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Focus paper

Origins of the supercontinent cycle

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ABSTRACT

The supercontinent cycle, by which Earth history is seen as having been punctuated by the episodic assembly and breakup of supercontinents, has influenced the rock record more than any other geologic phenomena, and its recognition is arguably the most important advance in Earth Science since plate tectonics. It documents fundamental aspects of the planet's interior dynamics and has charted the course of Earth's tectonic, climatic and biogeochemical evolution for billions of years. But while the widespread realization of the importance of supercontinents in Earth history is a relatively recent development, the supercontinent cycle was first proposed thirty years ago and episodicity in tectonic processes was recognized long before plate tectonics provided a potential explanation for its occurrence. With interest in the supercontinent cycle gaining momentum and the literature expanding rapidly, it is instructive to recall the historical context from which the concept developed. Here we examine the supercontinent cycle from this perspective by tracing its development from the early recognition of long-term episodicity in tectonic processes, through the identification of tectonic cycles following the advent of plate tectonics, to the first realization that these phenomena were the manifestation of episodic supercontinent assembly and breakup.

1. Introduction

Although the existence of the supercontinent Pangea (Fig. 1) was first proposed a century ago (Wegener, 1912), the proposition that other supercontinents existed prior to Pangea (e.g., Valentine and Moores, 1970; Piper, 1974, 1975; Piper et al., 1976) has only become widely accepted over the past two decades (e.g., Hoffman, 1989, 1991; Dalziel, 1991, 1992, 1997; Williams et al., 1991; Stump, 1992; Powell et al., 1993; Powell, 1995). This has led, in recent years, to a rapidly widening recognition that much of Earth history has been punctuated by the episodic amalgamation and breakup of supercontinents (e.g., Zhao et al., 2002, 2004; Murphy and Nance, 2003, 2013; Rogers and Santosh, 2003, 2004; Santosh and Zhao, 2009; Condie, 2011; Yoshida and Santosh, 2011; Huston et al., 2012; Mitchell et al., 2012) with profound consequences to the Earth's geologic, climatic and biological records (e.g., Hoffman et al., 1998; Hoffman and Schrag, 2002; Lindsay and Brasier, 2002; Dewey, 2007; Condie et al., 2009, 2011; Goldfarb et al., 2010; Hawkesworth et al., 2010; Santosh, 2010a,b; Bradley, 2011; Hannisdal and Peters, 2011; Strand, 2012; Young, 2012a,b). This history of episodic supercontinent assembly and breakup, which constitutes the supercontinent cycle, has influenced the rock record more profoundly than any other geologic phenomenon (e.g., Condie, 2011). Its existence points to fundamental aspects of the Earth's interior dynamics (e.g., Condie, 2003; Evans, 2003; Zhong et al., 2007; Santosh et al., 2009; Zhang et al., 2009) and its recent recognition is arguably the most important advance in Earth Science since the advent of plate tectonics.

Yet the idea of a supercontinent cycle was first advanced thirty years ago, and the notion of episodicity in tectonic processes predates plate tectonics by decades. So while the widespread recognition of the significance of supercontinents in Earth history is a relatively recent phenomenon, a long history has led to this fundamental realization. In this paper, we provide an historical perspective to this important and rapidly growing development in Earth Science by tracing the history of the supercontinent cycle

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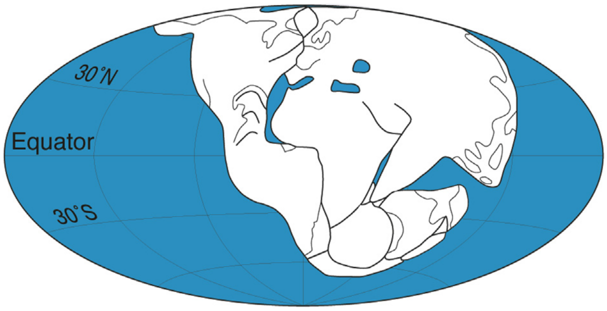

Figure 1. The late Paleozoic supercontinent Pangea as envisioned by Wegener (1922) (from Domeier et al., 2012).

from its beginnings in the many pre-plate tectonic ideas on episodicity in geologic processes to the first recognition that this episodicity was a manifestation of the assembly and breakup of supercontinents.

2. Episodicity prior to plate tectonics

Recognition of episodicity in tectonic processes occurred long before plate tectonics provided the framework to account for its occurrence. Of the many early advocates for such tectonic episodicity, one of the first, and certainly the most prescient, was the Dutch geologist Johannes Umbgrove who was arguing for periodicity in terrestrial processes more than two decades before the seminal papers on sea-floor spreading by Dietz (1961), Hess (1962) and Vine and Matthews (1963) ushered in the theory of plate tectonics (Umbgrove, 1940). In his remarkably modern book, "The Pulse of the Earth" Umbgrove (1947) complied a wealth of data in support of a ~250 m.y. periodicity in Phanerozoic sea level, orogeny, basin formation, climate and magmatic activity (Fig. 2). Consistent with the assembly and breakup of a supercontinent, he further argued that there were stages to this periodicity in which global sea level regression accompanied by increased crustal compression, continental erosion and climatic deterioration, was followed by orogeny, granitoid magmatism and glaciation, and finally, by mafic magmatism, global transgression and climatic amelioration.

Over the following two decades, tectonic episodicity was advocated by some of the foremost geologists of the day and was recognized in a wide variety of phenomena. For example, orogenic episodicity was recognized in Precambrian fold belts by Holmes (1951), Wilson et al. (1960) and Burwash (1969), and periodicity in the formation of continental crust was proposed by Holmes (1954) and further developed by Gastil (1960). Distinct peaks were also noticed in early radiometric age compilations (Voitkevich, 1958; Vinogradov and Tugarinov, 1962; Runcorn, 1962, 1965; Dearnly, 1966), and the notion of tectonic episodicity was inherent in the cratonic sequences recognized by Sloss (1963), whereby the late Precambrian to recent sedimentary record of the continental interior of North America was shown to comprise six major rock-stratigraphic units separated by regional unconformities.

But of all the early advocates for tectonic episodicity, it was Sutton (1963) who came closest to formulating a supercontinent cycle. His "chelogenic cycles", or global-scale shield-forming events, called for the episodic clustering of continents. However, rather than producing a supercontinent, the chelogenic cycle resulted in the periodic recurrence of two antipodal continental clusters, the assembly and breakup of which were held to be responsible for the record of orogenic episodicity. The cycle was thought to occur because small subcontinental convection cells first resulted in continental clustering and orogeny in continental interiors, but then coalesced into larger cells that fostered continental breakup, orogenic quiescence, and the later regrouping of the rifted continental blocks into two new antipodal clusters. According to Sutton, the cycle had a periodicity of 750–1250 m.y. and had been repeated at least four times during Earth history.

3. Plate tectonics and tectonic cycles

Following the introduction of plate tectonics, the concept of tectonic episodicity was specifically advocated by Wilson (1966) in what are now known as the "Wilson cycles" of ocean opening and closure. The concept was also employed in regard to evolutionary biogenesis by Valentine and Moores (1970) and Hallam (1974) who showed how Phanerozoic marine diversity and sea level fluctuations could be related to patterns of continental fragmentation and reassembly with close correspondence to the observed geological record.

Episodicity was also observed in the pattern of Phanerozoic sedimentary cycling by Mackenzie and Pigott (1981), who argued that the cyclic nature of Phanerozoic sedimentary rock distribution and material transfer among sedimentary reservoirs were controlled by tectonic factors, and that a strong tectonically controlled correlation existed between the long-term cyclicity in the Phanerozoic global sea level curve and the distribution of carbon and sulfur among the major exogenic reservoirs.

Tectonic episodicity was also identified in the distribution of ore-forming processes through time by Meyer (1981), who linked such episodicity to characteristic peaks in the abundance of specific styles of metallic mineralization. Tectonic cycling was also recognized in the Phanerozoic record of strontium isotopes by Burke et al. (1982), whose curve for the variation of seawater $^{87}Sr/^{86}Sr$ with time was shown to be strongly influenced by the history of both plate interactions and sea-floor spreading. The episodicity in orogeny observed by earlier workers also found support in increasingly precise radiometric ages, most clearly illustrated in the compilation (Fig. 3) of Condie (1982).

The case for episodicity in geologic phenomena was brought to a culmination by Fischer (1981, 1984), who revived Umbgove's (1947) visionary model in a plate tectonic context. Using a geologic timescale 100 m.y. longer than that employed by Umbgrove, Fischer's compilation of the available data made a compelling case for two ~300 m.y. supercycles in the Phanerozoic record of climate, sea level and granitoid magmatism (Fig. 4). He interpreted the "greenhouse" to "ice house" climatic supercycles as reflecting variations in the levels of atmospheric CO_2 caused by changes in the pattern of mantle convection recorded in concordant variations in global sea level and the proxy record of felsic volcanism in the emplacement of granitoids. Fischer further linked oceanic aeration to periods of global cooling and showed that several major biotic crises coincided with the boundaries between climatic states.

4. Recognition of the supercontinent cycle

Despite compelling evidence for episodicity in geologic processes, it would be seventy years after Wegener's (1912) vision of moving continents, and more than forty years following Umbgrove's (1940, 1947) insightful claim for periodicity in terrestrial processes, that a case would be made that this long-recognized history of tectonic episodicity was the manifestation of a long-term cycle of supercontinent assembly and breakup. The case for such a supercontinent cycle was first put forward by Worsley et al. (1982, 1984).