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Integrating Advanced Geoscientific Studies and Comprehensive Resource Assessment in Geothermal Exploration

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ABSTRACT

This paper outlines methodologies for advancing geothermal exploration through integrated geoscientific studies, conceptual modeling, resource assessment, and standardized classification frameworks. Central to the discussion is the development of conceptual models that synthesize geochemical, geophysical, and geological data. Multi-component thermodynamic geothermometry refines reservoir temperature estimates by modeling fluid-mineral equilibria, while magnetotelluric (MT) surveys image subsurface structures (e.g., conductive caps, fault zones) to delineate heat sources and fluid pathways. Field observations (thermal features, mineral deposits) and laboratory analyses (general chemistry and stable isotopes,) further constrain these models, enabling robust interpretations of upflow zones and reservoir boundaries.

For resource assessment, the lognormal power density method quantifies probabilistic capacity estimates (P90-P10) by integrating reservoir area and power density (MW/km^2), validated against analogous volcanic systems. This approach is complemented by 3D structural modelling to predict permeability heterogeneity and Monte Carlo simulations to assess uncertainty. The United Nations Framework Classification for Resources (UNFC) is applied to standardize evaluations, categorizing projects by socio-economic viability, technical feasibility, and confidence in estimates. This framework aligns resource potential with global benchmarks, facilitating risk-informed investment and policy decisions.

By integrating these methodologies, cohesive exploration strategies demonstrate reduced uncertainty, prioritize drilling targets, and support scalable geothermal development. The UNFC's role in harmonizing, in this case, geothermal resource

evaluations, underscores its value in advancing sustainable energy transition, including geothermal development.

INTRODUCTION

This study advances geothermal exploration methodologies through integrated geoscientific analyses of the Picard River geothermal system in northern Dominica. Dominica's volcanic geology, characterized by recent ignimbrite flows (22,000–46,000 years BP) and structural controls from the Morne Diablotins Fault Zone, provides an ideal setting for testing interdisciplinary workflows. The primary objectives were to refine a previous conceptual model, quantify resource capacity, and classify project maturity using standardized frameworks to de-risk future development.

METHODOLOGY

Geochemical analysis prioritized submarine hot springs (Volcano and Hot Sophia at 25–28 m depth. See Figure 1) due to pressure conditions preserving in-situ reservoir fluid signatures and minimizing re-equilibration artifacts, with supplementary terrestrial sampling (Gloshow and Avie's Ville. See Figure 1) excluded from quantitative geothermometry due to dilution/steam loss effects. Three submarine samples per site underwent seawater correction via magnesium-zero extrapolation and CO_2 recombination modeling to derive endmember compositions. Multi-component geothermometry [1] in Geochemist's Workbench then modeled mineral-fluid equilibria using the Reed-Spycher algorithm [2] (e.g., quartz, K-feldspar) for precise temperature estimation, while stable isotopes ($\delta^{18}O$, $\delta^{2}H$) traced fluid origins and mixing processes.

Geophysical Surveys deployed 24 new magnetotelluric (MT) stations to augment existing dataset (58 stations), covering gaps in the Morne Diablotins, Portsmouth corridor. Data underwent 3D inversion using ModEM, resolving resistivity structures to 3 km depth. Key outputs included the base of conductor (BoC) at 10 Ω·m, inferred as the reservoir top (Figure 1). Field geology validated structures (e.g., flank collapse scarps, fault zones) using aerial imagery and outcrop mapping.

Resource Quantification applied the lognormal power density method [3]. Reservoir areas (P90: 2.9 km^2; P50: 9.3 km^2; P10: 35 km^2) were derived from MT-derived BoC contours, thermal feature distribution, and fault geometries. Power density (7–12 MW/km^2) was calibrated against the analogous Bouillante field (Guadeloupe). Monte Carlo simulations combined area and density distributions probabilistically. The United Nations Framework Classification for Resources (UNFC) categorized socio-economic viability (E-axis), technical feasibility (F-axis), and confidence in estimates (G-axis) [4].

RESULTS

Reservoir characterization confirmed a 220–240°C deep outflow zone via multi-component geothermometry, with mineral equilibria curves converging sharply (R^2 >

0.99). Submarine springs exhibited negligible sulphate, indicating boiling-induced H_2S degassing. MT imaging revealed a 5–7 km deep magmatic heat source beneath Morne Diablotins, overlain by a 1.5–2 km conductive clay cap. The NW-SE Morne Diablotins Fault Zone controlled fluid upflow and outflow pathways, with acid-sulphate features (Balvin) marking shallow outflow emergence (Figure 1).

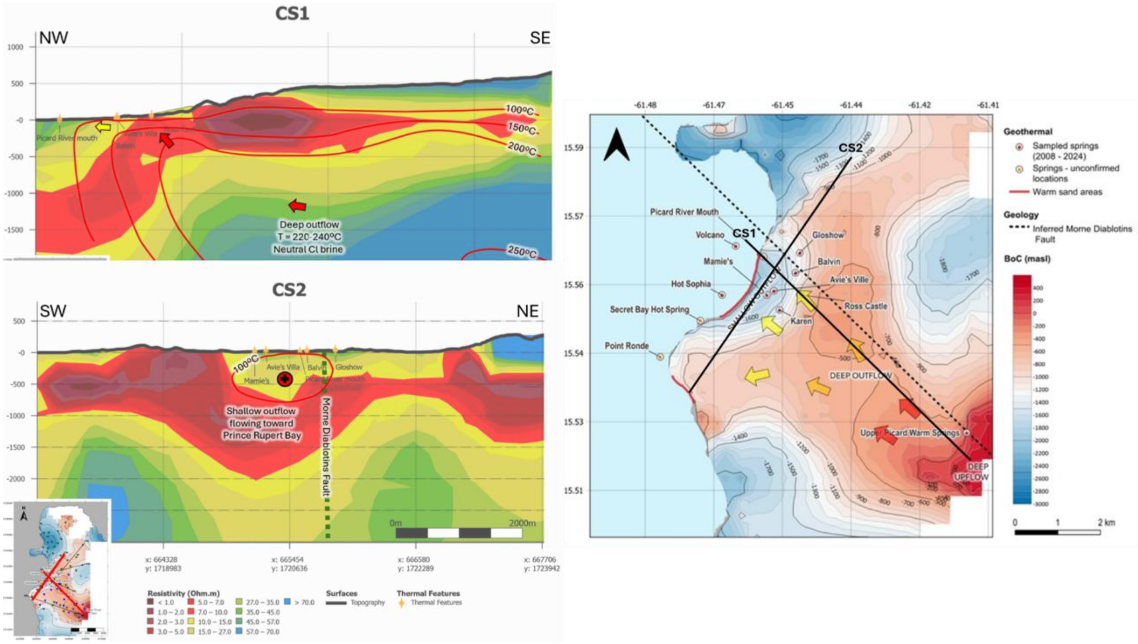

Figure 1. Right: Conceptual model map of the Picard River geothermal system overlying the elevation of the base of conductor (BoC) at 10 ohm.m from the 3D inversion. The BoC can be inferred as the ‘top of the reservoir. CS1 and CS2 are conceptual model cross-sections.

Resource capacity estimates were: P90: 25 Mwe, P50: 80 Mwe, P10: 280 Mwe. Directional drilling in the SE upflow zone (inferred >250°C) could expand these figures.

UNFC classification designated the project E3.2/F3.1/G4 under the United Nations Framework Classification for Resources. This classification signifies confirmed technical feasibility (F3.1), warranting exploration drilling, while socio-economic viability remains undetermined (E3.2) pending environmental and market studies. The resource is classified as prospective (G4) with a 40% discovery probability, where subclasses G4.1–G4.3 quantify the P90 (25 MWe), P50 (80 MWe), and P10 (280 MWe) estimates, respectively.

DISCUSSION

Methodological synergy reduced uncertainty: Multi-component geothermometry provided precise temperatures where classical methods yielded ambiguous ranges (163–270°C); MT inversion resolved the clay cap’s western limit, excluding nonproductive zones; integrating geochemistry (fluid types), geology (faults, flank collapse), and geophysics (resistivity) identified the SE upflow zone as the optimal drilling target.

UNFC's Role standardized risk communication. The 40% discovery probability, derived from temperature (85%), permeability (50%), and chemistry (95%) confidence metrics, is guidance for stakeholders toward phased investment. The framework's granularity (e.g., G4.2 = P50–P90 increment) clarified upside potential despite socio-economic unknowns (E3.2).

Scalability was demonstrated for volcanic arc settings. The Bouillante analogue validated power density assumptions, while 3D structural models predicted permeability heterogeneity.

CONCLUSIONS

1. Integrated workflows confirmed a 220–240°C reservoir in Dominica, with a >250°C upflow zone beneath Morne Diablotins.
2. Probabilistic resource estimates (25–280 MWe) and UNFC classification provided standardized metrics for investment decisions.
3. Exploration drilling is prioritized for the SE upflow to validate permeability and resource extent.
4. This methodology offers a replicable template for volcanic geothermal systems globally, enhancing resource delineation and de-risking.

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