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Invited review

# Quantifying the evolution of the continental and oceanic crust

Stephen J. Puetz [a,*], Kent C. Condie [b], Sergei Pisarevsky [c], Anne Davaille [d], Carl J. Schwarz [e], Carlos E. Ganade [f]

[a] Progressive Science Institute, Honolulu, HI 96815, USA
[b] Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801, USA
[c] Earth Dynamics Research Group, ARC Centre of Excellence for Core to Crust Fluid Systems (CCFS), The Institute for Geoscience Research (TIGeR), Department of Applied Geology, Curtin University, GPO Box U1987, WA 6845, Australia
[d] Laboratoire FAST, CNRS/Universite Paris-Sud, Orsay 91405, France
[e] Department of Statistics and Actuarial Science, Simon Fraser University, British Columbia, Canada
[f] Geological Survey of Brazil, Rio de Janeiro, Brazil

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A better understanding of how zircon ages vary with time requires sophisticated statistical analysis of U/Pb isotopic ages from both bedrock and detrital zircon databases. Researchers mostly interpret variation in the preserved zircon age distribution as representing periods of enhanced production of continental crust coupled with recycling of older crust. Yet, estimates from several global databases show considerable variation, which suggests the need for standardizing sampling and statistical analysis methods. Grid-area sampling and modern sediment sampling are proposed for future database development with the goal of producing statistically consistent estimates of zircon age distributions at four scales – global, continental, regional, and intra-basin. Application of these sampling methods and detailed statistical analysis (time-series, spectral, correlation, and polynomial and exponential fitting) indicates possible relationships among continental and oceanic crust formation, large igneous province (LIP) events, the supercontinent cycle, geomagnetic polarity and geomagnetic intensity. Results show a strong correlation of zircon and LIP age spectra with major peaks at 2700, 2500–2400, 2200, 1900–1850, 1650–1600, 1100, 800, 600, and 250 Ma, with a pronounced cyclicity in both events of about 274 million years. Cross-correlation analysis indicates that LIP peaks precede zircon peaks by 10–40 million years. Furthermore, oceanic crust age peaks at 170–155, 135–125, 115–100, 80–70, 55–45 and 33–15 Ma correspond to zircon-LIP peaks. Also correlation analysis indicates a link between the zircon-LIP events and geomagnetic reversal frequency, as well as a possible link between geomagnetic polarity and paleointensity. Improved quantification of geological and geochemical measurements should help solve lingering questions about why time-series records of continental and oceanic crust, the supercontinent cycle, and global LIP events indicate evolution in quasi-periodic episodes.



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* Corresponding author.
*E-mail addresses:* puetz.steve@gmail.com (S.J. Puetz), kent.condie@nmt.edu (K.C. Condie), sergei.pisarevskiy@curtin.edu.au (S. Pisarevsky), davaille@fast.u-psud.fr (A. Davaille), cschwarz@stat.sfu.ca (C.J. Schwarz), caegeo@gmail.com (C.E. Ganade).

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## 1. Introduction

The U/Pb age distributions of zircons from granites and detrital zircons from rivers exhibit quasi-periodic variation (sometimes referred to as zircon episodes), the cause of which remains the subject of ongoing debate (Belousova et al., 2010; Condie et al., 2009; Condie and Aster, 2010; Hawkesworth et al., 2009, 2010, 2013; Iizuka et al., 2005; Rino et al., 2004). When studied on a global scale, Condie and Aster (2010) determine that major peaks occurred at ~2700, ~2500, ~2150, ~1900, ~1000, ~600 and ~300 Ma.[1] The standard explanation is that the episodes represent periods of enhanced production of continental crust coupled with recycling of older crust (Condie, 1998; Wang et al., 2009).

In addition to factors that contribute to continental crust development, the evolution of oceanic crust plays an important role in tectonic activity. However, reconstructing ages when oceanic crust formed presents formidable challenges because the ocean floors have relatively brief life expectancies. Almost all oceanic crust recycles into the mantle every 200-myr (Burchfiel, 1979). Despite this brevity, the preserved ocean floors have a somewhat predictable distribution, with the youngest ages generally found near mid-ocean ridges and the oldest ages found near subduction zones. Müller et al. (2008) and Rowley (2002) estimate the age distribution of preserved oceanic crust by analyzing the spreading patterns for all regions of the oceans, including small basins.

Debates continue about the degree of association among zircon formation, oceanic spreading and subduction, and stages of the supercontinent cycle (Belousova et al., 2010; Hawkesworth et al., 2010; Iizuka et al., 2005). The supercontinent cycle develops from quasi-periodic collisions of plates carrying continental crust. Subsequently, continental break-up occurs when the plates rift and then fully break apart. Assembly and break-up ages predominantly serve as the beginning and ending stages of the supercontinent cycle (Condie, 2015). Bradley (2011) expands upon supercontinent quantification by including measures such as oceanic crust age distributions, the number of continents, and the relative size of the largest continent. However, Bradley (2011) only estimates these components for ages younger than 500 Ma.

Additionally, ongoing improvements in paleomagnetic studies (Evans and Mitchell, 2011; Gibbons et al., 2013; Nance et al., 2014; Pisarevsky et al., 2014; Zhang et al., 2012) continually increase the reliability of paleo-pole and paleo-latitude estimates further into the past. Even though the paleomagnetic-related records are incomplete, especially for Precambrian times, it is possible to make estimations that extend to 630 Ma for paleo-latitudes, to 540 Ma for geomagnetic polarity, and to 430 Ma for paleointensity. The extensions are given here to gain further insights into possible links among continental crust formation, geomagnetic-related variation, and the supercontinent cycle.

To help resolve ongoing debates about what causes the continental and oceanic crust to evolve as they do, the work here describes a number of analytical methods for quantifying geological processes. One goal is to find the current age distribution of preserved zircons. This is done by developing two methods to adjust for the non-equal probability sampling that researchers currently utilize. A second goal is to estimate the periodicity of the zircon age distribution from a U/Pb zircon database that adjustments for non-equal probability sampling with continental surface areas. A third goal is to explore possible relationships among the geological processes by analyzing coincident correlations, as well as using cross-correlation analysis to determine possible lead-lag relationships.

To accomplish these goals, Section 2 describes the data for this work, Section 3 provides useful analytical methods for quantifying geological processes, and Section 4 discusses how the results shed light on the growth, preservation, and destruction of the continental crust as it evolves through time, and how these processes are related to the supercontinent cycle and mantle dynamics.

## 2. Data

All tables and figures in this study are developed from nine databases, which are available as supplementary materials. Details follow.

[1] The age-related abbreviation used here is Ma (million years ago), which refers to a specific time in the past. Conversely, the interval-related abbreviation myr (million years) refers to a span of time, often used to designate the period of a cycle.