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Salinity sources in geothermal groundwater of the Moroccan Sahara Aquifer: Evidence from Noble Gases and Hydrochemistry

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Geothermal systems are widely investigated worldwide; however, the relationship between geothermal groundwater and salinity remains insufficiently constrained, particularly in coastal and Saharan aquifers. This study examines these interactions within the deep, multi-aquifer system of the Sahara in southern Morocco through an integrated approach combining hydrochemistry, stable isotopes (δ^2H, $\delta^{18}O$), noble gases (He, Ne), and geothermometers. Both geothermal and non-geothermal groundwater exhibits high mineralization (electrical conductivity ranging from 2.5 to 20 mS/cm) and is characterized by Na^+–Cl^- facies with notable SO_4^{2-} enrichment. Meaningful correlations between chloride and major ions, together with $\delta^{18}O$ vs. Cl^- relationships, seawater contribution estimates (F_{sea}%), and elevated dissolved helium concentrations (>7.05×10^{-8} ccSTP/g), indicate that salinity is primarily controlled by geogenic processes associated with prolonged water–rock interaction rather than seawater intrusion. δ^2H and $\delta^{18}O$ compositions suggest paleo-meteoric recharge under cooler climatic conditions than present, consistent with U-Th/^{4}He residence times ranging from approximately 3 to 202 ka BP. Reservoir temperatures estimated using the K–Mg geothermometer range from 59 to 174 °C and increase westward toward the west, in agreement with the regional geothermal gradient, which is controlled by the Canary Islands Volcanic (CIV) heat anomaly. Salinity and temperature show strong correlations with distance from the CIV (R > 0.79), reflecting progressive groundwater deepening and conductive heating along the regional flow path. Noble gas systematics (^{3}He/^{4}He ratios) and CO_2/^{3}He mixing models reveal a dominant crustal radiogenic helium contribution (>80% in most samples), while CO_2 is mainly derived from carbonate decarbonation processes (46–79%), with no mantle input detected. Overall, the findings suggest that groundwater salinity and thermal anomalies in the Moroccan Sahara are predominantly governed by deep geogenic processes and conductive heat transfer rather than marine intrusion.