Geological consequences of superplumes

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ABSTRACT

Superplumes are suggested to have caused the period of constant normal magnetic polarity in mid-Cretaceous time (124–83 Ma) and, possibly, the period of constant reversed polarity in Pennsylvanian-Permian time (323–248 Ma). These times coincide with increases in world temperature, deposition of black shales, oil generation, and eustatic sea level in the mid-Cretaceous, and increased coal generation and gas accumulation in the Pennsylvanian-Permian, accompanied by an intracratonic Pennsylvanian transgression of epicontinental seas. These geologic anomalies are associated with episodes of increased world-wide ocean-crust production and mantle outgassing, especially of carbon and nutrients. These superplumes originated just above the core-mantle boundary, significantly increased convection in the outer core, and stopped the magnetic field reversal process for 41 m.y. in the Cretaceous and 75 m.y. in Pennsylvanian-Permian time.

INTRODUCTION

During the mid-Cretaceous, starting in earliest Aptian time (124 Ma), there were eruptions from an extraordinary upwelling of heat and deep-mantle material in the form of one or several very large plumes. I refer to this as a “superplume episode” and suggest that this material came from just above the core-mantle boundary. The size of these plumes suggests both the “super” modifier and their depth of origin, because it is unlikely that they would have fit into the mantle above shallower thermal boundary layers (i.e., 670 km). These plumes initially erupted beneath the Cretaceous Pacific basin and created most of the oceanic plateaus in the present-day western Pacific. The eruptions from these mantle upwellings then spread to other oceans, and sea-floor-spraying rates increased during this period; the overall effect was a 50% to 100% increase in Earth’s ocean-crust production (Fig. 1) from 125 to 80 Ma (Larson, 1991).

The onset of this superplume eruption was abrupt; ocean-crust production doubled in about 5 m.y. This coincided with the onset of the long mid-Cretaceous interval of normal magnetic polarity (Fig. 1). I suggest that the removal of a large amount of heat and deep-mantle material to fuel the superplume episode stopped the reversal process of Earth’s external magnetic field. I assume here that magnetic reversals are intrinsic frequency oscillations of the geomagnetic dynamo. This dynamo acts as a large nonlinear oscillator, whose amplitude (i.e., its convective intensity) is inversely proportional to its frequency (R. L. Larson and P. Olson, unpublished). The removal of high-temperature material increased the temperature gradient just above the core-mantle boundary and allowed heat to be conducted more rapidly out of Earth’s core. This increased heat transfer forced the outer core to convect more rapidly to restore the larger loss of heat. This speeded up Earth’s geomagnetic dynamo and stopped magnetic field reversals by a process that is not well understood but is probably related to the increase in kinetic

Figure 1. Combined plot of magnetic reversal stratigraphy (Harland et al., 1989), world ocean-crust production (modified from Larson, 1991), high-latitude sea-surface paleotemperatures (Savin, 1977; Arthur et al., 1985), long-term eustatic sea level (Haq et al., 1988), times of black shale deposition (Jenkyns, 1980), and world oil resources (Irving et al., 1974; Tissot, 1979) plotted on geologic time-scale calibration of Harland et al. (1990).

energy of the convection system (Olson and Hagee, 1990). As the superplume episode dissipated, and the temperature gradients returned toward their initial conditions, the magnetic field began to reverse again at 83 Ma. Reversal frequency then increased almost monotonically to the present day.

The "pulse" in ocean-crust production, accompanied by at least a proportional increase in outgassing of mantle volatiles, had substantial geologic consequences. These include corresponding increases in world temperature, black shale deposition, oil generation, and eustatic sea level. I first summarize these geologic consequences for the mid-Cretaceous and then explore the possibility that other long periods of constant magnetic polarity can be used as markers of superplume episodes in pre-Cretaceous time.

MID-CRETACEOUS SUPERPLUME EPISODE

The ocean-crust production curve (Fig. 1) is a revised and expanded version of one I constructed (Larson, 1991) by calculating the volume of oceanic crust formed at normal spreading centers and within oceanic plateaus for the world's oceans. The oceanic plateau component has been expanded in Figure 1 to include seamount chains and continental flood basalts. In addition, the Ontong-Java Plateau has been re-dated from Albian-Aptian to early to mid-Aptian (J. A. Tarduno et al., unpublished). The most prominent feature of the ocean-crust production curve is the 50% to 100% increase in production from 125 to 80 Ma that resulted mainly from increases in spreading rates and oceanic plateau production, including the production of now-subducted "twin plateaus" (Livaccari et al., 1981) in the Pacific basin.

The paleotemperature curves are an attempt to represent the history of sea-surface temperature at high latitudes (~50°), although the two curves are the results of individual studies that, I hope, show the true long-term average variations. The Cenozoic curve is Savin's (1977) δ18O study of benthic foraminifera mainly from the North Pacific; the Cretaceous curve is Arthur et al.'s (1985) δ18O study of northwestern European belemnites and inoceramids. Bottom-water temperatures (recorded by benthic foraminifera) anywhere in the deep ocean should equal sea-surface temperatures at high latitudes (Emiliani, 1954), so the two studies should be compatible. Both the Cenozoic and Cretaceous curves have been corrected for the assumed δ18O concentration of oceans on an ice-free Earth.

It was originally thought that the Cretaceous paleotemperature anomaly, which coincides with the ocean-crust production anomaly, could be explained by a rearrangement of the continents. This is partly true, but computer modeling (e.g., Barron and Washington, 1982) has resulted in the conclusion that the magnitude of the temperature anomaly cannot be explained by continental rearrangement alone, and another effect, probably excess CO2 in the atmosphere, must be invoked. In the extreme, this might have required six to eight times the present-day partial pressure of CO2 (pCO2) to produce a super "greenhouse" effect and raise the mid-Cretaceous temperatures to the required level (Barron, 1983). As suggested by Arthur et al. (1985), part of the source of this extra CO2 was the extra ocean-crust production of the mid-Cretaceous that brought additional carbon into the system from the mantle. Arthur et al. (1991) and Caldeira and Rampino (1991) have shown that the mid-Cretaceous increase in ocean-crust production can explain the remaining paleotemperature anomaly with a combination of increased CO2 input at spreading centers and behind subduction zones. The latter effect is associated with increased island-arc volcanism in proportion to increased subduction rates. Such results, however, vary widely, owing to a number of uncertainties.

Prominent times of black shale deposition have been correlated world-wide in strata ranging in age from latest Barremian through Santonian (Schlanger and Jenkyns, 1976; Jenkyns, 1980). The onset of this period of black shale deposition is typified in Italy by the basal Aptian Selli level at the base of the Fucoid Marls that correlates with the onset of the pulse in ocean-crust production and the long Cretaceous normal magnetic polarity interval. These prominent black shale horizons have been interpreted as markers of oceanic anoxic events that resulted variously from large increases in organic productivity and poor basin ventilation (Schlanger and Jenkyns, 1976; Jenkyns, 1980). Like the paleotemperature and oil-generation anomalies, the black shales probably resulted from increased levels of nutrients and carbon supplied by the increase in ocean-crust production. This is especially likely for the Aptian and Cenomanian-Turonian oceanic anoxic events. Force (1984) also noted the coincidence between times of mid-Cretaceous black shale deposition, the long interval of normal magnetic polarity, and increased worldwide spreading rates, and he proposed linkages similar to the ones I discuss here.

The world oil resources histogram in Figure 1 is a slightly altered version of that of Tissot (1979) in accord with Irving et al. (1974), who stated that 60% of the world's known oil was generated in the Albian through Turonian stages (112 to 88 Ma). This is the peak shown in Figure 1 that correlates with the anomaly in ocean-crust production. There is also a broader peak in gas accumulation for the entire Cretaceous (Bois et al., 1980) that may have resulted from a similar mid-Cretaceous anomaly in gas generation.

Irving et al. (1974) suggested, on the basis of the then-speculative spreading-rate history of Larson and Pitman (1972), that the anomaly in oil generation resulted in part from the larger amount of ocean-crust production during that period. Oil (and probably gas) generation was favored by the pulse in several ways. First, it produced extra carbon as the basic raw material. In addition to mantle carbon, the pulse produced extra sulfur and phosphorus (and perhaps nitrogen) as nutrients for plankton that converted this raw material into organic matter. These plankton thrived in the warm mid-Cretaceous oceans produced by the super-greenhouse effect discussed above. The pulse also caused a mid-Cretaceous transgression and super highstand of world sea level. This vastly increased the marine continental shelf areas that became depositional sites for this organic matter.

The eustatic sea-level curve in Figure 1 is the "long-term" sea-level curve of Haq et al. (1985). The ~125 m rise in sea level from late Aptian through Turonian time also resulted from increased ocean-crust production. This raised sea level by the mechanism proposed by Hays and Pitman (1973) on the basis of changes in spreading rates alone, whereas the ocean-crust production histogram in Figure 1 also includes changes in ridge/crest lengths and production of oceanic plateaus. Note that the peak in eustatic sea level is near the end of the pulse in ocean-crust production (Gaffin, 1987), as predicted by the above mechanism. Some aspects of the sea-level curve, especially the Eocene sea-level rise, are not explained by the ocean-crust production curve. Eustatic sea level began to rise in the Jurassic (Vail et al., 1977), well before the pulse in ocean-crust production began in the Aptian. Thus, ocean-crust production alone cannot explain all variations in the sea-level system, or the paleotemperature, black shale, and oil-generation variations, because it represents only one source function for these systems. However, this source function is very important, and large pulses in ocean-crust production appear necessary to explain the largest anomalies in all four of the derivative systems.

PENNSYLVANIAN-PERMIAN SUPERPLUME?

It seems reasonable that the mid-Cretaceous superplume is only the most recent of a longer history of aperiodic releases of heat from the core-mantle boundary; therefore, it should be possible to recognize other superplume episodes by identifying other intervals of constant magnetic polarity, such as the Pennsylvanian and Permian periods, that are almost entirely reverse-ly magnetized. Irving and Pullaiah (1976) placed the base of this interval in the Namurian or between the Namurian and Westphalian series of Europe, nearly equivalent to the Pennsylvanian/Mississippian boundary in North America (Harland et al., 1990). The top of the interval
is at the lower/upper Tartarian boundary in the USSR (Irving and Pullaiaih, 1976), equivalent to the Longtanian stage of the Zechstein epoch near the top of the Permian in Europe (Harland et al., 1990). Little, if any, normally magnetized material is found within this 75 m.y. interval, whereas the Triassic through Lower Cretaceous (up to M0 in the early aptian) and the lower Carboniferous (Mississippian) are intervals of completely mixed polarity.

If this long constant-polarity interval resulted from superplume activity, then geologic anomalies similar to those of the mid-Cretaceous should be recognizable. No quantitative studies of paleotemperature have been done for this interval, and the geologic record contains contrasting evidence. Swampy, tropical, wet conditions were present in the Northern Hemisphere, whereas the Southern Hemisphere supercontinent of Gondwanaland was glaciated at high latitudes. This was part of a longer, semicontinuous glaciation that began in the Ordovician and continued sporadically until mid-Permian time. This Paleozoic glacial history resulted from the drift of Gondwanaland across the South Pole (Crowell, 1978). I speculate that even superplume activity in Pennsylvania-Permian time could not prevent glaciation of such a large landmass at polar southern latitudes.

The Carboniferous name (Pennsylvanian and Mississippian in North American) originated in England to describe the time of formation of the English Coal Measures. These are equivalent to the Westphalian coal deposits of northern Europe (Gignoux, 1955), and to the Pennsylvania coal deposits of Appalachia in the United States. These classic formations actually compose only about one-half of the coal generated (Fig. 2) during the long interval of reversed magnetic polarity (Bestougeff, 1980). About 45% of the giant coal deposits of the USSR and China are Permian in age; these make up about 95% of Earth's Permian coal (Bestougeff, 1980).

Thus, a large anomaly in coal generation corresponds to the Pennsylvanian-Permian reversed interval, much as the oil-generation anomaly corresponds to the mid-Cretaceous normal interval (Fig. 2). About 50% of the world's coal reserves are found in the Pennsylvania-Permian reversed interval, a figure that is more certain than any similar statistics for oil and gas, because coal is not subject to postdepositional migration. This anomaly in coal generation is especially important in terms of the world's total fossil-fuel resources. Rough energy equivalencies can be used to calculate that coal contains about nine times more fossil fuel energy than oil and gas combined (histograms, Fig. 2).

Figure 2 also shows that the Permian was a time of great gas accumulation and that the Paleozoic rocks, in general, contain more gas than oil. Bois et al. (1980) speculated that the Paleozoic gas may have originated as Paleozoic oil and that hydrocarbon maturation has simply gone further toward completion, having been given more time to convert oil to gas with minor contributions from coal. Figure 2 is a plot of reservoir age for gas, as opposed to source-rock age for oil, so the present gas distribution also may be the result of a combination of source-rock age and subsequent migration.

The possibility of a Pennsylvania-Permian sea-level highstand is shown in Figure 3. This is a time-stratigraphic diagram of the stable North American craton (Sloss, 1963) for the Phanerozoic correlated with a similar diagram for the Russian platform (Sloss, 1972). They represent integrated histories of deposition and nondeposition on these cratons. The North American diagram is along a cross section from approximate Nevada to Pennsylvania, and the Russian platform diagram shows areas of preservation of stratigraphic units over the entire Russian platform. The Phanerozoic cratonic record for North America is made up of six unconformity-bounded assemblages of strata, termed "sequences" by Sloss (1963) and given Native American names in Figure 3. The Pennsylvania-Permian reversed magnetic interval corresponds to the Absaroka sequence, the transgression of which began at the same time as the

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**Figure 2.** World fossil-fuel resources compared to long periods of constant magnetic polarity in mid-Cretaceous and Pennsylvanian-Permian time. Coal plot is age of all world coal resources above maximum burial limit of 2000 m for coal and 1500 m for lignite (Bestougeff, 1980). Gas plot is reservoir age of world gas reserves (Bois et al., 1980). Oil plot is estimated to be 85% of world's oil resources plotted as source-rock age (Tissot, 1979).

**Figure 3.** Phanerozoic sequence stratigraphy of North American craton (Sloss, 1963) and Russian platform (Sloss, 1972) compared to long periods of constant magnetic polarity in mid-Cretaceous and Pennsylvanian-Permian time, as well as earlier potential periods of constant magnetic polarity. Nondeposition and deposition representations are for both time and space. Russian platform sequence stratigraphy is plot of areas of preserved sedimentary units as percentage of maximum area covered by sediments in Middle Devonian time.
constant-polarity interval. Sloss (1972) showed that the Absaroka and subsequent sequences correlate with times of deposition and nondeposition on the Russian platform (Fig. 3), establishing the world-wide nature of this sequence stratigraphy. Wise (1974) conducted a related analysis of North American geology that verified the Carboniferous to Holocene sequence stratigraphy of Sloss (1963).

Like the mid-Cretaceous transgression, the Absaroka transgression is probably superimposed on a longer term fluctuation of eustatic sea level not explained by pulses in ocean-crust production. The long-term trend in the late Paleozoic was one of falling eustatic sea level (Vail et al., 1977), in contrast to the Jurassic-Cretaceous rise. These opposing long-term trends may have contributed significantly to oil being formed in the Cretaceous and coal being formed in the Pennsylvania-Permian (Tissot, 1979). Thus, in the Cretaceous, the completely flooded continental platforms promoted marine deposition of organic carbon as phytoplankton that was eventually converted to oil. However, during Pennsylvania-Permian time, the long-term fall in sea level was in opposition to the Absaroka transgression. The net result was swampy continental areas where paralic, non-marine deposition of peat near flat sea coasts was eventually converted to coal.

It thus appears that the Pennsylvania-Permian interval of reversed magnetic polarity is characterized—qualitatively by sequence stratigraphy and climate, and quantitatively by coal and gas generation—by the same anomalies that were present during the mid-Cretaceous. This supports the hypothesis that this interval also was a time of superplume activity.

EARLY PALEOZOIC SUPERPLUMES?

A statistical compilation of polarity data allows the possibilities of relatively long reversed-polarity intervals in the Late Devonian, Middle Ordovician, and Late Cambrian (Irving and Pallaiia, 1976). These may correspond to the Kas-kaskaia, Tippecanoe, and Sauk stratigraphic sequences of Sloss (1963). However, pre-Carboniferous magnetic stratigraphy is sparse and fraught with potential errors. In addition, the North American sequence-stratigraphic analyses of Sloss (1963) and Wise (1974) correlate well back through, but not prior to, the Devonian. Potential times of constant polarity must be targeted and analyzed in continuous sections. Figure 2 shows that the majority of Earth's oil, gas, and coal resources correlate with the last two constant-polarity intervals, so there is little potential to correlate earlier pulses with peaks in fossil-fuel generation.

It seems likely that superplumes were present, and probably more abundant and intense, when Earth was significantly younger. Such a recurring phenomenon was termed "pulsation tectonics" by Sheridan (1983). A higher concentration of radioactive isotopes and a larger outer core would have contributed to the formation of more and larger superplumes. In contrast, the present-day outer core size and Earth's surface heat flow suggest that this planet still has a long future of tectonic activity. Figures 1 and 3 show that this is a time of frequent magnetic reversals and an extremely low eustatic sea level. Given that the last interval of constant magnetic polarity ended 83 m.y. ago, the next superplume episode might occur in the near geological future.

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