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Singularity analysis of magmatic flare-ups caused by India – Asia collisions

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A B S T R A C T

Frequency distribution (histogram) calculated on the basis of igneous and detrital zircon U-Pb ages has been commonly utilized to interpret the age (range) of magmatic events. The temporal properties revealed by these types of data have also been integrated with other types of isotope data (e.g., neodymium, hafnium, and oxygen) to describe the high magmatic addition rate (MAR) and its association with the growth or reworking of the continental crust. Major peaks are picked to associate with pulses of high-volume magmatic flare-ups related to episodic evolution of continental crust. With the development of modern isotope identification technology which results both in reduction of analytical error of isotope data and rapid accumulation of massive high-quality data, the temporal and frequency variances of these types of data ought to be quantitatively analyzed to study magmatic evolution with respect to tectonic background. A new fractal density concept and a local singularity analysis (LSA) method have been recently and successfully applied to analyze the geometric property of the age peaks in global zircon U-Pb age database by power law models. The anomalies of age peaks identified are linked to deeply rooted avalanches associated with short spurts of convection during formation of supercontinents and continent crust growth. In this paper, the method is further used to analyze a small dataset of U-Pb ages from Gangdese arc to characterize the causational relationship of age peak and India-Asia collision. The results show that the age density around peak at 51 Ma can be fitted by power law functions. Both the scaling range of the age distribution and the exponents of the power law functions observed from the data suggest that the age peak may reflect magmatic flare-ups which would have been caused by superimposing of subduction, exhumation and slab breakoffs. It has been demonstrated that the LSA can be used as a new way to quantitatively characterize magmatic flare-ups based on U-Pb age data from a fractal density point of view.

1. Introduction

Study of igneous activities is important in many ways not only for understanding plate tectonics, continental crustal growth and recycling, but also for assessments of mineral resources, thermal energy and as well as global CO_2 cycling, that are associated with magmatic events. How magmatic activities are related to deep earth processes still remains as a fundamental question that has attracted a great deal of interest by geoscientists. There are many studies in the literature that have investigated the causational relationship between the occurrence of magmatic events and tectonic processes, such as plate subduction, slab breakoff, collision and plumes (see a review in Cheng, 2017b; Hawkesworth et al., 2010). Major age peaks are often identified from igneous and detrital zircon U-Pb age distribution to intuitively interpret the evolution of magmatic addition rate (Breitkreuz and Kennedy, 1999; Ducea et al., 2015; Yang and Santosh, 2015). Global datasets of igneous and detrital zircon U-Pb age distributions have been analyzed to identify age peaks that reflect the episodic continental crust growth rates (Nelson and DePaolo, 1985; Reymer and Schubert, 1986; Stein and Hofmann, 1994; Condie, 1998; Condie et al., 2009; Kemp et al., 2006; Voice et al., 2011). These age peaks correlate well with the supercontinental cycles (Stein and Hofmann, 1994; Kemp et al., 2006; Patchett, 1983; Allègre and Rousseau, 1984; DePaolo et al., 1991; McCulloch and Bennett, 1994; Rino et al., 2004; Class and Goldstein, 2005; Gopalan, 2007; Parman, 2007; Pearson et al., 2007; O'Neill et al., 2007; Hawkesworth et al., 2010; Arndt and Davaille, 2013; Evans, 2013). However, the causal association between these age distribution peaks and the evolution of the formation of continental crust still remains as a hot topic that has attracted considerable attention (Pearson et al., 2007; Parman, 2007; Santosh and Zhao, 2009; Hawkesworth et al., 2010; Dhuime et al., 2012; Condie et al., 2013; Yuan, 2015; Puetz and Borchardt, 2015; Gazel et al., 2015; Roberts and Spencer, 2014; Spencer et al., 2016). There are two general interpretations about the cause of these peaks (Arndt and Davaille, 2013; Condie et al., 2017): one relates the peaks to short spurts of accelerated magmatic activities due to episodic convection of the mantle linked to "superplumes" (e.g., Condie, 1998; Davaille, 1999), slab avalanches (e.g., Condie, 1998; Davies and von Blanckenburg, 1995), accelerated plate motion and

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subduction (e.g., O'Neill et al., 2007) or large, potentially global, melting events (Parman, 2007; Pearson et al., 2007). The other interpretation relates the peaks to periods of enhanced preservation of continental crust; especially, the onset of collisional tectonics, during the formation of supercontinents (Kemp et al., 2006; Campbell and Allen, 2008; Hawkesworth et al., 2009, 2010; Belousova et al., 2010; Cawood et al., 2012; Spencer et al., 2016). Different types of isotope data (e.g., Hf, O, He, Os, Nd) have been integrated to characterize the possible causes of formation of the U-Pb age (Stein and Hofmann, 1994; Condie, 1998; Condie et al., 2009; Kemp et al., 2006; Voice et al., 2011; Parman, 2007; Pearson et al., 2007; Spencer et al., 2014). Numerous quantitative methods have been applied to global isotope age data to assist in characterizing the periodic nature of the age distribution and understanding the association of age peaks with the evolution of continental crust growth and formation of supercontinents. These studies include, but are not limited to, cluster analysis of the age data for identifying superclusters of events (Condie et al., 2009), time series of ultramafic and mafic rocks with the major peaks inferred to represent mantle plume events (Isley and Abbott, 2002), spectral analysis and time-lagged cross-correlation techniques applied to time-series records for testing cyclicity (Puetz and Borchardt, 2015; Prokoph et al., 2004; Cawood and Hawkesworth, 2014), and fluid mechanics experimental models applied to explain the distinctive peak-and-trough pattern of U-Pb zircon ages of the Precambrian (Arndt and Davaille, 2013). Types of distributions of peaks were also analyzed by Spencer et al. (2014) to differentiate old and young age peaks on the basis of $\delta^{18}O$ isotopes and as well as to characterize reworking and harbingers of supercontinent tectonics. Sawada et al. (2016) used linear cumulative frequency curves of detrital zircon ages in distinct time intervals for recognizing the overall evolutional trend of continents. The age peaks observed in detrital zircons and igneous zircons were qualitatively described as “smooth” or “spiky” distributions representing the volume of stable continental crust versus the generation of new continental crust (McCulloch and Bennett, 1994; Condie, 1998, 2005; Hawkesworth et al., 2010). Keller et al. (2017) combined zircon saturation simulations with a dataset of ~52,000 igneous whole rock geochemical analyses to quantify secular variation in relative zircon abundance throughout Earth history. Recently Cheng (2017b) used a scale invariant model, which is less sensitive to preferential preservation, to relate the singularity (nonlinearity) of the age peaks to short spurts of accelerated magmatic activities due to “avalanches” (superplumes, slab breakoff, lithospheric roots detachments etc.) that occurred during episodic convection of the mantle. In the current paper, the objective of the study is to use a smaller but less biased igneous zircon U-Pb age data to validate the local singularity analysis method for quantifying nonlinear property of age peaks and relate them to avalanches that occurred during recent subduction and collision of India – Asia plates. The study area was chosen from the Gangdese arc which is related to India-Asia plate collision. It has been reported by Zhu et al. (2015) that the U-Pb age distribution peak derived from analyses of igneous zircons in the Gangdese arc may indicate the cause of slab breakoffs which would have occurred around 53 Ma during the processes of subduction and collision of the India – Asia plates. The question to be tackled is whether the age peak is solely caused by breakoffs or other activities?

2. Fractal density and singularity analysis

2.1. Power law distribution and singularity

There are several mechanisms in the context of plate tectonics as introduced in Cheng (2017a, 2017b) which may generate the following power law distribution of attributes:

$$y(x) = cx^{-k}, \tag{1}$$

where the value y is proportional to some power $(-k)$ of the input x (> 0). The power law function is determined by two factors: constant c and exponent k, the former determining the height or amplitude of the curve (at a unit scale $x = 1$), whereas the latter describes shape the curve. If the exponent (k) of power law is a positive value ($k > 0$) then the power law function (y) approaches to infinity when scale x tends to 0 ($x > 0$). The power law distribution is different from Gaussian distribution. The peaks described by Gaussian functions are smooth but those for power law functions are spiky (singular) around the origin. More discussion about the property of power law distribution and comparison of Gaussian distribution can be found in Cheng (2017a, 2017b). The rate at which a power law curve approaches infinity is determined by the magnitude of the exponent (k). This exponent is therefore referred to as a singularity index, which quantifies the nonlinearity of the curve at very small scale ($x \to 0$). While the scale invariance property of power law function is well-known, the singularity of power law function may be less familiar to readers since the power law distribution may not show singularity implicitly, especially because power law distributions such as the Gutenberg–Richter law and the Pareto distribution focus on the truncated upper tail (very large x). Since the two parameters of power law function (c and k) do not have clear physical meaning in some applications such as number – size modeling, power law function in these applications is often simply considered as an empirical curve fitting. To improve the interpretability of power law distribution the author has proposed a new way to interpret the parameters of the power law function in the context of fractal density and fractal dimension (Cheng, 2007, 2015, 2016). In order to illustrate the concepts of fractal density and local singularity analysis, in the next section the concept of ordinary density will be briefly reviewed and followed by a comparison with fractal density.

2.2. Ordinary density and fractal density

The ordinary density, or more precisely, the volumetric mass density, can be calculated by the following equation:

$$\rho = \frac{m(v)}{v}, \tag{2}$$

where $m(v)$ represents the mass contained in a volume and ρ is the average density of the object with volume v and mass m. If the density of the object is homogenous then the density calculated in Eq. (2) becomes independent of the volume which represents physical property of substance determined by its elements and atomic structures. The unit of density is then determined by the ratio of mass and volume, for example, g/cm^3. However, if the object has heterogeneous properties, the density may vary from place to place and accordingly the average density varies with different sizes of v. Then, a localized density must be calculated using the derivative of mass over volume:

$$\rho = \frac{dm(v)}{dv} = \lim_{v \to 0} \frac{m(v)}{v} \tag{3}$$

The preceding density exists only if the limit converges when the volume becomes infinitesimal. As a generalization of Eq. (3) a new equation was proposed which involves a parameter α (with positive value) so that the following limit converges (Cheng, 2016):

$$\rho_\alpha = \lim_{v \to 0} \frac{m(v)}{v^{\frac{\alpha}{3}}} \tag{4}$$

The value of ρ_α can be considered as the generalized “fractal” density which is no longer volumetric mass density but the “fractal” mass density. The ordinary density defined in Eq. (3) becomes a special case of the fractal density defined in Eq. (4) when $\alpha = 3$ (the normal dimension of volume). This new form of density was named “fractal density” by the author considering it is defined as mass or energy per unit “fractal set” (Cheng, 2016). The fractal density defined in model Eq. (4) has as unit the ratio of mass over a fractal set of α dimension; for example, g/cm^α or kg/m^α. Based on formula (4) the author has also proposed new concepts of fractal integral and differential operations