Across the next four blogs, I shall discuss the geological character of the Danakhil fill and the controls on potash in the depression via four time-related discussions; A) Current continental fan – saltflat hydrology that typifies present and immediate past deposition in the depression (Danakhil Blog1). B) A time in the latest Pleistocene when there was a marine hydrographic connection exemplified by a healthy coralgal rim facies (probably ≈ 100,000 years ago, and a subsequent drawdown gypsum rim facies. Both units are discussed in this blog, (Danakhil Blog1), and C) a somewhat older Pleistocene period when widespread potash salts were deposited via a marine seepage fed hydrology (Danakhil Blog2). Then, within this depositional frame, we will consider D) the influence of Holocene volcanism and uplift.

The Danakhil dichotomy

The Danakhil region, especially in the Dallol region of Ethiopia, is world renowned for significant accumulations of potash salts (both muriates and sulphates), and is often cited as a modern example of where potash accumulates today. What is not so well known are the depositional and hydrological dichotomies that control levels of bittern salts in the Pleistocene stratigraphy that is the Danakhil fill. Geological evolution of the potash occurrences in the Dallol saltflat and surrounds highlights the limited significance of Holocene models for potash, when compared to the broader depositional and hydrological spectra preserved in ancient (Pre-Quaternary) evaporite deposits (see Warren, 2010, 2015 for a more complete analysis across a variety of evaporite salts).
driving remobilisation of the somewhat older potash-rich evaporite source beds into the Holocene hydrology (Danakhil Blog 3) and finally how this relates to models of Neogene marine potash deposition (Danakhil Blog 4). These observations and interpretations are based in large part on a two-week visit to the Dallol, sponsored by BHP minerals, and focused on the potash geology of the region.

**Dallol Physiography**

The Danakhil Depression of Ethiopia and Eritrea is an area of intense volcanic and hydrothermal activity, with potash occurrences related to rift magmatism, marine flooding, and deep brine cycling. The region is part of the broader Afar Triple Junction and located in the axial zone of the Afar rift, near the confluence of the East African, Red Sea and Carlsberg rifts (Figure 1a; Holwerda and Hutchison, 1968; Hutchinson and Engels, 1970; Hardie, 1990). The depression defines the northern part of the Afar depression and runs SSE parallel to the Red Sea coast, but lies some 50 to 80 km inland, and is separated from the Red Sea by the Danakil Mountains. The fault-defined Danakil Depression is 185 km long, up to 70 km wide, with a floor that in the deeper parts of the depression is more than 116 meters below sea level. It widens to the south, beginning with a 10 km width in the north and widening up to 70 km in the south (Figure 1a). In the vicinity of Lake Assele, the northern portion of the Danakil is known as the Dallol Depression and has been the focus for potash exploration for more than a century and is in the deepest region of the depression with elevations ranging between 50m to 120m below sea level (Figure 1b, c). Shallow volcano-tectonic barriers, behind Mersa Patma, Hawakil Bay, and south of the Gulf of Zula, prevent hydrographic (surface) recharge to the depression. Marine seepage is not occurring at the present time, but likely did so at the time the main potash unit was precipitated. Lake Assele (aka Lake Kurum) with a water surface at -115m msl should not be confused with Lake Asal (-155 msl), located 350 km to the southeast of the Danakil. Asal an active marine-fed hydrographically isolated lacustrine drawdown system, which today is depositing a combination of pan halite and subaqueous gypsum in the deepest part of the Asal-Ghubbat al Kharab rift (Figure 1a; Warren, 2015).

Today the halite-floored elongate saltpan, known as the Dallol saltflat, occupies the deepest part of the northern Danakil Depression, extending over an area some 40 km long and 10 km wide (Figure 1b, c). The pan's position is asymmetric within the Danakil Depression; it lies near the depression's western edge, some 5km from the foot of the escarpment to the Balakia Mountains and the Ethiopian Highlands, but some 50 km from the eastern margin of the depression, which is in Eritrea. The Dallol saltpan and adjacent Lake Assele today constitute the deepest continental drainage sump in the Afar depression (Figure 1b, c). The area, located east and northeast of the main modern Dallol saltpan depression, is mostly an extensive gypsum plain (Bannert et al., 1970). As we shall see, the gypsum pavement, and its narrower equivalents on the western basin flank, defines a somewhat topographically higher (still sub-sealevel) less-saline, lacustrine episode in the Dallol depression history fill. To the south of the Dallol salt pan, bedded Pleistocene evaporites may underlie the entire Danakil depression, but younger lava flows of the Aden Volcanic Series in combination with alluvium washed in from the surrounding bajada obscure much of the older Pleistocene sedimentary series in southern part of the depression beyond Lake Assele (Figures 1a).

**Climate**

In terms of daily and monthly temperatures, the Dallol region currently holds the official record for highest average, year-round, monthly temperatures; in winter the daily temperature on the saltflat is consistently above 34°C and in summer every day tops 40°C, with some days topping 50°C (Figure 2; Oliver, 2005). These high temperatures and a lack of rainfall, typically less than 200 mm each year, place the Dallol at the hyperarid end of the world desert spectrum and so it lies at the more arid end of the BWh Köppen climate zone (Kottek et al., 2006; Warren, 2015).
History of extraction of Danakhil salt products and their transport (Table 1)

Using little-changed extraction and transport methods, salt (halite) has been quarried by local Afar tribesmen for hundreds of years. First, using axes, a crust of pan salt is chopped into large slabs (Figure 3a). Then workers fit a set of sticks into grooves made by the axes. Next, working the stick, workers lever slabs of bedded salt, which is cut into rectangular tiles of standard size and weight, called ganfur (about 4kg) or ghelao (about 8kg). Tiles are stacked, tied and prepared for transport out of the depression on the backs of camels and donkeys (Figure 3b). Around 2,000 camels and 1,000 donkeys come to the salt flat every day to transport salt tiles to Berahile, about 75 km away. Previously, salt tiles were carried via camel train to the city of Mekele, some 100 km from the Danakil. Mekele, located in the Ethiopian highlands is known as the hub of Ethiopia's former "white gold" salt trade and still today is known as the "old" salt caravan city. Today, the salt caravans walk the extracted salt to Berahile, located some 60 km from Mekele. From there, trucks transport the salt to Mekele. Each truck can transport up to 350 camel salt loads. From the Mekele salt market, Dallol salt blocks are transported and sold to all parts of Ethiopia for use mainly as table salt or as an add-on in animal feed. The lifestyle of the miners and the camel trains is likely to change in the next few decades as sealed roads are now under construction that will link Mekele to Dallol.

Historically, Danakhil salt was a monetary unit

Worldwide, pre-refrigeration salt was a high value traded commodity as the “old” salt caravan city. Today, the salt caravans walk the extracted salt to Berahile, located some 60 km from Mekele. From there, trucks transport the salt to Mekele. Each truck can transport up to 350 camel salt loads. From the Mekele salt market, Dallol salt blocks are transported and sold to all parts of Ethiopia for use mainly as table salt or as an add-on in animal feed. The lifestyle of the miners and the camel trains is likely to change in the next few decades as sealed roads are now under construction that will link Mekele to Dallol.

Once potash (sylvite and carnallite) was discovered in the Dallol region in 1906, an Italian company by the name of Compagnia Mineraria Coloniale (CMC) established the first mining operation. In 1918 a railway was completed from the port of Mersa Fatma to a termination some 28 km from Dallol (Table 1). Rail construction took place from 1917-1918, using what was then the British and French “military-standard” 600 mm rail-gauge Decauville system. “Decauville” rail construction used ready-made sections of small-gauge track and so the trackway was rapidly assembled; <2 years to complete more than 50 km of track. Once completed, the railway transported extracted potash salt from the “Iron Point” rail terminal near Dallol, via Kululli to the port. Potash production is said to have reached some 50,000 metric tons in the 1920s, extracted from an area centred on the Crescent Deposit, which is located near the foot of uplifted lake beds on the southern flanks of Mt Dallol. However, significant salt production had ceased by the end of the 1920s, as large-scale mines in Germany, the USA, and the USSR began to supply the world market with cheaper product. Unsuccessful attempts to reopen potash production were made in the period 1920-1941. Between 1925-29 some 25,000 tons of sylvite were shipped by rail from the Dallol, with a product that averaged 70% KCl. After World War II, the British administration dismantled the railway and removed all traces of it. In 1951-1953, the Dallol Co. of Asmara sold a few tons of product from the Dallol.

The potash concession title was transferred to the American “Ralph M. Parsons Company” (Parsons) at the end of the 1950s. Parsons initiated the first systematic exploration for potash in the Danakil depression and drilled more than 250 exploration holes during their 9-year evaluation campaign. Major potash resources were confirmed a few km west of Mount Dallol, in a mineralized zone that was named the “Musley” Deposit. Following on from positive exploration results, they began an engineering study to investigate potential processing and mining
methods for the Musley Deposit and subsequently in October 1965 sank a shaft into the orebody. They installed underground mine facilities and established a pilot processing plant on surface, to investigate recovery from the bulk samples collected from the underground workings. They envisaged developing the Musley Deposit as a conventional room-and-pillar operation and to this end developed six underground drifts totalling some 805 m in length. Unconfirmed reports suggest that an influx of water flooded the mine (possibly triggered by a seismic event) and after failed attempts to solve the water problem, the activities Parsons ceased activities in 1968. As of end 2014, some salt block buildings built by the Italian and other companies still partially stand as ruins, along with rusting equipment.

Based on the previous work conducted by Parsons, a German potash producer, Salzdetfurth AG (SAG), began a new exploration campaign in the Danakil Depression in 1968 and 1969. In addition to their work in the Daloll depression, SAG drilled a number of wells in a concession south of Lake Assale, and conducted a geological mapping campaign as far north as Lake Badaa, on the border with Eritrea. SAG’s exploration work away from the known Daloll deposits did not prove fruitful as they drilled only one drill hole that reached the potash level. This drill hole, located approximately 25 km to the southeast of Mount Daloll, intersected a kainitite bed, with no sylvinite intersecion. The SAG concession was returned to state authorities of Ethiopia. Subsequent drilling by other explorationists in this region has confirmed the deepening of the kainitite level to the southeast of Daloll and the lack of sylvinite at greater depths.

Since the dismantling of the railway, there has been no high-volume transport system to carry potash product the Red Sea coast. Currently, the Ethiopian Government is constructing all-weather roads from Daloll to Mekele and Afdera. When complete this road system will facilitate transport of future potential potash product from the Daloll to Afdera, from where existing roads provide access to Serdo and from there to the seaport of Tadjoura in Djibouti (Figure 1a). This section requires an addition 30 km of all-weather road to be completed to the coast and will facilitate cost-effective transport of potash product to the large agricultural markets of India and China. The transport distance to the Eritrean coast from Daloll is much shorter, but political considerations mean such a route is not a viable option at the present time.

Ground instability is related to the sump's rift setting

Large volume extraction will use solution mining and brine processing, not conventional mining

<table>
<thead>
<tr>
<th>Exploration company</th>
<th>Year</th>
<th>Localization</th>
<th>Activities</th>
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<tr>
<td>Compagnia Mineraria Co-benefice (Italy)</td>
<td>1917 to 1929</td>
<td>Hear Bash Mountain (GR of Daloll)</td>
<td>Exploration of superficial Sylvinite and Cummal Ile</td>
</tr>
<tr>
<td>Società Company (unknown)</td>
<td>October 1941</td>
<td>Al Daloll and Zanga (river Gailall)</td>
<td>Sulfur exploitation</td>
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<tr>
<td>Drill Potech, Magnesium and Sulfur Mines (Minerica Co. (Dallol))</td>
<td>1965 to 1968</td>
<td>Kainitite of Daloll</td>
<td>Prospecting and mining of potash and sulfur, export to India</td>
</tr>
<tr>
<td>The Ralph M. Parsons Company (PARTHS), (United States of America)</td>
<td>1965 to 1968</td>
<td>2 km SW of Mount Daloll and 5 km N of 15 km NW of Mount Daloll</td>
<td>Exploration drilling, chemical analyses, resource modelling, shaft sinking, mine evacuation, drilling (Lake Ankolat, mining of Lake Dakel)</td>
</tr>
<tr>
<td>Salzgitterberg (Germany)</td>
<td>1964 to 1969</td>
<td>S of Lake Arok, N of Lake Bada</td>
<td>Exploration drilling and chemical analyses for potash</td>
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<tr>
<td>Ethiope Potash Company Inc. (EPC, Ethiopia)</td>
<td>1969 to 1970</td>
<td>Area in border region Entebe (Mile of Daloll)</td>
<td>Re-examination of the data from PARTHS activity</td>
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<tr>
<td>ETHOS-Engineering (France) / EMCO (Ethiopia) / Empresa Minera de Chile (EMC, France)</td>
<td>1994 to 1996</td>
<td>2 km SW of Mount Daloll and 5 km NW of Mount Daloll</td>
<td>Site expedition, preparation of assessment study, mining conception, re-evaluation of the data from Parsons activity</td>
</tr>
<tr>
<td>Hydro Agil International (RSI, Norway) / Kassevær / Unternehmens GmbH ( Walter Glacier, Germany)</td>
<td>1987 to 1988</td>
<td>2 km SW of Mount Daloll and 5 km EW of Mount Daloll</td>
<td></td>
</tr>
<tr>
<td>Alkana Potash Corporations</td>
<td>2006 to present</td>
<td>The company owns two mineral licenses for potash and related salts that encompass most of the southern Daloll and Musley regions and regions to the south.</td>
<td>Proposed potash extraction will utilize targeted solution mining methodologies. Pilot program for KCl extraction from new completed. Mineral Resources for the Sylvite Member in the licenses are estimated to be 2.4 billion (based on a cut off grade of 15% K2O) and a minimum Sylvite Member thickness of 1.0 m.</td>
</tr>
<tr>
<td>SAG Bilten</td>
<td>2006 to present</td>
<td>Endersina region south of Alkana inclusion and extending west south of the Potash Daloll depression</td>
<td>Complete initial phase seismic survey (drilling a length of approximately 500 km to 400 km) had</td>
</tr>
<tr>
<td>Ethiope Potash Corporation (EPC), This Canadian listed exploration company has an agreement in place with C. G. and Bilten African Resources Limited to conduct exploration work in their license areas.</td>
<td>2006 to present</td>
<td>License areas are located north of the Alkana properties</td>
<td>Exploration commenced with diamond drilling in May 2011 and to date the company has completed over 4,500 m in 25 exploration holes. Drilling intended similar potash stratigraphy as seen within the Alkana properties to the north and returned similar potassium K2O grades and thicknesses in some of the exploration attitudes.</td>
</tr>
<tr>
<td>Ethiopepotash BV (Dutch/Africa Potash Private Limited)</td>
<td>2006 to present</td>
<td>Etiopepotash BV, a joint venture between Fiske International (a fertilizer company based in Norway) and Sukie Potash Private Limited, has been carrying out exploration drilling in its concession areas since 2013.</td>
<td>Recently completed their exploration drilling program. Ethiopepotash BV has now ended an in a delegation mining pilot program and has recently conducted pilot evaporation ponds and developed pilot solution schemes within their project areas.</td>
</tr>
<tr>
<td>Samaara Private Limited</td>
<td>2006 to 2007</td>
<td>Samaara will define the exploration rights to their exploration license, through the area has little potential as it covers a large portion of unmineralised Daloll Mountain</td>
<td>To date, the company has not completed any work in the area and subsequently the mining license was removed by the Ethiopian Ministry of Mining and awarded to Hans Petroleum Corporation. This license was then acquired by Alkana in 2019.</td>
</tr>
<tr>
<td>South Boulder Mines Ltd</td>
<td>2006 to present</td>
<td>South Boulder Mines Ltd is an Australian based company developing its Daloll property which is located in the depression, across the border in Eritrea.</td>
<td>The company has reported positive drilling results, along with a JORC compliant resource of 944 Mt grading 18% K2O. South Boulder is currently in the Feasibility Study phase and is targeting an initial production of 1 Mt per year. Drilled a total of 50 drill holes.</td>
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EVAPORITE DEPOSITIONAL PATTERNS IN OUTCROP

Surficial sediment distributions outline classic drawdown facies belts in the Dallol region, with a wadi-fed alluvial fan fringe passing down dip into sandflats (local dune fields), dry mudflats (with springs), saline mudflats and ephemeral to perennial brine pans of Lake Assele (Figure 1b,c). The fans, especially along the western margin of the depression are indented or locally covered by a mostly younger succession of constant-elevation marine, biochemical and evaporitic sediments fringes or “bathtub rim” facies (Figure 4).

Alluvial Fan fringe (Bajada)

Pleistocene alluvial/fluvial beds, exposed by local uplift, deflation and ongoing water table lowering, outcrop about updip edges to the salt-crust parts of the northern Danakil, and form low flat-topped plateaus or mesas on the plain. These mesas define the tops of alluvial fans aprons, which are heavily dissected and eroded by occasional storm runoff and rainfall. This fan fringe contains relatively fresh water lenses in a desert setting that is one of the world’s harshest (Kebede, 2012).

The last marine episode in the basin is much younger than any potash bed(s)

A well-exposed at-sea level reef rim defines the last hydrographic connection to the Red Sea

Most of the depositionally active fans line the western margin of the basin and many of the downdip fan edges occur slightly updip a still-exposed gypsum pavement (Figure 5a), showing depositional equilibration largely with an earlier higher lake stage, while others, such as the Musley fan, have flowed across cut into the gypsum pavement level and now feed water and sediment directly into the edges of the saltflat that defines the lower parts of the depression (Figure 4). Watercourses of the fans that have dissected earlier wadi (bajada) deposits as well as the earlier lacustrine gypsum and limestone pavements so create excellent windows into the stratigraphy of these units. Fan avulsion is indicated by palaeosol layers exposed by downcutting of younger streams (Figure 5b, c).

The Musley fan characteristics are well documented by current and previous potash explorers in the basin as these permeable gravels and sands store a reliable water source for potential solution mining/ore processing in the Musley area and so has been cored by
a number of proposed water wells. Internally, the fan is composed of interfingering layers and lenses of sand, gravel and clay (paleosols), with highly porous intervals in the sand and gravels (Figure 5b, c). Depth to the water table varies from >2m to 60m, and salinities from 760 ppm to more than 23,400 ppm. The principal source of recharge is flash flooding, originating in Musley Canyon, which drains the Western Escarpment, along with minor inflows from the adjacent uplifted volcanic block and local highly intermittent rains (Figure 1a). Of six potential water wells drilled in the fan by the Ralph M. Parsons Company in the 1960s, four returned water of good quality (<2000 mg/l), while the other two had waters with salinities in excess of 20 g/l. Pumping test data indicate average transmissivity of the water-bearing beds around 870m²/day, with salinities in the fan increasing from west to east, approaching the saltflat.

Chemical sediments outcropping in the depression

Overall, surface sediment patterns in the Danakil depression define a depositional framework of brine drawdown, related to basin isolation from an earlier hydrographic (at surface) marine connection to the Red Sea, followed by stepped evaporative drawdown. This is indicated by fringing topographically-distinct belts or rims of now inactive coralgal carbonates and gypsum evaporites (aka “bathtub ring” patterns) that cover earlier Pleistocene and Neogene clastics (Figures 1a, e, Figure 7a-c). These “rims” of marine limestone and subsequent gypsum were followed by today’s drawdown saline-pan halite-dominant hydrology (Figure 4).

The modern depositional setting is a continental brine-fed saltflat/salt pan

The underlying potash (kainitite/carnallitite) bed is a subaqueous marine-fed deposit
The current hydrological package of sediments encompassing the current drawdown episode lies atop and postdates the Pleistocene potash-hosting Lower Halite Formation in the depression and is probably equivalent to the uppermost part of the clastic overburden facies, as illustrated in the drilled and cored portions of the depression stratigraphy. As we shall discuss in the next blog, only the uppermost portion of the recovered core stratigraphy has equivalents in current depression hydrology (Figure 6).

In earlier work, some authors interpreted the fringing belts, especially the exposed coralgal reef belt, as being possibly of Pliocene or even Miocene age. However, when one looks at the stratiform nature of the outcrop trace of both the reef belt and the gypsum belt, and the carapace nature of its depositional boundaries in the field, it is immediately apparent they must be younger (Figure 5a, c; Figure 7a-c). Both the reefal and gypsum belts track horizontal hydrological intersections with the landscape, in what is an ongoing volcanogenic and tectonically active depression.

When the reefal belt image is overlain by a DEM it shows the reef belt is consistently at sea level (Figure 1c). If the outcrops of the reef belt and the gypsum pavement were older than late Pleistocene or Holocene, then ongoing episodes of tectonism and volcanism would have modified the elevations of the two outcrop belts in the landscape, as is seen in Miocene redbed outcrops. These underlying and centripetal Miocene sections clearly show the influence of ongoing tilting and tectonism and hence why the flat-lying tops to the reef and gypsum belts imply a late Pleistocene-Holocene (Figure 5d).

Textural styles of today are similar to those in the Upper Rocksalt formation (URF)

Evaporite textures in Lower Rocksalt Formation (LRF) are not

That is, the topographic distribution of the top of the reef facies, which lies within a metre or two of current sea level, implies that the Danakil depression had a relatively recent connection to the Red Sea. The pristine preservation of aragonitic corals and sand dollars in the adjacent marls suggest the connection was either related to the penultimate interglacial (around 104,000 years ago) or to an early Holocene transgression into the depression. Bannert et al. (1970) assign a C14 age of 25.4-34.5 ka to this formation. However, we consider this is unlikely as DEM overlay levelling shows the reef rim, wherever it outcrops, lies within a meter of current sealevel. World eustacy clearly shows that sealevel was more than 50-60m below its present level some 25,000-30,000 years ago. A 25-35 ka determination of the reef rim would require the whole basin was subject to a single basinwide wide vertical uplift event that did not fragment or disturb the lateral elevation of the rim.

The coralgal reef terrace indicates normal marine water were once present in the Dallol depression, while the occurrences of the stratiform gypsum pavement are consistent with a former arid lake hydrology at a somewhat lower elevation than the reef rim (Figures 1c, 5a, 7a-c). Like the reef rim, the gypsum pavement fringe defines a consistent elevation level or surface, most clearly visible.
The exposed sump geology is a series of “rim” facies

The sump's modern geology is a clear response to an increasingly saline drawdown hydrology

Active today in the lowest parts of the Dallol saltflat is an ephemeral saltpan hydrology indicated by bedded salt crusts dominated by megapolygonal crusts made up of aligned-chevron halite stacks separated by mm-cm thick mud layers. This current pan hydrology is associated with even greater drawdown levels compared to the former gypsum-dominant hydrology (Figure 8). Current deposits, made up a series of stacked brine-pan salt sheets, are still quarried as a renewable resource by the local tribesmen (Figure 3). These modern brine flats accumulate pan halite whenever the Lake Assele brine edge (strandline) is periodically blown back and forth over the modern brineflat. It driven by southerly winds, which are frequent in the annual weather cycle, and can move thin sheets of brine kilometres across the pan in a few hours (Figure 4, Figure 8). Superimposed on this southerly supply of brine is an occasional land-derived sheetflood event, driven by rare rainstorms and the deposition of silt-mud layers from water sheets sourced from the adjacent wadi belt. This ephemeral brineflat hydrology is stable with respect to the current climate (groundwater inflow ≈ outflow). It
Potash at the sump’s surface is a response to a set of hydrothermal overprints

No widespread bedded potash is forming from a saltflat-wide hydrology

Most importantly there is no evidence of primary potash deposition in the modern lake/pan hydrology of the Dallol saltflat. It is clear that the world-famous bedded potash (mostly kainitite) units of the Danakil accumulated in a bittern hydrology that is not present in today’s Dallol depositional hydrology (Blog 2). As we shall see, Holocene potash only occurs in the vicinity of the Dallol Volcanic Mound, where uplift has moved older, formerly buried, potash beds into a more active hydrothermal hydrology (Blog 3).
References


Geology of the Danakhil is a response to an evolving rift hydrology
Salts in the sump indicate a longterm transition from marine to continental -hydrothermal waters