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Arc Mantle Redox since Archean: Insights from Machine Learning, Statistics and Thermodynamic Modeling

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Introduction

Understanding how subduction has operated throughout Earth's history is crucial for comprehending the evolution of plate tectonics, a topic that remains highly debated (Lenardic, 2018; Stern, 2018; Brown et al., 2020; Cawood et al., 2022). Evidence suggests that processes akin to subduction were at work at various times throughout the Precambrian (Palin et al., 2020). Arc basalts, significant magmatic assemblages within subduction zones, typically form from the melting of the mantle wedge, triggered by the influx of slab-derived fluids and/or melts. These melts carry geochemical signatures characteristic of arcs, such as depletion in Nb and Ta, and enrichment in Ba and Rb (Tatsumi et al., 1983). However, traditional binary discrimination diagrams based on these geochemical features often fail to accurately distinguish arc basalts from those originating in other tectonic settings (Figure 1). Thus, tracing the temporal evolution of Archean subduction necessitates a comprehensive geochemical approach to accurately identify arc-type basalts.

To this end, we have employed a supervised machine learning (ML) model known as Extreme Gradient Boosting (XGBoost), which excels in high-dimensional classification tasks (Chen and Guestrin, 2016). Utilizing the XGBoost classification model, we aimed to differentiate basalts produced in subduction zones from those generated in other environments, including Ocean Island Basalts (OIBs), mid-ocean ridge basalts (MORBs), oceanic plateau basalts (OPBs), and continental basalts.

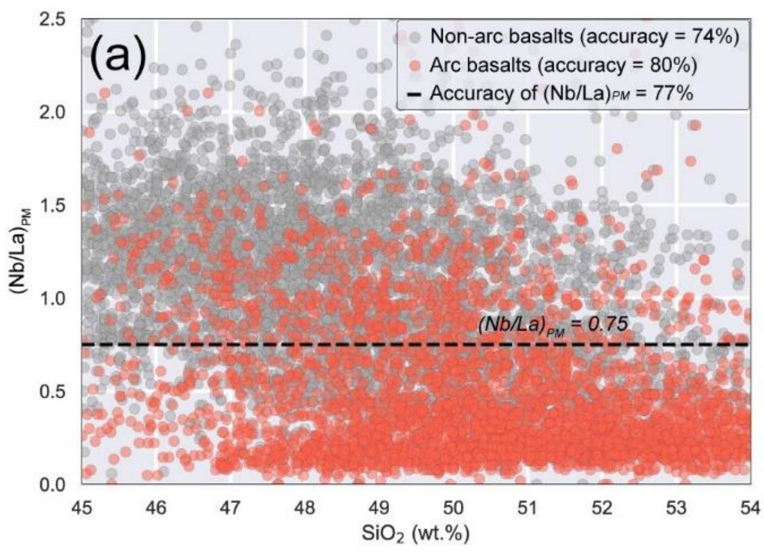

Figure 1. Traditional bivariate discrimination plot. The accuracy of $(Nb/La)_{PM}$ in distinguishing between arc and non-arc basalts is 77% (Liu et al., 2024). The PM indicate normalization to the primitive mantle (Sun and McDonough, 1989).

Main results

The training model achieved an average accuracy of 0.95 and an average F1 score of 0.93. These high metrics demonstrate the ML model's reliability in classifying arc and non-arc basalts based on their geochemical characteristics.

Feature importance scores, which enhance the interpretability of ML models, have been instrumental in deepening our understanding of geological processes (Zhao et al., 2019; Petrelli et al., 2020; Qin et al., 2022). In this study, we utilized the XGBoost algorithm to determine the relative importance of each input feature (Figure 2). The findings reveal that the ratio of Nb/La, along with features Ti, U/Nb, Nb, and Pb/Nd, were the most influential features in our arc/non-arc basalt classification model. However, the relative importance of all input parameters was below 0.1, indicating that no single feature overwhelmingly dictates the model's outcome in this high-dimensional classification task. Consequently, unlike traditional binary discrimination methods, our model, which incorporates multiple parameters, is less susceptible to the influence of individual features. Therefore, it is imperative to include all parameters when constructing the arc/non-arc classification model.

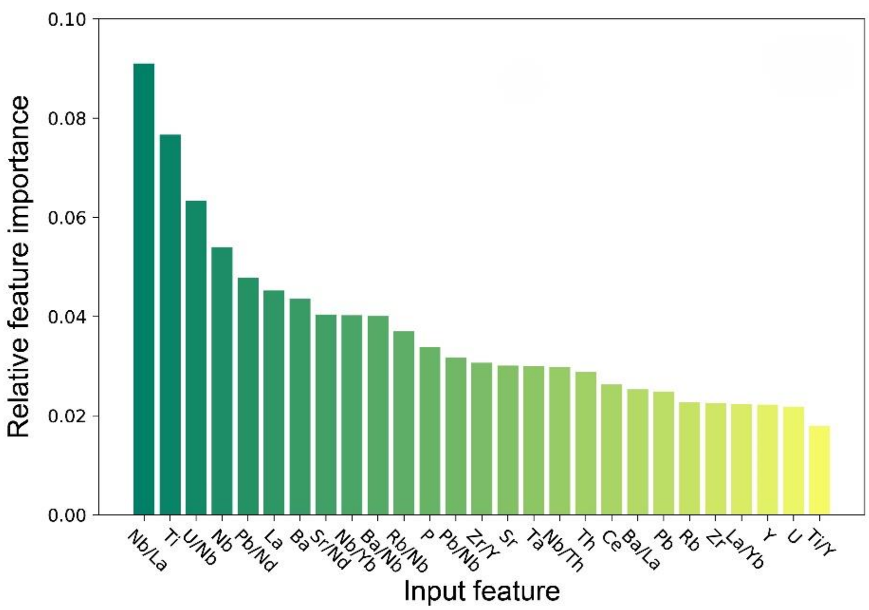

Figure 2. Results of our XGBoost model. The relative feature importance scores of input features in the training dataset (Liu et al., 2024).

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