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Integration of Deep-time Digital Data for Mapping Clusters of Porphyry Copper Mineral Deposits

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1 Introduction

PCDs are generated in continental arcs in response to plate converging processes (subduction and collision) (Hou et al., 2009; Richards, 2013). It is generally accepted that the formation of PCDs is associated with igneous activities either originating from lower crust or upper mantle, with contributions of crusts during the evolution of continental lithosphere, especially in association with plate convergence. These igneous activities are often episodic with intermittency and anomalous high magmatic addition rate (MAR) and pulses of high-volume magmatic flare-ups caused by deep rooted avalanching geological events. Several key processes need to operate efficiently and additively for a PCD to ultimately form (Richards, 2013). These processes include mantle wedge partial melting; mantle-derived melts need to interact with the lithosphere and undergo density differentiation at the Moho zone. Along the shallow depth where the magma interacts with the hydrothermal system, country rock and surface water systems may involve a phase transition zone of supercritical fluid. There are two schools of thoughts on what may govern the episodic behavior of arc systems: external and internal attributes. External include plate reconfigurations, changes in mantle flow, and changes in magma production etc. In contrast, internal attributes include crustal thickening, melting, delamination, slab break off, roll back, slab split, and flattening etc. With the above considerations, we will demonstrate that integrating various databases can assist in revealing spatial and temporal associations of PCDs and local singular characteristics of lithosphere transition, plate motions and slab geometries. The databases that need to be integrated include, but not are not limited to, GPlates, a system generating motion of plates, a USGS Mineral Deposits Database providing the world inventory of PCDs, an Igneous Rock Database with isotope databases showing the magmatic activities, and seismic data catalogues showing geometrical properties of subducting slabs.

2 Clustering of PCDs

Clustering distribution is a common characteristic of mineralization associated with igneous activities. For example, Bertrand et al. (2014) reported that along the Western Tethyan and Andean subduction zones, the distribution of Cretaceous and Cenozoic PCDs are not random, but are in distinct regional clusters. The authors further proposed a two-phase geodynamic model favoring emplacement of PCDs: a high melt production in the mantle wedge, followed by an extensional regime (Bertrand et al., 2014). In order to comprehensively investigate the internal association of clustering of PCDs with their governing factors, the research must analyze the clusters of PCDs in various forms: (1) frequency distribution and size distribution of PCDs, (2) Temporal distribution of PCDs: a number of mineral deposits and sizes of deposits versus the age of PCDs (Fig. 1b), and (3) spatial distribution of PCDs with respect to subduction zone either along a profile parallel or perpendicular to the subduction zone (Fig. 2a). These temporal and spatial clustering distributions are further compared with the local abrupt change (or local singularity) of kinematic and geometrical changes of subducting plates. The example given in Figure 1 shows an area chosen from the Andean subduction zone which contains 62 young PCDs with ages less than 100 Ma, among which 32 mineral deposits have tonnages ranging from 186 to 21,277 million tones. The histogram is based on the ages of 62 mineral deposits (Fig. 1a). It indicates that three groups of clusters can be identified with peaks at 15 Ma, 40 Ma and 65 Ma, respectively. The peaks of each consecutive cluster are separated in time approximately by about 25 Myrs. The durations of these groups are about 15-20 Myrs. These periodicities are similar to the high-flux episodes (HFEs) recorded in Cordilleran arcs (DeCelles et al., 2009). The HFE's generate up to 75–80% of the arc mass within periods of 10-15 Myr, and their peaks are separated in time by approximately 25–50 Myr.

The Second example shown in Figure 2 is in regards to the analysis of spatial distributions of PCDs with respect to the Andean subduction zone. A profile was drawn parallel to the Andean subduction zone passing through the central locations of PCDs about 250 - 300 km inward into continents parallel to the trench from a starting point (-73.211/7.498 decimal degree) to an end point (-72.256/-46.259 decimal degree). This profile was drawn using a GIS vector analysis tool. It passes the most concentrated regions of locations of PCDs. The nearest distances of PCDs from the profile show a strong cluster around that profile. A large number of deposits are located very close to the line. Very few are far from the line which can be described by a power law decay function (the results are not shown here). The majority of the PCDs are located close to the profile and within a 10km distance. These deposits when projected to the curve show strong clusters along the profile as shown in Figure 2a. Five clusters show their peaks separated by almost an equal distance from each other at 11 units (1100 km) apart. The similar processes have been applied to many other areas chosen along Tethyan zones and Pacific zones. In the next section, these clusters of PCDs will be compared with the plate motion and geometrical properties of subducting slabs.

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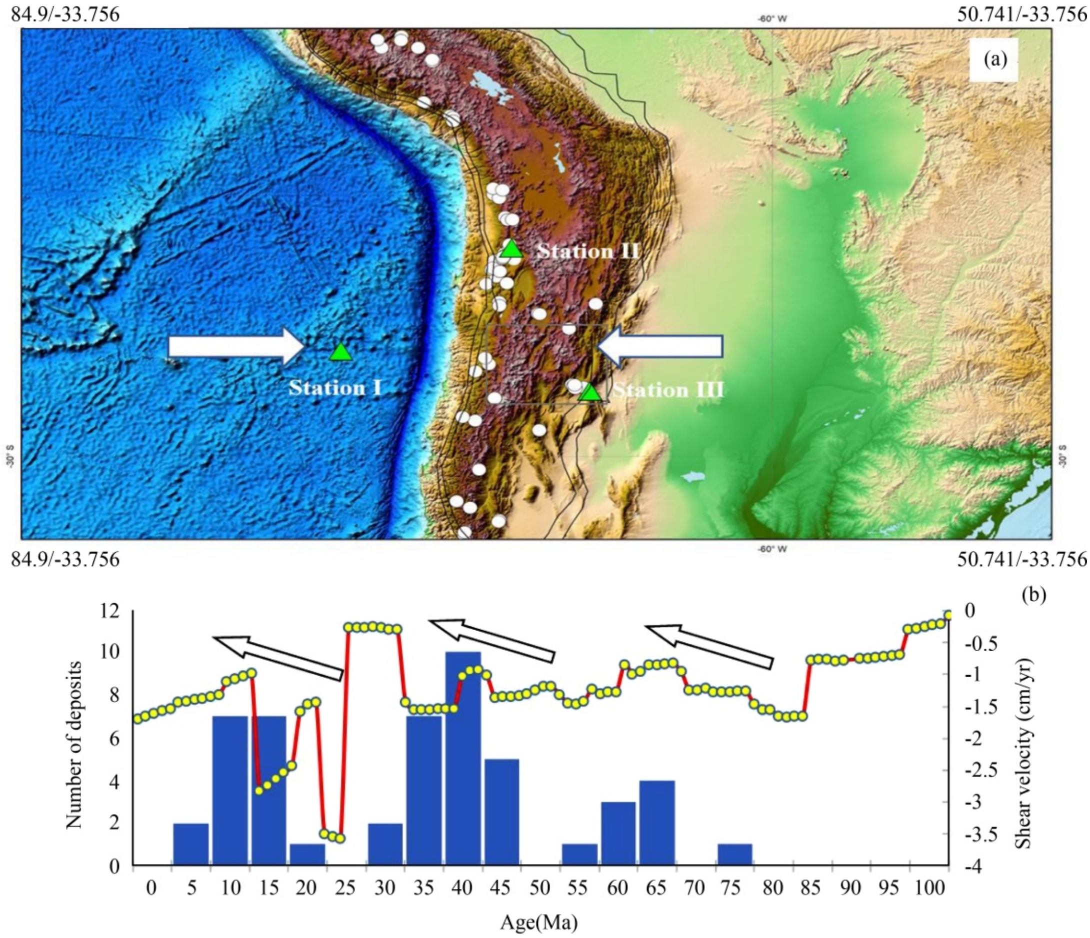

Fig. 1. Analysis of frequency distribution of PCDs and plates motion in a study area chosen along the south section of Andean subduction zone.

(a) The area contains 62 mineral deposits with Age < 100 Ma (white circles). Two stations (reference points marked as green triangles labeled Station I and III) are chosen to compare the motion of plate at the two reference points for the past 100 Myrs; The background map in color represents the digital elevation model (ETOPO1); and (b) a histogram showing the distribution of 62 PCDs grouped in an age bin 10 Myr. Superimposed red curve with yellow dots represents the sheared velocity as calculated at the two reference points. Details about the calculation are referred in the text.

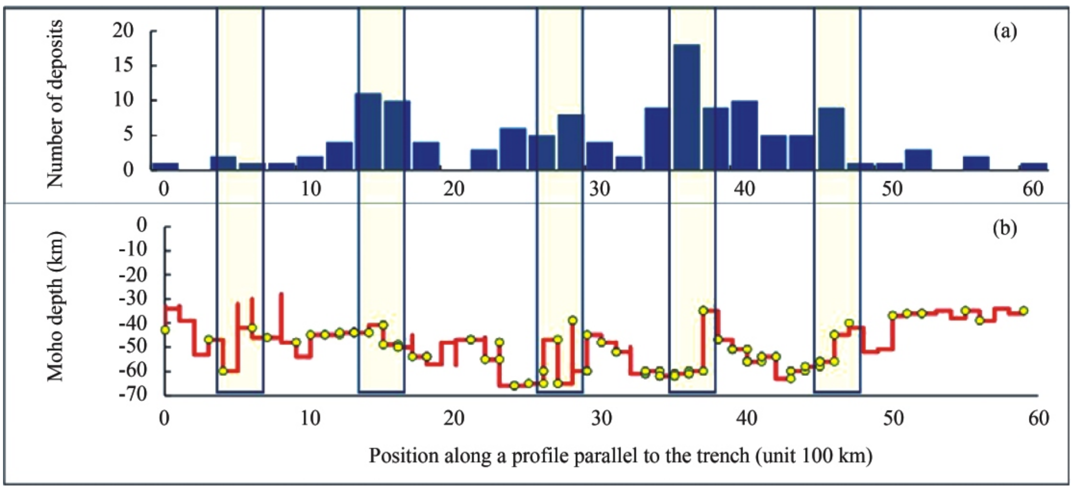

Fig. 2. Analysis of Moho depth at the locations of PCDS in Andean subduction zone.

(a) Frequency distribution of PCDs along a profile drawn passing through the central locations of PCDs and parallel to the Andean subduction zone. The profile is drawn in about 250 - 300 km inward continents from the trench from a starting point (-73.211/7.498 decimal degree) to an end point (-72.256/-46.259 decimal degree); and (b) Moho depth along the same profile as shown in (a). Data of Moho depth are from the image CRUST1.0 (Laske et al., 2013).

3 Clusters of PCDs and abrupt Changes of Plate Kinematics and Slabs Geometries

In order to understand the governing factors of clustering of PCDs, the clusters of PCDs need to be compared with the abrupt change or singularity of kinematical properties of plate motion and geometrical property of subducting slabs. For example, Figure 1b gives the results of linking temporal clusters of PCDs to change of velocity of subducting plates at the Andean subduction zone. The GPlates computer system was utilized to calculate the velocity and direction of motion at various preassigned reference points. For example, two stations (reference points), one on the oceanic plate and the other on continental plates were chosen to compare the relative velocities of the plate subduction underneath the Andean magmatic arc. By comparing the relative motions of plates at these two reference points, one can generate the relative compressional or extensional velocity difference norm to the trench. One can also calculate the velocity difference in direction parallel to the trench. This difference of velocity can be considered as a sheared velocity difference. For example, the red curve with yellow dots in Figure 1b represents the velocity differences projected in the northward direction (parallel to the local trench) at these two stations (Station III and I). The negative difference of the “shear velocities” along north direction indicates “right lateral shear difference”, meaning the left plate moves faster than the right plate at the time in which the north direction is parallel to the trench. The results in Figure 1b indicate that the two plates (at station I and III) generally maintain right lateral shear over the period of 100 Myrs. The shear velocity changes gradually except during several ages where rapid changes occur. This is generally coincidental with the peaks of magmatic activities (e.g. 85Ma, 50 Ma and 25 Ma, results are not shown here). These peaks of magmatic activities mark the increases of mineralization intensity (reflected as the frequency of mineral deposits) which reach the peaks in about 10 Myrs. These results may imply that the period at the maximum mineralization intensity may continue for about 10 Myrs after the peak intensity of magmatic activities. The compressional velocities (results are not shown here) are generally small from 100 Ma until 20-25 Ma when the compressional velocity increased rapidly from zero to about 12 cm/yr. At the same period, the shear velocity depicts strong variability which may indicate that 20-25 Ma marks an abrupt change of regime.

The example in Figure 2b represents the analysis of Moho depth at the locations of clusters of PCDs in Andean. The depths of Moho zone along the profile were calculated and plotted to show the association with the locations of clusters of PCDs. The Moho depth along the profile varies from 30 km to 70 km in depth. The depths around the two ends (north and south) are generally shallower than those in the middle segments. Significant changes occurred in several locations along the profile that are coincident to the clusters of PCDs as identified in Figure 2a. The abrupt changes of Moho depths may indicate some types of bending or splitting of slabs and these types of local singularity of slab geometry can correspond to origination of volcanism and PCD mineralization.

4 Discussion and Conclusions

The case studies introduced in the current research aim to demonstrate that integration of various geodatabases through deep time and paleogeographical references can link deep processes associated with plate subduction and the mineralization processes that occurred in the crust. Temporal and spatial clusters of PCDs with respect to palaegeographical and geological location for the past 100 Ma can be linked to localized plate motion and geometric properties of subducted slabs. Linked databases can reveal the elements that govern cluster distributions of PCDs, a fundamental question for models to be proposed to describe formation of PCDs in relation to the episodic behavior of arc systems. The data and interpretation have implications for a better understanding of the distribution and size of PCDs which are vital for modern industry, technology and decarbonization. Given the limitation of the length of this abstract, detailed analysis of other types of data are not shown. For example, regarding the findings of abrupt change of shear velocity around 20-25 Ma as illustrated in Figure 1b, we further integrate the current results to the data reported by Delph et al. (2017) in imaging a magma plumbing system from MASH zone to magma reservoir and we found this regime change around 20-25 Ma may be indeed associated with slab shallowing, flattening, splitting, and delamination which corresponded to volcanism and PCD mineralization. Regarding the association of clusters of PCDs and geometry of slabs as mentioned in the example given in Figure 2b, other types of data have been utilized, for example, depths and events of seismic centers from a global seismic center catalogues were used to model the local geometry of subducting slabs in the same area. The results indicate that the clusters of PCDs along the Andean subduction zone do coincide with the local singularity caused by abrupt change of geometry of slabs (shallowing, flattening, splitting, and delamination). Moreover, petrological and geochemical data of igneous rocks including isotope data and trace elements as well as rare earth elements (RRE) have also been linked to interpret the potential causes of extreme events such as slab break offs (avalanches due to self-organized criticality) on the clustering of the PCDs.

Key words: porphyry mineral deposits, mineral deposits clustering, simulation and prediction, plate tectonics, big data

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