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Large igneous provinces and giant dike swarms: proxies for supercontinent cyclicity and mantle convection

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Abstract

The temporal distribution of large igneous provinces (LIPs) and giant dike swarms (GDS) indicates that both occur periodically and are the result of insulation of the mantle following supercontinent assembly. These data define seven possible supercontinent events since 3.0 Ga. The periodicity of these events (300 to 500 Myr) is consistent with previous estimates of mantle and supercontinent cycling rates. The Mackenzie Dike Swarm (1267 Ma) and the Siberian Traps (250 Ma) are synchronous with two dramatic increases in the rate of GDS production. These events define three episodes of mantle activity since 3.0 Ga. A 475 million year gap in the LIP record occurs during a time of relatively dispersed continents between ∼725 and 250 Ma. This 'LIP gap' coincides with a period of Earth history characterized by marine oxygen, carbon, strontium, and sulfur isotope ratios indicative of relatively small mantle fluxes.

Keywords: continental crust; convection; mantle; mantle plumes; dike swarms

1. Introduction

Several workers have postulated that the formation of a supercontinent insulates the underlying mantle and modifies convective activity (e.g., formation of mantle plumes and positive geoid anomalies) that ultimately causes the destruction of the supercontinent via rifting [1–6]. Large igneous provinces (LIPs) and giant dike swarms (GDS) are thought to be the geologic products of these mantle plumes [7,8]. The depth of generation and the dimensions of these plumes are currently being debated but there is increasing evidence that these plumes originate near the core–mantle boundary [9–11]. Therefore, LIPs and GDS should have temporal distributions that are closely related to supercontinent aggregation, the periodicity of which should be comparable to supercontinent cycles (∼500 Myr; [3,12]). Here we examine the temporal relations of LIP and GDS as proxies for supercontinent cycling and mantle convection.

LIPs are bodies of extrusive, typically tholeiitic basalt and associated intrusive mafic rock that have volumes greater than 100,000 km^3 [13]. Basalt flows produced during these events are thought to have erupted violently from fissures produced by the interaction of a mantle plume with either continental or oceanic crust. Many have suggested that these plumes originate near the core–mantle boundary [14–16]. Anderson [17] has argued that mantle plumes may not be required to produce such phe-

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nomena. Radiometric dating of LIPs indicates that these eruptions occur over geologically short periods of time (10^5 to 10^6 years; [13,18–21]).

Ernst et al. [8] define mafic dike swarms as a 'concentration of dikes of basic composition emplaced in the same igneous episode'. Dike swarms that have lengths of greater than or equal to 300 km are referred to as giant dike swarms [22,23]. Of these, dike swarms which demonstrate a radial pattern about a central point are called giant radiating dike swarms [22,23]. Ernst et al. [22] cite the following evidence that relates giant radiating dike swarms to mantle plumes (see Ernst et al. [22] for references): (1) the dike swarm's radiating pattern indicates a central magma source; (2) an emplacement time that spans less than a few million years for the entire dike swarm; (3) the occurrences of volcanic and plutonic rocks at the center of the swarm that are coeval and thus may be the remains of LIPs; (4) topographic uplift at the center of the dike swarm that may indicate the presence of an impinging mantle plume; (5) evidence of lateral flow of magma in the dikes except in the central source area. Ernst et al. [24] define mantle plume centers as the focal points of giant radiating dike swarms of similar age and whose radiating patterns converge at a point thought to be the locus of a mantle plume center. Twenty seven possible mantle plume sites have been identified by correlating the occurrences of giant radiating dike swarms on the basis of radiometric age and paleogeographic reconstruction [24].

2. Discussion

2.1. Age distributions and preservation of LIPs, giant dike swarms, and plume centers

Eighteen LIPs are documented during the last 250 million years [25]. However, no LIPs have been documented between 723 and 250 Ma (Fig. 1). Nine Precambrian LIPs have been documented (723 Ma [26]; 800 Ma [27]; 1108 Ma [28]; 1267 Ma [29]; 2450 Ma [30,31]; 2705, 2715, 2740 and 2770 Ma [32,33]. The temporal distribution of LIPs and GDS suggests that there are seven major episodes of mantle activity during the last 3 billion years (2800–2700 Ma, 2550–2400 Ma, 2250–2000 Ma, 1900–1600 Ma, 1350–1000 Ma, 850–550 Ma, and 350–0 Ma; Figs. 1–3). There is a strong correlation between GDS and LIP episodes and plume centers since ~1300 Ma (Fig. 1). We suggest that this mantle activity is related directly to supercontinent assembly.

The timing of supercontinent assembly has been chosen primarily on the basis of the relation observed in Fig. 3a that couples LIP production and the assembly of Pangea [34]. Secondary importance has been assigned to various paleogeographic reconstructions and interpretations [35–37], given the imprecision of the various factors used to determine the timing of supercontinent aggregation and break-up. Our synthesis of supercontinent cycle reconstructions is found in Fig. 1. Clearly, the timing of pre-Rodinia supercontinents is relatively unconstrained.

Examination of the temporal distributions of LIPs and GDS finds that they occur periodically ([24,38]; Figs. 1 and 2). GDS afford excellent potential for preservation as they are relatively deep intrusive structures that occur vertically in the crust. Therefore, unlike their extrusive counterparts (LIPs), erosion has relatively little impact on GDS preservation. As a result, the GDS record is relatively complete for the last 3000 million years (Fig. 2). We have selected only dikes for which both map dimensions of length and width were reported and for which the age was constrained to better than ±50 million years. In three instances, the reported error was larger than ±50 million years. However, these ages correspond with other dikes from the same region with well-constrained ages.

The cumulative curve of GDS occurrences can be modeled using regular periods of GDS activity with a constant rate of occurrence, punctuated by periods of no activity. Superimposed on this periodic production is a modest loss of occurrences due to erosion and tectonic processes (an exponential decay function with a half-life of 1386 Myr ([39]; Fig. 2a). The mathematical expression used to describe this frequency distribution is:

$$\text{Survival Rate} \times \text{Periodic Production Rate}$$
$$= \text{Occurrences Remaining after Decay}$$

where the Survival Rate $= e^{-kT}$ and the Periodic Production Rate = 3.5 occurrences per 50 Myr for

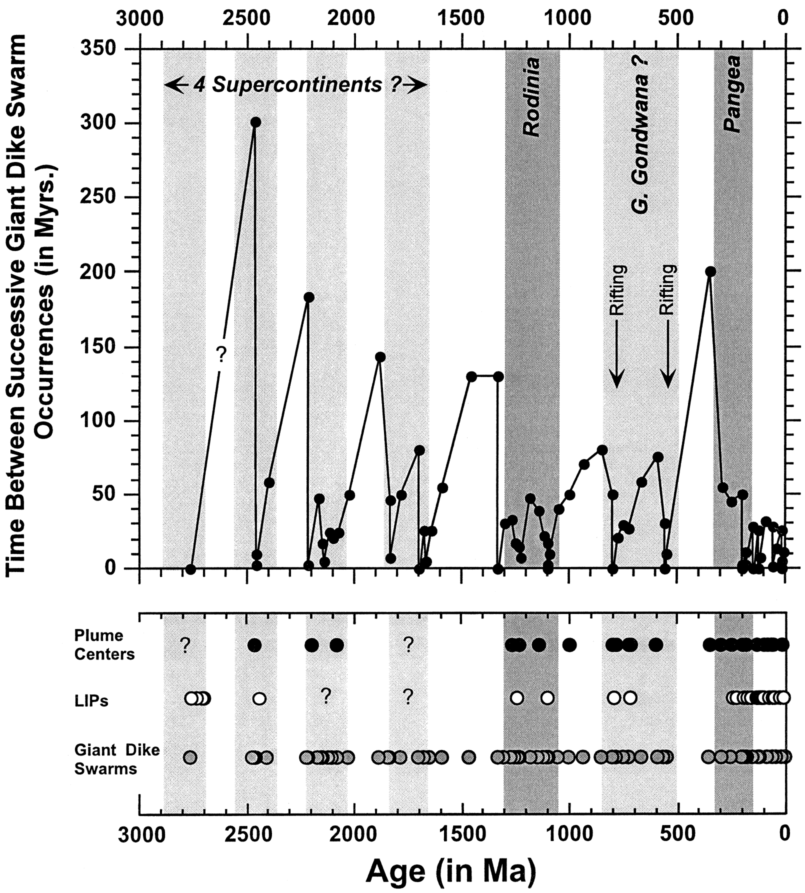

Fig. 1. (Upper Panel) Plot of relative age differences between successive dike swarm occurrences vs. age of occurrences. Rapid rates of GDS occurrence (low values for successive age differences) are thought to be related to supercontinent assembly, whereas, lower rates of GDS occurrence (high values) indicate dispersal of continents. Shaded areas represent times of inferred supercontinent assembly and white areas represent times of relative continent dispersal (see text for explanation). (Lower Panel) Temporal distribution of Plume Centers (black circles), Large Igneous Provinces (white circles), and Giant Dike Swarms (grey circles) for the last 3 billion years [23–32].

350 Myr (supercontinent assembly) punctuated by periods of no production for 150 Myr (dispersed continents). Alone, the periodic production of GDS produces 147 occurrences. When a decay function is superimposed on this function, 78 GDS remain (compared with 79 actual occurrences). The number of occurrences remaining are summed and the cumulative % calculated. This model also can be used to explain similar cumulative curves for carbonatites and kimberlites [38,40].

Different values for k have been calculated following the method of Veizer et al. [38]: giant dike swarms (half-life = 1386 Myr), $k = 5.00 \times 10^{-4}$; carbonatites (half-life = 450 Myr), $k = 1.54 \times 10^{-3}$; kimberlites (half-life = 200 Myr), $k = 3.46 \times 10^{-3}$. The frequency distributions of carbonatites and kimberlites indicate a significantly lower preservation potential than giant dike swarms [38,40]. Interestingly, the overall structures of all of three trends (e.g., timing of plateaus) are similar (Fig. 2b). Our rather simple model suggests that all three rock-types (giant dike swarms, carbonatites and kimberlites) can be produced using the same periodic driving mechanism in conjunction with a unique preservation potential or half-life (Fig. 2b).

Although the actual timing of supercontinent assembly and breakup may not be as regular as our model, the excellent fit of the model output suggests

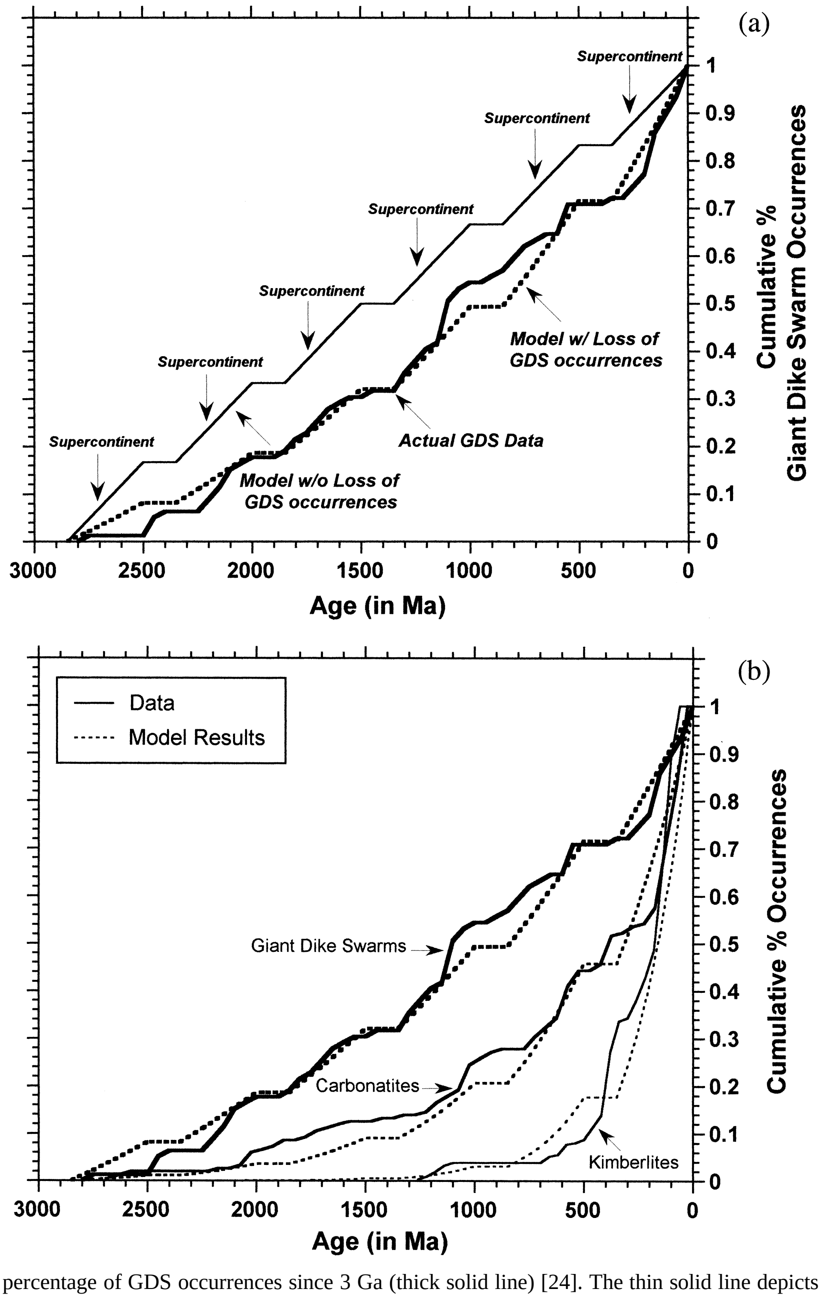

Fig. 2. (a) Cumulative percentage of GDS occurrences since 3 Ga (thick solid line) [24]. The thin solid line depicts a simple model using a periodic production of GDS. The dashed line represents a combination of this function and an exponential decay with a half-life of 1386 Myr. [39]. The excellent agreement of the empirical data with our model results suggest that GDS have an excellent preservation potential and are the result of a periodic phenomenon (interpreted as supercontinent assembly). (b) Comparison of cumulative % occurrences for GDS (thick lines), carbonatites (intermediate width lines), and kimberlites (thin lines). The dashed lines represent model results using the periodic production and exponential decay function described in Fig. 2a but with different half-lives (GDS = 1386 Myr; Carbonatites = 450 Myr; Kimberlites = 200 Myr). Carbonatite data are from Veizer et al. [38]. Kimberlite data are from Haggerty [40].

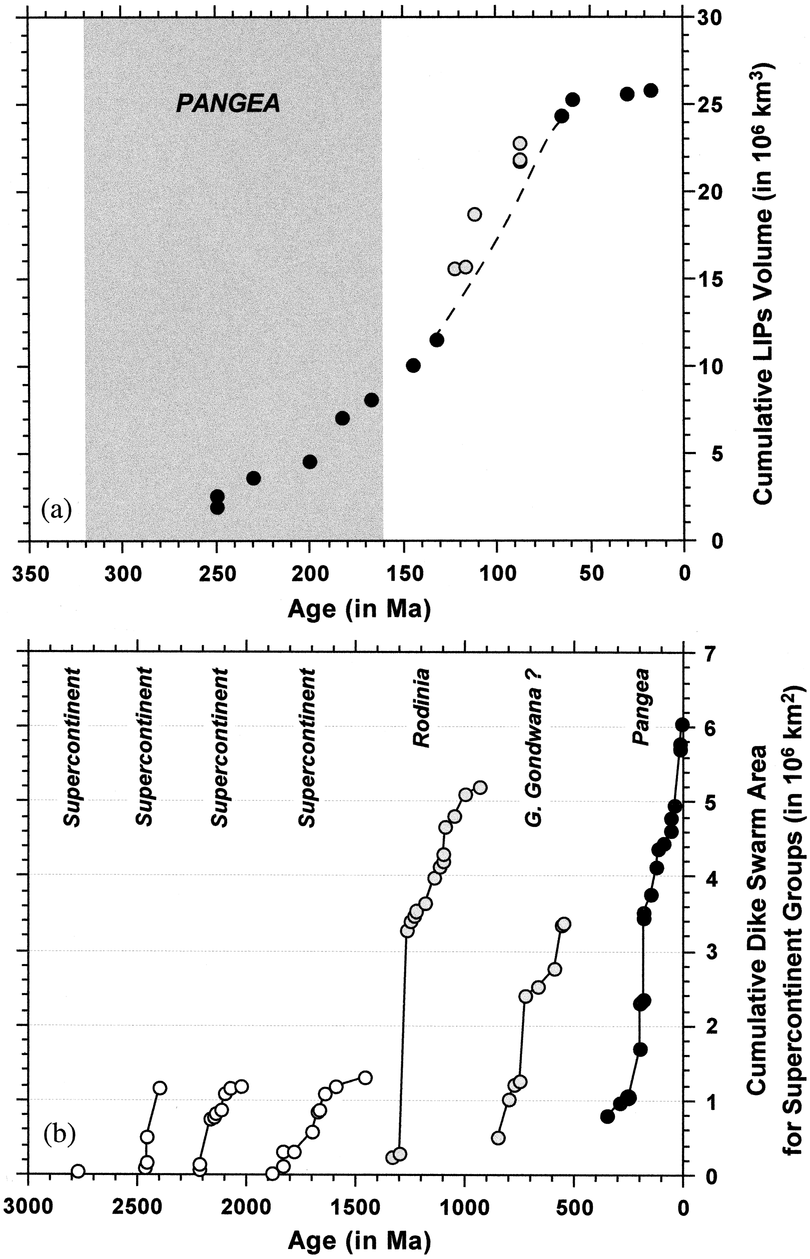

Fig. 3. (a) Cumulative volume of LIPs associated with the assembly and break-up of Pangea (data from Yale and Carpenter [25]). Grey circles represent LIPs occurring between 120 and 80 Ma and represent the timing of the supposed Mid-Cretaceous superplume event. The dashed line is a 4th-order polynomial fit through the data exclusive of the Mid-Cretaceous data. (b) Cumulative map area of Giant Dike Swarm occurrences since 3.0 Ga for seven supercontinent groupings (data compiled from Ernst et al. [24]).

that GDS production is periodic (assuming some variation in supercontinent cyclcity between 300 and 500 Myr). The production rate of GDS occurrences used in the model (above) is held constant through time. As can be seen in Fig. 2b, the model deviates from the actual dike occurrence data between ∼1200 and 700 Ma. This deviation suggests that the production rate of GDS during that time period may have

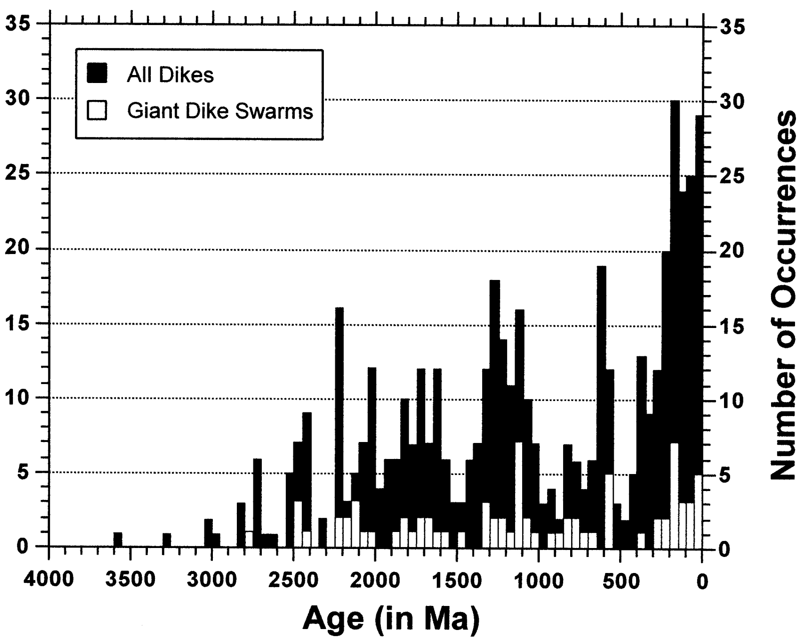

Fig. 4. Histograms of the number of diabase dike swarm and giant dike swarm occurrences since 4 Ga (Data from Ernst et al. [24]). See inset for explanation of symbols.

been higher than modeled. Prior to 2200 Ma, the model overpredicts the number of dike occurrences. The rate of production during this time may have been less than that predicted by our model. Conversely, this overestimate could be the result of poor preservation of the early GDS record. As modeled, the survival rate only affects the absolute number of occurrences at a given time and does not affect the periodicity observed in the cumulative distribution of dike swarm occurrences. The same periodicity observed in GDS is observed in the temporal distribution of all diabase dike swarms (Fig. 4; [24]).

Greenstone belt occurrences have a periodicity that is grossly similar to that of GDS and have been correlated with supercontinent assembly [41]. Condie [41] notes the absence of greenstone belts from 2450 to 2200 and 1650 to 1350 Ma. These gaps roughly correspond with gaps in GDS occurrences (2400 to 2250 and 1600 to 1350 Ma; Fig. 1). However, the relation between mantle plumes and greenstone belts is not well established [42]. The term 'greenstone belt' is broadly defined, encompassing a wide range of volcanic rocks and associated sediments. Therefore, we have avoided examination of their temporal distribution in this study.

Yale's [25] compilation of post-250 Ma LIPs (data used here) finds that less than one third of the 18 LIPs are wholly oceanic. Due to subduction of oceanic crust, oceanic LIPs are not part of the pre-150 Ma data set. Given that oceanic LIPs and oceanic crust have similar compositions, we find no reason to argue that oceanic LIPs would escape subduction. Taira et al. [43] have found that a large proportion of the Ontong Java Plateau is currently being actively subducted. As a result, an uncorrectable bias toward continental magmatic activity exists in the LIPs data. Use of the pre-150 Ma LIPs data is justified as generation of mantle plumes associated with their origin is argued to be related to supercontinent assembly and mantle insulation [1–6]. Therefore, as it is the supercontinent record that we seek, this bias does not preclude examination.

The temporal distribution of LIPs and intervening gaps suggest that the process controlling LIPs eruptions is periodic (Fig. 1). Given the small number of LIP occurrences ($N = 27$) it is not possible to calculate accurately an exponential decay function [39]. Assuming that LIPs are produced at a constant rate, and using an exponential decay function to account for a loss of LIPs occurrences with time, the large gaps in the LIP frequency distribution cannot be explained entirely by lack of preservation (Fig. 1). The occurrence of several LIPs between 3 and 1 Ga suggests that the preservation of LIPs erupted during the last billion years is relatively good. We must conclude that the LIP record is inherently periodic, yet is modified to some extent by diminished preservation with age. Taken together, the LIP, GDS, and plume center data accurately represent the temporal distribution of mantle plumes, and thus, the vigor of mantle convection [44]. The causal mechanism for this periodic activity is supercontinent aggregation and dispersal [1–6].

2.2. Pangea and LIPs

The correlation between LIP eruptions and the assembly of supercontinents is best observed in the relation between the assembly of Pangea and the cumulative volume of LIPs erupted since 250 Ma (Fig. 3a). Following the assembly of Pangea, the rate of change in extrusive LIP volume increases modestly from 250 to 200 Ma, rapidly from 200 to 60 Ma, and finally plateaus over the last 60 million years (Fig. 3a). The initiation of LIPs eruptions ~70 Myr after the assembly of Pangea is consistent with Anderson's [1] estimate of ~100 Myr for the formation of a 50 m geoid anomaly under a supercontinent (Fig. 3a). Courtillot and Besse [45] have suggested that plume ascension rates could be as high as 30 cm/y. A more conservative rate of 5 cm/y [40] and travel distance of ~2900 km (depth of D'') yields a time of 58 Myr (Fig. 3a). These estimates are consistent with the timing of initial flood basalt eruptions (250 Ma) and the aggregation of Pangea at (320 Ma).

The maximum increase in LIP volume is achieved between 150 and 70 Ma. This period of rapid volume increase coincides with the mid-Cretaceous 'superplume' event (122 to 83 Ma) described by Larson [15] and Larson and Kincaid [16]. The extrusive LIP volume data during this time period are elevated relative to a 4th-order polynomial fit through the other data. This deviation is probably the result of elevated mantle fluxes during this interval ([25]; Fig. 3a). The decline in the rate of LIP production over the last 60 million years suggests that the effect of Pangea-induced mantle heating is waning. Interestingly, this decline corresponds with Alpine orogenic activity and Himalayan uplift. These potentially lower mantle fluxes may provide a partial explanation of the marine strontium isotope record for the last 50 Myr.

2.3. Pre-Pangea supercontinents

Map area and age data for GDS have recently been compiled [24]. If, as described by Ernst et al. [8] and Heaman [30], GDS are related to mantle plumes and are the feeder dikes for LIPs, we can use the crude approximation that GDS map area (in km^2) is proportional to volume of erupted flood basalt. Thus, cumulative plots of GDS map area and LIPs volume should be analogous. However, it should be noted that not all dike swarms may have produced LIPs. In addition, Heaman [30,31] points out that over twenty separate Proterozoic dike swarms have been documented in North America and that not all are associated with LIPs. This is clearly seen in the occurrence of pre-Pangea dike swarms (which begin at ~350 Ma) and the lack of LIPs until the eruption of the voluminous Siberian Traps at 250 Ma (Fig. 1).

We have used the relatively well-preserved and well-understood relations associated with the assembly of Pangea as a guide in our interpretation of the timing of supercontinent assembly (Fig. 1). We have assumed that there is a significant increase in the rate of GDS occurrences following supercontinent assembly. Therefore, a plot of the time between successive GDS vs. GDS age should provide an estimate of the clustering of these occurrences (Fig. 1). Estimates of supercontinent assembly have been made using these data together with similar data for LIPs, plume centers, and information from the literature that places constraints on the age of supercontinent assembly and break-up (Fig. 1).

Using the groupings of GDS ages as a guide (Fig. 1) and the relation between the assembly of Pangea and LIP production (Fig. 3a), we have constructed cumulative curves for seven GDS groupings (Fig. 3b). The time difference between the initial points for each group decreases with increasing age (from ~500 to ~300 Myr; Fig. 3b). This periodicity is similar to supercontinent and mantle cycling times [3,12]. Implicit in this scheme is the need for an assembled supercontinent for each GDS group. Seven supercontinents need to be invoked (four unnamed supercontinents, Rodinia, Greater Gondwana or Pangea B [34,35], and Pangea; Figs. 1 and 3b). If this interpretation is correct, it implies that the periodicity of supercontinent assembly and breakup has been relatively constant for the last 3 billion years.

The time interval between the break-up of Rodinia and the assembly of Pangea is one of dramatic geochemical and geophysical change [46,47]. However, continental configurations are not well constrained. We have used the term Greater Gondwana coined by Stern [35] (~700 to 500 Ma) to describe the supercontinent(s) occurring during this time interval (comparable to Pangea B (~720 to 560 Ma) of Veevers et al. [37]). We have modified the timing of Greater Gondwana assembly (~850 to 500 Ma; Fig. 1). By defining a separate supercontinent during this time interval we have broken with conventional wisdom that suggests that the late Proterozoic supercontinent Rodinia assembled at ~1100 Ma (Grenville Orogeny) and rifted apart between 750 and 700 Ma and again at 550 to 520 Ma [48–54]. We do this on the basis of the temporal distribution of LIPs and GDS and the relatively well understood relations associated with the assembly of Pangea (Figs. 1 and 3a). The paucity of GDS occurrences at ~1000 and 850 Ma (Fig. 1) suggests that Rodinia was partially disaggregated at this time. In addition, the pattern for the timing of GDS occurrences between 1100 and 300 Ma is unlike other periods of Earth history (Fig. 1). It is likely that these patterns result from the assembly of various continents and supercontinents that are significantly smaller than Rodinia and Pangea. If, on the other hand, Rodinia were assembled from ~1200 to 500 Ma, it is unclear what mechanism would drive mantle convection so that a supercontinent could be assembled for ~700 million years [1,3,5]. Although the cumulative GDS area data suggest that Rodinia strongly influences GDS production from 1267 to 250 (?) Ma (Fig. 5), it is unlikely that a single supercontinent was assembled for ~1 billion years.

The cumulative curves for each supercontinent group resemble the general shape of the cumulative LIP volume curve as shown in Fig. 3a. These curves generally have a period of rapid increase in the center of each curve followed by a decrease at the youngest portion (Fig. 3b). Cumulative areas for each supercontinent group may correspond with the size of each supercontinent (Pangea > Rodinia > Greater Gondwana > Early Proterozoic Supercontinents). Small, thin, early Proterozoic supercontinents may account for the relatively small cumulative areas of Early Proterozoic GDS, as juvenile cratons are unlikely to have appreciable amounts of accreted terrains and basaltic underplating. Poor preservation alone cannot account for these small individual cumulative areas (Fig. 2a). If the cumulative areas of GDS are reconstructed to account for lack of preservation (as modeled), the early Proterozoic dike swarm areas still do not approach the values reported for Rodina and Pangea (Fig. 3b).

The dramatic increase in GDS area at 1267 Ma is the result of the Mackenzie Dike Swarm, clearly one of the most significant volcanic/igneous events in geologic history. Without this dramatic increase in area, the Rodinia-related GDS group (Fig. 3b) would have a cumulative area that is intermediate between the fourth unamed supercontinent (~1850 to 1650 Ma) and Greater Gondwana, thus producing a successive increase in the cumulative areas for each supercontinent. Another feature of these cumulative curves is the gradual increase in the starting position of each successive supercontinent grouping (~100,000 to ~800,000 km^2; Fig. 3b). We speculate that the cause of these features (size of initial GDS area and cumulative area) is due to increases in continent (and thus supercontinent) area and thickness with time. Hofmann [4] has speculated that prior to 1.8 Ga, the total mass of continental crust may have been insufficient to form a 'true supercontinent' and thus the insulating effect on the mantle would be diminished. Evidence presented here suggests that, although small, early Proterozoic supercontinents were capable of producing GDS and LIPs (Fig. 3b).

2.4. Episodes of mantle activity

A plot of cumulative map area of GDS (Ernst et al., 1996) versus age for the last 3000 Myr produces three distinct periods of GDS activity (Period I: 2771–1300 Ma; Period II: 1270–250 Ma; Period III: 250–0 Ma; Fig. 5). Each period is defined by a highly significant linear relation ($r^2 = 0.94$, 0.98, 0.90, respectively). The slopes of these trends increase dramatically at two important times in Earth history; emplacement of the Mackenzie Dike Swarm (1267

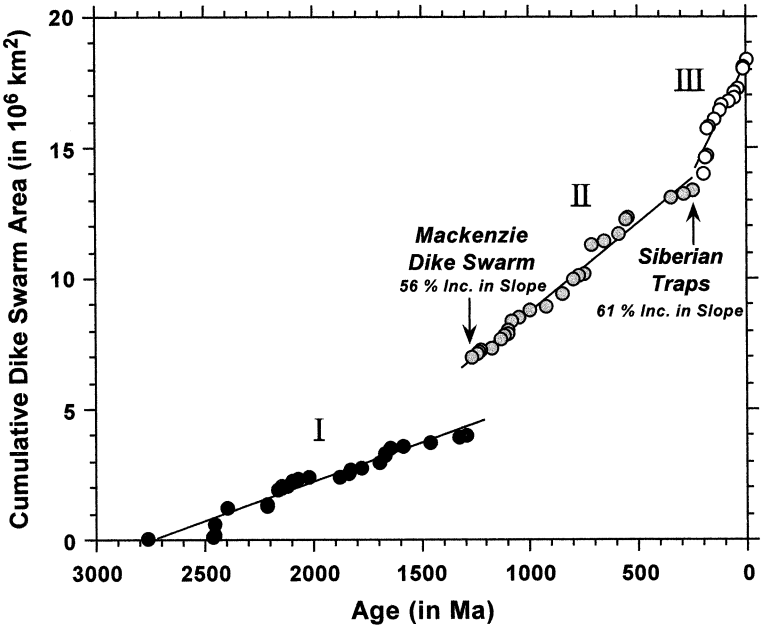

Fig. 5. Cumulative map area of Giant Dike Swarms occurring since 3.0 Ga. Unlike Fig. 3a where each supercontinent has its own cumulative curve, this is a cumulative area curve for all GDS. The three portions of the trend represent three distinct linear segments ($r^2 = 0.94$, 0.98, 0.90, respectively) [24].

Ma) and the eruption of the Siberian Traps (250 Ma) (Fig. 5). If the areal extent of GDS is closely related to volume of flood basalt and the GDS record is relatively well-preserved (Fig. 2), then the trends observed in Fig. 5 represent significant increases in the production of mantle-derived magmas (56 and 61%, respectively). It is not coincidental that the dramatic changes in the slope of these trends occur synchronously with two of the largest igneous events in Earth history and that these events occur at times of supercontinent assembly (Rodinia and Pangea; Fig. 5). We suggest that the causal mechanism for these changes is supercontinent assembly, insulation of the mantle, and modification of mantle convection. Implicit in this statement is the need for an increase in the size of continents during the last 3 billion years (areal extent and/or thickness). Increases in the amount of continental crust since the Archean may be a possible cause [55].

Allegre [9] has suggested that mantle convection was modified significantly within the last one billion years. This change caused the two layer convection to break down and allow cold downgoing slabs to reach the lower mantle and hotspots/plumes generated at the core mantle boundary to reach the surface as flood basalts. The data presented here do not support this hypothesis. In contrast, the periodic mixing catastrophe model described by Tackley et al. [56] seems more plausible, with the two mantle catastrophes being associated with the Mackenzie Dike Swarm and Siberian Flood Basalt events (Fig. 5). In addition, LIPs/flood basalts have erupted periodically since the end of the Archean, suggesting that several perturbations of a two-layer mantle convection scheme have occurred during the last 3 billion years.

2.5. Ocean chemistry changes and the early Paleozoic LIP gap

The increase in LIP volume following the assembly of Pangea (Fig. 3a) strongly suggests that mantle fluxes to the ocean should be positively correlated, as plumes interact with continental and oceanic crust (e.g., LIPs and increased seafloor hydrothermal activity). Increases in mantle fluxes would serve to lower seawater $^{87}Sr/^{86}Sr$ ratios and $\delta^{34}S$ values and increase marine $\delta^{18}O$ and $\delta^{13}C$ values [25,57–59].

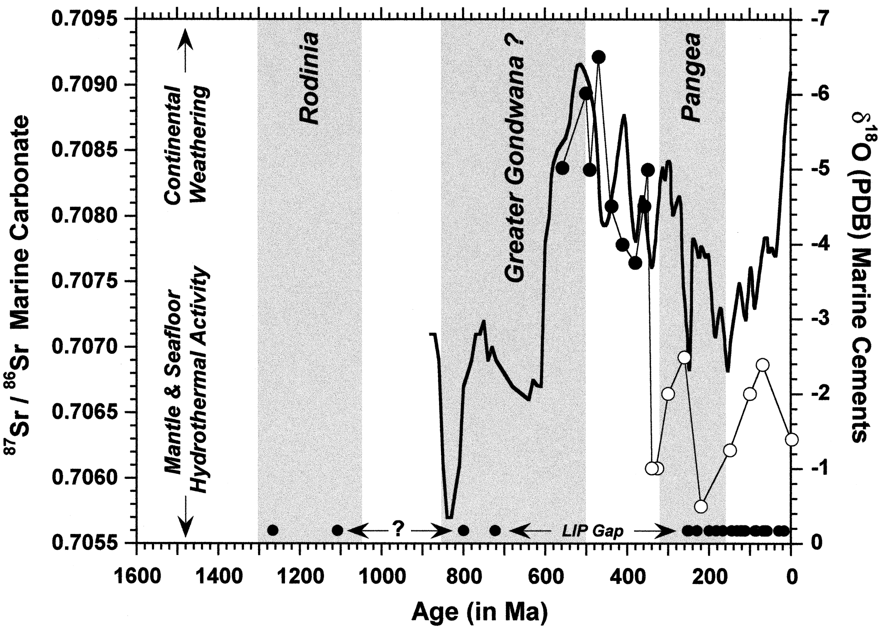

Fig. 6. Distribution of LIPs and Sr and O isotopes since 1.5 Ga [25,58,61]. The thick black line is the $^{87}Sr/^{86}Sr$ ratio of marine carbonates; circles are marine cement $\delta^{18}O$ values. The black circles represent data interpreted to be from a period dominated by low temperature silicate exchange reactions and white circles from a period dominated by high temperature exchange reactions.

In general, these isotopic changes should mimic supercontinent cycles (with appropriate lag times for different elements) (Fig. 6).

The lack of LIPs or 'LIP gap' occurs during the interval between the initial assembly of Greater Gondwana and Pangea (723 to 250 Ma; Fig. 6). This 'LIP gap' coincides with the Late Neoproterozoic and early Paleozoic which is characterized by marine carbonates with low $\delta^{18}O$ (and $\delta^{13}C$ values) ([58]; Fig. 6). Walker and Lohmann [57] and Carpenter et al. [58] have suggested that the low $\delta^{18}O$ values of Early Paleozoic seawater (Cambrian–Devonian) were produced by a dominance of low temperature silicate weathering reactions versus exchange reactions associated with high temperature seafloor hydrothermal activity [60]. This hypothesis is supported by the relatively high $^{87}Sr/^{86}Sr$ ratios [61] and $\delta^{34}S$ values [62] of this time period that also suggest a dominance of continental over mantle fluxes [59]. The lack of LIPs during the late Neoproterozoic and Early Paleozoic is additional evidence for diminished mantle fluxes during this time interval (Fig. 6).

Metabasalts from the Catoctin volcanic province, in the Blue Ridge Mountains of the eastern United States, have been dated at 570 ± 36 Ma [63] and metarhyolites have been dated at 572 ± 5 Ma [64]. This occurrence has not been included in our compilation of LIPs as it does not meet the minimum size criterion of 100,000 km^3 as defined by Coffin and Eldholm [13]. Furthermore, the occurrence of intercolated metasediments and metarhyolites with the Catoctin metabasalts is uncharacteristic of other reported LIPs [63–65]. Although the reported 2-km thickness of the Catoctin metabasalt [64] is typical of other reported LIPs, its areal extent [63,64,66,67] is several orders of magnitude smaller than those reported for the LIPs used in this study [13,25]. If this basalt is considered a LIP, the LIP gap of the Paleozoic would span the 320 million year interval from 570 to 250 Ma, rather than from 723 to 250 Ma (Figs. 1 and 6).

Kominz and Bond [68] also recognized that intracratonic basins began to subside rapidly at ~350 Ma, heralding the initial aggregation of Pangea over a cold, downwelling region. Once Pangea was assembled, thermal blanketing of the underlying mantle commenced and plume formation began, ultimately culminating in eruption of the Siberian Flood Basalt and break-up of the supercontinent. Thus, this middle Paleozoic subsidence marks the transition from dispersed continents and cool mantle to assembled continents and a warm mantle.

Given the long residence time of oxygen in seawater (~40 to 100 Myr; [69,70]), a perfect correlation between marine $\delta^{18}O$ values and LIPs occurrences is not expected. However, a globally significant shift toward higher $\delta^{18}O$ values occurs at the Devonian–Carboniferous boundary (~350 Ma) [58,71]. On the basis of empirical measurements of marine carbonates, this ~4‰ change occurs over ~10 to 20 Myr [71]. Correlation of this increase in $\delta^{18}O$ values with the initial assembly of Pangea argues for supercontinent assembly and insulation of the mantle as the mechanism for a change from low- to high-temperature dominated silicate exchange reactions. Given that the previous supercontinent assembly was in the late Neoproterozoic, it is unlikely that mantle heating from that event induced isotopic changes at Devonian–Carboniferous boundary. The absence of LIPs during the early Paleozoic may reflect the beginning of a period of mantle quiescence that coincides with continental dispersal. This reduction in mantle fluxes persists until the initial assembly of Pangea (Fig. 6). This implies that the size of Gondwana (present during the early Paleozoic) is insufficient to modify mantle convection.

The dramatic evolutionary changes at the end of the Proterozoic Eon coincide with geochemical changes, due perhaps to an abrupt decrease in seafloor hydrothermal activity and an increase in dissolved O_2 in seawater [59,72–74]. On the basis of marine carbon and sulfur isotope data, Carpenter and Lohmann [59] have argued that there is a period of diminished seafloor hydrothermal activity at the end of the Neoproterozoic and early Paleozoic. This reduction may have provided the O_2 necessary for the dramatic evolutionary changes recorded during the Vendian [59,72]. Conversely, the onset of LIP eruptions (and associated seafloor hydrothermal activity) in the late Permian may have had an equal and opposite impact on life [75]. The record of LIPs since 800 Ma is consistent with the reduction of mantle fluxes near the Proterozoic–Paleozoic boundary and an increase of mantle fluxes prior to the Permian–Triassic boundary.

3. Conclusion

Giant dike swarms and large igneous provinces provide new proxies for supercontinent assembly and mantle convection that are consistent with the marine isotopic record. Further geochemical analyses of GDS and LIPs are needed to better constrain the age and origin of these potentially useful proxies. Continued study of the timing of supercontinent assembly is needed to test the hypotheses presented here. The events associated with the Mackenzie Dike Swarm and the Siberian Traps are particularly significant and warrant further investigation.

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