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# Challenges in Utilization of Precious Opal in Ethiopia: A Case Study from the Delanta Area, South Wollo, Ethiopia

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## ABSTRACT

Even if, the Delanta precious opal is promising natural resources for economic development and expansion of gemstone industry, there are serious problems faced in utilization of the resource. This study aimed to assess the major problems affecting the utilization of opal resources in Delanta district, Ethiopia, and to recommend possible solutions to the main actors of the sector. In this study, statistical methods and fishbone diagrams were employed and the data for the study was collected using interviews, focus group discussions, and physical observation. The results of the study revealed that there are problems which can be categorized into four main categories: mining technique related problems (opal cracking problem due to traditional mining tools, inappropriate handling, and land sliding accidents), market-related problems (such as poor national and international market attachment, meager promotion, unfair market price, corrupted and illegal marketing practices), problems related to value addition (shortage of modern lapidary machines, lack of domestic skills for jewelry production, poor monitoring mechanisms for value addition, low local market price of value-added products and lack of access to sell value-added opal products to the international market and skill gaps of opal cutters) and problems related to lack of environmental impact assessment (deforestation, land degradation and pH change of land soil due to waste disposal). In general, the results of this study indicates that, even though the study area has a promising opal potential, problems related to marketing system, mining, and value addition practices are serious challenges hindered the surrounding community and the country as a whole not to utilize the resource properly.

***Keywords:*** Delanta, Lapidaries, Opal Utilization, Precious Opal, Value addition.

## INTRODUCTION

Opal gemstones (queen of gems) are water-bearing materials, composed of micro-spheres of hydrated silica ($SiO_2$*$nH_2O$) with a high degree of structural disorder (Leechman, 1984; Webster, 1975). Because of their optical properties, opal has been largely used in jewelry and as ornamental elements in art works. Opal utilization has a long history in Ethiopia like other countries: Greek, Rome and other countries (Caucia, 2012). Ethiopians used opal as expensive gifts for respected individuals like Kings, religious fathers and warriors. For example, in myth, it is usual for us to hear that the Queen of Sheba adorned herself using precious opal and she used opal as a gift to him during her visit to King Solomon in Jerusalem (Bergman, 2015). Even though, opal has long back history in Ethiopia, there are no enough researches conducted on it and recognitions have not given to the resource so as to earn foreign currency and to support Ethiopian economy. In world's opal industry, Australia is a well-known country and opal is a national gemstone for the country (Dutkiewicz et al., 2015) and currently producing about 95 % of the world's precious opal from widely scattered fields throughout the central Australia. In Ethiopia, beyond the myth, the first published report appeared in 1996 (Johnson et al., 1996) with a discovery of precious opal (dark brown in color) around North Shewa (Menz Gishe district). This opal was of volcanic origin, found mainly within weathered layers of rhyolite and had tendencies of cracking (Filin et al., 2009). Consequently; this opal became unpopular in the gem trade. After few years, Ethiopia has become known with new precious opal (opal with best play-of-color) discovered by farmers around Wegel Tena in northwestern part of Ethiopia in 2008 (Rondeau et al., 2010). However, there are serious problems encountered in utilization of the resource to support

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the economic development of the country. These problems are related to; marketing system problems (smuggling and unfair trade), mining process problems (traditional mining practice and cracking) and social problems (health and safety problems) as reported by world bank (Kyngdon-McKay et al., 2016). On the other hand, reports showed that the resource is exported widely to other counties like India, China and others unlawfully and sold in global market in the name of Ethiopian opal (Cross et al., 2010). In this regard, little work has been done on the problems those mired the country not to use the Delanta precious opal properly. Consequently, there are no sufficient and reliable published reports on this issue. The wastage of this valuable resource motivated the research team and paves the way for conduction of an assessment study focusing on identifying problems related to: mining practice, value addition processes, and marketing system in Delanta district.

In this work, we report the major problems hindering the country from efficient utilization of the Delanta opal by conducting statistical data analysis methods. The results of the data analysis revealed that traditional mining practice, lack of modern mining tools and techniques, lack of appropriate trainings to opal beneficiaries, uncontrolled market system, skill gap of opal cutters (lapidaries), weak and unclear legal frame works for opal market were the most serious problems. Moreover, different health related problems of opal miners, problems related to lack of environmental impact assessment and root causes for existing problems in opal business sector are presented.

## MATERIALS AND METHODS

### Geographical description of the study area:

Delanta district is one of the 22 districts of South Wollo administrative Zone. The main town of Delanta district is Wegel Tena. This town is located 98 km far away from Dessie (the capital city of South Wollo Zone in Amhara Regional State (ARS)), at a Universal Transverse Mercator (UTM) grid reference of 113541 Northing and 3911300 Easting coordinates and at an elevation of 2963 meters above sea level (Fig.1)..

### Geological description of Delanta:

The entire region around Wegel Tena consists of a thick (>3,000 m) volcano-sedimentary sequence of alternating layers of basalt and rhyolitic ignimbrite (Rondeau et al., 2010). Ignimbrite is a volcanic rock of andesitic-to-rhyolite composition that forms sedimentary-like layers after the volcanic plume collapses and falls to the ground. The particles that form this rock are a heterogeneous mixture of volcanic glass, crystals, ash, and rock fragments. This volcanic sequence was emplaced with the opening of the East African continental rift during the Oligocene epoch (Cenozoic age), about 30 million years ago (Yirgu, 2003; Ayalew, 2009). Over the entire volcanic series, only one very thin seam (<1 m thick), hosted by rhyolitic ignimbrite, is mineralized with opal (Rondeau et al., 2010). The study area field photograph is shown in Fig.2.

### Formation process of opals:

Until now, three main formation processes of crystallized opals mainly (opal-CT or -C)) have been identified: biological precipitation, hydrothermal alteration, and continental weathering. The main producers of biogenic silica are planktonic siliceous microorganisms (diatoms, radiolarians and silico-flagellates) accumulating in oceanic or lacustrine sediments at a rate that can be greater than 400 Mt per year (DeMaster, 2014). Biogenic opal is frequently constrained to oceanic and lacustrine

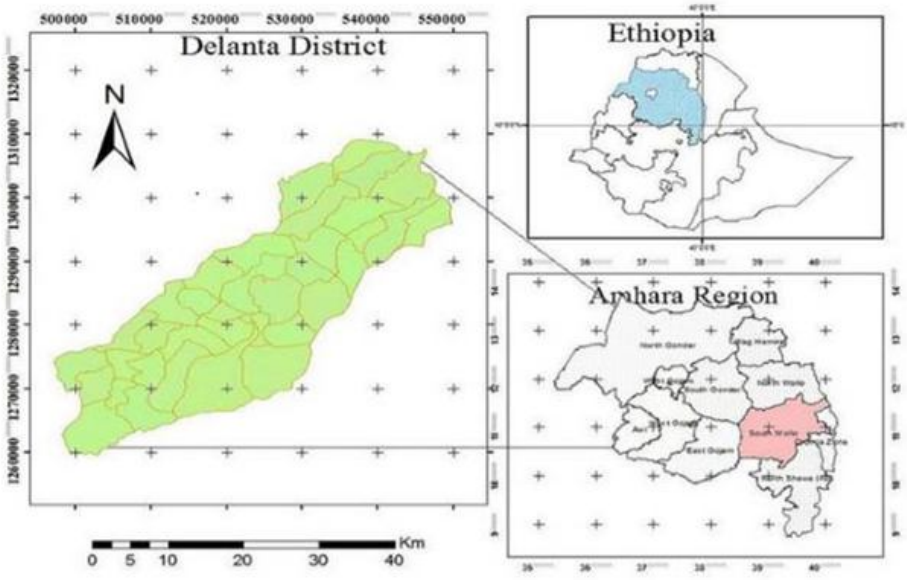


**Fig.1: Location map of Delanta District.**


**Fig. 2: A field photograph showing some parts of the mining sites in study area (Rondeau et al., 2010).**

contexts. Hydrothermal alteration is involved in amorphous silica precipitation in hot springs (e.g. geysers) and hydrothermal vents (e.g. black smokers (Lalou, 1991; Campbell et al., 2015). Supergene, continental weathering of rocks also dissolves primary minerals and liberates silica available for the formation secondary minerals, including opal (e.g. silcretes) (Thiry et al., 2006).

The difference between biogenic, hydrothermal, and continental weathering conditions may be ambiguous for opal samples in the field, because paleontological features are not always preserved in biogenic opal, and because hydrothermal alteration and continental weathering can generate rocks that appear similar in aspect, texture outline and mineralogical composition. This is true on Earth, where silica is used to develop a better understanding of past climate history (Robert et al., 2006) and even more striking on Mars, where observations are much more indirect (Milliken et al., 2008). Hence, several opal properties have been explored as possible proxies of opal genesis conditions. Both opal-A and opal-CT form through hydrothermal alteration and continental weathering (Jones et al., 2003). Hence, the type of opal (A or CT) is not of itself a useful criterion to infer its origin. Additionally, digenesis can superpose on the original formation processes, leading to the transformation of opal-A into opal-CT, in particular for biogenic opal (Lynne et al., 2004). Recently, several tools based on hydration features of opals and their related infrared signatures (Rice et al., 2013) have been proposed to differentiate hydrothermal opals from continental weathering opals, regardless of their structure (Opal-A or Opal-CT). From the economic point of view, a better understanding of precious opal formation may provide significant tools for gem opal exploration. A dozen deposits have been discovered in the Wegel Tena area, Ethiopia, within the last few years using small-scale, opportunistic, amateur exploration. But in the present, study the main focus is not on the formation process of rather the main focus is on the challenges of utilization.

**Data sources:**

In this study, the target population consisted of traditional opal miners, miners' association leaders, opal-cutters, and Delanta district authorities, mining officers and Technical Vocation Education and Training (TVET) center leaders. During data collection of this study, there were 27 opal miner associations engaged in traditional mining in Delanta district and all the association leaders have been interviewed. In order to collect representative data from miners, 12 miner associations were selected from the 27 miner associations by considering the homogeneous nature of the data found from interview of all the association leaders in the district. Again 10 respondents from each of the 12 miner associations; a total of 120 respondents were selected to collect data through structured questionnaires, interviews, and focus group discussions (Fig.3). Additionally, data were collected from focus group discussions with 5 opal-cutters in Wegel Tena, the principal of Wegel Tena TVET center, district administrator and 7 districts mining officers. Moreover, physical observations have been made in order to triangulate the collected data through questionnaires, interviews and focus group discussions.

**Fig. 3: A field photograph captured during data collection at Angot mining site.**

Moreover, geological survey was made for data collection from the different mining sites in the study area. Here GPS data were recorded to survey altitude of opal bearing layers in a given topography and geological setting in assessment basis.

**Data analysis:**

Data collected by interviews and physical observations during our site visit is analyzed qualitatively and those data collected by questionnaire were analyzed using statistical methods quantitatively. Hence, we used both qualitative and quantitative methods of data analysis. Furthermore, to understand the cause and effect relationship of the collected data, we have applied a fishbone diagram method.

**RESULTS**

**Mining related problems:**

In this section, data concerning mining problems in the study area is presented. As it is show in Table 1, the main problems related to mining practice includes: opal cracking due to traditional mining tools and inappropriate handling techniques,collapse hazards during opal mining and lack of trainings related to modern opal mining processes. Table 1 represents problems in percentage which are related to opal mining in the study area and the data was obtained from respondents through questionnaires. Furthermore, the data in Table 2 showsmining related problems identified during the study and recommended solutions by the researchers. The data was obtained from open-ended questions, focus group discussion, and field observations.

**Table 1: Percentages of responses for mining related problems**

| Identified Problems | % of the prevalence of the problem |
|---|---|
| Opal cracking problem during mining process due to traditional mining tools | 90.5% |
| Cracking problems due to inappropriate handling techniques after the opal being mined | 90% |
| Accidents due to land slide during opal mining | 89.5% |
| Lack of training related to opal mining | 91.7 |

**Market related problems:**

In this section, the assessment results related to opal market system and practices in the study area were presented (Table 3). The data presented in Table 3, denotes the main problems related to opal marketing system and practices in the study area. These problems includes: lack of market attachments for miners, poor market promotion for opal market and besmirched market system. The data was obtained from questionnaires and converted into percentages. The photograph images presented in Fig.4, cracked opals (Fig.4a), unpolished precious opals (Fig.4b) and polished precious opals (Fig.4c), were taken from the study area with different market prices. Furthermore, the pie chart in (Fig.5) denotes the percentage of main beneficiaries from opal market system in Delanta district.

**Value addition related problems:**

In this section, data related to value addition is presented. Here, the root cause for value addition problems includes: lack of modern lapidary machines, insufficient lapidary centers, lack of domestic skills for jewelry production, low demand of local market for value added opal products and the existence of smugglers are the main ones.The data in Fig.6, illustrates the root causes of existing

**Table 2: Additional mining related problems versus suggested solutions**

| S/N | Identified problems | Suggested solutions to overcome the problems |
|---|---|---|
| 1 | Traditional mining tools causing opal cracking | Miners have to use modern mining tools like jack hammer |
| 2 | Water leakage which causes difficulties to dig in the mining holes | Miners have to use water removing pump |
| 3 | Challenges to discard waste soil disposal | Miners have to use modern soil removing tools |
| 4 | Lack of training on opal mining and risk minimization | Miners need training on modern opal mining techniques and risk management |
| 5 | Difficulties in digging, removal of soil disposals and problems of air circulation due to Narrowness of the mining holes | Keep the height and width of the holes to the standard for ease of soil disposal and use ventilation system to avoid staffed |
| 6 | Eye injury, infectious disease on mouth(skin), serious head ache and etc. | Miners have to use eye goggle, helmet and safety work cloths |
| 7 | Problems of deforestation, land degradation, pH change of land soil due to waste disposal and coverage of agricultural fertile top soil around mining areas by waste soil that makes arable land non-productive due to mining practices without environmental impact assessments | Practice environmental protection measures like: use of disposal storage not to affect arable agricultural land, monitoring and site inspection of the mining sites and progressive site rehabilitation by afforestation, filling old holes and avoiding of digging in fragile landscapes |

**Table 3: Problems related to market attachment and promotion**

| S/N | Identified Problems | % of the prevalence of the problem |
|---|---|---|
| 1 | Lack of market | 68.4% |
| 2 | Poor market promotion for opal market like trade shows | 100% |

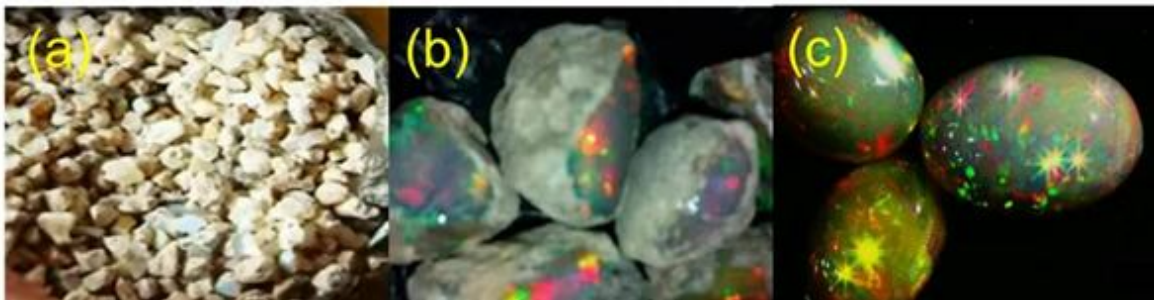


**Fig. 4: (a) Cracked (Ajara) opal sold in kilo grams, (b) Unpolished Delanta precious opals sold in grams, and (c) Polished precious opal with beautiful play of color sold in grams but not in carat.**

problems in opal business sector in Delanta district. The fishbone diagram was used to summarize the findings of this study (Loftus, 1990).

**Environmental impact assessment related problems:**

In this section, problems related to lack of environmental impact assessment are presented. As it is presented in Table 2, the identified problems resulted as a result of lack of environmental impact assessment includes: deforestation, land degradation, pH change of land soil due to waste disposal and coverage of agricultural land with fertile top soil by waste soil that makes arable land non-productive.

**DISCUSSION**

major problems which have big impacts on the gemstone industry. The data in Table 1 clearly shows that, in Delanta district opal cracking is a serious problem and the causes of cracking problems are mainly two. The first one was the use of traditional mining tools. From the total opal miners in different mining sites, 90.5% encountered opal cracking problems due to the use of traditional mining tools and techniques. The second case for the cracking problems was inappropriate handling techniques after the opal being mined. The analysis of the data collected on this particular problem showed (Table 1) that 90% of miners in different mining sites faced opal cracking problems related to inappropriate handling. Due to the inappropriate handling (majority of the miners expose the samples

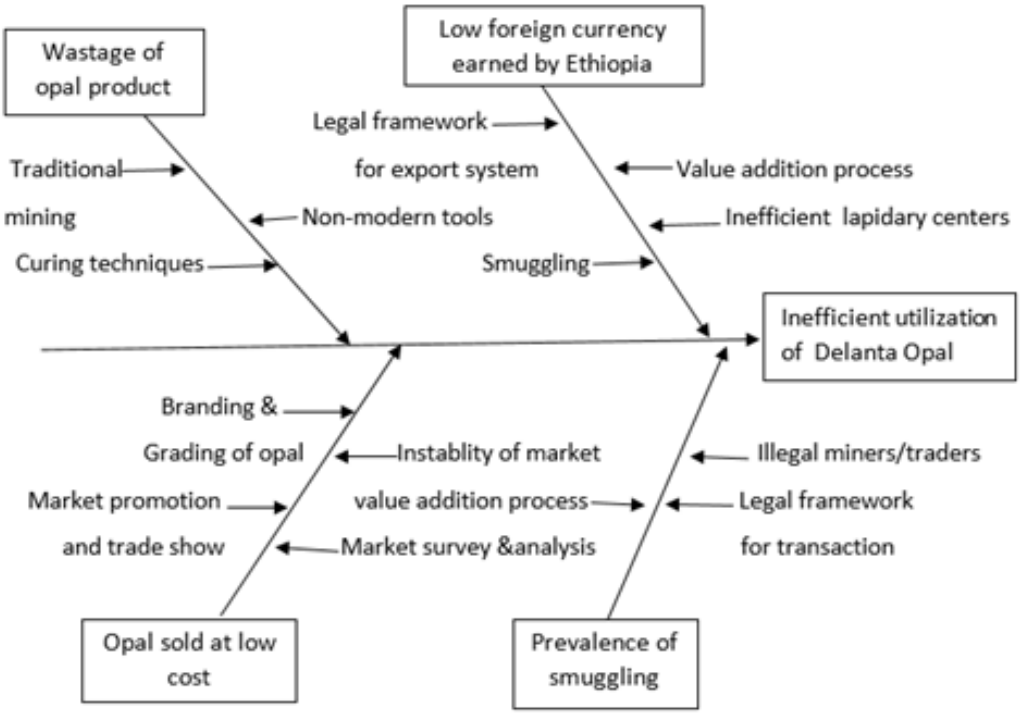


**Fig. 6: Fish bone diagram illustrating root cause of existing problems in opal business sector in Delanta district.**

**Challenges of mining practice:**

In Delanta district, there are many problems which are related to opal mining practices. In the present study, the researchers were only focused on the

to air without any care and few used plastics to cover samples), opals could be cracked due to its fragile nature as it is exposed to open air after being mined from host rock.

The percentages of the two cases of cracking problem indicate that opal cracking was a serious problem in mining process. As the data obtained from opal dealers, Woreda sales officers, cutters and other respondents of this study, the price of cracked opal is much lower than the price of non-cracked one due to the fact that opal price depend on 4c's (carat or size, color, clarity and cut).

In the words of one opal miner who always faces opal cracking problems: When we break the precious of opal (they call it gram eka) during mining process in the long and narrow mining hole with traditional mining tool, we feel like burring of birrs which can be counted in hundred thousand. This, in turn, is causing very low price of the cracked samples (the miners call it Ajara).

The other problem related to opal mining was miners faced accidents due to landslides hazards during traditional mining process in a very narrow holes (Alemu, 2018). As the data obtained from interview of association leaders (Table 1) showed that large number of miners (89.5%) faced accidents during mining activities and there was death report in some mining sites(Rondeau et al., 2010).

The main cause of collapse was traditional ways of mining. The miners did not care about the nature and bearing capacity of the pillars in the long horizontal holes. Since pillars in the holes are mandatory to prevent underground collapse, it must be tunneled systematically to avoid accidents (Rondeau et al., 2010). The data collected from respondents about precautions related to mining related problems revealed that the majority of miners (91.7%) did not take trainings on safety precautions and measures related to opal mining and how to prepare standard pillars in the holes. Moreover, miners were suffered from lot of problems related to mining practices mainly inside the mining holes. As presented in Table 2, difficulties to discard waste soil disposal, lack of air circulation due to narrowness of the mining holes, water leakage which causes troubles to dig in the mining holes, eye injury, infectious disease on mouth (skin), snake bite, respiratory diseases and serious head ache were the main challenges that the miners faced (Alemu, 2018).

**Challenges of market system:**

The market system was identified as a serious problem in the study area (Alemu, 2018; Kyngdon-McKay et al., 2016). From Table 3, it can be clearly observed that, in Delanata district, miners have very small market attachments; 68.4% of the miners do not have direct market attachments both nationally (local market) and internationally (foreign market). Furthermore, there were no market promotions (100%) by the miner associations to attract more customers for opal market all over the world. Since the miners have no awareness about the world's opal market, they shall sell their opal with relatively low prices ranged from 3 to 15 USD per gram of precious opals depending on the color of opals. On the other hand, as data obtained from opal miners, they were selling a kilogram of cracked opal (Ajara, Fig.4a) with a price of 23 to 1,330 USD. This wide variation in opal price was due to the carking level of opals during mining process.

Moreover, the researchers tried to examine groups who were highly benefitted among the different opal beneficiaries in the opal market by investigating the average net profit of the market participants. As it can be clearly seen from the pie chart (Fig.5), illegal sellers were the first level profiteers (36%) from the opal market and exporters were in the second level (28%). However, cutters, miners and legal sellers were 8%, 12% and 16% profiteers from the market, respectively. This shows that, how much the existing opal market system is corrupted and being one of the critical problems in Delanta's opal market. The illegal sellers (brokers) widely exporting the opal resource. According to the information we got from the focus group discussion of the study, illegal sellers (brokers) bought opals with a very cheap price without legal authorization for trade. They always buy opal (both cracked and un-cracked) from miners in the mining site from cutters, and even from few officers who are working in opal market system at Delanta district (local brokers) and they export illegally to Asian countries mainly to India and China using illegal trade routes through Kenya and Sudan boarders.

**Challenges of value addition:**

In order to utilize the Delanta precious opals properly for the economic development of the country, one of the best approaches is value addition to increase the market value by cutting/polishing and jewelry production rather than exporting the rough opal products.

In this study, opal cutters were interviewed about the existing situation of opal value addition and they confirmed the existence of several problems. These problems includes: shortage of modern lapidary machines which are essential for value addition, insufficient lapidary centers, lack of domestic skills in relation to jewelry production from natural gemstones, poor monitoring mechanism for value addition, absence of cutters association that helps them to prevent smugglers who are always exporting the raw opal without value addition, low demand of local market for value added opal products, lack of access to sell value added opal products directly to the international market, poor national and international market attachments.

The present study showed that even if the Delanta district has a promising potential of precious opal resource (Rondeau et al., 2010), but its sector is constrained by several challenges (Alemu, 2018). In this study, the main problems were identified and the

possible causes of the problems were analyzed using the data collected through different data collecting tools (observation, interview, questionnaires) using cause-and-effect diagrams (fishbone diagram). The presentation of the causes and effects of the problems in the study area using the fishbone diagrams is essential to summarize the different causes in different aspects, the relationships between different causes and the effects of these causes as presented in Fig. 6 (Loftus, 1990).

**Lack of environmental impact assessment:**

In mining industry, environmental safeguard is one of the essential issues to be considered to improve the economic, social and environmental sustainability of the artisanal miners and the whole community(Githiria, 2020).

In Delanta district, the other problem identified during the present study was lack of environmental impact assessment. Problems resulted due to traditional mining practice without considering environmental impact assessments includes: deforestation, land degradation and pH change of land soil due to waste disposal. Besides, agricultural land with fertile top soil may be covered by waste soil that makes arable land non-productive. Hence, potential adverse environmental impacts of mining practices should be identified and the corresponding mitigation measures should be taken and there should be legal enforcement. As indicated in Table 2, corrective measures to be taken after and during mining includes: use of disposal storage not to affect arable agricultural land, monitoring and site inspection of the mining sites by government authorities and progressive site rehabilitation by afforestation, filling old holes and avoiding of digging in fragile landscapes.

In conclusion,among the many potential natural resources found in Amhara regional state, the Delanta precious opal is the promising one in the gemstone industry. In this study, the main objective was to assess the main challenges on the utilization of the Delanta opal focusing on mining process, marketing system, and value addition aspects. The findings of this study revealed that traditional mining practice, lack of modern mining tools, lack of appropriate trainings to opal beneficiaries, uncontrolled market system, skill gap of opal cutting (value addition), and weak and unclear legal frame work were the most pronounced problems of opal mining and market system as a whole. Moreover, lack of scientific based knowledge about the nature, quality parameters and care on handling of opal mineral is one of the most disastrous problems of the resource. Based on the data analysis, modern mining tools like jack hammer and water removing pump, trainings on modern opal mining techniques, risk management skills and how to create standard pillars, use of air ventilation in the mining holes, use of protective equipment (eye goggle, helmet and safety work cloths), creating strong monitoring mechanisms, large scale excavation, establishing of lapidary centers for value addition processes, chemical characterization of opal, establishing opal marketing centers and avoiding black-markets are recommended as possible solutions.

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## REFERENCES

Alemu, M. G. (2018). Artisanal small-scale opal mining (ASOM) insecurity in the Delanta wereda, Ethiopia: The shifting landscape of multidimensional insecurity in the face of emergent ASOM wealth. *African Security Review, 27*(1), 61-87.

Ayalew, D., & Gibson, S. A. (2009). Head-to-tail transition of the Afar mantle plume: Geochemical evidence from a Miocene bimodal basalt–rhyolite succession in the Ethiopian Large Igneous Province. *Lithos, 112*(3-4), 461-476.

Bergman, J. (2015). Ethiopian opals: Facts, fears & fairytales. Retrieved from www.gemstone.org

Campbell, Kathleen A., Guido, Diego M., Gautret, Pascale, Foucher, Frédéric, Ramboz, Claire, & Westall, Frances. (2015). Geyserite in hot-spring siliceous sinter: Window on earth's hottest terrestrial (paleo)environment and its extreme life. *Earth-Science Reviews, 148*, 44-64.

Caucia, F., Ghisoli, C., Marinoni, L., & Bordoni, V. (2013). Opal, a beautiful gem between myth and reality. Neues Jahrbuch für Mineralogie-Abhandlungen: *Journal of Mineralogy and Geochemistry*, *190*(1), 1-9.

Cross, J., van der Wal, S., & de Haan, E. (2010). *Rough Cut: Sustainability Issues in the Coloured Gemstone Industry*. Amsterdam: SOMO.

DeMaster, D. J. (2014). 9.4 - the diagenesis of biogenic silica: Chemical transformations occurring in the water column, seabed, and crust. In H. D. Holland & K. K. Turekian (Eds.), *Treatise on geochemistry (2nd ed.)* (pp. 103-111). Oxford: Elsevier.

Dutkiewicz, A., Landgrebe, T. C., & Rey, P. F. (2015). Origin of silica and fingerprinting of Australian sedimentary opals. *Gondwana Research, 27(2)*, 786-795.

Filin, S., & Puzynin, Alexander. (2009). Prevention of cracking in ethiopian opal. *The Australian Gemmologist, 23*, 579-582.

Githiria, J. M., & Onifade, M. (2020). The impact of mining on sustainable practices and the traditional culture of developing countries. *Journal of Environmental Studies and Sciences, 10,* 394–410.

Johnson, M. L., Kammerling, R. C., DeGhionno, D. G., & Koivula, J. I. (1996). Opal from Shewa Province, Ethiopia. *Gems and Gemology*, *32*(2), 112-120.

Jones, B., & Renaut, R. W. (2003). Hot spring and geyser sinters: the integrated product of precipitation, replacement, and deposition. *Canadian Journal of Earth Sciences*, *40*(11), 1549-1569.

Kyngdon-McKay, Y., Jorns, A., Wheat, B., Cushman, T., & Nemomissa, S. (2016). An Analysis of the Commercial Potential of Ethiopia's Coloured Gemstone Industry.

Lalou, C. (1991). Deep-sea hydrothermal venting: a recently discovered marine system. *Journal of Marine Systems*, *1*(4), 403-440.

Leechman, F. (1984). The Opal Book. Sydney (1st ed.). Lansdowne Press.

Loftus, K. I. J. H. (1990). Introduction to Quality Control (3rd ed.). Tokyo,Japan: 3A Corporation.

Lynne, B., & Campbell, K. (2004). Morphologic and Mineralogic Transitions From Opal-A to Opal-CT in Low-Temperature Siliceous Sinter Diagenesis, Taupo Volcanic Zone, New Zealand. *Journal of Sedimentary Research, 74*, 561-579.

Milliken, R. E., Swayze, G. A., Arvidson, R. E., Bishop, J. L., Clark, R. N., Ehlmann, B. L.,&Weitz, C. (2008). Opaline silica in young deposits on Mars. *Geology, 36(11),* 847-850.

Rice, M. S., Cloutis, E. A., Bell, J. F., Bish, D. L., Horgan, B. H., Mertzman, S. A., & Mountain, B. (2013). Reflectance spectra diversity of silica-rich materials: Sensitivity to environment and implications for detections on Mars. *Icarus, 223(1),* 499-533.

Robert, F., & Chaussidon, M. (2006). A palaeotemperature curve for the Precambrian oceans based on silicon isotopes in cherts. *Nature, 443*(7114), 969-972. doi:10.1038/nature05239

Rondeau, B., Fritsch, E., Mazzero, F., Gauthier, J.-P., Bekele, E., & Gaillou, E. (2010). Play-of-Color Opal from Wegel Tena, Wollo Province, Ethiopia. *Gems & Gemology, 46,* 90-105.

Thiry, M., Milnes, A. R., Rayot, V., & Simon-CoinÇon, R. (2006). Interpretation of palaeoweathering features and successive silicifications in the Tertiary regolith of inland Australia. *Journal of the Geological Society, 163*(4), 723-728.

Webster, R. (1975). Gems: Their Sources, Description and Identification (5th ed.) CT: Hamdem.

Yirgu, D. A. G. (2003). Crustal contribution to the genesis of Ethiopian plateau rhyolitic ignimbrites: Basalt and rhyolite geochemical provinciality.*Journal of the Geological Society of London, 160(1),* 47–56.