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Seismic Geochemistry: A Sustainable Approach to Hydrocarbon Exploration in Libya

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ABSTRACT

The growing need for sustainable resource management and environmentally responsible exploration has highlighted the importance of integrating emerging geoscientific approaches into national development strategies. Although Libya possesses significant hydrocarbon resources and diverse geological settings, the application of seismic geochemistry remains limited despite its considerable potential for supporting both energy exploration and environmental management. This study explores the role of seismic geochemistry as an innovative tool for sustainable development in Libya. The proposed framework emphasizes the integration of geochemical indicators with seismic surveys, geological information, well data, hydrogeochemical observations, and environmental monitoring to improve subsurface characterization and resource assessment. Particular attention is given to the identification of geochemical anomalies associated with tectonic activity, hydrocarbon migration, groundwater systems, and environmental hazards. The study demonstrates that integrating seismic geochemistry within multidisciplinary exploration workflows can improve hydrocarbon prospecting, reduce exploration uncertainty, enhance groundwater assessment, strengthen environmental impact evaluation, and support evidence-based resource management. Furthermore, the proposed approach contributes to minimizing environmental risks while improving exploration efficiency through advanced geochemical interpretation. The findings highlight the potential of seismic geochemistry as a strategic decision-support tool capable of promoting sustainable development in Libya by integrating scientific innovation, environmental protection, digital geological analysis, and responsible management of natural resources. The proposed framework further supports sustainable development in Libya's resource-rich regions by enhancing environmentally responsible hydrocarbon exploration, strengthening evidence-based resource governance, and promoting long-term economic and environmental sustainability.

الجيوكيمياء الزلزالية: نهج مستدام لاستكشاف الهيدروكربونات في ليبيا

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الكلمات المفتاحية
الجيوكيمياء الزلزالية
التنمية المستدامة
استكشاف الهيدروكربونات
الرصد البيئي
موارد المياه الجوفية
ليبيا

الملخص

رغم امتلاك ليبيا موارد هيدروكربونية كبيرة وتكوينات جيولوجية متنوعة، إلا أن تطبيق الجيوكيمياء الزلزالية لا يزال محدودًا. تستكشف هذه الدراسة دور الجيوكيمياء الزلزالية كأداة مبتكرة للتنمية المستدامة في ليبيا. ويركز الإطار المقترح على دمج المؤشرات الجيوكيميائية مع المسوحات الزلزالية والمعلومات الجيولوجية وبيانات الآبار والملاحظات الهيدروجيولوجية والرصد البيئي لتحسين توصيف باطن الأرض وتقييم الموارد. ويُولي البحث اهتمامًا خاصًا لتحديد الشذوذات الجيوكيميائية المرتبطة بالنشاط التكتوني وهجرة الهيدروكربونات وأنظمة المياه الجوفية والمخاطر البيئية. وتُبين الدراسة أن دمج الجيوكيمياء الزلزالية ضمن سير عمل الاستكشاف متعدد التخصصات يُمكن أن يُحسّن التنقيب عن الهيدروكربونات، ويُقلل من عدم اليقين في الاستكشاف، ويُعزز تقييم المياه الجوفية، ويُقوي تقييم الأثر البيئي، ويدعم إدارة الموارد القائمة على الأدلة. علاوة على ذلك، يُساهم النهج المقترح في تقليل المخاطر البيئية مع تحسين كفاءة الاستكشاف من خلال التفسير الجيوكيميائي المتقدم. تُبرز هذه النتائج إمكانات الجيوكيمياء الزلزالية كأداة استراتيجية لدعم اتخاذ القرارات، قادرة على تعزيز التنمية المستدامة في ليبيا من خلال دمج الابتكار العلمي، وحماية البيئة، والتحليل الجيولوجي الرقمي، والإدارة المسؤولة للموارد الطبيعية. كما يدعم الإطار المقترح التنمية المستدامة في المناطق الليبية الغنية بالموارد، وذلك من خلال تعزيز استكشاف الهيدروكربونات بطريقة مسؤولة بيئيًا، وتقوية إدارة الموارد القائمة على

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Introduction

The phenomenon of desertification involves the Seismic methods employ vibration to image underground structures by creating seismic waves and timing their reflections and refractions from geological formations. This destructive testing method is applied in various fields such as hydrocarbon exploration [1-7], hydrology [8-13], earthquake resistance studies for rock identification [13-18], fault detection [19-22], and bedrock depth determination. [23-28]. Important techniques used are reflection [29-35] and refraction [36-41]. Both provide different subsurface data. The importance of seismic techniques in sustainable development lies in their ability to help mitigate seismic hazards in the creation of sustainable cities and the development of environmentally friendly exploration techniques. Seismic techniques can be used in urban planning for disaster prevention, structural evaluation, and emergency evacuation routes, while in resource exploration, the technique is becoming environmentally friendly [42].

Seismology can be considered as the scientific discipline that combines seismic observations and geochemical observations to gain insight into subsurface structures and processes [43-47]. The two principal applications of combining seismic and geochemical observations include: (1) Interpretation of seismic surveys through correlation of geochemical data and seismic velocities to gain insights into rock structures [48 and 49]. (2) Seismic monitoring of the earth through geochemical phenomena like changes in dissolved ion and gas content of ground water, as well as crustal and mantle volatiles in ground gases [50]. Geochemists gather ground waters, thermal fluids, and overflow gasses from locations where there is movement in fault zones [51 and 52]. The collected fluids are then tested for alterations in the chemical make-up and the isotopic ratios [53].

Any alterations in the fluid geochemistry are correlated to seismic activity, which could be pre-, syn-, or post-seismic [54]. Seismic data are integrated with multiple types of geochemical plots: (1) Diagrams to determine the chemical composition of groundwater (Piper and Durov diagrams, Figs. 1a and b). (2) Diagrams to define the source of dissolved solids in groundwater (Na/(Na+Ca) versus TDS, Cl/(Cl+HCO_3) versus TDS (Figs. 2a and b [55]), Langelier-Ludwig diagram (Fig. 2c [56]), HCO_3 versus Na (Fig. 2d [57]), Cl versus B, B/Cl versus δ^{11}B (Figs. 2e and f [58]), 1/B versus δ^{11}B (Fig. 2g [59]), and Cl-SO_4-HCO_3 ternary diagram (Fig. 2h [60]). (3) Diagrams to show the source of gases (^{4}He/^{40}Ne versus R/Ra (Fig. 3a [61]), R/Ra versus δ^{13}C-CO_2 (Fig. 3b [62]), ^{36}Ar/^{40}Ar (10^{-3}) versus N_2/^{40}Ar, ^{21}Ne/^{22}Ne versus ^{20}Ne/^{22}Ne (Figs. 3c and d [63]), and δ^{18}O versus δD (Fig. 3e [64]). (4) Diagrams to illustrate the influence of mineral weathering and ion exchange processes on the water chemistry (HCO_3 versus Ca/Mg (Fig. 4a [65]), HCO_3+SO_4 versus Ca+Mg (Fig. 4b [66]), Ca/Na versus HCO_3/Na (Fig. 4c [67]), and Cl versus Na (Fig. 4d [68])).

Any chemical variations are regarded as a consequence of the deformation of the earth's crust and variation in rock permeability due to earthquakes [69]. The final aim would be utilizing any geochemical anomalies as indicators for predicting earthquakes more accurately [70]. Understanding the connection between flowing fluids and the mechanical processes within active fault zones is made easier by seismic geochemistry [57]. Geochemical proxies found in sedimentary formations may also be utilized in paleoseismology to determine historical seismic events [53].

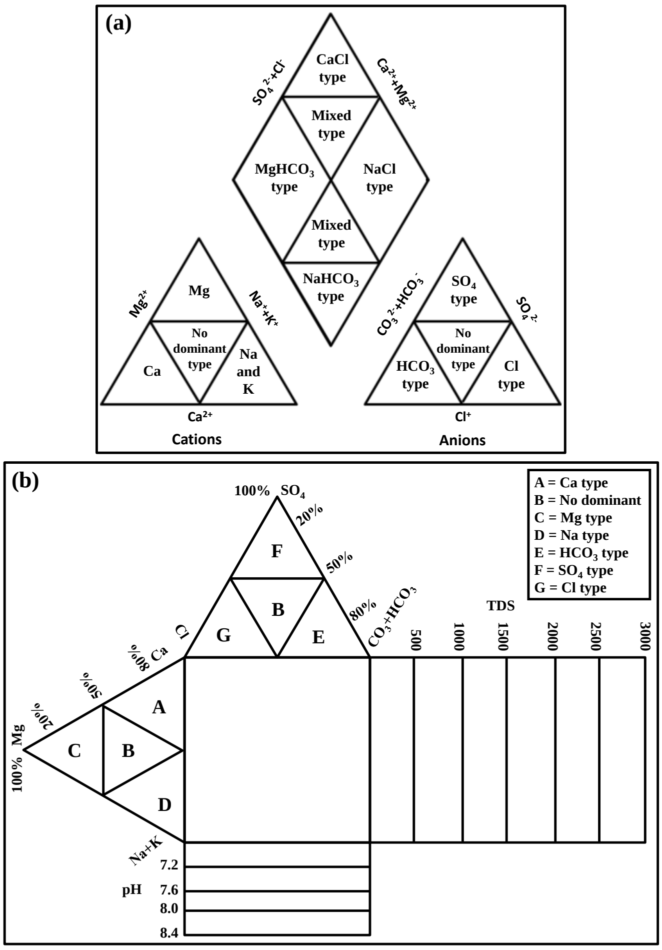

Figure 1: Diagrams illustrating how to determine the chemical composition of water (a) Piper diagram, and (b) Durov diagram

Objective

The goal of this paper is to propose the adoption of seismic geochemistry to promote sustainable development in Libya. Numerous studies [71,72] have demonstrated the importance of seismic geochemistry in supporting sustainable development. Fig. 5 shows a flowchart of seismic geochemistry as a sustainable development tool in Libya.

The country of Libya is known for having low to moderate seismic risk, but it has been affected by powerful earthquakes in the past. Being near the point of intersection between the African and Eurasian tectonic plates, there is a higher occurrence of seismic activity in the northern part of the country, especially near the coastlines. Geological and chemical studies associated with seismic activity in Libya require attention to the nature of the geological formation below the surface. This includes studying the elemental composition of shale rocks and how they move and are affected by the process of weathering. Another important topic in this area is the correlation between seismicity and the geological structure of the area, as well as stress and faulting mechanisms.

Application of Seismic Geochemistry in Libya

Support Sustainable Development in Libya

The use of seismic geochemistry can be an avenue for sustainable development in Libya through the enhancement of hydrocarbon exploration and resources management. However, seismic geochemistry can also serve other purposes such as conducting risk assessments as well as groundwater assessments. Through the interpretation of data from seismology and well geochemistry, geochemists will be able to analyze the underlying geological structure of a certain region as well as reservoir parameters, thus making possible the prediction of hydrocarbon-rich regions that can be exploited with minimal environmental impact. Seismic geochemistry can also provide useful data for conducting environmental impact assessments and groundwater analysis.

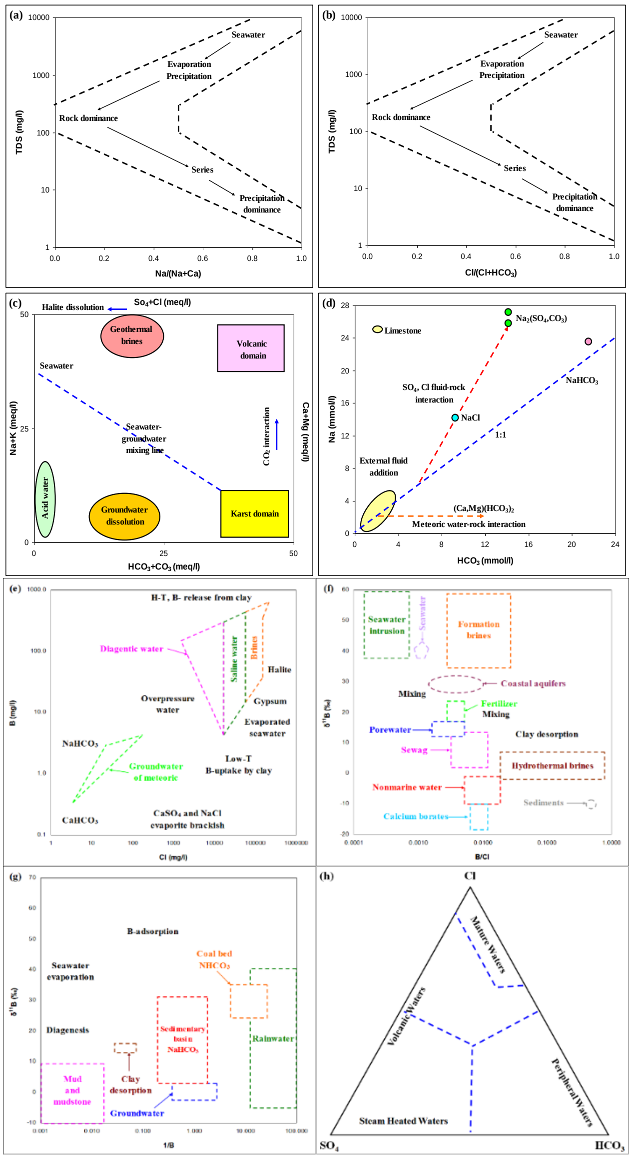

Figure 2: Diagrams showing how to define the source of dissolved solids in water ((a) Na/(Na+Ca) vs. TDS [55], (b) Cl/(Cl+HCO$_3$) vs. TDS [55], (c) Langelier-Ludwig diagram [56], (d) HCO$_3$ vs. Na [57], (e) Cl versus B [58], (f) B/Cl versus δ^{11}B [58], (g) 1/B versus δ^{11}B [59], and (h) Cl-SO4-HCO$_3$ ternary diagram [60])

Sustainable hydrocarbon exploration and management using the technique of seismic geochemistry in Libya could be outlined as follows:

(1) Enhanced modeling: The integration of seismic and geochemical studies as well as well data would enable us to construct high-quality three-dimensional models of subsurface formations that will enhance our ability to predict reservoir characteristics and understand geological processes influencing seismic activity.

(2) Efficient hydrocarbon resource extraction: With a higher level of information provided by seismic geochemistry, it will become easier and more efficient to extract hydrocarbons. Thus, fewer wells will be needed, which will decrease the footprint of exploration activities.

(3) Minimal environmental damage: As a result of more efficient hydrocarbon resource management, there will be minimal damage to the environment from exploration and extraction activities.

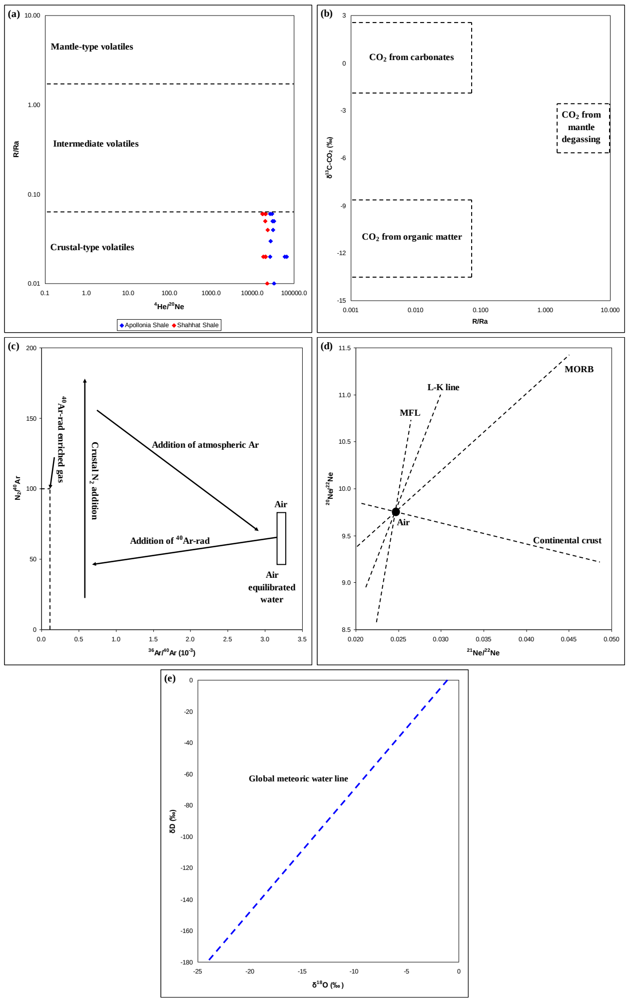

Figure 3: Diagrams used to identify the origin of gases ((a) ^{4}He/^{40}Ne vs. R/Ra [61], (b) R/Ra vs. δ^{13}C-CO$_2$ [62], (c) ^{36}Ar/^{40}Ar (10^{-3}) vs. N$_2$/^{40}Ar [63], (d) ^{21}Ne/^{22}Ne vs. ^{20}Ne/^{22}Ne [63], and (e) δ^{18}O vs. δD [64])

Environmental risk assessment using seismic geochemistry in Libya can be summarized in the following manner:

(1) Hazard identification: Seismic techniques can be applied in identifying seismogenic structures and hazards such as faults and fractures. These data are necessary in determining seismic risks in various regions and in deciding how structures are constructed in those regions.

(2) Subsurface geology mapping: Seismic attribute analysis can be used in mapping the extent of subsurface structures that could serve as routes for contaminants to move out of industrial facilities.

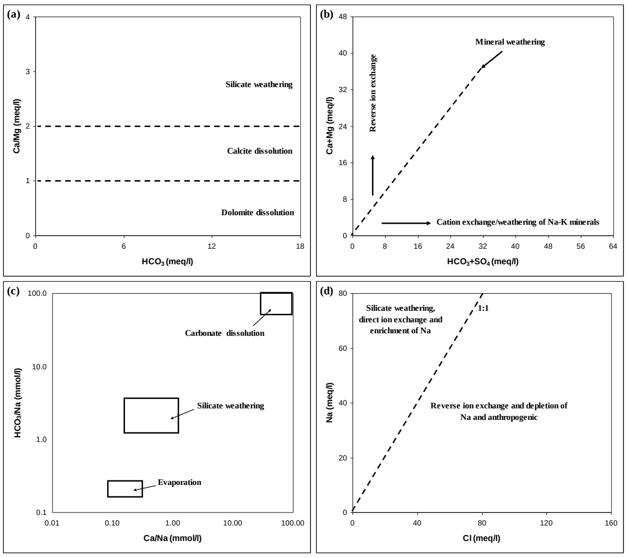

Figure 4: Diagrams used to illustrate the influence of mineral weathering and ion exchange processes on the water chemistry ((a) HCO_3 vs. Ca/Mg [65], (b) HCO_3+SO_4 vs. Ca+Mg [66], (c) Ca/Na vs. HCO_3/Na [67], and (d) Cl vs. Na [68])

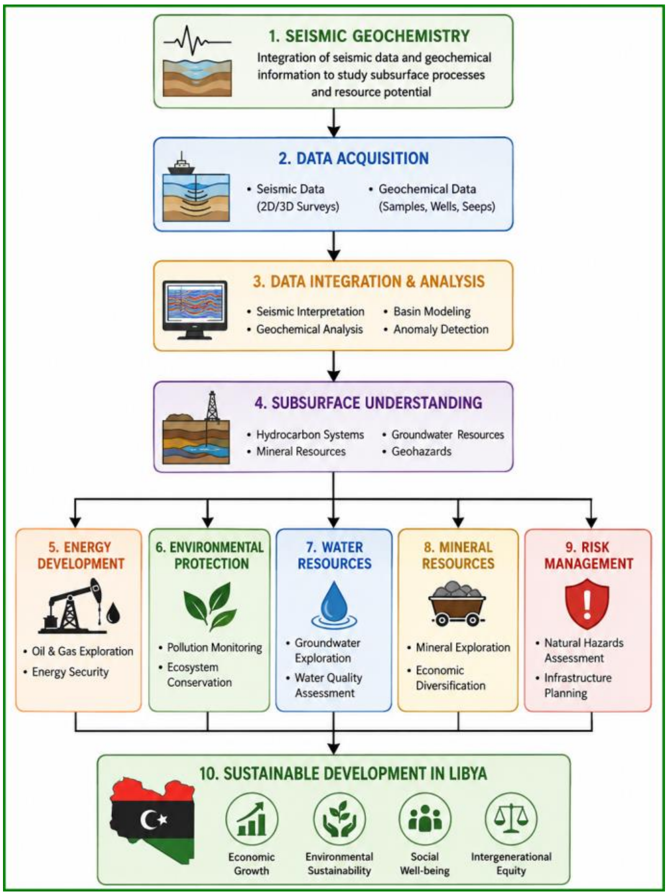

Figure 5: Flowchart of seismic geochemistry as a sustainable development tool in Libya

The main applications of seismic geochemistry in groundwater resource management in Libya are as follows:

(1) Water-rock interaction study: Seismic geochemistry can be applied for studying water-rock interaction. Such knowledge is essential in protecting water sources from contamination by other natural elements as it is necessary to ensure protection of underground water resources in arid countries such as Libya.

(2) Groundwater quality assessment: By combining data on seismic activities, geochemistry, and wells, one can define contaminated areas and assess future changes in groundwater chemistry related to subsidence of the land surface and improper maintenance of wells.

Conclusions

In order to facilitate sustainable development in Libya, it is advised to use seismic geochemistry methods. Researches into Libyan seismic geochemistry must focus on the geological and chemical composition of the subsurface to understand the nature of the seismicity in the region. For further analysis of weathering processes and element migration in connection with seismicity, it would be reasonable to look into shale formation trace elements. Interaction between geological formations and seismicity and between seismic phenomena and stress/faulting systems is an equally interesting research issue. Fluid effects can often be analyzed using seismic data. The key way in which seismic geochemistry can facilitate sustainable development in Libya is the enhancement of hydrocarbon exploitation. Seismic geochemistry techniques can also be helpful for assessing environmental hazards and water resources. Seismic data can be employed in combination with geochemical and well data to provide better structural mapping, reservoir prediction, and determination of locations where hydrocarbons may be found. This will enable more efficient extraction with fewer environmental costs incurred. Seismic geochemical methods can also be applied in water resources research for determining the groundwater chemistry and risks of pollution as well as for the assessment of environmental hazards due to subsurface geological formations.

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