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Economic geology value of oil shale deposits: Ethiopia (Tigray) and Jordan

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\textbf{ABSTRACT}

Oil shale is an organic-rich, fine-grained sedimentary rock, containing kerogen, from which liquid hydrocarbons (called shale oil) can be produced. The oil shale deposits in the Tigray region are found in the northern parts of Ethiopia, Eastern Africa. They are of Upper Paleozoic age, existing as remnants of the Cretaceous erosion period, underlain by tillites and overlain by sandstones. They were formed during the glacial retreat followed by marine deposition of shales in a basin created by the enormous load of the glaciers. The Ethiopian-Tigray oil shale deposits cover an area extending over approximately 30 km\textsuperscript{2}, with an average mineable bed-thickness of 55 m, showing on the upper part inter-beds and laminations of shaley limestones. The oil shale resources in this region are estimated to be approximately 4 billion tonnes. The exploitation of the Ethiopian-Tigray oil shale deposits is an excellent alternative to fulfill the fuel and other petroleum products’ demand of Ethiopia. This study sheds light on the oil shale resources in the Ethiopian region of Tigray, as they are fairly investigated, regarding their geological characterization, and future strategies for their exploration and exploitation potential. In addition, the oil shale deposits in Jordan are also moderately investigated, as Jordan is considered a promising country for shale oil, taking into account that Jordan has no other hydrocarbon resources (such as crude oil and natural gas), unlike many other countries in the MENA (Middle East and North Africa) region, as MENA sets on “seas” of oil and natural gas. Furthermore, oil shale in the USA is also briefly investigated, as the USA is being the world’s largest country of oil shale resources and reserves. Also, some other issues related to the oil shale industry are investigated, such as economics, extraction technologies of shale oil, and the environmental impacts.

\textbf{INTRODUCTION}

\textbf{The terms of “oil shale” and “shale oil”}

The terms “oil shale” for the rock, and “shale oil” for the retorted product (also known as “Light Tight Oil” (LTO)) have been well-understood for more than one hundred years now. Both terms (oil shale and shale oil) have been consistently applied to the fine-grained, organic-rich sedimentary rock that contains solid organic matter, from which a liquid hydrocarbon (shale oil) can be extracted when the rock is heated in the chemical process of pyrolysis, either on the surface or at depth. Most of the organic matter in the source rock (oil shale) is in the form of kerogen, which is insoluble in ordinary organic solvents, and some of the organic matter in the source rock is bitumen that is soluble in organic solvents (Dyni 2003).

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Oil shale was formed millions of years ago by deposition of silt and organic debris on lake beds and sea bottoms. Temperature and pressure transformed, over long geological periods of time, the materials into oil shale in a process similar to the process that forms the petroleum, but at less pressures and lower temperatures. Oil shale can be mined and processed to generate oil similar to oil pumped from conventional oil wells. However, extracting shale oil from oil shale is more complex and, thus, more expensive than recovering the conventional oil. This is mainly because the oil substances (shale oil) in the oil shale are solid and, thus, cannot be pumped directly out of the ground. Accordingly, the oil shale must first be mined and then heated at high temperatures (350–450°C and up to 500–600°C), through a process called “retorting”, and the resultant liquid must then be separated and collected. An alternative, but currently experimental process, is referred to as “in-situ retorting”, which involves heating the oil shale while it is still underground, and then pumping the resulting liquid to the surface.

**Worldwide reserves of oil shale**

As a source rock for most conventional oil reservoirs, oil shale deposits are found in many regions around the world, although most of the deposits are too deep to be exploited, economically. There are more than 600 known oil shale deposits around the world. Although resources of oil shale occur in many countries, only 33 countries possess known deposits of possible economic values. More than half of the identified oil shale resources are found in the USA, Russia, China, Argentina, Libya, Algeria, Canada, and Mexico (WEC 2016).

The largest recent estimates put the USA’s shale oil at 6 trillion barrel (bbl), China is second at 330 billion bbl, Russia third at 270 billion bbl, Israel (Historical Palestine) fourth at 250 billion bbl, and Jordan and the Democratic Republic of Congo tied for fifth at approximately 100 billion bbl, each. Estonia, which is on the way to become the largest producer of shale oil, soon, is currently 11th with only 16 billion bbl (WEC (World Energy Council) 2016). It is noteworthy to mention that the unit of volume for crude oil and other petroleum products is “barrel” (bbl). One bbl equals 42 US gallons or 35 UK (imperial) gallons, or approximately 159 liters, or 5.6 cubic feet; and 6.29 bbl equal one cubic meter (m$^3$), and 7.33 bbl weigh one metric ton (1,000 kg).

Some estimates set the total world’s resources of oil shale at around 689 gigatons (gigatonnes), which is equivalent to a yield of 4.8–5.0 trillion barrels (760–790 billion cubic meters (BCM)) of shale oil, of which 1.0–1.32 trillion barrels (160–210 BCM) of shale oil may be technically recoverable, as of January 2007 (Dyni 2010; IEA 2010). A 2016-estimate sets the total world’s resources of shale oil equivalent to yield of 6.05 trillion bbl (962 BCM) (WEC (World Energy Council) 2016). At the same time, for comparison, the world’s proven crude oil (petroleum) reserves are estimated to be 1.6976 trillion bbl (269.90 BCM) (WEC (World Energy Council) 2016), constituting approximately 28% of the world’s shale oil reserves (if considered 962 BCM).

**USA: the world’s largest oil shale reserves**

The largest resource deposits of oil shale exist in the USA, which are thought to contain 3.7 trillion barrels (590 BCM) of shale oil, forming about 75%–80% of the world’s shale oil’s potential, though only a part of it is recoverable (Dyni 2010). The USA’s oil shale resources are mainly found, in addition to other locations (Table 1), in the Green River’s Formation (Table 1), covering portions of Colorado, Utah, and Wyoming, with oil-resources’ estimates of 1.2–1.8 trillion barrels (Bartis et al. 2005). However, even a moderate estimate (800 billion barrels of recoverable shale oil from oil shale in the Green River’s Formation) is three times greater than the proven oil reserves in Saudi Arabia (Bartis et al. 2005). The present USA’s demand for petroleum products is about 20 million barrels per day. If the shale oil could be used to meet a quarter of the USA’s demand, then the estimated 800 billion barrels of recoverable shale oil from the oil shale of the Green River’s Formation would last for more than 400 years (Bartis et al. 2005).
The term “oil shale resources” may refer to all of the oil shale deposits that contain kerogen. On the other hand, the term “oil shale reserves” refers to the amount of “oil shale resources”, which are technically exploitable and economically feasible under current economic conditions. Table 2 shows the reserves by estimated amounts of shale oil in some regions and countries around the world.

The shale oil extraction technologies are still developing, so the amount of recoverable kerogen can only be estimated. Oil shale deposits range from small presently economically recoverable reserves to large presently uneconomically recoverable resources (Kilian 2016; Niu et al. 2013;...
Potapov 2016; Raukas and Punning 2009). However, defining oil shale reserves is difficult, because they vary considerably, in terms of their different chemical composition, and their kerogen content, as well as their extraction technologies.

Many oil shale deposits need more exploration to determine their potential as reserves. Well-explored deposits, which could ultimately be classified as reserves, include the Green River Formation’s deposits in the western parts of the USA; the Tertiary deposits in Queensland, Australia; the deposits in Sweden and Estonia; and the El-Lajjun (Al-Lajjun) deposits in Jordan; as well as some other deposits in France, Germany, Brazil, China, and Russia. It is expected that these deposits would yield at least 40 liters (0.25 bbl) of shale oil per metric ton of oil shale, using the Fischer Assay (Dyni 2006). The oil shale is converted into shale oil by assuming oil content of 100 liters or 0.09 tons of oil per a ton of shale (Lechtenböhmer et al. 2011).

Technologies used to extract shale oil from oil shale

Shale oil refers to synthetic oil obtained by heating the organic material (kerogen) contained in the oil shale to a temperature, which will separate it into oil, combustible gas, and the residual carbon that remains in the spent shale rock. The kerogen’s content of oil shale deposits differs widely, and the economic feasibility of its extraction is highly dependent on international and local costs of the conventional hydrocarbons (crude oil and natural gas) (Yihdego and Al-Weshah 2016a, 2016b). This means that if the price of crude oil per barrel is higher than the production price of shale oil per barrel, then the extraction of shale oil is economic, and if the price of crude oil per barrel is less than the production price of shale oil per barrel, then the extraction of shale oil is uneconomic.

Several methods are used to determine the quantity and quality of the products extracted from oil shales (Tao et al. 2016, 2013, 2012b, 2012c, 2012a). At their best, these methods give an approximate value to its energy potential. One standard method is the “Fischer Assay”, which yields a heating value—that is a measure of caloric output. This is generally considered a good overall-measure of usefulness. The “Fischer Assay” method has been modified, standardized, and adapted by the American Petroleum Institute (API). It does not, however, indicate how much oil could be extracted from a sample of oil shale. Some processing methods yield considerably more useful product than the “Fischer Assay” method would yield. The “Tosco II” method yields over 100% more oil than the “Fischer Assay”, and the “Hytort” process yields between 300% and 400% more oil than the “Fischer Assay” (Dyni 2006).

Environmental impacts of oil shale industry

Unlike renewable energy sources (Yihdego, Salem, and Pudza 2017), the issue of the environmental impacts of the oil shale industry is one of the main factors influencing the development of the industry itself. Many countries have paid much attention and, thus, they developed different effective pollution-control technologies to reduce the environmental impacts resulted from the oil shale industry. The oil shale industry includes mining, crushing, sieving, retorting, combustion, and oil upgrading, which lead to many environmental impacts. These impacts include environmental pollution (such as wastewater produced from mining, retorting, upgrading, ash moisturizing, etc.); dust (produced from mining, crushing, sieving, retorting, and combustion); oil sludge; shale ash, retorted shale handling, and disposal; waste gas from retorting and combustion; and land disruption due to surface mining (Lechtenböhmer et al. 2011; Raukas and Punning 2009; Wan 2009; Yihdego and Paffard 2017).

The environmental impacts of the oil shale industry include, particularly, wastewater discharge, groundwater contamination, air pollution, and shale-ash disposal (Yihdego and Al-Weshah 2016c). Wastewater discharged from a retorting oil shale industrial plant contains oil and suspension solids, as well as oxygen-, nitrogen-, and sulfur-compounds, which can be treated by sedimentation, oil interception, flocculation, air floatation, and biological treatment (Yihdego and Al-Weshah 2017). Air pollution is mainly due to the fly-ash, sulfur dioxide, and nitrogen oxides contained in the flue gas leaving the chimneys of the oil shale boilers in the power plant. High efficiency dust remover, and high efficiency
sulfur dioxide absorber or adsorber should be used, and, thus, adequate technologies should be applied for lower emissions of the nitrogen oxides. Shale ash formed from oil-shale power plants and oil-shale retorting plants may be used for mine backfilling, for agricultural utilization, and for cement making (Tao et al. 2010, 2011, 2012a, 2017).

**Ethiopia’s oil shale potential**

Ethiopia has the misfortune of being entirely landlocked as a result of the 30-year war with its neighboring country–Eritrea (Figure 1). Still, oil and gas exploration in Ethiopia is advancing much faster. Ethiopia has less potential and has no offshore prospects, which should make it less attractive than Eritrea which is neighboring the Red Sea (Figure 1), but foreign oil and gas companies favor it, nonetheless. Ethiopia has considerable resources of oil shale deposits, which are found in various locations (Figure 1).

The Ethiopian oil shale is dominated by long-chain aliphatic hydrocarbons, and it has low sulphur content. It also includes high total organic content (TOC), amounting up to 55%–60% (Tadesse 2015). So, according to the Schlumberger’s definition of TOC (Table 3), the Ethiopian oil shale deposits (with TOC up to 55%–60%) can be classified as “excellent”, in terms of the oil shale’s TOC and its kerogen’s quality (Table 3).

![Figure 1. Map of the locations of oil shale deposits in Ethiopia (after Tadesse 2015).](image)

<table>
<thead>
<tr>
<th>Total Organic Content (TOC) (%)</th>
<th>Oil Shale Kerogen’s Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.5</td>
<td>Very Poor</td>
</tr>
<tr>
<td>0.5–1.0</td>
<td>Poor</td>
</tr>
<tr>
<td>1.0–2.0</td>
<td>Fair</td>
</tr>
<tr>
<td>2.0–4.0</td>
<td>Good</td>
</tr>
<tr>
<td>4.0–12.0</td>
<td>Very Good</td>
</tr>
<tr>
<td>&gt; 12.0</td>
<td>Excellent</td>
</tr>
</tbody>
</table>
The TOC values indicate the possibility of kerogen filling the pore spaces of oil shale rather than other forms of hydrocarbons. The TOC is measured from 1-g samples of pulverized rock that are combusted and converted to CO or CO\textsubscript{2}. If a sample of oil shale appears to contain sufficient TOC to extract shale oil from it, the sample then may be subjected to pyrolysis. This can successfully be applied on the Ethiopian oil shale deposits, as they have high TOC (55%-60%).

Some oil shale deposits found in the west and south-west parts of Ethiopia, as well as the north-east central parts of Ethiopia occur in thick shale formations (400-800 m thick). Palynological studies confirmed that these deposits (found in W, SW, and NE central parts of Ethiopia) are of Eocene, Miocene, and Oligocene ages (Tadesse 2015). A total of about 653 million tons to one billion tons of oil shale reserves have been estimated in these regions (Ahmad 2008). Other studies indicate that Ethiopia has an estimated 3.89 billion tons of oil shale (enough to produce about one trillion barrels of shale oil) in the Tigray State alone (more details given below), located on the border with Eritrea (Tigrai Online 2013), which is of Upper Paleozoic to Mesozoic ages.

The Ethiopian Delbi-Moye basin (Figure 1) is a small rift basin, preserving a thick sedimentary succession of Eocene to Miocene age. Much of the area is covered by the Ashangie thick volcanic group, and within it coal and oil shale-bearing strata are enclosed. The oil shale (in addition to coal) exploration has been conducted in the Geba basin. The coal and oil shale-bearing sedimentary strata of this basin are found intercalated within the Tertiary volcanic rocks, similar to other deposits in other parts of the country. Although up to 25-m thick oil shale is found in the Geba basin, the resource is not evaluated (GSE 2016). The oil shale, found in the south-western parts of the country, occurs between the Lake Ziway and the Lake Abya at in the valleys of the Bulbul River and its tributaries. The inter-trappean fluviatile-lacustrine oil shale-bearing sediments are widely distributed on the south-western Plateau of Ethiopia in the Delbi-Moye, Lalo-Sapo, Sola, Gojeb-Chida, Mojo-anchema, and Yayu basins (Ahmad 2008). Recent drilling data has proved the presence of 120 million tons of oil shale deposits at the Delbi-Moye basin (Figure 1), while no details are known for the Bulbul River deposits (GSE (Geological Survey of Ethiopia) 2016).

### Oil shale in tigray, northern ethiopia

As indicated above, Ethiopia has a great potential of oil shale resources in most parts of the Country. The Tigray region, located in the north most part of the country, has, in particular, huge deposits of oil shale (Figure 2). The Tigray region is covered by the sedimentary succession of Upper Paleozoic to Mesozoic age, forming parts of the Edaga Arbi Formation, and is exposed as erosion remnants of cliffs that found underlain unconformably by the Basement of Proterozoic Upper Complex metamorphic rocks (Table 4). The Basement (named Upper Complex) has been folded but subjected to only the lowest grades of metamorphism, mainly of green-schist facies (Jembere and Yihdego 2016). It includes the Tsali Group, the Tembien Group, the Didikama Formation, and the Matheos Formation (Beyth 1971; Garland 1980). The Tembien Group, the Didikama Formation, and the Matheos Formation are meta-sediments, in contrast to the Tsaliet Group which is mainly of metabasalts (Garland 1980; Sembroni et al. 2017).

After the peneplanation of the continental land surface in the Lower-Middle Paleozoic, clastic deposition began, probably during the Upper Paleozoic (Garland 1980), and this whole succession is resting unconformably on the Precambrian rocks (Table 4). This succession consists of three formations, named Enticho Sandstone, Edaga Arbi Glacials, and Adigrat Sandstone (Blanford 1970; Dow, Beyth, and Tsegaye 1971; Garland 1980; Sembroni et al. 2016). The Enticho Sandstone Formation and Edaga Arbi Glacials can be observed underneath the Basement.

The Enticho Sandstone Formation is composed of a white medium-grained quartzite, without or with coarse cross-bedding, which grades to siltstones and then to friable black shales of the Edaga Arbi Glacials. The Glacial Unit consists of calcareous tillites, which is poorly sorted fragments of
quartz supported pebbles of meta-volcanic, rounded granite, and boulders of gneissic rocks. The Glacial Unit grades to the deposition of friable shales, which make-up the greatest thickness of the glacials. The thick shale deposition is the potential oil shale resource in the Ethiopian Tigray region.

The probable sequence of events to the Edaga Arbi Glacials and the Enticho Sandstone Formation is explained by Garland (1980) and Bussert and Schrank (2007) as following: 1) Deposition of sandstone in continental fluviatile and subaerial environment; 2) Glacial age begins, meaning outwash from glaciers formed coarse sandstone channeled by migrating braided streams; 3) After reduction of relief, the following occurred: A small rise in sea level, a change to a warmer climate,

Table 4. A summarized stratigraphy of the Tigray region, northern Ethiopia (after Garland 1980; Mohr 1963).

<table>
<thead>
<tr>
<th>Age*</th>
<th>Rock Unit</th>
<th>Composition</th>
<th>Description</th>
<th>Physiography</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tertiary</td>
<td>Trap Series</td>
<td>Basalts, Trachyte, Basanite</td>
<td>Lava flows horizontally underlying sandstone</td>
<td>Mountains, cliffs, hills</td>
</tr>
<tr>
<td>Jurassic</td>
<td>Adigrat Sandstone</td>
<td>Laterite</td>
<td>Weathering of sandstone rich in hematite</td>
<td>Steep cliffs, hill top plateau</td>
</tr>
<tr>
<td>Triassic</td>
<td>?</td>
<td>Sandstone</td>
<td>Medium grained, cross bedded pink-white sandstone</td>
<td>?</td>
</tr>
</tbody>
</table>
| Permian-Devenion | Edaga Arbi Glacials | Tillite                             | Composed of fragments of meta-volcanic and boulders of granite and gneiss. | Bottom of cliffs | ?
| ?       | Silty Shale       |                                      | Friable beds of silt and limestone                              | ?                             |
| ?       | Shale             |                                      | Black to grey, friable, with laminations of limestone            | ?                             |
| Carboniferous-Devenion | Enticho Sandstone | Glacial Sandstone and Conglomerate | Fragments of granites cemented mostly by calcite                  | Low cliffs, low terrains      |
| ?       | ?                 | Sandstone                            | Non or coarsely cross-bedded, with beds of shale, silt, and ferruginous bands | ?                             |
| Proterozoic | Precambrian basement rocks | Meta-volcanic-Sedimentary Rocks | Meta-andesite, dolomite, crystalline limestone, schists, slate, marble, granitoids | Ridges, low land areas       |

*Based on the relative age estimation of Mohr (1963) and Garland (1980).

Figure 2. Location map and potential of oil shale deposits in the Tigray region, northern Ethiopia (after Girmay 2006). For details (zoomed in), see Figure 3.
and deposition in very quiet lacustrine or shallow marine conditions; 4) Return of glacial conditions (deposition of moraine); 5) Gradual retreat of glaciers with rising sea level; and 6) Generally marine deposition of shale with some fresh water periods, forming thin limestones and varves.

The age of oil shale from the Edaga Arbi Glacials has been dated as Devonian or younger (Garland 1980) (Table 4). The uppermost unit of the clastic sequence (named Adigrat Sandstone) rests with undulating unconformity on the Edaga Arbi Glacials (shale) and on the Enticho Sandstone. The Adigrat Sandstone is yellowish to pink fine to medium grained, non-calcareous quartz sandstone with well-sorted rounded grains; it is cross-bedded and current-bedded (Garland 1980) and is estimated to be deposited during the Upper Triassic to Middle Jurassic (Table 4) (Enkurie 2010; Garland 1980; Mohr 1963).

These clastic successions are observed grading to the Antalo succession in the region, which consists of Antalo Limestone and Agula Shale. The Antalo Limestone is conformable on the Adigrat Sandstone and is estimated to be formed during Upper Jurassic, which consists of limestone and marl sequences. The Agula Shale, which includes limestone, shale, gypsum, and dolomite, appears more shaly and gypsiferous. These formations mainly cover the Mekelle basin and have been investigated for the probability of existence of petroleum resource (Bosellini et al. 1997).

**Geological characteristics of the tigray’s oil shales**

The oil shale deposits in the Tigray region (northern Ethiopia) are widely spreading under the Adigrat Sandstone, which covers a large portion of the region (Bussert and Schrank 2007; Enkurie 2010), and is found exposed covering a large area at Bizet, Edga Arbi, Nebelet, and Atebe (Table 5; Figure 2; Figure 3; Figure 4).

**Economic evaluation of the ethiopian oil shale deposits**

Ethiopia is a poor country on which each cent counts in its economic development (Yihdego and Kwadwo 2017). The country is dependent on agricultural and livestock products to earn hard currency. Ethiopia is a sole importer of fuels and fuel products. Estimates indicate that half of its hard currency is spent to fulfill the country’s fuels’ demand. Ethiopia has no any well-known

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**Table 5. Different occurrences of the oil shale deposits in the Tigray region, northern Ethiopia.**

<table>
<thead>
<tr>
<th>Area</th>
<th>Oil Shale Layers</th>
<th>Oil Shale Characterization</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bizet</td>
<td>They lay over the Enticho Sandstone Formation and clearly under the Tillites and Adigrat Sandstone Formation.</td>
<td>Black and marly. Some outcrops are massive and some others are friable.</td>
<td>4-A: Upper Left</td>
</tr>
<tr>
<td>Edaga Arbi</td>
<td>They are exposed all around the Edaga Arbi City and are observed overlain by the Adigrat Sandstone Formation, and sometime by tillites with horizontal bedding. Laminations of limestone increase in frequency as one rises up to the top.</td>
<td>Friable, black to dark brown in color, and shows brown streak.</td>
<td>4-B: Upper Right</td>
</tr>
<tr>
<td>Nebelet</td>
<td>They show horizontal bedding underlain by erosion remnant of the Adigrat Sandstone Formation. The thickness of the shale layers is difficult to estimate, because their bottom contact cannot be detected. However, the exposed shale layers thickness is about 45 m.</td>
<td>Black, friable, and it shows laminations of shaly limestone, which frequency increase to the top of the layers.</td>
<td>4-C: Lower Left</td>
</tr>
<tr>
<td>Atebe Area</td>
<td>They are exposed along the main Atebe River and also on the slope of the ridges, and are covered by Adigrat Sandstone Formation. The shale layers on the River are an under-thrown part of the main shale by a tectonic fault. They are underlain directly by the metamorphic rocks’ basement.</td>
<td>Black, friable, and has shown an intensive laminations of limestone. Their frequency increases towards the top of the layer. They are intruded by sub-volcanic dykes, striking the same as the trend of the fault.</td>
<td>4-D: Lower Middle</td>
</tr>
</tbody>
</table>
Figure 3. Location and area coverage estimates of the oil shale occurrences of the Tigray region, northern Ethiopia (after Girmay 2006).

Figure 4. A) Upper Left: Oil shale layers at Bizet overlying the Enticho Sandstone Formation and underlying the Adigrat Sandstone Formation; B) Upper Right: Oil shale at Edaga Arbi, overlain by the Adigrat Sandstone Formation and showing laminations of shaly limestone (increasing its frequency towards the top); C) Lower Left: Regular fractures trending N30°W, dipping 80°E and N70°E, dipping 75°NW on the Edaga Arbi Shale Formation; D) Lower Middle: Oil shale overlain by the Adigrat Sandstone Formation and partly covered by landslide debris of sandstone; E) Lower Right: Oil shale layers exposed on the bank of Atebe River, showing bed-mark of fault, trending N30°W and dipping 80°E (after Girmay 2006).
conventional petroleum resources. However, it is blessed with extensive oil shale occurrences all over the territory of the country. Therefore, the only way to support the country’s economy is to search an alternative approach by reducing hard currency expenses on imported fuels, which can be reached by developing its oil shale industry through producing the shale oil from the oil shale deposits.

The Ethiopian Government needs to give attention and commence to exploration to discover oil shale deposits without any delay to support its need of hard currency. The oil shale occurrences in Ethiopia have been known since the mid-1950s, and investigations have been done at the Wollo Province in the northern parts of the country. The laboratory results of sample analyses during that time proved that the oil shale deposits contain at least 6% petroleum volatiles (Astrup 1956). According to recent studies (Tadesse 2015), the oil shale deposits found in different parts of Ethiopia include up to 55%–60% TOC (as discussed above).

The quick survey done to discover oil shale in the Tigray region (northern Ethiopia) found very vast area coverage of shale overlain by the Adigrat Sandstone Formation. Most of the oil shale deposits in the Tigray region are covered by weathered floats of debris of sandstone, which are exposed at Bizet, Edaga Arbi, Nebelet, and Atebe. Potentially, there may be still many other undiscovered exposures in the region, in particular, and in the country, at large.

The estimation of the oil shale resources in the Tigray region was calculated based on the outcrops exposed on the surface and their area coverage of the overlying sandstones. Although these oil shale deposits have horizontal bedding, and are unconformably overlain by the Adigrat Sandstone Formation, they disappear at places or have thin beds (up to 10 m) like in the Adigrat area, where a thick succession of sandstone occurs. Such disappearance occurs on places of highlands and the shale thickness increases on the rims of Werri glacial basin.

The Werri glacial basin is surrounded by rims of peaks of sedimentary ridges and currently is covered by exposed basement rocks due to erosion. The oil shale deposits are found exposed on the slope of these rims of sedimentary ridges. Thus, to calculate the real potential of these oil shale deposits requires detailed exploration works, because the area coverage of the sandstone is extremely vast in the region. Based on the observations in each area of the four areas mentioned above (Figure 2; Figure 3; Figure 4), the oil shale deposits are estimated to cover an area of: 1) Bizet oil shale = 2.65 km$^2$; 2) Edaga Arbi oil shale = 21.11 km$^2$; Nebelet oil shale = 4.18 km$^2$; and 4) Atebe oil shale = 2.44 km$^2$, which all cover, in total, an area of 30.38 km$^2$. Based on the observations, the average possible mineable bed thickness (exposed thickness) is about 55 m. Therefore, the oil shale resource of the observed area in the Tigray region is estimated at 3.89 billion tons.

The Geological Survey of Ethiopia (GSE) has also conducted many exploration projects for oil shale discoveries in different parts of the country. The projects were successful in identifying many occurrences, and some of them have given a kerogen’s value of 120 liter/ton. This value may be taken as a theoretical threshold for oil shale to be considered as an energy input. The limiting kerogen’s content is a function of many parameters, but the lower quoted value is 5% organic content, which corresponds to an oil yield of 25 liter/ton of rock or 6 US gallons/ton (Ekinci 1995).

**Jordan: a good example on oil shale in the MENA region**

As related to the oil shale resources in the MENA region (Middle East and North Africa, where huge reserves of crude oil and natural gas exist), Jordan is considered a poor country in terms of crude oil and natural gas, but it is rich with respect to shale oil, representing a good example on the oil shale in the MENA region. The Jordanian oil shale deposits are of high quality, comparable to the USA’s oil shale deposits. They have TOC values ranging from approximately 18% to 23% weight (Table 6), and, thus, they can be classified as “excellent” (as demonstrated in Table 3), in terms of the oil shale kerogen’s quality, according to Schlumberger (2017). However, the Jordanian oil shale in some locations has a high content of sulfur (8%–10%) (Alali et al. 2015), while in some other locations the sulfur content is relatively low, ranging from 0.3 to 4.3% (Dyni 2006). According to various estimates, the oil shale deposits in Jordan underlie more than...
60% of the Jordanian territory, totaling approximately 40–70 billion tons. Some other estimates reach up to 100 billion tons of oil shale (as indicated above), which would make Jordan one of the richest countries in the world, with respect to the oil shale deposits. Oil shale is widely distributed in Jordan and can be identified in few outcrops and mostly in the subsurface (see Figure 5).

The most important oil shale occurs in the lower part of the Upper Cretaceous Muwaqqar Chalk-Marl (MCM) Formation, which outcrops across much of the central northern and central southern parts of Jordan. Although the oil shale in Jordan is widely spreading, it varies in thickness and in oil content. The Jordanian most significant oil shale deposits are found in more than 25 locations around the country; with the 8 most important deposits located in the central region of the country (see Table 6). The Jordanian best-explored oil shale deposits (Table 6; Figure 6) were found in the following regions: El-Lajjun (Al-Lajjun), Sultani, Jerf Ed-Darawish, Attarat Um El-Ghudran, Wadi Maghar, Wadi Thamad (Eth-Thamad), Khan Ez-Zabib, and Siwaga (Siwaqa). The oil shale deposits in these 8 locations exist in the west-central parts of Jordan (Figure 6), meanwhile the oil shale deposits in the Yarmouk region are found in the Yarmouk River’s region in northern Jordan, which is close to the Jordanian-Syrian borders, extending into the Syrian Territory (Figure 6).

The Jordanian oil shale deposits are kerogen-rich, bituminous, argillaceous limestones, deposited in shallow marine during the Late Cretaceous to early Tertiary (Maastrichtian-Danian) geological ages (Hussein 2013; Hussein et al. 2015; MEMR 2017). The origin of the kerogen is the dead plants and animals that found in the ancient seas and lakes during the Upper Cretaceous geological ages and after the burial process, along with high temperatures and pressures, which caused the change from organic matter to kerogen.

The Jordanian oil shale was not investigated thoroughly, as there has been only little interest in developing such resources during the 1980s and 1990s, when relatively low prices for crude oil on the

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of Boreholes</th>
<th>Area (km²)</th>
<th>Overburden (m)</th>
<th>Oil Shale Thickness (m)</th>
<th>Shale Oil Thickness (m)</th>
<th>Total Organic Content (TOC) (wt. %)</th>
<th>Bulk Density (g/cm³)</th>
<th>Oil Shale (10⁹ tons)</th>
<th>Shale Oil (10⁶ tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>El-Lajjun</td>
<td>195</td>
<td>20</td>
<td>30</td>
<td>30</td>
<td>10.5</td>
<td>22.1</td>
<td>1.81</td>
<td>1.3</td>
<td>126</td>
</tr>
<tr>
<td>Sultani</td>
<td>60</td>
<td>24</td>
<td>70</td>
<td>32</td>
<td>7.5</td>
<td>21.5</td>
<td>1.96</td>
<td>1.0</td>
<td>74</td>
</tr>
<tr>
<td>Jerf Ed-Darawish</td>
<td>50</td>
<td>91</td>
<td>70</td>
<td>64</td>
<td>5.7</td>
<td>18.0</td>
<td>2.1</td>
<td>8.6</td>
<td>510</td>
</tr>
<tr>
<td>Attarat Um El-Ghudran</td>
<td>75</td>
<td>348</td>
<td>50</td>
<td>45</td>
<td>11</td>
<td>23.2</td>
<td>1.80</td>
<td>11</td>
<td>1,245</td>
</tr>
<tr>
<td>Wadi Maghar</td>
<td>21</td>
<td>660</td>
<td>40</td>
<td>40</td>
<td>6.8</td>
<td>20.8</td>
<td>2.03</td>
<td>31.6</td>
<td>2,150</td>
</tr>
<tr>
<td>Wadi Thamad</td>
<td>12</td>
<td>150</td>
<td>140–200</td>
<td>70–200</td>
<td>10.5</td>
<td>11.4</td>
<td>11.4</td>
<td>1,140</td>
<td></td>
</tr>
<tr>
<td>Khan Ez-Zabib</td>
<td>6</td>
<td>?</td>
<td>70</td>
<td>40</td>
<td>6.9</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Siwaga</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>7.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 5. Some pictures of the oil shale deposits and the extracted shale oil in Jordan (MEMR (Ministry of Energy and Mineral Resources) 2017).
international market prevailed, which discouraged entrepreneurs from making investments in the oil shale industry (Jaber, Amri, and Ibrahim 2011). In 2006, this situation changed due to many factors, including, most importantly, the growing bill for imported energy. Thus, the Jordanian Government took the initiative to develop the oil shale industry by attracting international developers and experienced companies to work in this field.

The energy strategy of the Jordanian Government aims to increase the contribution of oil shale sources to 10% by 2025, while reducing the imported energy (crude oil and natural gas) resources. However, Jordan has lately (in September 2016) signed a historic 15-year, 10 billion USD gas’ deal with Israel to purchase 45 billion cubic meters (BCM) of gas from the Leviathan field in the Mediterranean Sea (TTOI 2016).

The oil shale exploitation in Jordan, with the support of international investors and technologies (from, for instance, the USA, Canada, China, Germany, Malaysia, Estonia, Saudi Arabia, Russia, Brazil, etc.), is considered a long-term strategic goal in meeting the Jordanian energy demands from indigenous resources. The Government of Jordan, through the Ministry of Energy and Mineral Resources (MEMR), is currently engaged with a three-track approach to deal with the oil shale development in the country, which includes: 1) In-situ exploration for deep oil shale to produce

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**Figure 6.** Location map of the major oil shale deposits in Jordan (after Alali et al. 2015).
shale oil; 2) Surface retorting for the mined oil shale to produce shale oil; and 3) Direct burning of oil shale for electricity generation.

In the neighborhood of Jordan, most of Israel’s (Historical Palestine) deposits are located in the Mishor Rotem Basin region of the northern Negev Desert near the Dead Sea (Minster 2008; Yihdego and Drury 2016a). In comparison with the Jordanian oil shale, the Israeli oil shale is relatively low in heating value and oil yield, though the deposits in both countries are, geographically, not far from each other. Based on measurements carried out in the USA, the oil shale beds of the Ghareb Formation in the Mishor Rotem deposits have oil yield values ranging from 12 to 27 gallons of shale oil per one metric ton of oil shale.

The Jordanian El-Lajjun (Al-Lajjun) Oil Shale Deposit

The exploration work for oil shale started in Jordan after the El-Lajjun (Al-Lajjun) deposit had been discovered by the German Geological Mission in the 1960s. After that, intensive exploration activities on oil shale in the central parts of Jordan were carried out during the 1980s as part of the technical cooperation between the Natural Resources Authority (NRA) of Jordan and the BGR (Bundesanstalt für Geowissenschaften und Rohstoffe) of Germany, which resulted in delineating other oil shale deposits (mentioned above). Recent estimates for the entire El-Lajjun deposit have identified approximately one billion tons of oil shale resources at a mean grade of 11 wt. % oil (DeWolfe, Horne, and Morgan 2010). Though it is kerogen-rich, the El-Lajjun’s oil shale has a Vitrinite Reflectance (Ro) of around 0.2%, which is far below the 0.5% needed to form petroleum; i.e. immature (Abed et al. 2009). El-Lajjun is categorized as a marinite oil shale deposit, hosted by marine sedimentary rocks of the Belqa Group that were deposited as syntectonic basin infill within the Late Cretaceous to early Paleocene geological ages, forming the El-Lajjun Graben. Calcite, quartz, kaolinite, and apatite make-up the major mineral components of the El-Lajjun oil shale, along with small amounts of dolomite, feldspar, pyrite, illite, goethite, and gypsum. The El-Lajjun’s oil shale occurs as massive beds of gray to black, kerogen-rich chalk-marl, comprising the approximately 30 m thick Lower Member of the Muwaqqar Chalk-Marl (MCM) Formation (Figure 7).

The Lower Member is overlain by approximately 30 m of barren chalk-marl known as the Upper Member of the MCM Formation. Differential throw on the Graben bounding faults resulted in asymmetric Graben floor that is tilted slightly to the west. Strata in the Graben are sub-horizontal with dips typically in the 2–4 degree range. Micro-paleontological studies indicate the depositional age of the MCM Formation is transitional between Maastrichtian to Paleocene geological ages, with deposition of the oil shale-bearing Lower Member occurring during Maastrichtian to Danian geological ages. However, though the El-Lajjun oil shale deposit is promising, there are some serious problems, including, most importantly, the water unavailability and the environmental impacts. Water is required for the retorting process, combustion of the residual carbon, refining the crude shale oil, consolidating the spent shale or the ash in the dumping areas, and for direct combusting the oil shale to generate electric energy (Hamarneh 1998), which all form environmental problems.

The water needed for the oil shale operations in Jordan is scarce, and therefore, groundwater has been tapped for that purpose (Yihdego and Drury 2016b). A shallow aquifer that underlies the El-Lajjun oil shale deposits, and that provides fresh water to Amman and other municipalities in central Jordan, is too small in capacity to meet the demands of the oil shale industry in the country. A deeper aquifer in the Kurnub Sandstone Formation (1,000 m below the surface) (Salem 1984; Salameh and Udluft 1985; Salem 1994; MWI 2000; Sawariek, Hützl, and Salameh 2009) may be capable of providing an adequate supply of water to be used for the oil shale operations. However, this groundwater source and other potential groundwater sources need further study (Dyni 2006).
Discussion and conclusions

Oil shale is a type of sedimentary rock that is rich in the organic matter, named “kerogen”. This substance is not liquid petroleum, but organic matter formed from prehistoric marine plants and animals. Kerogen is converted into oil (shale oil) when heated long enough and at high temperatures.

While oil shale is found in many countries of the world, the USA has the largest reserves found in the Green River’s Formation in Colorado, Utah, and Wyoming. The USA’s shale oil estimates are roughly up to 5 trillion barrels, of which 1.0–1.3 trillion barrels are recoverable. Even if only 800 billion barrels can actually be recovered, this is still three times greater than the 262.6 billion barrels in Saudi Arabia’s oil reserves. According to some estimates, the USA’s oil shale reserves could supply American oil needs (about 20 million barrels a day) for 400 years.

Regarding Ethiopia, though this country has considerable resources and reserves of oil shale, there is currently a lack of interest in exploring them, possibly due to the disputes over the area between Ethiopia and Eritrea, which led to unresolved conflicts between both countries. An estimated amount of 3.89 billion tons of oil shale will produce roughly about one trillion barrels of shale oil, which is considered a huge amount of oil, if it is successfully extracted. Thus, this amount of shale oil will not only satisfy the Ethiopian local market, but it will also have some left for export, earning much needed hard currency.

Geologically speaking, the oil shale in the Ethiopian Tigray region is found sparingly distributed under the Adigrat Sandstone Formation all over the erosion remnant of the sedimentary chain ridges. It is formed during the glacial retreat followed by marine deposition of shale in the Werri glacial basin created by enormous load of the glaciers. It is black, friable, having brown streak, and

Figure 7. Oil shale outcrop of El-Lajjun (Al-Lajjun) deposit, showing, from top to bottom, beds of gravel, chalk-marl, chalk, slightly bituminized marly limestone, and oil shale with gray color (Left); and El-Lajjun’s local geology (stratigraphic vertical column) (Right) (after DeWolfe 2010; Alali et al. 2015).
laminations of shaly limestone which their frequencies increase to the top of the shale formation. This is an evidence of frequent and continuous deposition of the oil shales in different environmental conditions. The oil shale formation has been displaced by tectonic faults, which caused closely spaced regular fractures, trending towards N300W, and dipping 800E, N700E, and 750NW. The oil shale formation is also intruded by sub-volcanic dykes, trending the same trend as the faults towards N300W, and dipping 800E.

Though the kerogen’s value of the Ethiopian Tigray’s oil shale deposits is not yet analyzed, the geological characteristics of the oil shales and the amount of resource in the Tigray region show that it is possible to be mined by in-situ retorting underground method. However, the resource is exposed and it will be more economical if mining is conducted by open-cast. The by-product ash can be used in many industrial purposes by the Ethiopian Government, companies, and/or by the local people of the area.

Regarding Jordan (as being one of the richest countries in the MENA region, with respect to oil shale resource, while it lacks crude oil and natural gas resources), it has significant oil shale deposits occurring in more than 25 known localities. Geological surveys indicate that the existing deposits underlie more than 60% of the Jordanian territory. The resource has been estimated to consist of 40–70 billion tons of oil shale, which may be equivalent to more than 5 million tons of shale oil. Some estimates of the oil shale in Jordan reach up to 100 million tons. Accordingly, the Jordanian Government has already launched a long-term energy strategy (2007–2020), in which the shale oil (extracted from the oil shale resource in the country) has been given considerable attention as a good Jordanian energy source (Sahawneh 2015).

In their study on the challenging geology of the oil shale deposits in Jordan, Puura, Soesoo, and Aosaar (2016) pointed out that the oil shale layers, subjected to sub-surface oxidation, show distinct lithological, mineralogical, and chemical characterizations, especially trace-elements’ patterns. The presence of mineralogical and geochemical trace elements in oxygenated primary oil shale deposits provides key information for the local and regional paleo-tectonic, paleo-hydro(geo)logical, and paleo-climatic investigations. This key information could be used together with micro-paleontological and stratigraphic studies for the detailed mapping and understanding of the oil shale deposits in the various locations in Jordan.

In brief, the geology value of the oil shale deposits in Ethiopia and Jordan (as two poor developing countries, with respect to oil and natural gas resources) can be translated into considerable and rewarding economic values that will greatly benefit the gross domestic product (GDP) of both countries. However, the environmental impacts of the oil shale industry, as well as its need for huge amounts of water required for the industrial operations of the oil shale should be seriously taken into consideration by the industrialists, environmentalists, hydrogeologists, engineers, and the policy-and decision-makers, who are concerned of this industry.

References


