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Monte Carlo-Enhanced Machine Learning: An Integrated Framework for Data-Driven Gold Mineralization Modeling

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The Tobique-Chaleur Zone, situated in northern New Brunswick and adjacent Gaspé Peninsula of Québec, is part of Appalachian orogeny—an orogenic region formed through several phases. The bimodal volcanic and sedimentary rocks Siluro-Devonian Tobique Chaleurs zone hosts numerous epithermal gold occurrences. In northern New Brunswick Acadian dextral transcurrent faults such as the Restigouche, Rocky Brook-Millstream, McCormack-Ramsay Brook, and McKenzie Gulch faults were critical in forming gold mineralization. Mineral Prospectivity Mapping (MPM) is a multi-criteria method developed to guide mineral explorers in identifying promising targets using available geoscience datasets. MPM combines geochemical (till samples), radiometric, and aeromagnetic data to identify anomalies and interpret geological features such as faults, extent of rock units, and lithological contacts. Key elements of the mineral system —including ore metal sources, fluid pathways, traps, and geological controls on ore formation—are converted into mappable criteria for regional-scale analysis. In this study, two GIS-based knowledge-driven and two machine learning-based data-driven approaches were employed to analyze 24 predictor maps, each with a 200-meter pixel size. We perform Monte Carlo Simulations to quantify uncertainties in all evidence variables, which are divided into geological, geochemical, and geophysical groups. Then, using stochastically generated sets from these multiple input layers, we apply Random Forest to derive various probability-based estimates of the mineral potential. According to the models, high prospectivity areas invariably correspond with existing epithermal gold occurrences. The study also uncovered untested exploration targets. By comparing the models to known gold mineralization with Receiver Operating Characteristic curves, we found that the final prospectivity models consistently attained an Area Under the Curve (AUC) > 0.8. This indicates that the MPM approach is robust and could be successfully applied to other regions and types of ore deposits. Combining knowledge-based techniques with a data-driven approach improved the accuracy and effectiveness of the prospectivity analysis. The study found that indicator minerals and pathfinder elements closely aligned with high-potential areas, and drill core analysis confirmed gold-bearing quartz veins, reinforcing the accuracy of the MPM models. Future exploration should concentrate on the high-potential areas highlighted by the models, with extra field verification and sampling to further enhance prediction accuracy.