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GR focus review

Precambrian geodynamics: Concepts and models

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ABSTRACT

In contrast to modern-day plate tectonics, studying Precambrian geodynamics presents a unique challenge as currently there is no agreement upon paradigm concerning the global geodynamics and lithosphere tectonics for the early Earth. This review is focused on discussing results of recent modeling studies in the context of existing concepts and constraints for Precambrian geodynamics with an emphasis placed on three critical aspects: (1) subduction and plate tectonics, (2) collision and orogeny, and (3) craton formation and stability. The three key features of Precambrian Earth evolution are outlined based on combining available observations and numerical and analogue models. These are summarized below:

- Archean geodynamics was dominated by plume tectonics and the development of hot accretionary orogens with low topography, three-dimensional deformation and pronounced gravitational tectonics. Mantle downwellings and lithospheric delamination (dripping-off) processes are likely to have played a key role in assembling and stabilizing the hot orogens on a timescale up to hundreds of millions of years. Both oceanic-like and continental-like lithospheres were rheologically weak due to the high Moho temperature (>800 °C) and melt percolation from hot partially molten sublithospheric mantle.
- Wide spread development of modern-style subduction on Earth started during Mesoarchean–Neoarchean at 3.2–2.5 Ga. This is marked by the appearance of paired metamorphic complexes and oldest eclogite ages in subcontinental lithospheric mantle. Numerical models suggest that the transition occurred at mantle temperatures 175–250 °C higher than present day values, and was triggered by stabilization of rheologically strong plates of both continental and oceanic type. Due to the hot mantle temperature, slab break-off was more frequent in the Precambrian time causing more episodic subduction compared to present day.
- Wide spread development of modern-style (cold) collision on Earth started during Neoproterozoic at 600–800 Ma and is thus decoupled from the onset of modern-style subduction. Cold collision created favorable conditions for the generation of ultrahigh-pressure (UHP) metamorphic complexes which become widespread in Phanerozoic orogens. Numerical models suggest that the transition occurred at mantle temperatures 80–150 °C higher than present day values and was associated with stabilization of the continental subduction. Frequent shallow slab break-off limited occurrence of UHP rocks in the Precambrian time.

Further progress in understanding Precambrian geodynamics requires cross-disciplinary efforts with a special emphasis placed upon quantitative testing of existing geodynamic concepts and extrapolating back in geological time, using both global and regional scale thermomechanical numerical models, which have been validated for present day Earth conditions.

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1. Introduction

Precambrian geodynamics stands as an intriguing and controversial issue and currently represents a fundamental barrier in furthering our understanding of how the Earth evolved through time. The lack of consensus regarding Precambrian geodynamics and the continuing controversy primarily can be associated to the scarcity of natural data related to this tectonic regime. Geodynamics aims at understanding the evolution of the Earth's interior and surface over time. A time–depth diagram (see Fig. 1) covering the entire Earth's history and interior can schematically represent this evolution. For a systematic characterization of geodynamic relationships, the entire diagram should be "covered" by data points characterizing the physical–chemical state of the Earth at different depths (ranging from 0 to 6000 km), for different moments in geological time (ranging from 0 to around 4.5 billion years ago). However, the unfortunate fact for geodynamics is that observations for such a systematic coverage are only available along two axes: geophysical data provides the present-day Earth structure and the geological record preserved in rocks formed close (typically within few tens of kilometers) to the Earth's surface. The rest of the diagram is fundamentally devoid of observational data (see the time span of the Precambrian geodynamics in Fig. 1). Not surprisingly, therefore, the topic of Precambrian geodynamics remains controversial. One should also note that four critical questions strongly linked to the evolution of the Precambrian Earth appear among the top 10 questions defining 21st century Earth sciences (DePaolo et al., 2008):

- "What happened during Earth's "dark age" (the first 500 million years)? Scientists believe that another planet collided with Earth during the late stages of its formation, creating debris that became the moon and causing Earth to melt down to its core. This period is critical to understanding planetary evolution, especially how the Earth developed its atmosphere and oceans, however scientists have little information because few rocks from this age are preserved."
- "How did life begin? The origin of life is one of the most intriguing, difficult, and enduring questions in science. The only remaining evidence of where, when, and in what form life first appeared springs from geological investigations of rocks and minerals."
- "How does the Earth's interior work, and how does it affect the surface? Scientists know that the mantle and core are in constant convective motion. Core convection produces the Earth's magnetic field, which may influence surface conditions, and mantle convection causes volcanism, seafloor generation, and mountain building. However, scientists can neither precisely describe these motions, nor calculate how they were different in the past, hindering scientific understanding of the past and prediction of Earth's future surface environment."
- "Why does Earth have plate tectonics and continents? Although plate tectonic theory is well established, scientists wonder why Earth has plate tectonics and how closely it is related to other aspects of Earth, such as the abundance of water and the existence of the continents, oceans, and life. Moreover, scientists still do not know how and when continents first formed, how they remained preserved for billions of years, or how they are likely to evolve in the future."

In this review, I will concentrate on the last two questions where significant progress has occurred in the recent decade. This progress has been fueled by both the dramatic increase in the quality and the quantity of geological, geochemical, petrological and geochronological data for Precambrian rock complexes and the ongoing development of analogue and numerical models for the early Earth dynamics (e.g., Benn et al., 2006; van Kranendonk, 2011; van Hunen and Moyen, 2012 and references therein). Taking into account the

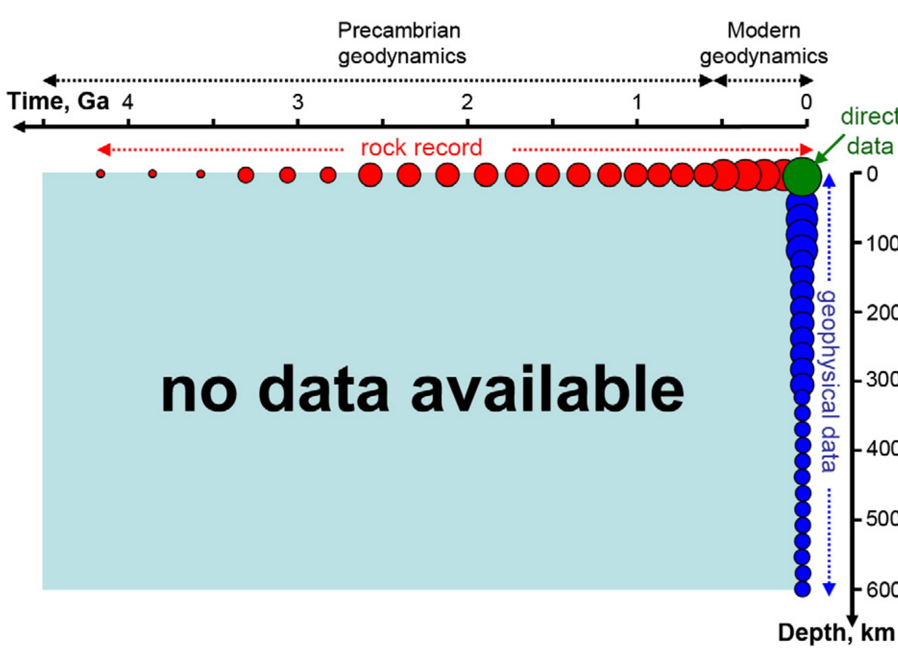

Fig. 1. Time–depth diagram presenting availability of data for constraining geodynamic relationship for the Earth. Size of data points reflect abundance of available data. This is obviously a simplified view since for a spherical Earth such a diagram should be four-dimensional.