Superkimberlites: A geodynamic diamond window to the Earth's core

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Superkimberlites: A geodynamic diamond window to the Earth's core

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Abstract

Carbon is the fourth most abundant element in the solar system. In the Earth carbon is in atmospheric CO_2, limestone, other organic products, graphite and trace diamond; interstellar diamond, however, is ubiquitous. Diamond is well known for some unique physical and chemical properties, but it is perhaps less well known that the mineral is geologically ancient (3.3 Ga), that its origins are deep in the mantle (> 180 km), and that diamonds are among the deepest solid objects to reach the surface of the Earth; rare diamonds are from the transition zone (400–670 km), and other diamonds possibly nucleated in the lower mantle (> 670 km). Transport to the surface is in volatile (C-O-H-N-S)-charged highly explosive kimberlite and lamproite volcanoes. These volcanoes are sited exclusively in the oldest (> 1.7 Ga), tectonically most stable, and thickest (~ 200 km) regions of crust and upper mantle lithosphere. The energetics required for volcanism are so exceptional and the sources so deep that possible connections between and among the core, geomagnetism, plumes and diamonds are explored. Some correlations are established and others are implied. The results are sufficiently enticing to propose that kimberlites and geographically and temporally associated carbonatites are continental recorders of plumes dating back to at least 2.8 Ga, and that some diamonds may have recorded core events dating back to 3.3 Ga, or possibly earlier.

Peaks in kimberlite magmatic activity correlate, on average, with normal and reverse superchron and subchron behavior of the geomagnetic field. The time lag between magnetohydrodynamic activity in the core and kimberlite eruptive cycles at the Earth's surface is of the order of 25–50 Ma, consistent with the travel times modeled for the passage of plumes from the D″ layer to the subcontinental lithosphere. Although the existence of plumes and the nature of D″ are debated, the correlations established for the past 500 Ma between and among superchrons, subchrons, kimberlites and entrained diamonds weigh heavily in favor of the following scenario: solid core growth, the consequent release of Si, O, C, H, S, K and possibly N and B to D″, disruption of D″ at some critically unstable threshold thickness (200–300 km), enhanced core convection and the stabilization of a constant non-reversing magnetic dipole field, rising plumes and subsequent volcanism. If protokimberlitic magma and entrainment begin at the core–mantle boundary, a number of geochemical and mineralogical anomalies in diamonds are at present best satisfied if D″ is invoked. These include but are not limited to intensely reduced (i.e., oxygen deficient) SiC, metallic Fe, an abundance of sulfides, silicate perovskite and wüstite–periclase mineral inclusions in diamonds. The most abundant source of diamonds is unequivocally from cratonic root zones with C possibly implanted by ancient plumes;

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eclogitic suite diamonds are equivocal, and diamonds transported from the transition zone and the lower mantle are best explained by entrainment in highly reduced plumes. Carbon in the overwhelming majority of diamonds appears to be primordial. By analogy with a chondritic Earth and chondrites, carbon was acquired during accretion in gaseous complexes, in the form of nanometer-size amorphous C, and as hydrocarbon particles; but carbon was possibly also added as crystalline nanodiamonds that served as seeds for subsequent diamond growth.

1. Introduction

Theories for the origin of the Earth by layered cold accretion or hot fractional condensation are at the heart of the great uncertainties that exist for the early thermal history of the planet [1,2,3]. The gross thermal figure of the latter day Earth is, however, well established. Temperature increases as a function of depth from the crust through the mantle to the liquid metallic outer core. Earth is cooling and the inner solid core is growing at the expense of its molten outer shell [4]. Global volcanism is an expression of heat dissipation from the interior of the planet. Approximately 90% of the heat budget is lost by slow and diffuse convective transfer through the insulating blanket of the magnesian silicate mantle. This energy loss is expressed in passive decompression melting of the mantle and volcanism along the world's spreading oceanic ridge systems; and by volatile-induced melting of the mantle wedge above subduction slabs. The remaining approximately 10%, although not well constrained, is heat lost directly from the core, through thermal plumes that are considered to originate at the D″ core–mantle boundary (CMB) layer [5,6,7]. High temperatures and hence low densities and low viscosities allow columns of D″ material, possibly of a distinct composition, to rise through the mantle. Melting of the mantle and volcanism are localized in hot spots and voluminous activity may be sustained for many millions of years because the thermal chimney is evidently unaffected by mantle convection and is rooted to the D″ layer [8]. In this view, the core is the ultimate heat engine for plume-related volcanism, but the core also generates the geomagnetic field and governs its intensity, its aperiodicity in polarity and switching frequency. Theoretically, this magnetohydrodynamic generator is sensitive to thermal perturbations [9]. Thus, heat siphoned from the core to fuel volcanism should be linked in some way to geomagnetism [10,11,12].

Some empirical correlations have been observed for the mid-Cretaceous (chalk-related) period (80–120 Ma) when the Earth's geomagnetic magnetic field (GMF) direction remained stationary (N-normal) for an extraordinarily long (40 Ma) period of time (superchron) and plumes were particularly vigorous: there was a 50–75% increase in the growth of oceanic crust by volcanism, a flourish in biota (and oil formation) resulted from seawater warming and increases in volcanologically related emanations of CO_2 and nutrients such as Fe, N and P, marine carbonate compensation depths were shallowed, carbonaceous black shales were deposited, and sea levels rose [10,13,14,15,16,17]. Other correlations for a longer (70 Ma) and reversed (R) period of the GMF are implied for coal and gas (7) in the Pennsylvanian–Permian (323–248 Ma). Correlations between plumes and true polar wander have also been attempted [18,19].

The carbon connection between plumes and geomagnetism is now extended in this review to diamonds, in the first instance to the timing of kimberlite and lamproite intrusions and the transport of entrained xenocrystic diamonds, and in the second to the timing, distribution and character of some diamonds that have an implied core connection.

2. Data and synthesis

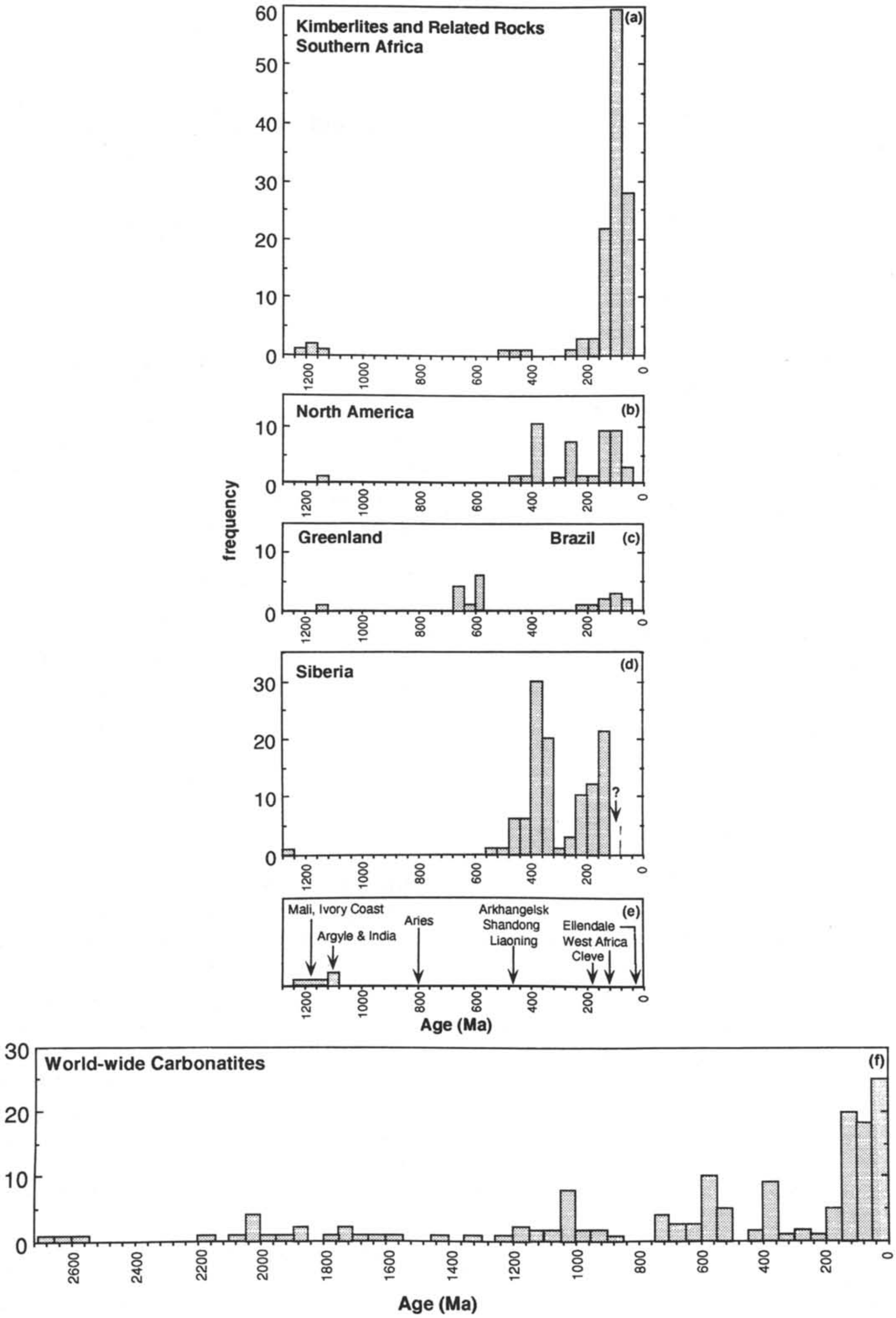
The case for plume-generated kimberlites [20,21] is greatly strengthened by the recognition of majoritic inclusions in diamonds [22], low-pressure equilibrated majoritic garnet (now pyrope + exsolved pyroxene) in xenoliths [23,24], by enstatite ($MgSiO_3$) + magnesiowüstite [25,26], SiO_2 + ferropericlase, and $CaSiO_3$ + $(FeMg)SiO_3$ +

SiO_2 [27,28] mineral assemblages occluded in diamonds. The majoritic associations are inferred to have originated close to or from the transition zone (TZ, at depths of 400–670 km), the thermoelastic discontinuity that separates the upper mantle from the lower mantle; the last named mineral associations are consistent with silicate perovskite and a derivation from the lower mantle below the 670 km discontinuity [29]. Xenoliths and diamond entrainment were most likely in melt and crystal mush as modeled for other plume-related volcanics [30,31]. There is neither evidence for nor models that would support the presence of large concentrations of heat-generating elements in the TZ; hence, the heat source for melting and protokimberlite–lamproite generation must be deeper than 670 km and on this basis is most reasonably from the D″ layer at the CMB. A test of the CMB-plume proposition lies firstly in the timing of eruptives—if kimberlites are plume related and the heat source is the convecting core it is reasonable to assume that deep-focus volcanism may be triggered contemporaneously on a global rather than a local scale [10]. Secondly, these global eruptive events should correlate with some distinct aberration of the GMF [10].

The first test is explored in Fig. 1a–e for a large set of dated kimberlites and a smaller number of lamproites (Appendix); not all intrusions are diamondiferous but mineral and bulk compositions, and xenoliths would place all but a few of these melts and rocks well into the diamond stability field at depths of 180–250 km. Most kimberlites are younger than 600 Ma but this distribution may be obscured by erosion and depositional cover (note that a similar distribution exists for carbonatites in Fig. 1f; see the discussion below). The mid-Cretaceous kimberlite spike (80–120 Ma) is prominent throughout Africa, North America, Brazil and Siberia; a second intrusive pulse is centered at 360–400 Ma in North America and Siberia; a third is at 360–320 Ma in Siberia; another is around 200 Ma in Africa, North America, Brazil and Siberia. Kimberlites dated at about 460 Ma are present in Shandong and Liaoning Provinces, China, at Arkhangelsk in the Eastern European Platform, and in Siberia, Canada and Zimbabwe. Although present in relatively small numbers there is a prominent population of kimberlites at 1.1–1.2 Ga in all of the major provinces cited but also in India, Canada, Australia and West Africa (Fig. 1). Among the oldest kimberlites are Kuruman (1.6 Ga), South Africa, and pipes and sills in Bolivar Province, Venezuela (1.7 Ga).

The second test for a possible relationship between the core, plumes, kimberlites and the GMF is summarized in Fig. 2. The major pulses in kimberlite activity are taken from Fig. 1 and are limited to the past 500 Ma [32] because the magnetic data are less reliable into the Cambrian and Proterozoic. Recognized and generally agreed to geomagnetic superchrons are shown as solid lines for the mid-Cretaceous (N, 80–120 Ma), the Pennsylvanian–Permian (250–320 Ma, mainly R), and the Lower–Middle Devonian (370–410, mainly R). The correlation with global kimberlite eruptive events is very good. Three other mainly N periods (subchrons in dashed lines) are centered at ~ 160 Ma (Middle Jurassic), ~ 210 Ma (Triassic–Jurassic) and ~ 440 Ma (Ordovician–Silurian). The correlation with kimberlite injection ages is good for the two older events and only moderately good for the younger, mainly N event. The only prominent intrusive pulse that does not correlate well with either a superchron or subchron is for kimberlite in the age bracket 320–360 Ma from Siberia (question mark and shaded in Fig. 2); although these ages may be in error, it is relevant to note that the time span corresponds to carbonatites elsewhere (Fig. 1f).

Larson [16] coined the term 'superplume' for the voluminous outpouring of basaltic magma that gave rise to the areally extensive Ontong Java Plateau in the Pacific Ocean between 80 and 120 Ma. Plumes are invoked in the great thicknesses of effusive basalt that have flooded the edges of fragmented continents [31,33,34,35]. Plumes are coincident with, and are assumed here, to be directly responsible for the rifting of plates [33], where the lithosphere is thin and weak and the rocks are largely accretionary at the edges of thick stable cratons (Fig. 3). Plateau basalts of the Karoo (190 ± 5 Ma) and Etendeka (130 ± 5 Ma), respectively along the eastern and


Kimberlites and Related Rocks
Southern Africa
(a)
North America
(b)
Greenland
Brazil
(c)
Siberia
(d)
?
Mali, Ivory Coast
Argyle & India
Aries
Arkhangelsk
Shandong
Liaoning
Ellendale
West Africa
Cleve
(e)
frequency
60
50
40
30
20
10
0
1200
1000
800
600
400
200
0
Age (Ma)
World-wide Carbonatites
(f)
2600
2400
2200
2000
1800
1600
1400
Age (Ma)

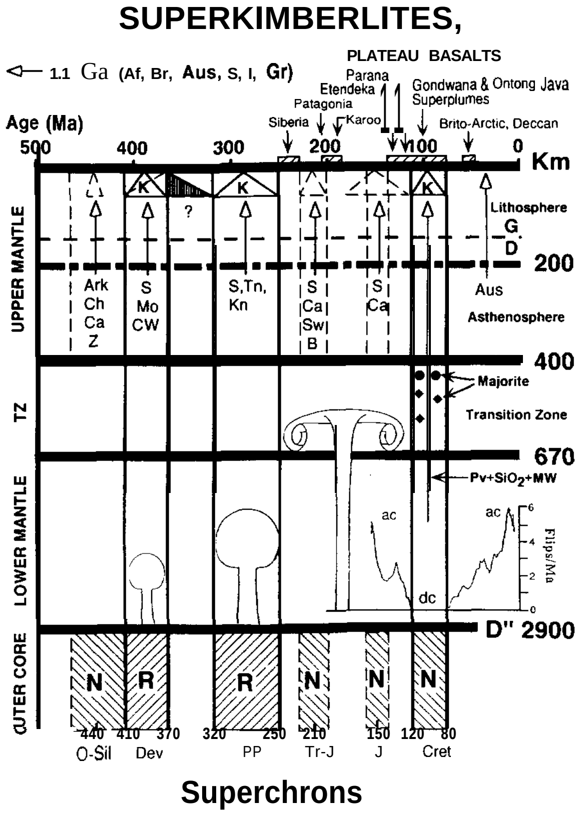


Fig. 2. An orthogonal and schematic cross section of the Earth. The abscissa is time (Ma) showing long N (normal) and R (reverse) periods of geomagnetic behavior; dominant polarities (superchron) are solid lines, and shorter periods with a mainly N or R polarity are dashed (subchrons). The flips/Ma curve is the frequency of polarity changes as a function of time for the interval 5-160 Ma; ac (alternating current) and dc (direct current), respectively, describe the geodynamo during rapid oscillations (N → R and R → N) and periods of quiescence [61,62]. Ages for pulses of kimberlite intrusions (Appendix) and plateau basalts [36] are shown in the upper portion of the diagram for Archangelsk (*Ark*), China (*Ch*), Canada (*Ca*), Zimbabwe (*Z*), Siberia (*S*), Missouri (*Mo*), Colorado-Wyoming (*CW*), Tennessee (*Tn*), Kentucky (*Kn*), Swaziland (Sw), Botswana (*B*) and Australia (*Aus*); the 80-120 Ma event is global (Fig. 1). The arrow pointing in the direction of 1.1 Ga is for kimberlites throughout Africa (*Af*), inferred kimberlites in Brazil (*Br*), and kimberlites in Australia, Siberia, India (*I*) and Greenland (*Gr*). The ordinate is depth: The diamond (*D*)-graphite (*G*) stability curve, although shown schematically, is correctly placed relative to the ∼ 200 km lithosphere-asthenosphere boundary. The lengths of the intrusion arrows are similar for all but the kimberlite pulse at 80-120 Ma; some of these kimberlites are majoritic garnet-bearing [22,23,24], shown by the dot (xenoliths) and diamond symbols, and others are silicate perovskite + SiO_2 + magnesiowiistite-bearing [25,26,27,28] with inferred origins in the lower mantle. D" is the thermal and chemical boundary layer between the outer metallic core (liquid) and the lower mantle (silicate). Plume geometry and development from D", and interactions with the transition zone, are taken from model experiments [47,48,49]; the time span is schematic. ***O-Sil*** = Ordovician-Silurian; ***Dev*** = Devonian; ***PP*** = Permian-Pennsylvanian; ***Tr-J*** = Triassic-Jurassic; ***Cret*** = Cretaceous.

Fig. 1. Age-frequency histograms for kimberlites, lamproites and closely related transitional rocks. These diagrams do not include, for example, melilitites and lamprophyres (a-e). The references for each dataset are given in the Appendix. Not shown in (e) are intrusion complexes in India at 108 Ma; Argyle, Aries, Cleve and Ellendale are pipes in Australia. Ages for worldwide carbonatites (f) are from [41]. The selected histogram interval of 40 Ma is well within the expected errors in dating kimberlites. Some methods and isotopic systems are more reliable than others: these range from highly confident levels for U-Pb in xenocrystic zircon to K-Ar in phlogopite. No screening has been applied to the dataset, except where earlier studies have been replaced by more precise data. Where multiple analyses are available, using different isotope systems, methods (e.g., fission track) or minerals (e.g., phlogopite, zircon, perovskite), both are plotted (i.e., no more than two ages for any intrusive). This is justified on the basis that all kimberlites are multiple intrusives, but not all components of a diatreme have the same composition, mineralogy or xenolith and xenocrystic suite. Moreover, in large explosive diatremes crustal intrusion temperatures are low (< 600°C) and isotopic resetting cannot always be assured. The peaks in activity may be viewed as a single event but this is clearly not the case given the spread in ages for intrusives over lateral distances of a 1000 km or more. Local districts may have clusters of intrusives (over 100 pipes in Kimberley, South Africa, and Colorado-Wyoming) that can be traced to systems of feeder dikes (exposed in deeply eroded terrains such as West Africa) that supply the explosive and eruptive breccias. Most intrusives probably never reach the surface (summarized in [43]); it is only the supercharged events that have sufficient energy to force xenoliths entrained in crystal-melt mush through 200 km (or deeper) of subcratonic lithosphere.

western margins of the Kaapvaal Craton, and counterparts in Patagonia and Paraná are excellent examples of volcanic pulses directly related to Mesozoic rifting [33,36]. Basaltic volcanism preceded the major pulse of Mesozoic (80–120 Ma) kimberlites in Africa and Brazil (peak at 110 Ma) by 20–80 Ma (Fig. 2). The Siberian Traps (235 Ma [37,38]) postdate earlier kimberlite injections but predate kimberlite pulses between 180 and 210 Ma by about the same interval in time that separates basaltic volcanism from kimberlite injections in the Gondwana event. The oldest kimberlites in Siberia are equivalent in age (1260 Ma) to the great McKenzie dike swarm that radiates for over a 1000 km [39]. This was closely followed by a global kimberlite event at 1.1–1.2 Ga, and Keweenawan flood basalt volcanism [36]. No ages have yet been published on the recently discovered diamond intrusives in the Slave Province; however, the prediction is that 1.1–1.2 Ga, 80–120 Ma, and possibly younger (~ 50 Ma, corresponding to the Williams Kimberlite pipe in north-central Montana [40], or the Columbia River Basalts and the Yellowstone hot spot at ~ 15 Ma [36]) kimberlites and lamproites will be found in the region.

Carbonatites are upper mantle derived melts and in a regional and geological context are closely related to kimberlites and lamproites [41,42,43]. Calcite is a common or essential mineral in kimberlites and CO_2 (along with water) is critical to kimberlite genesis [44]. Lamproites have

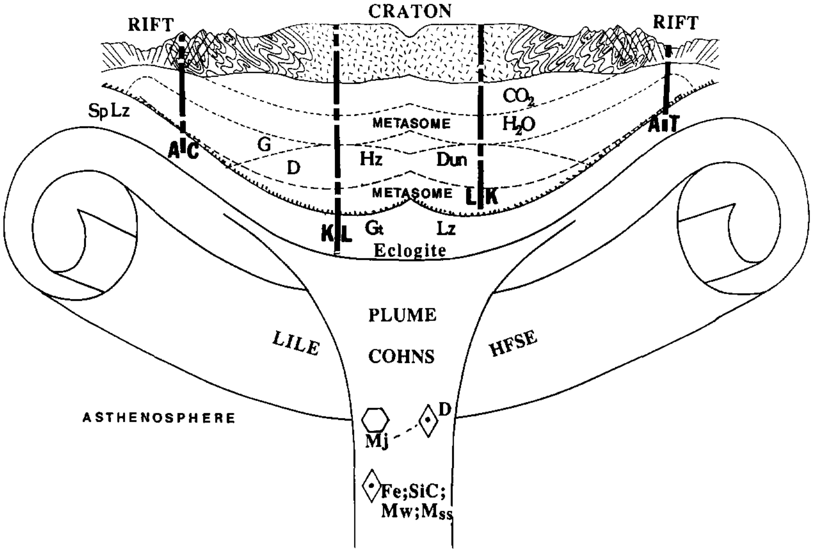


Fig. 3. Schematic diagram illustrating the elements of plume interaction with diamondiferous cratonic root zones. Funnelling of entrained xenoliths, diamonds with majoritic garnet, and diamonds with metallic Fe, moissanite (SiC), magnesiowüstite–ferropericlase (*MW*), silicate perovskite (*Pv*), and monosulfide solid solutions (M_{ss}) are considered to rise during surges of plume activity. The LILE (Ca, K, Rb, Sr, Na) and HFSE (Ta, Nb, Ti, LREE) are sequestered from the lower and upper mantle with contributions from the D″ layer. The supercritical gas and soluble gas species in melts are complexes of carbon–oxygen–hydrogen–nitrogen–sulfur (*COHNS*); the dominant melts are considered to be majoritic (high pressure) to eclogitic (lower pressure) in mineralogy (garnet + pyroxene) and basaltic in composition at the plume head, and picritic or komatiitic in composition and olivine-rich at the plume tail [47]. *G–D* = graphite–diamond stability curve; *Hz* = harzburgite; *Dun* = dunite; *Gt Lz* = garnet lherzolite; *Sp* (spinel) *Lz* = lower pressure Gt Lz counterpart. Metasomes are horizons of HFSE, LILE and volatile (*COHNS*) enrichment; the upper portion of the lithosphere is CO_2-rich and the lower portion is dominated by H_2O in amphibole and phlogopite. Basaltic volcanism is dominantly in rift zones (*T*), but rift zones are also prime locations for alkali-rich melts (melilitites, carbonatites, lamprophyres); intrusions into the central portion of the craton are dominantly kimberlitic. Conduits (heavy dashed lines) through the subcontinental lithosphere are for alkaline (*A*), carbonatite (*C*), tholeiite (*T*), kimberlite (*K*) and lamproite (*L*) intrusives. This schematic diagram is modified from [81].

large H_2O, F and Cl contents, phlogopite, K-Ti richterite, and Ba-K-Zr titanates and silicates [45], all typical of a carbonatite suite. Kimberlites, lamproites and carbonatites have stongly fractionated REE patterns with LREE enrichment factors of 100–500, 500–2000 and 1000–10,000 × chondritic respectively. Highly alkaline silicocarbonatite ring complexes occur on the margins of stable cratons or are located in intracratonic rift systems [41]. Unlike kimberlites, carbonatite volcanoes are active at present in East Africa and some intrusions date back to 2.8 Ga [41]. Carbonatite pulses that have similar ages to those of some kimberlites are at 1.1 Ga, 350–400 Ma, and in the Mesozoic (Fig. 1f). In detail and for specific locations carbonatites are either contemporaneous with or postdate kimberlites by about 20 Ma. The global synchroneity of carbonatitic intrusions has been previously noted with a 233 Ma periodicity and an inferred cosmological connection [46].

The temperature difference between plume heads and the surrounding mantle through which the plume passes is modeled at 250–350°C [47,48]; plume tails have an even smaller temperature contrast. The advancing and hot plume head is considered to mushroom on contact with subcratonic lithosphere (Fig. 3), producing basalts by partial melting of the upper mantle at depths of about 60 km [49], and residual, highly volatile carbonatites in rifts at depths of ~ 40 km [41,42,43]. While the cratonic lithospheric lid is susceptible to thermal erosion [50] it is also subject to metasomatism [51]. The compositions of kimberlite and lamproite are most easily achieved by assimilation of metasomatised lithosphere into primitive, deeply (> 200 km) derived komatiitic–picritic mantle melt; the case for very small degrees of partial melting [44] is difficult to support on chemical and experimental grounds [52] and in view of the high MgO and dominant olivine (> 80 vol%) mineralogy. A kimberlitic residue from eclogitic crystallization [53] is an attractive but undemonstrated alternative. A source of metasomatic agents (LILE, HFSE and volatiles—Fig. 3) is required and a time lag for preconditioning the craton between basaltic volcanism and kimberlite eruptions is necessary (Fig. 2); this is even more so for carbonatites where concentrations of REE, Nb, Ti and Zr may be so high as to be of ore-deposit grade.

3. Discussion

There are anticipated time lags between changes in the behavior in the GMF and plumes rising from the D″ layer [54]. The frequency of polarity switching (flips/Ma in Fig. 2) is well documented for the past 200 Ma [55]. There is a gradual decrease in N and R oscillations as the 80–120 Ma superchron is approached, and a progressive increase in switching as the condition is passed [55]; it is noteworthy that the N subchron centered at ~ 150 Ma is reflected in the polarity switching profile by a decrease in the number of oscillations, and that this event coincides with kimberlite intrusions in Siberia and Canada. Plumes are estimated to ascend at rates approximately equivalent to the present-day movements of plates at the Earth's surface. Given the uncertainties in mantle viscosities, plume rates of ~ 10 cm/yr may be possible [56], although 30 cm/yr is regarded as reasonable by Courtillot and Besse [18]. At a rate of 5 cm/yr a plume originating at D″ would intersect typical diamondiferous cratonic root zones (Fig. 3) in about 50 Ma; at 10 cm/yr the interval between release and intersection is ~ 25 Ma. A conservative range of 25–50 Ma is well within the decay portion of the frequency curve for polarity switching, and the interval between basaltic volcanism and kimberlite activity (Fig. 2).

The correlations between superchrons or subchrons and kimberlites are unlikely to be artifacts of dating uncertainties and imperfections in the magnetic record. Whereas time lags must exist between events in the core and activities at the surface each volcanic province cannot be viewed in isolation from earlier plume events and attendant metasomatism of subcratonic lithosphere. This follows from Proterozoic through Mesozoic kimberlites and carbonatites on virtually every craton, the cumulative growth curve for these intrusions with time (Fig. 1), and the evidence for ancient metasomatism preserved in 3.2—3.3 Ga garnet inclusions in diamonds [57]. Hence specific correlations in global eruptions may be assumed to result from thermal activation and chemical buoyancy that is more rapid and more vigorous during the height of a superchron [56]. Thinning of D″ and disruption of the thermal and chemical boundary layer would synchronously pipe heat directly from the core in larger fluxes along previously established and insulated conduits [58,59]; additionally, reaction at the CMB would lead to small but enhanced heats of formation from the ensuing crystallization of metal, iron oxide, Fe-FeO and Fe-Si solid solutions at the interface of the liquid outer core and the silicate lower mantle [60].

These inferences bear upon the contrasting views that are currently held for the relationship between outer core convection and polarity switching of the GMF [61, and references therein]. The first model holds that enhanced vigorous convection by disruption of the D″ layer leads to electromagnetic instabilities and rapid oscillations in polarity. In the second model rapid convective overturn induces a strong non-reversing dipole that may be stabilized over geologically significant periods of time. Frequent polarity oscillations are the norm and are analogous to alternating current (ac) behavior, whereas direct current (dc) behavior is ascribed to atypical superchron events [56,61,62]. The interesting ideas that metallic Fe accreted on the inner core with cooling is characteristic of N polarity, relative to Fe oxide (e.g., wüstite) precipitation at the CMB and R polarity, and the proposition that increased pressure on the inner core and pressure release from D″ are responsible for N and R superchrons, respectively [63], have not found support. It is, however, generally acknowledged that growth of the inner core is largely metallic relative to CMB reactions that are more likely to involve silica and oxygen [64,65].

The synchroneity of eruptive diamondiferous volcanics and superchrons depends on the existence of plumes. There is the alternative view that accepts shallow (200–400 km) 'hot spots' but not plumes from the 2900 km D″ layer [66]. In this view, because hot spots are preferentially located close to continental fragmentation boundaries and MORB generation, a localized and focused heat source for asthenospheric melting is assumed. The mechanism is from thermal storage below a thick and insulating lithospheric lid [66]. Ocean island basalts (OIB), which are generally considered characteristic of plumes, are modeled by Anderson [67] as contaminated MORB, contaminated that is by a globally encompassing metasome layer in the upper mantle. By extension, the continental equivalent would be kimberlite [66].

A second and blossoming uncertainty is whether convection is whole mantle or compartmentalized by the TZ. Closely related is the question of whether cold oceanic subducted slabs that undergo phase transformations and corresponding increases in density (i.e., eclogitic, majorite, and Mg_2SiO_4 spinel) permanently reside in the TZ, decouple (i.e., physical fractionation of eclogite from the depleted harzburgite upper mantle component), or continue to the CMB unimpeded [68]. Variations in rheology, composition and the thermal characteritics of the TZ are central to whether some or all of these phenomena are even remotely possible. The olivine to Mg_2SiO_4 spinel transformation is exothermic at the 400 km TZ boundary, but at the lower TZ boundary of 670 km the decomposition of Mg_2SiO_4 spinel to perovskite $MgSiO_3$ + magnesiowüstite is endothermic [69]. This contrast in thermal reaction behavior is accompanied by corresponding increases in density across the TZ. This has been modeled with spectacular success [70,71] and the broadly uniform conclusion is that "... catastrophic avalanches are precipitated, flushing regional volumes of upper mantle through broad cylindrical downwellings to the base of the lower mantle" [71]. Although these models assume a chemically homogeneous mantle and are at present plateless it appears that the TZ is neither a density nor viscosity barrier to cascading cold and subducted oceanic slabs. Perturbations of and accretion to the D″ layer, therefore, may not be directly or entirely from the core at depth but may also evolve from events at the Earth's surface [72]. Although still in its infancy, there is in addition the intriguing observation that GMF polarity changes appear to follow preferred paths across the Earth, one most recently controlled by the Americas, and a second longitudinally antipodal [73 and references therein].

Is there a core connection to the correlations suggested in Fig. 2? This question hinges on a demonstration that kimberlites or progenitor kimberlitic melts can be shown to be thermally activated at depths considerably greater than the conventionally held view of exclusive derivation from the upper mantle. The model by Ringwood and colleagues [52] is innnovative for kimberlite genesis in the TZ and has many qualities that fit the criteria of kimberlites. Their model, however, fails to account for the lack of oceanic kimberlites. The thermal accumulator model by Anderson [66] is equally meritorious but requires that the kimberlite source region be restricted to the upper mantle or possibly the TZ. Other models propose that protokimberlites (essentially komatiitic in composition and mineralogy) achieve kimberlite geochemical profiles (enriched in H_2O, CO_2, LREE, LILE and HFSE) by assimilation of metasomatic horizons at the lithosphere–asthenosphere boundary [51], and at the 75–100 km lithospheric metasome [42,43]; the source region in these models is exclusively in the upper mantle. At the very minimum, certain classes of kimberlites (at present these are only substantiated for the Mesozoic event; Figs. 1 and 2) justifiably require source region transport from the TZ (majoritic garnet) and possibly the lower mantle (inferred $MgSiO_3$ perovskite + magnesiowüstite). Unless phase transitions and attendant instabilities are invoked [74], the mechanistic driving forces for continental kimberlite injections from the TZ or from the shallow lower mantle are obscure. A sustained source of thermal energy is required and is clearly available if the core is invoked and by association plumes and the D″ layer; chemical buoyancy and viscosity contrasts in addition are critical to plume generation and upward migration [75]. This is regardless of whether disruption of the D″ layer is centroid controlled or surficially induced. The net flux from D″ preserved in kimberlites is unknown. Equally, entrainment of melts and minerals from the lower mantle and TZ are poorly constrained. The volume of material, however, may be substantial given that a disproportionately large number of ultradeep diamonds have been recognized fortuitously in routine studies. Other evidence for lower mantle and TZ heritage in protokimberlites may be preserved in unusual trace elements, trace element distributions, or in the relic crystal structure of macrocrystic olivine (Fo_{90-92}) that has undergone reaction from (Fe,Mg)O wüstite + $(Fe,Mg)SiO_3$ perovskite to $\gamma(Fe,Mg)_2SiO_4$ (ringwoodite) and inversion of γ to $\beta(Fe,Mg)_2SiO_4$ (wadsleyite) to $\alpha(Fe,Mg)_2SiO_4$ (olivine).

Questions of subduction and recycling [52], plume stabilities in convective systems [75], thermal accumulations below supercontinents [76], and slab-induced cyclicity to trigger superplumes [74] all bear directly upon, and are possible alternatives to, the model outlied here for the genesis of kimberlites and lamproites. However, apart from all previous lines of evidence presented, it is noteworthy that komatiites (protokimberlites) and carbonatitic metasomatism have both been linked to plume-related magmatism ([77] and [78] respectively). In addition, numerous observational anomalies in xenocrystic diamonds from kimberlites are satisfied if it assumed that the D″ layer and hence the core are involved as an early expression of protokimberlite genesis.

The D″ layer may have formed in one of several ways [79]: (a) reaction of core metal + mantle silicate; (b) cascading slabs; (c) primordial residue of a magma ocean; (d) primordial thermal and chemical boundary layer; (e) the residue of a continuously crystallizing inner core and underplating of the CMB. Zone refining of the core into a relatively pure metal and a compositionally more complex silicate, oxide and impure metal matte [65] is favored here for the D″ layer. Because the density of the core is approximately 10% less than pure metallic iron (or an Fe-Ni alloy), a number of density-dilutant elements have been proposed as alloying agents [80]; these elements include H, O, S, C, Si, Mg and K and are interestingly all related in one way or another to diamonds or the possible origin of diamonds:

(a) The D″ matte is a potential source of carbon in microdiamonds (termed high-pressure soot [81]), diamonds in eclogites (1.0–1.6 Ga [82]), majoritic garnet-bearing diamonds from the TZ [22], lherzolitic diamonds (2 Ga [83]) and diamonds of harzburgitic affinity (3.2–3.3 Ga [57]) at the base of cratons (Fig. 3).

(b) Sulfur is depleted in the upper mantle [84] but sulfides are prevalent in iron meteorites (planet cores) and sulfides are the most abundant trapped mineral inclusion in diamonds [85,86].

(c) The stable $\delta^{13}C$ isotopic ratio for ~90% of all diamonds measured is -5 to -7‰, precisely in the primitive peak recorded by carbon species in iron and stony meteorites; lighter $\delta^{13}C$ values in diamonds (down to ca. -20‰), which are commonly ascribed to recycling, are also present in meteorites [87].

(d) For redox reasons the D″ matte provides a more viable source (intensely reducing) than any other part of the mantle for exotic mineral inclusions in diamond such as SiC, metallic Fe, magnesiowüstite and ferropericlase (MgO-$Fe_{1-x}O$) solid solutions (Fe-C, Fe-S-C, and Fe-Si solid solutions are predicted as mineral inclusions in diamond).

(e) Potassium-rich mineral and fluid inclusions in volatile-rich cube diamond coats on octahedral diamonds [88] lack an obvious source for K in the upper mantle, and this is also the case for lithospheric K-metasomatism [43].

Among other low-density elements possible in the core, are carbon's ($Z = 6$) closest neighbors with boron ($Z = 5$) in blue electrically conductive diamond, and nitrogen ($Z = 7$) in most diamonds (yellow); N substitution is a potential and tantalizing link between core degassing, the redox precipitation of diamond [81], and the accumulation of Earth's most abundant atmospheric gas. Most or all of these core-related inferences are satisfied by signatures in meteorites. The connection is not directly meteoritic but the associations rather are expressions of preserved primordial accretion products hosted in some diamonds. If correct, the interesting and possibly testable proposition arises, given the ubiquitous presence of interstellar diamonds [89], that some diamonds or diamond nuclei may have been implanted during the T-Tauri event of the proto-Sun or by supernova explosions during early planetary accretion. Whether meteoritic nanodiamonds would survive recycling, as proposed for ^3He and other rare gases [90,91], remains unknown.

In conclusion, this review is neither the definitive word on the origin of diamonds nor the final statement on the genesis of kimberlitic and lamproitic intrusives. These rock bodies are unique petrologically and in common with other plume-related volcanics have distinctive geological settings; the source regions are deep and in diamond-associated rocks the intrusives are in old, cold and stable cratons. The correlations of temporally related kimberlites and lamproites on a global scale with geomagnetic behavior are seemingly beyond coincidence. Although substantial advances have been made, we require more precise dating of events, statistical refinement, and a better understanding of metallomagnetic dynamics, the nature of chemical and physical interactions at discontinuities, the influence of phase transitions, the effect of convection, the role of recycling, and the triggering mechanisms for plumes at thermal and chemical boundary layers.

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5. Appendix

The earliest attempt at dating kimberlites with an internally consistent dataset was by G.R. Davis [1st Int. Kimberlite Conf., Cape Town, unpaginated, 1973 (late Abstr.)]. Although not readily accessible, some data are given in 'Annu. Rep. Geophys. Lab., Washington, D.C.' [Yearb. 75, 821, 1975; Yearb. 76, 631, 1977; Yearb. 77, 895, 1978]. These data are summarized in compilations by Crough et al. [20], England and Houseman [Earth Planet. Sci. Lett. 67, 109, 1984] and J.B. Dawson [Geol. Soc. Aust. Spec. Publ. 14, 323, 1986]. The histograms in Fig. 1 are from the above sources and from the following:

Southern Africa includes South Africa, Lesotho, Botswana, Swaziland, Namibia, Angola, Zimbabwe and Zaire: H.L. Allsopp, J.W. Bristow, C.B. Smith, R. Brown, A.J.W. Gleadow, J.D. Kramers, O.G. Garvie [Geol. Soc. Aust. Spec. Publ. 14, 343, 1989]; E.M.W. Skinner, K.S. Viljoen, T.C. Clark, C.B. Smith [5th Int. Kimberlite Conf., Araxa, Brazil, pp. 373–375, 1991 (Abstr.)]; L.R.M. Daniels, C.M.H. Jennings, J.E. Lee, J.L. Blaine, F.R. Billington, B.C. Cumming [ibid., pp. 58–59 (Abstr.)].

West Africa: Crough et al. [20].

Brazil: L.A. Bizzi, C.B. Smith, H.O.A. Meyer, R. Armstrong, M.J. DeWit [5th Int. Kimberlite Conf., Araxa, Brazil, pp. 17–19, 1991 (Abstr.).].

Greenland: L.M. Larsen, D.C. Rex, K. Secher [Lithos 16, 215, 1983]; D.R. Nelson [ibid., 22, 265–274, 1989].

Russia: *Siberia*: J.W. Bristow, F. Brakhfogel, C.B. Smith, W. Compston, I.S. Williams, J.B. Hawthorne [5th Int. Kimberlite Conf., Araxa, Brazil, unpaginated, 1991 (Abstr.).]. *Arkhangelsk* (*White Sea*): A.V. Sinitsyn, L.A. Ermolaeva, V.P. Grib [ibid, pp. 367–369 (Abstr.).]

China (Lioaning and Shandong Provinces): P.N. Dobbs, D.J. Duncan, S. Hu, S.R. Shee, E.A. Colgan, M.A. Brown, C.B. Smith, H.L. Allsopp [ibid., pp. 76–78 (Abstr.)].

Australia: N.J. Towie, M.R. Marx, M.D. Bush, E.R. Manning [ibid., p. 435 (Abstr.)]; B.A. Wyatt, S.R. Shee, W.L. Griffin, P. Zweistra, H.R. Robinson [ibid., pp. 463–465 (Abstr.); R.T. Pidgeon, C.B. Smith, C.M. Fanning [Geol. Soc. Aust. Spec. Publ. 14, 369, 1989].

India: B.H. Scott Smith [Neues Jahrhb. Mineral. Abh. 161, 193, 1989]; D.K. Paul [Int. Round Table Conf. Diamond Exploration and Mining, New Dehli, p. 95, 1992 (Abstr.)]; A. Kumar and K. Gopalan [ibid., p. 97, 1993 (Abstr.)].

North America: H.O.A. Meyer [J. Geol. 84, 377, 1976]; C. Alibert, F. Albarede [J. Geophys. Res. 93, 7643, 1988]; S.P. Phipps [Nature 334, 27, 1988].

Worldwide carbonatites: A.R. Woolley [41].

6. Note added in proof

H.S. Yoder [pers. commun., 1994] has pointed out that the range of predicted phases possibly present as inclusions in diamonds may also include Ni-Si solid solutions and complex sulfides of Ca, Mg and Fe. These compounds are anticipated if Earth's core and mantle are akin to enstatite chondrites as modeled by Herndon [92,93].

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