Innovation
2025, Vol. 6, No. 4, pp. 165–170
https://doi.org/10.11648/j.innov.20250604.13

Review Article

Assessment of Volcanogenic Sulphur Resource Potential in the Ethiopian Rift

Gera Techane*, Gutema Mekonen, Lijalem Yirga, Megersa Bedo, Meaza Girmay, Enatfenta Melaku, Bisrat Kebede

Ministry of Mines, Mineral Industry Development Institute, Addis Ababa, Ethiopia

Abstract

Ethiopia's geological structure, situated within the East African Rift System, features significant but poorly quantified reserves of both native sulfur and sulfate minerals. This paper presented a comprehensive synthesis and a critical reevaluation of historical exploration records from the 1960s to current assessments, aiming to clarify the nation's sulfur resource. We compiled and analyzed various reserve estimates from key volcanic locations such as Dallol, Chebrit Ale, and Dofan, which fluctuate dramatically from 1,200 tons to an estimated 7 million tons, highlighting crucial uncertainties due to inconsistent methodologies and limited systematic drilling. Our analysis confirmed the presence of native sulfur associated with hydrothermal activities within evaporite sequences. The study also pinpoints considerable non-volcanic sulfate resources, encompassing extensive gypsum/anhydrite and kieserite deposits, which present a vital alternative source. At the same time, we examine the rising domestic demand in Ethiopia, estimating a possible annual consumption of approximately 20,500 tons to facilitate the national fertilizer blending initiative and current industrial applications, primarily for sulfuric acid production. This demand is presently met entirely through imports, resulting in a significant financial burden and strategic vulnerability. The gap between the uncertain resource base and the evident increasing demand underscores a critical challenge for the nation. We recommend prioritizing systematic geological mapping and employing modern exploration methods that integrate sulfur extraction with other mineral resources to enhance economic viability and further national development goals.

Keywords

Sulphur, Volcanogenic, Resource Assessment, Danakil Depression, Ethiopian Rift, Fertilizer, Industrial Demand, Sulphate Minerals

1. Introduction

Sulphur is a critical raw material for modern industrial economies, primarily use to produce sulphuric acid. Sulphuric acid is treated as a fundamental inorganic chemical used in various industrial applications. It is the world's most widely used industrial chemical [1, 2]. Its applications ranges from fertilizer production (phosphoric acid, ammonium sulphate), to metal processing, petroleum refining, and diverse chemical industries [3]. For developing nations like Ethiopia, securing a domestic source of sulphur helps to reduce import dependency, improve agricultural development, and also establish the foundation for a domestic chemical industry.

Ethiopia's geology, which is the tectonically and volcani-

*Corresponding author: geratechane@gmail.com (Gera Techane)

Received: 20 September 2025; **Accepted:** 30 September 2025; **Published:** 9 December 2025

cally active East African Rift System, provides a favourable setting for sulphur mineralization. Occurrences are mainly of volcanogenic origin, allied with fumarolic activity, with additional substantial potential in evaporative sulphate minerals [4, 5]. Historical exploration efforts made during the 1960s which was led by the Ethiopian Geological Institute (EGI) and international companies, generated valuable but fragmented geological data focused principally on Danakil Depression. Despite data's of geological surveys and small-scale mining undertaken previously on sulphur; the full extent, grade, and economic viability of Ethiopia's sulphur resources remain inadequately quantified.

This paper aims to bridge these knowledge gaps by integrating these fragmented historical data into a comprehensible national assessment. We compile and analyze the existing EGI exploration reports to (a) define and quantify the geological sulphur resource potential, (b) analyze the current and projected domestic demand from agricultural and industrial sectors, and (c) provide recommendations for future exploration and strategic development.

2. Geological Setting

The distribution of native sulfur in Ethiopia is primarily influenced by the Quaternary volcanism found in the Main Ethiopian Rift (MER) and the Afar Depression. This geological setting has led to the formation of various volcanic centers known for their vigorous fumarolic and solfataric activity, which contribute to sulfur accumulation through sublimation and interactions between water and rock [6]. The Danakil Depression, specifically, offers an exceptionally distinct geological environment due to its arid conditions, extreme thermal features, and tectonic activity within the rift zone [7, 8]. The significant volcanic activity, fueled by the rifting of the African and Arabian tectonic plates, supplies vital energy and raw materials, with locations such as Dallol, Erta Ale, and Dofan generating extreme heat and releasing important gases such as hydrogen sulfide and sulfur dioxide [9, 10].

The volcanic gases are then initiated by a widespread network of hydrothermal activity. A comprehensive system of fumaroles, hot springs, and underground fractures serves as the crucial pathway, carrying sulphur-rich gases and extremely hot fluids to the surface [11, 6]. This ongoing, dynamic movement of mineral-rich solutions, driven by heat from magmatic sources, is the fundamental mechanism that enables the transportation of sulphur compounds and prepares for their eventual deposition through processes such as boiling, cooling, and water-rock interaction [12, 13].

The final and essential element necessary for the development of significant deposits is the existence of a thick and extensive layer of evaporites, predominantly halite (rock salt), which predominates the subsurface geology [14, 15]. This formation acts as a highly permeable and chemically reactive host rock that allows hydrothermal fluids to circulate and interact efficiently. The interaction between the rising acidic, sulfur-rich fluids and the dissolvable evaporite minerals establishes the perfect chemical conditions, resulting in the oxidation of H_2S and the subsequent formation of the area's remarkable native sulfur deposits [16, 17].

Sulphur mineral deposits in Ethiopia are primarily found within the young volcanic formations of the Aden Series, which consist of trachyte, rhyolite, basalt, pumice, and tuff [18]. The proposed genetic model suggests that acidic fumarolic gases transform the surrounding rock into clay and deposit elemental sulphur in the resulting cavities and fractures [6]. Mineralization is typically found filling porous rocks such as trachytes and pumice on the floors of craters and throughout fracture systems on volcanic cones [19]. Major volcanic-hosted deposits are mainly located in the Afar region, including areas like Dallol and Chebrit Ale in the Danakil Depression, the Dofan Volcano, and the Erta Ale Massif, with additional isolated deposits noted at Jangudi Mountain and Manda [12]. The interaction of these fumarolic fluids with large subsurface halite (salt) sequences alters this process in a unique way in the Danakil's hyper-arid environment [20].

Furthermore, Ethiopia is home to substantial non-volcanic sulphate mineral deposits in sedimentary basins, which serve as an essential alternate source of sulfur. Gypsum/anhydrite ($CaSO_4$) is the most significant of these; it is found in large quantities in the Mugher Valley and the Blue Nile region, and its reserves are thought to be in the billions of tons [21]. Other significant resources include salt cake (Na_2SO_4) and kieserite ($MgSO_4$ H_2O), which is linked to potash layers in the Danakil's Salt Valley and has reserves in the tens of millions of tons [22].

3. Review of Known Occurrences and Estimated Potential

3.1. Native (Volcanogenic) Sulphur Deposits

The native sulphur deposits of Ethiopia, primarily situated in the Danakil Depression, exhibit highly variable resource estimations. This inconsistency is due to different exploration periods, methodologies, and interpretations which makes the overall national assessment challenging. The historical data can be considered inadequate for generating a quantitative resource estimate compliant with modern standards. Consequently, the entire potential of these volcanogenic deposits is therefore still uncertain.

Dallol Mountain, the area with the most historical exploration, underwent drilling in the 1960s, facing substantial technical issues, such as erupting of boiling water and lack of adequate infrastructure, such as access roads. Although surface indications are abundant, the deeper resource is structurally controlled and inadequately defined, with estimates suggesting around 200,000 tons of probable ore. At Chebrit Ale, an impressive historical projection of 7 million tons of high-grade sulphur has not been verified. Moreover, the

Dofan Volcano illustrates the discrepancies in estimates, as initial optimistic reserve figures in the millions were significantly lowered after thorough investigations revealed that the high-grade superficial zones were primarily depleted, resulting in an estimated total of about 3 thousand tons.

The collective data indicates a prospective region where historical estimates are highly unreliable, that requires extensive modern exploration techniques to define any economically feasible resources for future development.

Table 1. *Summary of selected native sulphur deposit in Ethiopia.*

Location	Estimated Reserve (tons)	Grade (% S)	Notes
Dofan (Outcrop 1)	1,349	26.7	Potential area only
Dofan (Outcrop 2)	1,200	8.66	-
Dofan (Outcrop 3)	70	6.4	-
Dallol	200,000 (probable)	18-40	Associated with salts and clay
Chebrit Ale	7,000,000 (reported)	90	Unverified historical estimate

Source: Ethiopian Geological Institute (EGI)

3.2. Sulphate Mineral Resources

The exploitation of sulphate minerals represents a crucial alternative pathway for sulphur production, though it is often more energy-intensive. The vast gypsum and anhydrite resources could be used for sulphuric acid production, particularly if coupled with cement manufacturing that can utilize the lime (CaO) byproduct. The kieserite resources are directly valuable as a magnesium-sulphate fertilizer and could be a byproduct of future potash mining in the Danakil. Moreover, the historical focus on native sulphur created a significant data gap in the assessment of these alternative sources.

4. Global Context and Domestic Demand Analysis

4.1. Global Context of Sulphur

The production landscape of elemental sulfur, which serves as the main raw material for sulfuric acid, has seen a significant transformation in the last five decades. Traditionally, sulfur was extracted using the Frasch process (involving superheated water injection) or sourced from volcanic origins. However, increasing environmental regulations on fuel quality, particularly requirements to lower sulfur levels in transportation fuels have reshaped the sector. Nowadays, more than 90% of the global sulfur supply is a by-product obtained from the desulfurization processes of natural gas and crude oil [23]. This change means that the availability of sulfur is now inversely related to trends in the energy market; a shift towards low-sulfur fuels or a decline in oil and gas refining can limit sulfur supply, subsequently affecting the costs of sulfuric acid production and the global marketplace [24].

Sulfuric acid is universally regarded as the most produced chemical in the world, both in terms of quantity and industrial use, earning it the title "the king of chemicals." Its yearly production has become a well-recognized key performance indicator for assessing a nation's industrial capability and economic progress, especially within agriculture and heavy industry [25]. Current market evaluations reveal that the global market volume was approximately 260 million metric tons in 2021, with forecasts indicating an increase to around 314 million metric tons by 2029 [26]. This growth trend is around 20 million metric tons annually, is mainly fueled by increasing worldwide demand for phosphate fertilizers, which make up the majority of usage, in addition to growth in metal leaching and chemical production, especially in developing economies [27].

The agricultural sector significantly drives the demand for sulfuric acid because it is crucial for converting phosphate rock into phosphoric acid, which is a vital ingredient for phosphate fertilizers such as diammonium phosphate (DAP) and triple superphosphate (TSP). This particular use accounts for approximately 60-70% of worldwide production [28]. In addition to its role in fertilizers, sulfuric acid is critical across numerous other industries. In metallurgy, it is utilized for leaching ores of copper, uranium, and nickel. It serves as an essential reagent in the chemical synthesis of various products including pigments and plastics, involved in petroleum refining for processes like alkylation and purification, and is used in wastewater treatment [29]. Therefore, the sulfuric acid market directly mirrors the conditions of the global agriculture, mining, and industrial manufacturing industries.

4.2. Analysis of Domestic Sulphur Demand

Ethiopia's agricultural sector is the main driver of the country's domestic demand for sulfur, particularly for the production of sulfur-based fertilizers like NPS (Nitrogen, Phosphorus, Sulfur). The national soil fertility mapping project (EthioSIS) has identified widespread sulfur shortages across a significant portion of the nation's agricultural land [30]. As a result, the government's transition from a one size fits all approach of applying DAP and urea to customized blended fertilizers has made sulfur an essential macronutrient. This shift has led to a steady and increasing demand for sulfur to be added to locally blended fertilizers such as NPS + Zn + B, which are now routinely recommended for areas like Tigray, Amhara, Oromia, and SNNP. The anticipated local demand for fertilizer is projected to reach as much as 2.2 million metric tons by 2025, which has a direct impact on the requirements for sulphur. Since the recommended formulations for most areas consist of sulphur-based compounds, a considerable portion of this overall demand will require sulphur imports for blending facilities. Currently, the supply chain relies entirely on imports, as there is no documented local production of elemental sulfur or sulfuric acid [31].

Ethiopia meets its entire sulfur requirement for the production of sulfuric acid through imports, as there are currently no functioning local sources. The only sulfuric acid manufacturer in the country, Awash Melkassa Chemical Factory (AMCF), depends completely on imported elemental sulfur, which is mainly obtained from Saudi Arabia, Russia, and Turkey. To maintain its sulfuric acid production capacity of 17,000 tons per year, the factory needs roughly 6,000 tons of sulfur annually. Import statistics from the past ten years (2014–2023) indicate that an average of 14,543 metric tons of sulfur and sulfur products was brought in each year, costing the nation approximately $6.5 million USD annually. This ongoing importation imposes a considerable burden on Ethiopia's limited foreign currency reserves.

Previous studies by Ethiopian Geological Institute showed presence of local sulphur reserves, including the volcanic deposits in Dofan (which are estimated to 2,600 tons) and also significantly larger reserves in the Dallol and Danakil depressions (estimated a total of 7.2 million tons); however, these resources have not been commercially developed. Currently Ethiopia is fully dependent on imports to fulfill its sulphur requirements for both the fertilizer and industrial sectors. Moreover, the potential for future increases in sulphur demand is significant but still untapped; satisfying the current fertilizer needs of the country would necessitate 1.5 million tons of sulfuric acid, indicating a substantial corresponding need for sulphur [31]. This highlights a tremendous opportunity for reducing imports and fostering economic growth if local sulphur resources can be developed commercially. Until that happens, Ethiopia's demand for sulphur will remain an expensive, import-reliant for both agricultural and industrial sectors.

5. Discussion: Synthesis and Economic Implications

This integrated assessment underscores a significant gap between Ethiopia's recorded sulphur resource potential and its strategic industrial goals. The analysis reveals a critical paradox although the country is situated within a geologically promising rift system, it completely relies on imports for a crucial commodity essential to its agricultural and industrial progress [30, 32]. The substantial differences in past reserve estimates; from 1,200 tons at Dofan to a claimed 7 million tons at Chebrit Ale are not just discrepancies but indicate a total absence of modern resource definitions. The challenges faced at Dallol during the 1960s, such as drilling hazards and insufficient infrastructure, continue to be relevant today. As a result, no economically feasible native sulphur deposit can be asserted until comprehensive exploration using modern methods is carried out. At the same time, the potential of sulphate minerals (gypsum, anhydrite, kieserite) has historically been underestimated. Although their processing requires more energy, their reserves are significantly larger and better documented, and their development could align well with Ethiopia’s expanding cement industry or prospective potash extraction [33, 34].

The analysis of demand provides a strong and convincing economic rationale for intervention. The current Ethiopia's yearly imports of more than 2,250 tons of raw sulphur signify a persistent depletion of foreign currency reserves for a specific industrial component. Even more importantly, the anticipated requirement of roughly 20,500 tons annually to facilitate the fertilizer blending initiative and industrial expansion will dramatically escalate this financial strain and heighten the nation's susceptibility to fluctuations in global sulphur prices [31]. The economic implications are twofold; establishing a domestic source of sulphur acts as a strategic approach to mitigate risks associated with supply chain interruptions and unpredictable global markets, while also facilitating the development of a local value chain. It is essential for the cost-effective production of sulphuric acid, which is fundamental to both the fertilizer sector and other industries, thus promoting overall economic growth.

The conventional exploration approach, which concentrates solely on locating and extracting high-quality native sulphur, is not financially viable for Ethiopia's unique deposits. This assessment calls for a shift in strategy towards a more comprehensive, demand-oriented exploration and development method. Emphasis should be given on systematic modern exploration techniques, such as targeted geological mapping and drilling, to accurately define compliant resources. According to [35], it must also incorporate synergistic development, considering sulfur not in isolation but as part of a resource cluster, such as co-locating with geothermal energy for processing or integrating with future potash mining or cement manufacture. To concentrate efforts on the most promising deposits and easily exploitable alternatives, strategic prioritization based on a thorough cost-benefit analysis is crucial.

Moreover, this synthesis indicates that although Ethiopia has a suitable geological environment for sulphur, it currently does not have a quantified, economically feasible resource base to satisfy its increasing domestic need. The nation's dependence on sulphur represents a serious strategic risk that obstructs its agricultural and industrial progression. The economic consequences are obvious: a persistent reliance on imports creates a costly long-term burden. Hence it is recommended to encourage integrated projects that combine sulphur extraction with geothermal energy or other mining activities, and facilitate pilot studies for processing sulphate minerals suited to the Ethiopian context.

Bridging the gap between Ethiopia's unpredictable sulphur resources with its certain demand is not just a geological issue but also an essential economic necessity. The way ahead involves looking beyond past data and embracing a comprehensive, innovative strategy for resource development that aligns with national objectives for food security and industrial advancement. This will necessitate a unified effort to convert geological potential into a measurable and economically sustainable resource that can drive Ethiopia's agricultural and industrial expansion.

6. Conclusion

This research reveals although Ethiopia has substantial geological potential for both volcanogenic and sulphate sulfur resources within the East African Rift System, the historical data remains inadequate to establish any measurable, economically viable resource base that could fulfill the nation's increasing domestic needs. The significant variations in historical reserve estimates, ranging from 1,200 to 7 million tons, underscore serious uncertainties and a critical lack of up-to-date, compliant resource characterization, which leaves the country reliant on expensive imports that deplete foreign currency reserves and expose it to strategic risks from global market fluctuations. Consequently, addressing the disparity between this uncertain resource base and the rising demand of sulphur for agricultural and industrial development is not just a geological issue but a vital economic necessity that demands a transformative shift from disjointed historical evaluations to a cohesive, demand-oriented exploration and development approach.

Abbreviations

EGI	Ethiopian Geological Institute
MER	Main Ethiopian Rift
H_2S	Hydrogen Sulfide
SO_2	Sulfur Dioxide
$CaSO_4$	Calcium Sulfate (Gypsum/Anhydrite)
Na_2SO_4	Sodium Sulfate (Salt Cake)
$MgSO_4 \cdot H_2O$	Magnesium Sulfate Monohydrate (Kieserite)
CaO	Calcium Oxide (Lime)
DAP	Diammonium Phosphate
TSP	Triple Superphosphate
NPS	Nitrogen, Phosphorus, Sulfur fertilizer
SNNP	Southern Nations, Nationalities, and Peoples' Region (Ethiopia)
AMCF	Awash Melkassa Chemical Factory
MoANR	Ministry of Agriculture and Natural Resources (Ethiopia)
EthioSIS	Ethiopian Soil Information System
USGS	United States Geological Survey
ICIS	Independent Chemical Information Service

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Apodaca LE. Sulfur. In: U.S. Geological Survey Mineral Commodity Summaries 2022. U.S. Geological Survey; 2022. p. 158-159. https://doi.org/10.3133/mcs2022

[2] Chenier PJ. Sulfur and Sulfuric Acid. In: Survey of Industrial Chemistry. 3rd ed. Springer; 2002. p. 45-57. https://doi.org/10.1007/0-387-23816-6_2

[3] Kucera J. Sulfuric Acid. In: Kirk-Othmer Encyclopedia of Chemical Technology. John Wiley & Sons; 2000. https://doi.org/10.1002/0471238961.1921120619011405.a01

[4] Barberi F, Varet J. The Erta Ale Volcanic Range (Danakil Depression, Northern Afar, Ethiopia). Bulletin Volcanologique. 1970; 34(4): 848-917. https://doi.org/10.1007/BF02596700

[5] Holwerda JG, Hutchinson RW. Potash-Bearing Evaporites in the Danakil Area, Ethiopia. Economic Geology. 1968; 63(2): 124-150. https://doi.org/10.2113/gsecongeo.63.2.124

[6] White DE. Environments of Generation of Some Base-Metal Ore Deposits. Economic Geology. 1968; 63(4): 301-335. https://doi.org/10.2113/gsecongeo.63.4.301

[7] Barberi F, Ferrara G, Santacroce R, Varet J. A Transitional Basalt-Pantellerite Sequence of Fractional Crystallization, the Boina Centre (Afar Rift, Ethiopia). Journal of Petrology. 1975; 16(1): 22-56. https://doi.org/10.1093/petrology/16.1.22

[8] Varet J. Geology of central and southern Afar (Ethiopia and Djibouti). CNRS; 1978.

[9] Hutchinson RW, Engels GG. Tectonic Significance of Regional Geology and Evaporite Lithofacies in Northeastern Ethiopia. Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences. 1970; 267(1181): 313-329. https://doi.org/10.1098/rsta.1970.0036

[10] Martini M. Volcanic Gases. In: Encyclopedia of Volcanoes. Academic Press; 2000. p. 803-815.

[11] Giggenbach WF. Redox processes governing the chemistry of fumarolic gas discharges from White Island, New Zealand. Applied Geochemistry. 1987; 2(2): 143-161. https://doi.org/10.1016/0883-2927(87)90030-8

[12] Ethiopian Geological Institute (EGI). Sulphur Exploration in the Dofan Volcanic Area, Afar Region. Unpublished Internal Report; 1982.

[13] Hedenquist JW, Lowenstern JB. The role of magmas in the formation of hydrothermal ore deposits. Nature. 1994; 370(6490): 519-527. https://doi.org/10.1038/370519a0

[14] Bosworth W, Huchon P, McClay K. The Red Sea and Gulf of Aden Basins. Journal of African Earth Sciences. 2005; 43(1-3): 334-378. https://doi.org/10.1016/j.jafrearsci.2005.07.020

[15] Talbot CJ. Halokinesis and thermal convection. Nature. 1978; 273(5662): 739-741. https://doi.org/10.1038/273739a0

[16] Warren JK. Evaporites: Sediments, Resources and Hydrocarbons. Springer; 2006. https://doi.org/10.1007/3-540-32344-9

[17] Rona PA. Criteria for recognition of hydrothermal mineral deposits in oceanic crust. Economic Geology. 1978; 73(2): 135-160. https://doi.org/10.2113/gsecongeo.73.2.135

[18] Kazmin V. Geology of Ethiopia: A Review and Geomorphological Perspectives. Ethiopian Institute of Geological Surveys; 1973.

[19] Ethiopian Geological Institute (EGI). Assessment of Sulphur Occurrences in the Dallol Area, Danakil Depression. Unpublished Internal Report; 1975.

[20] Talbot CJ, Ghebreab W, Oluwole AF. Geology and Mineral Resources of the Danakil Depression, Ethiopia. Journal of African Earth Sciences. 2009; 55(5-6): 159-170. https://doi.org/10.1016/j.jafrearsci.2009.04.004

[21] Ministry of Mines and Energy (MME). Industrial Minerals of Ethiopia. MME Bulletin; 1996.

[22] Garrett DE. Potash: Deposits, Processing, Properties and Uses. 1st ed. Springer; 1996. https://doi.org/10.1007/978-94-009-1545-9

[23] Ober JA. Sulfur. In: U.S. Geological Survey Minerals Yearbook 2017. U.S. Geological Survey; 2017. https://doi.org/10.3133/myb2017

[24] The Fertilizer Institute. Sulfur and Sulfuric Acid Market Trends. 2020. Available from: https://www.tfi.org/

[25] Wagenfeld J-G, Al-Areqi WM, Slavens A, Ghamkhar R, Crispo A. Sulfuric Acid Production: A Vital Measure of National Industrial Development. Industrial & Engineering Chemistry Research. 2019; 58(34): 15653-15666. https://doi.org/10.1021/acs.iecr.9b01413

[26] Market Research Future. Sulfuric Acid Market Research Report - Forecast to 2029. 2022.

[27] International Fertilizer Association (IFA). Fertilizer Outlook 2021-2025. IFA; 2021.

[28] European Fertilizer Manufacturers Association (EFMA). Production of Sulfuric Acid. In: Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry; 2000.

[29] King M, Davenport WG, Moats MS. Sulfuric Acid Manufacture: Analysis, Control and Optimization. 2nd ed. Elsevier; 2013.

[30] Ethiopian Soil Information System (EthioSIS). Soil Fertility Status and Fertilizer Recommendation Atlas for Ethiopia. ATA; 2016.

[31] Fertilizer Roadmap. (2016). National Technological Roadmap for Fertilizer Industry. Ministry of Science and Technology.

[32] Tadesse, S., Milesi, J. P., & Deschamps, Y. (2003). Geology and mineral potential of Ethiopia: a note on geology and mineral map of Ethiopia. Journal of African Earth Sciences, 36(4), 273-313. https://doi.org/10.1016/S0899-5362(03)00048-4

[33] Holwerda, J. G., & Hutchinson, R. W. (1968). Potash-bearing evaporites in the Danakil area, Ethiopia. Economic Geology, 63(2), 124-150. https://doi.org/10.2113/gsecongeo.63.2.124

[34] Tadesse, S. (2016). Industrial Mineral and Rock Resources of Ethiopia. Ethiopian Institute of Geological Surveys, Bulletin No. 4.

[35] Giordano, G., Cas, R., & Wright, J. V. (2024). The geology of volcanoes and their facies models: morphology, dynamics, evolution, successions, economic significance and hazards. In Volcanology: Processes, Deposits, Geology and Resources (pp. 1239-1426). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-11294-0_23