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Geochemistry and Structural Control of Brines in the Middle Benue Trough, Nigeria

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Abstract - Brine occurrence in the Middle Benue Trough, Nigeria, is strongly influenced by the region's structural and stratigraphic framework. This study integrates geological mapping, geophysical interpretation and hydro-chemical analysis investigations to assess structural control on brine migration. Field observations reveal that NE–SW and NW–SE trending basement-rooted faults, particularly at intersections and terminations, are the principal pathways for the vertical ascent of mineralized fluids. Aeromagnetic and Source Parameter Imaging (SPI) data confirm the presence of deep fault corridors coinciding with brine-rich localities. Hydro-chemical analyses show extremely high salinity, predominantly Na–Cl facies, and elevated potassium, calcium, and trace metal concentrations, suggesting evaporite dissolution and prolonged water–rock interaction. These evidences, supports a model of structurally focused brine migration and stratigraphic confinement within permeable sandstones such as the Keana Formation. The findings have dual implications: (1) exploration targeting should prioritize fault intersections, anticline closures, and structurally confined porous units for economically valuable brines; and (2) environmental management should focus on monitoring and protecting shallow aquifers in structurally active zones. This multidisciplinary approach provides a robust framework for both resource development and groundwater protection in tectonically complex basins.

Keywords: Aeromagnetic interpretation, Brine migration, Hydrochemistry, Middle Benue Trough, Structural Control

I. INTRODUCTION

Brines are waters containing total dissolved solids (TDS) over 50 g/L, and represent chemically evolved fluids that hold significant scientific, industrial, and economic relevance. These saline fluids, enriched in various dissolved ions including sodium (Na^+), chloride (Cl^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), lithium (Li^+), and trace elements such as strontium (Sr^{2+}), boron (B), rubidium (Rb), and cesium (Cs), are of particular interest due to their association with critical minerals like halite (NaCl), lithium carbonate (Li_2CO_3), and potassium chloride (KCl) (Flexer *et al.,* 2018; Zheng *et al.,* 2020). The formation and distribution of these brines are intimately linked to the geological, structural, and hydrochemical characteristics of the host basin.

Inland brines, unlike their coastal counterparts, are often formed through complex interactions of sedimentary processes, structural deformation, evaporite dissolution, and fluid migration. Their occurrence is typically associated with sedimentary basins containing evaporite sequences or tectonically active regions where deep-seated fluids ascend through permeable pathways such as faults and fractures. The classification of saline groundwater has evolved to include marine-derived connate water, evaporative brines, hydrothermal fluids, and brines of mixed or anthropogenic origin (Ferguson *et al.,* 2018). Understanding the genesis, migration pathways, and structural controls on these brines is crucial for both resource development and environmental management.

The Middle Benue Trough (MBT) of Nigeria, which is a part of a larger Cretaceous intracontinental rift system formed during the opening of the South Atlantic, offers a compelling setting for studying inland brine systems. Despite being flanked by the better-studied Northern and Southern Benue Trough segments, the MBT remains relatively under-investigated, especially about its saline groundwater systems (Ekwok *et al.,* 2024; Joshua *et al.,* 2023). Notable occurrences of brines have been documented in towns such as Keana, Awe, Akiri, and Ribi, where highly saline waters often emerge along fault-controlled zones and structural highs. These brines exhibit elevated levels of Na^+, Cl^-, and other constituents, suggesting a combination of evaporite dissolution, deep fluid interaction, and vertical fluid migration as controlling mechanisms (Tijani, 2004).

The MBT's stratigraphy comprises a sequence of Albian to Turonian formations, including the Asu

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River Group, Awe Formation, Keana Formation, and Ezeaku Formation, interbedded with marine shales, fluvio-deltaic sandstones, and minor limestones. Structurally, the region is dominated by NE–SW trending faults and folds related to rift tectonics and subsequent basin inversion. These faults serve not only as conduits for hydrothermal fluid migration but also as sites for brine concentration and mineral deposition. The Keana anticline and associated fault zones have been particularly noted for brine outflows and salt ponds, indicating ongoing or reactivated fluid movement (Offodile, 1976; Benkhelil, 1989).

Given the increasing global demand for critical minerals such as lithium and potassium, especially from sustainable sources like brine, there is a growing impetus to evaluate the MBT's potential in this regard. Additionally, salinization of shallow aquifers poses environmental concerns, especially in regions where faults intersect potable water zones. These twin considerations underscore the need for a multidisciplinary investigation into the structural, geochemical, and isotopic characteristics of the brines in the Middle Benue Trough. This study aims to evaluate the structural controls on brine migration in the MBT through integrated field mapping, aeromagnetic data interpretation, hydro-chemical analysis, and isotope geochemistry. The findings of the research will enhance understanding of fluid flow systems in rift basins and provide insights into the exploration of mineralized brine. Additionally, the research will add valuable input for managing groundwater resources in regions where saline intrusion could threaten freshwater aquifers.

II. GEOLOGICAL AND STRUCTURAL SETTING

The Middle Benue Trough (MBT) represents the central sector of the larger Benue Trough. This NE–SW trending intracontinental rift basin formed during the Early Cretaceous because of the opening of the South Atlantic Ocean and the separation of Africa from South America (Figure 2.1). Structurally, it is a tectonically active and geologically complex region, shaped by repeated episodes of subsidence, magmatism, and deformation during the Cretaceous (Ekwok *et al.,* 2024; Olade, 1975; Benkhelil, 1989).

Geologically, the MBT is underlain by a thick succession of Cretaceous sediments, predominantly composed of alternating marine and continental facies. These include, in ascending order, the Asu River Group (Albian), characterized by marine shales, micaceous siltstones, and mudstones; the Awe Formation (Late Albian–Cenomanian), comprising feldspathic sandstones and carbonaceous shales; the Keana Formation (Cenomanian–Turonian), noted for its massive, poorly sorted cross-bedded sandstones and subordinate shales; and the Ezeaku Formation (Turonian), consisting of calcareous shales, shelly limestones, and friable sandstones (Offodile, 1976). These formations are exposed across various brine-bearing towns, including Keana, Awe, Akiri, and Ribi.

The geological map of the study area (Figure 2.2) illustrates the surface distribution of these lithostratigraphic units and their spatial relationships. Importantly, field investigations indicate that most brine occurrences are associated with formations containing interbedded shales and sandstones, which provide both sources of salinity and conduits for fluid flow.

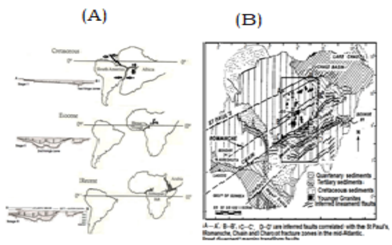

Figure 2.1: (a) Map showing Stages of Origin of the Benue Trough as a rift arm abandoned during separation of Africa from South America in the Gulf of Guinea (Modified after Hoffman *et al.*1974, Grant, 1971-stage 1 and Wright, 1968- stage 2). (b) Geological Map of Nigeria showing the location of inferred lineaments and faults (Ajakaiye *et al.,* 1986)

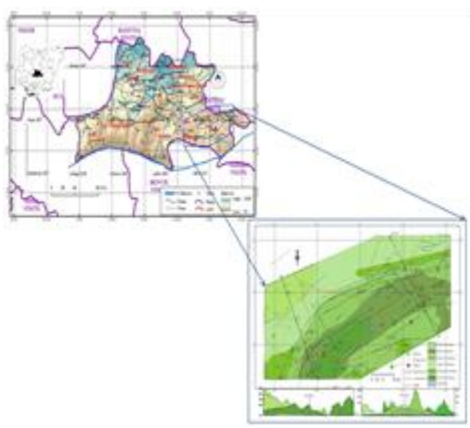

Figure 2.2: Geological Map of The Study Area Showing Lithostratigraphic Units and Key Brine-Bearing Towns (Keana, Awe, Akiri, Ribi).

From a structural perspective, the MBT is defined by a network of major faults trending NE–SW and NW–SE, inherited from pre-existing basement fractures and further reactivated during Cretaceous rifting. These faults exert a strong influence on sediment distribution, groundwater pathways, and brine migration. The Keana Anticline, a prominent fold structure extending NE–SW across the region, is bounded by fault systems that are spatially associated with high-salinity brine discharges, particularly around Keana and Awe (Figure 2.3).

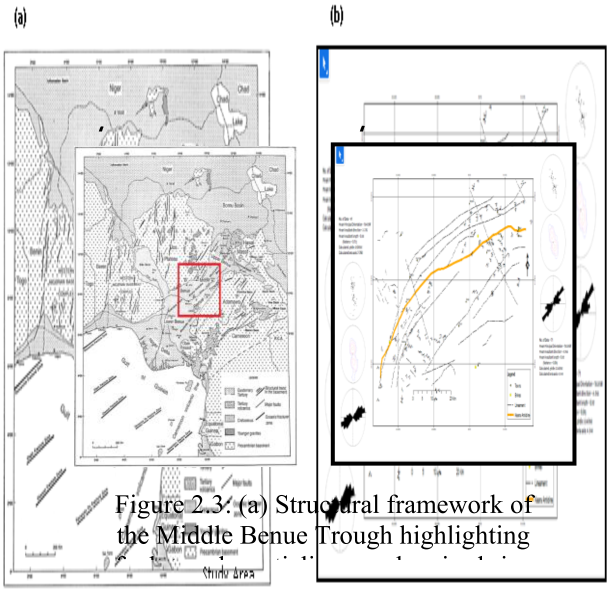

Figure 2.3: (a) Structural framework of the Middle Benue Trough highlighting fault trends, anticlines, and major brine sites [(Adopted from Benkhelil *et al*, 1997 in Osinowo *et al* (2023)]. (b) NE – SW trend direction depicting the Keana Anticline

The structural map (Figure 2.3) reveals that fault intersections and terminations serve as primary zones of vertical fluid movement. These deep-seated faults not only allow upward migration of mineralized fluids but also enhance fluid mixing where they intersect porous sandstone units. The faults often cut across multiple formations, linking deeper evaporite horizons with near-surface aquifers.

Topographically, the area features an undulating landscape with ridge-valley systems influenced by structural deformation [(Figure 2.3 (b)]. The Digital Elevation Model (DEM) (Figure 2.4) underscores the structural control on surface geomorphology, showing elevated zones along the Keana anticline and aligned drainage systems that may coincide with fault traces. These elevated regions are often linked with brine seepage points due to pressure-driven discharge along fault planes.

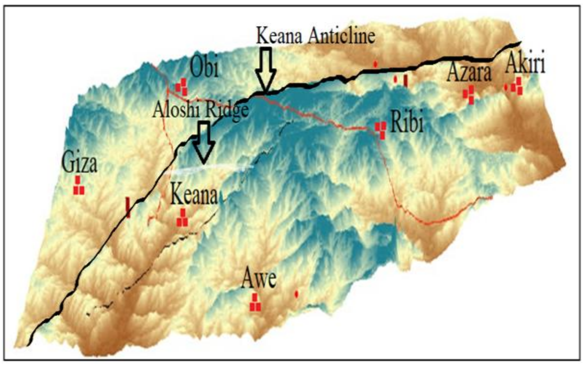

Figure 2.4: Digital Elevation Model (DEM) of the Study Area Showing Topographic Highs (Keana Anticline) and Drainage Features

III. RESEARCH AND ELABORATIONS

This study adopted a multidisciplinary approach integrating geological mapping, structural analysis, geophysical interpretation, hydrochemical sampling, and isotopic investigations to evaluate the structural control on brine migration in the Middle Benue Trough. The research design involved both desk-based and field-based methodologies, with laboratory analyses conducted on rock and brine samples collected from key brine-bearing localities.

3.1 Geological and Structural Mapping

Detailed field mapping was carried out across selected sites in Keana, Awe, Akiri, and Ribi to document lithological units, stratigraphic boundaries, and structural features. Structural data, including strike, dip, and orientation of faults and fractures, were collected using a compass clinometer. Rock samples were obtained from representative outcrops and petrographically analyzed through thin-section microscopy under plane and cross-polarized light to determine mineralogical composition and textural characteristics.

Lineament analysis was conducted using Spot-5 satellite imagery and Shuttle Radar Topography Mission (SRTM) data. Edge enhancement and contrast stretching techniques were applied in ILWIS and ArcGIS to extract fault trends, alignments, and fracture zones from surface morphology. These structural elements were cross-referenced with brine occurrence points to assess spatial correlations.

3.2 Geophysical Data Interpretation
High-resolution aeromagnetic data obtained from the Nigerian Geological Survey Agency (NGSA) and the National Centre for Remote Sensing were processed to reveal subsurface structural features. The total magnetic intensity (TMI) data was analyzed using Source Parameter Imaging (SPI) to estimate the depth and geometry of magnetic anomalies, which are indicative of faults, intrusions, and lithologic contacts.

Spectral analysis techniques were applied to the magnetic data using Oasis Monta and ArcGIS platforms to delineate basement architecture and sedimentary thickness. Depth slices and magnetic lineament maps were generated to identify potential conduits for fluid migration. These geophysical interpretations were used to augment surface structural mapping and guide hydro-chemical sampling.

3.3 Hydro-chemical Sampling and Analysis
Brine samples were collected from surface ponds, hand-dug wells, and boreholes in structurally significant areas. In situ measurements of temperature, pH, electrical conductivity (EC), and total dissolved solids (TDS) were recorded using a calibrated HACH field meter. Samples were preserved and transported under standard protocols for laboratory analysis.
Major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (Cl^-, SO_4^{2-}, HCO_3^-) were analyzed using Flame Atomic Absorption Spectrometry (FAAS) and Ion Chromatography (IC). Trace elements and heavy metals were determined via Inductively Coupled Plasma Mass Spectrometry (ICP-MS), employing the Agilent 7700 series.

3.4 Cluster and Statistical Analysis
Multivariate statistical methods were employed to interpret hydro-chemical data. Cluster analysis was conducted to group brine samples based on chemical similarity and structural location. This was complemented by bivariate plots and ion correlation matrices to identify geochemical trends and infer water–rock interaction processes.

3.5 Integration and Interpretation
All geological, geophysical, and geochemical datasets were spatially integrated using a Geographic Information System (GIS) platform. Brine occurrence was mapped against fault zones, lithologic units, and elevation data to delineate structural controls. Geophysical anomalies were overlaid with mapped lineaments and sample points to validate the connectivity between deep structures and surface brine expressions.

This integrative approach allowed for the development of a conceptual model of brine migration, highlighting the roles of fault intersections, stratigraphic juxtaposition, and lithological permeability in controlling brine pathways in the Middle Benue Trough.

IV. RESULTS AND DISCUSSION

4.1 Hydrogeochemical Characteristics of Brines
Hydrochemical analyses from hot and cold brine springs and boreholes within the Middle Benue Trough reveal marked variability in salinity, ionic composition, and trace element content (Table 4.1). Total dissolved solids (TDS) values range from ~3,116 mg/L in Akiri Hot Pond to ~13,770 mg/L in Ribi Cold Pond, thereby spanning the *moderately saline to very saline* categories (Frank et al., 2009). On average, the brines contain TDS levels (7,295 mg/L) well above potable water standards (NSDWQ, 2015; WHO, 2017), confirming their strong mineralization.

Electrical Conductivity (EC) values (2,285–27,540 µS/cm) further corroborate elevated salinity levels (Table 4.1). The waters are slightly alkaline (pH ~7.6–7.7) with relatively stable hydrogen ion activity across all sites.

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Table 4.1: Chemical Composition of Brine

Sample ID	Parameters													
	pH	EC	TDS	Na^+	K^+	Ca^{2+}	Mg^{2+}	NO_3^-	Cl^-	CO_3^-	HCO_3^-	SO_4^{2-}	NO_2^-	F^-
Awe hot pond	7.65	8803	4399	202.42	86.89	68.62	24.14	31.24	513.03	34.04	324	12.42	0.2	1.04
Akiri hot pond	7.67	6230	3116	454.86	98.4	54.05	39.42	28.3	682.81	32.24	346	21.51	0.42	1.25
Akiri Pond	7.68	7422	3720	508.08	106.75	85.24	32.25	54.28	846.02	30.56	450	19.83	0.24	1.45
Keana	7.62	2285	11420	584.02	91.39	78.42	40.42	42.6	927.89	48.76	176	22.06	0.61	2.91
Awe cold Pond	7.74	10100	5053	366.89	115.8	90.1	50.02	10.78	822.52	31.61	464	30.55	0.89	2.13
Ribi Cold Pond	7.65	27540	13770	202.42	90.08	58.95	44.66	32.05	600.44	23.24	234	34.28	0.32	1.29
Minimum	7.62	2285	3116	202.42	86.89	54.05	24.14	10.78	513.03	23.24	176	12.42	0.2	1.04
Maximum	7.74	27540	13770	584.02	115.8	90.1	50.02	54.28	927.89	48.76	464	34.28	0.89	2.91
Average	7.671	11526	7295.5	388.14	99	72.441	38.13	33.04	729.2	34.06	329.25	23.419	0.471	1.75
NSDWQ,2015	6.5-8.5	1000	500	200		100	20	50	250			100	0.2	1.5
WHO, 2017	6.5-8.5	1000	600	100	75	250	20	50	250			200	3	1.5

Note; pH – Degree of Acidity or Alkalinity, EC – Electrical Conductivity, TDS – Total Dissolved Solids

Cations are dominated by sodium (Na^+), ranging from ~200 mg/L in Ribi and Awe springs to over 584 mg/L in Keana borehole, followed by potassium (K^+) (~87–116 mg/L average), calcium (Ca^{2+}) (54–90 mg/L) and magnesium (Mg^{2+}) (24–50 mg/L). Sodium concentrations consistently exceed the NSDWQ/WHO guidelines, indicating strong evaporitic or basement-derived input.

The major anions are chloride (Cl^-) (513–928 mg/L; far above the permissible limit of 250 mg/L), bicarbonate (HCO_3^-) (176–464 mg/L), and carbonate (CO_3^{2-}) (~23–49 mg/L). Sulphate concentrations (12–34 mg/L) remain relatively lower. The predominance of Na–Cl and Na–HCO_3 water types reflects both evaporite dissolution and water–rock interaction processes. Schoeller and Piper plots (Figures 4.1a and b, & 4.2) confirm the brines' consistent enrichment in chlorides and alkali cations.

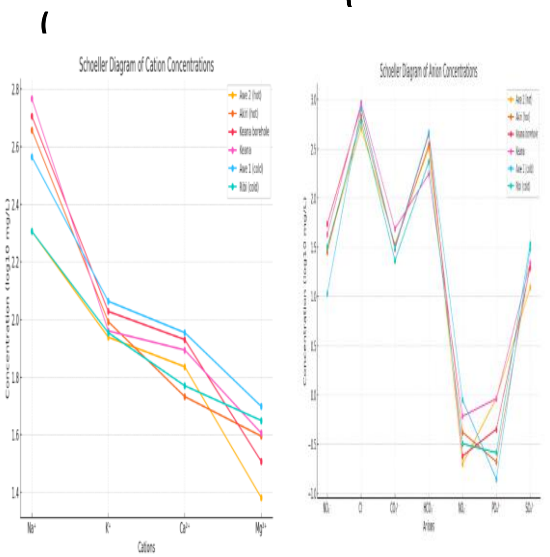

Figure 4.1: (a) Relative Concentration of Cations in the Brine Samples of the Study Area. (b) Relative concentration of Anions in the Brine Samples

The mineralization pattern is further depicted in Piper and Schoeller diagrams (Figures 4.1a and b), which affirm the cationic dominance of Na^+ and the strong presence of Cl^- and HCO_3^- among anions. The positive correlation between Na^+ and Cl^- ($r^2 = 0.95$; Figure 4.2) reflects a shared origin likely linked to evaporite dissolution and the influx of saline connate waters, a mechanism supported by other continental brine systems worldwide.

4.2 Spatial Trends and Structural Control

Brine accumulations in the MBT are not randomly dispersed but instead closely follow the significant fault and fractured networks mapped in the field. Petrographic and field observations highlight the importance of these structures in enhancing permeability and channelizing both vertical and lateral migration of fluids.

Prominent zones such as Keana, Akiri, and Awe correspond to areas of fault intersections, where brines migrate from deeper evaporitic and geothermal sources towards the surface. The spatial clustering of brine occurrences in these structurally focused zones, underscores the role of tectonics in both brine genesis and its present distribution. These findings align the MBT with classic hydrothermal brine provinces, where episodic fault reactivation acts as a driver of permeability and mineralization.

4.3 Petrography and Trace Elements

Petrographic examination of sandstones from key localities within the Middle Benue Trough, notably Keana and Awe, reveal a predominance of whitish, medium-grained quartz-rich arenites. Hand specimen analysis confirms a uniform texture and mineral composition with quartz as the dominant phase, a feature that is central to the effective porosity and permeability of these rocks. Such

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characteristics facilitate fluid migration, making these sandstones ideal conduits for brine movement and mineralization within structurally controlled pathways.

Microscopic evaluation under polarized light reinforces these observations. Photomicrographs illustrate well-defined boundaries between quartz grains, granular texture and the absence of significant lithic or feldspar constituents. This supports a mature sedimentary environment and indicates minimal diagenetic overprinting. The microstructural features, such as grain contacts, occasional microfractures, and alteration patterns, are consistent with secondary processes like weathering and the movement of mineralizing fluids. These images provide direct evidence of the connectivity and textural maturity pivotal for brine-hosting potential.

Additionally, the presence of alteration features and minor inclusions suggests intermittent geochemical interaction, potentially tied to brine migration. Trace element concentrations, summarized in the analytical tables, further reflect local enrichment where fluid–rock interaction is most pronounced, underscoring the structural and lithological controls on resource distribution.

Plate 4.1: (A) Outcrop of Sandstone Exposure in Awe (L1), while (B), is a close-up view of a particular portion showing large grains of quartz.

4.4 Implications for Resource Development and Environmental Health

The enriched chemistry of MBT brines, particularly in sodium, potassium, and chloride, highlights potential for resource development. Potassium concentrations approach economic viability for regional potash production, and localized lithium enrichment necessitates further targeted exploration. Nevertheless, increased fluoride levels raise public health concerns. As noted in the thesis, concentrations over 1.5mg/L risk dental and skeletal fluorosis, as well as other chronic health problems, which should be mitigated through public-health interventions and further monitoring.

Synthesizing geological and geochemical data, the MBT brine system may be best explained by a hydrothermal-evaporative model; viz-a-viz connate and geothermal fluids ascend through fault-controlled pathways, mingle with meteoric inputs and dissolve evaporite minerals, leading to the formation of highly saline brines. Recurrent cycles of fluid migration and surface evaporation result in significant halite and gypsum accumulations, structurally trapped along fault corridors.

V. CONCLUSION

This study establishes that brine occurrence and migration in the Middle Benue Trough are fundamentally governed by the interaction between deep-seated structural features and the basin's stratigraphic–lithologic framework. The geological mapping, geophysical interpretation, and hydro-chemical analyses reveal that NE–SW and NW–SE trending basement-rooted faults act as the principal conduits for the vertical ascent of mineralized fluids. These structures, particularly where they intersect or terminate, as observed around Keana, Awe, and Akiri, create zones of enhanced permeability that focus fluid discharge. Once mobilized, the ascending brines migrate laterally within permeable sandstone units, such as those of the Keana Formation, where they may be further concentrated by the juxtaposition of low-permeability shale barriers, exemplified by the Asu River Group.

Aeromagnetic and Source Parameter Imaging (SPI) data corroborate these field observations, revealing subsurface fault corridors and depth anomalies that coincide with brine-rich areas. The hydro-chemical analyses show that brines in structurally controlled zones possess extremely high salinity, predominantly Na–Cl facies, and elevated concentrations of potassium, calcium, and trace metals, consistent with evaporite dissolution, long residence times, and possible mixing with connate or hydrothermal waters. This reinforces the model of structurally focused brine migration.

Given these findings, it is recommended that future brine exploration efforts in the Middle Benue Trough concentrate on fault intersections, anticline closures, and structurally confined sandstone bodies, where the likelihood of economically valuable brines, such as lithium-, sodium-, and potassium-rich fluids is most significant. High-resolution geophysical surveys and remote sensing should be integrated to refine structural mapping and identify priority targets. At the same time, attention must be paid to groundwater protection: structurally active areas where deep brines could encroach on shallow aquifers should be subject to continuous water quality monitoring, and borehole placement in such zones should be regulated to prevent salinization. Pilot extraction programs should be undertaken to evaluate the economic feasibility of brine resource development. At the same time, isotopic and geochemical studies, extended over seasonal cycles, would provide deeper insight into recharge–discharge dynamics. Incorporating numerical groundwater flow models that simulate fault-controlled permeability could also enhance predictive capabilities and support both sustainable resource utilization and aquifer conservation.

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