

# Genesis of the Supercontinent Cycle

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## 1. Title slide

Good afternoon everyone. As you know, over the past couple of decades data from a wide variety of sources have led to the general realization that Wegener's Pangea, seen here, rather than being the Earth's only supercontinent, was simply the most recent in a series of supercontinents that have punctuated Earth history for billions of years. This history of episodic supercontinent assembly and breakup, which has come to be known as the supercontinent cycle, is now recognized as having profoundly influenced the course of the Earth's geologic, climatic, and biological evolution. Its existence documents a fundamental aspect of the Earth's interior dynamics and its recognition is arguably the most important development in geology since the advent of plate tectonics.

## 2. Google Scholar

Indeed, interest in the supercontinent cycle has recently achieved bandwagon status, manifest, as this chart illustrates, in a near-exponential increase in the number of papers on the subject. Obtained from a 10-minute search of that most flawless of scientific databases, Google Scholar, using the keyword "supercontinent cycle", it simply tracks the number of hits for any given year for the past 30 years, and shows rather clearly the dramatic way the idea has taken off since the millennium. But I would like to start this session by taking you back to some of the ideas that led to the supercontinent cycle and, in particular, to a paper by Tom Worsley, Judith Moody and myself, published exactly 30 years ago, in which the case for such a cycle was first presented.

## 3. Runcorn (1962)

So the supercontinent cycle is not a new idea. Indeed, while the widespread recognition of the importance of supercontinents in Earth history is quite recent, the notion of episodicity in tectonic processes predates plate tectonics, as illustrated in this figure from a recent paper by Joe Meert that shows the 52-year old orogenic peaks of Keith Runcorn matched against the contemporary detrital zircon record.

## 4. Umbgrove (1947)

One of the most prescient of the early advocates for tectonic episodicity was the Dutch geologist Johannes Umbgrove (1947) who called for the existence of two circa 250 m.y. "pulses" in Phanerozoic sea level, orogeny, climate and magmatic activity, as early as 1940.

## 5. Tectonic episodicity

In the 1950s and 60s, tectonic episodicity was recognized in Precambrian fold belts, in continental crust formation, and in early radiometric age compilations, and is inherent in the cratonic sequences of Sloss.

## 6. Sutton (1963)

But of all the early advocates for tectonic episodicity, it was John Sutton who came closest to formulating a supercontinent cycle. His "chelonogenic cycles", or global-scale shield-forming events, called for the episodic clustering of continents. But rather than producing a supercontinent, the cycle resulted in the periodic recurrence of two antipodal continental clusters, the assembly and disruption of which were thought 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 disrupted continental masses 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.

### *7. Tectonic Episodicity and Plate Tectonics*

Following the introduction of plate tectonics, the concept of tectonic cycles was specifically advocated by Tuzo Wilson in the Wilson cycles of ocean opening and closure, and by Valentine and Moores, and Hallam with regard to evolutionary biogenesis. Episodicity was also observed in the pattern of Phanerozoic sedimentary cycling and the distribution of ore-forming processes through time, and orogenic episodicity was supported by increasingly precise radiometric ages,

### *8. Fischer*

This work culminated with Alfred Fischer, who revived Umbgove's model in a plate tectonic context by calling for two circa 300 m.y. supercycles in the Phanerozoic record of climate, sea level and granitoid magmatism.

### *9. Worsely et al. (1984)*

However, that this long-recognized history of episodicity in tectonic processes was the manifestation of a long-term cycle of supercontinent assembly and breakup was first proposed by Worsley et al. at the San Francisco AGU in 1982. Since the assembly of supercontinents requires continents to collide, whereas supercontinent breakup requires them to rift, we argued that the existence of a supercontinent cycle would be manifest in the geologic record by episodic peaks in collisional orogenesis and rift-related mafic dike swarms.

Using the available age data (largely Rb/Sr and K/Ar) we suggested that such peaks could be recognized and that global episodes of orogenic activity lagged slightly by mafic dike swarms had punctuated Earth history at relatively regular intervals of about 500 m.y. for at least the past 2.5 billion years.

Based on these data, we predicted the existence of five, pre-Pangean supercontinents at circa 0.6, 1.1, 1.6, 2 and 2.6 Ga. In addition, the apparent correspondence of supercontinents with ice ages, and their break-up with major evolutionary events, suggested a controlling connection between supercontinents, climate and life, which we suggested was a consequence of the profound effect of the supercontinent cycle on sea level.

### *10. Supercontinent Cycle and Sea Level*

We viewed the effect of the supercontinent cycle on sea level as a two-component system involving both continental elevation and ocean basin volume. Drawing on Anderson's (1982) assertion that continent lithosphere should act as a thermal insulator to mantle heat flow, we argued that supercontinents would be epeirogenically uplifted as heat accumulated beneath them, and so would correspond to periods of low sea levels. But on break-up, the dispersing continental fragments would cool and subside as they separated so that sea level would rise.

However, the break up of supercontinents also creates new oceans at the expense of older ones. These new oceans are initially flooded by young, hot, buoyant crust so that ocean basin volume is reduced as a result of their formation and sea level rises. But as these oceans get older and colder, they become deeper, causing sea level to fall until the oceans start to close.

## 11. *Model Curve*

To test the model, we attempted to quantify both of these effects on sea level. We modeled the amount of epeirogenic uplift by assuming a minimum figure of 400 m based on available data for the present day thermal elevation of near-stationary Africa.

And to quantify the cycle's effect on ocean basin volume, we applied Parsons and Sclater's (1971) age-versus-depth relation for oceanic lithosphere to Berger and Winterer's (1974) calculations for the average age of the world's ocean floor as a function of the breakup of Pangea.

Their model curve simply combined these two components.

## 12. *Model Phanerozoic sea level*

Calibrated to the Phanerozoic using the known amalgamation and breakup ages for Pangea, we were able to show that their model sea level curve closely matched the first-order sea level curve of Vail et al. (1977).

## 13. *Model and Vail Phanerozoic sea level*

The supercontinent cycle so defined had a duration of about 440 m.y., and predicted amalgamation of the next supercontinent in about 150 m.y.

## 14. *Proposed mechanism*

With regard to a driving force for the supercontinent cycle, we suggested that one might be provided by the counteracting influences of the insulating effect of supercontinents on mantle heat flow, and the cooling effect of age on the buoyancy of oceanic lithosphere. We argued that the former might be expected to lead to the eventual breakup of supercontinents, whereas the latter might be expected to result in their assembly since it ensured that the new oceans created by supercontinent breakup would eventually close.

This mechanism was based on the history of Pangea and has come to be known as introversion, which at the time, we preferred over extroversion since closure of the exterior ocean, in this case Panthalassa, required the interior oceans to age well beyond the maximum age of oceanic crust in today's world of 180 m.y.

## 15. *Biogeochemical cycles*

Subsequently, we explored the supercontinent cycle's potential influence on the Earth's tectonic, biogeochemical and paleoceanographic record. Subdividing the cycle into three main phases – supercontinentality, breakup and dispersal, and supercontinent assembly – we identified a variety of trends in tectonic activity, platform sedimentation, climate, life, and the stable isotope record that would be expected to accompany each phase.

The figure is too busy to explore in detail but identifies strong signals as boxes and weak ones as lines, and includes both signals as they were then known as solid symbols and predicts other where they were not as open boxes and dashed lines.

## 16. *Supercontinentality*

Among these trends, we argued that, during supercontinentality: (1) tectonic activity would be dominated by epeirogenic uplift as trapped mantle heat accumulates beneath the largely stationary supercontinent,

(2) opening of back-arc basins and terrane formation would be expected at the margins of exterior (Panthalassic) ocean, now at its largest size, (3) with sea level at its lowest elevation, terrestrial deposition would be enhanced, (4) sequestering of isotopically light carbon in non-marine and organic-rich sediments, and heavy sulfur in evaporites, would be expected to produce a record of low  $\delta^{13}\text{C}$  and  $\delta^{34}\text{S}$  in the reciprocal marine platform reservoir, (5) massive extinctions would be expected to accompany the loss of shallow marine habitat, and (6) cold climates (potentially leading to continental glaciation) might be expected to develop as carbon dioxide is removed from the atmosphere by the weathering of large areas of subaerially exposed continental crust.

#### *17. Supercontinent breakup and dispersal*

During supercontinent breakup and dispersal, we argued that: (1) younging of the world ocean floor through rifting and the opening of new (interior) ocean basins, coupled with subsidence of dispersing continental fragments, should raise sea level to its maximum elevation, (2) collisional orogeny should be minimal, although terrane accretion might be expected on the margins of the exterior ocean, (3) rapid biotic diversification and enhanced preservation of platform sediments with increasing high values of  $\delta^{13}\text{C}$  and  $\delta^{34}\text{S}$  should accompany continental drowning, and (4) warm, equable climates should develop as continental flooding allows atmospheric  $\text{CO}_2$  levels to build.

#### *18. Supercontinent assembly*

Finally, during supercontinent assembly, we argued that: (1) accretionary and collision orogenesis should increase to a maximum, (2) global sea level should first rise and then fall as subduction consumes first the old and then the young floor of the interior oceans (opening and then closing back-basins along their margins), (3) active margin sedimentation should increase, and (4) atmospheric  $\text{CO}_2$  levels should fall, causing global climates to deteriorate.

#### *19. Worsley et al. (1984)*

Even in 1984, we were by no means the first to suggest that supercontinents had formed prior to Pangea. Indeed, the existence of a Neoproterozoic supercontinent had been implied by Valentine and Moores as early as 1970 and, in the mid-70s, Piper was arguing for the existence of a single supercontinent for much of the Proterozoic, although the evidence was disputed. The early version of the supercontinent cycle was also necessarily simplistic, particularly with regard to the mechanism, and it is apparent from contemporary U-Pb data that the cycle is not as regular as the Rb/Sr data suggested.

#### *20. Worsley et al. (1984) with supercontinents*

Nevertheless, although the message fell on largely deaf ears in the 1980's, the proposition that the assembly and breakup of supercontinents had occurred episodically throughout much of geologic time with profound consequences to the course of Earth history has now been substantiated. Of the five supercontinents we predicted, four are now recognized as corresponding to the amalgamation of Pannotia (Gondwana), Rodinia, Columbia (or Nuna) and Kenorland, and while data in support of the proposed effects of the supercontinent cycle on sea level, climate and biogeochemical trends were limited at the time, many of the effects we predicted have since been borne out by more sophisticated analyses of the contemporary database.

#### *21. Condie (2011)*

Indeed, nowhere is this vindication better expressed than in this statement from Kent Condie – a most appropriate message, I think you will agree, with which to continue this session.

Thank you very much.