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Identifying tectonic niche environments of South American porphyry magmatism through geological time: a spatio-temporal data mining approach

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SUMMARY

Porphyry ore deposits are well known to be associated with arc magmatism related to subduction on the overriding plate. Furthermore, the regional mechanisms for magmatism and the resulting formations of porphyry deposits are well established. Specific parameters leading to these events have been inferred, but not formally tested. We aim to identify the specific set of tectono-magmatic parameters that result in a subducting slab producing particular types of magmatism on the overriding plate, and their link to the formation of ore deposits. We use a four-dimensional approach to reconstruct age-dated magmatism back through space and time to isolate the tectono-magmagic parameters leading to the formation of a metalliferous deposit during subduction. By utilising machine learning techniques we identify and quantify geodynamic parameters that are robust predictors of back-arc magmatism and porphyry formation. The 'random-forest' ensemble and 'support vector machines' learning classification methods are employed to prioritise parameters that are considered influential in the development of magmatism and the subsequent metallogenesis of porphyry ore deposits. We find that a combination of convergence rates and directions, seafloor age, subduction obliquity, and the distance to a trench edge help predict whether magmatism and related ore deposits occur.

Key words: South America, Machine Learning, Porphyry, Plate kinematics.

INTRODUCTION

The South American cordillera is rich in porphyry deposits. The Andes is the longest orogenic and volcanic belt primarily formed by long-lived subduction since the Jurassic along the Pacific margin (Maloney et al., 2013). During its evolution, the Andean margin was host to a variety of magmatic events leading to the formation of porphyry deposits interspersed in distinct spatio-temporal clusters (Figure 1).

Although the close relationship between porphyry deposits and subduction is generally well established, there is no consensus on which subduction parameters primarily control the genesis of porphyry deposits. The interplay of specific geodynamic parameters, resulting in a particular coupling between the down-going and overriding plate, are likely key to particular types of magmatism and subsequent ore formation. Porphyry deposits are most often associated with calc-alkaline and adakitic magmatism in subduction zones and refertilisation of the sub-continental lithospheric mantle (Thieblemont et al., 1997, Griffin et al., 2013), with two distinct melting processes required for porphyry genesis. An initial melting in the metasomatized mantle wedge generates relatively oxidized and sulfur-rich mafic magmas with incompatible chalcophile or siderophile elements (Bertrand et al., 2014). This is followed by an injection of dykes and sills into the MASH (Melting, Assimilation, Storage, Homogeneization) zone of the lower crust resulting in a melt of a crust-mantle derived hybrid magma (Bertrand et al., 2014). The second phase has a high content of volatile and metalliferous elements, and a density that is low enough to allow its upward migration through the crust (Richards, 2003).

Numerous tectono-magmatic conditions have been implicated as drivers of magmatism and the formation of ore deposits in the subduction arc, including a link between deposits in the periphery of stagnating subducted slabs (Khomich et al., 2014), the rate and evolution of convergence between subducting and overriding plates (Bertrand et al., 2014), the absolute velocity of the plate overriding a subducting slab and the development of extensional features (Ramos, 2010, Khomich et al., 2014), the age of the subducting oceanic lithosphere (Capitanio et al., 2011), the dip of the subducting slab (Jarrard, 1986), trench migration and the obliquity of subduction (Macpherson and Hall, 2002; Jingwen et al. 2013), and the lateral length of the subducting slab (Schellart, 2008). The age of the subducting oceanic lithosphere influences the rate of uplift and hence the topography of the overlying magmatic arc, partially through changes to the dip angle of the subducted slab. The subduction angle is also dependent on the absolute plate velocities of the downgoing and overriding plate. Subduction of young, warm, and light oceanic lithosphere will tend to flatten at about 100 km depth, cause rapid uplift of the overlying crust, modify magma chemistry, and eventually close down magmatic activity (Shatwell, 2004). It may result in destruction (by erosion) of existing Au-Ag deposits, and exposure of underlying porphyry systems. Subduction of an active mid-ocean ridge as well as aseismic ridges (extinct spreading ridges, oceanic plateaus) are thought be instrumental in the development of porphyry-rich ore-deposits on the overriding plate. Presently subducting crustal features from the Nazca and Antarctic plates, including the Nazca-Antarctic Ridge, have been considered to play a role in the development of ore-deposits in the Andes (Rosenbaum et al., 2005). As yet, no single parameter has been satisfactorily identified as a primary controller of overriding plate magmatism (Maloney et al., 2013), implying that interaction between the conditions likely plays an important role in determining tectonic regime, magmatism, and porphyry genesis. The relative influence of each of these various conditions on magmatism is unclear, as are the effects of any potential interactions between the conditions.

A major increase in discoveries occurred in the period 1970-1990 due to new geophysical and geochemical surface detection techniques. Since then discovery rates have been in decline, as most of the near surface deposits have probably been found (Schodde, 2011). Either new detection techniques or better methods of predictive modeling are required for sustained economic viability of porphyry ore exploitation. Analytical techniques utilising spatio-temporal data-mining (Cracknell and Reading, 2014) provide a novel four-dimensional approach for analysis on the interplay of geodynamic parameters associated with magmatism and porphyry deposits (Richards, 2013). We seek to improve the efficiency of future exploration and further our understanding of porphyry ore deposit formation processes, by assessing and quantifying past tectonic conditions and configurations that are most likely to yield ore deposits.

METHOD AND RESULTS

We reconstruct the plates using pygplates, a python module that expands on the plate-reconstruction functionality of GPlates (www.gplates.org) and enables automation of spatio-temporal data analysis. The plate reconstructions provide information on the plate kinematics at any particular point along the South American margin. We use the plate model and associated rotation file of Shephard et al. (2013). We take a discrete sampling of South American subduction zones every 0.5 degrees in 1 Myr time steps since 200 Ma, and determine various tectono-magmatic parameters at each sample point. Absolute motion of the subducting plate is calculated as the stage rotation between the subducting plate and absolute reference frame. Likewise, the overriding plate motion is calculated as the stage rotation from the overriding plate and the absolute reference frame. Convergence is calculated as the relative stage rotations of the overriding and subducting plate. Obliquity of subduction is determined by finding the angle between the direction of convergence and the lateral direction of the trench at each of the sampling points. We use the oceanic paleo-age grids of Seton et al. (2012) as an additional spatio-temporal dataset related to the downgoing plate's coupling with the overriding plate.

We then use the plate model to rotate and track a set of age-dated magmatic events as far back as 200 Ma with a focus around the time of emplacement (Figure 1). We track the deposits for 20 Myr prior to ore formation to capture the kinematic history in our correlations. We perform a nearest neighbour look-up to find the closest tectono-magmatic and kinematic parameters associated with each ore deposit through time. Porphyry deposits along the South American margin fall into distinct spatio-temporal clusters (Figure 1). Analysis can be performed on deposits individually or can be partitioned in space and time to capture the tectonic niche environments leading to porphyry magmatism.

We transform the data into a matrix consisting of the location of the porphyry deposits through time, along with the tectonic parameters associated with that deposit including, age of subducting slab, convergence rate history, overriding and subducting plate velocity, obliquity of subduction, distance from slab edge. The key parameters of mean plate convergence rates, overriding plate velocity, and subducting seafloor ages are shown in Figures 2, 3, and 4. To compare the negative-case, that is, when a set of tectonic parameters does not result in an ore deposit, we simply include data points for training our classifiers that we know do not result in a porphyry deposit at a particular time. From Figure 2 we identify three types of convergence history leading to ore formation. Firstly, a relatively slow rate of convergence followed by an acceleration in the Cretaceous, Oligocene, Miocene clusters. Second, a decrease in convergence rate precedes metallogenesis in the Jurassic, Paleocene, and Quaternary clusters. Finally, Eocene deposits have a relatively stable convergence rate leading to ore genesis – thus convergence rate seems to play no role in the Eocene deposits. We further find that the mean or gradient in absolute motion of the overriding plates appears to have no connection to ore deposit formation (Fig. 3). The age of the downgoing plate associated with ore deposit formation ranges from about 25 to 65 million years, with a mean close to 50, indicating that slab windows, associated with the subduction of mid-ocean ridges and very young ocean crust, have not resulted in significant ore deposits along South America.

The random forest classifier (Brieman, 2001) combines the prediction of an ore deposit forming due to each parameter individually. It utilises test cases of known ore deposits to train what parameter combinations are most likely to result in those ore deposits. We retain a portion of the data to test the predictive power of the classification of geodynamic parameters on (Figure 5).

Using a support vector machine (SVM) (Cortes, 1995) we can also predict the formation of a porphyry deposit even in the presence of an unknown nonlinear relationship with its parameters. Furthermore, using a SVM with cross-validation and automatic relevance determination techniques, we can establish correlations between, and the importance of, these parameters in the formation of porphyry deposits.

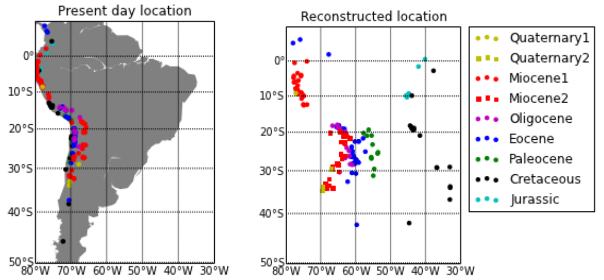

Figure 1. Present day and reconstructed positions of magmatic events associated with porphyry deposits (data compiled by Bertrand et al., 2014). Colours represent the geological epoch associated with each deposit, as shown in the legend. The Miocene and Quaternary deposits fall into two distinct spatial clusters.

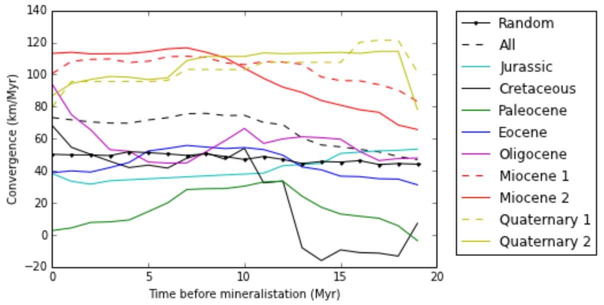

Figure 2. Convergence rates for 20 Myr prior to the formation of a porphyry deposit. Each line represents the average of a different cluster of deposits, from Figure 1, as listed in the legend. The dashed black line is the average for all deposits. The random line is the average of the negative-cases, and is representative of an average for the South American margin.

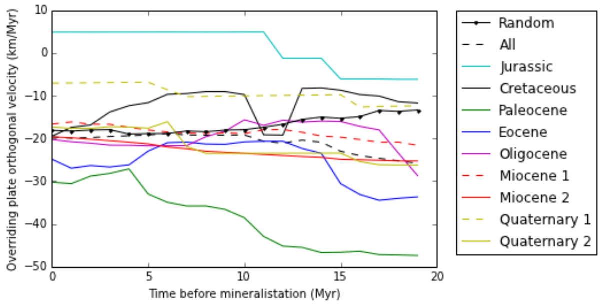

Figure 3. Overriding plate velocity for 20 Myr prior to the formation of a porphyry deposit. Same clusters as described in Figure 2. Overriding plate advance is defined by negative velocity. The similarity between the data and negative-cases indicates overriding plate motion has minimal influence on porphyry magmatism along the Andes.

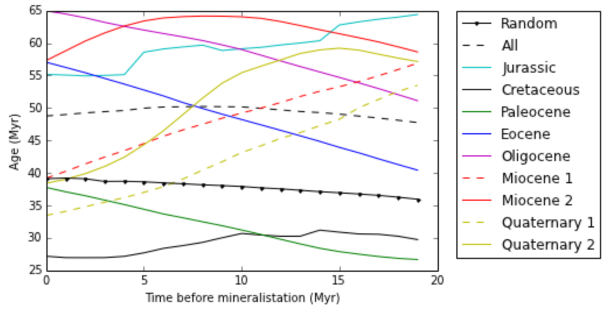

Figure 4. Age of seafloor subducted underneath ore deposits for 20 Myr prior to the formation. Same clusters as described in Figure 2. Ore deposits preferentially form when seafloor is relatively old. Note the lack of association of ore deposits with the subduction of mid-ocean ridges (very young ocean floor).

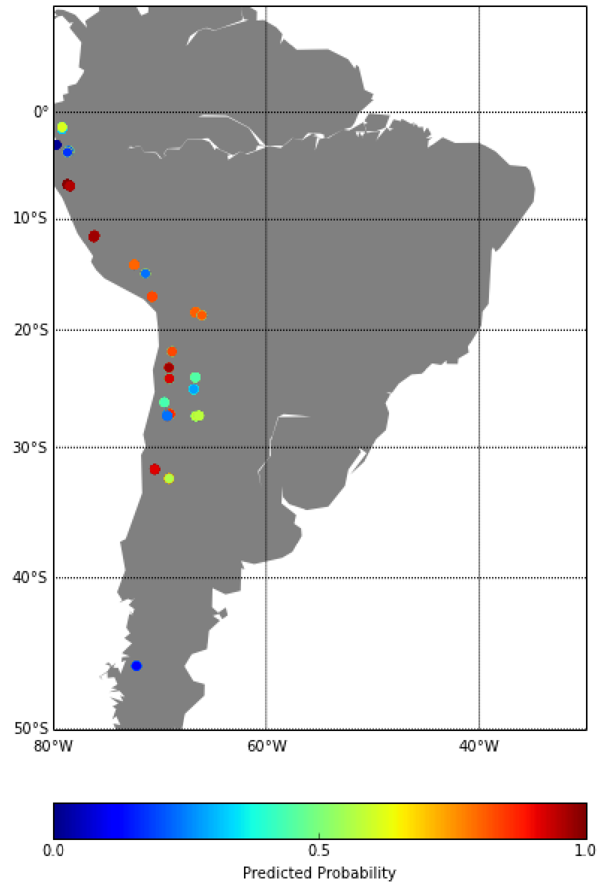

Figure 5. Predicted probability of known porphyry deposits based on dataset trained with a random forest classifier.

CONCLUSIONS

Using a random forest classifier with subduction parameters associated with the formation of magmatic porphyry deposits including the age of the downgoing plate, the convergence rate leading to ore genesis, subduction obliquity, distance from the subducting trench edge, and the absolute velocities of the overriding and subducting plates, allow for characterisation of a set of known ore deposits. The most important parameters for determination of porphyry magmatism along the South American margin using this approach are the age of the downgoing slab and the motion of the overriding plate. However, as previous work has suggested, the interplay of the parameters is significant, as a single parameter alone cannot predict porphyry magmatism. Expanding on this approach will not-only allow for the development of prospectivity maps based on plate reconstruction models and paleo-geodata, but will aide in discovering new knowledge pathways for a deeper understanding for how arc-magmatism and porphyry deposits evolve. An in-depth analysis using advanced classification techniques such as support vector machines may further pin down these key interactions. This method remains somewhat ignorant of the underlying geochemistry of the subducting slab, mantle wedge, and overriding plate, thus distinguishing between magmatism and porphyry ore genesis requires additional work.

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