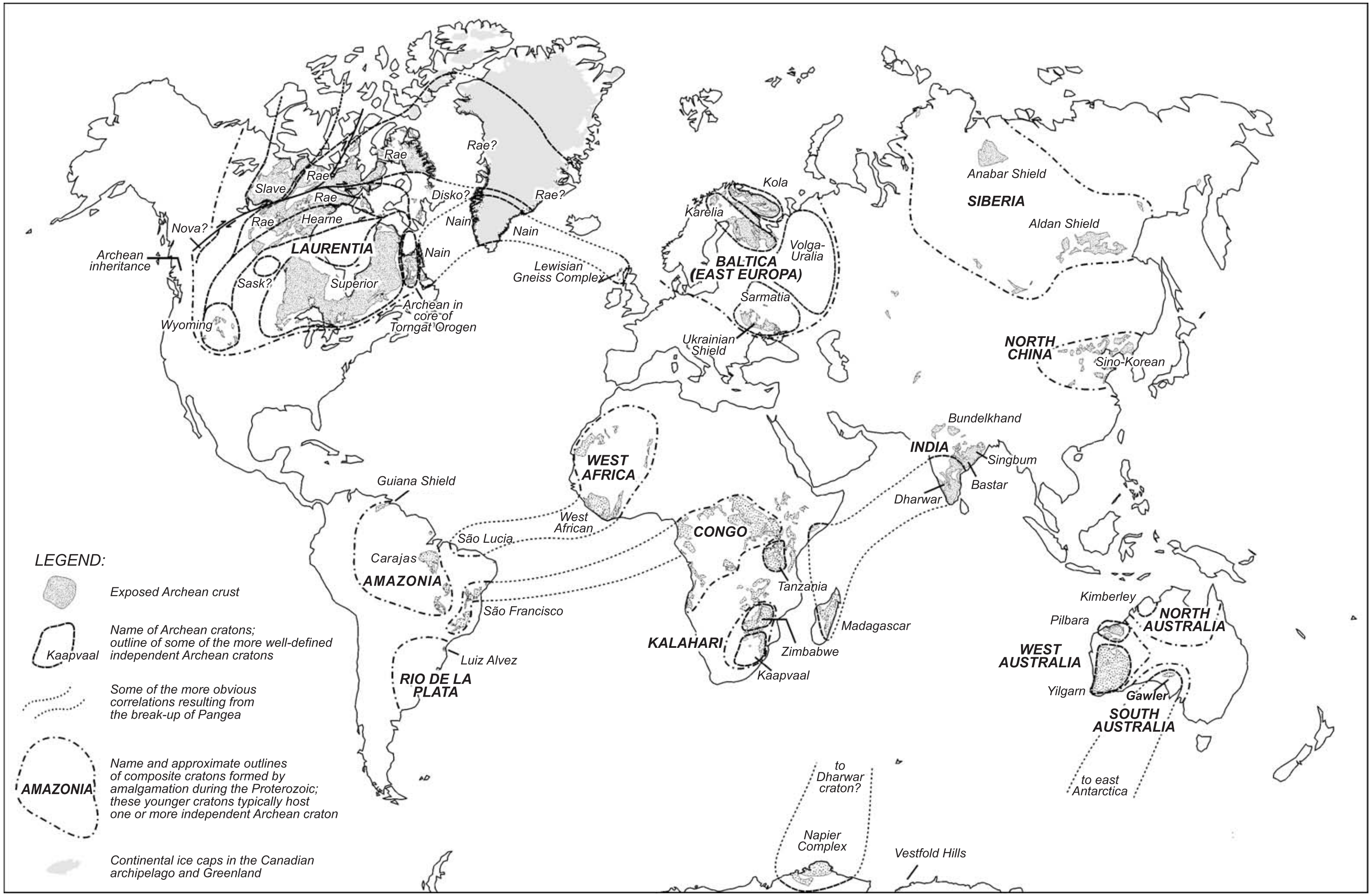


Fig. 3. Global distribution of exposed Archean crust (stippled pattern; from Geological Survey of Canada's Map of the World database). Map is annotated with (1) names of Archean cratons and shield areas (lower case, e.g., Slave), (2) obvious correlations resulting from the break-up of Pangaea, and (3) outlines of composite cratons that were amalgamated during the Proterozoic (upper case, e.g., LAURENTIA).

supercontinental aggregations such as Rodinia, and possibly Nuna (Hoffman, 1997), to evaluate when and where similar fragments of Archean crust may have joined up. However, proposed Rodinia configurations, guided by the principle of disparate continental blocks being stitched together by a global network of Grenvillian orogenic belts (e.g., Hoffman, 1991), tend to minimize contacts between Archean cratons, thus allowing only a limited number of craton correlations. This is counter-intuitive as one would predict that break-up of Rodinia, just like break-up of Pangea, would have increased the number of Archean fragments significantly, unless rifting occurred preferentially along Proterozoic orogenic belts. Nevertheless, Rodinia reconstructions did prompt at least one potential correlation: several authors have placed Siberia next to northern Laurentia at Rodinia time. This led Condie and Rosen (1994) to look for a counterpart to the Slave craton among the Siberian cratons. They suggested that Archean rocks of the Aldan Shield may have been contiguous with the Slave although further tests by Rainbird et al. (1998) have called this particular correlation into question.

Other potential craton correlations may result from the apparently long-lived mid-Proterozoic Laurentia–Baltica connection ("Nena" of Gower et al., 1990; see also Herz, 1969; Hurley and Rand, 1969). Although widely accepted (e.g., Gorbatschev and Bogdanova, 1993; Park, 1995; Karlstrom et al., 2001), it is intriguing that this connection survived unscathed through at least one, if not two, Wilson cycles: (1) break-up of mid-Proterozoic Nuna and subsequent formation of Grenville-age crust along the east coast of Greenland, between Baltica and Laurentia. This suggests that Baltica may be exotic relative to Laurentia, colliding only at Grenville time. To some extent this is implicit in the Rodinia reconstruction of Hoffman (1991, Fig. 1A), which places Laurentia and Baltica on opposite sides of the Grenvillian belt. (2) Several hundred million years later, Laurentia and Baltica are involved in the break-up of Rodinia, leading to 650–600 Ma opening of Iapetus Ocean. Eventually, closure of this wide ocean basin (e.g., Torsvik et al., 1996) led to the Caledonian Orogen and suturing of Baltica to Laurentia (Wilson, 1966). Although paleomagnetic data (Torsvik et al., 1996; Buchan et al., 2000) are permissive of a mid-Proterozoic Laurentia–Baltica fit, they also indicate complex relative motions between both continents during the life span of Iapetus Ocean (Torsvik et al., 1996), thus greatly reducing the probability that Baltica somehow came back to its pre-break-up position. This paradox strongly suggests that the mid-Proterozoic Laurentia–Baltica connection needs to be revisited.

From this brief discussion, it is clear that significant uncertainties remain in the reconstruction of Rodinia. Hence, the configuration of a possible precursor supercontinent to Rodinia, mid-Proterozoic Nuna, and its significance for Archean craton correlations therefore remain shrouded in mystery.

Despite these significant uncertainties, it appears that the present crustal record preserves ca. 35 large Archean fragments and a less well defined number of smaller, poorly preserved slivers (Figs. 3 and 4). With further age dating and an improved understanding of the architecture of some of the more complex Precambrian shields and buried platforms (e.g., Brazil, Siberia, Congo) this number may rise somewhat. On the other hand, a failure to recognize some of the post-1.7 Ga fragmentation events will tend to artificially inflate this estimate. A preliminary count of ca. 35 preserved, independent, Archean cratons is therefore reasonable.

At least five of these independent cratons (Slave, Rae, Superior, Wyoming, Nain) were amalgamated in the Proterozoic supercraton Laurentia during 2.0–1.8 Ga convergence (Hoffman, 1989). The independent status of three others (Hearne, distinct from Rae?; Sask, leading edge of Superior?; Archean core of Torngat Orogen) remains a matter of debate. As discussed above, this large post-1.8 Ga landmass may have extended into Baltica and into the larger East European craton. Here at least four large Archean cratons are present (Karelia, Kola, Volga–Uralia, Ukrainian Shield; Fig. 3). Whether Karelia and Kola are independent cratons in the sense defined above or rifted fragments of the Nain craton and a second Archean craton underlying much of central Greenland (Rae?) is an important question dependent on the history and exact configuration of the Laurentia–Baltica connection. If they indeed correlate, as suggested in the reconstruction by Gorbatschev and Bogdanova (1993), Karelia and Kola should not be treated as independent cratons. However, given the uncertainties described above, the present author

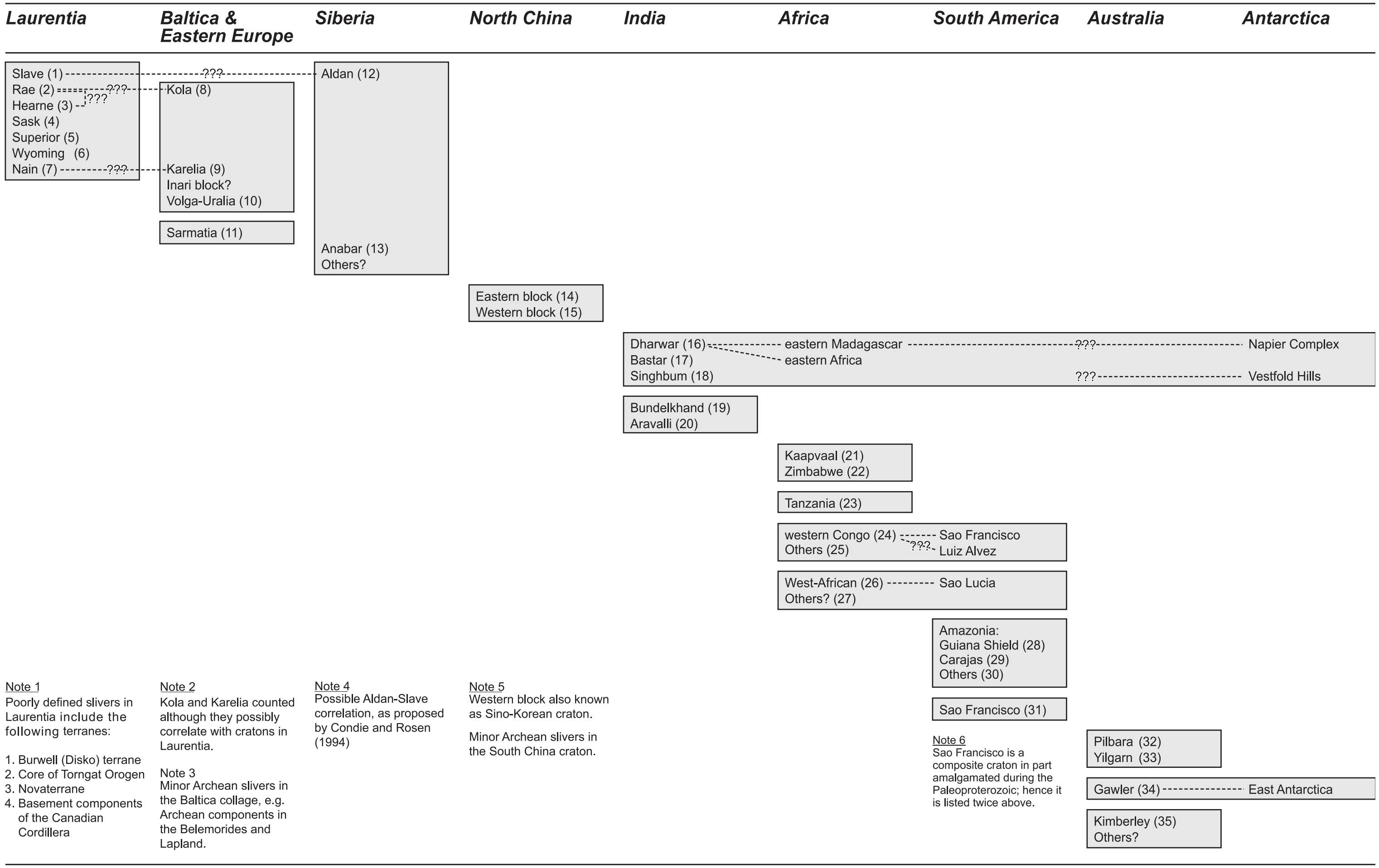


Fig. 4. A preliminary estimate of the number of independent Archean cratons preserved in the global Archean record. Names across the top are those of composite Proterozoic landmasses (“amalgamated cratons”) or present-day continents. Names below these headings are Archean cratons or areas of significant Archean exposure. Shaded boxes represent “amalgamated cratons” with one or more Archean craton, some stretching across different continents due to break-up of Pangaea or Gondwana. Dashed lines further highlight possible correlations due to break-up of either Rodinia (e.g., Slave–Aldan correlation proposed by Condie and Rosen, 1994) or Gondwana. Although our knowledge of some complex shield areas remains insufficient, a preliminary count suggests that the Archean records represent a puzzle in ca. 35 significant pieces and a less well defined number of smaller slivers.

favours to treat Karelia and Kola as independent cratons.

Processes similar to the growth of Laurentia amalgamated other subsets of Archean cratons in other Proterozoic landmasses, e.g., Western Australia (Pilbara, Yilgarn; Gawler craton collided later; e.g., Myers et al., 1996) or Penisular India (Dharwar, Bastar, Singbhum). The relative disposition of these Proterozoic landmasses and whether they indeed may have formed a Mesoproterozoic supercontinent Nuna (Hoffman, 1997) remains speculative.

Accepting the estimate of ca. 35 independent Archean cratons as reasonable, a next important question is: how accurate an estimate is this of the true number of independent Archean cratons that may have existed during Paleoproterozoic drift? In other words, how many cratons could have been entirely erased from the record by erosion and tectonic processes in the last 2 billion years. As these processes are irreversible it is clear that the estimate of ca. 35 cratons must represent a minimum. However, many of the (preserved) cratons show a record of remarkable relative stability, with the present erosion surface, at the craton scale, being close to the enveloping surface of folded Phanerozoic, Proterozoic, and in the case of the Slave and Kaapvaal cratons, even Archean uncon-

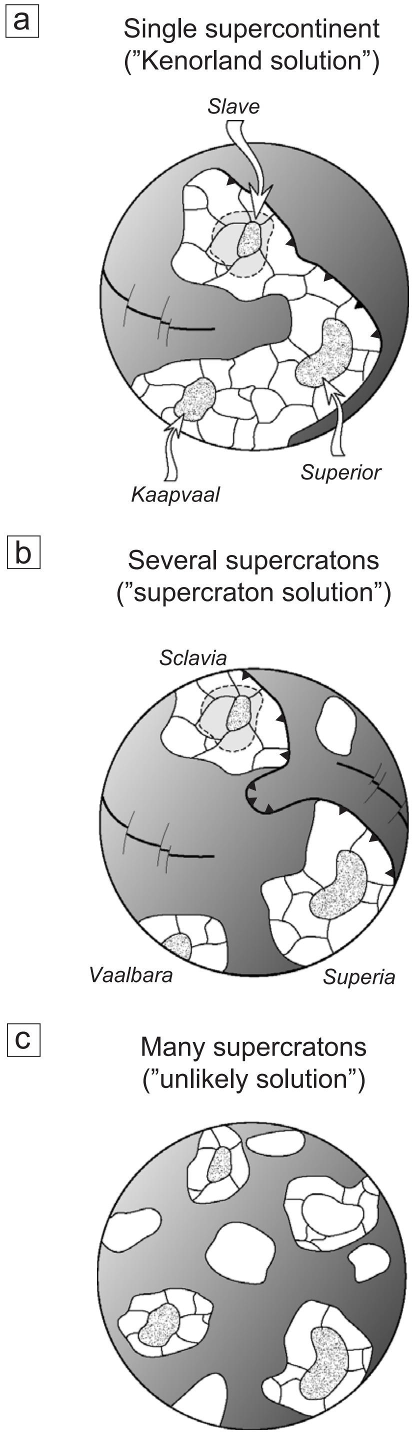


Fig. 5. Cartoons representing Earth in the latest Archean and across the Archean–Proterozoic boundary. Three end member solutions can be envisioned. (a) A single late Archean supercontinent, Kenorland (Williams et al., 1991). Break-up of this postulated supercontinent is thought to have spawned all rifted Archean cratons preserved today. Three cratons are indicated schematically (Slave, Superior, Kaapvaal). Each of these, with their respective nearest neighbours, must have formed a supercraton. Due to significant differences between the better-known cratons, these supercratons must have occupied distant parts in a sprawling Kenorland. (b) Alternatively, as preferred in this paper, some of these supercratons may never have shared a common history in a single late Archean supercontinent. A supercraton like Sclavia, which on break-up spawned the Slave and related cratons (the "Slave clan" of cratons) may have been underlain by a supercratonic lithospheric root (grey outline), parts of which are now likely dispersed around the globe with their host cratons. Note that Vaalbara may have rifted as early as 2.77 Ga, spawning the Kaapvaal and Pilbara cratons, at a time when Superia had not yet amalgamated. (c) A late Archean Earth with many supercratons and smaller landmasses. This configuration is unlikely for both geodynamic and geological reasons (see text). It would predict a high proportion of "external" fragments, i.e., Archean cratons that show long-lived passive or active margins across the Archean–Proterozoic boundary.

formity surfaces (e.g., Hoffman and Hall, 1993; Bleeker et al., 1999a,b; Tankard et al., 1982). A craton like the Slave thus appears to have been "bobbing" rather gently in the convective upper mantle since approximately 2.8 Ga, with effects of rifting, break-up, and collision events being restricted mostly to narrow margins since the Paleoproterozoic. Between ca. 2.6 and 2.2 Ga, it retained its stability as part of the late Archean supercraton Sclavia; after 1.8 Ga, it did so while being amalgamated within Laurentia. Maximum uplift of the Slave craton is constrained by high temperature–low pressure metamorphic facies across the craton, with andalusite being a characteristic index mineral over large areas. Intervening areas are characterized by either lower or higher grade. Over time, erosion has thus removed a maximum of 10–12 km from the surface of the craton and locally much less. Most of this surface erosion must have occurred between 2.6 and 2.2 Ga, during slow uplift accompanied by protracted cooling (Bethune et al., 1999). The size of the craton may have been further reduced by small crustal slivers being "filleted" off the edges during 2.0–1.8 Ga collisional events that amalgamated the Slave into Laurentia but the core of the craton remained stable. If similar stability and survivability is typical for Archean cratons in general, the remaining ensemble of ca. 35 cratons may be an accurate estimate of the number of independent Archean fragments that rifted and drifted around the globe at some time during the Paleoproterozoic.

Hence, if a craton like the Slave has three to four rifted margins bordered by Proterozoic orogenic belts, break-up of its supercraton Sclavia must have spawned circa three to four other cratons that were "nearest neighbours" to the Slave in the ancestral supercraton Sclavia (e.g., Fig. 5). This in turn suggests that 3–4 out of ca. 35 cratons or, in other words, approximately 1 in 10 cratons anywhere around the globe may represent a "missing piece" of the Slave. As at least half of the ca. 35 cratons are reasonably well characterized it should thus be possible, theoretically, to identify a significant number of likely correlations for well-known cratons like the Slave, Kaapvaal, Superior, and others. A reasonable approach then is to group known cratons into "clans" based on degree in similarity in their stratigraphic and structural histories, e.g., Kaapvaal and Pilbara, and then test these similarities in detail using a variety of modern correlation tools, notably sequence stratigraphy (e.g., Cheney, 1996), precise U–Pb dating of stratigraphic marker horizons (e.g., Zegers et al., 1998; Nelson et al., 1999; Byerly et al., 2002), granitoid chronology, and dating and paleomagnetism of mafic dyke swarms (e.g., Heaman, 1997; Wingate, 1998, 1999, 2000).

4. End member solutions

Possible end member solutions to the problem of craton correlations are: (1) a single late Archean supercontinent; (2) a limited set of late Archean supercratons; and (3) many dispersed supercratons and craton-size landmasses.

The single supercontinent solution (e.g., Fig. 5a) is based in part on similar logic as discussed in this paper (i.e., most cratons have rifted margins and therefore must have come from a larger ancestral landmass) and on the general concept of a supercontinent cycle (e.g., Williams et al., 1991; Hoffman, 1992, 1997). Williams et al. (1991) introduced the name Kenorland[4] for this hypothetical late Archean supercontinent and proposed that all Archean cratons within 1.8 Ga Laurentia originated from diachronous early Proterozoic break-up of this landmass.

The second solution, that of a limited set of somewhat independent late Archean supercratons (Fig. 5b), is similar in nature but emphasizes the significant differences between many of the preserved cratons. Discriminating between these two solutions is difficult but could be achieved once several cratons have been correlated into ancestral supercratons. High-quality paleomagnetic data on precisely dated coeval rock formations ("key poles", Buchan et al., 2000), and other paleogeographic indicators, could then test relative proximity between these landmasses. Other possible tests are that a large supercontinent implies a Panthalassa-like ocean with abundant mature oceanic lithosphere. It is thus predicted that supercontinent aggregation should have been accompanied and followed by a eustatic fall in sea levels and

[4] Named after the Kenoran orogeny (Stockwell, 1961, 1964, 1972), the late Archean mountain building event that is thought to have progressively built the Superior Province.

widespread continental emergence. However, there are many uncertainties related to the overall issue of continental freeboard and, therefore, whether this test is sensitive enough to differentiate between a sprawling supercontinent and several somewhat independent supercratons is questionable. On the other hand, several somewhat independent supercratons would have a higher perimeter to surface ratio (e.g., Fig. 5a versus b). Hence, this would predict a higher proportion of cratons with long-lived (e.g., 2.6–2.0 Ga) passive or active margins.

The third solution of many dispersed supercratons and smaller landmasses (Fig. 5c) seems unlikely as it is in conflict with the observation of rifted margins and with general geodynamic understanding. Only sufficiently large landmasses (a single supercontinent or a small number of large supercratons) create the thermal insulation of the mantle that leads to mantle upwelling and continental rifting (e.g., Anderson, 1982; Gurnis, 1988; Davies, 1999).

Independent of configuration, a worst-case scenario would be that the original number of independent cratons was much higher than ca. 35 and that due to progressive fragmentation, erosion, and efficient Proterozoic recycling of Archean crust only a fairly unique set of ca. 35 nonmatching pieces has been preserved. This sobering possibility would imply that the amount of Archean continental crust at ca. 2.5 Ga was many times that what is preserved today. This in turn would be compatible with those end member models of continental growth which suggest that all of the net growth of continental crust happened early in Earth history (Fyfe, 1978; Armstrong, 1981, 1991). A further implication of this scenario would be that the preserved Archean cratons may comprise a nonrepresentative set of crustal (lithospheric) fragments that survived because of above-average stability. This "Darwinian solution" (i.e., survival of the fittest) would severely limit the prospects for successful craton correlations.

5. Craton "clans" based on degree in similarity

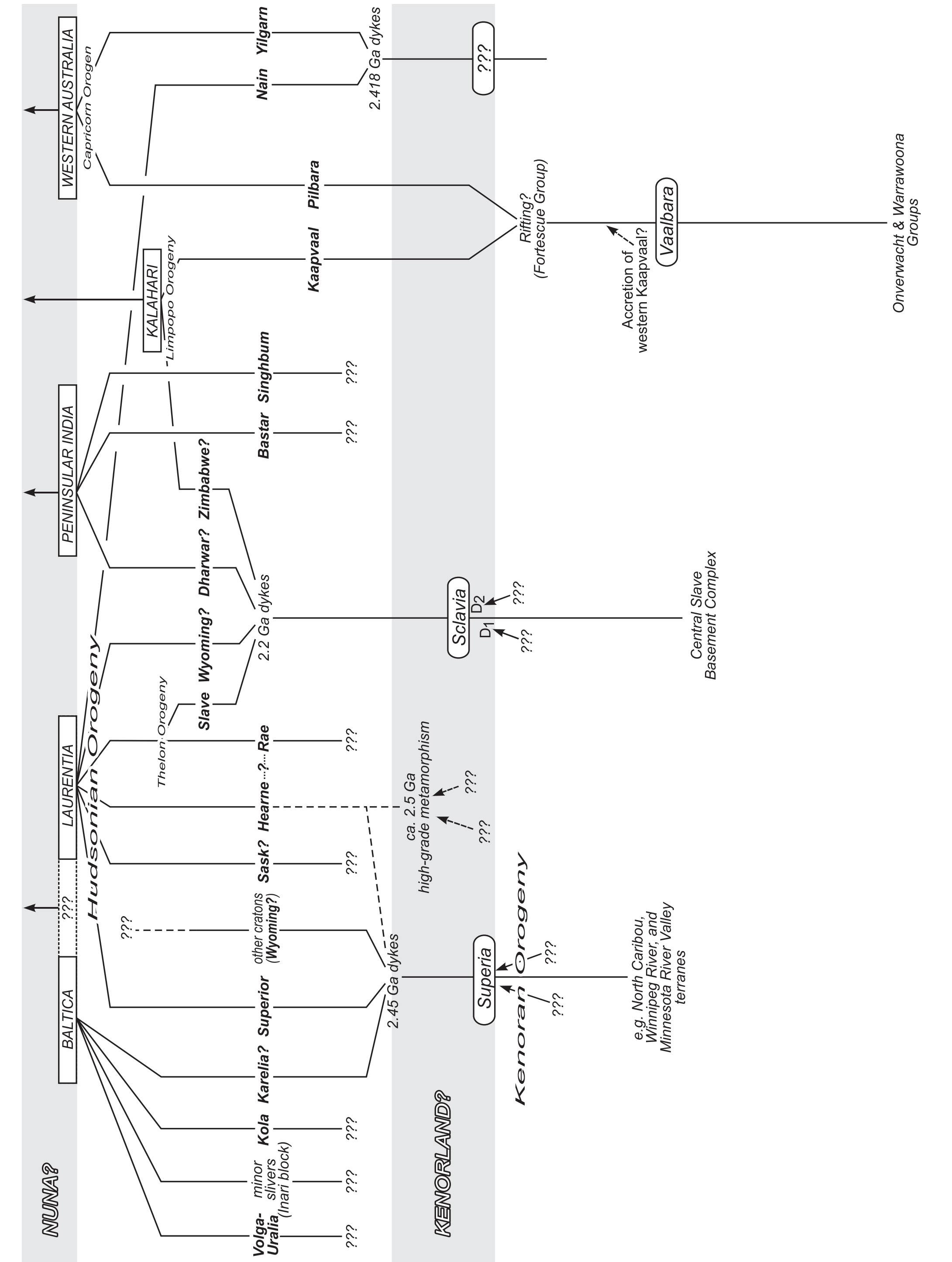
Of the five to eight Archean cratons that were amalgamated in Laurentia, several are sufficiently different that they are unlikely to have been nearest neighbours at any point in time prior to their amalgamation. This is particularly true for the two better-known Archean crustal fragments of Laurentia, the Slave and Superior cratons (Fig. 2). Although it is perhaps permissible that these two cratons were distant parts of a single large supercontinent at ca. 2.6 Ga, Kenorland (Williams et al., 1991; Hoffman, 1992, 1997; e.g., Fig. 5a), there is presently no compelling evidence to support such a notion. Perhaps it is more realistic to propose that the Slave and the Superior trace their ancestry to different ancestral supercratons, Sclavia and Superia, that were in existence across the Archean–Proterozoic boundary (Figs. 2 and 5b).

Similar arguments apply to the Pilbara and Yilgarn cratons of Western Australia, which show few if any correlatable features (e.g., Myers et al., 1996). Whereas the Pilbara craton may have been connected with the Kaapvaal craton of southern Africa (e.g., Zegers et al., 1998), the ancestry of the Yilgarn craton is unknown although it clearly is a substantial rifted fragment of a much larger ancestral supercraton. The latter is indicated by its rifted margins and by the fact that it is cross-cut, from edge to edge, by large, parallel trending, mafic dykes of the ca. 2.41–2.42 Ga Widgiemooltha swarm (Tyler, 1990; Nemchin and Pidgeon, 1998; Doehler and Heaman, 1998). One dyke of this swarm has been precisely dated at 2418 ± 3 Ma, an age that is identical to older Scourie dykes in the Lewisian gneiss complex of northwest Scotland (Nain craton; Heaman and Tarney, 1989). These identical ages and the scale of the Widgiemooltha dyke swarm raise the possibility that the Yilgarn and Nain cratons preserve different parts of a large late Archean supercraton (Fig. 6) that at 2418 Ma was intruded by a giant mafic dyke swarm (Doehler and Heaman, 1998; Nemchin and Pidgeon, 1998). This example not only illustrates the critical role that large mafic dyke swarms play in identifying and testing possible craton correlations, but also emphasizes that due to Paleoproterozoic and younger break-up and dispersal events the preserved Archean cratons have been so thoroughly "shuffled" that correlations among proximal and distal cratons are probably of equal likelihood. Hence, correlations largely based on current proximity, such as the first supercontinent "Ur" as proposed by Rogers (1996), the Kenorland configuration as proposed by Aspler and Chiarenzelli (1998), or the Laurentia–Baltica connection discussed earlier, should be viewed with suspicion. Rogers (1996) postulates his ca. 3 Ga Ur on the basis of the post-0.55 Ga paleogeography of east Gondwana (e.g., see Fitzsimons, 2000), whereas Aspler and Chiarenzelli (1998) apply the post-1.8 Ga paleogeography of Laurentia to the Archean. The random shuffling of the Archean record once again emphasizes the need for a global scope.

Based on the first-order differences between some of the best known cratons, I suggest there are at least three distinct "clans" of cratons, each exemplified by a type craton: a Slave-like clan, a Superior-like clan, and a Kaapvaal clan. Each clan likely traces its ancestry to a different supercraton (Table 1; Fig. 6). An important difference between these three clans is their relative age of cratonization. Granite–greenstone terrains of the Slave craton were cratonized after a terminal "granite bloom" that is dated at ca. 2600–2580 Ma across the craton (van Breemen et al., 1992; Davis and Bleeker, 1999; Davis et al., 2003). In contrast, much of the Superior craton (Card, 1990) experienced late stage granite plutonism between 2680 and 2640 Ma and hence was cratonized at least ca. 50 million years prior to the Slave craton. The Kaapvaal and Pilbara cratons were largely cratonized by 3.0 Ga (e.g., Moser et al., 2001). Other fundamental differences between these type cratons (or their clans) are the chronology of mafic dyke swarm events and the stratigraphy and chronology of Paleoproterozoic cover sequences. For instance, the Superior craton is intruded by the large Matachewan dyke swarm, which fans from a focal point along its southern margin. Dykes of this swarm have been dated at 2473 and 2446 Ma (Heaman, 1997). The significance of the two discrete ages is presently unknown but it seems likely that the composite swarm is associated with rifting along the southern margin of the Superior craton and deposition of the rift and passive margin sequence of the Huronian Supergroup (Young, 1973; Young et al., 2001). An important feature of the Huronian Supergroup is that it contains ca. 2.2–2.4 Ga glaciogenic deposits (e.g., Young et al., 2001). On the other hand, there is no indication of 2.47–2.44 Ma mafic dykes in the Slave craton, nor for marginal Proterozoic sequences of the right age to have recorded the 2.2–2.4 Ga glaciation events. Instead, the Slave craton appears to have broken out of its Sclavia supercraton starting at ca. 2.2 Ga (Fig. 2). In contrast with both the Superior and Slave cratons, the Kaapvaal and Pilbara are overlain by extensive Paleoproterozoic cover sequences of the Transvaal and Hamersley basins with important carbonate and banded iron formation deposits (e.g., Cheney, 1996). Rifting of these two cratons, or rather of their ancestral supercraton Vaalbara (Fig. 6), may have occurred as early as 2775 Ma with the onset of voluminous mafic volcanism of the Fortescue Group (Wingate, 1998, 1999; Strik et al., 2001).

In addition to the three clans defined above there may be others. Perhaps the possible Yilgarn–Nain correlation based on 2418 Ma mafic dykes (Doehler and Heaman, 1998) suggests a fourth group. An interesting feature of at least parts of the Nain craton (Lewisian gneiss complex) is a significant ca. 2.5 Ga high-grade metamorphic and deformation event (Corfu et al., 1994; Friend and Kinny, 1995). A similar event is known from large parts of the Hearne craton in Laurentia, but appears absent from the Slave and Superior cratons. Other observations relevant to the Yilgarn craton are that the general chronology of ca. 2720–2630 Ma events is very similar to that of the southern Superior craton (e.g., Nelson, 1998). This view is reinforced by apparent similarities between the Widgiemooltha (Yilgarn) and Matachewan (Superior) dyke swarms, each of which cuts at nearly right angles through the belt-like arrangement of contrasting granite–greenstone domains in both cratons. However, the precise age dating of both swarms (2418 Ma for the Widgiemooltha swarm, versus 2446 and 2473 Ma for the Matachewan swarm) rules out a direct correlation.

In summary, first-order differences between some of the best-known cratons suggest an ancestry from different supercratons (Fig. 2). As an initial step towards identifying and testing such supercratons it is useful to group known cratons into different clans based on their degree of similarity (Table 1) using the chronology of latest Archean events, and Paleoproterozoic mafic dyke swarms and cover sequences. Among the well-characterized cratons, there appear at least three if not four distinct clans, with the Slave, Superior, Kaapvaal, and possibly Yilgarn, as type examples. Other clans may exist but an exhaustive survey is presently difficult due to the incomplete knowledge of all 35 cratons. It is also beyond the scope of this paper. Below, I will discuss the Slave



NUNA?
KENORLAND?
BALTICA
LAURENTIA
PENINSULAR INDIA
KALAHARI
WESTERN AUSTRALIA
Capricorn Orogen
Limpopo Orogeny
Hudsonian Orogeny
Thelon Orogeny
Kenoran Orogeny
Volga-Uralia
minor slivers (Inari block)
Kola
Karelia?
Superior
other cratons (Wyoming?)
Sask?
Hearne
Rae
Slave
Wyoming?
Dharwar?
Zimbabwe?
Bastar
Singhbum
Kaapvaal
Pilbara
Nain
Yilgarn
2.45 Ga dykes
2.2 Ga dykes
2.418 Ga dykes
ca. 2.5 Ga high-grade metamorphism
Superia
Sclavia
Vaalbara
D1
D2
Rifting? (Fortescue Group)
Accretion of western Kaapvaal?
e.g. North Caribou, Winnipeg River, and Minnesota River Valley terranes
Central Slave Basement Complex
Onverwacht & Warrawoona Groups
Time (Ma)
1800
1900
2000
2100
2200
2300
2400
2500
2600
2700
2800
2900
3000
3100
3200
3300
3400
3500

Table 1
Craton clans based on degree in similarity[a]

Craton clan and type craton	Slave	Superior	Kaapvaal	Yilgarn?[b]
Ancestral supercraton	Sclavia	Superia	Vaalbara	???
Approximate age of cratonization	2.58–2.50 Ga	2.68–2.63 Ga	ca. 3.0 Ga	2.68–2.63 Ga
Major dykes swarms and possible initiation of break-up	ca. 2.22 Ga	ca. 2.47–2.45 Ga	ca. 2.77 Ga	ca. 2.42–2.41 Ga
Other possible cratons in clan (i.e., possible "nearest neighbours" to type craton in ancestral supercraton)	Dharwar? Zimbabwe? Wyoming?[c] Others?	Karelia? Hearne? Wyoming?[c] Others? Yilgarn?[b]	Pilbara?	Nain?

[a] See text for explanation and references; question marks highlight significant uncertainties in all correlations.
[b] The Yilgarn clan is less distinct than the other three; e.g., age of cratonization of the Yilgarn is similar to that of the Superior and both clans may collapse into a single clan with more data.
[c] The Wyoming craton shows many similarities to the Slave craton and herein is considered a member of the Slave clan. Others have argued for proximity of the Wyoming craton to the Superior, based on lithostratigraphic comparisons of the undated Snowy Pass Supergroup with the Huronian Supergroup (e.g., Roscoe and Card, 1993).

clan in some detail before returning to broader correlation questions in the Discussion.

6. The Slave clan: possible progeny of a Sclavia supercraton

The Slave craton (Padgham and Fyson, 1992; Bleeker and Davis, 1999a) is characterized by a large Hadean to Mesoarchean (ca. 2.85 Ga) basement complex, which includes the oldest known, intact, terrestrial rocks, the Acasta gneisses (e.g., Bowring et al., 1989; Stern and Bleeker, 1998; Bowring and Williams, 1999). This basement is exposed in large antiformal basement culminations and is overlain by basalt-dominated Neoarchean greenstone belts and turbiditic sedimentary rocks (Figs. 7 and 8). Together with synvolcanic and several post-turbidite granitoid intrusive suites, these Neoarchean supracrustal rocks of the Yellowknife Supergroup dominate the surface geology of the craton (Fig. 1). Although there are minor regional differences, the overall stratigraphy and granitoid geochronology is rather similar across the craton and can be characterized as follows (Fig. 8):

- Pre-2.86 Ga basement, overlain by a thin sequence of fuchsitic quartzites and banded iron formation (Central Slave Cover Group, Bleeker et al., 1999a,b; see Fig. 7b–e).
- 2730–2700 Ma, widespread basaltic volcanism across the basement complex (Kam Group, Fig. 7f), with minor komatiitic rocks, and locally intercalations of rhyolite, tuff, and reworked volcaniclastic rocks, particularly towards the top of the pile; precisely dated tuff layers at 2722 to 2700 Ma (e.g., Isachsen and Bowring, 1997).
- 2700–2660 Ma, transition to more intermediate, felsic, or bimodal volcanism (Banting Group, e.g., Henderson, 1985; Helmstaedt and Padgham, 1986); dacite–rhyolite complexes typically became

Fig. 6. Cladogram showing possible relationships between about half (17) of the ca. 35 independent Archean cratons. Archean supercratons, break-up of which spawned the independent Archean cratons, are shown at the bottom (Superia, Sclavia, Vaalbara, and possibly a fourth supercraton). Composite cratons that resulted from collisional amalgamation of the Archean cratons during the Paleoproterozoic are shown at the top (names in capital letters). In this cladogram, divergence represents break-up, whereas convergence represents amalgamation, typically associated with significant orogenies; question marks represent significant uncertainties or unknowns. Williams et al. (1991) argued that all the Archean cratons originated from break-up of a single late Archean supercontinent, Kenorland (possible life span of Kenorland represented by lower grey band). Alternatively, it is argued here that the cratons may have originated from break-up of several distinct supercratons, each supercraton spawning a clan of similar cratons. Supercraton Vaalbara may have rifted prior to amalgamation of Superia. The Sclavia supercraton was stabilized only after 2.6 Ga and remained intact for ca. 400 million years, after which it broke up and spawned some of the ca. 35 independently drifting Archean cratons. After ca. 1.9–1.8 Ga amalgamation, the resulting composite Paleoproterozoic cratons (e.g., Baltica, Laurentia, etc.) may have formed a mid-Proterozoic supercontinent, Nuna (Hoffman, 1992, 1997).

emergent; abundant volcaniclastic material (Fig. 7i); widespread tonalite–trondhjemite–granodiorite-type subvolcanic plutons.

- 2670–2650 Ma (locally as young as 2625 Ma), widespread turbidite sedimentation across the craton (e.g., Burwash Formation, Fig. 7j,k; Bleeker and Villeneuve, 1995; see also Isachsen and Bowring, 1994; Pehrsson and Villeneuve, 1999; and summary diagram in Davis and Bleeker, 1999, Fig. 6).
- 2645–2635 Ma, first major folds in Burwash Formation turbidites resulting in NE–SW trending F_1 fold belt (see Figs. 1 and 7k; e.g., Bleeker and Beaumont-Smith, 1995; Bleeker, 1996; Davis and Bleeker, 1999).
- 2630–2610 Ma, abundant tonalite–granodiorite ± diorite plutons, possibly diachronous across the craton from southeast to northwest (Defeat and Concession Suites; Davis and Bleeker, 1999).
- 2605–2590 Ma, more evolved granites, particularly two-mica granites in areas of down-folded turbiditic sedimentary rocks (e.g., Prosperous Suite; Henderson, 1985; Davis and Bleeker, 1999). Coeval craton-scale deformation resulting in north- to northwest-trending F_2 folds, which refold F_1 fold belt.
- 2590–2580 Ma, terminal "granite bloom" of evolved, commonly K-feldspar megacrystic granites across the craton (Fig. 7m); no apparent age trends (e.g., Morose Suite; Davis and Bleeker, 1999).
- ca. 2600–2580 Ma, late-kinematic conglomerate sequences (Fig. 7l; e.g., Corcoran et al., 1998), and large-scale strike-slip faulting.

Ca. 2.47–2.41 Ga mafic dyke swarms appear to be absent from the Slave craton. The Malley swarm, currently the oldest known Paleoproterozoic mafic dykes in the craton, has been dated at 2230 Ma (LeCheminant and van Breemen, 1994). Numerous other swarms have been dated between ca. 2.2 and 2.0 Ga (e.g., see Ernst and Buchan, 2001), suggesting break-up of the Sclavia supercraton during this time. Proterozoic marginal sequences such as the Coronation Supergroup are younger than 2.2 Ga and lack the ca. 2.4–2.2 Ga glaciogenic intervals of older cover sequences overlying other cratons such as the Superior. It should be pointed out, however, that the Paleoproterozoic rift-passive margin sequence overlying the eastern margin of the craton is inadequately known due to its involvement in the high-grade Thelon orogen.

Using these first-order characteristics of the Slave craton, I identify the Dharwar craton (southern India), Zimbabwe craton, and Wyoming craton as the most "Slave-like" and hence possibly as nearest neighbours to the Slave in the 2.6 Ga Sclavia supercraton. All three have extensive basement complexes going back to 3.3–3.5 Ga or older (e.g., Horstwood et al., 1999; Frost, 1993), which are overlain by lithostratigraphically remarkably similar Meso- to Neoarchean successions (Fig. 9): quartz pebble conglomerate and fuchsitic quartzites on heterogeneous basement including abundant ca. 2.9 Ga tonalites (e.g., for Zimbabwe: Bickle et al., 1975; Blenkinsop et al., 1993; Hunter et al., 1998). These basal quartzitic rocks are in turn overlain by thin banded iron formations or ferruginous cherts; ca. 2.73–2.70 Ga flood basalts; younger calc-alkaline volcanic rocks and turbidites; and late-kinematic conglomerates. In addition, these Slave-like cratons show a similar progression of late Archean granitoid suites, all culminating at 2.6 Ga or shortly thereafter. In the Zimbabwe craton this would be the widespread Chilimanzi Suite (e.g., Wilson et al., 1995; Jelsma et al., 1996), whereas in the Dharwar craton the late-stage Closepet granite suite would be the closest analog (Friend and Nutman, 1991), although where dated, in the high-grade migmatite and granulite terrain of the southern Dharwar craton, it appears to be younger.

In contrast, basement complexes, general stratigraphy, granitoid chronology, and the chronology of mafic dyke swarms of the Superior craton differ in detail and timing and the Superior is clearly not part of the same clan (e.g., Fig. 2). This raises an interesting point as it has been previously suggested that the Wyoming craton and Superior cratons were connected (Roscoe and Card, 1993). The potential Wyoming–Superior correlation has been largely based on the similarities in stratigraphy, including glaciogenic intervals, between the Snowy Pass Supergroup overlying the southern flank of the Wyoming craton and the Huronian Supergroup (Roscoe and Card, 1993). The Snowy Pass Supergroup remains poorly dated however. Furthermore, the postulated ca. 2.45 Ga mafic dykes (Heaman, 1997) remain to be identified in the Wyoming craton (Heaman, personal communication, 2002). The Archean geology of the Wyoming

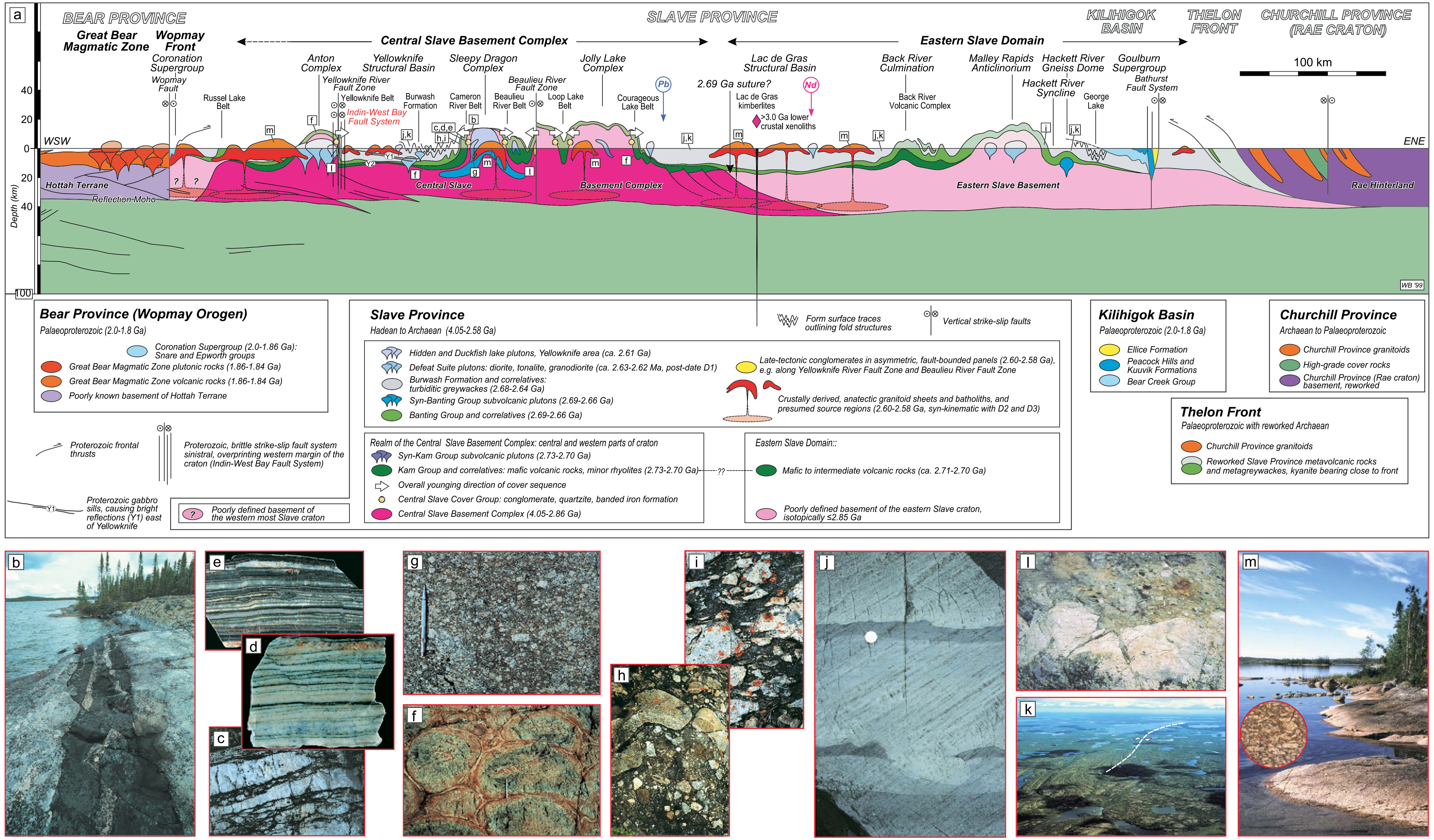


Fig. 7. (a) WSW–ENE structural-stratigraphic section across the Slave craton (see Fig. 1 for location of profile). Letters b–m refer to illustrations below section. Present erosion level at 0 km depth; some units are shown above this level in lighter tones for ease of interpretation; no vertical exaggeration. Deep structure in the western part of the profile interpreted from LITHOPROBE's SNORCLE seismic reflection profile (Cook et al., 1999). Volcanic units <2690 Ma and overlying turbidites overlap the boundary between different basement domains. Field photos: (b) Typical 2.95 Ga foliated tonalites of the Central Slave Basement Complex with transposed 2734 Ma mafic dykes. (c–e) Basal quartz pebble conglomerate, fuchsitic quartzite, and banded iron formation of the Central Slave Cover Group that overlies the basement complex. (f) Variolitic pillow basalts of the Kam Group, Yellowknife. (g) Syn-Kam Group K-feldspar porphyritic granodiorite pluton in basement below greenstone belts. (h) Polymict conglomerate, including 10–30 cm granitoid cobbles, which occurs locally at the base of the younger, 2.69–2.66 Ga, volcanic cycle. (i) Carbonate-cemented rhyolite breccia typical for the younger volcanic cycle. (j) Well-preserved sub-biotite grade turbidites in the core of the Yellowknife structural basin, showing graded bedding and load casts. (k) Areal photo of large scale, upright, fold structures in turbidites of the Yellowknife structural basin. (l) Late-tectonic conglomerates, <2600 Ma, unconformably overlying unroofed granitoid rocks, Point Lake. (m) Late-tectonic, 2585 Ma, K-feldspar megacrystic granite of the Morose Suite in the core of the domal Sleepy Dragon Complex; inset shows 1–2 cm-large K-feldspar megacrysts.

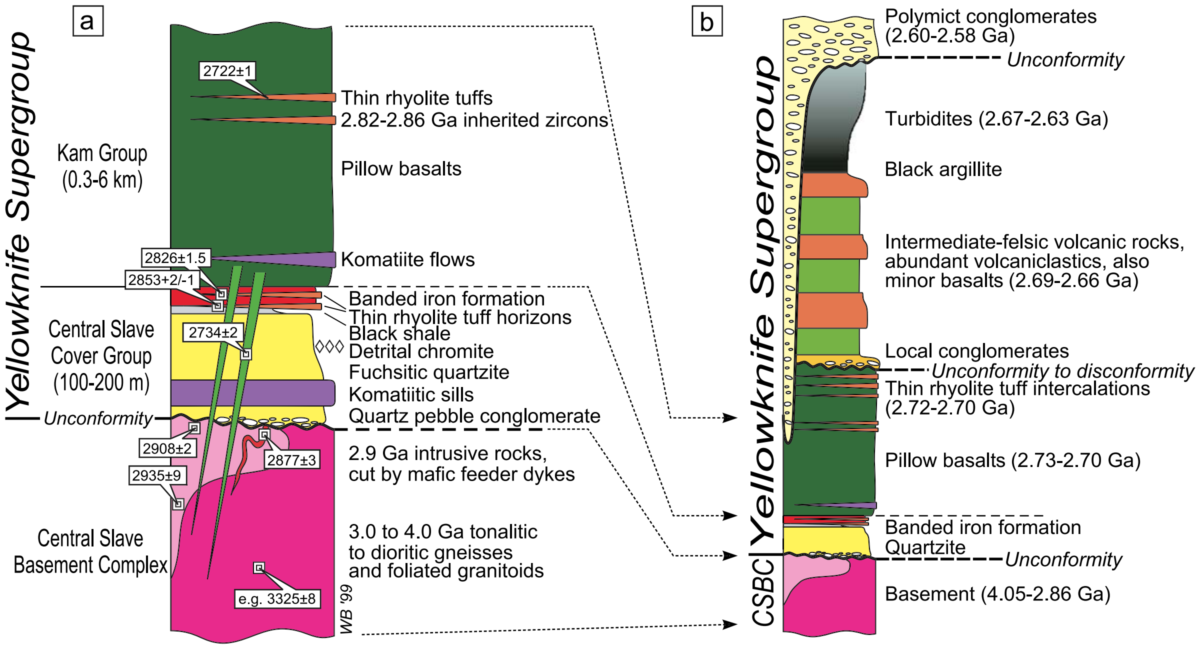


Fig. 8. Generalized stratigraphy of the Slave craton (precise zircon ages from Bleeker et al. (1999a,b), Isachsen and Bowring (1997), and Ketchum and Bleeker (unpublished). (a) Typical stratigraphy of the Central Slave Basement Complex and its overlying sedimentary and volcanic cover. (b) Entire stratigraphy; ca. 2.69–2.66 Ga volcanic rocks and overlying turbidites occur across the craton, their distribution overlapping isotopic boundaries (Bleeker, 2001b). Late-stage polymict conglomerates occur in small restricted basins.

craton (e.g., Houston et al., 1993), including highly evolved Pb isotopic compositions (Wooden and Mueller, 1988), and ancient detrital zircons up to ca. 4 Ga (Mueller et al., 1992, 1998), is more similar to that of the Slave (see also Frost, 1993; Frost et al., 1998, 2000). On the southern flank of the Wind River Range, Wyoming, Archean stratigraphy is exposed that matches that of the central Slave craton in both detail and known age constraints. Here, basement tonalite, cut by abundant mafic dykes, is overlain by fuchsitic quartzite, banded iron formation, and pillow basalts; ultramafic sills intrude near the basement contact (e.g., compare with Fig. 8); overlying units include ca. 2.65 Ga felsic volcanic rocks and a thick package of metaturbidites with abundant cordierite porphyroblasts. The latter are intruded by ca. 2.60–2.55 Ga late-stage granites, while lower in the section the hornblende–titanite bearing granodiorite of the ca. 2630 Ma Louis Lake batholith has an age and composition that is identical to that of Defeat Suite plutons in the Slave craton. Plutonism of this age is absent from the Superior craton.

Expanding on the Slave–Dharwar similarities, the Peninsular Gneiss complex of the Dharwar craton remains to be dated in detail but existing data leave little doubt its history goes back to ca. 3.5 Ga. In the Bababudan greenstone belt (Chadwick et al., 1985a,b; Chardon et al., 1998), a thick basaltic sequence overlies heterogeneous basement. Basalt extrusion was preceded by deposition of a thin, locally fuchsitic, quartz pebble conglomerate and, in some localities, a thin unit of ferruginous chert (Chadwick et al., 1985a). Rhyolite tuffs towards the top of the Bababudan basalt sequence are dated at ca. 2720 Ma (Trendall et al., 1997), an age that is within error of the first rhyolitic tuffs in the basalt sequence overlying the basement complex in the Slave craton. Younger stratigraphic units, including widespread turbidites in the northern part of the Dharwar craton[5] also match

[5] The western Dharwar appears to be gently tilted towards the north, presenting an oblique section from deep crustal granulites in the south to uppermost stratigraphic levels, including widespread turbidites, in the north.

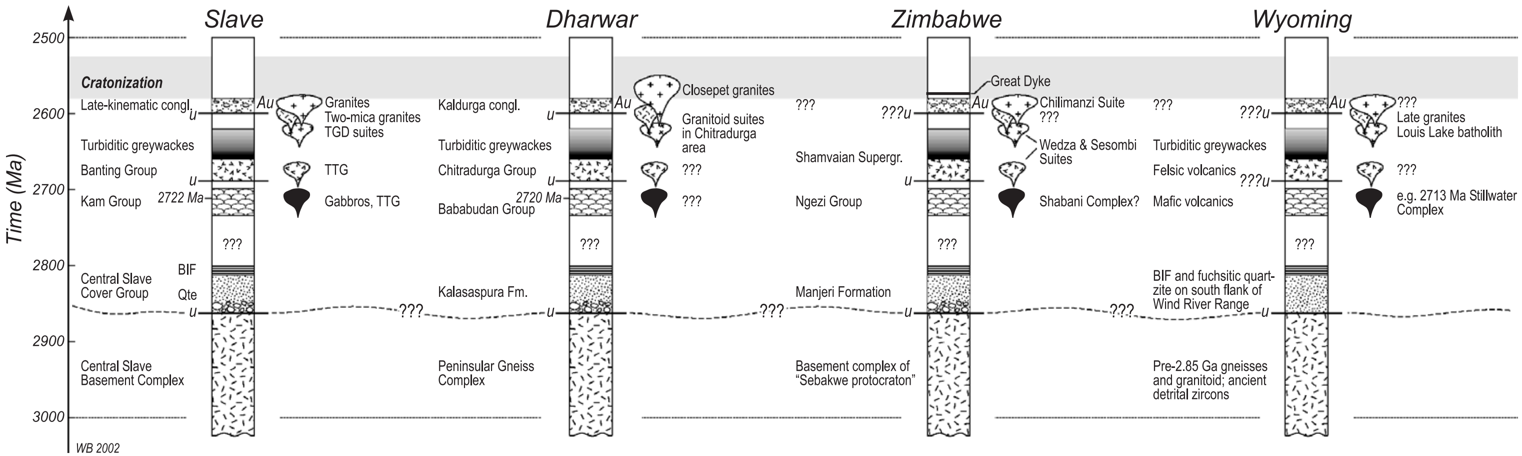


Fig. 9. Comparison of key stratigraphic elements and granitoid suites between cratons of the "Slave clan": Slave, Dharwar, Zimbabwe, and Wyoming. The column of the Slave craton is used as a template. Possible correlative features in the other cratons are identified. Features that have not (yet?) been identified are marked with question marks (e.g., ca. 2.60–2.58 Ga late-kinematic conglomerates in the Zimbabwe craton?). Although precise U–Pb dating is needed to test these possible correlations in detail, the overall similarities require an explanation. The explanation favoured here is that some or all of these cratons may have been nearest neighbours to the Slave craton in the supercraton Sclavia.

the broad stratigraphy of the Slave. And finally, the late-stage Kaldurga conglomerate of the Bababudan greenstone belt, with its abundant granitoid clasts, resembles the late-kinematic conglomerates at the top of the Slave craton stratigraphy (Fig. 8).

Clearly, the broad similarities identified above and illustrated in Fig. 9 require extensive further testing, particularly with high-precision U–Pb dating of key stratigraphic units, granitoid suites, dyke swarms, and Proterozoic cover sequences.

7. Discussion

Irrespective of whether some of the detailed potential correlations will stand the test of time, the broad similarities between certain cratons, but not others, demand an explanation. Although synchronized tectonic processes between distant localities ("parallel evolution") should be considered (e.g., superplume events; or global mantle overturn events), break-up of supercratons and dispersal of cratonic fragments around the globe seems a more likely solution, particularly where there are detailed matches involving several rock units across a broad time span: late Archean stratigraphy, the ages and nature of late Archean granitoid suites, and Paleoproterozoic dykes swarms and cover sequences. High-quality paleomagnetic data sets on coeval rock units across several cratons are needed to test for proximity of potentially correlating cratons.

The statistics of correlations are reasonable, unless the ca. 35 remaining cratonic fragments are just a small, unique, and possibly nonrepresentative sample of an originally much larger set of independent Archean crustal fragments in existence during Paleoproterozoic dispersal. This question is intimately related to models of crustal growth. If a Taylor and McLennan-type model of crustal growth is broadly correct (Taylor and McLennan, 1985), the ca. 35 cratonic fragments will be a reasonable representation of the total count of independent fragments. In that case, a craton such as the Slave, with three or four rifted margins, may have a ca. 10% probability of matching any other craton around the globe. Multiple break-up and dispersal events probably mean that distal and proximal correlations are equally likely. Hence, proposed correlations based on current proximity should be viewed with suspicion, unless there are independent data to suggest that intervening ocean basins were restricted in size.

Based on distinct differences between some of the better known cratons, it seems likely that the ca. 35 preserved cratons trace their origin to several different late Archean supercratons, rather than a single supercontinent, although it is difficult to eliminate the possibility that some of these supercratons occupied distant positions in a sprawling Kenorland. However, several additional lines of evidence lend support for the interpretation of several independent supercratons.

Firstly, if the topology of Fig. 6 is broadly correct, it appears that Vaalbara may have broken up prior to amalgamation of a possible Kenorland, thus complicating the concept of a single late Archean supercontinent (Kenorland).

Secondly, and of a more fundamental nature, a hotter Archean Earth, with at least twice the heat production of today and with a more substantial fraction of its primordial heat budget retained, was probably characterized by more vigorous mantle convection and smaller, faster, plates (e.g., Pollack, 1997; see also Burke and Dewey, 1973; Burke et al., 1976; Hargraves, 1986). Such a regime, characterized by less organization and shorter length scales, is more likely to have favoured smaller, transient, continental aggregations in the form of several independent supercratons rather than a single large supercontinental aggregation. Later in Earth history, secular cooling and a resulting growth in average plate size would have increased the likelihood of supercontinental aggregations and mid-Proterozoic Nuna probably represents the first true supercontinent (Fig. 10). The same fundamental argument may also explain why, since the mid-Proterozoic, the time gap between successive supercontinental aggregations (e.g., Nuna to Rodinia, Rodinia to Gondwana/Pangaea) appears to have been decreasing. Presently, Earth is in the aftermath of the break-up of Pangaea and well on its way to a new supercontinental aggregation cored by Asia ("Amaesia"[6], Fig. 10). India has already collided with Eurasia; Africa, various Mediterranean micro-

[6] Contraction of the *Am*ericas, *A*frica, *E*ura*s*ia, *I*ndia and *A*ustralia. Changed from "Amasia" informally proposed by Hoffman (1997).

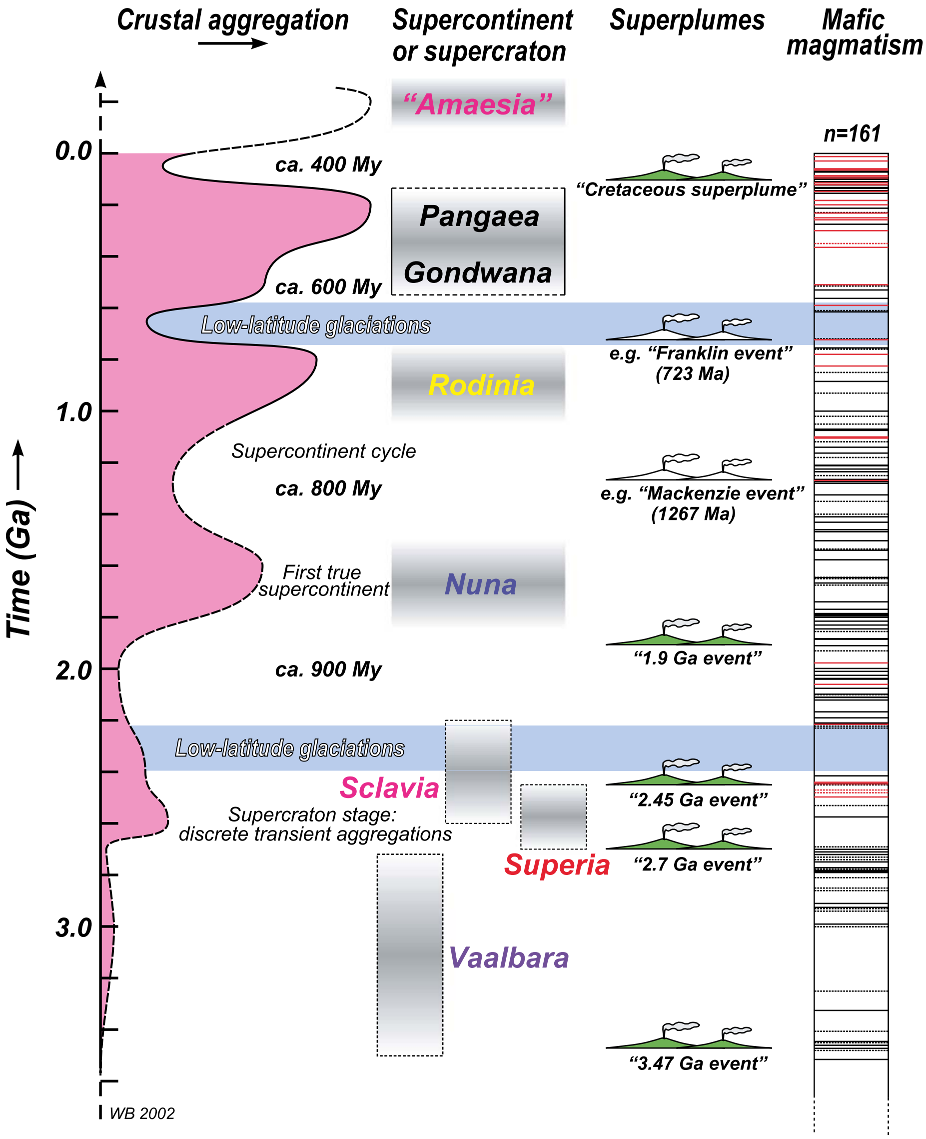


Fig. 10. Qualitative diagram of crustal aggregation states (supercratons, supercontinents) through time (vertical axis). The diagram also shows several other first-order events in Earth evolution that may relate, directly or indirectly, to the crustal aggregation cycle: superplume events (e.g., Condie, 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). 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 break-up of these supercratons, in the Paleoproterozoic, spawned the present ensemble of ca. 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. Note the correlation of intervals of global glaciation with periods of continental break-up 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). Further note that inferred break-up of Nuna appears anomalous in this context, i.e., it is not followed by an interval of global glaciation.

plates, and Arabia are in the process of collision; and Australia, drifting rapidly northward, has just started to make contact with southeastern promontories of Eurasia. The exact trajectories of the Americas are more difficult to predict but, possibly, they will continue their westward drift to join the growing supercontinent 200–300 million years from now. Alternatively, the Atlantic basin may collapse due to aging of its oceanic lithosphere and rapid expansion of the Caribbean and Scotian arcs into the Atlantic realm. This would lead, perhaps on a similar time scale, to the Americas being welded to the Euro-African side of the future supercontinent. Hence, the time gap between maximum states of aggregation will have lasted 400–500 million years. This contrasts with a 500–600 million years time gap between the Rodinia and Gondwana/Pangaea maxima and an even longer time gap between the Nuna and Rodinia maxima. In summary, faster, smaller, and therefore more numerous Archean plates may have never amalgamated into a single aggregation, whereas large modern continental plates, after break-up of one supercontinent, quickly run out of room and thus rapidly re-aggregate.

Irrespective of which configuration will best represent the late Archean Earth, the grouping of cratons into clans based on broadly similar characteristics seems a useful step that will help guide formulation of specific tests. Based on some of the better known Archean cratons of Laurentia, Southern Africa and Western Australia, at least three, if not four distinct clans can be recognized, with type cratons being the Slave, Superior, Kaapvaal, and Yilgarn, although a possible Yilgarn–Superior connection deserves further investigation. Another interesting age match that has been noted in the literature is that of the 2449 ± 3 Ma Woongarra rhyolites and interlayered mafic volcanics of the Hamersley basin overlying the Pilbara craton (Barley et al., 1997) and coeval rift-related magmatism of the Huronian Supergroup in the southern Superior craton (e.g., the 2450 + 25/ − 10 Ma Copper Cliff rhyolite of the Sudbury area; Krogh et al., 1984). This apparent age match may reflect proximity between the Pilbara and Superior cratons at ca. 2.45 Ga. Heaman (1997) has suggested that 2.45 Ga magmatism may have been global in nature. Magmatism of this age appears absent in the Slave craton, however, and viewed from this craton it are the striking similarities with the Dharwar, Zimbabwe, and Wyoming cratons that deserve further investigation.

An interesting point, particularly in the context of this volume, is the relationship between the Zimbabwe and Kaapvaal cratons. Several authors have proposed that these two cratons collided along the Limpopo orogen in the late Archean, some proposing a date as early as 2.68 Ga (e.g., de Wit et al., 1992 and references therein). This seems impossible as the Zimbabwe craton only became a craton after 2.60 Ga. Furthermore, major contrasts between Archean stratigraphy, structure, time of cratonization, chronology of mafic dyke swarms, and chronology and stratigraphy of Proterozoic cover sequences, appear to preclude a shared history prior to 2.0 Ga. The Transvaal Supergroup and Bushveld Complex have no expression in the Zimbabwe craton and, vice versa, the craton-wide ca. 2600 Ma Chilimanzi Suite and 2574 Ma Great Dyke do not cross the high-grade Limpopo orogenic belt into the Kaapvaal craton. From the perspective of a distant observer, these two cratons appear radically different and probably did not collide until ca. 2.0 Ga, the age of final high-grade metamorphism in the Limpopo belt (e.g., Holzer et al., 1998; see also Zhao et al., 2002, for a similar perspective).

I should end this discussion with a word of caution. Supercratons, like their dispersed fragments (the ca. 35 remaining cratons), were heterogeneous to variable degrees. Some of this heterogeneity, particularly where it manifests itself in a belt-like topology such as in the Superior craton, may have resulted from late Archean accretionary and collisional tectonics that contributed to the growth of the supercratons (but see discussion in Bleeker, 2002). Subsequent rifting and break-up in the Paleoproterozoic may have followed late Archean sutures between distinct terrains, thus spawning two or more distinct cratons that may share few elements in Archean stratigraphy but, nevertheless, were “nearest neighbours” in their ancestral late Archean supercraton (Fig. 11). In this end member scenario, successful correlation can only be based on shared remnants of pre-drift Paleoproterozoic cover sequences and mafic dyke swarms. This end member scenario may be rare though as most cratons show characteristic attributes that ignore terrain boundaries. In particular, the products of late stage granitoid plutonism (e.g., the 2590–2580 Ma

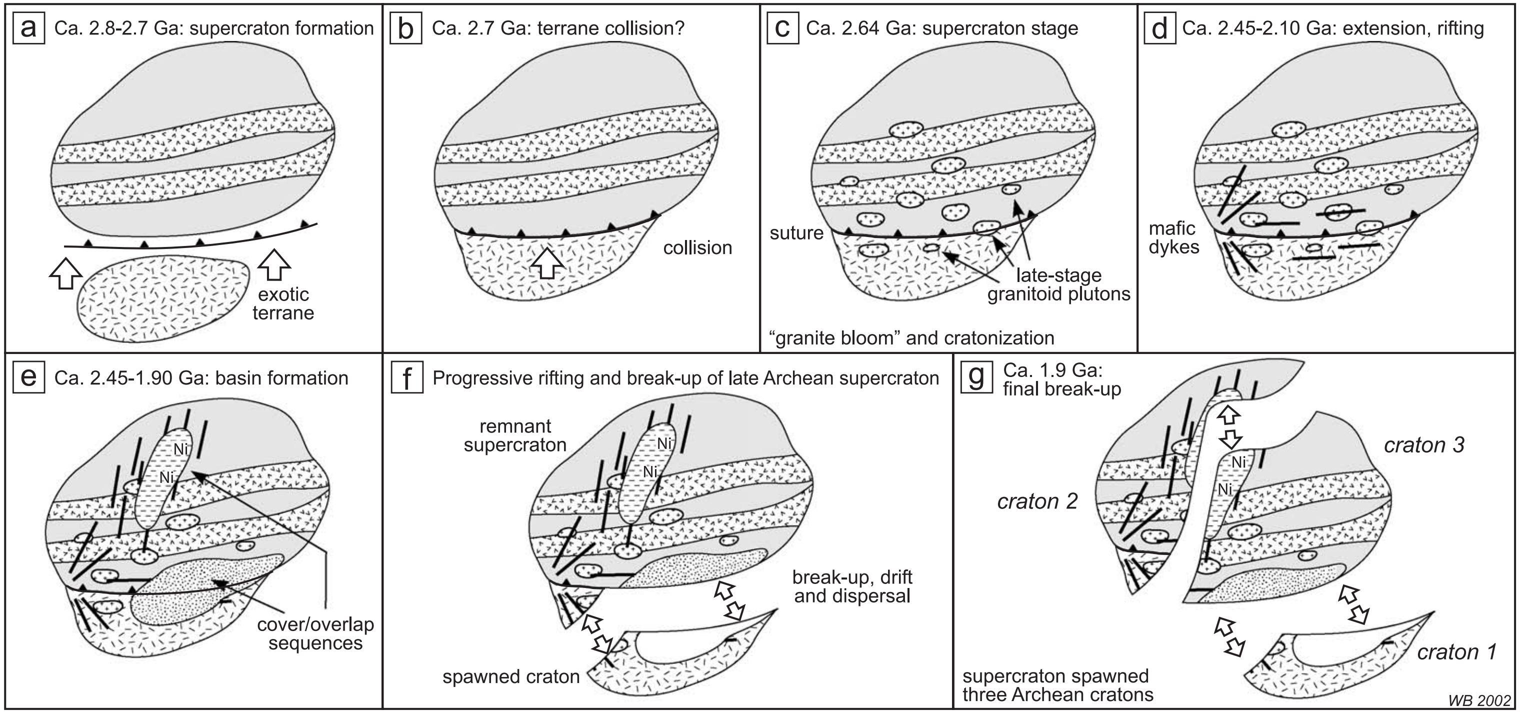


Fig. 11. Schematic illustration of the relationships between a heterogeneous, late Archean, supercraton and its progeny of three cratons (modeled here, in part, with the Superior craton in mind). (a–c) Progressive formation of a late Archean supercraton (e.g., Superia) involving the collision of a large, exotic, Mesoarchean terrain, and culminating in wide-spread, post-collisional, granitoid plutonism at ca. 2.64 Ga ("granite bloom"). (d,e) Progressive rifting, mafic dyke swarm intrusion, and deposition of Paleoproterozoic, rift-related, cover or overlap sequences (e.g., the Ospwagan Group of the western Superior craton margin, with important Ni deposits in ultramafic sills). (f) Rifting and dispersal of a first craton ("craton 1"), consisting largely of the Mesoarchean exotic terrain. (g) Rifting and dispersal of a second craton ("craton 2"). Because rifting and break-up of "craton 1" occurred along an old suture, its Archean stratigraphy is largely unique, whereas "craton 2" and "craton 3" are near-similar twins. In this end member scenario, "craton 1" only reveals its transient residence in the late Archean supercraton through the chronology of the late granitoid suite, and more definitively, through correlation of the dyke swarms and the sedimentary cover/overlap sequence.

"granite bloom" in the Slave, see Davis and Bleeker, 1999; the Chilimanzi Suite of the Zimbabwe craton) tend to occur across entire cratons and thus can be expected to be present also in rifted and drifted fragments of crust that otherwise are distinct in their Archean stratigraphy. Although this end member scenario should be kept in mind, it does not invalidate the cladistic approach of looking for common attributes among Archean cratons as an initial basis for correlating the ca. 35 remaining cratons into their ancestral supercratons.

8. Conclusions

The Archean record preserves ca. 35 cratons and a less well defined number of small crustal slivers. In general, these cratons are rifted fragments of larger ancestral landmasses and tectonic systems—supercratons—that must have existed in the late Archean and across the Archean–Proterozoic boundary.

Based on the marked differences between some of the better known cratons, some of these supercratons (e.g., Sclavia, Superia, Vaalbara) appear to have experienced distinct geological evolutions and therefore are unlikely to have been adjacent pieces of Archean crust. Whether these supercratons were entirely independent ("the supercraton solution") or part of a sprawling supercontinent Kenorland ("the Kenorland solution") remains to be established, although break-up of one supercraton, Vaalbara, appears to predate possible amalgamation of Kenorland. A strict interpretation of the Kenorland hypothesis (Williams et al., 1991; Hoffman, 1992, 1997) thus seems unlikely. Thermal arguments also favour several distinct, transient, late Archean supercratons rather than a single large supercontinent.

Diachronous 2.5–2.0 Ga break-up of these larger supercratons, perhaps preceded by earlier break-up of Vaalbara, spawned a minimum of ca. 35 independently drifting Archean cratons before their amalgamation in younger landmasses such as Laurentia and the potential Mesoproterozoic supercontinent Nuna (Hoffman, 1997). Nuna probably represents the first true supercontinent in Earth's history.

Our ability to correlate the remaining cratons into the original supercratons is strongly dependent on how many cratons were lost from the record. If the number of ca. 35 Archean cratons is a reasonable approximation of how many independent cratons existed during Paleoproterozoic dispersal, a typical craton with three to four rifted margins has ca. 10% maximum probability of correlating with any other craton in the world. This probability would be significantly reduced if the original number of independent cratons was much larger as would be implied by Armstrong-type crustal growth models. If such end member models are true, only the most stable Archean fragments may have survived, possibly representing a unique, nonmatching, and nonrepresentative set of Archean cratons (the "Darwinian solution"). Archean craton correlation problems are thus critically intertwined with crustal growth models and, ultimately, the success rate of such correlations may provide an important test between Taylor and McLennan-type and Armstrong-type models of crustal evolution.

Because of their rifted margins, the tectonic evolution of Archean cratons and that of their mantle keels should always be viewed in the context of the larger ancestral supercratons, even if we are not (yet) able to reconstruct these ancient landmasses in detail. Failure to take this into consideration leads to simplistic models for craton evolution. Due to their limited size, most cratons are too small to preserve their complete tectonic context and critical tectonic elements that shaped the evolution of one craton may now be preserved on a distant but correlating craton.

A first logical step towards craton correlations involves the grouping of cratons into clans based on their degree of similarity. This approach already led to the Vaalbara hypothesis (e.g., Cheney, 1996). Among the better known cratons, at least three obvious clans, and possibly more, can be established. Each clan may represent the progeny of a different supercraton. Similarities between the Slave, Dharwar, Wyoming, and Zimbabwe cratons suggest they may all be part of the Slave clan, which traces its origin to a postulated Sclavia supercraton. This supercraton stabilized in the very latest Archean (ca. 2.58 Ga or shortly thereafter), well after stabilization of another well-known craton, the Superior, and its inferred supercraton, Superia. Stability of Sclavia lasted until ca. 2.2 Ga, at which time it started to experience progressive break-up. By ca. 2.0 Ga the Slave craton had broken out of its ancestral supercraton and was drifting as an independent craton or microcontinent, just prior to its collision with the Rae craton and its eventual amalgamation into Laurentia.

A next critical step towards craton correlation involves establishing detailed chronostratigraphic profiles for all of the ca. 35 cratons (e.g., similar to Fig. 2), including precise ages for all first-order features that are essential to craton correlations: general stratigraphy, particularly the latest Archean events; chronology and character of late Archean granitoid suites; age and character of late Archean craton-scale faults; age of late-kinematic conglomerate basins; ages of all Paleoproterozoic mafic dyke swarms prior to dispersal; and sequence stratigraphy and chronology of Paleoproterozoic cover sequences. High-quality paleomagnetism on key rock units (e.g., precisely dated coeval mafic dyke swarms) is then required to test for proximity. Only then will we be able to view the Archean at the global scale required.

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