35TH EDITION

AL HAJAR

APRIL 2023

The First Record of an Impact Crater in the Sultanate of Oman

"We Have to Act Now" – Omani Entrepreneur Turning CO_2 Into Rocks

The Scenery & Geology of Kilimanjaro and Mount Meru, Tanzania

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Dear readers,

Despite the rapid pace of advancement that occurred in the geosciences over the past 250 years, our world continues to harbor many secrets, mysteries and questions that must be investigated and answered in order to satisfy our curiosity and our need to understand. Exploration plays an important role in clarifying the ambiguous and in discovering truth. James Hutton (the founder of modern geology) said: “In matters of science, curiosity gratified begets not indolence, but new desires. ” Curiosity about our world motivates humans to discover new resources, new inventions and to achieve better ways of living. Moreover, each new discovery opens other doors leading to many more exciting findings about the Earth and how people can best manage the rapid changes occurring on our planet. An example of such ingenuity is the creative ways that humans have developed to minimize CO_2 emissions by using renewable energy, green hydrogen and CO_2 capture.

Here at AL Hajar magazine, we seek to share new findings and discoveries because we believe that reading such will encourage you to explore our world, expand your knowledge and find enjoyment in Nature. Therefore, in this 35th edition of AL Hajar, we introduce you to some new discoveries, such as a report on the first documented impact crater in Oman, and a report on how an innovative Omani start-up company is proposing to turn carbon dioxide into rock. Then, we take you on a journey to explore the geology of Kilimanjaro and Mount Mero in Tanzania, as well as evaluate potential geo-hazards along a proposed National Highway in India. I hope the topics in this edition satisfy some of your curiosity, inspire your soul and encourage you to continue learning and discovering.

Laila AL Zeidi
GSO Content Editor

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Location: Peridoite outcrop photos showing calcite veins and alteration textures in the Wadi Fins serpentinized harzburgites. These photos were taken in the deep canyon up wadi fins, Oman 2,532,838 to 2,533,636 m N and 721,824 to 722,551 m E

The First Record of an Impact Crater in the Sultanate of Oman

Sobhi Nasir[1], Nikolaos Oikonomoy[1], Khalil AlHooti[1], Talal Al-Hosni[1], 1 Sultan Qaboos University

Abstract

This report describes the first known impact crater found within the Sultanate of Oman. The evidence is based on geological, morphological, and petrological surveys of 200 samples from the crater area. The newly discovered crater is a simple impact crater near the town of Mahout in Oman's central desert. The impact crater consists of an elliptical ridge about 770 m long and 550 m wide, oriented roughly NNE to SSE. The elliptical shape and relief asymmetry indicate an oblique collision. The original morphology of the crater is well-preserved, and within the crater are found, various types of impact materials including melt lenses. The exact age of the crater is unknown. However, crater shape and ejecta patterns suggests formation by northeasterly impacts during the late Cretaceous to early Cenozoic, after uplift and peneplanation of the central desert region of Oman. The hypervelocity impact origin of the structure is determined based on field observations of shatter cones and microscopic observations of planar fractures (PF) and planer deformation features (PDF) in quartz, feldspars, carbonates, mono- and polymict breccias, globules, and various types of melts and the presence of coesite.

Introduction

The impact of asteroids and comets with the Earth's surface is one of the most catastrophic of geological processes, and preserved impact craters provide important information for understanding impact events and related structures. Currently, there are 190 impact structures known on Earth, and of these, only 21 (11.5%) have small diameters of less than 1 km (Earth Impact Database, http://www.passc.net/Earth Impact Database/index.html), and most of the these are very young (0.1 to 1 Ma). Most terrestrial impact craters are not pristine as they are affected by later erosion, deformation, alteration, or post-impact sedimentation. Thus, the ultimate proof of an impact crater usually depends on documentation of mineralogical transformations, which are uniquely formed by shock waves, such as shattercones, planar deformation features (PDF), or high-pressure polymorphs (Osinski 2008).

Shocked grains will show planar microstructures that formed upon shock compression and that are crystallographically controlled. Planar microstructures are mainly of two types (Osinski et al. 2022):

(1) planar fractures, which are parallel, thin open fissures

(2) PDFs, which are narrow, individual planes of amorphous material comprising straight parallel sets spaced 2–10 μm apart that generally occur in multiple sets per grain.

Engelhardt (1997) classified impact structures into two main types based on morphology:

(1) Simple impact structures - These are usually bowl-shaped and up to 4 km in diameter.

(2) Complex impact structures - These are usually more than 4 km in diameter, with a broad, flat floor, terraced rims, and a distinct central uplift.

The discovery of meteorites in the deserts of Oman has lent international recognition to the Sultanate as a promising destination for scientific research. Several meteorite expeditions concluded that Oman could be one of the largest and most spectacular meteorite collection areas in the world. The Sultanate contributed around 14% of all the world's meteorite finds excluding Antarctica. The desert of Oman had yielded more than 5,000 meteorites as of mid-2011. Included among these are a large number of Lunar and Martian meteorites (Hofmann et al. 2014). However, no surface impact craters had yet been identified in Oman. The nearest confirmed impact feature is the Wabar crater in Saudi Arabia that has been dated at 290 years old (Prescott et al. 2004). Wabar consists of three small craters approximately 11 m, 64 m and 116 m in diameter formed by an iron meteorite impactor. Oman's central desert contains several geomorphological ring structures that were thought to be associated with either volcanic eruptions or collapsed salt domes, and in fact the Mahout structure was long believed by local geologists to be a volcanic crater. However, detailed studies by the present authors have confirmed that the Mahout structure is likely a good example of a simple impact crater.

Field Description

The Mahout crater is located in the rocky Al Huqf desert area of Central Oman, which is approximately 30 km southeast of Mahout City, and 500 km south of Muscat.

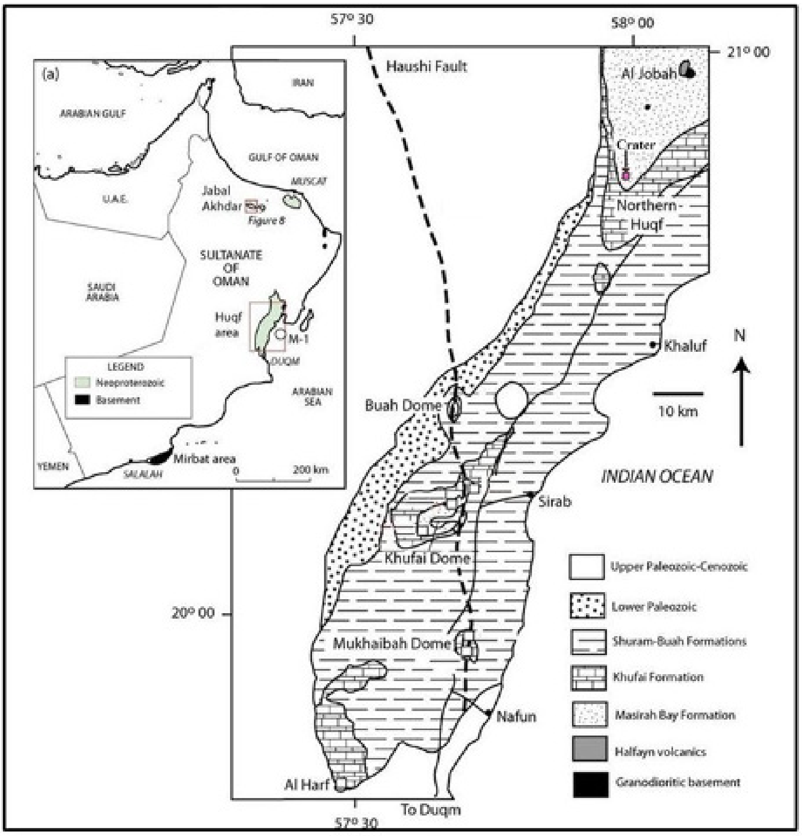

Figure 1. Location map of the Mahout crater.

The Mahout crater (Figure 1) consists of an elliptical ridge about 770 m in length and 550 m in width and is aligned roughly NNE to SSW (Figure 2A-D).

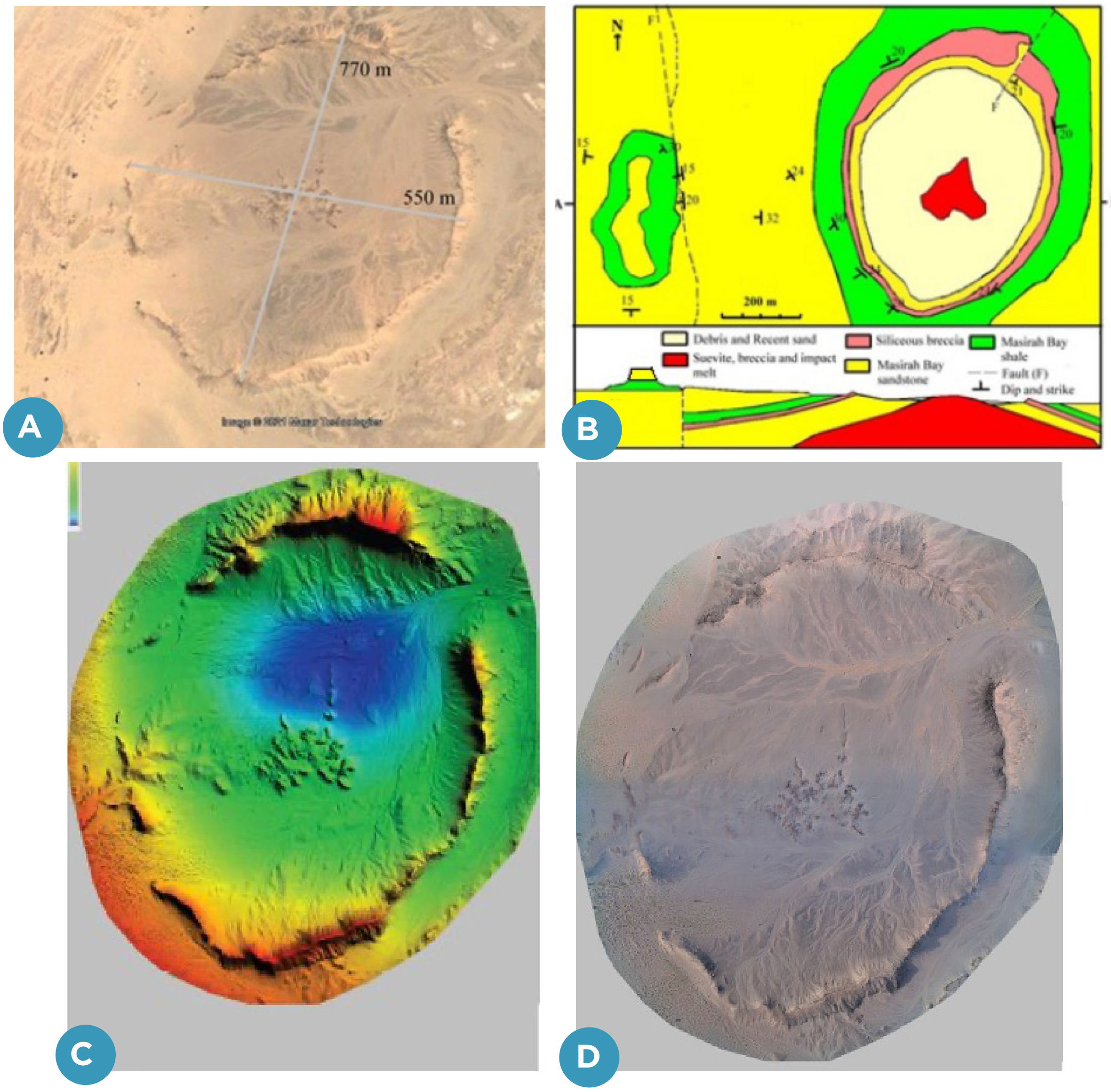

Figure 2A-D. Google earth image showing the impact crater (A) and geological map, cross section in the crater (B), elevation and 3D model of the crater (C-D).

The elliptical shape and asymetrical relief indicate an oblique impact. The crater occurs in a relatively simple geological context with a flat, and rocky desert surface, and impacted rocks comprised of sub-horizontal layered siliciclastics underlain by thin carbonates and acidic volcanics. The Al Huqf area is a low-relief (<70 m) piedmont sitting 40-50 m above sea level and sloping gently to the west. It lies at the base of some fault aligned, NS-trending elongated hills, and mesas as high as 100 m above sea level. There are a few shallow drainage lines or dry wadis (<1 m deep) that also slope toward the west. The area is virtually devoid of vegetation. The Masirah Bay Formation is the main stratigraphic unit that outcrops in the Mahout crater area. This forms the base of the Al Huqf Supergroup which ranges in age between 630 to 550 Ma (Allen and Leather, 2006). The Masirah Bay Formation consists of a Precambrian siliciclastics and is composed mainly of quarzitic sandstone, siltstone and shale, with intercalations of limestone (Allen and Leather, (2006). Rock layers penetrated by the impact include the Late Proterozoic Masirah Bay sandstone and the underlaying dolomitic and acidic volcanics and volcaniclastics of the Halfayn Formation which in turn is underlain by Pre-Cambrian basement rock (consisting mainly of acidic volcanics and granodiorite) (Figure 3).

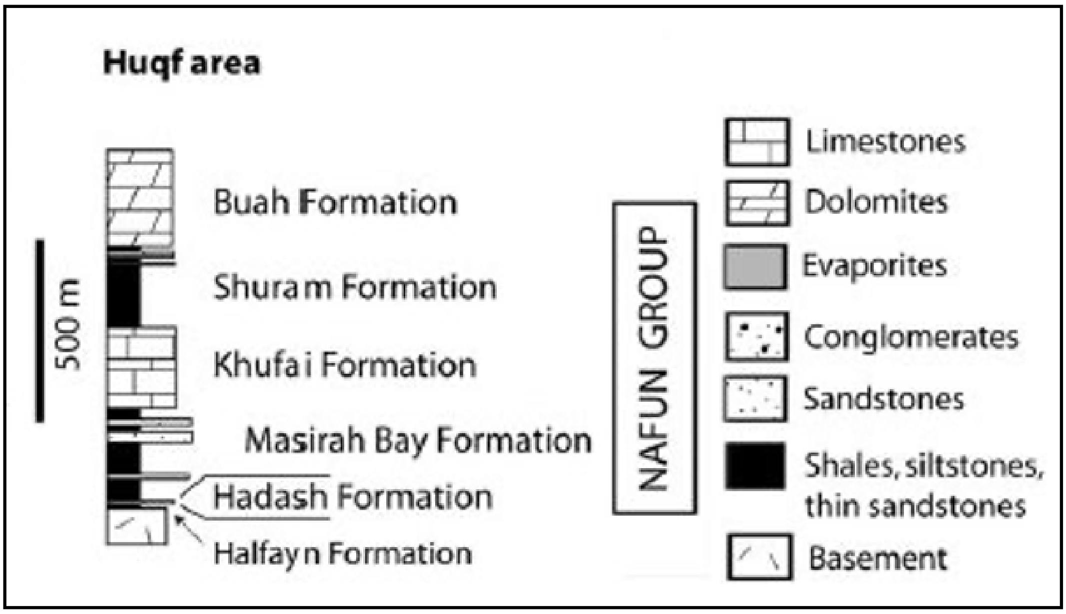

Figure 3. Geological formations outcropping in the impact crater area.

The central peaks inside the crater contain breccia that was pushed upward from the deepest impacted levels of the crater, and includes representatives from all the formations intersected by the crater in the form of melted materials or highly shocked rock. Several melted iron meteorite specimens have been identified in the area of the crater (Figure 4). However, no original meteorite specimens were found in the crater or in the surrounding area. This could indicate that the incoming impactor, of a size between 40-50 m in diameter, experienced no fragmentation or breakup during atmospheric flight. Additionally, it may have melted, and chemically and physically interacted with the shocked and melted target rocks.

Figure 4. Hematite samples within the ejecta.

The rim of the crater basin, which rises to a maximum of 15 to 20 m above the floor, is composed of shocked jasper and siliceous breccia, chert, normal sandstones, and silty shales of the Upper Precambrian Masirah Bay Formation. The structure geometry suggests that a hypervelocity impact, domed the affected sediments to form the structure mapped in (Figure 2B). The bowl shaped crater and asymetric in ejecta pattern coherently indicate that the impactor came from the SW and struck the ground at an incidence angle of approximately 30 to 45 degrees. The crested rim is blanketed with a mixture of ejecta and debris cored from the pre-existing surface. The identified asymmetries, including the off-center bottom of the transient crater floor downrange, maximum overturning of target rocks along the impact direction, and lower crater rim elevation downrange, can be diagnostic of oblique impacts in well-preserved craters. The crater has a continuous, encircling, raised rim, flanked by an ejecta blanket, extending for 500 to 1000 m. The ejecta blanket directly overlies non metamorphosed Masirah Bay siliciclastics and contains unsorted agate and chert clasts / fragments embedded within the pulverized silica groundmass. The longest ejecta rays extend as far as 500 m from the crater rim in the north, northeast, and northwest directions. The center part of the crater splays off several dykes with a NNE-SSW trend parallel to the long axis of the structure, which is occupied by low outcrops of suevite, polymictic and lithic impact breccia and rock melt (Figure 2B). A wind-blown recent sand deposit (few centimeters thick) covers only a small part of the crater wall and crater floor. At the crater walls, bedrock layers are upturned and dip radially outward. An overturned flap of ejected material is locally present at the rim crest. Variable amounts of overturned strata are observed on the northern and western crater rims. The beds dip as gently as 30 degrees from horizontal at the northern, eastern and western rims and 20 to 24 degrees in the southern part. The overturn is most severe to the north-northwest. Ejecta consists mainly of shocked sandstone blocks and impact melt lapilli and bombs. The bulk of the ejecta is preferentially concentrated in the northeastern part of the impact. This is consistent with the ejecta distribution, which suggest the projectile came in from the southwest. Within the crater rim unshocked shale and siltstone sandstone clasts and impact melt lapilli and agate bombs are more common; further away, the shocked agate and chert clasts dominate.

Petrography

An interesting aspect of the Oman crater is that the outcrops of impact melt-bearing lithologies are well-preserved with regard to their entire original context. Lithic and polymict breccia consists of a matrix and clasts (Figure 5).

Figure 5A-C. Field photo showing rim and breccia in the center (A) samples of suevite (B) and shatter cone in carbonate (C) .

The clasts account for about 60-70% of the breccia and are composed of a variety of different minerals, including carbonate, quartz, feldspar, coesite, apatite and glass class. The matrix, accounting for about 30-40% of the breccia, and is mainly composed microcrystalline quartz (chalcedony), coesite, celadonite, barite, calcite, feldspar and vesicular glass. Carbonate spherules, with liquid immiscible and quench textures, as well as euhedral calcite crystals within impact glass clasts are very common within the impact breccia. Quartz grains show 1-4 sets of PDFs. The suevite (melt rich polymict breccia) consists of clasts, a matrix, and glass clasts. Mixed melt glass and clasts are observed only in the suevite and occur as irregular patches with sizes of up to 1 × 10 mm. Most of these shows obvious flow texture. The glass occurs as ovoids, droplets, ribbons, or irregular fragments of different sizes, and display brown and yellow colors. Highly deformed carbonate and feldspar grains are the main components of suevite. Carbonate, feldspar and quartz impact melts occur as groundmass-forming grains within impact melt-bearing ejecta deposits. They occur as globules, spherules, single crystals and irregular shaped grains within impact glass clasts of the ejecta deposits. The melt origin for carbonates and feldspars includes carbonate spherules, euhedral carbonate and feldspar grains within impact glass, calcite intergrown with feldspar and liquid immiscible textures (Figure 6).

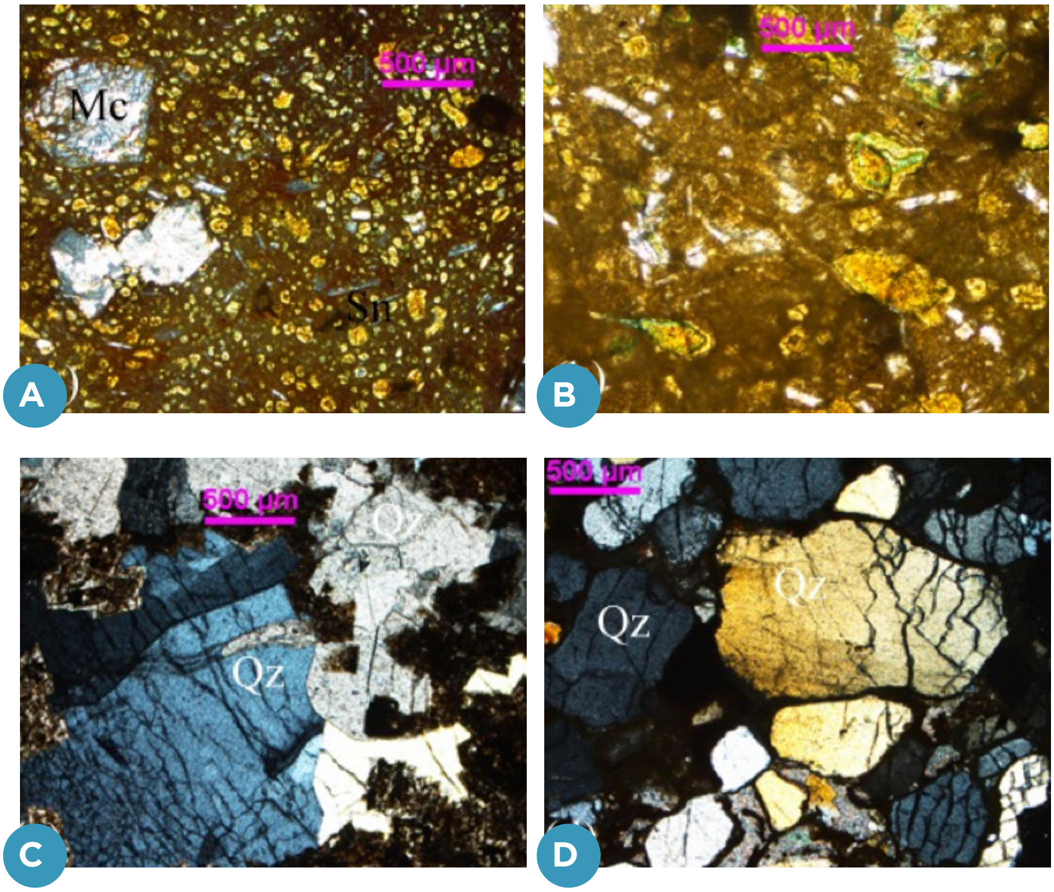

Figure 6A-D. Microcline clast and sanidine laths embedded in vesicular glass. B. Mixed vesicular glass showing a flow texture. C-D. Quartz grains display many irregular fractures and undulatory extinction Cc: calcite, Mc: microcline, Pl: plagioclase, Qz:quartz.

The crater rim is composed of shocked quartzite, jasper, agate, monomict siliceous breccia, and is underlain by shocked shale (Hornfels). All clasts show, irregular fractures, planar deformation features (Figure 7) and diaplectic glass melt, indicating different shock stages which ranges from moderately shocked to whole rock melting. This indicates a shock stage of F-S6. Abundant felsic rock melting occurs as mixed melt glass-clast and belongs to the F-S7 stage, and SP and PST are >60 GPa and >1500 °C, respectively (Stöffler et al., 2018). Figure 5-7 show varieties of shocked samples with planar deformation features, as well as remains of iron oxide samples and highly shocked quartzite and agate samples from the crater.

Figure 7A-F. Deformation features (shatter cones), e-planar fractures.

Geophysical Survey

Density and magnetic surveys were performed over the Mahout structure in order to confirm the meteorite direction and to image the deformational structures. A high induced magnetization area was mapped at the center of the crater with a magnitude large enough to dominate, the magnetic data (Figure 8). Ahigh susceptibility structure was imaged at the center of the crater, with susceptibility values varying from 0.03 up to 0.08 SI units. This seems to be a highly magnetic body dipping to the north and to the south with an uplift at its center.

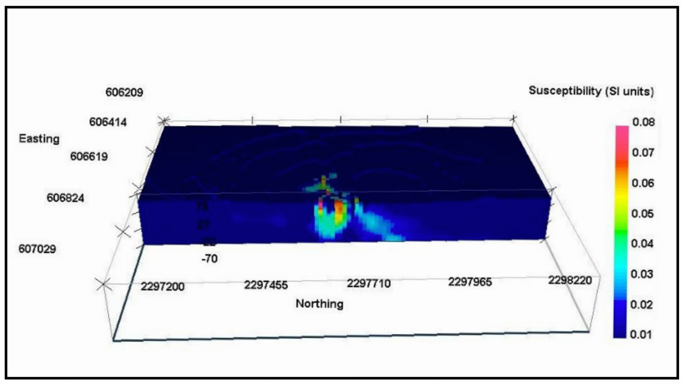

Figure 8. Magnetic susceptibility of the area of the crater.

Gravity data indicate a density variation up to 1.8 g/cm3 (Figure 9). This variation indicates a gradual density increase with depth, both due to the increase of the upper formations pressure with depth, but also due to the impact. A low-density sandy formation overlaps the rest of the subsurface structures.

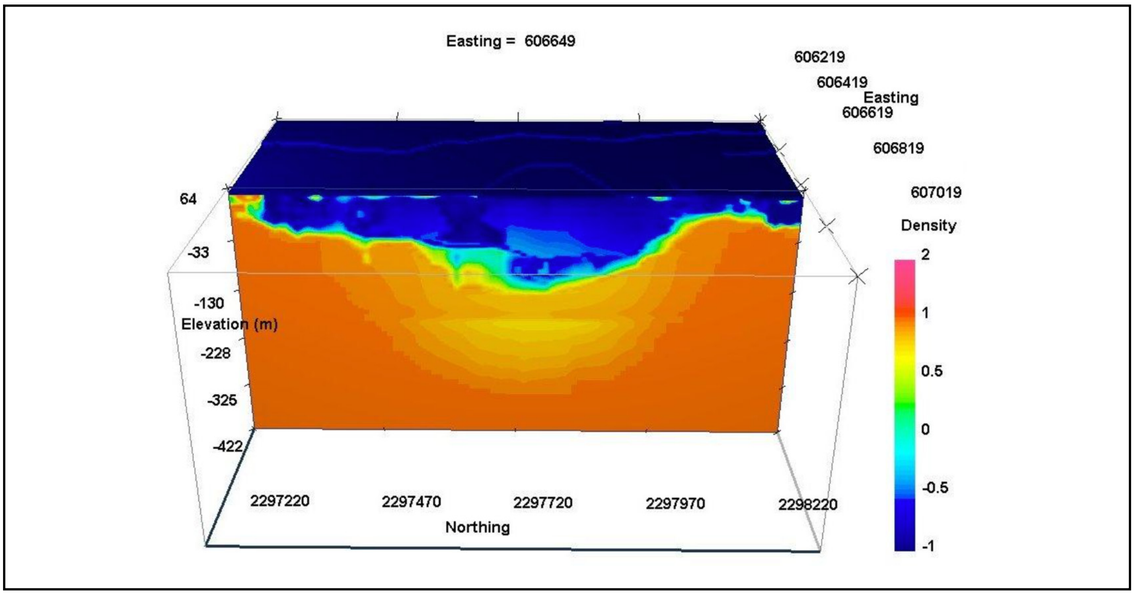

Figure 9. Gravity density model of the crater.

Discussion and Conclusions

The Mahout structure has all the characteristic features of an impact crater. These initially include a simple bowl-shape morphology and a raised rim, but geophysical investigations together with petrological and geological observations, also provide strong evidence confirming the impact origin of the Mahout structure. Samples from the crater walls and floor are highly fractured and show plenty of evidence of shock deformation including shatter cones, significant monomict and polymict brecciation and sandstone deformation. Additionally, shock features, such as impact melting, abdundant globules, a high-pressure SiO polymorph (coesite), fused quartz, diaplectic glass, PFs, and PDFs are all strongly diagnostic features of a hypervelocity impact, and their presence, distribution and characteristics provide valuable information on the meteorite cratering process (Grieve, R.A.F., Pilkington, M., 1996). The Mahout structure is best classified as a' mixed targets' type crater as it formed on impact with both crystalline and sedimentary rocks. This resulted in a broad spectrum of impact-formed lithologies. including characteristic centimeter-sized glass particles within whole-rock impact melts. Given the suspected Late Cretaceous EarlyCenozoic age of the crater, its long-term survival in the desert area is likely due to the relative hardness of the metamorphosed agate and quarzitic rock that mantles the crater rims and resists erosion and transport by the wind.

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The Scenery and Geology of Kilimanjaro and Mount Meru, Tanzania

Alan P Heward (Malvern, U.K.)

It was a conversation while walking back from outcrops in Dhofar that prompted my first ascent of Kilimanjaro. Was I up to the challenge? I found I was in 2018 and seeing Mount Meru out to the west decided to return in 2022 to climb that volcano and Kilimanjaro by a different route. The scenery and geology on both mountains above the forest zone is stunning (Figure 1). As I dug into the literature, I discovered a Sheffield University connection I had not known before.

Figure 1. Kilimanjaro from Mount Meru at sunrise. The three volcanic centres of Kilimanjaro are the Shira plateau, left and oldest, Mawenzi, small peak to right and Kibo, centre, largest and youngest.

The cone-shaped volcanoes of Kilimanjaro and Mount Meru are the highest and 5th highest mountains in Africa, at 5,895 m and 4,566 m, respectively. They lie on a trend east of the eastern branch of the African Rift system (Figure 2). Radiometric dating of minerals in lavas and ashes show they have been active over the past 2.5 M with activity on Kilimanjaro mainly older than that of Mount Meru. They were never significantly active at the same time. Kilimanjaro is thought to be dormant or in a declining phase of activity

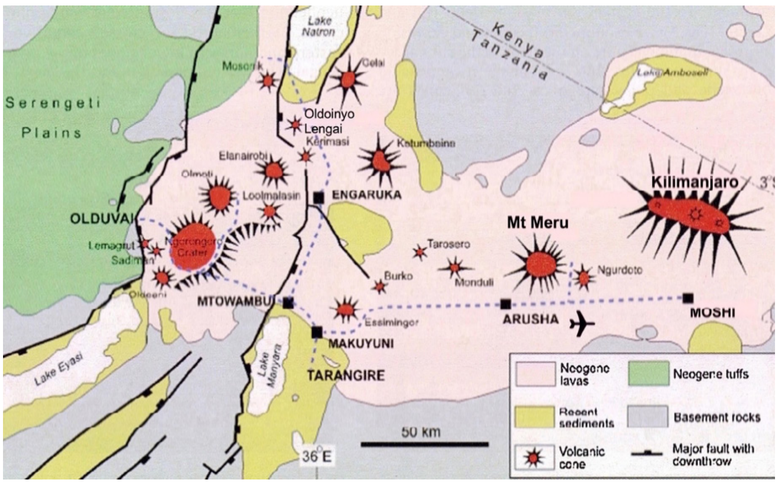


Figure 2. Map of Northern Tanzania from Dawson (2008) showing the relationship of Kilimanjaro and Mount Meru to the East African Rift system and other volcanic cones in the area. Olduvai Gorge, famous for its hominid fossils, is also marked.

whereas Mount Meru is active and last erupted about a hundred years ago. The explosive, Plinian, nature of Mount Meru means that it is a potential hazard to the growing population of Arusha (Figure 2) and the area further west towards the rift valley, due to the prevailing wind direction.

My first ascent of Kilimanjaro in 2018 followed the Lemosho Glades Route (Figure 3), over the Shira Plateau and around the southern side of Kibo before summiting via Barafu Camp and Stella Point. My ascent in 2022 was by the Umbwe Route alongside the Barranco canyon and up to the summit via the Western Breach Route. The second ascent was over fewer days as we had already begun acclimatising to altitude on Mount Meru. Both times we descended by the Mweka Route.

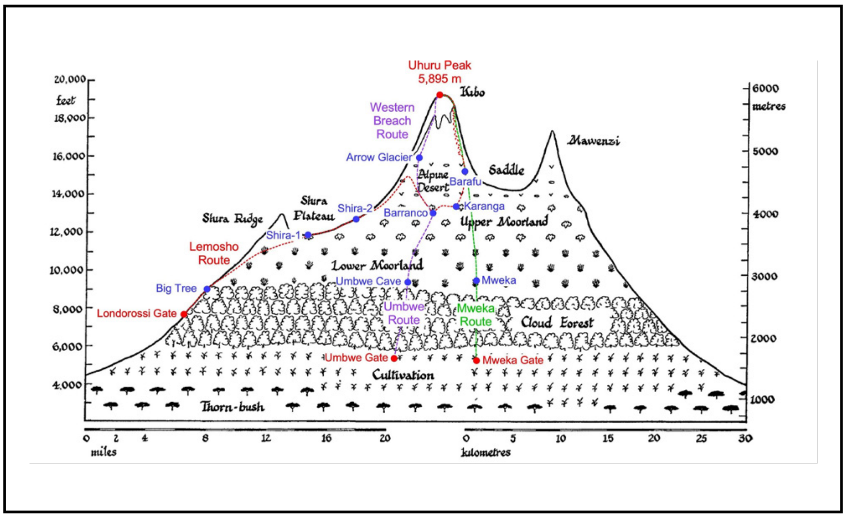


Figure 3. Routes followed in 2018 and 2022 superimposed on Salt's (1954) summary of vegetation zones on the southern side of Kilimanjaro (2018- Lemosho route in red and Mweka route in green; 2022- Umbwe and Western Breach routes in purple and Mweka route in green). The geology is well exposed above the forest zone and evidence of glaciation is visible from around 3,000 m upwards.

Sheffield University Geologists

In the 1950s, parts of Tanzania had not been mapped geologically. Two former students of the department at Sheffield University had joined the overseas geological survey and the idea arose of an expedition to map and investigate the mountain. It was the era of great university expeditions to study new problems overseas: Oxford to Greenland to study the Skaergaard layered intrusion, Cambridge to Svalbard investigating various aspects of the sedimentology and palaeontology, etc. The first Sheffield University expedition to Kilimanjaro took place in the summer of 1953, and included five members of the Geology Department and three from the Tanzanian Geological Survey. As well as producing a geological map, questions over the status of the glaciers (important to water supply for agriculture) and whether the volcano was showing increased signs of activity were to be addressed. A follow-up expedition took place in 1957 when preliminary work on samples had been completed (>1,000 thin sections). The geological mapping was hindered by poor topographical control, remedied by the issue of new maps in 1964. Several smaller expeditions. to Mount Meru took place in the 1970s, resulting in another map and petrological studies of that mountain as well. Charles Downie, an expert in the study of fossil pollennd spores, was a somewhat surprising member of these expeditions and their reporting!

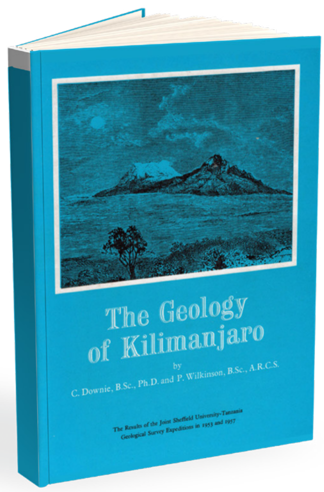


Figure 4. Front cover of Downie and Wilkinson (1972) reporting the results of the joint Sheffield University – Tanzania Geological Survey Expedition in 1953 and 1957.

One of the most iconic features of Kilimanjaro is its shining ice cap in the morning and evening (Figure 5; during the day the peak is often shrouded by clouds). The name Njaro may be derived from the Swahili to shine ('ku-ngaa' or 'ngara'). In the mid-1850s there was debate among scientists as to whether it was possible to have an ice cap only 3° south of the Equator. Anyone who has been to the summit will know how cold it can be at nearly 6,000 m. Overnight temperatures at the summit are around -7°C, with a significant wind chill on some days. Ice cores cut in 2000 show the Kilimanjaro ice cap is more than 12,000 years old, up to 50 m thick and is a relic of wetter times in the Late Pleistocene-Early Holocene. There has been an 85% reduction in the area covered by ice in the past 100 years and it has been predicted that the mountain may be ice-free in the next 40 years. The reduction in ice has made it easier to reach the summit than when it was first climbed 134 years ago, but the loss of its shining cap will be a tragedy for the mountain and its visitors. Snowfall quite often occurs on the mountain above 4,000 m but contributes little to the maintenance of the ice fields and glaciers. There have been at least six glacial episodes on Kilimanjaro in the past 500,000 years, waxing and waning as humid periods alternate with drier ones. There is a good correlation between these humid and drier periods and the changing levels of lakes in Africa. There may be a correlation too with the humid and drier periods in Oman as these too were driven by changing circulation patterns in the Indian Ocean.

Figure 5. The shining ice fields of Kilimanjaro in the early morning, viewed from the Mweka route.

Features of the most recent glaciation were apparent on my first visit to Kibo. It was like being in upland areas of the U.K. with moraines, erratics, U-shaped valleys, striated pavements, roches moutonnées and more (Figure 6). The most widespread glacial detritus is from about 210,000 years BP (Late Glacial Maximum) and reaches down to about 3,000 m on the southern side of the mountain. Evidence of the earlier glaciations occur interbedded with lavas and can be distinguished by the different clasts of lava they contain (Figure 6D). There is little evidence that the volcano was ice covered when active. That would have resulted in distinctive features of the lavas and sediments due to rapid chilling and the melting of ice (hyaloclastites). There is no evidence that Mount Meru was ever high enough to be glaciated at this latitude.

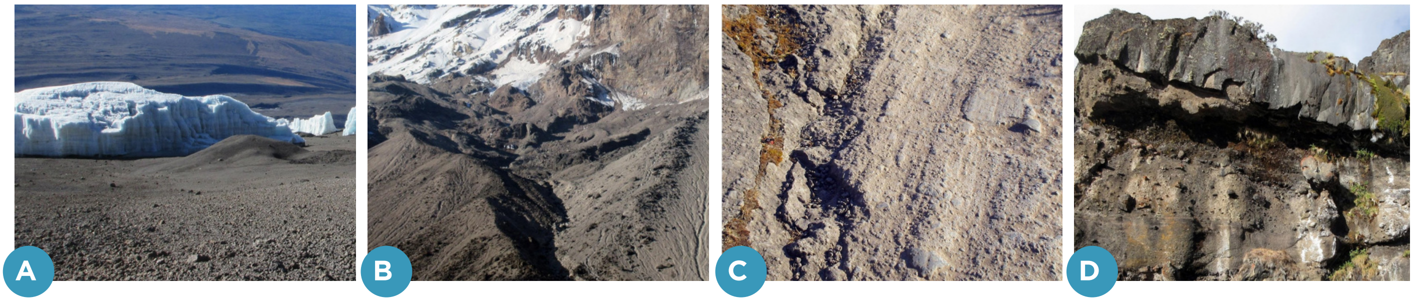


Figure 6. Modern ice and recent glacial deposits and features on Kilimanjaro. A. Northern ice field as viewed from the crater rim looking west. B. Lateral moraines of the Great Barranco glacier formed by the retreat of ice over the past few hundred years. Snow and remnant ice above 4,300 m.C. Striated pavement on ash deposit near Barafu Camp. D. 0.5 Ma glacial moraines interbedded with lavas, base of the Barranco Wall above Barranco Camp.

Volcanics

Two major phases of deformation and volcanism have been recognised in northern Tanzania, an older phase of larger, basaltic-trachytic, shield volcanoes and a younger phase of smaller, steeper cones of more alkaline and silicic composition. The Shira and Mawenzi centres of Kilimanjaro are representatives of the older phase, and Kibo and Mount Meru of the later one. The weathering of alkaline igneous rocks results in some of the streams and ground water that drain from Mount Meru and Kilimanjaro having levels of fluoride which exceed the guidelines of the World Health Organisation for drinking water.

What is immediately obvious is that Kilimanjaro is constructed primarily of lava flows and Mount Meru of volcanic ash (Figure 7A and B). The lavas on Kilimanjaro rest on flow breccias, pyroclastic deposits or other intervening sediments which weather out more quickly than the harder, more massive, lava flows and lead to rock overhangs (Figure 7C). These overhangs or 'caves' were used by early visitors and porters for overnight camps (several of the modern campsites are named after these 'caves'). Kilimanjaro's lavas are often porphyritic with large phenocrysts of different types of feldspar which, from their size, must have formed in a magma chamber before eruption (Figure 7D).

Some phenocrysts are visibly zoned and others are flow-aligned. Ten different units of lavas have been distinguished and mapped on Kibo, erupted over the past 0.5 Ma. They change in composition from basalts and trachytes to more alkaline phonolites. Without following out units and looking carefully at the phenocrysts, it is not easy to know exactly which unit you are in despite having geological maps (1:125,000 scale and 1:50,000 for the Crestal Area of Kibo). The 1965 and 1983 geological maps don't show all the modern trekking routes.

When I climbed Kilimanjaro in 2018, the views over the crater were limited by cloud but I could smell sulphur from the fumaroles in the ash pit more than a kilometre away. In 2022, views over the crater were clear but there was no discernible odour of sulphur. We did not attempt to walk over to the ash pit to look down to where the fumaroles are located. Do the fumaroles represent the last signs of activity of Kibo or will there be another phase of deformation and volcanic eruption?

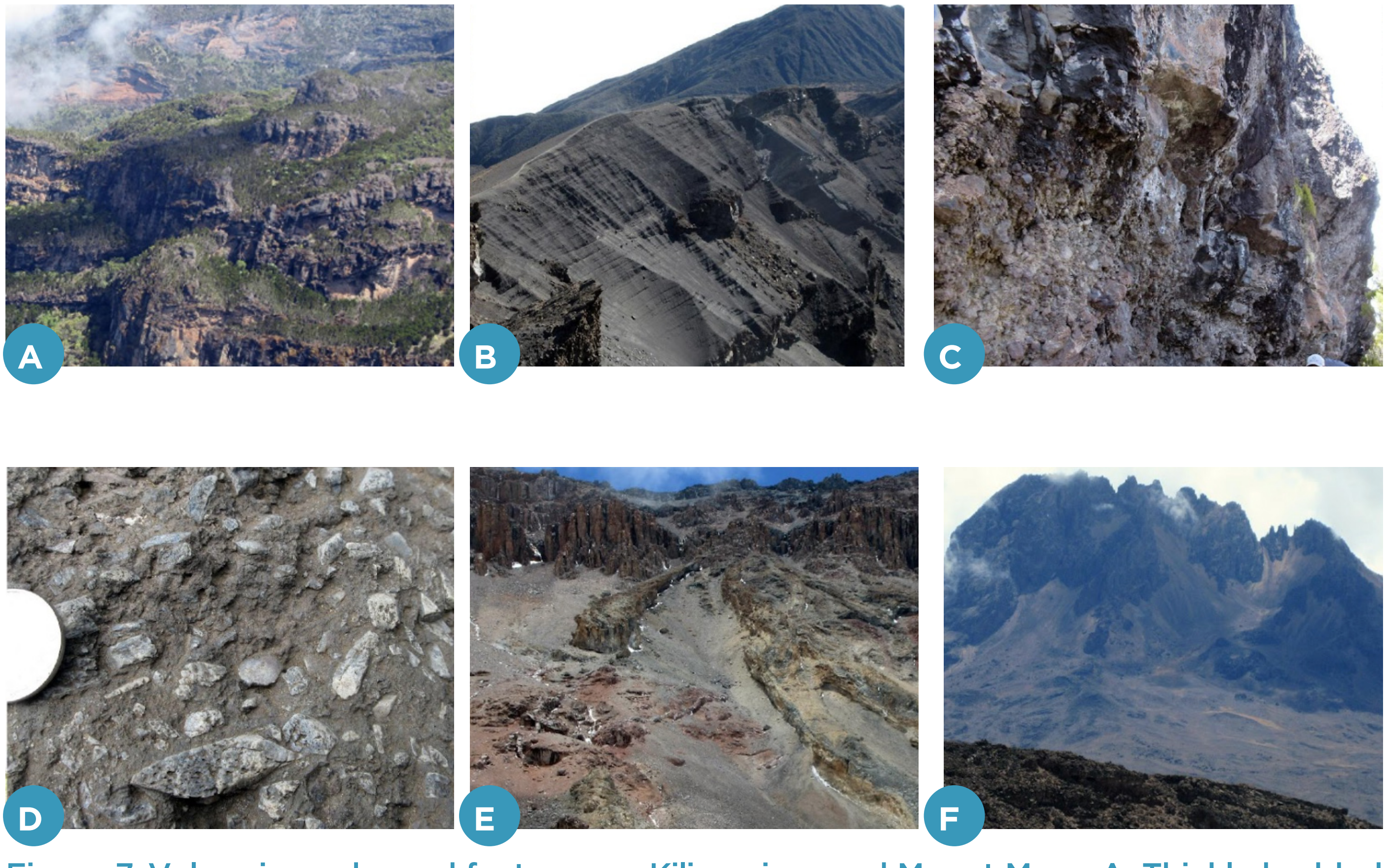
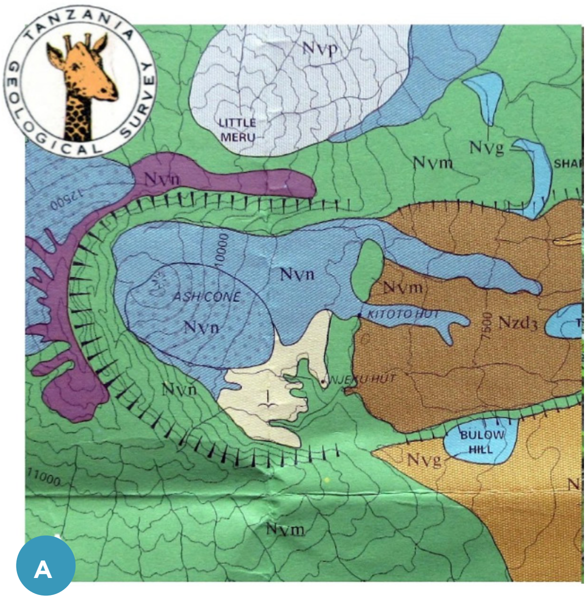


Figure 7. Volcanic rocks and features on Kilimanjaro and Mount Meru. A. Thickly bedded lava flows of the Rhomb Porphyry Group on the Machame escarpment of Kilimanjaro. B. Thinly bedded pyroclastic deposits forming the main cone of Mount Meru. Tiring ground to walk over when the ash is poorly consolidated. C. Softer sediments with rounded clasts occurring beneath a massive lava flow on the Umbwe route. D. The lavas on Kibo often contain phenocrysts, the size, shape and composition of which are used to distinguish the groups of flows. The coin is 28 mm in diameter. E. Pink syenite body, interpreted to be the fill of a caldera, with unusual horizontal jointing resulting in the 'rock-stairs' of the Western Breach Route. F. The rugged peak of Mawenzi with its numerous dyke intrusions.

Debris Avalanche Deposits (DADs)

The eastern side of the main cone of Mount Meru is missing and there are several great scars and canyons on the peaks of Mawenzi and Kibo (Figure 8 and 9). These scars and canyons provide sections into the older parts of these volcanoes. Inspection of the geological maps show large areas of the plains in between the volcanoes mapped as lahars (Figure 9), though this implies transport by water, and perhaps more accurately they should be termed Debris Avalanche Deposits (DADs). The latter can move over tens of kilometres on a cushion of air, though they may later be reworked by water. The scars are created when part of a crater rim or volcano becomes unstable and collapses, perhaps during an eruption or an earthquake, as was dramatically demonstrated by the collapse of the northern flank of Mount St Helens in the U.S.A. in May 1980 (www.youtube.com/watch?v=UK--hvgP2uY). The DAD deposits formed are unsorted, with hummocky tops and practically no through-going river drainage. The Mount Mero DAD can be dated to be > 8,600 years old from the lake sediments that overlie it.



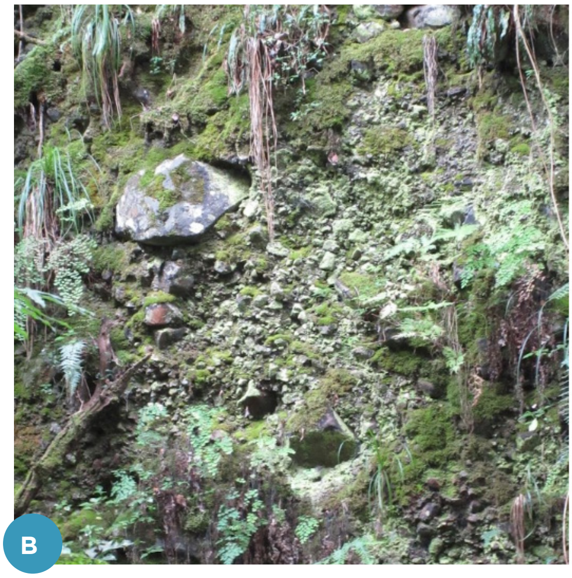


Figure 8.A. Extract from the 1983 geological map of Mount Meru showing the horseshoe-shaped scar on the east side of the volcano and source of the Momella 'lahar' or DAD (brown area Nzd3 to right of map. B. Section through the 'lahar' or DAD in the banks of the Lenganassa river on the eastern flank of the Mount Meru. (Giraffe and other game animals are commonly seen in grassland areas on the lower slopes of the volcano).

If you are tempted to climb these mountains, make sure you are with experienced guides, have suitable clothing for the summit nights/ days and take time to acclimatise to altitude. Both volcanoes are ones you can walk to the summits of without too much difficulty, except for overcoming the effects of altitude. 30,000 – 40,000 visitors attempt to climb Kilimanjaro each year and bring revenue to the National Park and employment for guides and porters. Enjoy the scenery, geology and the challenge!

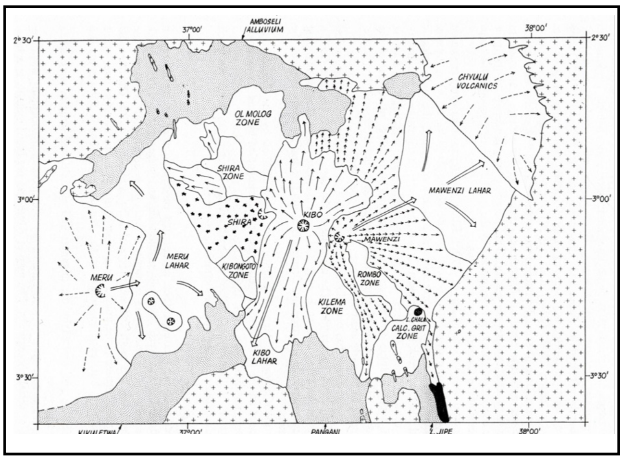


Figure 9. Regional map showing the distribution of lahars from Downie & Wilkinson (1972). The Mount Meru or Momella lahar covers an area of 1,400 Km2 & is estimated to have a volume of 10-20 Km3.

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“We Have To Act Now” - Omani Entrepreneur Turning CO_2 Into Rocks

44.01 is an Omani start-up that is working to reverse climate change by turning carbon dioxide into rock. The company accelerates the natural process of CO_2 mineralisation in peridotite to eliminate CO_2 forever. 44.01 was recently recognized by HRH Prince William’s Earthshot Prize, and the company has ambitious aims to eliminate a billion tonnes of CO_2 by 2040.

Talal Hasan, 44.01’s founder and CEO, was inspired to set up the company when he saw the impact climate change was having here in Oman. From increased cyclones to the presence of a huge ocean ‘dead-zone’ off the coast, it was clear that excess CO_2 in the Earth’s atmosphere is already affecting Oman and our way of life.

“The world has exceeded its limit for carbon dioxide emissions,” says Talal. “We have to act now.”

Talal is not alone in arguing for CO_2 removal. The Intergovernmental Panel on Climate Change (IPCC) says that, if we are to avoid the worst impacts of climate change, humankind will need to start removing billions of tonnes of CO_2 from the atmosphere every year, as well as transitioning to renewable forms of energy such as solar and wind.

The 44.01 team are receiving the Earthshot Prize.

There are a number of emerging technologies capable of removing CO_2 from the atmosphere (a process called Direct Air Capture) or capturing emissions from the smokestacks of industrial processes (a process called Point Source Capture), but the challenge remains what to do with the CO_2 once it has been captured. Too many of the traditional 'CO_2 storage' solutions do not remove CO_2 permanently. Instead, they seek to lock it underground from where it could potentially escape, and where it has to be monitored and insured forever. Often the cost of this monitoring and insurance falls on governments and ultimately citizens.

"We wanted to provide a truly permanent way of removing CO_2, not just storing it but eliminating it forever," says Talal.

Oman's rocks offered a potential solution. Peridotite is a type of rock usually found deep under the ocean floor, but here in Oman and in the UAE it has been pushed up to the surface. Peridotite naturally reacts with CO_2 dissolved in water (for example rainwater or seawater) to form carbonate material, or rock. This process has been going on for millennia in Oman, but in nature it can take decades to mineralize even a small amount of CO_2. 44.01 set out to accelerate the process.

The company drew on the work of Professors Juerg Matter and Peter Keleman, two of the world's leading experts on mineralisation and enhanced weathering. Professors Matter and Keleman were the first to identify that CO_2 mineralisation was happening naturally in Oman and have worked closely with Talal and his co-founders to develop technology that can accelerate the process.

44.01's technology works by dissolving captured CO_2 in water and then injecting it deep underground into peridotite formations. By dissolving CO_2 at high concentration, and adjusting variables like pressure and temperature, the company can speed up the reaction over 100,000 times, enabling them to mineralise CO_2 in less than 12 months.

So far, 44.01 has completed two successful pilots here in Oman. These pilots demonstrated that the company's process works, and that it has no negative impact on the local environment. This was vital, according to Talal. "We are, first and foremost, an environmental company", he says. "Our number one priority in everything we do is to protect the local environment, while trying to save our climate."

44.01's technology could potentially play a role in helping Oman meet its 2050 National Net Zero Plan. Peridotite has a unique capacity to mineralise CO_2, and Oman's peridotite could potentially mineralise billions of tonnes of carbon dioxide.

As the world transitions to clean forms of energy, 44.01 is also providing new employment opportunities for engineers and geologists working in the fossil fuel industry. Given that Oman has one of the largest surficial deposits of peridotite in the world, carbon mineralisation could also be a boon for workers in the region and for the energy transition.

2023 looks set to be an exciting year for 44.01. Having won the prestigious Earthshot Prize in December, the company now plans to begin commercial-scale injection, on its way to eliminating a billion tonnes of CO_2 by 2040.

"We're fortunate to have an excellent team, here in Oman," says Talal. "We're all very aware that we don't have a lot of time left to save our climate. We're very focused on delivery."

Peridotite outcrop photo showing calcite veins.

Outcrop of Barzaman Formation

Al- Khod Area, Oman

The photograph shows a strike-slip fault near to the rock hammer in a well-exposed outcrop of the Barzaman Formation located in the Al- Khod area at the Sultan Qaboos university campus. This fault has a measured thickness of 30 cm. The fault fills by tough brownish mineralized fluid and surrounded by clayey material. An X-ray diffraction analysis shows that the fluid related minerals along the fault include sepiolite, dolomite and quartz. The surrounding lithofacies in this outcrop are: conglomerate, pebbly sandstone, sandstone with medium to coarse grain size and claystone.

Lat: 23°35' 10"N   Long: 58°10' 32"E

Photo by: Othman Al Jabri   Instagram: @othman_aljabri

A NOTE ON THE GEOLOGICAL MAPPING OF NATIONAL HIGHWAY (NH-444), BEMINA CHOWK SRINAGAR TO QAZIGUND CHOWK ANANTNAG, KASHMIR, INDIA

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INTRODUCTION

The Roads and Buildings Executive Engineer from the Project Circle Division, Srinagar, approached the Department of Geology and Mining Srinagar for an expert opinion on upgrading the existing National Highway (NH-444) from Bemina Chowk Srinagar to Qazigund Chowk Anantnag, Kashmir. The evaluation of geological information and the preparation of a surface geological map were important considerations for the proposed project. Accordingly, the authors and the project site engineer conducted a feasibility study along the existing road alignment over a period of one month. The geological mapping was intended to delineate different lithological units and define their extent as well as understand the nature of structural features along the proposed highway. The positive aspects and concerning features of the various lithological formation units and members were examined and discussed by the authors based purely on consideration of the surface geological mapping which was restricted to within 20 m of either side of the road. The work was unaided by any new sub-surface explorations such as test pits or trench profiles, sub-surface sampling and drilling. However, log data from exploratory boreholes were available from the Department Technical Library and were utilized for subsurface geological information and data interpretation.

GEOLOGICAL SETUP

The background mountain ranges and associated geological structures near National Highway NH-444 are mostly, if not entirely Tertiary in age and include some complicated tectonic structures such as nappes, thrusts, and faults which are responsible for the high seismicity of the valley. This places Kashmir in seismicity Zones IV and V as per the Seismic Zonation Map of India (IS 1893, 2002). The length of the valley from the upper reaches of River Jhelum near Verinag to the outlet of the River Jhelum near Behramgul at Baramulla, extends over 135 km, whereas the average width of 40 km is maintained near its central part. The general configuration of the valley fill is nearly flat with a gentle gradient toward the northwest. At the upper reaches of the River Jhelum near Verinag station, the elevation of the valley floor is 1860 m, whereas, near the river's outlet at Baramulla station, the elevation is about 1556 m.

MATERIAL AND METHODS

Figure 1. A. The authors collecting vital information regarding the updation of National Highway at Shypain (B) A great thickness of Nagum Formation (Pampur Member) exposed along the National Highway at Pampur outshirks.

The surface geological mapping was carried out on a base map scale of 1:500 m with reference to the proposed road alignment which covers a total distance of 103 km. The study area is bounded between N 33°35'26.2" to N 34°04'18.4" latitude and E 74°46'03.3" to E 75°10'08.2" longitudeas defined by the Survey of India topographic maps (reference numbers 43J/16; 43J/12; 43K/13; 43K/14 and 43O/2). Every lithological unit as well as structural feature that was observed and examined in the field, were mapped by the authors on a 1:500 m geological base map. Log data from exploratory boreholes were also utilized to understand the subsurface geological information and aid in data interpretation.

DESCRIPTION OF THE LITHOUNITS FOUND WITHIN THE STUDY AREA

Two main rock units were encountered along the proposed National Highway (NH-444) road alignment. These include the Nagum Formation and the Hirpur Formation which are both part of the Karewa Group. The Karewa Group of Late Neogene to Quaternary Age, is more than 1300 m thick and consists of an unconsolidated to semi-unconsolidated gravel-sand-mud succession which forms large plateau-like terraces, standing above the gravel and alluvium of present-day rivers. Nearly half the area of the Kashmir valley floor is occupied by such deposits. These deposits are widely known as Karewa (Wudirs). The Karewa Group covers by and large the whole area of the proposed national highway road alignment and are sub-divided into two litho-stratigraphic units (I. B. Singh 1982).

The Nagum Formation is characterized by brown /grey sandy clays, medium to coarse grained sand, cream colour marl, conglomerates and loess sediments. This Formation is mostly horizontally bedded. These deposits are highly susceptible to landslides due to their soft and unconsolidated nature and in the presence of an inadequate drainage system. Loess deposits invariably cap the Karewa sequence in some places within the study area. These loess sediments have the ability to stand almost vertical when dry but can become unstable when saturated with water making it possible to behave as a thick viscous liquid. From Gowharpura to Neva, the Nagum Formation is encountered along the right side of the proposed national highway road alignment (Figure 2, 3A, 3B and Table 1).

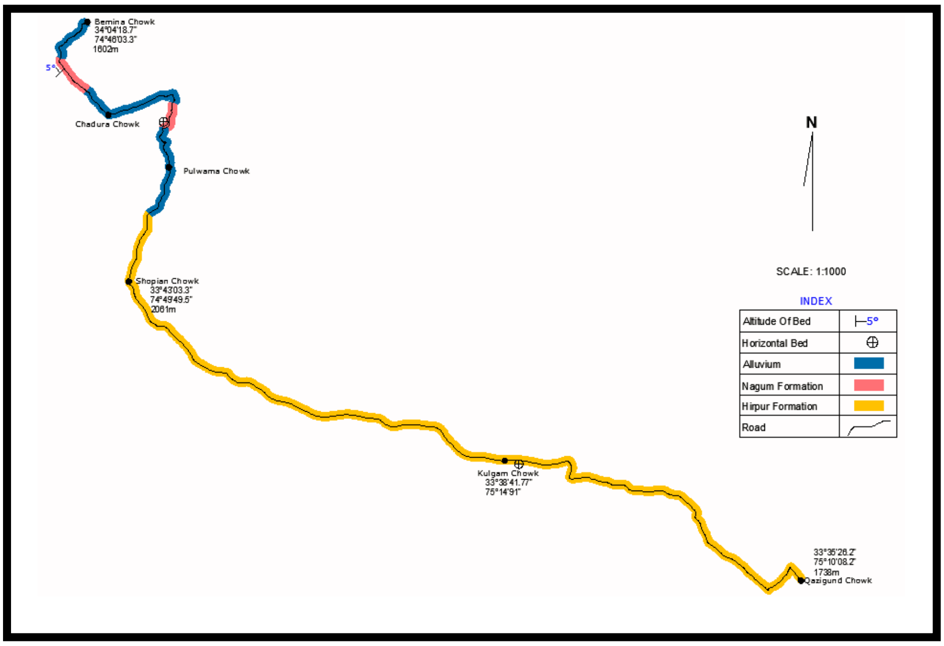

Figure 2. Gelogic map of natonal highway 444 from Bemina Chowk Srinagar to Qazigund Chowk Anantng kashmir.

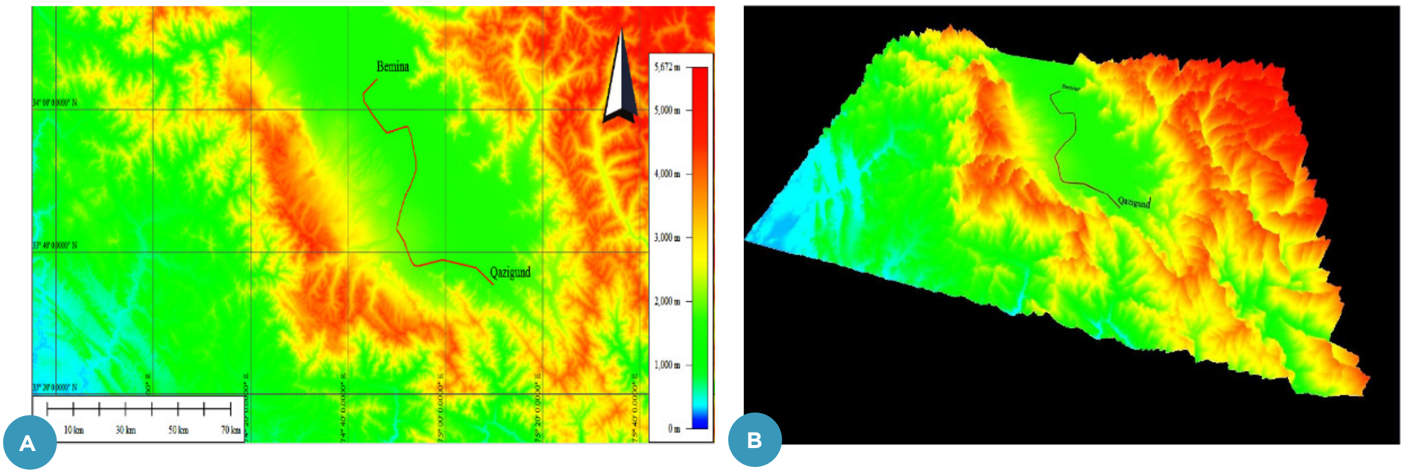

Figure 3A. Satellite Image of National Highway (NH-444) Bemina Chowk Srinagar to Qazigund Chowk Anantnag. B) 3D view of National Highway (NH-444) alignment Bemina Chowk Srinagar to Qazigund Chowk Anantnag.

Table 1. Geologic Log along National Highway (NH-444) from Bemina Chowk Srinagar to Qazigund Anantnag Kashmir India.

Distance from Bemina Square (Km)	Lithology/ Formation	Period/ Epoch	Coordinates with altitude (m)	Remarks
Bemina Bypass Station	Alluvium	Holocene	N34°04´18.7˝ E74°46´03.3˝ 1602 m	Loose/ unconsolidated Gaseous
0.0 to 6.7	Alluvium	Holocene	N34°01´56.2˝ E74°43´22.5˝ 1606 m	Loose/ unconsolidated Gaseous
6.7 to 13.3	Nagum Formation	Quaternary	N33°59´03.4˝ E74°45´12.6˝ 1640 m	Inslope dip 05° and 205° direction
13.3 to 25.5	Alluvium	Holocene	N33°57´40.8˝ E74°51´30.5˝ 1615 m	Unconsolidated to Semi-consoli-dated
25.5 to 32.9	Nagum Formation	Quaternary	N33°57´40.8˝ E74°51´30.5˝ 1615 m	Horizontal beds (pampur Member)
32.9 to 43.9	Alluvium	Holocene	N33°48´10.2˝ E74°51´43.7˝ 1618 m	------------
43.9 to 44.3	Reworked Karewa underlain by bluish plastic clay	Holocene/ Lower Karewa	N33°41´00.1˝ E74°51´35.5˝ 2039 m	Waterlogged
44.3 to 103	Hirpur Formation	(Neogene-Quaternary)	N33°35´26.2˝ E75°10´08.2˝ 1738 m	5°to 15° dipping due East Hirpur Formation

The Hirpur Formation which is nearly 1200 m thick, is characterized by plastic grey to bluish grey clays, light grey sandy clays, lignite clays, coarse to medium grained sand and conglomerate. This Formation is more argillaceous in nature than the Nagum Formation. The rock strata dip northeasterly between 5° to 25°. Artesian conditions are common in this formation from a confined aquifer that consists mainly of saturated and reworked Karewa sediments that are underlain by impermeable sediments as observed between Vihel and Nehama.

From Checkpura (Romshie Nala) Pulwama, the Hirpur Formation (bluish Clays deposits associated with gravels of various sizes) extends up to Shpyian. These unconsolidated boulders, underlain by plastic clays, are widely distributed from Shpyian up to the Vishu Bridge. Beyond that, impervious bluish clays predominate all the way to Qazigund. At the Qazigund Railway Station, bluish clays, silty clays and gravel associated with sand occur in order of predominance up to a depth of 300 feet below ground level (DGM Srinagar 2010).

Alluvium

Alluvium deposits occupy the low-lying areas especially between Bemina to Mirgund and in the areas lying in the vicinity of the River Jhelum and its tributaries such as between Dudh ganga and Tsodur-Dualthpur and onwards. The alluvial sediments consist of unconsolidated (under the processes of lithification) clays, silt and sand in order of predominance with intercalation of a lignite/peat material. These sediments have been reworked mostly from the unconsolidated Karewa sediments and are deposited in the vicinity of the present streams within the low-lying areas sucas topographic depressions. These reworked Karewa sediments are underlain by impervious clayey horizons making some portions of the valley water-logged and prone to sliding where the gradient is steep. The areas from Bemina to Mirgund contain some shallow gas especially at Sebden as authenticated by exploratory drilling up to 515 feet below ground level (DGM Srinagar 2010).

Result and discussion

This report is based purely on preliminary surface geological studies with special reference to the proposed national highway (NH-444) road alignment, stretching from Bemina Chowk Srinagar to Qazigund Chowk Anantnag, Kashmir. Based on our analysis of surface geological field observations and subsurface borehole log data, we conclude that the geological conditions appear favorable for the proposed project.

ACKNOWLEDGEMENT

The authors are indebted to Mr. Om Prakash Bhagat, Director (J&K) and Mr. Nisar Ahmad Khawaja, Joint Director (K), Department of Geology and Mining, Union Territory of Jammu and Kashmir, India for overall support and guidance. Thanks are also due to our colleague Mr. Khursheed Ahmad Mir, Mineral officer (K) Department of Geology and Mining, Union Territory of Jammu and Kashmir, India. The Geological Society of Oman are highly acknowledged for encouraging the authors to share the manuscript in Al Hajar Magazine.

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