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Contemporaneous mass extinctions, continental flood basalts, and 'impact signals': are mantle plume-induced lithospheric gas explosions the causal link?

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Abstract

Contemporaneous occurrences of the geologic signals of 'large impacts', craton-associated continental flood basalts, and mass extinctions have occurred far too often during the past 400 Myr to be plausibly attributed to random coincidence. While there is only a 1 in 8 chance that even one synchronous large impact within the interval of a continental flood basalt and mass extinction event should have happened during this period, there is now geologic evidence of four such 'coincidences', implying causal links between them. The ~66 Ma (K–T) evidence suggests that impacts do not trigger flood basalts, since the Deccan flood basalt had started erupting well before the Chicxulub impact event. If extraterrestrial impacts do not trigger continental flood basalt volcanism, then we are really only left with two possible resolutions to the dilemma posed by these mega-coincidences: either the reported 'impact signals' at the times of great mass extinctions are spurious or misleading, or – somehow – a terrestrial process linked to continental rifting and the eruption of cratonic flood basalts is sometimes able to generate the shocked quartz, microspherules, and other geologic traces commonly attributed to large extraterrestrial impacts, while also triggering a mass extinction event. Here we explore a promising mechanistic link: a large explosive carbon-rich gas release event from cratonic lithosphere, triggered by mantle plume incubation beneath cratonic lithosphere, and typically associated with the onset phase of continental rifting. Sudden CO_2/CO and SO_2 release into the atmosphere would provide the primary killing mechanism of the induced extinction event. Such explosive deep-lithospheric blasts could create shock waves, cavitation, and mass jet formation within the venting region that could both create and transport a sufficiently large mass of shocked crust and mantle into globally dispersive super-stratospheric trajectories. We suggest these be called 'Verneshot' events.

Keywords: mass extinctions; flood basalts; large impacts; cryptoexplosions

1. Introduction

In the past two decades, there has been an often acrimonious debate between proponents of the idea that large extraterrestrial asteroid or comet impacts caused many, if not all of the five great

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Table 1
'Impact signals' found at the four most recent great Phanerozoic mass extinctions and their interpretation in terms of the Verneshot hypothesis

'Impact evidence'	At	Unresolved questions regarding impact interpretation/extinction	Possible Verneshot explanation
Crater I – classic impact sites (Chicxulub; Siljan; Manicougan)	K–T; FF	FF site (Siljan, 50 km diameter) too small for mass extinction [12]. Some large craters (Manicougan, 214 Ma) not associated with extinctions [12]	Some craters may have been caused by impact following Verneshot. Verneshot, not impact, responsible for extinction.
Shocked quartz	K–T [13]; (P–Tr [97]; Tr–J [7]; FF [12])	Only K–T examples convincing. Tr–J; P–Tr cases equivocal [12]: FF cases≠extinction interval [12]	Explosive gas release OR collapse of pipe OR impact of Verneshot projectile
Nanodiamonds – shock formation	K–T	Source of carbon?	Form during cavitation, shock of pipe collapse
Microspherules – imply vaporization	K–T; Tr–J; P–Tr [98]; FF [99]	FF microspherules local. Upper Eocene microspherules (impacts)≠extinction [12]	Vaporization possible during initial explosive release of energy and pipe collapse
Iridium anomaly – not *crustal*, consistent with meteoritic noble metal abundances	K–T [11]; Tr–J; P–Tr [12]; FF [100]	Only well developed at K–T [11]. Other anomalies weak at best [8,12]	K–T anomaly compatible with vapor-rich eruption from a *mantle* plume – e.g. Reunion. Other plumes (and Verneshots) may have different noble metal chemistry
PGE anomaly – not crustal, appears meteoritic		PGE pattern variable, neither crustal, meteoric, or a simple combination of the two [101]	
Nickel anomaly	K–T; P–Tr	Relative Ni–PGE calcophile element ratios not meteoritic [101]	Concentrations compatible with plume+craton C-,S-rich vapor phase's chemistry?
C_{60}–C_{70} fullerenes ('buckyballs') – formed in space [102]	K–T; P–Tr	How did buckyballs survive impact and vaporization? C_{60}–C_{70} fullerenes not found in meteorites [102]	Formed during Verneshot decompression from ambient plume+craton-derived carbon vapors?
Helium and argon in C_{60}–C_{70} buckyballs – meteoritic/'outer space' isotopic ratio [103]	P–Tr	concentrations imply high pressures+stellar origin [10]	Ratios+concentrations appropriate for cratonic+plume carbon-rich regions
C, O isotopes [H+W] ($\delta^{13}C$, $\delta^{18}O$ decrease)	K–T; Tr–J; P–Tr;	Evidence of biosphere productivity collapse (mass extinction) not of impact	Extinction (hence C, O isotopes) due to Verneshot
Sulfur isotopes – increase in $\delta^{34}S$	(K–T [12]); P–Tr [9]; FF [12]	Isotopic signature not meteoritic [9]. Requires impact-related volcanism	Sulfur isotopes consistent with mantle degassing (Verneshot)
Rapidity of extinctions	K–T; Tr–J, P–Tr [12]	Also evidence that great mass extinctions occur within longer environmental disturbances [12]	Each Verneshot instantaneous; their occurrence related to longer-term CFB 'extreme volcanism'
Fern spores	Tr–J [8], K–T [12], P–Tr [12]	Implies only rapid recolonization of devastated region	Verneshot equally instantaneous. Tr–J study area (Newark Basin) lies near CAMP volcanic province

Phanerozoic mass extinctions, and proponents who have favored a terrestrial origin for mass extinctions linked to the rifting of continental shields and associated (carbon-rich) kimberlite/carbonatite activity and continental flood basalt eruptions. Since Alvarez et al.'s suggestion that the presence of a large iridium concentration anomaly in sediments at the Cretaceous–Tertiary (K–T) boundary was evidence of a large bolide impact at this time that caused the K–T mass extinction, geologists have searched for and reported many possible 'impact tracers' at the times of great mass extinctions, summarized in Table 1. During this debate, impact proponents have become largely convinced that basaltic volcanic processes cannot create the 'impact signals' of shocked quartz, microspherules, and fullerenes that presently have been reported at the times of the most recent four of the five great extinctions. What has become somewhat lost in this muddled debate is that there is also increasingly well documented geologic evidence for continental flood basalts and rifting-related kimberlite/carbonatite activity at the four most recent of the past five great Phanerozoic extinctions. Here we discuss that these multiple coincidences of apparent synchronicity of great Phanerozoic mass extinctions with *both* cratonic continental flood basalts (CFBs) [1–6] *and* the geologic 'traces' of large bolide impacts [7–11] is *extremely* unlikely to arise by chance – strongly arguing for either a causal link between all three or that the reported geologic evidence of 'impact signals' is spurious or the byproduct of much smaller non-lethal impacts. (The occurrence and apparent near-synchronicity of great mass extinctions and CFBs is not in doubt.) To begin we briefly review the evidence for CFBs and geologic 'impact signals' at the time of each of the four most recent of the five great Phanerozoic mass extinctions.[1]

As summarized in Fig. 1 and Tables 1 and 2, geologic tracers consistent with bolide impacts and CFBs have now been documented for the most recent four great Phanerozoic mass extinctions: the K–T at ~66 Ma, the Triassic–Jurassic (Tr–J) at ~201 Ma, the Permian–Triassic (P–Tr) at ~251 Ma, and the Late Devonian (including the Frasnian–Famennian (FF)) mass extinction which apparently happened in several sharp pulses between ~380 Ma and ~364 Ma. (We will refer to the geologic tracers of bolide impacts as 'impact signals', the rarest of which is a large crater which has only been inferred for the K–T.) Cratonic flood basalts are best known as the eruption sites of extremely large volumes ($>10^6$ km^3) of tholeiitic (mid-ocean-ridge-like) basalts within a time span of a million years or less (documented by paleomagnetic reversal evidence, cf. [2,15], and Ar/Ar dating [16,17]). However, within continental cratons, these flood basalts are sometimes associated with the eruption of carbon-rich kimberlites [16] and carbonatites. Kimberlites are carbon- and volatile-rich basaltic magmas that appear to have the most rapid and explosive ascent from their source of any terrestrial magmas, and which are the only known transport vehicle rapid enough to carry metastable diamonds from their source depth to Earth's surface.

The ~66 Ma K–T boundary is the time of the synchronous occurrence of one of the largest known terrestrial impact structures, Chicxulub, and a very large CFB, the Deccan Traps event associated with continental rifting above the Reunion plume (see Fig. 2). Other impact geosignals of this event are an iridium-rich sediment stratum [11] (found worldwide, also between two of the lower Deccan Traps massive basalt flows [18]), globally distributed findings of altered microspherule deposits [13], rarer shocked quartz microcrystals and even rarer stishovite (high-pressure quartz) microcrystals [12], and nanodiamonds [19]. Other geosignals of a sudden mass extinction event are sudden excursions in marine δ^{13}C, δ^{18}O, and ^{87}Sr/^{86}Sr, and a spike in the abundance of fungal spores [12] that is inter-

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[1] For the reader wishing good introductions to the vast literature in mass extinction research, Hallam and Wignall [12] have written an excellent recent book on the subject, Alvarez et al. [11] is still one of the best short and compelling presentations of the impact hypothesis for mass extinctions, Smit [13] provides a good recent review of the impact evidence at the K–T boundary, and Courtillot [2] and Wignall [14] provide good, complementary overviews of the catastrophic volcanism hypothesis for mass extinctions.

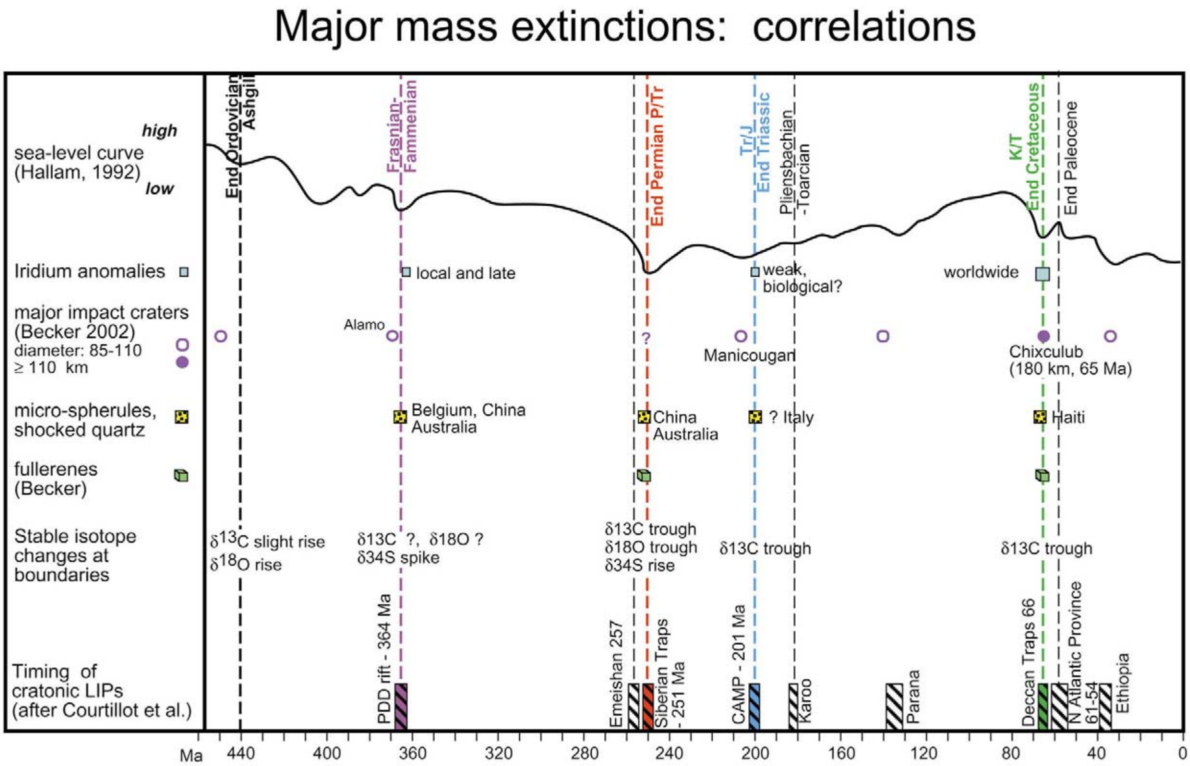

Fig. 1. Known correlations between the timing of the five great Phanerozoic mass extinctions, CFBs, and the geologic 'impact signals' associated with these mass extinctions.

preted as evidence of an equally sudden 'killing time' on land.

The ~201 Ma Tr–J boundary is the time of near-synchronous Central Atlantic Magmatic Province (CAMP) flood basalt volcanism [17] associated with the initial slow rifting of North America from Africa and South America (see Fig. 2), and 'impact signals' of shocked quartz (in Italy [7]), a small Ir sediment excursion (eastern USA [8]), and possible impact-induced slump deposits (seismite) across the UK [20]. Note that these end-Triassic 'impact signals' are distinct from those caused 10–15 Myr earlier by the Manicougan impact, which created a large crater as well as widespread shocked quartz and microspherules [21] but which is *not* associated with a mass extinction (Fig. 1). The Tr–J extinction record is also associated with a sudden excursion in marine δ^{13}C [22], and a spike in the abundance of fern spores [8].

The ~251 Ma P–Tr boundary has been long known to be the time of both the largest Phanerozoic mass extinction and the largest well documented CFB, the Siberian Traps (Fig. 2). Recently, it has been recognized that the end-Permian extinction is likely to have occurred in two sudden pulses [23], a smaller pulse at ~257 Ma (end-Guadalupian) believed to be synchronous with the Emeishan CFB now preserved in China (Fig. 2) [23], and a second larger pulse at ~251 Ma, synchronous with the Siberian Traps CFB [24]. 'Impact signals' at the P–Tr boundary are reported as non-atmospheric rare gas ratios trapped in P–Tr C_{60} and C_{70} fullerenes [10] (this reported finding has been recently disputed [25]; note also that it occurs in the same bentonite bed of altered volcanic ash that was used to date the P–Tr event by Renne et al. [24]), microspherules and shocked mineral ejecta [14], and a sudden rapid change in δ^{34}S which is interpreted to rec-

Table 2
Verneshot hypothesis resolution of difficult-to-explain CFB-related origins for mass extinction-related events

Observation	CFB explanation	Problem	Verneshot explanation
Extinction mechanism	Nuclear winter – aerosols and particles in stratosphere	Getting material into stratosphere [104]	Instantaneous – gas explosion injects SO_2 propellent into stratosphere
	greenhouse gases – cause sea level rise+anoxia	Short extinction interval [101]	Sudden injection of greenhouse gas only part of extinction mechanism
Ir anomaly at K–T	Ir in plume-derived lavas	Ir content far too low [101]	See below
	Volatiles from Reunion have high Ir [105]	Ir content slightly too low [48]	Initial catastrophic outgassing of plume+craton volatiles fundamental to a Verneshot
Other PGE anomalies	Plume-derived PGE close to chondritic	PGE concentrations not known	Possible problem remains. Work needed on plume/craton volatiles
Microspherules	Volcanic droplets	Quantity? Wide distribution? Composition – condensates from vapor?	Generated at explosion and at subsequent landing? – Wide distribution, various compositions possible
Shocked quartz	Explosive volcanism	Not explosive enough? [49]	May be generated by explosion, by pipe collapse or perhaps during landing of a Verneshot mass jet 'projectile'
Simultaneous crater	No explanation, unless impact caused CFB	K–T CFB and plume activity predates impact signature [18,40]	Mass jet 'projectile' landing site or Verneshot pipe (both shock events, but different geologic structures!)
Nanodiamonds	none		Formed by explosion/pipe collapse
Sulfur isotopes	Plume signature		Plume signature

ord the sudden release of mantle sulfur triggered by melting induced by an oceanic bolide impact [9]. The P–Tr extinction is also associated with sudden marine excursions in $\delta^{13}C$ [26], $\delta^{18}O$ [27], and a spike in the abundance of fungal spores [28]; late Permian (Changxingian) marine fauna disappears at the base of a 5 cm thick smectite white clay (volcanic ash) layer bounded by pyrite lamellae characteristic of anoxic ocean conditions [29].

The geologic record of the ~380 Ma and ~364 Ma (Late Devonian) mass extinction events is more complex than the record of the three more recent ones, with evidence for two or three extinction 'surges' within a ~15 Myr period. At ~380 Ma, there is evidence for both 'impact signals' including shocked quartz [30] and plume-influenced [31] cratonic kimberlite and carbonatite emplacement on the Kola Peninsula (Baltic Shield) [32]. It has been proposed that the ~50 km diameter Siljan crater in Sweden (close to the Kola Peninsula, but considered too small to cause a mass extinction) was formed at this time, and the ~364 FF boundary appears to also be synchronous with the eruption of the now almost completely buried and hence poorly documented Pripyat–Dniepr–Donets CFB [33] in the Ukraine and southern Russia and recorded kimberlite activity at both the Kola Peninsula [32] and near what is now the southernmost exposure of the Siberian Traps [34]. While microspherule and shocked mineral traces have also been found in some sediment records of this era (see Table 1), $\delta^{13}C$, $\delta^{18}O$, and $\delta^{34}S$ excursions appear to be more complex in the Late Devonian events than at the three younger great mass extinction boundaries [12].

Thus, at least three and maybe four synchronous CFBs (with associated kimberlite activity), 'impact signals', and mass extinctions have occurred within the past 390 Myr (Fig. 1). How likely is this to arise by coincidence?

2. Do two (or more) synchronous CFB/bolide impact events imply a causal link?

Bolide impacts that produce a ~180–300 km

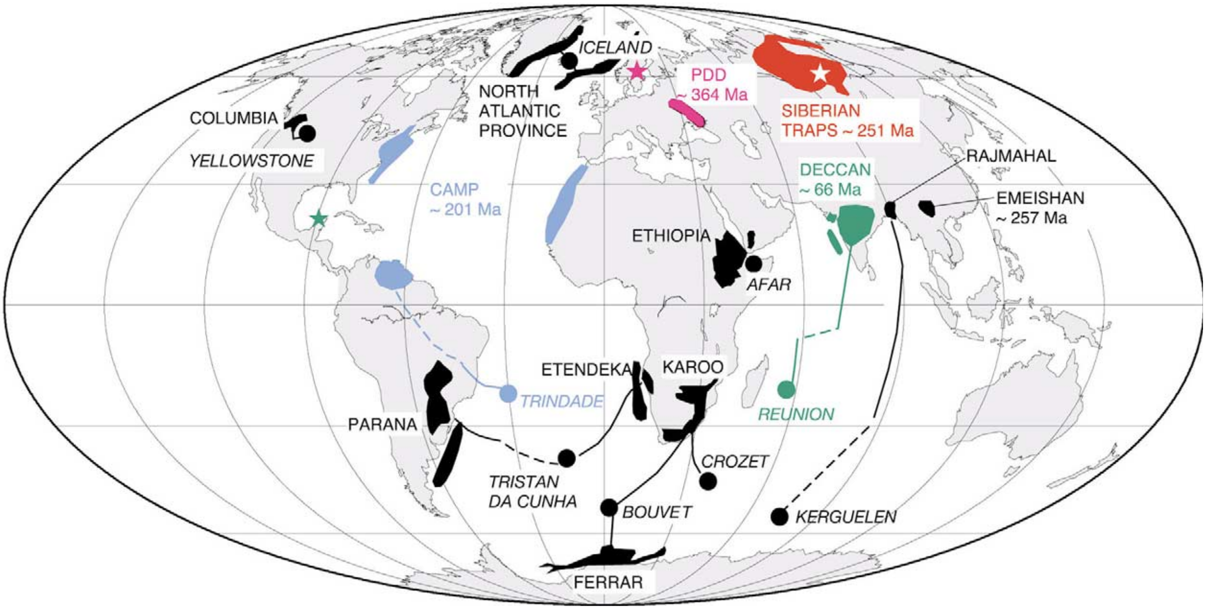

Fig. 2. Map of CFBs known to have occurred in the past 400 Myr and their present-day hotspot traces (where known). The Deccan Traps (K–T flood basalts, ∼66 Ma) are linked by a chain of volcanism to the presently active Reunion plume. The Central Atlantic Magmatic Province (CAMP) Traps (Tr–J, ∼201 Ma) in Guyana can be rotated back using Morgan's [94] reconstruction for the opening of the Atlantic to the site of the present-day Trindade hotspot. Although poorly known this appears to be a fairly strong hotspot because it has recently created a chain of volcanism on old, ∼120 Ma, thick oceanic lithosphere. It is not known whether the Siberian Traps (P–Tr, ∼251 Ma) or Emeishan Traps (∼257 Ma) were created above any presently active hotspot. The Pripyat–Dniepr–Donets (FF, ∼364 Ma) CFB is an almost entirely buried structure with scarce surface outcrop. The spatial extent of almost all flood basalt provinces is likely to be underestimated because of their subsequent erosion above now high-standing cratons and burial beneath the rifting-related sedimentary basins to which their formation is closely tied. Stars show the sites of the Chicxulub (K–T), Siljan (∼FF), and Great Tunguska Depression (P–Tr) structures.

multi-ring basin the size of Chicxulub [35] are believed to occur less than once every 10^9 years. The initial characterization [11] of the impact mass extinction hypothesis proposed that 'large enough' bolide impacts could occur every ∼100 Myr [36]. Within the last 250 Myr for which a continuous continental record is reasonably well known, CFB events also occurred infrequently [2], roughly once every ∼30–50 Myr, with the primary volcanic pulse lasting at most ∼1 Myr – this duration is often constrained to be within a single magnetic reversal [2]. Assuming, as Alvarez et al. [11] did, that 'large enough' impacts occur once every 100 Myr, we see that the odds of a single impact randomly occurring at the same time as a cratonic flood basalt within the last 400 Myr are (1/30)×(1/100)×400 or 13%, or one in eight times, odds that are unlikely but perhaps within the realm of terrestrial bad luck. (The apparent synchronicity of the Deccan Traps and Chicxulub crater formation could be exactly such a 1 in 8 bad luck coincidence.) Two such temporal coincidences would occur by chance only $(0.13)^2$ or 0.0169 of the time, three 0.0022 of the time, and four with a probability of 0.00028.

While even one such coincidence is relatively unlikely to occur by chance within the past 400 Myr (it should have happened roughly once over the last 3 Gyr of Earth evolution), two or more synchronous CFBs, impact signals, and mass extinctions are so unlikely to occur by chance that it seems prudent to explore if there exist causal links between geologic 'impact signals' and flood basalts. If the near-consensus view that 'impact signals' are genuine indicators of a major shock event is true, then two possibilities exist: either large impacts cause CFBs [15,37–39] – so initiating associated successor hotspots like the Reunion hotspot – or alternatively, CFB-related processes have somehow created the geologic 'impact signals' found at the times of the largest Phanerozoic mass extinctions.

3. Can large bolide impacts initiate CFBs and their subsequent long-lived hotspot activity?

The most recent and best preserved K–T record contains strong geologic evidence which implies that large impacts *do not* initiate either flood basalts or mantle plumes. A sediment pocket containing the iridium 'impact signal' is found lying *between* two of the lower Deccan Trap lava flows [18], documenting that the impact must have postdated the onset of, and thus cannot have caused, the Deccan CFB. Furthermore, the Deccan–Reunion trace can be followed as a time-progressive lineament of ^{3}He-rich small alkalic continental eruptions for >3.5 Myr *before* the eruption of the oldest, lowermost, Deccan Traps [40]. This implies that the Deccan Traps/Reunion Plume were not created by a 'sister' impact shortly before the Chicxulub impact, instead the plume was ponding beneath Indian cratonic lithosphere for at least 3.5 Myr prior to the main Deccan flood basalt activity.

In spite of this evidence – which is so critical in its implications that it deserves more thorough corroboration – it has been repeatedly proposed that, somehow, large impacts on continents can initiate both CFBs and their associated (often long-lived) mantle plumes. When Melosh looked at this problem [41], he determined that the energetics of a large impact imply that a Chicxulub-like terrestrial impact would not initiate volcanism at either the impact region or its antipode. However, more recently Jones et al. [38] have proposed two physical hypotheses by which impact-related decompression could potentially generate flood basalts above major impact sites. The first hypothesis is that the unloading or rarefaction phase of the impact shock event could induce extensive partial melting of continental lithospheric mantle, the second that an impact excavates a large and deep enough crater to induce longer-duration pressure-release melting in underlying continental lithosphere and asthenosphere. Both hypotheses have such serious physical and petrological shortcomings that they seem nonviable to us. The shock decompression phase of an impact lasts only a few seconds (lasting the time it takes for a shock wave to traverse the impacting body twice) and is followed by a quick return to lithostatic pressures. Thus, even if flash-pressure-release melting could occur, it would be followed a few seconds later by a similar 'flash-freezing' event. Furthermore, CFBs are clearly *partial* melts of the mantle that do not have the composition of the bulk mantle but rather of a partial melt *in chemical equilibrium with its source mantle mineral assemblage*. During flash-melting, there is simply not enough time to equilibrate a flash melt with its surrounding matrix. For example, typical Fe–Mg diffusion rates in olivine at 1200°C are $\sim 4\times10^{-16}$ m^2/s ([42], p. 195), and cation diffusion rates in basaltic melts are $\sim 10^{-11}$–10^{-12} m^2/s ([42], p. 191). In 1 s, Fe–Mg between an olivine crystal and adjacent flash-melt could only equilibrate over a distance of $\sim 2\times10^{-8}$ m. Even if rates of chemical diffusion were as fast as those of thermal diffusion – 10^{-6} m^2/s – which they are not, in 1 s diffusion would only equilibrate a mm-scale volume, 1000 times smaller than the characteristic cm-scale volume thought typical to mantle minerals.

The second proposed idea – that the excavation of the crater site causes a lasting pressure release – clearly can and does happen. However, except above an already active plume or mid-ocean ridge, even the excavation of a deep crater would be unlikely to induce *any* pressure-release melting. Quite simply, during continental rifting even thinner non-cratonic lithosphere must thin to at least a half or a third of its initial thickness before the onset of pressure-release melting [43], in which case more than 75 km of 'overburden' would have to be excavated from the top of ~ 150 km thick lithosphere for such melting to begin. Even the extremely large Chicxulub impact excavated a post-impact crater that is much shallower than this (there is little evidence of crustal thinning, with post-impact sediment fill at most a few km thick [44]). Thus both of the mechanisms proposed by Jones et al. [38] appear to contain serious physical and petrologic problems. Furthermore, they cannot explain the near-synchronicity of the Deccan Traps and the Chicxulub impact, except by arguing that there were at least *two* large nearly time-synchronous impacts – one (Deccan) at the site of prior continental hotspot volcanism that initiated a CFB, while another large impact at Chicxulub excavated a crater only a few km deep and did not trigger a flood basalt.

4. Do subcratonic mantle plumes cause 'impact signals' and CFBs?

Thus we are seemingly left with only two possibilities: either the reported 'impact signals' at all except maybe one of the K–T, Tr–J, P–Tr, or Late Devonian mass extinctions must be spurious (since the geologic evidence for extinction-synchronous CFBs is clear, and the odds of even one such large extraterrestrial impact/CFB/extinction coincidence within the past 400 Myr are only 1 in 8); or we must seriously consider the implication that 'impact signals' were somehow created by processes occurring during the onset of continental rifting, causally related to the genesis of cratonic CFBs and Earth's largest mass extinctions – even though the general consensus of previous work was that CFB-related basaltic volcanism cannot, by itself, create these 'impact signals' [14].

Note that *if* the P–Tr, Tr–J, and Late Devonian mass extinctions *all* have spuriously reported impact signals, then there is not only no need for the subsequent Verneshot hypothesis, but also clear geologic evidence that CFB-related processes, *not* large impacts, have been the dominant (even sole?) cause of the great Phanerozoic mass extinctions, as has been already well argued by Courtillot [2]. In this case, the conclusion of this reassessment will be that large impacts were *not* the cause of most, if not all of the great Phanerozoic mass extinctions, instead CFB-related processes were – a strong affirmation of the CFB-linked mass extinction hypothesis and strong negation of the hypothesis that large impacts drove the great mass extinctions.

However, there is another possible resolution to the dilemma raised by these multiple coincidences that involves the resurrection and extension of earlier geologic speculation [45–47] that continents can be sometimes the sites of 'cryptoexplosions' much more vehement than any 'normal' explosive volcanic eruptions. In the rest of this paper we will consider the hypothesis that at least some of the many reported 'impact signals' at times of great mass extinctions are real, and explore the corollary that they formed during times of eruption of voluminous plume-related and probably volatile-rich magma through rifting *cratonic* lithosphere characterized by previous and concurrent kimberlite activity. We will next discuss a possible physical mechanism to explain these causal links in which the rifting of plume-incubated cratonic lithosphere can 'routinely' produce all of the 'impact signals' of large bolide impacts (shocked quartz, tektite fields, nanodiamonds, 'non-crustal' iridium/noble metals, fullerenes, etc.). Many of the above geochemical 'impact signals' really only indicate the rapid injection of non-crustal, non-atmospheric material into the biosphere. For example, the archetype K–T iridium anomaly, while definitely non-crustal in its relative abundance, lies within the field of iridium concentrations observed in the volatile phases degassing from current plume volcanoes such as Kilauea, Hawaii, and Piton de la Fournaise, Reunion [48]. (In fact, Reunion's present-day Piton de la Fournaise volatile release is particularly rich in noble metals [48], offering a possible explanation as to why the K–T boundary could be particularly rich in iridium relative to other great extinction boundaries.) Plausible CFB volcanic origins for all 'impact signals' except shocked quartz, stishovite, nanodiamonds, non-atmospheric rare-gas-filled fullerenes, and, of course, an impact crater itself are well summarized in Courtillot's recent book [2] and Wignall's recent review article [14]. Thus here we focus our discussion on a possible CFB-related terrestrial origin for currently unexplained 'impact signals'.

While it has previously been concluded that shocked quartz, stishovite, and nanodiamonds are impossible to make or erupt during 'normal' terrestrial volcanic processes (for a good review of the evidence, see [2,49]), the physical mechanism we next explore, explosive volatile release from ~80 km depths within cratonic lithosphere, may be capable of creating and/or ejecting these minerals into its globally distributed fallout, in addition to ejecting large amounts of C_{60} and C_{70} fullerene clathrates that preserve the 'non-atmospheric' He and Ar isotope ratios of their mantle plume carbon-rich melt plus 'metasomatized craton-lithosphere' source.

5. Cratonic lithospheric gas explosions – the great extinctions' missing terrestrial link?

As noted above, the K–T, Tr–J, and P–Tr boundaries are times of eruption of voluminous plume-related and probably volatile-rich magma through rifting *cratonic* lithosphere up to ~250 km in thickness, leading to cratonic eruptions of kimberlite-type diatremic alkaline volcanism [50] in addition to more voluminous basaltic lava flows. Kimberlite activity is a likely indicator of plume material ponding beneath and incubating the base of old, cold, volatile-rich, cratonic lithosphere [51,52]. We suggest these preconditions may sometimes lead to the formation of what we will term *Verneshots*, catastrophic carbon- and sulfur-gas-driven craton-lithospheric explosions fracturing a thick lithospheric column, even perhaps capable of shooting large terrestrial mass jets into suborbital trajectories in a natural analogue to the explosive transport mechanism first discussed by Jules Verne [53].

The buildup and catastrophic release of carbon- and sulfur-rich vapors from cratonic lithosphere hinges on three factors, each apparently feasible. The first is whether deep plume melting can preferentially extract and transport enough carbon into the overlying cratonic lithosphere to build up a large carbon-rich gas-overpressured volume within portions of continental cratons. The second is whether the warming of cratonic lithosphere above a subcratonic plume puddle can mobilize enough carbon-rich magmas (both from the current plume and from previously solidified C-rich melts) upward to the ~80 km depths where CO_2 exsolution and vapor buildup is petrologically favorable. The third is whether the gas release 'explosion' associated with sudden lithospheric failure above an ~80 km deep overpressured CO_2-rich portion of the lithosphere can release enough energy, CO_2/CO, and SO_2 to create a Verneshot and its associated ecological catastrophe.

Each of these aspects appears possible for plume ascent and melting beneath ~175–225 km thick continental cratons (Fig. 3), whereas when plume material melts beneath thinner and hotter oceanic lithosphere it is more difficult, if not impossible, to build up and trap much CO_2 for a geologically significant period of time. This implies that CO_2 buildup and catastrophic release should be a feature of cratonic, not oceanic flood basalt volcanism. Furthermore, the possibility of Verneshots and large-scale CO_2 breakouts should be greatly enhanced by the onset of continental rifting, and subsequently reduced after rifting since lithospheric extension would enhance the pathways for deep lithospheric CO_2 escape while also providing pathways for any subcratonic plume material to drain laterally upwards towards neighboring thinner oceanic lithosphere. Lithospheric gas explosions being preferentially associated with early CFB activity is consistent with Wignall's conclusion that mass extinctions appear to be associated with the onset phase rather than the acme of the CFB activity [14]. They are also favored beneath nearly stationary cratons as a moving continent will tend to spend only a relatively short time above any particular (nearly stationary) plume.

In the rest of this paper, we will first discuss a possible mechanism for carbon- and sulfur-rich vapor buildup at ~80 km depths within cratonic lithosphere through the combined effects of intruding new carbon-rich plume-derived magmas within the craton, and remobilizing upwards previously frozen carbon-rich magmas through plume warming of the base of the craton. We will report geophysical observations of the lithosphere beneath present-day cratonic kimberlite fields which are consistent with the presence of a significant trapped vapor phase at ~80 km depths. Then we will outline the physical and chemical implications of a sudden gas release event due to explosive failure of the resulting overpressured cratonic lithosphere. We demonstrate that this mechanism has the potential to release sufficient explosive gas decompression energy to eject a 'Verneshot' mass jet from the failing lithospheric column, and that the outward explosion phase of the largest events and the pipe collapse phase of both large and small events are likely to form and globally distribute microspherules, shocked quartz, and fullerenes. We will then discuss the potential geologic indicators of a fossil Verneshot explosion pipe. For completeness, we will briefly discuss some of the catastrophic ecological aspects of a Verneshot event.

6. Carbon-rich plume melts can bring significant mantle carbon into cratonic lithosphere

Carbon's actual volume fraction within the convecting mantle is poorly known, in large part because any carbon-rich mantle components are likely to have much lower melting (solidus) temperatures within the upper mantle [54,55] than their host carbon-poor peridotites or pyroxenites, thus are most likely to be efficiently extracted into deep-forming carbonatitic/kimberlitic magmas. Such magmas would be a normal low-volume by-product of plume volcanism – and their presence is infrequently observed in normal oceanic plume volcanism (e.g. Cape Verde and Canary Islands [56], Hawaii [57]). However, beneath thick continental cratonic lithosphere, these magmas would be the *only* ones extracted by pressure-release melting of the upwelling plume mantle, while beneath thinner oceanic lithosphere shallower pressure-release melting of more abundant carbon-

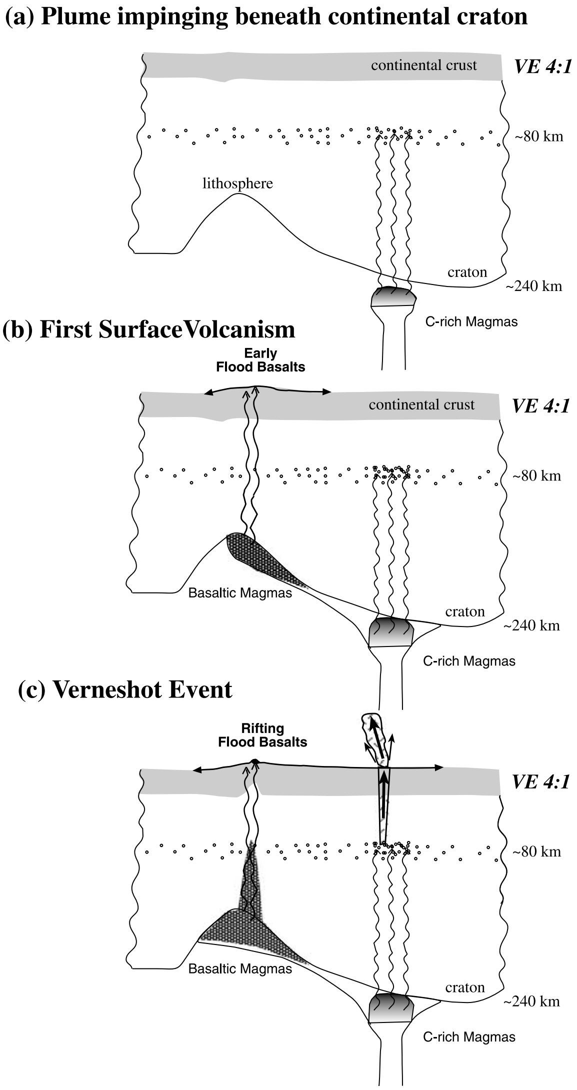

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Fig. 3. Proposed Verneshot mechanism for generating terrestrial 'impact signals'. (a) CO_2 buildup within cratonic lithosphere underlain and warmed by upwelling, melting, plume mantle. (b) Plume material flows laterally and upwards beneath thinner (off-craton) lithosphere, where it pools beneath the thinnest continental lithosphere and melts to form the earliest flood basalts. Ponding of plume material uplifts the flood basalt province, while the plume stem continues to add CO_2, incubate the deep cratonic lithosphere, and remobilize preexisting frozen 'metasomatic'/C-rich magmas upwards towards the ~80 km, 2.5 GPa threshold pressure of CO_2 exsolution from a carbon-rich silicate magma. This continues to increase the overpressure within the overlying cratonic lithosphere. (c) Catastrophic explosive lithospheric failure produces a Verneshot. The C- and S-rich vapor of the explosive gas release event produces the sudden environmental stresses that lead to a mass extinction. After the Verneshot, the region around the expelled launch pipe suddenly becomes extremely underpressured relative to surrounding lithosphere. The bottom-up collapse surface of this near-vertical hole can propagate upwards at hypersonic speeds even when the side walls are collapsing inward at the much slower speeds associated with earthquake slip. Such a hypersonic collapse front can create and expel shocked minerals during collapse-induced shock cavitation and mass jetting.

poor peridotitic and pyroxenitic lithologies would also occur within the plume's melting column – and these more abundant shallower melts would tend to mute most of the signal from more deeply generated carbonatite–kimberlite melts. McDonough and Sun [58] estimate the upper (MORB) mantle's carbon abundance to be 50–250 ppm, with this being a *lower* bound on the abundance of mantle carbon, which could easily range up to 1200 ppm or more if the average mantle has more carbon than the depleted, relatively devolatilized MORB source.

Earth's near-surface carbon budget implies that more than 2.2×10^{21} mol/Gyr of carbon must be presently cycling into and out of the mantle [59]. This *minimum* rate of net mantle outflow only requires the MORB mantle to be 50 ppm carbon (by weight). Even in this case it is likely that typical cratonic lithosphere will have geologically significant amounts of carbon (and sulfur) brought into it by episodic 'metasomatism' caused by C-rich magmas generated within underlying subcratonic mantle plumes. For example, if cratons cover one sixth of the Earth's surface, and are randomly distributed above upwelling mantle plumes which bring up mantle carbon at only the present-day mid-ocean ridge release rate of 2.2×10^{21} mol/Gyr, then subcontinental cratons would be potentially accumulating carbon at a rate of 7000 'atmospheres' (or 100 'oceans') of CO_2 per Gyr.

7. Cratonic lithosphere incubation – a possible mechanism for CO_2 buildup

Experimental petrologists have long noted that CO_2 remains stably 'dissolved' within a carbon-rich magma only at pressures greater than ∼2.5–2.7 GPa (∼80 km) [54,60,61]. At lower pressures, for almost any plausible upper mantle/deep continental lithosphere temperature (see Fig. 4), silicate magmas tend to exsolve CO_2 into an immiscible vapor phase [55] that forms bubbles within the surrounding matrix. As can be seen from the phase diagram in Fig. 4, the exothermic carbonate magma–lherzolite reaction at ∼2.7 GPa (the reaction dolomite phase (magma)+orthopyroxene ⇒ clinopyroxene+CO_2 (gas) [60]) will transform a magma into solid plus gas phases, thus providing a natural barrier to halt liquid magma ascent. (Note that the phase diagram and cratonic lithosphere geotherms shown in Fig. 4 imply that, once they ascend shallower than ∼180 km depths, ascending carbon-rich melts will tend to partially freeze during ascent due to conductive heat loss to surrounding wallrock. At the exsolu-

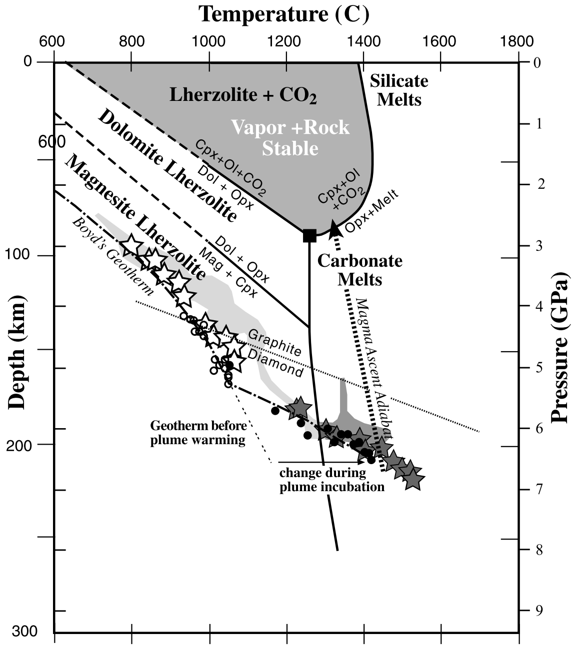

Fig. 4. Phase diagram for carbon-rich silicate melts [95]. At high temperatures and pressures carbon readily dissolves in silicate liquids, however below ∼2.7 GPa, it exsolves into a critical gas CO_2 phase. Any rising melts will spontaneously exsolve CO_2 at this depth as the magma transforms from a liquid phase to solid plus gas phases. The open (low-T 'unsheared peridotite') and filled (higher-T 'sheared peridotite') circles show the kinked kimberlite xenolith-inferred geotherm first suggested by Boyd [65] for the Southern African craton. The open ('unsheared') and filled ('sheared') star symbols show another example of a South African cratonic geotherm inferred from xenoliths within a single kimberlite pipe [96], while the light gray ('unsheared') and dark-gray ('sheared') clouds show the P–T bounds to cratonic lithosphere P–T conditions from Koehler and Brey's compilation of all kimberlite xenolith samples with P–T estimates from their preferred thermobarometer [67]. A simple explanation for these geotherms is that the 'kink' in this geotherm reflects the effects of transient plume reheating at the base of the lithosphere during times preceding kimberlite formation [63,64,66,67]. See text for further discussion.

tion threshold at ∼2.7 GPa, this effect is enhanced by the ∼200 K increase in the ascending magma's solidus temperature and the changing character of the phase transition.) Typical carbonate melts in experimental melts of C-rich lherzolite compositions [60] contain 45% CO_2 by weight. If we assume the density of carbon dioxide given by Bowers [62] for this pressure, 1.6 Mg/m^3, assume the density of the magma to be ∼3 Mg/m^3, and the density of wallrock to be ∼3.3 Mg/m^3, then the net volume change of the reaction per unit volume of magma is 34%, with a 1% CO_2 volume fraction being a byproduct of the reaction of ∼1% carbonate magma with surrounding peridotitic wallrock (we choose a 1% CO_2 volume fraction addition prior to failure because this amount induces the ∼1 GPa overpressure necessary to cause ∼700°C, 2.7 GPa cratonic lithosphere to fail, as will be further discussed below). The heat generated by this reaction can be determined from the Clapeyron slope of the phase diagram, when given the reaction's volume change and the heat capacity of the magma. For a heat capacity 1200 J/kg/K, this gives an estimate for the reaction's heat release that is equivalent to ∼400 K per mass of reacting magma, or ∼4 K throughout a ∼1% magma, 99% wallrock mixture, which is much less than the ∼200 K temperature rise that would be needed to keep the mixture molten (Fig. 4).

If hot plume mantle ascends to pond beneath the base of cratonic lithosphere, it will not only add new carbon-rich melts to the overlying lithosphere, but will also heat the overlying lithosphere. (We envision here that the base of the cratonic lithosphere provides a barrier to diapiric plume ascent, but not to the rise of the plume's melts and heat.) This heating can be deduced [63,64] from the kinked geotherm (Fig. 4) derived from thermobarometry on xenoliths in kimberlites [65–67] and is thought to be the cause of kimberlite magmatism [51,66]. In the currently most widely accepted geotherm [67] this kink occurs at a depth of ∼190 km and corresponds to a sharp increase in temperature over the next 10–20 km from temperatures of ∼1250°C to in excess of 1400°C. Assuming that the thermal diffusivity of the mantle is 10^{-6} m^2/s, the time taken to produce the kinked geotherm by heating the basal 20 km of the lithosphere would be about 4 Myr, and the basal 40 km 16 Myr. If heat transport within the craton's 'kinked' transient thermal boundary layer were faster due to the extra upward heat advection within remobilized ascending C-rich melts, a shorter reheating time would be appropriate. Thus subcratonic plume reheating provides a straightforward explanation for the subcontinental geotherm recorded in kimberlite xenoliths [63,64,66,67], implying that this geotherm is actually a transient geothermal profile associated with the usual preconditions to kimberlite ascent.

Heating of the base of the cratonic lithosphere will promote the remelting and upward migration of carbon-rich melts previously frozen and trapped within the base of the lithospheric craton. Deep carbon-rich plume melts (generated by pressure release at >200 km depths) transport plume carbon and sulfur into the craton, thus 'metasomatizing' it along the tracks of subcratonic melting plumes. If the upwelling plume material is several hundred degrees hotter than the ambient upper mantle beneath a continental craton (cf. [68]), then subcratonic ponding of plume material within a thin spot or 'catchment basin' at the base of the craton would lead to the reheating of the base of this region, thereby remelting previous trapped, frozen carbon-rich melts so that they migrate to shallower depths within the lithosphere. The result is a gradual buildup of lithospheric pressure at ∼80 km depths and above, as carbon-rich magmas accumulate at the ∼2.7 GPa pressure threshold. Carbon *gases* can only accumulate at pressures less than this, thus gas accumulation is capable of raising the lithospheric pressure to ∼2.7 GPa, but not higher, but gas overpressure can also cause lithosphere at depths shallower than ∼80 km to have its internal pressure raised to 2.7 GPa. The vertical pressure gradient can diminish or even become locally inverted below the region of gas accumulation, inducing later-ascending carbon-rich magmas to temporarily halt (and tend to pool) beneath this pressure threshold to form an overpressured carbon-rich magma pool at the base of the gas-rich overpressured region, as sketched in Fig. 5a. The

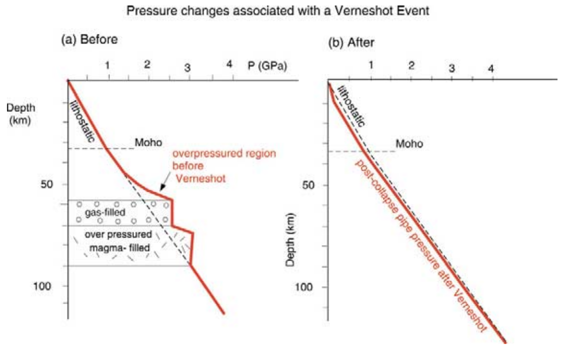

Fig. 5. Lithospheric pressure changes before and after a Verneshot explosion. (a) Before the explosion, pressures are limited by gas exsolution at a pressure of ∼2.7 GPa (see Fig. 4). As a result, the lithosphere around the depth of the 2.7 GPa isobar becomes overpressured, resulting in an upward migration of the 2.7 GPa isobar and the formation of a gas-rich overpressured lithospheric region underlain by an overpressured region of pooling carbon-rich melts. (b) After a Verneshot explosion, a column of lithosphere has been removed, resulting in local lithospheric underpressure that decays by inward faulting, viscous relaxation, and subsequent magma intrusions. The initial pressure drop of the Verneshot event can trigger local pressure-release crustal melting and deeper (plume/craton-base) pressure-release melting, with these magmas rising as ring-like 'tension dikes' within the fossil collapse pipe. Much later, this region may still be underpressured relative to lithostatic, attracting kimberlite (and other) melts that reoccupy this low-strength passage through the cratonic lithosphere.

maximum overpressure will be limited by the size of the deviatoric stress that the surrounding cratonic material can support prior to its failure; for a cool (∼650°C – Fig. 4) and dry olivine rheology for the surrounding cratonic lithosphere, a conventional yield strength envelope estimate would imply that the surrounding region could support a maximum deviatoric stress of $>\sim 1$ GPa before failure ([69], pp. 268–269) if the ambient strain rate during the buildup phase is 3×10^{-17} s^{-1} as would be implied by a 1% lithospheric volume expansion during a time of 10 Myr. For simple load geometries this also equals the maximum internal overpressure before failure ([70], p. 71). Since failure would first happen in the highest-deviatoric-stress region surrounding the zone of overpressure and would propagate upwards into regions of lower strength and confining pressure, it would likely be catastrophic. We suggest that this is the lithospheric pressure distribution that can initiate a Verneshot event.

Recent measurements of the electrical conductivity of the Slave cratonic lithosphere in Canada reveal an "unexpected and remarkable anomaly in electrical conductivity ... collocated with the Lac de Gras kimberlite field" [71]. Here, at depths of ∼80–100 km there exists a spatially confined high-conductivity region ($\rho < 30\ \Omega$ m) consistent with either the presence of an interconnected free gas phase or its relic traces as continuous graphite films and/or interconnected sulfide melts [71]. This may be direct geophysical evidence of carbon vapor buildup within subcratonic lithosphere beneath a known region of kimberlite activity.

8. Energetics of a large lithospheric gas explosion

The energy release from a large Verneshot may be as much as that from a large bolide impact. During a Verneshot, mechanical energy will be released by the decompression of escaping gases [72] and strain relaxation of the overpressured lithosphere itself. To estimate the energy release from explosive decompression of a compressed lithospheric gas phase, consider isothermal gas expansion following the ideal gas law. (This assumes that any gas expansion cooling during decompression is buffered by heat from the surrounding rock.) In this case, the mechanical energy release W from the pressure release of this expanding gas is given by:

$$W = \int_{V_0}^{V_f} P(V)\mathrm{d}V = P_0 V_0 \int_{V_0}^{P_0 V_0 / P_f} \frac{\mathrm{d}V}{V} = P_0 V_0 \ln(P_0/P_f)$$

where P_0 is the initial gas pressure and V_0 is the initial gas volume within the overpressured region, and P_f and V_f are the final gas pressure and volume when it reaches the surface. For an initial gas pressure of 2.5 GPa and an initial average gas volume fraction of 1% (corresponding to an average overpressure of ∼1 GPa) within a 40 km diameter sphere of overpressured cratonic lithosphere extending from ∼40 to 80 km depths, the resulting mechanical work done by sudden gas escape would be of order 10^{22} J. Loper and McCartney obtained a similar estimate of order 10^{22} J in their analysis of the energetics of shallower (~ 300 MPa) magma chamber explosions induced by carbon dioxide exsolution [72]. Since carbon dioxide is not an ideal gas and gas expansion is likely to occur in closer to an adiabatic than an isothermal state, this is an overestimate. (One way to see this is an overestimate is that this ideal carbon dioxide gas would have a density 10 times that of the 1520 kg/m^3 density of real carbon dioxide at 2.5 GPa [62].) Another estimate of the gas energy release comes from equating the adiabatic heat change of the expanding carbon dioxide to the potential work by its gas expansion, which leads to the estimate $W = MC_V\Delta T$, where M is the mass of the initial 1% carbon dioxide fraction of the overpressured lithosphere, C_V is its heat capacity (roughly $C_V \approx 1200$ J/kgK), and ΔT is the ~ 700°C cooling that it would experience during explosive release from an ambient temperature of ~ 1000 K to ~ 300 K. This adiabatic estimate yields a near-minimal estimate for the gas expansion energy release of $\sim 5 \times 10^{20}$ J.

The mechanical strain energy release from the overpressured region is easier to estimate, by finding the internal strain energy associated with this region of overpressured gas-rich lithosphere and assuming that it is entirely released during the explosive gas release event. This strain energy is roughly $(\Delta P \Delta \varepsilon)(V) = K\Delta\varepsilon^2(V)$. It will be roughly equally partitioned between the overpressured region and its surroundings, where K is the elastic bulk modulus, $\Delta\varepsilon$ is the average compressional strain, and V the volume of the overpressured region from which gas escapes. For the spherical volume 40 km in diameter with a compressional overpressure strain $\Delta\varepsilon$ of 1% (equal to the pre-explosion gas volume), the strain energy release for $K = 100$ GPa would be $\sim 5 \times 10^{20}$ J, comparable to the decompression energy release of such a gas explosion or the energy release of a magnitude 11 earthquake.

This energy release, if sudden enough, is large enough to eject a large mass jet of lithospheric mantle and overlying crust into a ballistic trajectory. For example, an energy release of $\sim 10^{21}$ J applied to uniformly accelerate a mass of 2×10^{13} kg (equivalent to the mass of a ~ 60 km high, ~ 400 m diameter column of overlying 3000 kg/m^3 rock) would cause this mass to reach an average speed S of 10 km/s, which is obtained by equating the kinetic energy ($MS^2/2$) of the ejected mass to the mechanical energy release of the explosion. This ejection speed is large enough for ballistic transport of such a Verneshot's mass jet to any other point on the Earth's surface with its subsequent impact releasing an equivalent amount of kinetic energy – although it is certainly debatable whether such a mass jet could maintain its coherence during ejection.

Even for much smaller Verneshot events, the collapse phase of the transiently opened launch pipe would generate internal shock waves and mass jetting of the resulting shocked minerals. The basic physics is discussed by Melosh [73] and Spray [74,75] for meteor impact scenarios, for which this mass jetting mechanism has been proposed to be the origin of regionally strewn tektite fields [73], and of local shattercones and pseudotachylites at the site of the shock disturbance [74,75]. The essence of this phenomenon is that if two nearly parallel surfaces (here the pipe crack walls) collapse rapidly enough (i.e. at the typical speeds of seismic deformation), then the pipe will close from bottom to top at a speed much greater than the shock velocity of the medium, resulting in the formation of an internal compressive shock wave and mass jetting. We propose that this type of shock cavitation collapse of a gas explosion pipe is the mechanism that creates and globally distributed the shocked mineral 'impact signal' associated with the great mass extinctions. Furthermore, the phase of rapid gas-propellent decompression prior to pipe collapse may be associated with extensive fullerene formation, with the fullerenes ejected during the subsequent collapse mass jet. The above crude estimates suggest that Verneshots may have the potential to occur on Earth. Indeed, the detailed physics of such events – in which both gravity and the cohesive strength of the lithosphere are included – deserve in-depth dynamic modeling. For example the ejection of such a 'straw-like' pipe of overlying lithosphere would involve the minimal surface area of failure and minimal pressure-induced gravitational work during each step of the Verneshot breakout process, hinting that this could indeed be the mode of 'bottom-up' lithospheric failure in the presence of internal overpressure, cohesion, and gravity. However, numerical experiments incorporating the effects of cohesive strength, gravity, and gas expansion are needed to see whether this mode of failure can actually occur for geologically reasonable scenarios.

After the gas release, the site of the lithosphere explosion goes from being overpressured to underpressured relative to neighboring lithosphere as sketched in Fig. 5b. Removal of the thin (pipe-filling) column of lithosphere and subsequent lithospheric collapse to fill this void will create a slight relative low-pressure radial stress around the missing column and furthermore, a sudden pressure drop in underlying lithosphere and mantle. This state of stress is consistent with the subsequent emplacement of vertical 'ring-like' intrusion structures that are the form of several carbonatite (and synenite) intrusions, the largest known to us being the 20 km diameter Khibiny massif emplaced during the Late Devonian carbon-rich volcanism in Kola. Local decompression induced by mass jet removal of a column of lithosphere could induce local pressure-release melting of the lower crust near the pipe region, and a surge of melting in an underlying sublithospheric plume. For a much longer time thereafter, the relic pipe will also provide a low-pressure attractor for any subsequent crustal and kimberlite intrusions that would preferentially intrude as 'ring-form' dikes oriented perpendicular to the maximum local tensile stress direction – which may help disguise the origin of a preserved Verneshot pipe.

9. Recognizing a preserved Verneshot pipe

The model outlined above predicts a number of characteristic features of the Verneshot pipe that may be recognizable in the geological record.

1. A subcircular crater/depression containing shattered/brecciated rock.
2. Shocked quartz in the surrounding country rock.
3. Shattercones pointing toward the center of the pipe (possibly generated during the initial explosive gas release, more likely generated during the subsequent snapping shut of the pipe).
4. Pseudotachylite generated by the seismic faulting accompanying the Verneshot.
5. A distinct gravity anomaly similar to that expected for an impact crater.
6. Association with nearby voluminous CFB-style volcanism. This means that in the most recent examples the pipes may be buried beneath the trap basalts (e.g. Deccan).
7. The most likely geochemical signature we suggest to be excessive carbon, perhaps occurring as fullerenes or nanodiamonds concentrated in breccias around the pipe, or as high levels of carbon within the subsequent igneous rocks (e.g. carbonatites associated with Deccan [40] and Siberian [16] Traps).
8. The pipes should remain as a weak zone within the lithosphere and so may be expected to be re-used by both igneous intrusions (including kimberlites and alkali basalts), plus escaping carbon-rich gas (CO_2, CO).
9. The eruption of the pipe may be preceded by doming resulting from the impact of a plume at the base of the lithosphere.

The first five of these characteristics are very similar to those of impact craters, so the latter four (not explicable by bolide impacts) will be particularly diagnostic of gas explosion pipes. These include the presence of excess carbon, the spatial and temporal association of the shock features with CFB volcanism, the subsequent reactivation of the pipes for volcanism and gas escape from deep within the lithosphere, and regional doming prior to crater formation. However, the most recent Verneshot pipes are likely to be buried under thick sequences of their associated CFBs. For instance a Verneshot pipe associated with the K–T extinction would likely still be buried under many km of Deccan Trap basalts and only possibly recognizable from geophysical data: several subcircular Bouguer gravity anomalies have indeed been recognized within the Deccan region [76].

Verneshot(s) for the Tr–J mass extinction should be located within or near the CAMP province. Kimberlite indicators have been found in Venezuela [77], and there are reports of a large quasi-circular igneous structure associated with the initial CAMP rifting of West Africa [78]. However, none of these has yet been investigated for the presence of preserved shock signals.

Verneshot(s) for the P–Tr mass extinction should be located within or near the Siberian Traps, which have been partially eroded. Within an eroded part of this flood basalt province is the Great Tunguska Depression [79], a Permo–Triassic crater (about 8 km in diameter and containing both shocked quartz and Fe-rich microspherules [79]) that apparently formed during the eruption of the traps since it both apparently disrupts and is intruded/cross-cut/overlain by trap basalts. Intriguingly this Permo–Triassic crater is the exact site of the 1908 Tunguska event, in which ∼2000 km^2 of forest [80] was flattened by an explosion generally attributed to a bolide 'meteoroid explosion'.

10. Kimberlites – byproducts of 'micro'-Verneshots?

Kimberlites are ultramafic, volatile- and carbon-rich magmas formed under reducing conditions, which ascend through the lithosphere faster than any other preserved magma type. Furthermore, their association with cratons, with volatiles and with hotspot tracks [51] suggests that they may be the nearest analogue for the type of event we envisage. However, the mechanics of kimberlite emplacement is hotly debated, with evidence for both hot emplacement of magma and cold emplacement of fluidized rock fragments. We suggest that probably both occur and represent the late and early stages of a kimberlite eruption following a 'small' Verneshot-like gas explosion precursor from ∼60–80 km depths. The speed of kimberlite ascent lends support to this hypothesis.

The minimum rate of ascent of kimberlite magma can be estimated in various ways: from the size and density of xenoliths transported [81], from xenolith disequilibration, and from the presence of unstable high-pressure mineral phases such as coesite, assuming that the cooling time equals the ascent time [82]. These minimum rates of 3–20 m/s are usually taken as a good estimate of actual ascent rates due to our natural reluctance, on the basis of 'common sense', to contemplate higher ascent rates (e.g. [83]). However, they may considerably underestimate the actual ascent speeds of kimberlite magmas. Speed estimates based upon the flow transport of xenoliths typically assume that the magma density was equal to the current kimberlite density, but, as discussed below, a substantial vapor phase is likely to have been lost – in which case inferred ascent rates would be substantially higher. Other estimates of kimberlite ascent rates yield faster speeds. Xenolith heating ([84], discussed by Milashev [83]) suggests that the average ascent rate must be >500 m/s. If the ascent speed accelerates uniformly during kimberlite ascent, this latter estimate would imply a kimberlite 'muzzle velocity' >1000 m/s, faster than a bullet leaving a gun barrel, thus considered unrealistic by Milashev [83]. More recently, garnet dissolution systematics have been used to infer kimberlite source to surface transit times of seconds to minutes [85]. Most of these estimates could be too low, since they are inferred from the magmas that still remained within the pipe. Any preserved kimberlite material must have decelerated near the surface, or else it would have been expelled into the atmosphere. The rapid ascent of decimeter-size or greater peridotite xenoliths entrained in kimberlite eruptions is also a strong mechanical hint that a shallower lithospheric gas explosion provides the trigger for deeper kimberlite eruptions. Such xenolith entrainment must occur in kimberlite–magma-filled cracks that were at least as wide as the entrained xenoliths. However, at the ∼200 km depths and ∼1400°C temperatures [67] estimated for the most deeply entrained xenoliths, the inferred lithospheric viscosity would be low enough ($<10^{21}$ Pa s) to viscously relax within ∼1000–10 000 years to relieve any magma intrusion-related stress buildup, hence magma buildup in this region would be an unlikely candidate to initiate the rapid fracture process involved in kimberlite ascent. However, if the ambient stresses were *sud-*

denly changed at ~200 km depths as they would be in the wake of an explosive gas release precursor from ~60–80 km depths, then a rapid fracture process could be triggered under *P–T* conditions where ductile creep would otherwise be the dominant deformation mechanism.

It is also clear that kimberlite magmas once had a very large amount of associated carbon dioxide that has since been lost from the geologic record. When recorded, subsidence within kimberlite pipes implies that the near-surface kimberlite magma density may have been only half the present-day rock density [86] – i.e. half the magma's volume near the surface was filled by a now lost gas phase. This evidence suggests that observed kimberlites may have been gas-rich magmas that ascended following the fracture paths created by the escape of even more gas-rich precursor 'gas explosions'. Any such vapor-dominated 'magmas' would be extremely difficult to spot within the geologic record as they can only be seen by their indirect effects on preserved xenoliths and wallrock – and by deconstructing a very recent event or directly viewing the 'fireball' of an event like the 1908 Tunguska cryptoexplosion (a fireball was seen by several 1908 Tunguska eyewitnesses, which was the basis for it being classed as a meteor event, and such fireballs are now routinely searched for by atomic bomb test monitoring satellites).

11. Ecological effects of a Verneshot

The ecological effects of a Verneshot are those previously proposed for a CFB-induced mass extinction [2,6,14,87], with the only difference that a Verneshot event would be even more sudden. Multiple Verneshot events could also occur within a single phase of rifting. The massive amounts of carbon and sulfur vapor 'propellent' released during the Verneshot considered above would instantaneously poison the atmosphere and the ocean's thin surface photosynthetic layer (more than doubling its CO_2 content and increasing its sulfur content by 50–1000-fold), catastrophically adding to any already strong environmental stresses induced by any ongoing 'normal' flood basalt volcanism. The resulting stressed, low-productivity, and stratified/anoxic oceanic biosphere may be extremely poor at removing subsequent 'normal' flood basalt release of CO_2, leading to the formation of an extended low-productivity globally anoxic ocean characteristic of great extinctions. As previously proposed by CFB mass extinction proponents [2,6,14,87], we think the primary killing mechanisms are, first, a sharp global cold pulse associated with high levels of global SO_2-rich acid rain that was very effective at exterminating global (including oceanic) photosynthetic activity. This sharp cold pulse could also be associated with a sudden sea level drop that could both greatly reduce the area of shelf habitats and destabilize deposits of shelf methane clathrates [88], leading to the sudden release of the greenhouse gas methane. Atmospheric SO_2 would rapidly rain out and be mixed into the deeper ocean, after which the biosphere would experience the deleterious effects of much longer global heating (at least thousands of years long) driven by the 'greenhouse' effects of the Verneshot's slower-to-purge CO_2. Sudden warming of the oceans' surface layers would lead to their global stagnation and anoxia.

12. Was the Chicxulub crater caused by the impact of a Verneshot mass jet?

It seems unlikely that the Chicxulub crater itself was formed by the impact of a mass jet from a Deccan/Reunion Verneshot, more likely Chicxulub is just the 1 in 8 'bad luck' coincidence of a cratonic flood basalt and bolide impact that could happen by chance within the past 400 Myr. If indeed due to a Verneshot (intriguingly, the proposed low-azimuth southeast arrival direction of the Chicxulub impactor [89] is also consistent with the Verneshot hypothesis), its location 135° away from the Reunion plume at 65 Ma requires that a single Verneshot be at least as large as that previously discussed – i.e. the explosive gas release from a >40 km diameter sphere of 1% strain overpressured cratonic lithosphere – and that a very large fraction of the ejected mass travel as a nearly coherent jet. In the absence of quantitative modelling, we anticipate that it would be more likely for the ejected mass jet to break into multiple smaller pieces, so that if Chicxulub were caused by a Verneshot, other (so far unobserved) smaller craters should also have been created by the same Verneshot event. However, even if the Chicxulub crater was due to a coincidental bolide impact, this does not invalidate the Verneshot hypothesis. It is still needed to explain how even one of the Tr–J, P–Tr, and FF mass extinctions could *also* be a time where both 'impact signals' and CFB events are found – unless the many documented 'impact signals' at the times of all of these mass extinctions are simply spurious or misleading.

13. Unresolved problems of the Verneshot hypothesis

We are well aware that the Verneshot hypothesis is extreme, and that the mechanical arguments marshalled in this study only demonstrate that it appears to be *possible* that Verneshots have occurred in the past, with many problems remaining to be sorted out. For instance, is it possible, as 'classical' craton yield strength envelope arguments imply, for ~1 GPa stresses to build up within a few Myr at ~70 km depths within continental lithosphere, or will a more complete model of an elastic–plastic lithosphere fail (non-catastrophically) at much lower deviatoric stress? Under what conditions can bottom-up catastrophic failure occur, and are these conditions viable for Earth? Does the 2.7 GPa CO_2 exsolution threshold form a barrier to C-rich magma ascent (except during the post-gas-release kimberlite transient discussed in the text)? Will plume ascent stop at the base of cratonic lithosphere, or can plume asthenosphere somehow continue to diapirically rise? We will remain cautious about the Verneshot hypothesis until these problems are better resolved.

14. Summary

Since Alvarez et al.'s proposal in 1980 that the impact of a large extraterrestrial chondritic meteorite was the cause of the K–T mass extinction, postulated 'impact signals' have been searched for and reported at the times of the four largest mass extinctions within the past 380 Myr. During the past 20 years, greatly enhanced precision in geologic radiometric and paleomagnetic dating techniques has developed to the point where at least three and most likely all of the most recent four great mass extinctions can also be linked to times associated with continental rifting and the rapid emplacement of the large CFBs. For many impact proponents of mass extinctions, the recognition in the early 1990s that the Chicxulub structure was a strong candidate for the site of the postulated K–T impactor 'closed' this debate; many pro-impact articles are now written as if the Alvarez et al. hypothesis were proven 'fact' and the hypothesis that CFBs caused most, if not all of the great mass extinctions were negated by the 'impact signals' that have now been reported to be synchronous with the other great mass extinctions. However, simple statistical inferences argue that the apparent synchronicity of at least three of the last four great Phanerozoic mass extinctions with *both* large cratonic flood basalts and geologic 'impact signals' strongly implies that *either* there are causal links between these extremely rare geological events *or* the reported 'large impact signals' at all except one of these times are spurious, sampling artifacts, or just 'background impact signals'. (Geologic evidence for continental rifting-related kimberlite and carbonatite activity and the emplacement of millions of cubic kilometers of flood basalts at these times is too massive to easily dismiss as 'artifact'). While the K–T extinction – the only one for which an appropriately aged large impact crater has been reported – has a 1 in 8 chance of being due to the random coincidence of a synchronous cratonic flood basalt and large extraterrestrial bolide impact, the fact that three or four synchronous 'impact signal'/cratonic flood basalt/great extinction events are now proposed to have occurred within the past 400 Myr makes it extremely likely that many of these events are causally linked. K–T Deccan evidence implies that the K–T bolide impact did not create this flood basalt, as several flood basalt flows happened before the deposition of the iridium 'impact signal'. (Furthermore, even at the K–T, reported impact signals appear to occur at multiple levels both before and after the peak iridium boundary [90,91]. Only one of these layers can correspond to the Chicxulub crater, with the other layers appearing to require a different mechanism. While multiple Verneshot events could be linked to the same continental rifting/flood basalt episode, multiple '100 Myr recurrence' large impacts occurring within a 10 000–100 000 year time interval seem extremely improbable.) Thus one is left with the apparently inescapable conclusion that if the 'impact signals' found to be synchronous with the great mass extinctions and CFBs are indeed real, then they have been created as a byproduct of mantle plume–continental craton interactions during periods of rifting and CFB volcanism. Furthermore, one is also left with the apparently inescapable conclusion that terrestrial, not extraterrestrial processes were responsible for all but one, if not all of the great mass extinctions; a conclusion quite similar to that reached by Vincent Courtillot (seven flood basalts, one impact) in his study of the causes of the lesser mass extinction events during the past 200 Myr. In this study we chose to focus on only the largest mass extinction events. It should be noted that impacts have also been recently proposed to be the cause of lesser mass extinctions that are known to be linked to cratonic rifting/flood basalt activity; a particularly good example is the ∼57 Ma Paleocene/Eocene extinction which is well linked to Greenland/North Atlantic rifting, explosive alkalic Greenland volcanism, and the emplacement of flood basalts, yet for which the mass extinction has been recently proposed to be the byproduct of a large cometary impact [92]. Any additional such 'coincidences' will only strengthen the simple statistical argument that synchronicity between such rare events implies there must be causal links between these rare events. Note that we are not disputing that large impacts occur, and do themselves cause genuine impact signals (e.g. the large Manicougan impact at ∼210 Ma appears consistent with findings of shocked quartz and microspherules roughly ∼10 Myr before the Tr–J mass extinction event [21]), but instead are disputing their role in creating the 'impact signals' reported to be synchronous with mass extinctions and CFB magmatism unless there exist causal links between all.

While statistics provides a powerful tool to discern the existence of causal linkages, it is a much poorer tool for unraveling their mechanistic links. During this study, we unable to find loopholes in the current 'conventional wisdom' that normal basaltic volcanism could not have created the 'impact signals' reported at the times of great mass extinctions. This led us to examine the hypothesis apparently first proposed by Loper and McCartney [72,93] that mantle plume-induced lithospheric gas explosions may be the necessary terrestrial causal link between large cratonic rifting-related CFBs, impact signals, and mass extinctions. The initial analysis presented here suggests that such Verneshot events may be a viable mechanism to produce the necessary causal links, and that (smaller) craton lithospheric gas explosions from ∼60–80 km depths will also be possible to test as the potential trigger for 'normal' kimberlite-type eruptions.

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