SYMPOSIUM BOOK

(ABSTRACTS and PROCEEDINGS)

15TH INTERNATIONAL SYMPOSIUM ON VULCANOSPELEOLOGY

The Hashemite University
Zarka – Jordan
15-22 March, 2012

Organized by

Center of Environmental Studies

Edited by
Prof. Dr. Ahmad Al-Malabeh

كتـــاب المـــؤتمـــر
(الملخصـــات والابحـــاث)

المؤتمر العالمي الخامس عشر لمكتشفي الانفاق والكهوف البركانية

الجامعــة الهاشمية

الـزرقـاء - الأردن
15-22 آذار 2012

ينظم المؤتمر
مركـز الـدراسـات البيئية

تحرير ومراجعة
أ.د. أحمـــد مـلاعبـــة

Preface

The Organizing Committee would like to welcome you to the 15th INTERNATIONAL SYMPOSIUM ON VULCANOSPELEOLOGY. The symposium will be held at the Hashemite University in Zarka/Jordan in the period from 15th-18th of March 2012, followed by a four-days special field trip to the recently discovered lava caves, volcanoes and many other volcanological and archaeological features in the Jordanian Harrat.

We are very much honoured that Jordan was elected as a host for conducting this Symposium organized by the Hashemite University. This decision was taken by the International Union of Speleology and the researchers who participated in the activities of the 14th International Symposium on Vulcanopeleology held at Undara in Australia in 2010.

This symposium in Jordan is a special occasion for geologists, volcanologists and speleologists alike to present their scientific contributions. The symposium will focus on vulcanospeleological issues relevant to one of the large intra-plate volcanic plateaus of the world: The Harrat Al-Shaam. Therefore, it is important to encourage an international approach, sharing, exchange and update knowledge from all over the world at this special symposium.

We would like to thank all the scientists and researchers from different parts of the world for their contributions. The Symposium's distinguished plenary lectures cover highly diverse topics. Among the speakers there will be several young scientists, who bring new perspectives into the field.

The book of the Symposium contains the accepted abstracts by the symposium committee. Selected full manuscripts have been published in this book after critical review and the final acceptance decisions of distinguished international referees. It also includes an address list of the participants and their e-mails.

The Organizing Committee would like to thank Her Excellency Prof. Dr. Rowadia Maaitah (Minister of Higher Education and Scientific Research) and Prof. Dr. Kamal Bani-Hani, the president of the Hashemite University for all the facilities they provided. Sincere thanks are due to the staff members of the Center of Environmental Studies (Eng. Zeinah Waleed, Eng. Reem Rasheed, Eng. Ali Al-Ali Al-Husban and Ms. Mariam Al Omoush), Eng. Khaled Al-Zawahreh and other colleagues for their skillful efforts and long hours spent in the preparation for this symposium. We also highly appreciate the unconditional and professional help of many people without whom this symposium could not be successful and profitable.

The Organizing Committee would like to thank all sponsors of the symposium for their support and donations that made the symposium a reality.

Wishing all of you a successful and fruitful Symposium and an enjoyable stay in the hospitable Hashemite Kingdom of Jordan.

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SYMPOSIUM TOPICS

Lava caves

Basaltic plateaus (Harrat)

Hypogene Speleogenesis

Karstic sinkholes and dolines

Tectonic caves

Gypsum and salt caves

Shorelines caves sinkholes

Paleo-climates of caves and the surroundings

Taxonomy of animals and plants remains inside caves

Methods and techniques in caves discovery and survey

Geo-archaeology of the caves

SPECIAL WORKSHOP

Yarmouk-Decapolis Water Tunnel System (YDST)

Memorial
Recollections of Chris Wood (1947 –2012)

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This paper is a short résumé of Chris's significant contributions to caving in general, from his introduction in the UK in the mid-1960s, and subsequently to his study of lava caves in particular worldwide. It is not intended to be an all-encompassing dissertation on his speleological life but rather my personal recollections of our association over a period spanning nearly 50 years. He was planning to attend this XV International Symposium in Jordan, from March 15 – 22, 2012 but sadly Chris passed away in January. He had recently retired as Senior Lecturer in Heritage Conservation at Bournemouth University where he had been for 15 years. I would like to have this presented in his memory to his fellow vulcanospeleologists, but unfortunately am unable to attend and deliver it in person.

Chris was introduced to caving through the Boy Scout Movement in the early 1960s initially in the limestone area of the Mendip Hills in Somerset, UK, where he became a Scout approved caving leader. He joined the Shepton Mallet Caving Club in 1966 and remained a member until 1992. When the Club went to Iceland in 1970 for their 21st Anniversary trip for among other things a scientific study of Raufarhólshellir, Chris was introduced to lava caves which were to become a life-long interest for him and resulted in the publication of his first paper on the subject. He returned to Iceland with SMCC in 1972 for further research and there completed, with the author, a paper for the 1st International Symposium on Vulcanospeleology.

Whilst maintaining his interest in limestone caves both in the UK and abroad, Chris continued his exploration of lava caves in other parts of the world including Tenerife in 1973 and 1974, Iceland (the Heimaey eruption) 1974, Iceland and Sicily in 1975, Hawai'i in 1979. He was back in Iceland in 2000 and 2001 and latterly had been spending time in South Korea and China, achieving World Heritage Status for various important sites.

All this work over the years has resulted in a constant stream of publications and contributions to various International Symposia on Vulcanospeleology, UK National Caving Conferences and the 7th International Speleological Congress in Sheffield, UK, as well as a chapter in The Science of Speleology (1976) co-edited by T D Ford, and his PhD thesis.

In September 1996, Chris took up a position in the School of Applied Sciences at Bournemouth University and at the time of his retirement he was Senior Lecturer in Heritage Conservation. Chris retired at the end of October 2011 and was looking forward to a long, happy and productive retirement. Sadly this was not to be and Chris passed away suddenly on 19 January 2012.

Harrat Al-Shaam: The Largest Basaltic Plateau on the Arabian Plate

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Volcanic activity occurred on the Arabian Plate over distance of 7,000 km from Yemen through Saudi Arabia, to Jòrdan and Syria and up Turkey. These wide-spread, predominantly alkali olivine basalts are among the largest basaltic plateaus on Earth. The eruptive history of these rocks reaches from the Tertiary to the Present.

The tectonic evolution of these basaltic fields is closely related to the tectonic framework of the main regional structure in the region. The volcanism was contemporaneous with the African-Arabian rift system, the collision of the Arabian and Eurasian plates, and the Arabian dome. The rifting system includes the East African rift, the opening of the Red Sea and the Dead Sea transform fault system.

The Harrat Al-Shaam is the largest basaltic plateau on the NW-Arabian Plate. It covers an area of about 50,000 km2. This Harrat extends from southern Syria through Jordan down to northwestern Saudi Arabia. Geographically, the Saudi part of Harrat Al-Shaam is locally known as Harrat Al-Harrah or Harrat Al-Hammad that covers an area of about 15,000 km2. The Syrian extension of this plateau is locally known as the Basalt of Jabal Al-Arab or Jabal Al-Drouz.

The Jordanian Harrat covers an area of approximately 12,000 km^2. It is geomorphological characterized by a vast plain formed by a gently undulating plateau dotted with tephra cones , shield volcanoes, tuff rings, pressure ridges and cut by huge dike swarms. The plateau generally dips to the south and southeast, starting at an altitude of about 1000 m (a.m.s.l) along the Syrian border in the north, and dropping down to 700 m at Al-Mafraq city and to 550 m in the Al-Azraq area.

The basalts of Jordanian Harrat resulted from several major basalt flows. Based on detailed K-Ar dating, several researchers were subdivided the flows into three major episodes Oligocene to early Miocene (26-22 Ma), middle to late Miocene (13-8 Ma), and late Miocene to Pleistocene (7 Ma to < 0.5 Ma). Petrochemical studies of the basaltic rocks in the Jordanian Harrat indicate that the plateau is composed of alkali basalts and basanites.

Jordanian Lava Caves, an Overview

Stephan Kempe[1], Ahmad Al-Malabeh[2] and Horst-Volker Henschel[3]

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The center of Jordan is occupied by a vast intercontinental lava plateau, called the Harrat Al-Shaam, composed of Cenozoic (Oligocene-Quaternary) alkali olivine basaltic lava flows, the Harrat Al-Jabban volcanics or Jordanian Harrat (Al-Malabeh, 2005). The top most and therefore youngest flows are ca. 400 000 years old (Tarawneh et al., 2000). So far we explored, surveyed and studied a total of 23 lava caves since September 2003. 3164 m of passages were surveyed up to now (Table 1). These caves are, compared with most other lava caves quite old and many of them end in washed in loess. In addition to the Lava tunnels (pyroducts) that conveyed lava underground over large distances, Jordan has also a large fraction of pressure ridge caves (Kempe et al., 2010), all associated with Quis/Makais volcanoes. Two caves are of doubtful origin.

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Table 1. List of currently known and surveyed lava caves in Jordan, sorted by total passage length.

	Name of Cave	Latitude	Longitude	Stations	Length	Stations	Depth	Direction	Altitude	Type
1	Al-Fahda Cave	32°18,426	37°07,622	Complex	**923,5**	2 to 54	6,7	SW-NE	792 m	Pyroduct
2	Al-Badia Cave	32°07,91	36°49,42	32 to 23	445	1 to 23	17,2	NW-SE	783 m	Pyroduct
3	Hashemite University Cave	32°13,362	36°33,579	21 to 35	231,1	1 to 23	10,0	NW-SE	787 m	Pyroduct
4	Al-Ameed Cave	32°13,214	36°33,179	Complex	208	2 to 31	4,0	SW-NE	777 m	Pressure Ridge
5	Dabie Cave	32°10,387	36°55,583	0 to 14	193,6	0 1to 13	1,8	NW-SE	881 m	Pyroduct
6	Abu Al-Kursi East	32°15,401	36°39,442	20 to 34	153,7	1 to 34	12,2	W-E	883 m	Pyroduct
7	Kempe Cave	32°16,806	37°33,945	Complex	139,4	Comple x	11,5	N-S	939 m	Pyroduct
8	Hammam Cave N	32°13,219	36°34.340	Complex	123,4	0 to 28	4,5	NW-SE	780 m	Pressure Ridge
9	Al-Jolous Cave	32°13,925	36°34,206	0-15	112,6	-	n.d.	NE-SW	799 m	Pyroduct
10	Obada Cave	32°12,989	36°34,536	Complex	107,6	0 to 6	3,4	NW-SE	766 m	Pressure Ridge
11	Al-Howa	32°18,536	36°37,240	Complex	97,1	2 to 6	10,8	SW-NE	939 m	Pyroduct
12	Al-Haya Cave	32°17,743	36°34,745	1 to 11	81,3	1to 9	4,2	NW-SE	902 m	Pressure Ridge
13	Abu Al-Kursi West	32°15,401	36°39,442	2 to 18	77,1	2 to 18	8,1	N-S	883 m	Pyroduct
14	Haleem Cave	32°13,441	36°33,675	1 to 12.	70,7	1 to 12.	4,7	NW-SE	791 m	Pressure Ridge
15	Azzam Cave	32°17,104	36°36,594	13 to 25	44,1	1 to 25	4,2	NNW-SSE	902 m	Pressure Ridge
16	Al Ra'ye Cave	32°17,618	36°34,791	1 to 6	42	1 to 34	3,5	NW-SE	900 m	Pressure Ridge
17	Dahdal Cave	32°17,344	36°35,718	5 to 12	28,9	1 to 12	0,0	SW-NE	920 m	Pressure Ridge
18	Henschel Cave	32°13.355	36°33.841	Complex	21		2,50	W-E	788 m	Pressure Ridge
19	Eshaim Cave	32°16.887	36°51.305	1 to 3.	20,6	1 to 3.	0,0	N-S	1029 m	Artificial
20	Hammam Cave S	32°13,183	36°34.373	2 to 5.	12,4	2 to 4	2,4	NW-SE	780 m	Pressure Ridge
21	Uwaiyed Cave	31°39,186	37°29,900	Diameter	12		2,0	not def.	*681 m*	unknown
22	Beer al Wisad	31°44,527	37°27,991	Chamber	11,4	Depth	11,5	not def.	627 m	unknown
23	Treasure Pit	32°16,585	37°37,578		7,2	1-10,11	5,8	not def.	928 m	Pyroduct ?
				Sum	3164					

Lava Caves, Types and Development

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After limestone and gypsum, lava is the third most important cave-bearing rock. Apart from the standard notion that lava cave are simple, uninteresting and featureless circular "tubes", many different processes serve to create a score of various lava cave classes, with more being discovered from year to year. These include: (1) Longitudinal conduits that serve for long-distance, underground, post-eruptional transport of (with a few exceptions) basaltic lavas. They act to build low-slope (often <2°) shield volcanoes. First reported from Iceland, they were observed actively forming in Hawai'i and in 1842 named "pyroducts" (a term that should take precedence over the later - post 1940 - term "lava tube"). Within the pyroduct type at least for different formation modes exist: Pyroducts formed by inflation of the lava flow front and later downward erosion (1a), pyroducts formed by coalescence of small ducts and consecutive downward erosion (1b), pyroducts formed by the crusting-over of channels by jamming, floating lithoclasts and welding them together (1c), and by channels crusting-over by lateral shelf accretion and consecutive closure (1d). Pyroducts are the most numerous lava caves; the longest being Kazumura Cave (total length 65.5 km) (Hawai'i, Kilauea Volcano) and the longest duct-supported flow on Earth is the 160 km long Undara flow, Australian. In Jordan, the Al-Fahda flow could have pyroducts as long as 25 km. Another class is that of (2) pressure ridge caves. They form by up-doming of half-solidified lava sheets and are numerous in Jordan. Further classes include (3) volcanic vents, (4) the wide class of drainage features (5) lava sheet partings and (6) imprints of trees and animals. Secondary caves form also in lava, including (7) fissure caves, (8) pit craters and (9) erosional caves such as sea caves and caves formed by stream erosion such as Kuka'iau Cave, Hawai'i.

Hashemite University Cave, Jordan

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The Harrat Al Shaam, the lava deserts of Jordan, is a vast lava field, in which we have explored and surveyed as yet 23 lava caves with a total added length of 316 m. With 231 m in length, Hashemite University Cave is the third longest. It can be classified as a "pyroduct", i.e. serving as an underground conduit for molten lava away from the volcanic vent. Hashemite University cave is one of two known pyroducts in the 164 km^2 large flow field of the twin volcanoes Quis and Makais, one of the youngest in the Harrat. This flow field also contains the only known pressure ridge caves in Jordan: Azzam, Dahdal, Al-Ra'ye, Al-Haya, Obada, Hammam, Henschel, Haleem and Al-Ameed Caves. The discovery of Hashemite University cave illustrates the importance of pyroducts for the transport of lava across terrain of low slope. In case of the Quis and Makais Flow field the amounted to 28 km of distance with a slope of only 0.65°.

The Geomunoreum Lava Tube System on Jeju Island, Korea

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In the Quaternary volcanic province of Jeju Island, located off the southern tip of the Korean Peninsula, many lava tubes have been found.

Some of the longest and most spectacular lava tubes are associated with the Geomun volcano in the northeastern part of the island.

The tubes were formed between 100 000 and 300 000 years ago and today are, arguably, the most significant element of the Volcanic Province World Heritage site on Jeju, which also includes the Hallasan Nature Reserve (encompassing the highest peak in Korea) and Seongsan Ichulbong, an eroded tuff cone on the eastern coast of Jeju.

The Geomun lava tube system comprises at least eight separate caves separated by infilled lavas and breakdown. The system trends in a north-north-easterly direction from the crater to near the northern coast of Jeju, a distance of approximately 15km.

During field trips associated with the 13th International Symposium on Vulcanospeleology in 2008, participants visited three caves in the system (Manjanggul, Gimnyeongul and Yongcheongul). This paper focuses on some of the features observed on those field trips.

A History of Human Exploration and Occupation of the Lava Caves of the Zuni-Bandera Volcanic Field, New Mexico, USA

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In the high desert of New Mexico's Zuni-Bandera Volcanic Field (ZBVF) there are hundreds of volcanoes and lava caves. These caves have been occupied, explored, mined and even bombed over the past 10,000 years. Many of these caves contained large perennial ice accumulations. The Native Americans used the caves for ice, water, protection, religious ceremonies and food storage, primarily from 7500 BC to 1130 AD. Prehistoric Native American artifacts are still being discovered in the caves today. Under law, these artifacts are repatriated to the Native Americans.

Europeans (Spanish conquistadors) first entered the region in AD 1540. However, the first scientific exploration of the ZBVF did not began until the conclusion of the Spanish-American War in AD 1850, when surveying commenced for the first transcontinental railway. During World War II scientific exploration ceased as the ZBVF became a conventional bombing range. In 1945 the ZBVF was almost selected as the site for the first atomic bomb test.

The Space Race of the 1960s sparked an interest in lunar rilles (pyroducts). Scientists subsequently turned to the ZBVF to study terrestrial pyroducts. During the same period, the National Speleological Society (NSS) began exploring the caves of the ZBVF.

In 1987 the ZBVF became protected as a El Malpais National Monument and Conservation Area. The National Park Service (NPS) has completed two comprehensive surveys of the lava caves of the region, in 1988 and 1994-1997. The NSS has continued to survey the caves under the NPS, but currently all caves in the ZBVF are closed pending further characterization of the devastating bat disease White Nose Syndrome. The rugged terrain means that large areas have not yet been explored. The future of cave exploration in the ZBVF is unclear at the present time.

Distribution, Sizes, Function and Heritage Importance of the Harrat Al-Shaam Desert Kites: the Largest Prehistoric Stoneworks of Mankind?

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The Harrat Al Shaam, the lava deserts of Jordan, features the largest concentration of desert kites so far analyzed (e.g., Kempe & Al-Malabeh, 2010a). Our GoogleEarth count runs to at least 530 such kites, while aerial photography counts yielded 1155 kites (Kennedy, 2011; Table 1). In Saudi Arabia we have counted 254 more and Kennedy (2011) counted 407 kites in Syria. Few kites occur also in Turkey, on the Sinai and in Usbekistan. This shows that the largest numbers of kites is concentrated in Jordan, forming a significant part of its prehistoric heritage.

Desert kites are km-long stone wall constructions, consisting of two or more widely gaping guiding walls that converge to an opening (gate) behind a small sill. Behind is a walled enclosure. In the early stages, these enclosures were bag-like, later clover-like and in the latest development they attain a ha-sized, star-shaped shape. At the apexes of the inward curved enclosure walls, so called "blinds" were erected, 3 to 5 m wide stone circles. Some kites have well over a dozen of such circles. These circles were interpreted as "hides" for hunters to shoot gazelle. However, we argue that these were the actual traps. Once the gazelle had jumped into them, they could not jump out again lacking forward speed. More than 95% of the Jordanian kites open SE ward, arranged in eight chains extending N-S throughout the Harrat, thus effectively intercepting animal migration towards Syria and the Mediterranean Coast. In all probability they were built in early Neolithic times to intercept gazelle (G. subgutturosa). We present statistical evaluation of two such chains: The Eastern Border Chain and the Usaykim-Safawi Chain. Both chains follow sections of the eastern Harrat border and are thus comparable in situation. Analysis shows that the kites of the Eastern Border Chain are significantly larger than those of the Usaykim-Safawi Chain, both concerning their guiding wall length as well as the sizes of their enclosures. However, the Usaykim-Safawi Chain has more of the older kite types (bag- and clover-shaped) and may therefore have been occupied first. The overall length of walls existing in this chain (including guiding walls, enclosure perimeters and the additional meander walls and meander section walls) amounts to 264 km. This allows estimating that the entire wall length exiting in the Harrat may be as much as 3780 km representing a stone volume half of that of the Cheops pyramid. Thus the Harrat Al-Sham desert kites are a most valuable and yet not well-known part of the heritage of Jordan. Many kites, however, have already been destroyed due to field clearing and bulldozing.

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Investigation on the Vegetation and the Characteristic of Lava by Observing the Structure of Tree Moulds in Higashi-Usuzuka-Minami Lava Flow at Mt Fuji

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Tree molds are a record of both vegetation and interaction phenomena between lava flow and standing trees. The observation of tree mould diameter distribution can predict the vegetation succession phase at the eruption time and estimate the interval from the former eruption of lava flow if one piled up another. The diameter distribution study of 398 tree molds of Higashi-Usuzuka-Minami lava flow ejected on the southern flank of Mt.Fuji shows 1000 to 1200 years lapse after the former eruption of Kotengu lava flow. This lapse was compared with the recent tephra study and C14 dating (Kotengu-Lava flow: 2120±40y BP, Higashi-Usuzuka-Minami Lava flow: 1190±40y BP) and consistent with them.

By observing also the structure of tree mold, lava flow characteristics such as lava thickness, flow speed, flow direction etc., can be deduced. Here, the speed and viscosity of the basaltic lava flow of Higashi-Usuzuka-Minami were estimated by upposing that all the tree of diameter below the minimum diameter of the existing tree has been thrown down with collision of lava flow. From this diameter, the speed of lava flow was estimated as about 4m/sec. Substituting the slope angle, lava flow thickness and density of lava to the simple slope flow equation, the viscosity of lava can be obtained. The estimated viscosity was about 4000 poise, which seems to be reasonable as a viscosity of low fraction silica content basaltic.

Characterization of Lava Caves, Using 2D Induced Polarization Imaging, Umm El-Quttein area, NE Jordan

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The possibility to detect lava caves in the basaltic flows in the shallow subsurface using Induced Polarization (IP) imaging survey was a significant subject in recent years. The application of this method to caves in the large intra-continental volcanic field of the Harrat Al-Shaam, NE Jordan is reported. The Harrat is composed of a series of basaltic flows that stretch for many kilometers below their eruptive vents. Such long flows are possible only because lava tends to build long tunnels in which the lava is thermally isolated, thus preventing its early solidification.

The IP imaging technique is very sensitive to horizontal changes in the resistivity method and is an excellent tool to map vertical structures such as cavities or intrusive dikes. This technique was used in the Umm El-Quttein area to investigate the subsurface and test if we can image existing caves and if these might be a potential hazard of the roads in the area. The IP measurements were made with the time-domain method and processed by using the least square inversion approach that will automatically determine true 2D resistivity models. The quantitative interpretation obtained from 2D inversion modeling indicates that the lava caves produce anomalies characterized by a high resistivity at around 3010 Ohm-m with a depth of less than 19 m, and very intense anomalies; likely ascribable to open fractures. These may be filled with clay or carbonate sediments that decrease the apparent resistivity values but increase the chargeability (M) and metal factor (MF). This technique therefore was successful in detecting lava caves within the complex structures of the Jaba Quis volcano. Furthermore processing is possible within a few hours.

The Lava Caves of the Zuni-Bandera Volcanic Field, New Mexico, USA

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The Zuni-Bandera Volcanic Field (ZBVF) is located in the high desert of New Mexico in the southwestern United States. The ZBVF encompasses 2,200 square kilometers between the elevations of 1,900 and 2,600 meters. There are over 100 volcanic vents, about 15 pyroducts up to 29 kilometers in length, and over 200 caves. Dozens of these lava caves contain massive perennial ice accumulations despite summertime temperatures in excess of 40 degrees Celsius.

The volcanic stratigraphy of the ZBVF has been under investigation for over 100 years. Technological advances in science and detailed fieldwork have refined knowledge of the sequence of eruptions. Almost all of the caves in the ZBVF are found in the most recent Quaternary lava flows that were emplaced between 200,000 and 3,000 years ago.

The lava caves in the Zuni-Bandera Volcanic Filed (ZBVF) have a variety of interesting features such as a lava driblet column, a unique lava "bomb," driblet stalagmites, lava stalactites, "sharktooth" lavacicles, lava "soda straws," pahoehoe, lava cascades, massive perennial ice accumulations, and archaeological artifacts. The longest single cave is 964 meters long. The longest segmented cave system is composed of 14 caves and is 2,750 meters long.

Much of the ZBVF has not been explored due to the rugged terrain and remote location. The National Park Service and the National Speleological Society have partnered to continue exploration. However, as of December 6, 2010 all of the caves in the ZBVF were closed over the concerns of the White Nose. The caves will remain closed until the disease is further characterized and the role of the human as a vector is better known.

The Volcano-Stratigraphy of Jabal Al-Shahba Cinder Cone, South Syria

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The Tertiary-Quaternary basaltic lavas of southern Syria are divided into three separate volcanic phases, of Miocene, Pliocene and Quaternary age. These basalts are parts of the large intra-continental basaltic terrain of Harrat Al-Shaam, which covers an area of about 45,000 km2. and lies in NW-Arabian plate.

Detailed field investigation shows that Jabal Al-Shahba is one of a large number of scoria and basaltic cones that are distributed in the Syrian parts of Harrat Al-Shaam. Jabal Al-Shahba volcano forms a single, relatively small hill of circular shape. It has a height of 50 m and covers an area of bout 3 sq. km. The flanks of the volcano have slopes of about 25-30o, producing almost a symmetrical geometry.

The stratigraphy of the volcano is mainly composed of bedded scoria, fall lapilli that make up the volcano from the base upwards. The ejecta are dominated by angular to subangular clasts that are generally of less than 2.5 cm in diameter. This classifies Jabal Al-Shahba as a cinder cone.

Petrographically, the rocks of the studied volcano are dominated by scoriaceaous olivine- and plagioclase-phyric basalt. They have modal olivine (3-6 vol.%), plagioclase (4-8 vol.%), volcanic glass (35-40% vol%) and vesicles (30-35 vol.%). The rocks are mostly fresh; however, slight alteration has been recorded in some samples.

The volcano appears to have resulted from multiple eruptions of one prolonged phase. Its volcanic activity consisted of a series of discrete explosion intervals. The time gap between each explosive interval producing the successions was relatively long as deduced from the existence of separation sections. The ejecta of Jabal Al-Shahaba are of Strombolian type of volcanicity. The small dispersal area and the height of the cone support this interpretation. The cone was originated by a magmatic mode of fragmentation.

Kahuenaha Nui, Hawaii, a Cave Developed in Four Different Lava Flows

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Exploration and survey of Kahuenaha Nui Cave in March 2011 yielded astonishing insights into the processes that act to enlarge the tunnels of underground lava conduits (pyroducts). The cave is situated in lavas of the SW Rift of the Mauna Loa, Hawaii, within the area of the former Kahuku Ranch, south of the Belt Road at an altitude of 564 m a.s.l.. On the geological map of Hawaii, these lavas belong to the stratigraphic group Qk2, dated to between 1500 and 3000 aBP. These flows are bordered by the 1868 pahoehoe flow on the E and the 1887 A'a flow in the W and occupy ca. 70 km2. The cave survey yielded a total length of 1850 m, a total vertical extent of 55 m and an average slope of 5.7° (Bauer, 2011). The cave features a main trunk that is up to 18 m wide and 11 m high. Its floor is in parts formed by terminal A'a . Above this trunk passage, we explored numerous small to very small interconnected p~hoehoe ducts. At the entrance puka (breakdown hole) and at a large open puka we were able to study the cave formation process. The trunk passage formed by eroding an underlying A'a rubble layer. In places, even the underlying A'a core layer has been cut into. Above, a stack of seven superimposed p~hoehoe flows with small ducts occurs, forming the primary roof of the cave. The lava flowing in this stack of sheets managed to combine into one flow, eroding the main trunk underneath. After cave formation first an A'a flow and then a thin p~hoehoe flow transgressed the area. The cave's roof partly collapsed, not only exposing the transgressed A'a but also forming the two pukas (so called cold-pukas). This cave forming mechanism is fundamentally different from the "inflation" and the "crusting-over of channels" mechanisms identified as pyroduct formation modes so far.

Refrences

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Potential for Vulcanospeleology on the Kamchatka Peninsula and the Kuril Islands

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Kamchatka and the Kuril Islands are in the Russian Far East. They form a section of the Ring of Fire, which encircles the Pacific Ocean. The deep Kuril-Kamchatka Trench lies approximately 150 km offshore in the Pacific and hence earthquakes and tsunamis are common in the area. This volcanism in this region results from the subduction of the Pacific Plate. The Kamchatka Peninsula has more than 300 volcanoes; they include caldera, strata-volcanoes and somma-volcanoes, 29 are currently active. In addition, there are thermal and mineral springs, geysers and other phenomena resulting from volcanic activity. Six groups of volcanoes have been inscribed as UNESCO World Heritage sites. The literature on lava tubes of Kamchatka is modest. There are two lava tubes in a flow from the Gorely volcano; other lava tubes are believed to exist there. In the Kronotsky Nature Reserve, The Uzon Caldera and The Valley of the Geysers have several entrances too active for investigation. The coast of the World Heritage, South Kamchatka Sanctuary has numerous littoral caves and natural bridges. The Kuril Islands have over100 volcanoes, some 40 of which are active, and many hot springs and fumaroles. The Kuril Islands are the summits of strato-volcanoes that result from the subduction of the Pacific Plate under the Okhotsk Plate. The potential for vulcanospeleology on three of the Kuril Islands will be discussed. Atlasova Island which contains Alaid a somma-volcano. Matua Island, which was a Japanese Base in World War II and is known to have kilometres of tunnels. Entrances to some tunnels were destroyed by Japanese or have been buried in lava and ash. Exploration of accessible tunnels was halted when accidents resulted from collapse and the presence of poisonous gases. Bliznecy Island where numerous littoral caves and natural bridges are found amongst the columnar basalt.

Two Examples of Single-Trunk Type Caves in the Eclipse Lava Flow, Mauna Loa SW Rift, Hawai'i

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In March 2011, we investigated and surveyed two small pyroducts in the former area of the Kahuku Ranch area, south of the Mamalahoa Highway at an altitude of 580 m (Kahuenaha Iki) and 573 m (IlioLilo). Both caves are situated in the "Eclipse Lava Flow" (named after Eclipse Cave further to the north in the same lavas), which is the topmost of the Ka'u basalts in this area, dated back to 1500-3000 aBP. The "Eclipse Flow" is bordered to the west by an olivine-rich A'a flow and to the East by the picritic 1868 p~hoehoeflow. Both caves are accessible through small pukas, formed by cold breakdown of the thin roof, consisting only of a few thin lava sheets. Kahuenaha Iki has two entrances, strikes S and is 193 m long with a maximum width of 10m and a slope of 4.1°. The pyroduct did not cut down significantly into underlying lavas and seems to be to have been short-lived, as suggested by the low ceiling height of max. 1.7 m.At the exploration endpoint the pyroduct becomes gradually lower while branching more and more. The mauka end is blocked by welded boulders preventing any further investigation. A secondary ceiling indicates the existence of a hot breakdown puka during the active stage of the pyroduct. The sinuosity of 1.48 supports the assumption of a slowly progressing lavaflow, transporting only small amounts of lava.The entrance to the IlioLilo cave is also a cold breakdown hole in the only 0.3m thick roof. The cave strikes south-west and is 93 m long. In contrast to Kahuenaha Iki, an inverted keyhole profile gives evidence oferosive downcutting into an older underlying A'a rubble layer resulting in a maximum height of 2.5 m and a width of 5.3 m.IlioLilo and Kahuenaha Iki are examples for small pyroducts, carrying small lava volumes of an Mauna Loa's south-west-rift eruption.

Goat Sanctum, Part of an Old, Deep-Seatedcave System on Mauna Loa's South-Westflank, Hawai'I

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In March 2011, we investigated a large, deep-seated, partly collapsed pyroduct in the area of the former Kahuku Ranch, south of the Belt Road at an altitude of 290 m. The cave is situated in a strip of relatively old Mauna Loa lava, bordered to the W by the 1887 A'a Flow and to the east, partly transgressing the lower part of the system, by the complex lava flows containing the Kahuenaha Caves. According to the geological map it dates back to 1500 to 3000 aBP.A SW-striking, 160 m long and up to 23 m wide collapse trench separates two caves: Rain cave, to the north and Goat Sanctum to the south. Rain Cave is entered down a very steep sloping floor composed of goat pellets. It was only explored, is about 200m long and ends in a lava sump. Goat Sanctum is also accessed down a steep slope of loose breakdown blocks, some of them > 10 m3, covered with a thick layer of goat pellets. The cave floor is composed of breakdown blocks and the deepest point reached is 38 m below the surface. At no place the original cave floor is visible and the cave's morphology at present is determined entirely by cold (post-activity) breakdown. Goat Sanctum is 155 m long and up to 9 m high and 14 m wide, ending in breakdown. The original cave roof seems to have collapsed entirely and an overlying loose '~'arubble layer is responsible for the large upward growth of the cave. The trench and the cave roofs offer valuable insight into the stratigraphy of the lava. A stack of p~hoehoe-sheets (possibly the primary roof) is overlain by a subsequent thick, picritic A'a flow. At a later date apicriticslabbyp~hoehoe-flow covered the A'a , forming the present surface. It intruded partially the underlying A'a rubble, solidifying it with "squeezeballs" of p~hoehoe.From the NW a small feeder discharged into the trench. Rain Cave and Goat Sanctum give evidence of large pyroducts that conducted very large lava volumes from SW Rift eruptions seawards.

The Queen's Bath, a Littoral Cave in Mauna Loa lava, Hawai'i, Formed by Coastal Erosion

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Queen's Bath is a (locally) famous littoral cave at the SW-Flank of Mauna Loa, Hawai'i (18° 59.298'N/155° 46.288'W).It was eroded into the lower rubble layer of a several meter thick A'a flow of alkali-basalt. This A'a' may belong to the complex flow field exposed in the Eclipse/Kahuenaha area further uphill which is transgressed by the black A'a' flow of ~~1868~~ 1887. The ~~1868~~ 1887-lava stopped about 50 m north of the coastline, just barely failing to burry Queen's Bath. Queen's Bath is actually composed of three parallel, inland directed excavations. The easternmost is a bay open to the sea and filled with polished and rounded recent boulders. In the center and in the west there are two deep vertical openings within the thick A'a' core. They are partially occupied by gravel-floored pools. The openings are seaward closed by the still intact solid 4.5 m highA'a core, and landward grade into caves eroded into the lower rubble layer of the A'a flow, also filled with water. This water appears to be brackish and is devoid of the normal coastal tidal pool fauna and flora. With the present sea-level situation and low tides of about 0.5 m,waves cannot reach the pools and the caves cannot have been eroded. Therefore, it must be assumed that the caves (and the A'a' flow) date back ca. 4 ka when in the Pacific sealevel stood significantly higher than today. It must further be assumed that the seaward barrier formed by the '~'a core today was undermined to remove the collapsed a'a core from the present openings and the A'a' rubble from the landward caves and that these former wave inlets were later filled with coastal gravel and boulders, material that could have been provided by the ~~1868~~ 1887-flow as it cascaded into the ocean a few hundred meters east of Queen's Bath.

A Method of Organizing a Lava Cave Data Base for Field Work

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More often than not, cave databases are simply computerized lists that are organized by geographic region and/or alphabetically by cave name. However, alphabetical cave databases are not very useful for field work. A cave database that is useful for field work should allow an investigator to seamlessly translate between field observations, maps and the database. A database that has been organized for field work might be called a "field guide."

Fortunately, the nature of volcanic eruptions and pyroducts aids in constructing a logical structure for a caving field guide. This is because lava caves are emplaced temporarily in sequential flow units and longitudinally as pyroduct "streams." Therefore, a lava cave database can be organized to mirror the chronological and structural nature of the lava flows. This preserves the relationship between the caves and the eruptive events that formed them. The "El Malpais" method is one such method of organizing a lava cave database.

Given that there are an infinite number of variations in volcanic eruptions, there are also in infinite number of possible variations in the structure of the database. This is both a limitation and an advantage. The "El Malpais" method allows the database to be organized in a manner that is advantageous for local purposes.

Another significant limitation of the "El Malpais" method is that structure of the database depends on scientific understanding of the local volcanic events. This understanding can and will change with time, which can require significant re-organization of the database.

Middle Paleolithic to Neolithic Cultural History of North Iraq

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Six sections of one to 2.7 meters depth contain ten sediment samples each are collected from caves of Shanidar, Hawdian and Hazar Merd with nearby river valley sites of Zawi Chemi, Gawra River and Barda Balka respectively in North Iraq. They have been analyzed palynologicaly for their climatic significance and vegetational cover during late Quaternary in northeastern Iraq.

The main information gathered from these palynological analyses as well as stone tools is ancient open site settlements in Barda Balka of Paleolithic interglacial Acheulean culture. During the last ice age (120.000-10.000 years B.P.) people refuged to cave settlements. Baradost Mountain as well as Aqra and Piera Maqroon mountains cavemen of the Middle Paleolithic Period are related to steppe vegetation with cold climate and glacial storms. Those cavemen manufactured stone artifacts of Mousterian to Gravetian culture and have their own religious believe and funeral ceremony especially recorded in Shanidar cave. They lived by hunting and food collecting from nearby valley to each cave. During earliest Holocene time (10.000 years B.P.), changing climate to moderately warm climate with Quercus forests and poacean vegetation was recorded, and the cavemen evolved to Neolithic culture and hence moved to settle in plain areas and built the oldest villages of the world, viz, Zawi Chemi and Jarmo with continuing temporarily living in the caves as well. Their habit changed from food collectors to farmers who cultivated the land with wheat, barley, fruits, olive, legumes and flowers of brilliant colors, nice odor and nectariferous as well as domesticated animals for their food resources .Clay tablets of the Sumerians, Babylonians and Assyrians have documented (Arapha) for Kirkuk as one of their cities since 5.500 years B.P. Stone writing records of Assyrian King Sennacherib (705-681 B.C.) states of making irrigation canal flowing to the temple of Ishtar in Erbil. On the other hand, similarity of Jarmo village in the present Kurdstan region of Iraq to ancient Tell Hassuna village south of the present Mosul city (within ancient Nineva city) and pottery of Jarmo villages to Nineva pottery could give evidence for Jarmo peoples as followers to the Babylonian- Assyrian cultures within their Empire and to improve that peoples of North Iraq and South Iraq are interrelated cultures through the history within Mesopotamian cultures.

The Indication of Tectonic Movements in Forming the Seeps on Caves in Thrust Zone within Zagros Fold Belt

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Intensive tectonic activity during Zagros Orogeny (Late Cretaceous - Late Tertiary) and the final uplift in Holocene, reactivated folds and faults and eroded parts of the Lower and Upper Cretaceous, northern Iraq forms so many caves precisely in Qamchuqa Formation characterize by being massive not bedded. Subsequently, within the Study area, the post Jurassic tectonics and the Upper Jurassic paleo-depositional environments left potential carbonate reservoirs at the basin margin (the Najmah Formation) and a potential evaporite cap rock (the Gotnia Formation) basin wards. Such relationship sealed the generated hydrocarbons and there are evidences of seep oil within the studied area, but it unlikely sealed the laterally migrated oil into the Najmah Formation. The major N-S fault planes of the Khleisia uplift that extended from northwestern part of Iraq to the southwestern is some forming a barrier to laterally migrated oil and putting an end to the potential migration pathways from the Basinal Sargelu Formation in north Iraq. At the same time the prolonged thermal activity may have convert the organic matters within Paleozoic layers to thermogenic gases.

Total petroleum system enabled us to better understand the provenance of oil and the activity of the tectonics in this area that seem to be causes complication to the whole scenario, that the huge caves permit the conduits carrying oil and natural gas via carrier beds to expose to surface of the cave walls, giving indication for micro and macro seepage, leading to focus on nearby and surrounding areas to reserves giant oil and gas fields.

Tawke oil field near Zakho district, which produces nearly 100.000 bbl/day is discovered recently as a consequence of intensive detection and adequate exploration processes. The current study refer also to promising area for generates natural gas.

Caves as Man First Shelters and Stone Tool

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Caves of the Zagros Mountains in Iraq are all formed by karsts topography. Some of our caves are old enough that they may have provided early man, not only shelter from other humans, but animal as well. What better way to escape a charging bear than to squeeze into a small cave opening that you can block with a rock or log door? The caves were also perfect places to get out of a rain, or snow storm. Prehistoric humans were cave dwellers. Approximately 100,000 years ago, some Neanderthal humans dwelt in caves in Europe and western Asia.

Stone tools and the remains of eaten animals have been found in caves. This study will focus on some stone tools collected from Iraqi caves, this collection show the evolution of the stone tools industry in ancient Mesopotamia, oldest axe in Iraqi caves was acheulean hand axe made by homo erectus 200000 years ago, more than 20 stone tools were studied. This study has explained the development in manufacturing of stone tools.

Origin and evolution of the Tar Al-Sayyed and Tar Al-Najaf Caves in Injana Formation within Najaf-Karbala district, Central Iraq

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Caves that are scattered within Injana Formations and sometime extend to be hosted within Dibdibba Formation in Tar Al-Najaf and Tar Al-Sayyed within Najaf-Karbala district have been studied through many field trips. Mineralogical composition was done to facilitate the investigation of cave-forming factors. Calcite, quartz, feldspar, dolomite as well as clay minerals are the constituents of Injana Formation in the study area. Caves appear to be hosted within claystone beds and concentrated within Injana Fornation, whereas Dibdibba Formation seems to form the roof of caves. Caves formed in beginning as microfractures; then with time they have developed to be vertical joints. These joints were gradually enlarged as a result of claystone exfoliation along joint plains. Chemical weathering, physical weathering and sedimentary structure (mud balls) play a key role in the processes of evolution of caves. Some caves appear to be irregular, but others tend to be regular with rectangular shape and enough for hosting human. These caves may be used as homes for old human to protect and improve his life. At the same time that the caves were formed by, there were other factors working continuously to destroy the cave. These factors are dissolution, soil creep and mass sliding. This work highly recommend for further research and archeological investigation on these caves to discover the ancient civilization in this area, if any.

Yarmouk–Decapolis Tunnel System: The Most Important Underground Discovery in Jordan of the Last Decade

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This research deals with the discovery of the longest antique water tunnel. The tunnel is located in northern Jordan in the area between the towns of Al-Turah and Um Qais (Gadara) and constructed in Roman times. Many major springs exist along the tunnel such as: Um-Ejreen, Rahoob, Hobras and Ibdar. This "Yarmouk-Decapolis Tunnel System (YDTS)" can be traced over a distance of about 140 km; only a small part has been surveyed underground yet. The tunnel may be as high as three meters in most of its parts, with an average width of 1.8 meter.

Two surface water canals were discovered that collected the water for the Yarmouk-Decapolis Tunnel. The first canal comes from the Al-Esrayieh spring north of Deli lake in southern Syria, while the second canal started at Mzayreeb (Al-Baja lake), located at the Syrian-Jordanian border.

The tunnel may be the most important underground discovery in Jordan, a masterpiece of antique civilization as well as a true miracle, confirming the genius of antique engineers that managed to collect water from many springs in the area between Al-Turah and Al-Shajarah, and diverting them towards Wadi Shalalah in the region of the town of Mugayier (springs Rahoob). The tunnel then passed through the towns of Al-a'l, Abu Al-Loqas, Al-Khreibeh and Qwailbeh near the ruins of Abila. From there it continued in the direction of the springs of Hobras and Yubla, Kufr Soum, Samar, Ibdar and Malka.

The main aim of the canal and tunnel system was to link the cities of the Decapolis along the tunnel, i.e. Dion-Abila-Arbila-Jadara, giving them the security of a constant and calculable water supply. The final destination of the tunnel was the famous city of Umm Qais.

Mineralogical, Geochemical and Engineering Properties of Chalk in Northern Jordan and the Evaluation of the Al-Kreibeh-Al-Sileh Segments of the Roman Yarmouk-Decapolis Tunnel System

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The Yarmouk-Decapolis Tunnel System is the longest yet reported tunnel in history. It extends for about 140 km through northern Jordan, between Al-Turah and the antique town of Umm Qais. This study is aimed at the detailed surveying, exploration and mapping of the Yarmouk-Decapolis Tunnel parts in between Al-Khreibeh and Al-Sileh. This area is located about 5 km to the northeast of city of Irbid. The investigated area covers about 10 km2. Field investigations show that the tunnel in this area is accessible for about 200 m, while the rest of it is blocked by debris and rock fall. However, about 20 entrances can be followed on the surface. The studied tunnel slopes towards the northeast which is reasonably classified as returned tunnel. According to Folks- and Dunham-classifications, the studied chalk rocks of the tunnel are classified as biomicrite. Geochemical analyses of major oxides and trace elements were performed. The CaO concentration is 68.2 % on average. The trace elements Zn, Ni, V, Cr, Mo, Cu, Ba, S and Sr have relatively low concentrations. Diagenetic studies show that the chalk was deposited in a shallow marine environment.

Geo-engineering, field exploration and stabilization of chalk rocks in Hobras – Abila Segment of Yarmouk-Decapolis Tunnel System, Jordan

by

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Abstract

This research describes the exploration and evaluation of tunnel-influence on the stresses in the rock which in turn may influence the geotechnical and hydraulic properties of the tunnel. The starting point in this thesis is a simplified description of the techniques constructing a tunnel between two distant points that involves mastering several sophisticated fields, including engineering, architecture, geodesy, hydraulics, and geology. Understanding the methods of constructing of ancient tunnels may shed light on early stages of these sciences, since they must have been developed through practical experience. In the last years in central Italy many Roman and pre-Roman hydraulic tunnels have been explored and their architecture has been described and discussed. These engineering works were built according to complex projects and by using sophisticated techniques. These findings are compared with similar findings in north Jordan in the Abila Segment (HAT) of the Yarmouk-Decapolis Tunnel System, specifically in the tunnel of the Hobras – Abila Segment.

Physical and engineering properties were determined on five rock core specimens that were extracted from the chalk. The rock bulk specific gravity was in range between 2.27 and 2.41g/cm^3 with a mean of 2.34g/cm^3. The absorption values were low ranging between 20 and 24% with a mean of 22%, and the degree of saturation ranges between 72.42 and 78.91% with a mean of 75.22%. The dry weight is 1.67gm/cm3 and the samples had porosities of between 15 and 45%. The calcite content amounted to over 95%. The point load strength is 0.39 MPa, and the durability is 99% recorded after second cycle. The studied chalk is classified as a biomicrite; the geochemical analyses results indicate high percentage of CaO with a mean of 50.8%. Moreover, the trace elements have relatively low concentrations of Zn, Ni, V, Cr, Mo, Cu, Ba, S and Sr. Digenetic studies show that the chalk is deposited in shallow marine environments.

Even though the area of northern Jordan was widely explored and surveyed, few of the surveys shed light on the true extent and geological preconditions of the Roman tunnel system. Some of the hypotheses say that it formed a link between northern Jordan – Um Qais and the southern part of Syria to supplied water to Jordan. The

investigated sections show that it is still in a very good and stable condition, as if carved yesterday.

Author Index

PROCEEDINGS

OF

15TH INTERNATIONAL SYMPOSIUM ON VULCANOSPELEOLOGY

Jordanian lava caves, an overview*

by

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*This paper is an updated version of Kempe et al. (2009).

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Abstract

The center of Jordan is occupied by a vast intercontinental lava plateau, called the Harrat Al-Shaam, composed of Cenozoic (Oligocene-Quaternary) alkali olivine basaltic lava flows, the Harrat Al-Jabban volcanics or Jordanian Harrat (Al-Malabeh, 2005). The top most and therefore youngest flows are ca. 400 000 years old (Tarawneh et al., 2000). So far, we explored, surveyed and studied a total of 23 lava caves since September 2003. 3164 m of passages were surveyed up to now (Table 1). These caves are, compared with most other lava caves quite old and many of them end in washed in loess. In addition to the Lava tunnels (pyroducts) that conveyed lava underground over large distances, Jordan has also a large fraction of pressure ridge caves (Kempe et al., 2010), all associated with Quis/Makais volcanoes. Two caves are of doubtful origin.

1. Introduction

The Arabian plate is covered by seven larger and several smaller Cenozoic (Oligocene-Quaternary) basalt fields, the "Harrats". They stretch over a N-S distance of about 3000 km from Jordan and Syria through Saudi Arabia to Yemen. The estimated volume of eruptive material equals to between 103 and 105 km3. These wide-spread, poorly studied basalt fields are considered to be among the largest of predominately alkali-olivine basalt plateaus in the world (e.g., Al-Malabeh, 1994).

Our group studies the lava caves contained in the Jordanian section of the Harrat Al-Shaam, the 700 km long, most northern of these plateaus that covers about 45,000 km2 (ca. 25% of the Arabian Harrats) (Fig. 1). This Harrat is in Jordan ca. 220 km wide in the N and 30-50 km in the south. Geomorphologically, it forms a gently undulating lava plateau dotted with prominent tephra cones, low shield volcanoes, numerous pressure ridges and crossed by a few, up to 80 km long eruptive fissures. The plateau generally dips to the S and SE, starting at an altitude of ca. 1100 m (a.s.l) along the Syrian border and dropping down to 700 m at Al-Mafraq and to 550 m in the Al-Azraq area. The overall slope is at most 4°. The structure of the basalt plateau is a succession of flow sheets which form stepped cliffs along wadi walls or faults. The youngest of these flows are over 400 ka old (Al-Fahda area) (Tarawneh et al., 2000). It - and the other younger lava fields - does not show wadi incision yet, while the older flow series are heavily incised. The Harrat is covered by a 1-2 m thick loess layer that has been washed into the depressions forming playas (locally known as Qa') giving the less incised areas a mottled appearance.

2. Lava Caves

In these lavas we explored, surveyed and studied a total of 23 lava caves since September 2003. 3164 m of passages were surveyed as of spring 2012 (Table 1). Of the total, 1,486 m, or 47%, was surveyed in September 2005, among them the 923.5 m long Al-Fahda Cave, currently the longest cave in Jordan. Nine of the lava caves are lava tunnels (pyroducts). One cave (Treasure Pit) is pit dug by treasure hunters that probably leads into a sediment-filled lava tunnel. Ten caves are pressure ridge cavities and two caves (Beer Al-Wisad and Uwaiyed) are of unusual origin and one cave in the list is artificial (Eshaim Cave).

Fig. 1: Map of the Harat As Shaam Lava field in the north of the Arabian plate.

Table 1: List of currently known and surveyed lava caves in Jordan, sorted by total passage length.

	Name of Cave	Latitude	Longitude	Stations	Length	Stations	Depth	Direction	Altitude	Type	Surveyed	Hyena Presence
1	Al-Fahda Cave	32°18.426	37°07.622	complex	**923.5**	2 to 54	6.7	SW-NE	792 m	Pyroduct	2005	xxx
2	Al-Badia Cave	32°07.91	36°49.42	32 to 23	445	1 to 23	17.2	NW-SE	783 m	Pyroduct	2003	no
3	Hashemite University Cave	32°13.362	36°33.579	21 to 35	231.1	1 to 23	10.0	NW-SE	787 m	Pyroduct	2005	xx
4	Al-Ameed Cave	32°13.214	36°33.179	complex	208	2 to 31	4.0	SW-NE	777 m	Pressure Ridge	2005	xxx
5	Dabie Cave	32°10.387	36°55.583	0 to 14	193.6	0 1to 13	1.8	NW-SE	881 m	Pyroduct	2004	xxx
6	Abu al Kursi East	32°15.401	36°39.442	20 to 34	153.7	1 to 34	12.2	W-E	883 m	Pyroduct	2003	xx
7	Kempe Cave	32°16.806	37°33.945	complex	139.4	complex	11.5	N-S	939 m	Pyroduct	2007	xxx
8	Hammam Cave N	32°13.219	36°34.340	complex	123.4	0 to 28	4.5	NW-SE	780 m	Pressure Ridge	2009	xxx
9	Al-Jolous Cave	32°13.925	36°34.206	0-15	112.6	-	n.d.	NE-SW	799 m	Pyroduct	2007	xx
14	Obada Cave	32°12.989	36°34.536	complex	107.6	0 to 6	3.4	NW-SE	766 m	Pressure Ridge	2008	xxx
10	Al-Howa	32°18.536	36°37.240	complex	97.1	2 to 6	10.8	SW-NE	939 m	Pyroduct	2004	no
11	Al-Haya Cave	32°17.743	36°34.745	1 to 11	81.3	1to 9	4.2	NW-SE	902 m	Pressure Ridge	2005	xxx
12	Abu al Kursi West	32°15.401	36°39.442	2 to 18	77.1	2 to 18	8.1	N-S	883 m	Pyroduct	2003	xx
13	Haleem Cave	32°13.441	36°33.675	1 to 12.	70.7	1 to 12.	4.7	NW-SE	791 m	Pressure Ridge	2009	xxx
15	Azzam Cave	32°17.104	36°36.594	13 to 25	44.1	1 to 25	4.2	NNW-SSE	902 m	Pressure Ridge	2003	no
16	Al Ra'ye Cave	32°17.618	36°34.791	1 to 6	42	1 to 34	3.5	NW-SE	900 m	Pressure Ridge	2005	no
17	Dahdal Cave	32°17.344	36°35.718	5 to 12	28.9	1 to 12	0.0	SW-NE	920 m	Pressure Ridge	2003	x
18	Henschel Cave	32°13.355	36°33.841	complex	21		2.50	W-E	788 m	Pressure Ridge	2009	no
19	Eshaim Cave	32°16.887	36°51.305	1 to 3.	20.6	1 to 3.	0.0	N-S	1029 m	Artificial	2009	no
20	Hammam Cave S	32°13.183	36°34.373	2 to 5.	12.4	2 to 4	2.4	NW-SE	780 m	Pressure Ridge	2009	x
21	Uwaiyed Cave	31°39.186	37°29.900	diameter	12		2.0	not def.	681 m	unknown	2008	xx
22	Beer al Wisad	31°44.527	37°27.991	chamber	11.4	Depth	11.5	not def.	627 m	unknown	2006	no
23	Treasure Pit	32°16.585	37°37.578		7.2	1-10,11	5.8	not def.	928 m	Pyroduct?	2006	no
				Sum	3164							

3. Lava Tunnels (Pyroducts)

Al-Fahda ("the lioness") Cave (Al-Malabeh et al., 2006) was named after the local name for one of the youngest lava fields (K–Ar age 0.46 ± 0.01 Ma sample HAS-7; Tarawneh et al., 2000) in the Harrat. It was first mentioned without any speleological details by Helms (1981, p.138) as El-Mughara in connection with the investigation of the famous Bronze Age desert city Jawa. Helms described a channel that leads to the entrance of the cave, apparently dug in an attempt to store water in times of plenty in the cave for times of need. This channel led to the rediscovery of the cave by the second author, who followed it from Wadi Rajil (830 m a.m.s.l) in the north downslope to the main entrance (730 m a.m.s.l) (Al-Malabeh et al., 2006) and surveyed by us in 2005 (Table 2; Fig. 2). The cave is also known under the name of Khsheifa Cave and was surveyed in parallel by Frumkin et al. (2008) yielding astonishingly similar results (their length 920 m).The cave has a very low slope, according to our survey of about 0.7°. Such a low slope is typical for tube-fed pahoehoe flows. Al-Fahda Cave is unusually wide but very low and has a very flat floor (at least were the rock floor is visible) (Fig. 3). It appears that this was caused by a later invasive flow filling the lower part of the tunnel. It shows a blocky surface and ends in two flow lobes shortly before the cave itself ends. It remains unclear if this fill is autochthonous, i.e, generated within the tunnel as a terminal slump of a higher viscosity, or allochthonous, i.e. caused by an invasion of a later flow of the Al-Fahda flow field through a ceiling hole (above the current accessible section of the cave). The main entrance to the cave today is through a late central ceiling collapse, exposing a cross section through the primary roof. It is composed of two relatively thick layers, in contrast to other caves that have up to 12 sheets in the primary ceiling (in case of Abu Al-Kursi) (for a more detailed study of the cave see Al-Malabeh et al., 2006).

Table 2: Survey results of Al-Fahda Cave (Al-Malabeh et al., 2006).

Stations	**Horizontal**	**m**	**Stations**		**m**
2-54a	Main survey downslope	488.60		End-to-end (as the crow flies)	**684.0**
8-11	Back of entrance	18.68		Sinuosity (771.03/684)	1.13
19-22	To second entrance	14.46	2-54a	Vertical (entrance to deepest point)	-6.74
50-51a	W-passage of terminal split	28.45	71-54a	Vertical extent of Main Passage	-8.41
4-5	Connection	6.05	71-54a	Horizontal length	755.12
5-71	Upslope passage	266.21	**Slope 1**	slope (°) ($\tan^{-1}$ (8.41/755.12)*	0.64°
67a-79	Mahmoud's Test Passage.	101.07	**Slope 2**	slope (°) ($\tan^{-1}$ (8.41/684)	0.70°
Total		**923.52**	**Width**	Maximal at St. 8	17.5
	Main Passage length			Minimal at St. 64	3.55
4-54a	Downslope passage	482.86		Mean of main passage (39 stations)	7.51
4-67a	Upslope passage	187.10	**Height**	Maximal St. 14	4.67
67a-79	Mahmoud's Test Passage	101.07		Mean of main passage (39 stations)	1.21
Total		**771.03**			

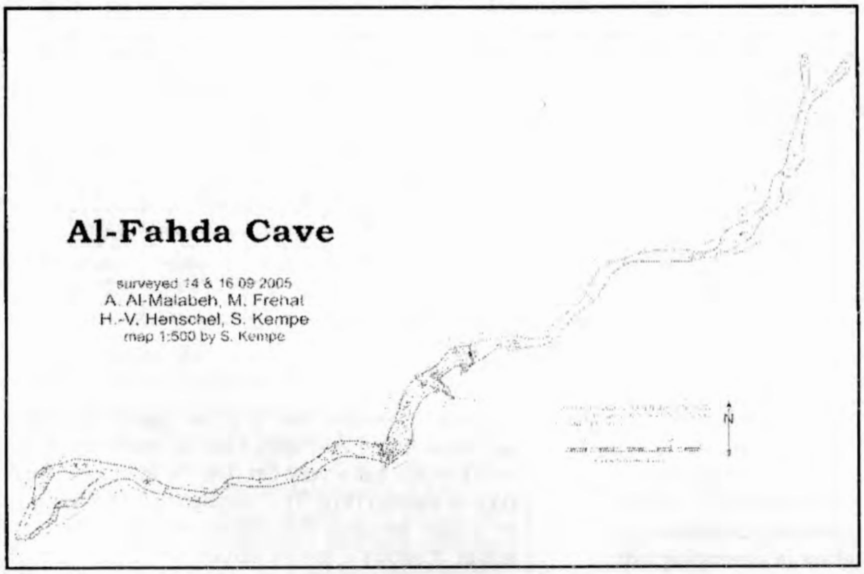

Fig. 2: Map of Al-Fahda Lava Cave, longest lava cave in Jordan

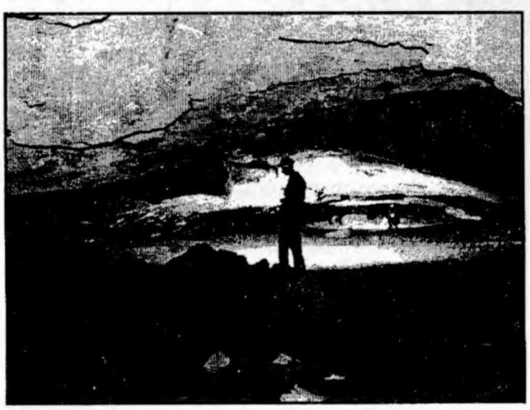

Fig.3: View up-slope into Al-Fahda Cave from the entrance. Note flat, sediment covered floor and low and wide character of the tunnel (persons for scale).

Hashemite University Cave is speleologically interesting also; it is reached through a collapse hole at the crest of a ridge. There the primary, 7 m thick roof is exposed consisting of only three pahoehoe layers. The uphill passage running NW is blocked by breakdown but from the north another low passage filled with sediment joins. The downhill tunnel is 180 m long before it opens up to a nearly circular room ca. 20 m in diameter. There, the cave ends in a lava sump. In a way, this is similar to the terminal lava sump of Thurston Lava Tube (Kempe & Henschel, 2009). It poses a structural riddle since one would expect that the back-up of the residual flow in the tunnel should close the cave at a narrow point but not at a wide passage. One possible solution could be assuming that the floor is a secondary ceiling (Kempe, 2002). A blowhole, situated near station 26, indicates that there could be an open passage underneath, giving some credibility to this hypothesis. In case of Kempe Cave, we can identify the source volcano for the first time in Jordan (Fig. 4) (Kempe et al., 2008). It is a low shield volcano in between larger stratovolcanoes. The crater is 120 m across and the rim is very even, suggesting that it once held an overflowing lava lake. The slope between crater (976 m a.s.l.) and cave (936 m) is only 1.2°. The cave itself (Fig. 5) is very low and curves around in half-circle; it is the most sinuous among the caves yet explored. Due to the fact that it is the cave furthest east and therefore the driest it also contains unusual speleothems, among them curvy gypsum flowers.

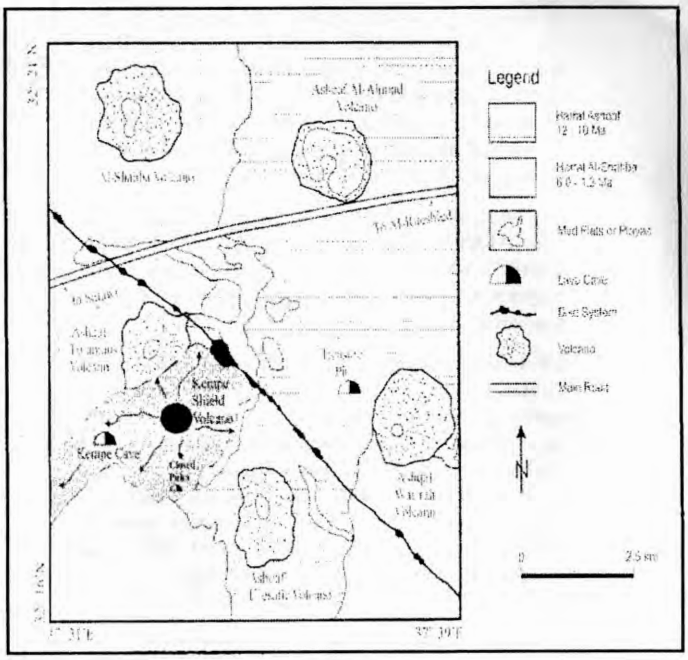

Fig. 4: Geological map of the Kempe Volcano (Map by Al-Malabeh and Kempe based on Field observations and Google Earth images).

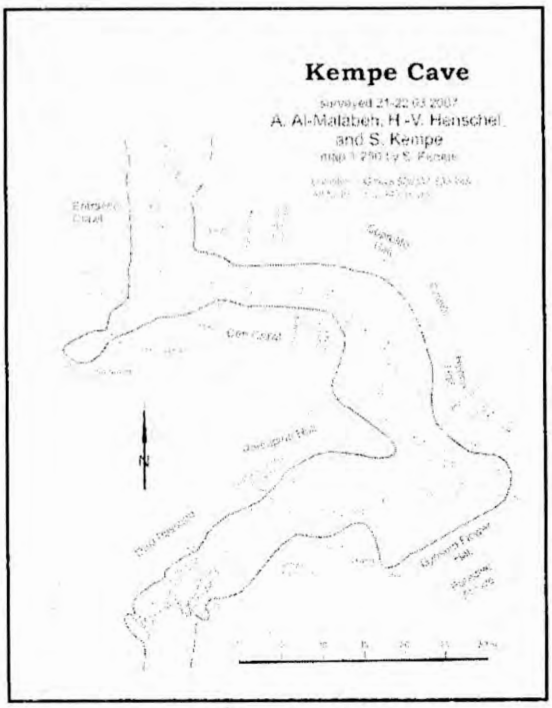

Fig. 5: Map of Kempe Cave

4. Pressure Ridge Caves

A group of caves not showing any clear direction of slope nor any signs of horizontal flow, is grouped as "pressure ridge caves" (Kempe et al., 2010). They can be quite long (Fig. 6, map of Al-Ameed Cave), are very wide and low in general and can have several branches, petering out at their ends. Similar caves are known from Hawaii, but are not well documented.

Pressure ridge caves apparently form when half-solidified surface sheets possibly yield to the shoving of the hotter lava below by doming upward, often with axes perpendicular to the direction of pressure. The caves are however, not bound to pronounced tumuli put can occur under low, dome-like rises.

5. Other Lava Caves

Uwaiyed Cave is a circular 10 m wide chamber in highly weathered old basalt that may be caused by upward stooping of a hypogene, collapsed limestone cave at depth (Al-Malabeh &Kempe, 2012) (Fig. 7). Another (Beer Al-Wisad) one is an 11 m deep pit, also in very old lava, of unknown origin.

The discovery of so many lava tunnels in the Harrat is surprising considering their old age and the fact that the loess is easily washed into caves filling them eventually. Al-Fahda, Hashemite University, Dabie, Kempe and the two Abu Al-Kursi Caves are all closed by sediments. Only Al-Howa Cave is terminated on both ends by roof collapse due to the loading of a later a'a lava flow.

Al-Fahda, Al-Badia (Beer Al-Hamam), and the two Abu Al-Kursi Caves are rather wide, while Al-Howa, Hashemite University, Kempe and Dabie Caves are of smaller dimensions. All have very low gradients.

Lava falls and plunge pools, so often encountered in Hawai'i (Kempe, 1997), were not found in these caves. A secondary ceiling is possibly present only in Hashemite University Cave. Benches and shelves marking older flow levels occur in Dabie Cave, Al-Fahda and in one place in Hashemite University Cave. Branching is rare, apart from Al-Fahda Cave only Hashemite University and possibly Kempe Cave display branching.

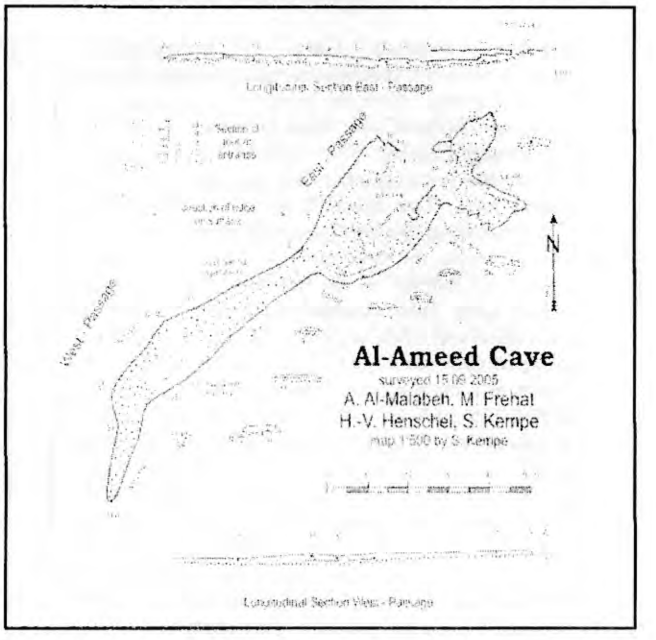

Fig. 6: Map of Al-Ameed Cave

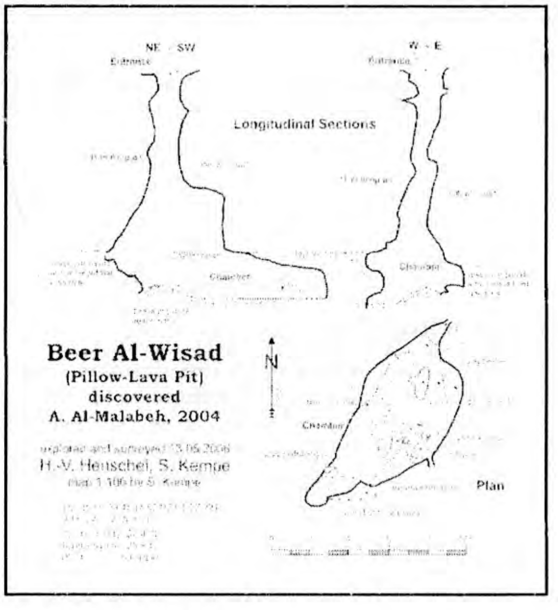

Fig. 7: Map of Beer Al-Wisad.

The presence of the lava tunnels underscores the fact that the Harrat consists to a large part of tube-fed pahoehoe thus explaining its overall low slope.

Compared to Hawaiian tunnels (see data in Kempe, 2002; Kazumura, Keala and Huehue, some of the longest caves on Hawaii have sinuosities of 1.30, 1.25 and 1.2), most caves show a rather low sinuosity (Al-Fahda: 1.13), in spite of the fact that it has a lower slope than the mentioned Hawaiian caves (1.51°, 1.51°, 4.58° resp.). The hypothesis that there should be a reverse relation between slope and sinuosity can therefore not be substantiated. The winding of the cave should have provided for a "Thalweg", i.e. a path along which the lava flow was maximal with slip-off and undercut slopes to the sides depending on curvature.

The high proportion of "pressure ridge caves" and their length are another interesting finding. One of the reasons for this high proportion of caves not formed by underground linear flow of lava may be the low slope of the terrain being in places even below 1°.

Many of the caves (compare Table 1) have been used by hyenas, wolves, foxes and porcupines. Specifically hyenas left many bones of their prey, abundant coprolites, dens dug into sediment and scent marks (Kempe et al., 2006a). The caves therefore are also of high paleontological and taphonomic importance.

Hashemite University Cave, Jordan

by

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Abstract

The Harrat Al Shaam, the lava deserts of Jordan, is a vast lava field, in which we have explored and surveyed as yet 23 lava caves with a total added length of 316 m. With 231 m in length, Hashemite University Cave is the third longest. It can be classified as a "pyroduct", i.e. serving as an underground conduit for molten lava away from the volcanic vent. Hashemite University cave is one of two known pyroducts in the 164 km^2 large flowfield of the twin volcanoes Qais and Makais, one of the youngest in the Harrat. This flowfield also contains the only known pressure ridge caves in Jordan: Azzam, Dahdal, Al-Ra'ye, Al-Haya, Obada, Hammam, Henschel, Haleem and Al-Ameed Caves. The discovery of Hashemite University cave illustrates the importance of pyroducts for the transport of lava across terrain of low slope. In case of the Qais and Makais Flowfield the amounted to 28 km of distance with a slope of only 0.65°.

1. Introduction

The study of lava caves, called "vulcanospeleology" by William R. Halliday, is still at its beginning. Most papers published appear in caving journals and remain descriptive. With a few exceptions (1 km long and 100 m deep fluvial-erosional Kuka'iau Cave in Hawai'i; Kempe and Werner, 2003; wave cut caves along shores and caves created by faulting; see Kempe this abstract volume and Kempe, 2012) lava caves are primary, i.e. they form during the emplacement of the lava itself. Lava tunnels (also termed "lava tubes" and "pyroducts" in the literature; see discussion in Kempe, 2002, 2008, 2009; Lockwood & Hazlett, 2010) are the most important features in spreading low viscosity basaltic lavas on land and an integral phenomena of shield volcanoes. The popular notice, often found in textbooks, that pyroducts form by "over-crusting of a channel" or by the "freezing of the lava flow from the outside" with its consecutive emptying of its still molten core can be found in many textbooks: this is, however, not how the majority of large lava caves form.

For a detailed description of these processes please see Kempe (2012) and Kempe this volume.

2. Jordanian lava caves

In the lavas of the Jordanian Harrat we explored, surveyed and studied a total of 23 lava caves since September 2003 (Al Malabeh et al., 2006; Kempe et al., 2006a, 2006b, 2008, 2009). 3164 m of passages were surveyed as of spring 2009 (see Table 1 in Kempe et al. this volume). Hashemite University Cave, a lava tunnel, has a total length of 231 m, is the third longest, after Al-Fahda Cave and Al-Badia Cave, yet explored in Jordan. Nine of the lava caves are lava tunnels. One cave (Treasure Pit) is a pit dug by treasure hunters that probably leads into a sediment-filled lava tunnel. Ten caves are pressure ridge cavities. One cave in the list is artificial (cinder having been removed from underneath a welded tephra layer) and two caves (Uwaiyed Cave and Beer Al-Wisad) are of unusual origin: Uwaiyed Cave may be the result of the stooping upward of an underlying cavity in limestone (Al-Malabeh & Kempe., 2012). Beer Al-Wisad is a pit in very old lavas that is of enigmatic origin.

Al-Fahda ("the lioness") Cave (Al-Malabeh et al., 2006) was named after the local name for one of the youngest lava fields in the Harrat (Ibrahim & Al-Malabeh, 2006). K–Ar dating yielded an age of 0.46 ± 0.01 Ma (sample HAS-7; Tarawneh et al., 2000). It was first mentioned without any speleological details by Helms (1981, p.138) as El-Mughara in connection with the study of the Bronze Age basalt-build city Jawa. Helms described a channel that leads to the entrance of the cave, apparently dug in an attempt to use the cave as a water reservoir. This channel led to the rediscovery of the cave by Al-Malabeh, who followed it from Wadi Rajil (830 m a.m.s.l) in the north downslope to the main entrance (730 m a.m.s.l) (Al-Malabeh et al., 2006) and surveyed by us in 2005 and turned out to be 923.5 m long. The cave is also known under the name of Khsheifa Cave and was surveyed in parallel by Frumkin et al. (2008) yielding astonishingly similar results (their length: 920 m). The cave is the only one yet discovered in the Harrat that shows clear branching. It appears to have been invaded by a late flow event, levelling its floor and covering it with a thin layer of loose a'a. This fill ends a few meters above the terminus of the cave caused by sediment infill.

Al Badia Cave is the lava cave discovered first in the Harrat (by Al-Malabeh in 1967). It is a very wide tunnel entered through a later 4 m deep roof collapse, overhanging on all sides. A little wadi is running into it that carried loess-derived sediment into the cave filling it gradually. Of the many kilometres, this cave may have measured originally, only 445 m are still accessible before the tunnel ceiling sinks below the sediment in fill. At times of flood, it may contain a sizable underground lake.

3. Hashemite University Cave

Hashemite University Cave is situated in a prominent lava field that was produced by the twin volcanoes Qais and Makais, 1.7 km apart (Fig. 1) (Al-Malabeh, 1994). The cinder cones are 50 and 20 m high, respectively. The lava field is crossed by the road between Mafraq to

Fig. 1: Google Earth picture of the Qais/Makais lava field. The two volcanoes in the north are marked by red marker. All lava tunnels are marked by yellow pins. Al-Howa and Abu Al-Kursi tunnels occur in older lavas. Pressure ridge caves are marked by white pins. The yellow lines mark roads, with the road from Mafraq to Safawi crossing in the center. The blue line marks the old Trans-Arabian-Pipeline. Note scale at lower left corner.

Safawi, it covers 164 km^2, i.e. an area 28 km long and 6 to 11 km wide. It is characterized by an irregular hummocky topography with many individual ridges and depressions. The depressions are filled with washed -in loess, forming little playas and giving the terrain a mottled appearance. The flow field appears to be relatively young and has not developed a wadi system and may be compared to the Al-Fahda flow field in age. The terrain drops from 910 m in the north to 590 m a.m.s.l. in the S, resulting in a slope of 0.65°, typical for pahoehoe flow fields.

Within the Qais/Makais flow field two lava tunnels are known: Hashemite University Cave and Al-Jolous Cave. The latter was discovered during road work and was investigated only briefly before it was closed by road construction. All the other caves belong to the pressure ridge type. In fact all of the pressure ridge caves as yet investigated in Jordan are found in the Qais/Makais lavas. In the north we investigated Azzam, Dahdal, Al-Ra'ye and Al-Haya Cave, in the south Obada, Hammam, Henschel, Haleem and Al-Ameed Caves (Kempe et al., 2020). These two groups may just represent the areas that we investigated in more detail and many other pressure ridge caves may exist in this flow field.

With only 231 m of total length, Hashemite University Cave is significantly less extensive then the Al-Fahdaand Al-Badia Caves but it is nevertheless of scientific interest.

It was investigated and surveyed by us in 2005. The cave runs roughly NW-SE (Fig. 2) along the topographic ridge of a lava flow (Fig. 3). Immediately to the south the ridge is accompanied by a depression, its floor (St. 41) 4 m below the entrance to the cave. The cave itself reaches a depth of up to 10 m below the entrance, suggesting that the depression represents a ridge of a previous lava flow that formed a topographic ridge, causing the younger flow to follow its northern flank.

The entrance on top of the ridge (Fig. 3) is very narrow and has been opened by humans. Several artificial circular holes, between 14 and 20 cm wide and up to 25 cm deep surround the entrance. They are of unknown purposes. Two of them were made in loose blocks. No archaeological features, however, were noticed within the cave and it is questionable if it was entered in antiquity at all.

After squeezing through a hole at the bottom of the entrance pit an irregular hall is entered. Its floor is composed of roof breakdown (Fig. 5). Some secondary flowstone is noticed along the walls.

Climbing further down narrow pits towards the SE, the floor of the original cave is reached at St. 19. The primary roof of the cave is composed of three relatively thick sheets of lava, about 7 m thick in total. Breakdown of the lower two sheets from the blocks in the entrance hall that appears to be strangely off-axis of the main lava tunnel.

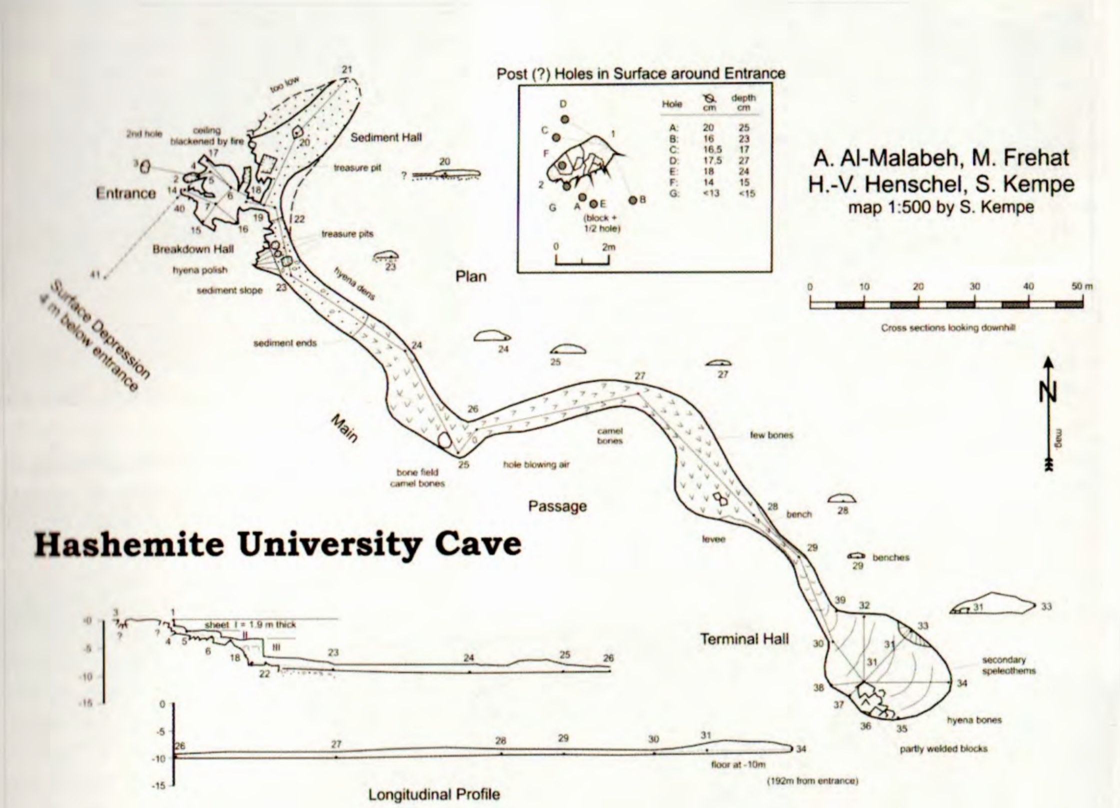

Fig. 2: Map and cross-sections of Hashemite University Cave.

Fig. 3: Southern view of the entrance area of Hashemite University Cave (marked by H.-V. Henschel for scale) on top of the flow ridge. Note continuation of the ridge on left side of picture to the SE. The pit in the foreground may lead to a different part of the cave. In the background is the depression S of the cave that may belong to a older flow ridge that forced the Hashemite University flow to flow SE (photo S. Kempe).

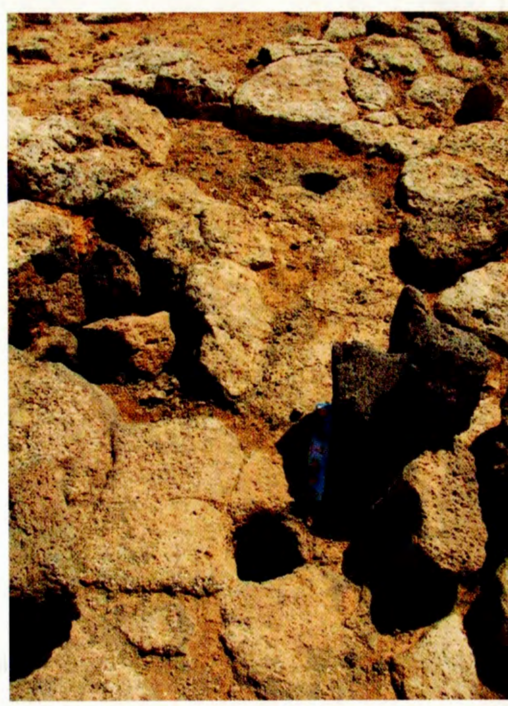

***Fig. 4:** Three of the artificial holes (A, E in the loose block and B; compare inset in Fig. 2) that are found in the immediate vicinity of the entrance of Hashemite University Cave (none occur further away). Their purpose is unclear (photo S. Kempe).*

Fig. 5: View into the narrow entrance, leading down through large breakdown blocks that represent the thick sheets of the cave's primary ceiling (photo S. Kempe).

At St. 19 one can go N to enter a wide and rather low hall, filled with sediment. This sediment appears to have been washed in from the entrance where today the loess has been totally been removed by erosion. To the N the continuation of the cave must be assumed. Treasure hunters dug a prominent pit into the sediment,

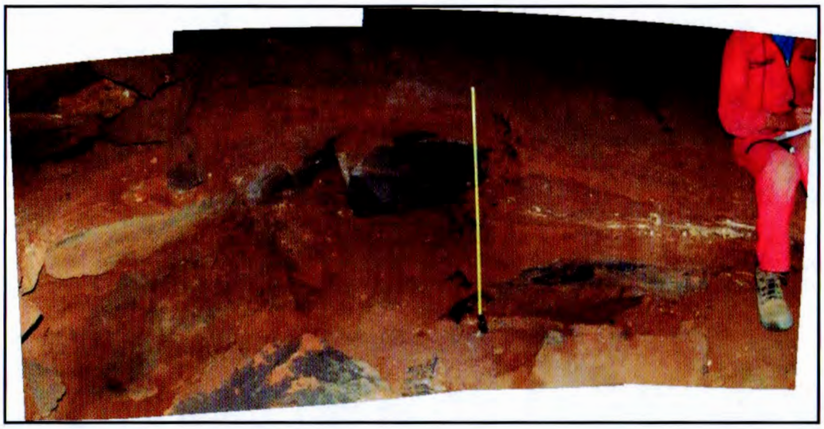

Fig. 6: Panorama view of the treasure hunter pit in the sediment hall. The breakdown of the entrance is partly buried in washed in loess. White strata mark fossil hyena coprolite layers (photo S. Kempe).

exposing several layers of re-deposited loess intercalated with white strata composed of disintegrated hyena coprolites (Fig. 6).

To the south, squeezing along a few breakdown blocks the main branch of the cave is reached. The floor is also covered with sediment and several pits witness to the activity of treasure hunters. Here coprolites and bones also testify to the presence of hyenas in the cave until recently. Hyenas dug several shallow depressions, typical dens that the hyenas used for resting and sleeping during daytime (Fig. 7). After about 25 m, the sediment cover ends and a flat floor is encountered, covered with small, irregular welded clinker (Fig. 8).

At St. 26 a fracture was found in the floor through which a strong air flow issued (Fig. 9). The tunnel is rather wide, but becomes very low at St. 28 (Fig. 10). Here we also find levees along the walls (Fig. 11). These were caused by a short-lived surge in the lava, temporarily increasing the lava flow, freezing out ridges along the already relatively cool wall. The appearance of the main passage is similar to Al-Fahda cave that is also wide and low.

Fig. 7: Hyena den dug into the washed-in loess at the beginning of the main passage (photo S. Kempe).

After St. 29, unexpectedly a 20 m wide and 25 m long hall is entered that allows standing up again (Fig. 12). The floor of it is composed of rough ropy pāhoehoe forming large flow lobes. At the end of the hall, floor and ceiling meet and the cave terminates. This situation is singular in Jordanian lava tunnels since all the others are terminated either by sediment or by breakdown (Al-Howa). The peculiar termination of Hashemite University Cave, generally called a "lava sump", is typical for lava tunnels that end at sea level (like the lower end of Kazumura). It is, however, also encountered at the end of Thurston Lava Tube in the Hawaiian Volcanoes National Park (Kempe & Henschel, 2008, 2009). In case of Thurston, it is suggested that the cave is an upper section of a more complex multi-level system. This may also be true for Hashemite University Cave. This hypothesis is further substantiated by the air-blowing crack at St. 26, suggesting that the floor of the cave is a secondary ceiling with an open, lower level below.

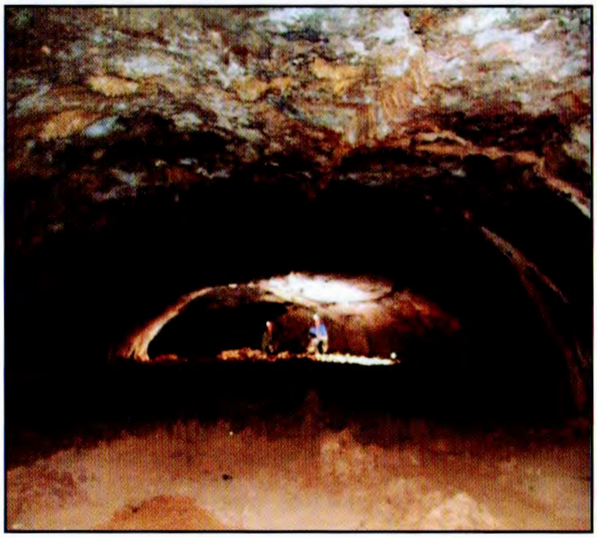

Fig. 8: View into the main passage SE showing a flat bottom covered with rough, welded clinker and a well rounded ceiling, partly showing lava stalactites (photo S. Kempe).

Fig. 9: Fracture in floor at St. 26 from which a strong airflow issues. To right and top two hyena coprolites and bone fragments are seen (foto S. Kempe).

Fig. 10: View into the main passage at St. 28, showing a well rounded ceiling and a flat floor. On the left wall the beginning of a levee is noticed (photo S. Kempe).

Fig. 11: Levee along the side of the main passage (photo S. Kempe).

Fig. 12: *Panorama of the terminal hall in Hashemite University Cave, view to the SE. Note welded blocks along the sides and person for scale (photo S. Kempe).*

Fig. 13: *Stalactites in the terminal hall of Hashemite University Cave (photo S. Kempe).*

In the terminal hall a variety of secondary flowstone is present, partly dissolving again (Fig. 13). Also the bones of a young hyena are found here (Fig. 14).

4. Conclusions

Hashemite University Cave, described in detail in this paper, is one of two lava tunnels (pyroducts, lava tubes) found as yet in the Quaternary flow field of the Qais/Makais Volcanoes. Its presence and the low slope of this lava field of <1° shows that the lavas were conduit-fed pāhoehoe. The lava field is the result of many individual flows that transported lava as far as 28 km below the volcanic vents.

Fig. 14: Bones and skull of a young hyena that died in the terminal hall (photo S. Kempe).

The presence of the many pressure ridge caves in the flow field shows that the lava must have had a specific characteristic, allowing thick primary sheets to be compressed laterally so that they could bulge upward to create low and wide cavities. The entrance of Hashemite University Cave shows that there three sheets have a total thickness of 7 m, i.e. the individual pāhoehoe sheets are relatively thick compared for example from caves in Hawai'i. This suggests that the eruptive temperatures were, for basaltic lavas, relatively low. Total erupted volume can be estimated by using the total flow areas of 164 km^2 and the depth of the Hashemite University Cave of 10 m, yielding a volume of 1.6 km^3. This is a conservative estimate since the thickness of the lava flow field may be thicker in many parts and a volume more than double is very well possible. Area and volume are comparable to the current (since 1983) lateral Kilauea eruption on Hawaii that has continuously produced (as of January 2007) 3.1 km^3 covering 117 km^2 (Pu'u 'Ō'ō entry Wikipedia). This comparison shows that the Qais/Makais Flow Field could have been produced within a few decades, even more so since its two known lava tunnels are comparable to the sizes of the transport tunnels of the that fed the Pu'u 'Ō'ō Flow Field (personal observation SK).

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Lava Caves, Types and Development

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Abstract

After limestone and gypsum, lava is the third most important cave-bearing rock. Apart from the standard notion that lava cave are simple, uninteresting and featureless circular "tubes", many different processes serve to create a score of various lava cave classes, with more being discovered from year to year. These include: (1) Longitudinal conduits that serve for long-distance, underground, post-eruptional transport of (with a few exceptions) basaltic lavas. They act to build low-slope (often <2°) shield volcanoes. First reported from Iceland, they were observed actively forming in Hawai'i and in 1842 named "pyroducts" (a term that should take precedence over the later - post 1940 - term "lava tube"). Within the pyroduct type at least for different formation modes exist: Pyroducts formed by inflation of the lava flow front and later downward erosion (1a), pyroducts formed by coalescence of small ducts and consecutive downward erosion (1b), pyroducts formed by the crusting-over of channels by jamming, floating lithoclasts and welding them together (1c), and by channels crusting-over by lateral shelf accretion and consecutive closure (1d). Pyroducts are the most numerous lava caves; the longest being Kazumura Cave (total length 65.5 km) (Hawai'i, Kilauea Volcano) and the longest duct-supported flow on Earth is the 160 km long Undara flow, Australian. In Jordan, the Al-Fahda flow could have pyroducts as long as 25 km. Another class is that of (2) pressure ridge caves. They form by up-doming of half-solidified lava sheets and are numerous in Jordan. Further classes include (3) volcanic vents, (4) the wide class of drainage features (5) lava sheet partings and (6) imprints of trees and animals. Secondary caves form also in lava, including (7) fissure caves, (8) pit craters and (9) erosional caves such as sea caves and caves formed by stream erosion such as Kuka'iau Cave, Hawai'i.

1. Introduction

Vulcanospeleology (a term coined by William R. Halliday) was, for a long time, mostly of local interest (e.g., in Australia, in the western US, on Tenerife, Sicily and Iceland). Lava caves did not play a role in general speleology textbooks and even in volcanological textbooks, the importance of "lava tubes" for the near-surface transport of lava and the morphology of shield volcanoes was not actually acknowledged. Very often only one image of a "lava tube" (often of Thurston Lava Tube, Hawai'i) would be shown followed by the explanation that they form by "crusting over of channels".

This state of the affair began to change when in the 1970's the tremendous cave potential of Hawai'i was understood, leading to the foundation of the Hawai'i Speleological Survey in 1989 (at the International Congress of Speleology in Budapest, Hungary) and the UIS International Commission of Vulcanospeleology in 1993. Today, the Vulcanospeleological Symposia, initiated by W.R. Halliday in 1972 (Halliday, 1976) and held every other year (#15th in Jordan, March 2012), attract speleologists and other scientists alike. The symposia proceedings are available at http://www.vulcanospeleology.org/symposia.html. A lava cave symposium was also conducted at the last International Congresses of Speleology in Kerrville, Texas, August 2009,with the proceedings accessible at: http://kong.lib.usf.edu:8881///exlibris/dtl/d3_1/apache_media/222325.pdf.

The Newsletters of the Hawaii Speleological Survey and the Hawaiian Grotto of the NSS are another source of information on the topic. A useful (US-focused) terminology of vulcanospeleology was compiled by Larson & Larson (1993).

Caves form in lava by a large variety of processes. Most are primary, but secondary caves form as well. Kant (or one of the editors of his work in 1803) was probably the first to suggest this partition, based, however, on inadequate data.

2. Primary Volcanic Rock Caves of Large Extent (Pyroducts)

Conduits that serve for lateral transport of lava within pāhoehoe lava flows are the most numerous group of primary caves. Within these ducts, heat is lost only conductively while surface lava loses heat convectively at its upper and conductively at its lower interface. Conduit transport is thus the reason why basaltic shield volcanoes evolve to feature flank-slopes of often less than 2° (compare Table 1) and why multiple eruptions can form extensive intracontinental lava plateaus. Individual "pāhoehoe flows" form low ridges topographically. They advance at their distal end being supplied with lava by the internal duct; uphill one can walk across an active tunnel without even knowing. "A'a flows" on the other hand form prominent ridges and advance like glaciers, sliding down-slope with their entire mass and moving like a caterpillar on a bed of rubble that falls down at the front and is overridden. On Hawaii a'a flows do not develop tunnels, but they seem do so on steep terrain, such as on Mount Aetna.

Eggert Olafsen (1774-75, § 358, p.130) was probably the first to describe a lava tunnel after having it inspected by himself. He visited Iceland 1752 to 1757 and noted about Surtshellir "*....the running lava flowed through this channel like a river...*". Uno von Troil (1779; p. 225), visiting the cave with Joseph Banks and Daniel Solander in 1772, wrote: "*The upper crust sometimes cools and solidifies, even though the molten* *matter keeps running underneath; ; in this way large caves form, the walls, floors and ceiling of which are composed of lava and where a lot of dripstones of lava occur*" (transl. from German by author). The first to report having seen an active tunnel was Coan (1844) in 1843 on Mauna Loa: "*But we soon had ocular demonstration of what was the state beneath us; for in passing along we came to an opening in the superincumbent stratum, of twenty yards long and ten wide, through which we looked, , and at the depth of fifty feet, we saw a vast tunnel or subterranean canal, lined with smooth 'vitrified matter, and forming the channel of a river of fire, which swept down the steep side of the mountain with amazing velocity. The sight of this covered aquaduct – or, if I may be allowed to coin a word, this pyroduct – tiled with mineral fusion, and flowing under our feet at the rate of twenty miles an hour, was truly startling.*" Thus Coan (even though also using "tunnel") coined a new and highly specific term: "pyroduct"; it should take precedence over younger terms describing the same phenomena.Early geologists like James Dana continued to use "tunnel"; J.W. Powell introduced "volcanic pipes" and Tom Jaggar used "tunnel" as well as "tube"; only after 1940 the term "lava tube" became standard (Lockwood, 2010). For reason of scientific priority, "pyroduct" should be given preference. Avoiding the word "tube" is also advisable, because it has invoked the picture of pipes in which lava can flow up and down under pressure like water in hoses and it implies a circular cross-section that is only rarely found.

The discovery of extensive lava flows on Venus, Moon, Mars and of active volcanism Io has spiked interest in terrestrial pyroducts lately. On Earth the longest surveyed lava tunnel is Kazumura Cave (main trunk length 41 km, total length >65 km) (Hawai'i, Kilauea Volcano) (Allred et al., 1997) and the longest Quaternary pyroduct-fed flow on Earth is that of Undara/Australia with a length of 160 km (Atkinson & Atkinson, 1995). In Jordan the Al-Fahda flow field is 25 km long containing at least one km long-pyroduct (Al-Malabeh et al., 2009). The author's group explored and surveyed many other caves on Hawai'i (e.g., Kempe, 2002) and in Jordan (Kempe et al., 2009) that give opportunity to study formation and evolution of pyroducts from the inside. Other areas of investigation are the islands of Galapagos, Rapanui, Jeju, Mauritius, Comores, Sicily, Iceland, Canaries, Azores, and the intracontinental lava fields of Syria, Saudi Arabia, East Africa, Western US, Mexico and Andes. Petrographically, almost all pyroducts documented (yet) occur in tholeiitic and alkali basalts, only the caves in the Mt Susua, Kenya, formed in phonolites (pers. com. C. Wood).

Formation of pyroducts:

Even though text books often describe pyroducts as having formed by "crusting over of channels" (e.g., Francis, 1993) we know of at least four different "recipes" to produce them (Fig. 1).

(1a) Most seem to form by "inflation" (Hon et al., 1994). At the distal end of pāhoehoe flows, hot lava rapidly covers the ground in a thin sheet. This sheet cools quickly, causing the dissolved gases to form vesicles diminishing the bulk density. This sheet will therefore float on top of the next pulse of advancing melt (the lava flow is "inflated" from below because of (buoyancy) before forming the next distal surface sheet. Multiple advances can occur, forming a primary roof composed of several sheets, separated by sheer interfaces (only the oldest or top sheet will display the subaerially formed typical ropy pāhoehoe structure) (Fig. 2).

Below the primary roof, the lava stays hot and keeps flowing. This is the initial conduit. Inflation caves are characterized by roofs build of one or several, sometimes more than ten, continuous sheets of lava. This structure can be studied at roof collapses, called "pukas" in Hawai'i. Many of the long Hawaiian caves are inflationary in origin (Kazumura, Keala, Huehue, Ainahou, Keauhou Trail; just to name a few).

(1b)A new way to form large pyroducts was discovered last year when we investigated Kahuenaha nui, a 1.8 km long cave within the SW-rift lavas of Mauna Loa (Bauer, 2011). Here lava oozing out from a stack of superimposed small p~hoehoe ducts pooled and excavated an underlying a'a flow. Erosion did not only remove the top rubble of the aa flow but also cut deeply into the underlying core, thus leaving a cave, with its main volume within the older a'a flow.

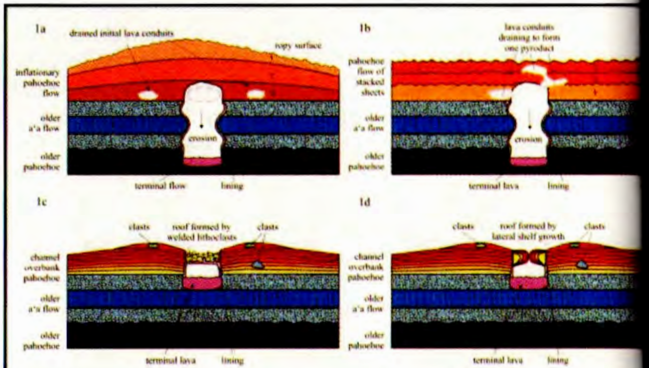

***Fig. 1**: Schematic cross-sections of the four as yet identified modi of pyroduct formation. The amount of erosion shown can be quite variable, even within the same pyroduct. Also, the underlying strata does not need to be an a'a flow necessarily. Cross-section 1a shows the inflationary mode where the roof sheets are oldest at the top and youngest at the bottom. There several ducts can develop in parallel that are drained once one of them cuts down, collecting all of the flowing lava into one bed. Cross-section 1b illustrates pyroduct formation by the collection of lava from several small conduits within lava sheets deposited on top of each other. Here the oldest lava sheet is at the bottom and the youngest on top. All flows converge and erode an underlying lava flow, preferentially an easily erodible layer of a'a rubble. Cases 1c and 1d illustrate the "crusting over of a channel". This can either happen by the jamming and welding of floating clasts (1c) or by the slow accretion of the side walls and closure across a channel along a central suture.*

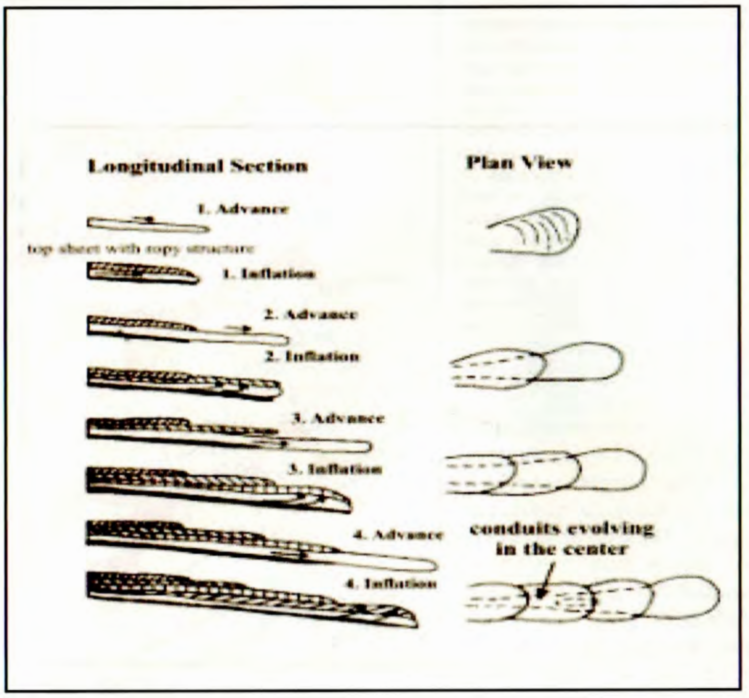

Fig. 2: Sketch illustrating pyroduct (lava tunnel) formation. At the tip of a pāhoehoe flow lava advances quickly in form of a delta of thin, ropy lava. The next pulse of lava lifts the first sheet up (inflation). This process is repeated until a stack of lava sheets (the primary roof) is formed, below which the hottest flow thread becomes the later main conduit.

(1c)The "crusting-over" of channels can also lead to long caves. Inspection of roof structure of the second longest cave on Hawai'i, the Kipuka Kanohina System (37 km of interconnected passages), has shown that it consists of welded, irregular fragments of pāhoehoe plates (clasts), stabilized by inserted lava fingers ("squeeze balls") and a lower 10 to 50 cm thick lining (Fig. 3), suggesting that the roof was formed by agglomeration of floating lithoclasts that are wedged into each other similar to a log-jam on a river.

(1d)Sometimes roofing-over may also occur by accretion of vertical to sub-vertical thin lava layers growing from the sides inward and having a central vertical parting where the growing lateral shelves meet. The levees of open-surfaced lava channels grow by overbank events of thin lava sheets or by stranded lava floats. Sometimes large sections of the bank break loose and float downstream. These can then jam and form short roofs that are stabilized by spatter. Examples have been documented for the channels of the Puhia Pele eruption of 1801 on the Hualalai.

Internal development: If the area to be covered by the first advance is rather flat, many small, parallel conduits can develop. Each of them can start to erode down soon after. One of the threads will, however, erode fastest and attract most of the molten lava. This passage will then drain the other parallel ducts, one by one, often leaving them as small-scale labyrinths high above the final floor. Since these mazes are drained when they are still very hot, their floors are mostly smoother than that of the later main tunnel where the terminal flow can convert to a'a rubble or intermediate phases (Fig. 4).

As the erosion continues, the lava flows with an open surface in a self-generated underground canyon cut into older rocks, not associated with the current eruption. This fact can be studied at places, where the thin lining of the side walls has fallen away (e.g., Greeley et al., 1998; Kempe, 2002). Often we find a'a blocks behind the lining or even ash horizons, both clearly not integral parts of pāhoehoe flows. Downcutting is facilitated by a variety of processes; one of the more spectacular is backcutting of lavafalls (e.g. Allred & Allred, 1997) (Fig. 5).

These are quite common in long Hawaiian caves, but none were yet found in Jordan. The falling lava acts like a sledge hammer, forcing loose rocks from the floor. These are less dense than the lava itself and float up and are transported on the surface of the river. Thus, unlike as in a water river, the bed is not protected by bedload and therefore prone to continued erosion. The mobilized blocks are cold and receive a coating of lava forming lavaballs that float downriver. Some of the lavafalls seem to be stationary forming large plunge-pools and chambers (Allred & Allred, 1997). Due to these erosive mechanisms the cave grows in depth and width in an uphill direction.

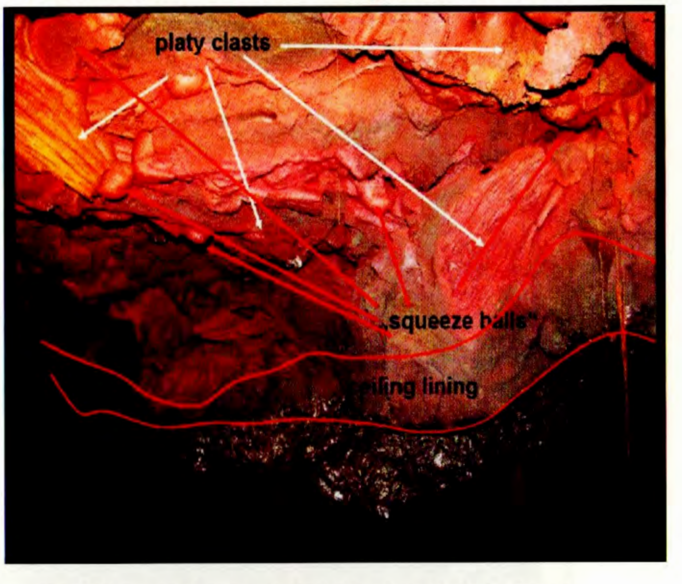

Fig. 3: Cave roof formed by interlocking lava clasts floating on the lava and stabilized by lava squeezed up into the interstices of the clasts ("squeeze-balls") and by a lining accreted from below (Kanohina Cave System, Hawai'i)

The passage above the lava falls is quite small in contrast. As one proceeds uphill, the canyon will become larger and larger until one enters the next plunge pool chamber. It is not quite understood how much mechanical erosion and how much melting of the river bed occurs (e.g. Greeley et al., 1998; and citations in Kempe, 2002). Other enlarging processes may occur, such as small phreatic explosions, blowing out sections of the wall or floor as intersected groundwater is vaporized.

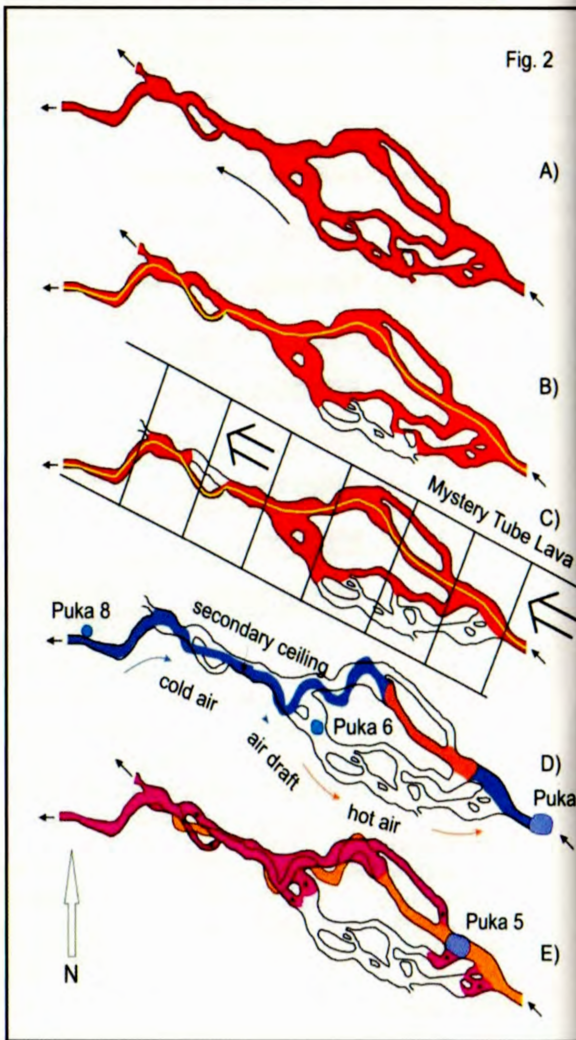

Fig. 4: Detail of the ground plan of the Huehue Cave illustrating how a primary maze of parallel lava threads (A) was drained until the master trunk that cut down fastest remained (E). (A) Initial pattern of lava tunnels, flow was from right to left in up to five parallel conduits. (B) The southern-most conduits were drained first. (C) Further downcutting reduced the number of active conduits to three. At the same time, lava from a parallel flow (Mystery flow) covered the area. (D) Only one tunnel remained (following the thick line in B and C), its bed 2 m below the original surface. The added overburden caused collapse of pukas (labeled 8, 6 and 4) the breakdown of which was removed by the lava river. Now external air began flowing uphill from Puka 8 to 4. As a consequence a secondary ceiling froze out up- and downhill of Puka 8. (E) Various spill-events reinforced the secondary roof, even spilling into the already drained upper conduits, closing the northern-most one. These spilled lavas were oxidized by the passing surface air and attained various shades of red caused by the crystallization of very fine-grained hematite. The last event was the collapse of Puka 5 while the tube cooled. Its material is still in place

As the downcutting continues the lava river meanders, undermining walls and destabilizing the roof. Breakdown falling into the flowing lava is also carried away. If the primary ceiling collapses entirely, a skylight or "puka" opens up. If the flow is still active, the rubble can be carried away and we speak of a "hot puka". If the collapse occurs after the flow terminated, breakdown will remain, sometimes giving easy access to the cave below, sometimes sealing it completely; this is termed a "cold puka". Through a "hot puka" gases can escape from the tunnel triggering convective cooling. Heat loss is specifically efficient if two pukas open up: cold air will be drawn into the lower one and hot gases will escape from the upper one, freezing out a "secondary ceiling" above the flowing lava in the canyon in between the pukas. Thus the passage is split into two levels on top of each other (Fig. 4).

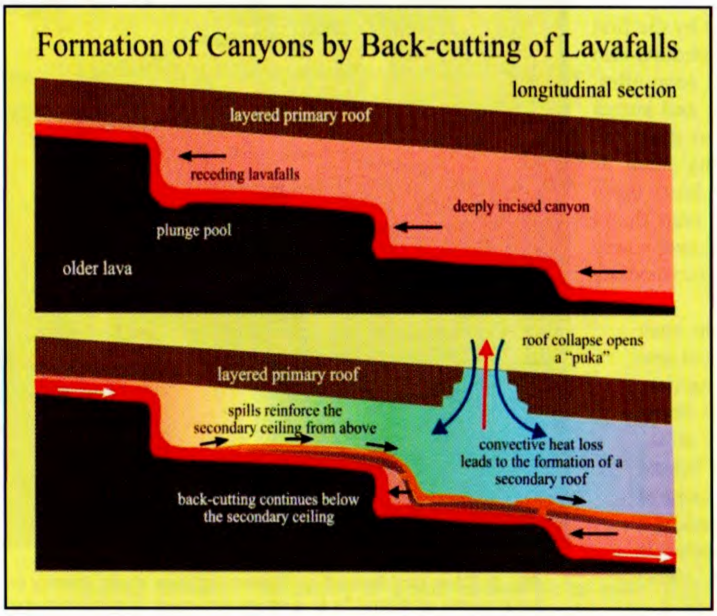

***Fig. 5**: Longitudinal section of an evolving lava tunnel. Top: Erosional enlargement of the underground canyon by backcutting lavafalls. Bottom: Upon static failure and partial collapse of the primary roof a skylight (puka) opens up, allowing cold air to enter the tunnel, freezing an internal secondary roof below which erosional enlargement can continue. Spills from uphill or through holes reinforce the secondary roof.*

This process can be repeated, forming even more internal ceilings. Later spills from below through breakdown holes or from spills upstream can reinforce these ceilings. In Ke'ala Cave, Hawai'i, one section of secondary ceiling is over 1 km long. Very often the upstream end of the secondary ceiling is sealed. This is caused by lavaballs floating on the lava river that are too buoyant to be dragged below the secondary ceiling. Instead they strand on the upper edge of the secondary ceiling. The accumulated blocks are then welded together by splashed-up lava. Floating blocks can be very large, in Waipouli Makai Cave there is a block about 12 m wide, 8 m long and 5 m thick welded into the ceiling of the cave.

The cold, oxygen containing external air that is drawn into the cave can oxidize lava surfaces that are still hot.
The iron, contained in the volcanic glass, is oxidized to fine-grained hematite, tinting the surfaces of secondary ceilings in various hues of red. If steam is present also goethite or limonite can be formed, introducing ocher or yellow colors.Hot pukas can also serve as temporary rootless vents when the tunnel below is obstructed or even closed entirely. Lava erupting from these pukas can form rapidly cooling, thin, ropy pāhoehoe, re-inforcing the primary roofs from above. The "Puka 17 Flow" out of the lower part of the Huehue tunnel (Fig. 6) is an example.
Pukas, cold or hot, can also serve as entrances for lava of later flows, such as at the upper and lower ends of Ke'ala Cave that are plugged by later invasive lava.
All these processes act to form caves of complex patterns, morphologically not representing "tubes" at all. Also the total length of the caves is usually much larger than the simple distance along the main tunnel. Table 1 gives some basic morphometric data, such as sinuosity and slope for some pyroducts.

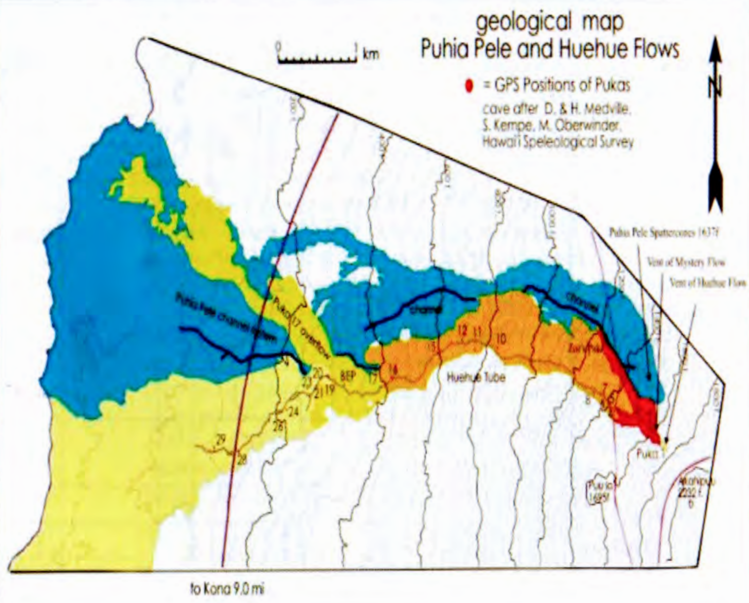

Fig. 6: Geological map of the Huehue flow (Hualalai Volcano, Hawai'i) of 1801 according to surveys of the author's group. Flow was from right to left, vertical distance 500 m. Oldest are the lavas (blue) of the Puhia Pele vent (a series of spectacular spatter cones) that was gas-rich and formed an open channel system (with a few roofed-over sections). After its termination the Huehue flow erupted (numbers label pukas on the Huehue Cave, thick line; lava light yellow-green at left and at Puka 1) accompanied by flow (brown). Zoe's Puka is a tunnel belonging to the Mystery flow. From Puka 17 a surface flow issued (light green) and the terminal lava from the mystery shield formed several short a'a flows (dark red-brown at the right). The Mystery Shield eruption that was active for only a short time (upper right) and covered much of the upper part of the Huehue.

General types of pyroducts: Overall, we can differentiate several general types of lava tunnels. These are: a) single-trunked systems, b) double (or multiple)-trunked systems and c) superimposed-trunked systems.
Most of the pyroducts yet documented in enough detail appear to belong to the **single-trunked** category. They are fed by one eruption vent and the meso-morphological internal structure can be explained by the processes discussed above. The tunnel size depends on the lava discharge rate and on the length of activity (days, weeks, months and possibly even years), i.e., on the time available for erosion. If the eruption stops or the cave collapses or is blocked, the pyroduct will cool. The next or even - in case of a blocked tunnel - the same eruption will then create a new pyroduct. Normally, it will be situated to either side of the previous flow ridge (flow lobe). Typical examples of single-trunked systems are Kazumura, Ainahou Ranch, Ke'ala and others of the long Hawaiian caves. If lava from the new tunnel should spill through a puka, or break (because of its overburden) into any older, underlying tunnel, then the older tunnel will be filled by lava cooling in the same pattern as at the surface.
Double-trunked systems involve two pyroducts, active side by side at the same time and fed by two separate eruption points. Such tunnels can interact and cause more complex morphologies than described above. One example is the interaction between the Huehue Flow and the secondary Mystery Flow (Fig. 6; Kempe, 2002). The Huehue flow established its tunnel first, then a second vent (the very inconspicuous, low "Mystery Shield") erupted lava, forming a small tunnel in parallel. Part of the Mystery lava quickly cooled forming a'a flows. These superseded the upper part of the Huehue tunnel. Once thick enough, the primary, sheeted roof of Huehue collapsed and left a roof composed of Mystery a'a lava. The resulting breakdown was removed by the still active Huehue lava river. Due to the large, hall-like cavity that formed, a secondary roof froze out over the active flow of Huehue. Later rockfall covering the newly formed "false floor" gives the upper passage the appearance as if the tunnel was formed in a'a, an impossibility near to a vent issuing very hot basaltic lava. The least understood and documented category is the **superimposed-trunked** system. It is defined as a set of lava tunnels superimposing and crossing each other, all being active at the same time. The upper tunnels stop their activity first, so that the lower ones carry on for some time before they also stop operating and become evacuated.

Table 1: Comparison of some morphological indices of some of the Hawaiian lava tunnels (for sources of data see Kempe, 2002). ML Mauna Loa).(K, A: Kilauea, Ai-la'au; H, HH Hualālai, Huehue flow of 1801; MK: Mauna Kea;*horizontal;** upper part of Huehue

Cave	Total length, km	Main trunk length, km	End-to-end bee-line, km	Sinuosity	Vertical distance m	Slope	Volcano
Kazumura Cave	65.50	41.86	32.1	1.30	1101.8	1.51°	K, A
Ke'ala Cave	8.60	7.07	5.59	1.25	186	1.51°	K, A
J. Martin/Pukalani System	6.26						K, A
Epperson's Cave	1.93	1.13	0.80	1.41	-	-	K, A
Thurston Lava Tube	0.490	0.490	432	1.13	20.1	2.4°	K, A
Ainahou Ranch System	7.11	4.82*	4.27	1.13	323	3.83°	K, A?
Ke'auhou Trail System	3.00	2.27	1.99	1.13	213.3	5.36°	K, A?
Charcoal System	1.5		1.4		60	2.6°	K
Earthquake System	0.34				33	4.7°	K
Huehue Tube	10.8	6.17	5.13	1.2	494.6	4.58°	H, HH
(Clague's Cave**	2.73	1.39	1.18	1.15	157.1	6.49°	H, HH)
Pa'auhau Civil Defense C.	1.00	0.58	0.50	1.14	49	4.87	MK
Whitney's Cave	0.651	0.509	0.438	1.15	17.3	1.97	ML
Manjang Gul, Jeju, Korea		4.304	3.197	1.32	32.4	0.4	Jeju

There may even be connecting openings between the levels exchanging lava between cross-overs. In such systems at least the lower ducts must have been filled to the ceiling until very late in their development. Such systems could arise when a volcanic vent increases its output volume during an ongoing eruption. Then the already established pyroducts cannot accommodate the increased flow volume and a new level of independently operating tunnels is built on top of the already active ones. The Kipuka Kanohina System on Hawai'i (Coons, 2009) is the largest example of such a superimposed-trunked system. Sistima Tlacotenco (16 km long), a segmented system of superimposed passages most probably also belongs to this category of conduits.

3. Primary Volcanic Rock Caves of Limited Extent

Other primary volcanic rock caves also occur in many different types: pressure ridge cavities, Hollow imprints of trees and animals, partings along the central plane of lava sheets, hollow tumuli, drained lava tongues, , volcanic vents and there may be more to be discovered.

a) Pressure ridge caves: This class of caves is much wider and longer than tumuli caves. In Jordan we know of ten caves of this type, all occurring in the lava field of the Qais/Makais eruption. The longest of these caves is Al-Ameed, with a total horizontal extent of 150 m. It actually consists of two low, 30 (now centrally collapsed) and 15 m wide chambers connected by a low passage. These caves are not related to tumuli nor do they show flow features suggestive of drainage. Rather they seem to be associated with low ridges that are thought to be created by the lateral compression of the upper lava layers, already solidified, caused by the general movement of the lower, still plastic layers, thereby pressed upward forming low, arched domes. On Hawai'i Eclipse Cave is of similar type, forming a 70 m long, up to 2.5 m high hall, perpendicular to the direction of the flow (Kempe et al., 2010).

b) Volcanic vents form pit-like or slanted caves, potentially very deep. However, solidified lava and wall collapse normally limit the accessible depth of such caves. Kaukako Crater on Molokai, probably over 350 m deep (100 m above and >250 m below water) is one of the deepest open vents on record. Its diameter narrows down to about 15 to 20 m, ca. 30 m below the water level. The lake is anaerobic below 4 m of depth and was dived by M. and S. Garman to a depth of 140 m, possibly one of the deepest cave dives in anoxic waters. Of similar depth is the Na-One pit on Hualalai, a vent explored to a depth of over 268 m. The current eruption on Kilauea, at the wall of the Halemaumau Crater, has opened up a 40 m wide and 160 m deep pit, at the bottom of which the top of the magma chamber is seen boiling and through which gases, clasts and ash are ejected. Many more vents exist on Hualalai and Kilauea that have not yet been explored due to the high risk of rock fall. On Iceland, the Þríhnúkagígur is 120 m deep (200 m total), funneling out to a width of 49*70 m below its orifice (pers. com. Stefánsson). On Terceira, Azores, the Algar do Carvão, a 90 m deep vent has been made accessible to the public. The vent leads into a large chamber hollowed out by convecting basalt magma in a body of trachyte. Into this class of caves we also must count caves in hollow dikes that have been reported from several places.

c) Hollow tumuli, peripheral lava rise caves and drained lobes: Tumulus is a morphological term describing a variety of hummocks or small hills rising above the general lava surface (Walker, 1991). Some appear to be pressed up by lateral forces; others may result from lava being injected from below under pressure, resulting in the extrusion of lava from the tumulus. A few of these tumuli are hollow forming dome-like cavities. Some of the largest occur in Kilauea Caldera in the Postal Rift flow of 1919 (e.g. Tumulus E1; Walker, 1991). Other caves follow the perimeter of larger lava rises (e.g., lava rise E5) that deflated in their centers once the lava drained from them. These can be rich in rock-speleothems, specifically cylindrical stalactites. Other caves in the same flow appear to be drained lava flow lobes and lava tongues. All in all about 250 mostly shallow caves have been recorded of various genetic origins in the 1919 caldera flow (pers. com. W.R. Halliday).

d) Partings: In the process of cooling, gas exsolves from the lava, forming small vesicles. The more time is available, the larger they become. Cooling is fastest from the surface downward and slower from the bottom of the sheet upward: therefore the largest vesicles are mostly found in the lower third of the sheet. Sometimes they become dense enough to cause a parting along which the upper section of the sheet can be separated and bent upward by lateral pressure. These caves are low, but can be quite wide; they are closed on all sides and only accessible if opened in a road cut or by erosion.

e) Imprints: One of the most astounding caves in any respect is the hollow imprint of a diceratherium in Miocene pillow lavas (Rhino Cave, US Quadrangle Park Lake, Grant Country, Washington, pers. com. C. Holler). Not only is it extremely rare that an animal gets encased in lava, even more unlikely is the fact that the cave is just now opened by erosion, so that it can be entered through "the rear". Imprints of trees are more common. A Mikado-like jumble of trees was encased in lava of Mount St. Helens and is now publicly accessible to the joy of kids that can easily crawl through the hollow imprints from one tree to the other. A large, accessible tree trunk is also encountered in Pa'auhau Civil Defense Cave on Mauna Kea, Hawaii (Kempe et al., 2003). Often tree trunks are still standing, encased with lava that cooled around. When the lava flow is subsiding around them they may be left standing, such as in "Lava Tree State Park", Hawaii, including an accessible pit-like imprint of the former tree.

4. Secondary Volcanic Rock Caves

Several kinds of secondary caves are known from volcanic rocks.

f) Tectonic fissure caves are a rare type; examples are Pit H (183 m deep) and Wood Valley Pit Crater (90 m deep) along the "Great Crack", the SW Rift zone of the Kilauea.

g) Pit craters form by the consecutive collapse of small magma chambers (large chambers produce calderas). An example is Devil's Hole (Hawaii National Park, Chain of Craters Road), beginning as a small hole in the apex of a ca. 50 m deep chamber that evolved into an open cylindrical pit over the decades. It is one of many pits in this section of Kilauea volcano. These pits are of interest mainly as analogues of the first cave-like sinkholes discovered on Mars and the Moon. Collapse of a hypogene karst cave and its gradual stooping upward formed a chamber in columnar basalt near Ortenberg, Germany, that was accidentally intercepted by quarrying. Uwaiyed Cave, a small breakdown-dominated chamber in basalt of the Naslet Al-Dhirwa volcano in Jordan may have formed in the same manner (Al-Malabeh & Kempe 2012).

h) Erosional volcanic rock caves can be excavated by coastal waves or by running water. Littoral caves may reach respectable sizes and are rather common, Fingal's Cave of the Island of Staffa, Scotland, being the most famous. The Na-Pali Coast of Kauai has several large caves as well. Wave erosion of basaltic dykes can lead to long, narrow caves such as the > 40 m long Sorte Gryde on Bornholm, Denmark. Many small caves are also produced along river courses that cut down into stacks of lava flows by preferentially removal of loose rubble from below the solid cores of a'a flows. Many such caves occur along the sides of Wadi Rajil in Jordan near the famous Bronze Age city of Jawa. Creeks intercepting primary lava caves can invade these, causing internal water erosion such as in Pa'auhau Civil Defense Cave on Mauna Kea, Hawaii (Kempe et al., 2003). There, waterfalls eroded the bottom of the cave, polished rocks and produced gravel, as if in a limestone cave. Kuka'iau Cave, Mauna Kea, is 1 km long and 100 m deep active stream cave eroded into a series of weathered pāhoehoe flows and diamict layers without following a preexisting primary cave (Kempe & Werner, 2003). It forms an up to now singular cave type, not only pirating the stream of a neighboring valley but also featuring sumps and chutes where the water moves upward, similar to the water flow in karstic caves under phreathic conditions. During peak flow the stream moves large amounts of water, gravel, rounded blocks and trees and may pond up to 60 m above its sump.

5. Conclusions

In spite of the tremendous progress made in lava cave exploration, we still are far from understanding all the features and processes that interact to form caves in volcanic rocks, specifically the large and extensive pyroduct systems. It is clear, that the concept of a "tube", simply piping lava downhill, is far too simple to explain the observed morphologies. Much more detailed studies are needed before a valid statistic can be made of the various cave types.

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Distribution, Sizes, Function and Heritage Importance of the Harrat Al Shaam Desert Kites: The Largest Prehistoric Stoneworks of Mankind?

by

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Abstract

The Harrat Al Shaam, the lava deserts of Jordan, features the largest concentration of desert kites so far analyzed (e.g., Kempe & Al-Malabeh, 2010a). Our Google Earth count runs to at least 530 such kites, while aerial photography counts yielded 1155 kites (Kennedy, 2011; Table 1). In Saudi Arabia we have counted 254 more and Kennedy (2011) counted 407 kites in Syria. Few kites occur also in Turkey, on the Sinai and in Usbekistan. This shows that the largest numbers of kites is concentrated in Jordan, forming a significant part of its prehistoric heritage.

Desert kites are km-long stone wall constructions, consisting of two or more widely gaping guiding walls that converge to an opening (gate) behind a small sill. Behind is a walled enclosure. In the early stages, these enclosures were bag-like, later clover-like and in the latest development, they attain a ha-sized, star-shaped shape. At the apexes of the inward curved enclosure walls, so called "blinds" were erected, 3 to 5 m wide stone circles. Some kites have well over a dozen of such circles. These circles were interpreted as "hides" for hunters to shoot gazelle. However, we argue that these were the actual traps. Once the gazelle had jumped into them, they could not jump out again lacking forward speed. More than 95% of the Jordanian kites open SE ward, arranged in eight chains extending N-S throughout the Harrat, thus effectively intercepting animal migration towards Syria and the Mediterranean Coast. In all probability, they were built in early Neolithic times to intercept gazelle (*G. subgutturosa*). We present statistical evaluation of two such chains: The Eastern Border Chain and the Usaykim-Safawi Chain. Both chains follow sections of the eastern Harrat border and are thus comparable in situation. Analysis shows that the kites of the Eastern Border Chain are significantly larger than those of the Usaykim-Safawi Chain, both concerning their guiding wall length as well as the sizes of their enclosures. However, the Usaykim-Safawi Chain has more of the older kite types (bag- and clover-shaped) and may therefore have been occupied first. The overall length of walls existing in this chain (including guiding walls, enclosure perimeters and the additional meander walls and meander section walls) amounts to 264 km. This allows estimating that the entire wall length exiting in the Harrat may be as much as 3780 km representing a stone volume half of that of the Cheops pyramid. Thus the Harrat Al-Sham desert kites are a most valuable and yet not well-known part of the heritage of Jordan. Many kites, however, have already been destroyed due to field clearing and bulldozing.

1. Introduction

Desert Kites is a term describing km-long stone wall patterns that occur throughout the Harrat Al-Shaam in Syria, Jordan and Saudi Arabia. A second area, where these structures are prominent is the Harrat Al-Khaybar another lava desert in Central Saudi Arabia. There we counted 207 kites already in an area of ca. 1000 km^2. Other areas, from which kites are known, are the Negev (Meshel, 2000; Bar-Oz et al., 2009), southern Turkey (Bar-Oz et al., 2011) and Usbekistan (e.g., Betts & Yagodin, 2000). The name "kite" derives from the similarity of the structure with a children's kite: long walls converge on an enclosure just like tails are attached on the lower side of a flying kite. They were discovered in 1925 by aircraft pilots (Maitland, 1927; Poidebard, 1928). In fact, the Harrat kites are the largest stoneworks of mankind erected up to their time and still among the largest on record, comparable with the Nasca lines in the Andes. An overview of previous publications, almost all of them appeared in Near-East archeological magazines, is given in Kempe & Al-Malabeh (2010a). The terminology describing the kites is not well developed because these structures have not attained wide-spread attention. Figure 1 gives a scheme of features as evident in most of the kites of the final development stage: Pairs or triplets of km-long straight or gently curving guiding walls with a km-wide gape converge to a low topographic sill, behind which a narrow opening ("gate", mostly 10 to 30 m wide) leads into a ha-sized enclosure. This enclosure is typically star-shaped with sets of inward curved walls converging at "blinds" or "hides" (Fig. 2). These blinds (named originally by archeologists who suggested that hunters would hide in them) consist of stone rings, 3 to 5 m in diameter. Sometimes these blinds are elongated with their long axis aligned with the enclosure perimeter. Most authors agree that these structures are traps for herds of gazelles, most likely *G. subgutturosa goitered gazelle*. The conventional view was that the herd would be driven into the enclosure and then hunters would shoot at the animals from inside the blinds. This interpretation is not taking into account the inward bending of the enclosure walls because it would be easier for hunters to shoot arrows or throw spears from the center of the curved walls, than from the

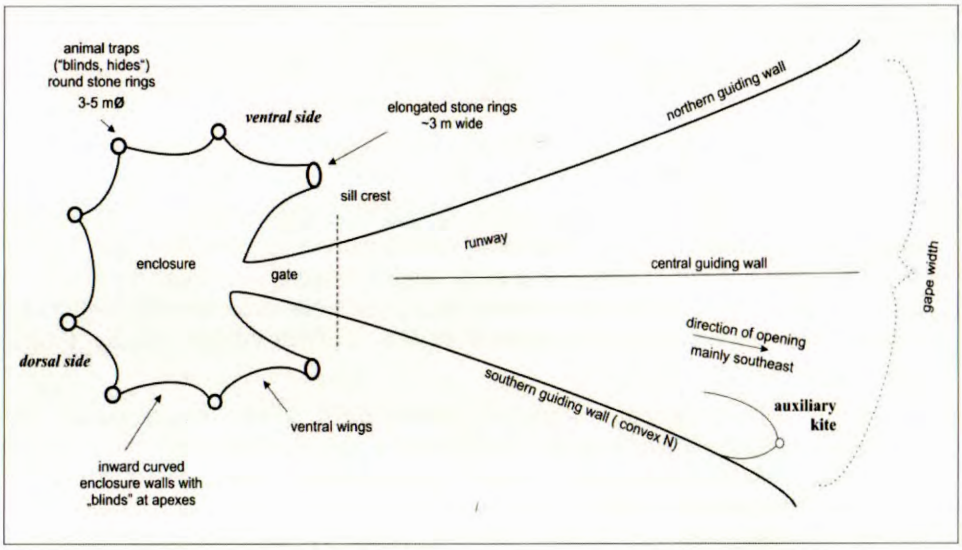

Fig. 1: *Scheme of the features of a late-generation Harrat desert kite. Note that the lengths of the guiding walls (they may be multiple) are not in proportion to the enclosure. The number of blinds can be larger or smaller and the shape of the enclosure can vary considerably due to terrain constrains. Auxiliary kites have been found on a few kites, they apparently served to trap any part of the herd that escaped the enclosure. Mostly these have only one blind.*

apexes, where the blinds are. Important for the usage of the kites is also the fact, that the blinds are always stone rings and not stone crescents that would be more appropriate to hide the hunters and give them easy access at the same time. Therefore, we offered another interpretation how the kites were operated (Kempe & Al-Malabeh, 2010): The herds, on their annual migration towards summer grazing grounds nearer to the Mediterranean coast, would enter the kites on their own, following the widely gaping guiding walls. Slowly they would converge on the sill, cross it and enter the enclosure behind. There they would face walls almost all around and even the gate way would look closed because of the sill behind.

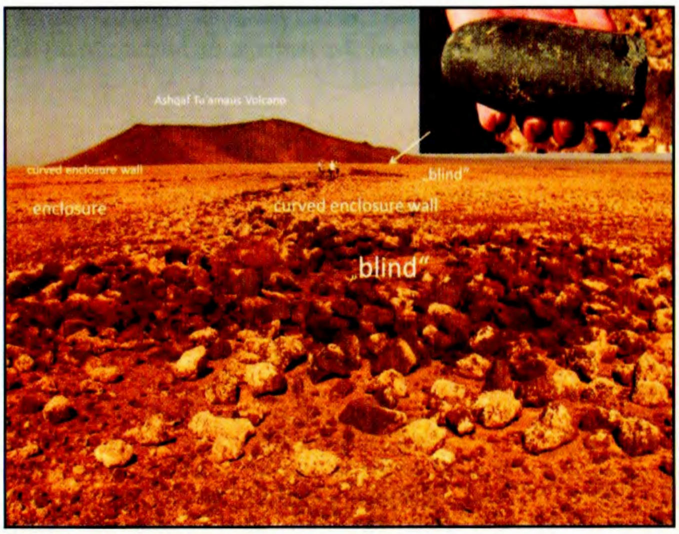

Fig. 2: *Northward view of part of the inward curved enclosure wall and two "blinds" of the isolated kite that is situated on the flat top of the "Kempe" shield volcano. The inset shows a broken club-like amphibolite artifact that was found in the blind where the persons are standing. The stone rings of the blinds appear to have had higher walls outward than inward to the enclosure, facilitating the gazelle to jump into the stone ring but not easily out of it.*

From the amount of rocks forming the now crumbled guiding and enclosure walls, one can estimate that the walls were about a meter high. In principle, gazelle should be able to jump them easily. If the trapped herd therefore converged towards an apex of the enclosure wall, the leading animals would have started to jump the wall, finding themselves in the stone ring of the blinds behind. Having lost speed and momentum and being hindered by others following them, some of them would be injured. The hunters would simply need to collect them after the bulk of the herd had escaped from the enclosure. Additionally, the hunters could send dogs into the enclosure through the gate, thus scaring the herd, dispersing them evenly into all of the blinds. The often elongated wings on the ventral side of the enclosure may in fact be useful in case that the herd is scared from the dorsal side of the enclosure, trying to escape backward. Here we find very often the elongated blinds, capable of trapping several dozen gazelles (Fig. 1, 3). That the blinds were not "hides" is also illustrated by blinds that were placed at a steep slope, for example at wadi shoulders, below the accompanying enclosure (such as seen on Kite 22 in the Usaykhim-Safawi Chain). From such a position shooting into the enclosure was impossible. Also, the single-pit traps excavated in the Negev (Bar-Oz et al., 2009), show that the blinds are actually traps. Calculation of energy needed to construct the kites (Kempe & Al-Malabeh, 2010a) shows that they must have been highly profitable in terms of caloric return. After the hunting period, kites were partly destroyed by houses and corrals build by later herders. Among them are "wheel" and "jelly fish" houses and other clearings, illustrating that the era of kite-hunting was largely discontinued.

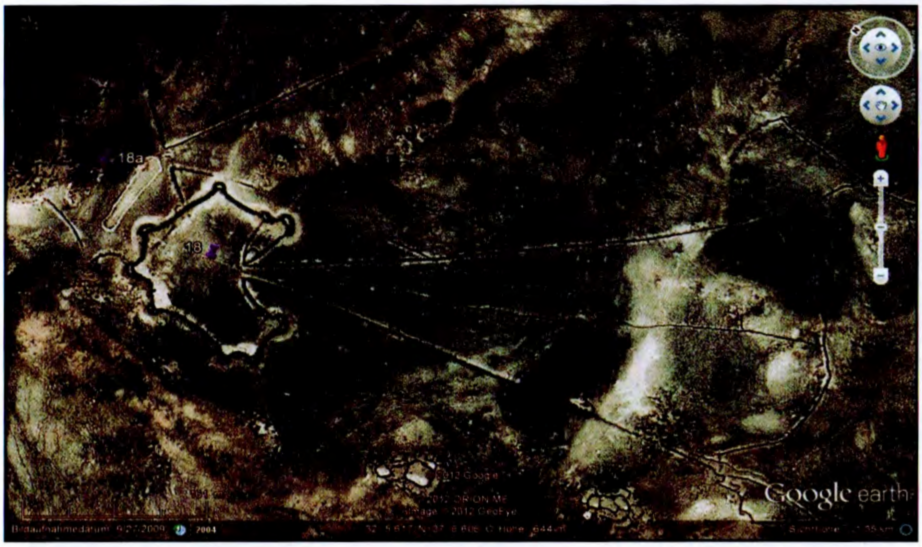

Fig. 3: Kite No 18 (32° 5.719'N - 37° 6.525'E) of the Usaykhim Castle - Safawi Chain. The kite has clearly elongated ventral wings with elongated blinds along their apexes. It is well preserved and was built according to a clear design. Later alterations include a wall cutting off the northern wing to create an animal pen. The kite is the second structure at this place, to the north the walls of an earlier, unfinished kite is visible. Building started with the curved enclosure walls and some guiding wall sections. This kite had a straight ventral wall, perpendicular to the gate way. This apparently represents an earlier design that was abandoned and replaced by the design with ventral wings. In the older kite there is also a "circular path" of unknown purpose. Note that NE is up

2. Methods

So far, kite research had to rely on field investigations, aerial photographs, or topographic maps. Betts (1998, c. fig. 10.10) evaluated the material available at the time, counting some 300 traps in the Jordanian Harrat. Now, GoogleEarth offers a new possibility to search for kites and to statistically evaluate them.

Within the high-resolution strips, most kite walls are visible as dark streaks and can be clearly differentiated from trails, truck ruts and bulldozer tracks.Not all of the Harrat is covered in this mode though, so that a final count of kites cannot be given as yet. So far we identified some 530 kites. Kennedy (2011) reports an even higher number, but it is not yet clear what his count contains, because the pouches of so called "meander walls" could be included in his count. In detail we evaluated a high-resolution strip along the eastern border of the Harrat (Kempe & Al-Malabeh, 2010a,b) first. Now we have additionally evaluated a strip of a similar geological situation, containing the kite chain between the Roman castle of Usaykhim and the southern end of the airport of Safawi. In both areas, the kites mark the eastern border of the Harrat, i.e. the gazelle herds would enter the lava fields after leaving the flint-covered Tertiary Hamad plains.

3. Kite Chains

Other than the kites in the Negev and also the kites in the Harrat Al Khaybar, the Jordanian desert kites are not distributed irregularly throughout the Harrat; rarely one encounters a kite that is not accompanied by adjacent neighbors. Some of those kites that are not part of a chain occupy specific positions. There is, for example, a small kite near the Roman castle of Burqu (32° 36.106'N 37° 57.383'E) because it (and the castle) was constructed on a small outlier of the basaltic Harrat. Also the kite on the Kempe-shield volcano is not part of a chain, because the terrain was so inviting, that a kite had to be built on the playa that occupies the flat volcano top (32° 17.299'N 37° 34.957'E). The majority of kites, however, appear to be members of chains (Fig. 4), these are directed N-S or NE-SW. Google Earth does not provide for high resolution Images for much of the Harrat. In some parts, only the most prominent star-shaped kites are therefore visible.

Furthermore, lichens cover the basalt blocks increasingly towards the west, thereby decreasing the contrast between rocks and the underlying loess, which makes it more and more difficult to follow the walls of the kites in the western portion of the Harrat than in eastern sections. In addition, bulldozing has destroyed a substantial part of the original surface, a process decreasing eastward. From west to east, there are three groups of chains, one in the west with at least three chains, one in the center of the Harrat with another set of three chains and one in the east with two chains. Kites occur also further south into Saudi Arabia and further north into Syria but they are not dealt with here.

1. The first chain is only 9 km long and has seven kites. Its southern end begins 14 km NW of Azraq (not shown on Fig. 4) (*W-Azraq Chain*).
2. The next chain consists of about 220 kites (light blue pins) that form several separate branches. It extends from Azraq all the way to the Syrian border north of Jawa (*Azraq-Jawa Chain*) extending for 66 km. It is the densest chain of the Harrat. Alone around Azraq it forms a crescent composed of 35 kites illustrating the former importance of the oasis for the Neolithic hunters. South of Azraq, on an isolated lava knoll there are remains of four smaller kites as well. From Azraq a chain of 33 kites leads northward, where several parallel branches with rest of the kites reach past the Bronze Age city of Jawa into Syria.

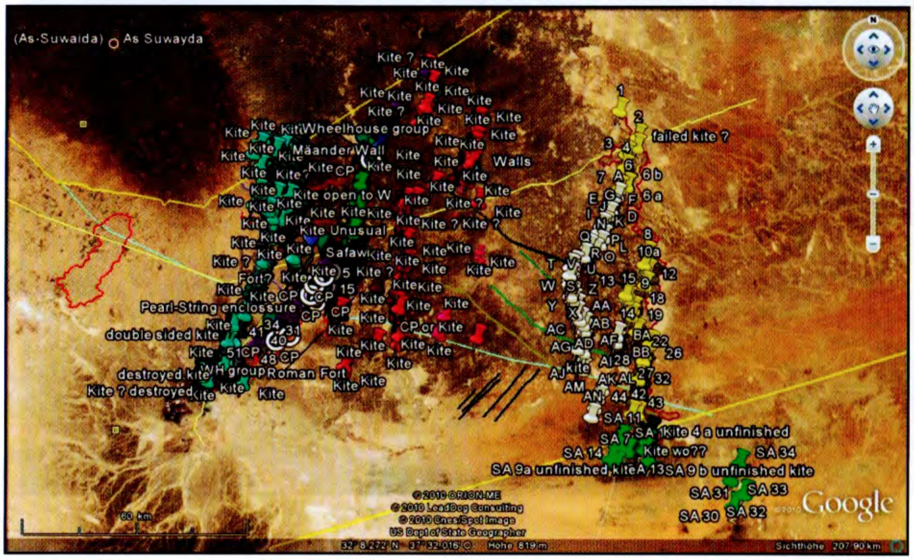

Fig. 4: Overview of kites identified on GoogleEarth images on the Jordanian Harrat. Not all of the kites already known are pinned on this image since at this scale, they overlap at most places. The alignment into chains is clearly visible.

3. The next chain extends from the Roman castle of Usaykhim to the southern end of the airfield at Safawi (dark blue pins) (*Usaykhim-Safawi Chain*). It is 31 km long, running NE-SW following the eastern border of the Harrat. It has some 50 kites of various ages and will be discussed below in more detail.

4. The next chain partly follows the eastern border of the Al-Fahda Flow field, the youngest lava field in Jordan (*Al-Fahda Chain*). It is 68 km long striking NNE-SSW and contains probably more than 90 kites. It extends from the southern border of the Harrat to the Syrian border (green, blue and red pins).

5. The next chain, striking NE-SW, is probably at least 91 km long (red pins), containing at least 55 kites and runs from the Quaa Mejalla at the southern border of the Harrat to the Hasad Volcano and beyond (*Mejalla–Hasad Chain*).

6. Due to the low resolution of the GoogleEarth images in this area this chain is only poorly visible, it is at least 21 km long containing less than 20 kites so far (magenta pins) (*Eastern Central Chain*).

7. After a 23 to 37 km wide gap, the next chain (yellow pins, white pins) extends for over 81 km N-S (*Interior Eastern Chain*). It begins at the Saudi Border and has at least 49 kites ending at the eastern border of the Harrat north of National Road 10. In the lower section a small separate chain of three kites is situated between this chain and the next one.

8. The eastern-most chain (yellow pins) follows the eastern border of the Harrat N-S for 54 km, 12 to 14 km from the Interior Eastern Chain and has 38 kites (Kempe & Al-Malabeh, 2010a,b) (*Eastern Border Chain*). It extends into Saudi Arabia (green pins) were it splits into two parallel chains containing an additional 10 and 4 kites.

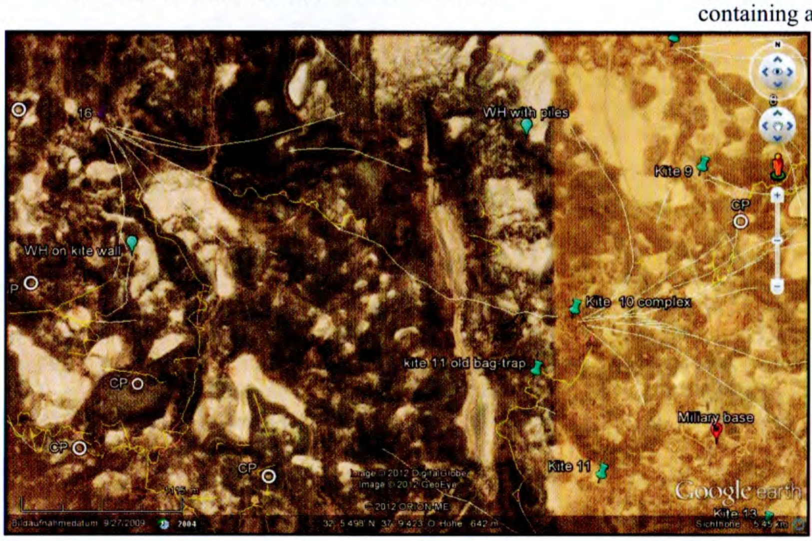

Fig. 5: Google Earth picture showing the 3.5 km connective wall between two kite chains, the Usaykhim-Safawi Chain Kite 16 (32° 6.090'N/37° 8.056'E) in the west and the a complex Al-Fahda Chain kite (32° 5.370'N 37°/10.142'E) in the east.

An interesting discovery is the fact, that the chains themselves are connected by extra-long guiding walls. The first of these walls discovered was a 10 km long wall that runs in between the Kite 40 of the Eastern Border Chain and the second most southern kite of the Eastern Interior Chain (from 31° 47.944'N/37° 54.269'E to 31° 48.288'N/38° 0.420'E). Likewise walls close the 3.5 km-wide gap between Kite 16 of the Usaykhim-Safawi Chain with a complex kite of the Al-Fahda Chain (32° 6.090'N/37° 8.056'E to 32° 5.370'N 37°/10.142'E; Fig. 5). Similarly the 8.5 km distance between a kite in the Azraq-Jawa Chain (32° 2.856'N/36° 56.479'E) and Kite 42 (31° 59.849'N/37° 0.556'E) of the Usaykhim-Safawi Chain is almost entirely closed by walls (Fig. 6).

4. Eastern Border Chain

Within the high resolution strip along the eastern border of the Harrat we recorded and evaluated statistically 44 kites, many more than previously known there (Kempe & Al-Malabeh, 2010a, b). Of these 33 star-shaped kites belong to the N-S oriented Eastern Border Chain. Their average distance amounts to 1.62±0.94 km, covering 42 km N-S (not including the kites in Saudi Arabia).

Northern, central and southern guiding walls average 1.81±1.29 km (N=33), 0.87±1.06 (N=23) and 1.95±1.35 km (N=33), respectively. The enclosures, all situated behind a low sill to hide them from view of approaching gazelle, are star-shaped and 1.82 ± 0.89 ha (from 4.27 to 0.23 ha) in size with circumferences of 633 ± 193 m (1056 to 228 m). Enclosures have up to 14 "blinds". The total length of all walls amounts to >150 km. Analysis of overlapping walls allows deducing a structural stratigraphy of trap construction in the area, beginning with meander walls, proceeded with bag-like traps and culminated with construction of the kite chain. Later some kites were decommissioned by extension of guiding walls of adjacent kites. This process was repeated twice and only 19 kites remained functioning from the original 36.

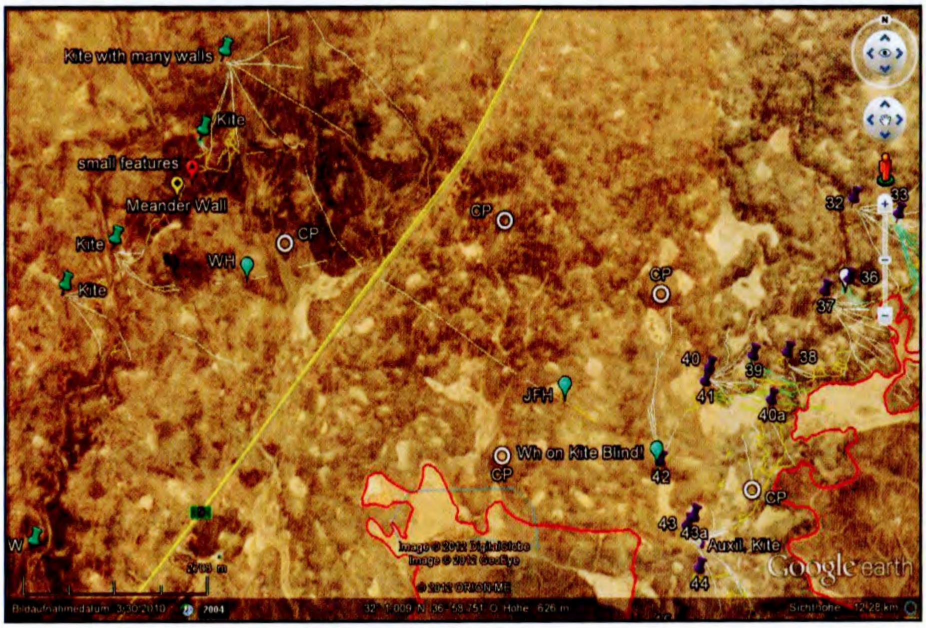

Fig. 6: Google Earth picture showing the 8.5 km long connective wall between two kite chains, the Azraq-Jawa Chain (kite at 31°59.849'N/37°0.556'E) in the west and the Usaykhim-Safawi Chain (Kite 42; 32°2.856'N/36° 56.479'E).

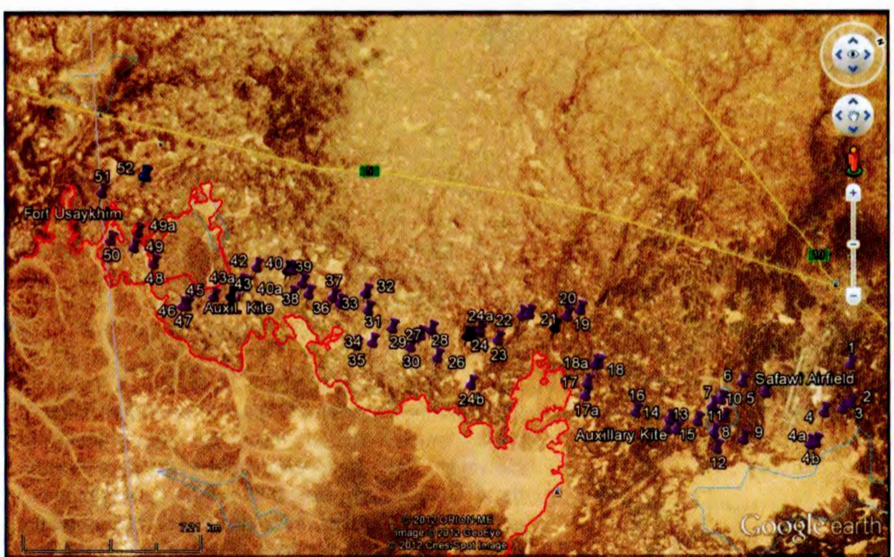

Fig.7: Overview of the locations of kites (blue pins) of the Usaykhim-Safawi Kite Chain on GoogleEarth. Note the airfield of Safawi to the right and its destruction of prehistoric sites in between Kite 4 and 5. The red line marks the eastern border of the Harrat with the Harrot to the right and the Hammad to the left. Yellow lines mark the National Highways 10 and 5. Blue line marks the trace of the former Trans-Arabian Pipeline. Note that north is to the right.

5. Usaykhim-Safawi Chain

Here we present for the first time the statistical evaluation of another kite chain that runs from north of the airfield of Safawi (Kite 1: 32° 10.789'N/ 37° 9.316'E) to Kite 51 (31° 57.434'N/ 36° 57.152'E), located 1.2 km north of the Roman Limes Arabica Castellum of Usaykhim (Fig. 7 to 9). In this chain 37 star-shape kites occur. 30 of these form the "front" line (1, 2, 3, 4, 5, 6, 7, 10, 13, 14, 15, 16, 17, 18, 20, 21, 23, 24, 27, 32, 37, 40, 42, 43, 45, 46, 48, 49, 50, 51) with an added distance of 40.5 km and an average distance of 1.40 ± 0.66 km between kites (min: 0.38, max: 3.0 km). Thus this chain is shorter and the kites are overall more densely spaced than in the Eastern Border Chain.

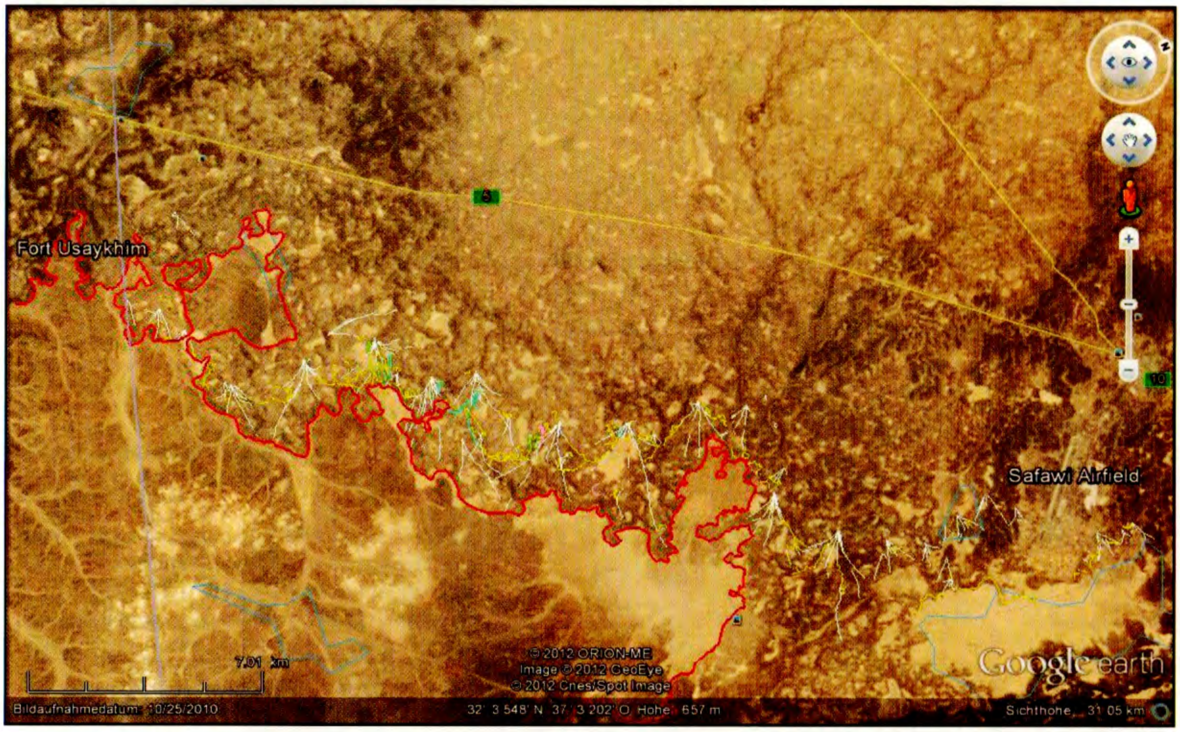

***Fig. 8**: Overview of the kite walls (guiding walls, white; meander walls yellow; older structure in blue and pink) of the Usaykhim-Safawi Kite Chain on GoogleEarth. Explantion as in Fig. 7.*

The overall lengths for guiding walls (marked in white in Figs. 7 and 8) are: North walls (N=36; no 5 partly destroyed by Safawi runway) 1020±843m (20 to 4050 m); central walls (N=26; kites 1,8,9,10,11,15,22,32,50,51 do not have central walls and no 5 is destroyed by the Safawi runway) 1038±855 m (75 to 3300 m), and south walls (N=36; in Kite 51 the southern wall is not visible) 892± 630 m (20 to 2840 m). North and south walls are therefore very much shorter than those of the Eastern Border Chain, while the central wall is longer and comparable to the length of the other walls. When calculating the total wall length we obtain (N=37) 3755±3208 m (40 to 10799 m) summing up to 138.9 km. The average gape width amounts to (N=34) 1143±816 m (117 to 3800 m) and the gate width (N=34) 16.8±6.1 m (7 to 37 m). The direction of the openings is (N=37) 110°±38°N (10° to 280°N).

Out of the 37 star-shaped kites, five (nos. 3, 4, 15, 35, 41) are destroyed to such an extent that their enclosures cannot be measured anymore. The remaining 32 kites have an average of 0.831±0.420 ha (0.094 to 1.64 ha) and an average perimeter of 430±143 m (138 to 652 m). Thus, these enclosures are significantly smaller than those of the Eastern Border Chain.

When calculating the measures only for the "front line" kites, then the numbers become: North walls (N=29) 1057±814m (232 to 4050 m); central walls (N= 24) 1070±875 m (75 to 3300 m), and south walls (N=29) 961± 642 m (54 to 2840 m). For the total wall length we obtain (N=30) 4190±3314 m (541 to 10799 m) summing up to 125.7 km. The average gape width becomes (N=28) 1226±824 m (300 to 3800 m) and the gate width (N=27) amounts to 16.8±5.9 m (7 to 37 m). The enclosure sizes (N=27) become 0.865±0.426 ha (0.147 to 1.63 ha) and the perimeter (N=27) becomes 442±143m (153 to 652 m). Thus the front line kites are somewhat larger than the kites not in front. The direction of the openings become (N=30) 106°±26°N (10° to 150°N), because the WWN-opening Kite 8 (which actually is only a small auxiliary kite to Kite 7) is influencing the mean of the measurement strongly.

The kite chain features not only the star-shaped kites, but a series of other, apparently older kite structures. These can be classified as bag-shaped (nos. 25a, 39, 40a, 43a, 47), clover-shaped (nos. 24b, 26, 28, 29, 31, 33, 34, 36, 38, 44, 52), or odd-shaped (nos. 25, 30). These represent 16.9, 3.57 and 1.82 km of walls, respectively. None of these have blinds. In addition, their guiding walls are much shorter and their gape width much smaller than the star-shaped kites. However, they have relatively wide gate ways. All these kites are older than the star-shaped kite generation; in places, the older walls were deliberately opened to allow the animals to pass through. Moreover, the chain also contains other wall types, best described as meander walls and meander cut-of walls. These amount to 75.5 and 3.9 km of walls, respectively, as compared with the 162.3 km of guiding walls of all types of kites. In addition, the perimeters of the kite enclosures sum up to 22.3 km of walls. This amounts to a total sum of 264 km of walls in the Usaykhim-Safawi Chain.

A riddle is still the purpose of the large number and length of "meander walls" (marked in yellow in Figs. 8 and 9). In the analysis of the Eastern Border Chain (Kempe & Al-Malabeh, 2010a, b) we suggested that they were older than the kites because they were transected by the kite guiding walls (Fig. 10 upper center). The meander walls appear in part to be distributed along the wadis and seem to have had the function to block easy exits out of the wadis (Fig. 10).

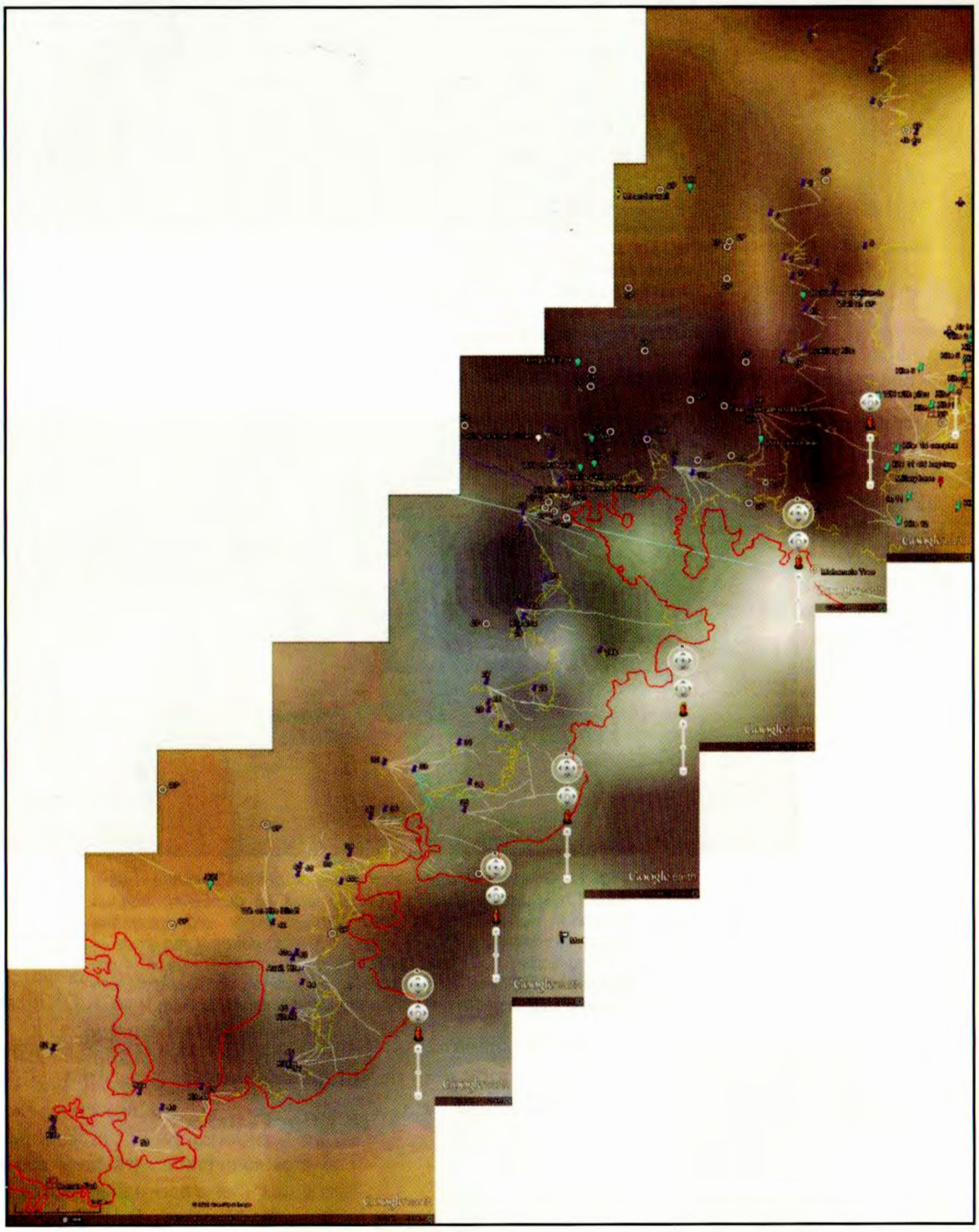

Fig. 9: Detailed view of all walls and features of the Usaykhim-Safawi Kite Chain. Guiding walls are marked in white, meander walls in yellow and walls of older kites in blue, pink and green. The figure gives also situation of a number of other archeological features: CP = circular paths, WH = wheel houses, JH jelly fish houses.

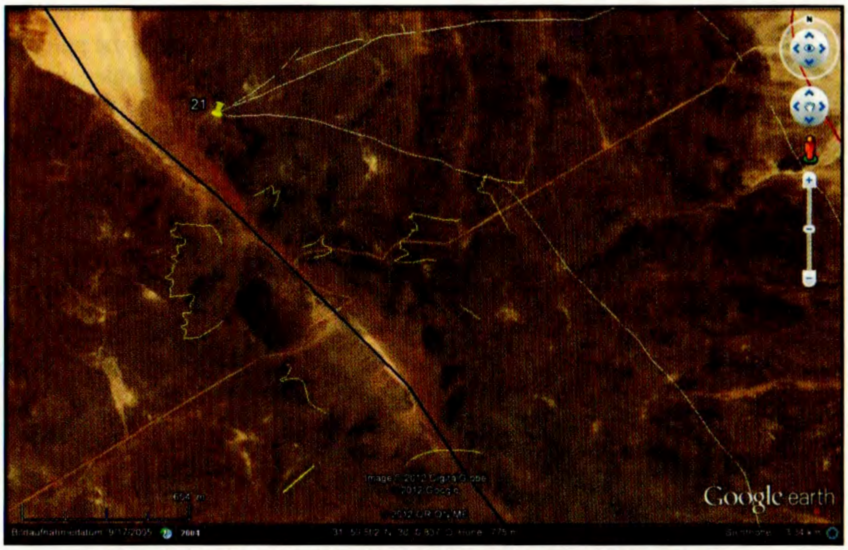

Fig. 10: Google Earth picture of a section of the Eastern Border Chain (yellow pin= Kite 21) showing the transgression of a kite wall across a meander wall and the placement of meander walls along easy excess out of the wadi. The black line marks a fault that gave rise to the wadi course

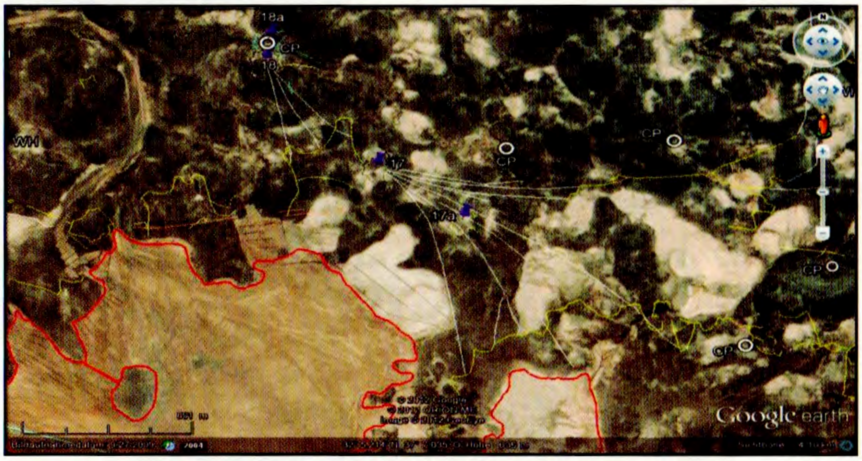

Fig. 11: Google Earth picture of a section of the Usaykhim-Safawi Kite Chain in the area of Kite 17 and 18 displaying various meander walls. Some of them appear to be older trap-like structures (center left), and others seem to connect the ends of guiding walls (upper right). Still others cut across the gape of the guiding walls (lower right) but close-up inspection on Google Earth suggest that they are older than the kite walls cutting them.

Typically, they have an open rectangular shape with the long side meandering back and forth. Possibly these "pouches" served to concentrate gazelle and forced them to jump the walls at a number of distinct places, causing their injury.

In case of the Usaykhim-Safawi chain, meander walls seem to display a different pattern. In the N (Fig. 9) there is a long section of wall following a playa border. Towards the south some of the walls seem to connect guiding walls of adjacent kites and therefore could be contemporary with the kites. However, there appear to be also older sections that display the rectangular pattern with wavy walls at their long sides (Fig. 11). Many of these meanders were later cut-off by straight walls, possibly in a trial to elongate guiding walls of the later kites.

6. Other Features

The most enigmatic structures found throughout the Harrat are "circular paths", alone 100 were found within the Eastern Boundary Chain, on average 43.3±17.7 m long and 31.7±13.7 m wide (N=103). Many were also located in the Usaykhim-Safawi Chain area (Fig. 9, marked "CP"). A particular clear one is found within the unfinished Kite 18a (Fig. 3). The paths seem to be very old features, since they are crossed by guiding walls in a few places. These circular, oval or dumbbell shaped courses are 1 to 1.5 m wide that double back on themselves. Nothing is found inside and the inner area is not cleared from stones. One can only speculate about their purposes.

Fig. 12: Google Earth picture of Kite 15 of the Usaykhim-Safawi Kite Chain where the enclosure was transformed into a "wheel house" encircled by a corona of small rock circle of unknown function.

Other features are the well-structured "wheel houses" (stone circles with radial walls like "spokes" inside), some accompanied by a ring of stone circles not unlike the blinds. That these "house" (more likely "kraals" of early herders) postdate the kites is clearly show by many of these that are built across guiding walls, or within the runways of the kites or inside the former enclosure. A good example is Kite 15 (Fig. 12) where the enclosure itself was transformed into a wheelhouse, thereby showing that the kite was of no service anymore. Less well structured "houses" are the "jelly fish houses" and other later structures.

All these structures form a rich heritage, unique worldwide, that is not only a challenge for further ground-based archaeological study but also urgently needs protection against further bulldozing and the spread of "civilization" into this area.

7. Conclusions

Our kite chain data show that the kites of the Usaykhim-Safawi Chain are significantly smaller on average and more closely spaced compared to the Eastern Border Chain. This may have to do with the fact that the herds, once they reached the west of the Harrat had already been diminished considerably by the more eastern kites and therefore smaller structures would suffice. Other interpretations are possible also, for example that the kites in the western chain are be older than those in the east. This conclusion could be substantiated by the fact that the western chain has many more older kites types (bag-, clover-, odd-shaped) than the eastern one that has actually only two (nos. 37, 42) kites that are different and smaller. Therefore, the eastern kites could have been planned on a larger scale, using the experience of the western chain that has seen more trial and error evolution.

In case of the Usaykhim-Safawi Chain for the first time, we have measured the total amount of walls present.

This sum is 264 km of walls. Considering that the chain contains about 37 kites of star-shaped design and that

most of the kites identified on GoogleEarth are star-shaped, then 530* 264/37 = 3780 km of walls could exist on the Jordanian Harrat. If the walls are 1 m high, 0.5 m wide, and having a porosity of 0.3, then the amount of stones moved is 3780000*1*0.5*0.7 = 1.32 10^6 m^3 of stones. This is half of the volume of the Cheops pyramid of 2.58 10^6 m^3 (Lehner, 1997). Thus the kites of the Harrat that, according to archeological evidence (reviewed in Kempe & Al-Malabeh, 2010a), date to the pre-pottery Neolithic, form the largest body of stone works of mankind up to that time. It is more than worth preserving and a yet hidden treasure of Jordan.

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The Volcano-Stratigraphy of Jabal Al-Shahba Cinder Cone, South Syria

by

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Abstract

The Tertiary-Quaternary basaltic lavas of southern Syria are divided into three separate volcanic phases, of Miocene, Pliocene and Quaternary age. These basalts are parts of the large intra-continental basaltic terrain of Harrat Al-Shaam, which covers an area of about 45,000 km2. and lies in NW-Arabian plate. Detailed field investigation shows that Jabal Al-Shahba is one of a large number of scoria and basaltic cones that are distributed in the Syrian parts of Harrat Al-Shaam. Jabal Al-Shahba volcano forms a single, relatively small hill of circular shape. It has a height of 50 m and covers an area of bout 3 sq. km. The flanks of the volcano have slopes of about 25-30^{o}, producing almost a symmetrical geometry.

The stratigraphy of the volcano is mainly composed of bedded scoria, fall lapilli that make up the volcano from the base upwards. The ejecta are dominated by angular to subangular clasts that are generally of less than 2.5 cm in diameter. This classifies Jabal Al-Shahba as a cinder cone.

Petrographically, the rocks of the studied volcano are dominated by scoriaceaous olivine- and plagioclase-phyric basalt. They have modal olivine (3-6 vol.%), plagioclase (4-8 vol.%), volcanic glass (35-40 vol.%) and vesicles (30-35 vol.%). The rocks are mostly fresh; however, slight alteration has been recorded in some samples.

The volcano appears to have resulted from multiple eruptions of one prolonged phase. Its volcanic activity consisted of a series of discrete explosion intervals. The time gap between each explosive interval producing the successions was relatively long as deduced from the existence of separation sections. The ejecta of Jabal Al-Shahaba are of Strombolian type of volcanicity. The small dispersal area and the height of the cone support this interpretation. The cone was originated by a magmatic mode of fragmentation.

1. Introduction

Harrat Al-Shaam plateau basalt covers an area of 45 000 km^2 and lies in the NW part of the Arabian plate. This plateau extends from Syria to Saudi Arabia through Jordan (Mouty et al., 1992). It is considered to be globally one of the largest alkali olivine basalt plateaus. The Syrian part of the plateau is locally known as Jabal Al-Arab basalts and occurs in the southern Syria. It covers an area of about 20,000 sq. km and extends from the southern rim of the Damascus Basin, which is marked by the folded mountain of the Antilebanon southwards to the Jordanian border. The basalt attains a thickness of about 1500 m and is of Neogene-Quaternary age (Mouty et al., 1992 and Otaki, M.198)

Large numbers of volcanic cones (scoriaceous and basaltic) with unlimited number of eruptive centers occur in the area and are distributed through the plateau. Jabal Shihan and Jabal Al-Shahba are the most outstanding volcanoes in this basaltic field. This study aims at a detailed investigation of Jabal Al-Shahba Volcano. The Volcano is located near Al-shahba Village which is lies about 15 km to the north of Al-Suweida (Fig. 1).
A trip around the volcano can be usaoll by newly established small tracks that meander to the summit of the volcano. The volcano has a height of about 65m and covers an area of about 3 km^2. An open pit mine (30m X 40 m) is located in the northern flank of the volcano.

Jabal Al-Shahba is exposed as a single, relatively moderate-lying hill of almost circular overall shape within a vast plain area. The flanks of the volcano have slopes of about 25-30^{o} in all directions, creating a nearly symmetrical conical geometry (Fig. 2). It is surrounded in the western and southwestern parts by several basaltic volcanoes forming a volcano group.

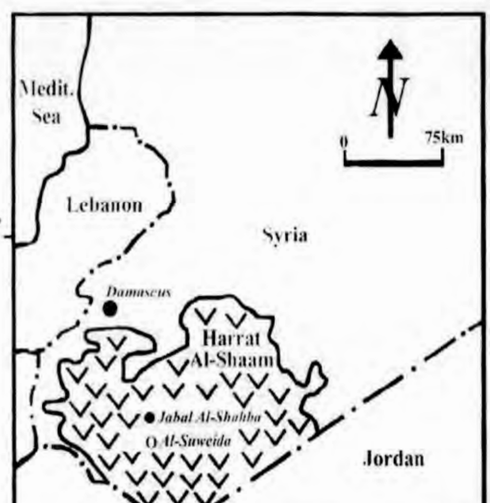


Fig. 1. Location map of Jabal Al-Shahba Volcano.

Volcanic succession of Jabal Al-Shahba

Jebal Al-Shahba is a medium-sized edifice. It represents one of the best developed scoria cones in the area. Stratigraphical investigations indicate that the volcano exhibits only limited vertical and horizontal variations. Thus, no subdivision into horizons was possible. The ejecta consists mainly of scoria fall, mostly of lapilli dominated by clast ranging in size between 2 and 4 cm and deposited as well-developed bedding. The layers have, in general, constant thickness with small lateral variation in all directions; they overlie each other gently without any post-eruption tectonics.

About 22 beds are counted within the succession with a total thickness of 18.9 m (Fig. 3). They are thick to very thick beds, the majority of which are well sorted. One badly sorted bed 200 cm occurs at the top of the succession. Grading is generally limited through the section. However, two beds show reverse grading and one exhibits normal grading. The ejecta are mostly black to grayish black in color and moderately vesiculated. The size of the clasts mainly ranges from 0.5 to 3 cm, but less than 2.5 cm is the dominant size.

The pyroclastics are mostly loose and friable with a limited degree of lithification and exhibit no welding or agglutination. They are almost fresh with limited alteration. Limited secondary minerals are recorded in the vesicles. No basaltic flows or dikes are observed. Moreover, xenoliths and accessory lithic fragments are totally absent.

Fig. 2: *General view of Jabal Al-Shahba Volcano, looking south, showing the northern part of the volcano. In front of the photo the open mine is exposed.*

Detailed stratigraphical description

The volcano-stratigraphy of Jabal Al-Shahb was studied by mapping and subdividing of the volcanic succession, determining the vertical and lateral facies changes, interpreting the types of eruptions, and looking at the origin and mode of fragmentation.

The beds drape gently over one another and are separated from one another by intervening soil layers, erosion surfaces and oxidation zones. Moreover, different types of beds were identified from one another by differences in: grain size, thickness, color, type of grading and relative stratigraphic position. From to base top, the succession consists of the following units (Fig. 3):

1-A well-sorted layer of 80 cm composed of lapilli with a grain size ranging between 2 and 5cm (hereafter 2-5 cm).

2- Four well-sorted beds of 20 cm (1-2 cm), 170 cm (2-5 cm), 30 cm (0.5-1cm), 40 cm (1-3 cm), respectively.

3- A multiple reversely graded bed. It has a thickness of 150 cm and a grain size range 2-5 cm.

4- A sequence of 3 well-sorted beds. The sequence starts with 170 cm thick bed of 1-4 cm, followed by 40 and 50cm thick beds with grain size (1-3 cm), (2-4 cm), respectively.

5- A normally graded bed, 80 cm thick. Normal grading is demonstrated by relatively coarse clasts (2-3 cm) finning upwards to fine lapilli 0.5-1 cm. The bombs included are general by about 15 cm in long diameter (Fig. 4).

6- A well-sorted, thick-bedded sequence consisting of four beds. The sequence is arranged in the following order: a well-sorted bed of lapilli (2-5 cm) with a thickness of 30 cm; it is followed by well-sorted, 80 cm thick bed, with clasts size ranging from 2-4 cm. The overlying bed is 110 cm thick, with well-sorted lapilli-sized clasts (2-5 cm). It is overlain by a well-sorted, lapilli-sized (2-4 cm) bed with 90 cm thickness (Fig. 5).

7- A reversely graded bed 80 cm thick, and a grain size ranging 0.7-1 cm coarsening upward to 2-4 cm.

8- A sequence of five well sorted beds as follows: 50 cm (2-4 cm), 30 cm (0.5-1cm), 130 cm (2-4 cm), 140 cm (2-6), 70 cm (2-3 cm), 50 cm (1-5 cm), respectively.

9- The topmost layer is markedly different and constits of a thickly bed of 2 m. The bed is of brown color and consists of 50% blocks and 50% of fine lapilli.

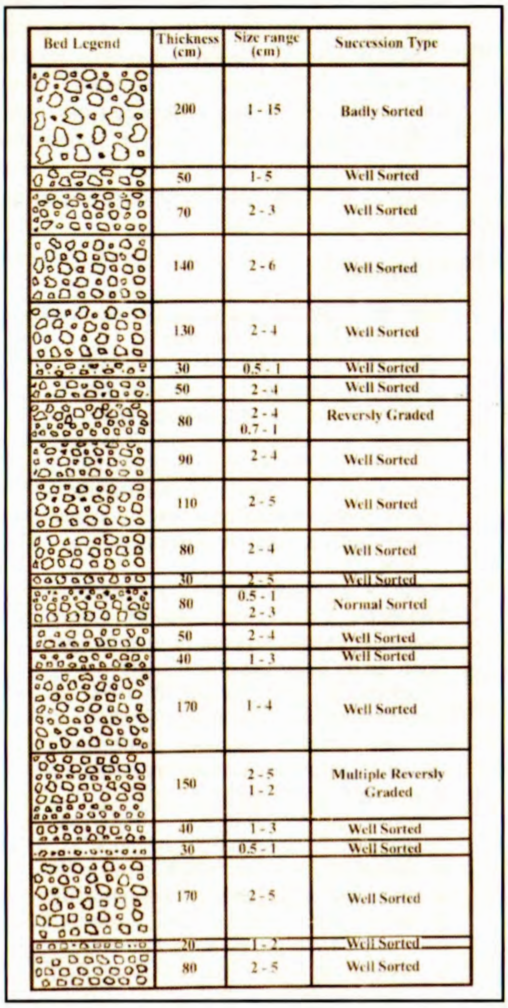
Petrography and Mineralogy

Petrographic and mineralogical analyses of the rocks of Jabal Al-Shahba has indicated that they consist of scoriaceous glassy olivine-plagioclase basalt. The constituents are olivine (3-6 vol.%) and plagioclase (4-8 vol.%), set in glassy groundmass (35-40 vol.%) and vesicles (30-35 vol.%).

The sideromelane (original glass) is fresh and has not undergone post-depositional alteration. They are light gray to black. However, the upper most bed is dark brown in color due to oxidation. The glass is vesiculated to different degrees, and serves as groundmass for the associated mineral phases. Palagonitization and other secondary minerals are not recorded.

The large number of vesicles indicated a huge volume of volatiles. Formation of the vesicles is the result of trapping of steam. This would require a gas phase trapped in a viscous, coating medium (Lorenz, 1970, Houghton; and Wilson,1989) The essential conditions governing this process are the dissolved gases and the relation of gas pressure in the bubbles to the strength of the liquid. When the total force exerted by entrapped gases exceeds the strength of the liquid fraction over the same cross-sectional area, the liquid will be torn apart as pyroclastic ejecta (Williams and McBirney, 1979).

Olivine is present both as phenocrysts and as groundmass ingredients forming seriate texture. The phenocrysts are up to 1.5 mm in length and have eu hedral to subhedral shape. They are mostly occurring in isolated crystals that are randomly oriented. The crystals are mostly fractured and resorption embayment is



Bed Legend	Thickness (cm)	Size range (cm)	Succession Type
	200	1 - 15	Badly Sorted
	50	1- 5	Well Sorted
	70	2 - 3	Well Sorted
	140	2 - 6	Well Sorted
	130	2 - 4	Well Sorted
	30	0.5 - 1	Well Sorted
	50	2 - 4	Well Sorted
	80	2 - 4 0.7 - 1	Reversly Graded
	90	2 - 4	Well Sorted
	110	2 - 5	Well Sorted
	80	2 - 4	Well Sorted
	30	2 - 5	Well Sorted
	80	0.5 - 1 2 - 3	Normal Sorted
	50	2 - 4	Well Sorted
	40	1 - 3	Well Sorted
	170	1 - 4	Well Sorted
	150	2 - 5 1 - 2	Multiple Reversly Graded
	40	1 - 3	Well Sorted
	30	0.5 - 1	Well Sorted
	170	2 - 5	Well Sorted
	20	1 - 2	Well Sorted
	80	2 - 5	Well Sorted

Fig. 3: *Columnar section through Jabal Al-Shahba Volcano, south Syria.*

very common. Iddingsite is restricted along the rims of crystals. Olivine groundmass occurs as small crystals and as needle-like forms.

Plagioclase also occurs in two generations as phenocrysts and in the groundmass. The phenocrysts are quite fresh and well developed, showing albite and Carlsbad twining. The extinction angle measured on several plagioclase phenocrysts, is between 30° - 34°, indicating a labradorite range in composition. The elongated, lath-shaped crystals of plagioclase measure up to 3 mm in length. They occasionally occur in glomeroporphyritic aggregates. Plagioclase groundmass is composed of microlites that exhibit pilotaxitic texture. They are partly altered to epidot.

Discussion and conclusions

The present study reveals that the Jabal Al-Shahba volcano was formed by consecutive eruptions, separated in time from each other and from a terminal pulse of volcanic activity that partially mantle them. The overall symmetrical geometry of the studied volcano indicates a magmatic source discharging through a simple conduit or "point source". The tephra–successions of the investigated cone consists of pyroclastic rocks, and scoriaceous ejecta. They posses features similar to those published on this type of ejecta (Walker, 1973, Blackburn, 1976, Heiken, 1978, Cas and Wright, 1987). About 95% of the rocks are made up of lapilli. The rest are blocks, dominantly around 10 cm in diameter; therefore the cone can be reasonably classified as a scoria cinder cone.

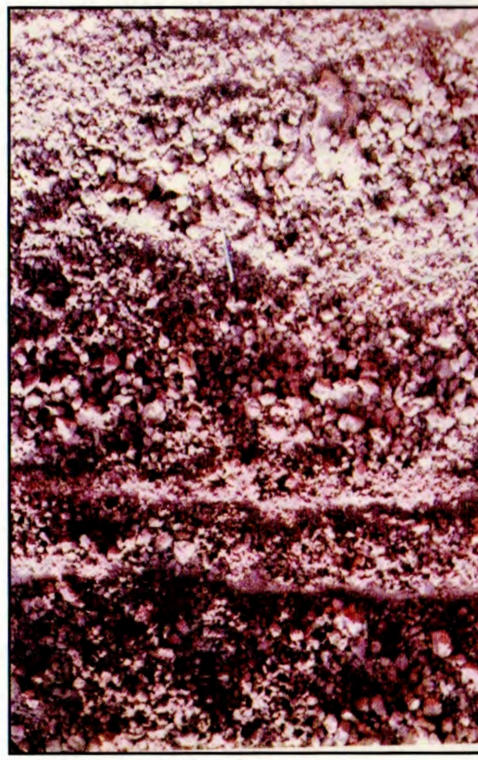


Fig. 4: *Field photograph, showing a sequence of well-sorted beds in the middle parts of Jabal Al-Shahba Volcano, south Syria*

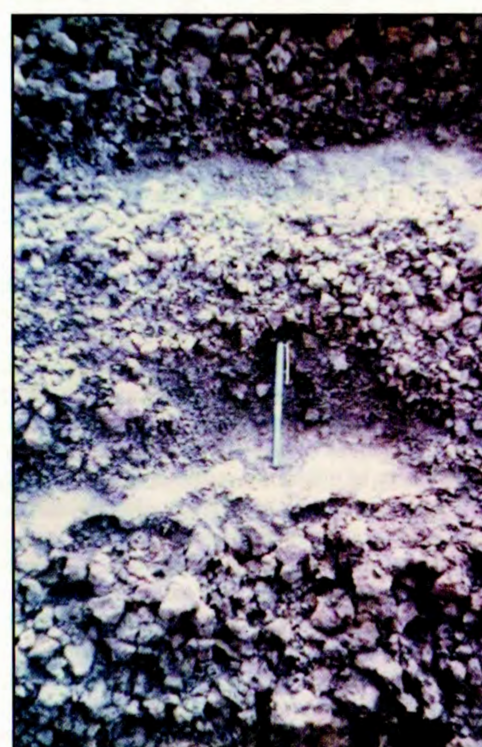


Fig. 5: *Field photograph, showing a well-sorted bed at the bottom topped by reversibly graded bed. Separation zone of mm thick is seen between the two beds*

The rocks of the volcano drape gently over one another. They consist mainly of well-bedded successions arranged in shower bedding and planar stratification. The parallel horizontal bedding shows that the volcano formed uniform blanket topography. The beds posses a uniform thickness; thus they may be described as "mantle bedding".

This study also shows that the volcano resulted from multiple eruptions and one prolonged eruptive phase, giving rise to dissimilar stratigraphic successions from the base upwards that nevertheless retain a comparable overall character.

The volcanicitiy occurred in pulses, that varied in pattern from eruption to eruption and that was not uniform within the individual eruptions. The time gap between each event was relatively long as deduced from the existence of a weathering surface, oxidation zones and other separations. However, the period of quiescence in volcanoes may repeat over time intervals as small as several days, or several weeks extending to several months or to two or more years (Fisher and Schmincke, 1984). The duration of each explosive interval was not identical, as is seen by the variation in the thickness of beds of the volcano. The occurrence of some ballistic clasts suggests more powerful explosions particularly in the last phase of history.

Concerning the genetic classification of Jabal Al-Shahba, the pyroclastics consist mainly of well-bedded successions arranged in planar stratification called "shower bedding". The bedding maintains a uniform thickness; thus it may described as "mantle bedding" (Cas and Wright, 1987). The pyroclasts are mainly scoria fall deposits and mostly angular to subangular and lapilli-sized. This would classify Jabal Al-Shahba as a "cinder cone" (Best, 1982) having a low content of "fines" (Walker, 1981). This was determined quantitatively, and reflects a low degree of fragmentation. The petrography showed that the ejecta mostly have a low crystal content (<10%), in keeping with a low degree of fragmentation. The latter "characterises sustained eruptions of fluids and Newtonian magma taking place from an open vent", having "free access to the surface" (Walker, 1981). Thus a magmatic type of eruption is proposed for Jabal Al-Shahba based on its lapilli-sized, vesiculated basic ejecta (Cas and Wright, 1987). The involvement of water in the explosive activity is unlikely here as phreatomagmatic eruptions are characterized by a high degree of fragmentation (Walker, 1981). The limited occurrence of ash is consistent with this result. The Strombolian style of eruption and the low degree of fragmentation as well as the low crystal content of the ejecta make an argument for this mode of formation (Zimanowski et al., 1997 and Buettner et al., 1999).

An elementary objective of this study is to classify the eruptive type of the investigated cone. The ejecta of Jabal Al-Shahaba are similar in most respects, to those of active volcanoes with Strombolian activity such as Stromboli in Italy and Heimaey in Iceland (Self et al., 1974 and Houghtoz and Hackett 1984). The suggested type of volcanicity is supported by several criteria; such as the low dispersal area (the actual area over which a pyroclastic deposits is dispersed) which is approximately 3km2. This low dispersal area hints at low height of the eruption column. The Strombolian eruption column is lower than 10 km (Wright, 1980, Wood,1980, Houghton and Schmincke, 1989). Additional features that support this type of eruption are the low degree of fragmentation, dominated by lapilli (average 2.5 cm). The black color of the ejecta may indicate that they did not suffer from extensive oxidation. However, the brown color of the upper most bed may reflect that it suffered from oxidation. However, strombolian pyroclastics are peculiar by the oxidation of steam which produces a bright red coloration (Walker and Croasdale, 1972).

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Characterization of Lava Caves, Using 2D Induced Polarization Imaging, Umm Al Quttein area, NE Jordan

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Abstract

The possibility to detect lava caves in the basaltic flows in the shallow subsurface using Induced Polarization (IP) imaging survey was a significant subject in recent years. The application of this method to caves in the large intra-continental volcanic field of the Harrat Al- Shaam, NE Jordan are reported. The Harrat is composed of a series of basaltic flows that stretch for many kilometers below their eruptive vents. Such long flows are possible only because lava tends to build long tunnels in which the lava is thermally isolated, thus preventing its early solidification.

The IP imaging technique is very sensitive to horizontal changes in the resistivity method and is an excellent tool to map vertical structures such as cavities or intrusive dikes. This technique was used in the Umm El-Quttein area to investigate the subsurface and test if we can image existing caves and if these might be a potential hazard of the roads in the area. The IP measurements were made with the time-domain method and processed by using the least square inversion approach that will automatically determine true 2D resistivity models. The quantitative interpretation obtained from 2D inversion modeling indicates that the lava caves produce anomalies characterized by a high resistivity at around 3010 Ohm-m with a depth of less than 19 m, and very intense anomalies; likely ascribable to open fractures. These may be filled with clay or carbonate sediments, that decrease the apparent resistivity values but increase the chargeability (*M*) and metal factor (*MF*). This technique therefore was successful in detecting lava caves within the complex structures of the Jabal Quis volcano. Furthermore processing is possible within a few hours.

Key words: Lava caves, archaeological importance, 2-D induced polarization imaging, time-domain, potential hazard environment, NE Jordan.

1. Introduction

The Harrat Al-Shaam lies in the northwest of the Arabian plateau and is composed of large fields of predominantly alkali olivine basaltic lava (Fig.1). The lava covers an area of 45,000 km² and stretches over 700 km NW-SE, from Syria through Jordan to Saudi Arabia (Coleman et al., 1983). The Jordanian part of the plateau is geomorphological known as Harrat El-Jabban with an area of about 11,400 km², it is estimated that the lava is less than 150 m thick (Osaka, 1989; Bender, 1974; Khalil, 1991; Al-Malabeh, 1994; and Shaw et al., 2003). The basalt plateau forms a very irregular landscape, difficult to access. Fissure eruptions produced vesicular pahoehoe and "aa" lava flows, isolated volcanoes, and pressure ridges (Bender, 1975; Guba and Mustafa, 1988; and Wallace at el., 1994). Eruption of these volcanic fields started in the Oligocene, the youngest are about 400 000 years old (Tarawaneh et al., 2002).

The volcanic and tectonic evolution of the Arabian Harrats was poorly understood. The lava flows is a key to understand the magma supply which transport for improving real time lava flow hazard assessment.

The volcanic lava fields of Harrat Ash Shaam comprises of sub-horizontal lava flows less than 25 m thick; several of scoria cones, extensional faults, and large fissure eruptions in strike NW-SE and N-S directions that emanated from dike systems, forming elongated ridges (Bender, 1974; Barazangi, 1983; and Guba and Mustafa, 1988; Al Malabeh 1994). The source of alkali basalts and basanites from Harrat Ash Shaam are melts of deep, garnet-bearing asthenosphere magmas, mixed with lithosphere mantle melts of Miocene to Pleistocene age (Shaw et al., 2003).

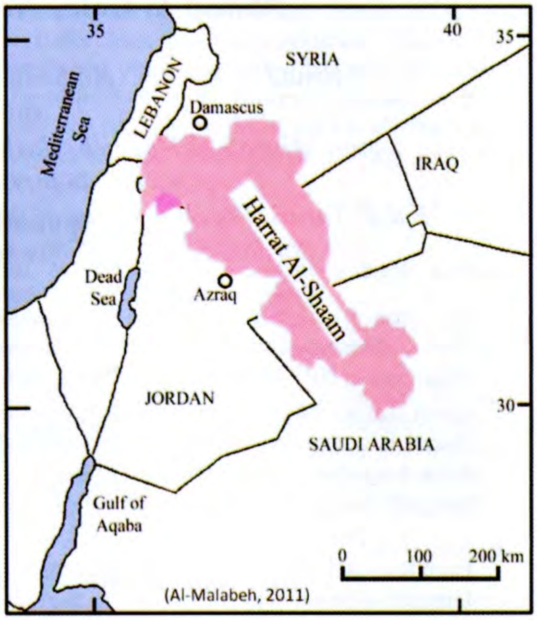
Generally lava tunnels (originally termed pyroducts; Coan, 1844) developed in low viscosity lavas with constant and low to moderate flow volumes (i.e., Peterson et al., 1994). They allow the lava to cover the topography at low slopes, typically of less than 2° (i.e., Kempe, 2002). Investigation of tunnels both inactive and active on Hawaii shows that these tunnels form in the majority by progressive advancement and inflation of sheets flow at the front of pahoehoe flows (i.e, Kempe, 2002; Kauahikaua et al., 1998). Less common is the formation by crusting over of lava cannels, a process mostly cited in textbooks on vulcanology (i.e., Ollier and Brown, 1965; Greeley, 1971; Calvari and Pinkerton, 1998). Apart from lava tunnels (often called lava tubes, a term that incorrectly assumes lava flow through a tube system upper pressure, while the lava in tunnels flows with an oven surface like a river in an underground canyon) other processes can also form caves, such as the deformation of half solidified lava sheets resulting in non-continuous pressure ridge caves. The study area contains both remnants of lava tunnels and pressure ridge caves in lavas formations of Umm El-Quttein, El-Mukeifteh, Al-Bishriyya, Al-Hamidiyya, and Asfar (Al-Malabeh, 2005; Kempe et al., 2008).

The first cave in the area was found by A. Al-Malabeh in 1985. In the visicinty of of Umm El-Quttein many sinkhole occur, possibly collapse feature above underlying lava tunnels . Such holes are also noticed near some of the ruins in the northern Badia, among them the Umm El-Jimal area, the largest of these ruined cites of the southern Hauran (fields observations of Al-Malabeh). The archaeological sites date back to Nabataean times as shown by inscriptions found in the ruins (Dussaud, 1907; Butler, 1907).
One of these mentions the name of the Nabataean King Rabbel, dated to the year 93 A.D. (Butler, 1907, 1920). The sites have then been occupied continuously in Roman and Byzantine times. It is a hypothesis that these old settlements are related to the lava caves that served as dwelling caves and as water resources.
The area currently is under speleological exploration and many caves have already been documented in this northwestern section of the Harrat El-Jabban (Kempe and Al-Malabeh, 2005; Kempe at al., 2006; Kempe et al., 2008). Furthermore Al-Oufi (Al-Oufi et al., 2008), used the VLF-EM technique to study the subsurface for the occurrence of lava tubes, faults and dikes and geoelectrical and seismic refraction methods have been used to study the location of a proposed dam in the volcanic lava fields (Batayneh et al., 2001).
Also the seismic activity at the locations of the ancient cities of Jordan (Al-Tarazi, 2003) was looked at. These investigation studies were gives results in more accurate definition and clearly interpretations on the lava caves of archaeological importance in northeast part of Jordan. In present study, 2D of Induced Polarization (IP) imaging survey using time-domain method was performed in Umm El-Qutein cave successions (Fig.1) based on principles electrical properties of the basalts; to determine characterize edges end of the lava caves, and to an evaluate their extent that are formed the potential hazard environment of road Umm El-Quttein.

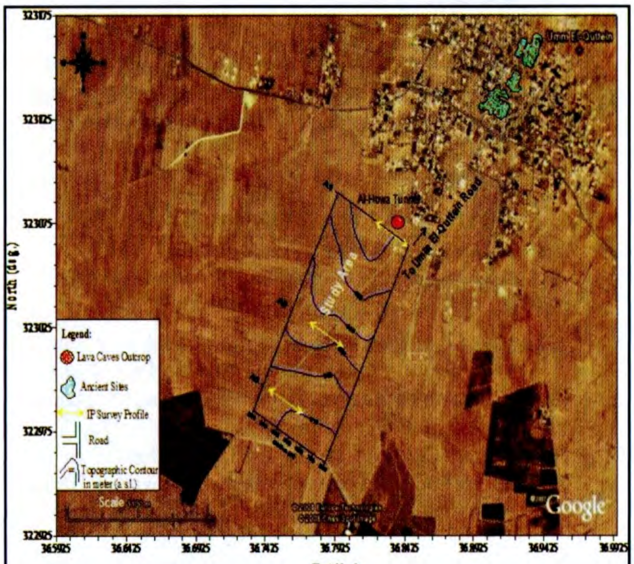
This technique is increasing use in the engineering and environmental studies, an especially in detect of the vertical structures such as cavities and dikes (Ward et al., 1995; Loke, 2001).

Engineering and environmental examples of the successful use of IP surveys include the detection of clay minerals (Iliceto et al., 1982; Vinegar and Waxman, 1984), the detection of inorganic and organic contaminations (Cahyna et al., 1990; Ruhlow et al., 1999; Olhoeft, 1985, 1992; Vanhala et al., 1992), permeability evaluation (Sturrock et al., 1999), and the detection of underground mine voids or tunnels (Sheets, 2002).

However, The IP techniques were development of the mineral exploration such as, mineralization of copper or gold mineralized (Telford et al., 1990). The IP parameters include the time-domain chargeability (*M*), normalized chargeability (*Mn*), percentage frequency effect (*PFE*), and the metal factor (*MF*). These parameters were developed as measured of instruments limitations and the way of the IP effect (Edwards, 1977; Ward et al., 1995).



(A)



(B)

Fig.1: *a) Location of the study area and distribution of Harrat Al-Shaam (Al-Malabeh, 2011) b) shows landsat image of the study area and illustrate locations of IP Imaging survey profiles (Modified after Google Earth Images, 2008).*

Generally, the dipole-dipole array configuration is based on used two current electrodes (A) and (B) and two potential electrodes (M) and (N) arranged on a straight profile (Fig.2). This array is widely used in resistivity surveys, because of the low electromagnetic coupling between the current and potential circuits (Reynolds, 1997). The study area is located in the lava caves successions of Pre-Quaternary age. One of these successions is called Al-Howa tunnel (Fig.1) (Kempe and Al-Malabeh, 2005).

Since the stability of the lava caves are depends on the presence of the fractures in the basalts rocks, collapse of the cave that almost by filled with sediments or carbonates (Fig.3), then the IP imaging survey was undertaken in order to achieve useful information for possible future restoration work, and interpretation IP data in an environmental investigation for these caves. Further, the chargeability (*M*) we find from the IP measured that is closely related to lithological structures and characteristic (*M*) due to lithology from IP data due to cavity fractures.

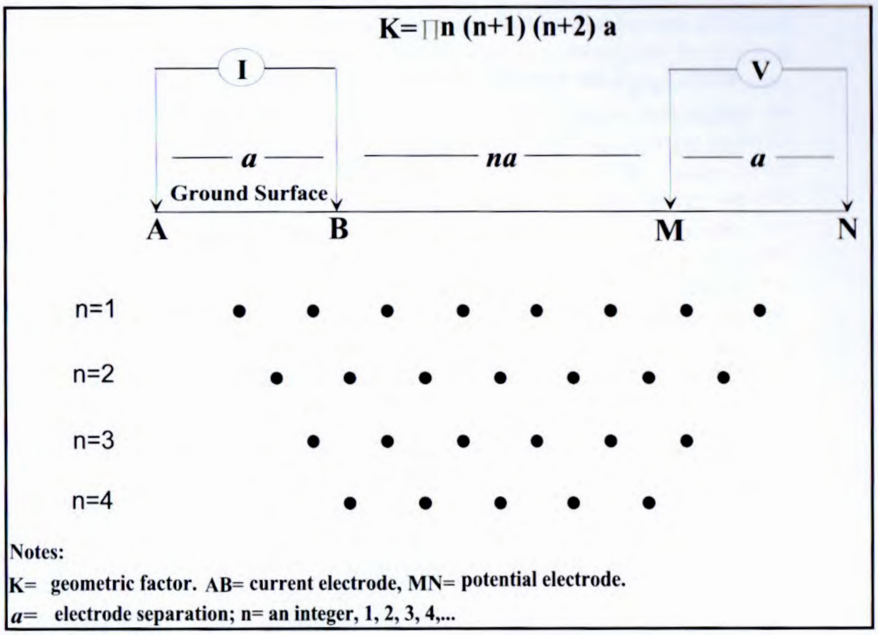


***Fig.2**:Conventional dipole-dipole array resistivity with geometric factor*

***Fig. 3**: Photograph of the field site showing the collapse or subsidence feature in the eastern part of Jabal Quis Volcano.*

2. IP Parameters and Model Inversion

The IP parameters (*M, PFE, and MF*) are very sensitive to the bulk conduction and the surface polarization properties of the rocks. The weight of the IP parameters are measured from the conductivity that yields the normalization IP parameters, where the conductivity is calculated from the resistivity equation (Wong, 1979; Seigel, 1959; Pelton et al., 1978):

$$\sigma_a(w) = \frac{1}{\rho_a(w)} \qquad (1)$$

where, $\rho_a(w)$ is the complex resistivity response function in unit (Ohm-m) at homogeneous media, $\sigma_a(w)$ is the conductivity of the material in unit siemen per meter Sm^{-1}. The apparent resistivity values for dipole-dipole array are given by the formula as follows:

$$\rho_a = \pi a n(n+1) * (n+2)\frac{V}{I} \qquad (2)$$

where, (ρ_a) the apparent resistivity (Ohm-m), (*a*) the spacing electrode, (n) the number of factor value. The spacing between both electrodes pairs is (*a*). The first sequence of measurements is made with a value of 1 for (n) between the current electrodes (A) pairs and potential electrodes (M) pairs (Edwards, 1977). The spacing (*a*) is integer multiple and (n) factor is increased to 2, 3, ... to 6, so increase the depth of penetration (Fig.2). The chargeability (*M*) is often measured with instruments that operate in the time domain method. This is characteristic of chargeability (*M*) measured (Summer, 1976; Schön, 1996) is defined as:

$$M = \frac{\int_{t_s}^{t_f} V_s dt}{V_p} \left(\frac{1}{\Delta t}\right) \tag{3}$$

where, *Vs* is a residual voltage integrated over a time window defined between times *ts* and *tf* after termination of an applied current, *Vp* is the measured voltage at some time during application of the current and Δt equals the length of the time window of integration. Units of chargeability are typically quoted as millivolts per volt (mV/V).

According to Van Voorhis et al., (1973) the IP effect is measured with the percentage frequency effect (*PFE*) in the frequency domain, and can be expressed by the following equation:

$$PFE = \frac{\rho(\omega) - \rho(A\omega)}{\rho(\omega)} \times 100 \tag{4}$$

where, *A* constant at the spread between measurement frequencies.

The metal factor (*MF*) value for IP properties can be calculated from either time domain or frequency domain measurements (Edwards, 1977), in the time domain expressed by equation:

$$MF_{td} = \frac{1000 \times M}{\rho_{DC}} \tag{5}$$

in the frequency domain expressed by:

$$MF_{fd} = \frac{100000 \times (\rho_{DC} - \rho_{AC})}{\rho_{AC}^2} \tag{6}$$

where, ρ_{DC} and ρ_{AC} the apparent resistivity values measured at low and high frequencies (Van Voorhis et al., 1973; Summer, 1976; Edwards, 1977).

The *PFE* and *MF* are both controlled by apparent resistivity (ρ_a) curves (Edwards, 1977), and it distinguished the relationship characterization of the anomaly. The weight of the IP parameters can measured conductivity that yields the following normalized IP parameters which mean quadrature conductivity, metal factor (*MF*), and normalized chargeability as called term (*Mn*). According to paper publishers Lesmes and Frye (2001) defined the normalized chargeability (*Mn*) as global estimate of interfacial magnitude (defined as chargeability divided by the resistivity magnitude), and that is given by:

$$M_n = \frac{M}{\rho} \tag{7}$$

(Slater and Lesmes, 2002) developments improved of IP interpretation and are given the normalized chargeability by equation:

$$M_n = \sigma'_{rock} M \tag{8}$$

and,

$$\sigma'_{rock}(w) = \sigma'_{bulk} + \sigma'_{surf}(w) \tag{9}$$

The bulk conductivity is given from Archie's Law (Archie, 1942):

$$\sigma'_{bulk} = \sigma_w \phi^m S^n \tag{10}$$

where, σ'_{bulk} is the bulk conductivity, σ'_{surf} is the surface conductivity , σ'_{rock} is the quadrature conductivity, σ_w is the solution conductivity, Ø is the porosity, *S* is the saturation, and *m* and *n* are the cementation and saturation exponents, respectively.

In addition, the relationship of resistivity with formation factor (*F*) can be expressed by:

$$F = \frac{a}{\phi^m} \quad >1 \tag{11}$$

where, *a* is empirical constant based on the geometry of the pores and equal to 1, m is the cementation present and ranges from 1.3 for un cemented soils or sediments to 2.6 for highly cemented rocks, such as dense limestone. These IP parameters are proportional to the quadrature conductivity measured in the complex resistivity.

Theoretically, the inversion modeling of electrical imaging (tomography) is based on the smoothness constrained last-squares approach and used to calculate apparent resistivity values (deGroot-Hedlin and Constable, 1990; Sasaki, 1992). This approach is depending on a quasi-Newton optimization technique (Loke and Barker, 1996a). The least-squares inversion is given by equation:

$$(J^T J + uF)d = J^T g - uFr \tag{12}$$

where, ***F*** is a smoothing matrix, ***J*** is the Jacobian matrix of partial derivatives, ***r*** is a vector containing the logarithm of the model resistivity values, ***u*** is the damping factor, ***d*** is model perturbation vector, and ***g*** is the discrepancy vector.

In the Gauss-Newton least-squares approach, the ***J*** is recalculated after all iteration either the finitedifference or finite-element method (Dey and Morrison, 1979 a,b; Silvester and Ferrari, 1990; and Sasaki, 1992). To reduce the computing time, a quasi-Newton used updating method to estimate the J after all iteration (Loke and Barker, 1996a). For more detail described about mathematical approach for Gauss-Newton least-squares inversion reading to publishers Loke and Barker (1996 a,b). Equation 12 tries to minimize the square of the spatial changes of the model true resistivity with depth, and produce a model with a smooth variation of resistivity values.

3. Geological Setting

The geology of the study area is little complex structures of pressure ridges, Cenozoic basaltic flows, basaltic dikes, vesicular basalts with affected by fractures that filled with carbonate sediments. The pressure ridges are represents one features structures in the study area, and appears elliptical ground plane and an asymmetrically rising small dome shaped with open fissures. These ridges are most probably related to the cooling process (Guba and Mustafa, 1988). Published investigation on the basalts plateau in NE Jordan revealed that they consist of six separated basalt flows, from B1 to B6 (Van Den Boom and Sawwan, 1966). The thickness of basalt decreases towards south of Jordan (Bender, 1974). Most recent flows still display visible flow textures, such as pahoehoe and "aa" lava flows that are producing features of lava caves. The average density of basalt about of 2.5 to 2.77 g/cm^3, and the saturate surface of 2.70 to 2.85 g/cm^3 (Nawasreh, 1993). The absolute ages for these basaltic flows were obtained from K-Ar dating that ranges from 13.5 to less than 0.5 Ma (Barberi et al., 1979; Moffat, 1988), whereas in recent years published as Tarawneh et al. (2000) subdivided the basalt Harrat Ash Shaam based on K-Ar dating into three phases; the first is of Oligocene age 26 to 22 Ma, the second phase is of late Miocene age 12 to 8 Ma, and the third phase is of Pre-Quaternary age 6 to less than 0.5 Ma. The pyroclastic rocks are most abundant in the study area; they are composed of olivine, pyroxene, plagioclase, and accessory minerals. All the basalts have been affected by fractures, joints, and fissures that become filled with secondary minerals. Due to interaction of water rock and chemical transport by the hydrothermal processes, the primary minerals in the basaltic rock matrix are partially transformed or altered, into different minerals. In the Umm El-Quttein area occur a few zeolite minerals of analcime type by recorded in some samples collected from the lower horizons of Jabal Quis volcano (Al-Malabeh, 1993). Common secondary minerals are zeolite; clay minerals such as smectite and kaolinite, calcite, and gypsum in the study area (Abed et al., 1985; Dwairi, 1987; Khalil, 1991; Al-Malabeh, 1993; and Tarawneh, 2002). Further, the secondary minerals were observed inside Al-Howa tunnel which is composed of calcite, gypsum, and quartz are abundant covered mostly the wall of tunnel, plagioclase and iron oxides. These minerals may formed secondary mineralized has filled with the caves within the investigated area.

4. Data Acquisition and Processing

The IP imaging field data were collected using an Iris Syscal R1 resistivity meter instruments with 250W converter and 12V, over the lava caves locations (Fig.1). The measured field data were processed by 2D inverse algorithm modeling based on work Loke and Barker (1996a). In our case the spacing (a) between both electrodes pairs in dipole-dipole array configuration equal to 20 m, and the maximum depth level of the investigation was used (n) equal to 4 that equal to 24.4 m depth. Three profiles were performed consisted of A1, A2, and A3. The IP imaging survey was used the time-domain method in the study area. This method is very sensitive to horizontal changes in resistivity, but relatively insensitive to vertical changes in the resistivity.

This means that it is good in mapping vertical structures, such as cavities and dikes, but a relatively poor in mapping horizontal structures (Loke, 2001). The forward problem is solved using the finite element method, and the IP resistivity is found using an iterative last-squares inversion approach. The chargeability data was processed and yield to filtering after the definition of Seigel (1959), to improve the IP measurements interpretation in the basalt plateau environment (Fig.4).

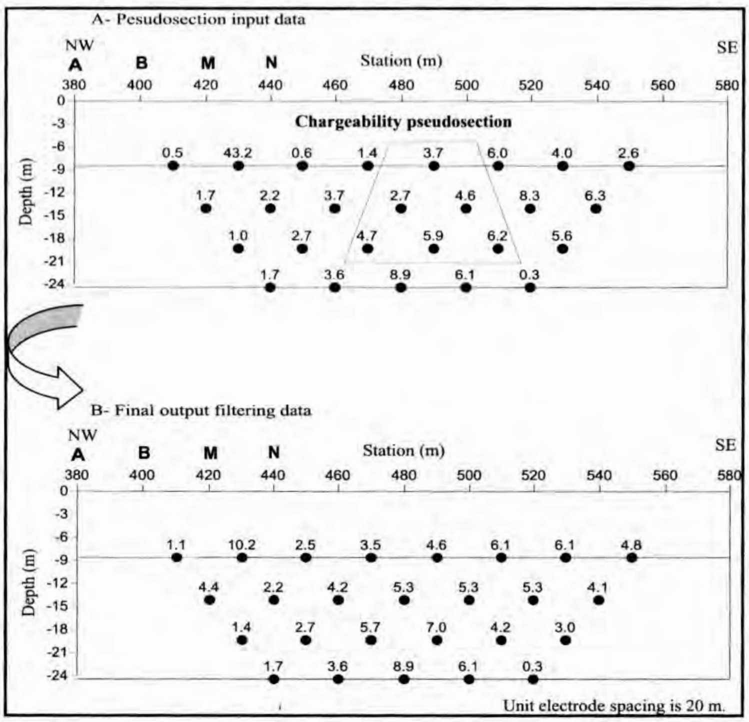


***Fig.4:** Diagram showing of window output filtering chargeability data for example profile A3.*

5. Field Results and Discussions

IP imaging survey was investigate to identify the subsurface structure of lava caves using time domain method at NE Jordan. The resistivity mapping results from a dipole-dipole array is shown in Figure (5), with different depth layers below the surface.

Areas of continuous high resistivity indicate good delineate the lava caves, whereas areas of low resistivity surrounding of the caves correlated with fractures zones that has been resistivity values of less than 760 Ohm-m.

The lava cave has been resistivity values may reach to greater than 3010 Ohm-m; with depth levels ranges between 8.32 and reached a maximum to 19.24 m. These limitations of the lava caves with different depth layers are indicate depicts the caves that resulted from lava sheets by inflation of initial lava delta within lava flows B6.

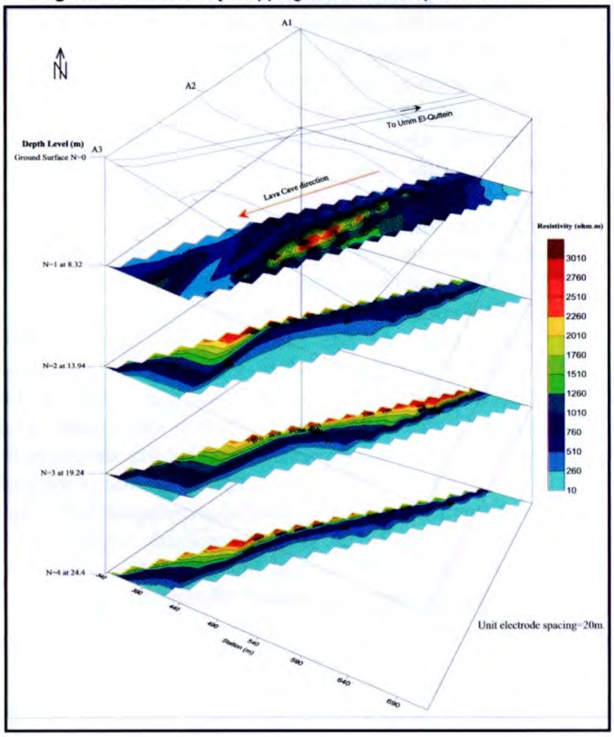
This interpreted indicates to demonstrated mechanism theory of lava caves formed has been described recent publishers Al-Malabeh et al. (2004) and Kempe and Al-Malabeh (2005). These anomalous from IP resistivity distributions measurements are indicating clearly continuation to the caves or tunnels flow in length and thickness, are coincides with interpretation results of VLF-EM technique (Al-Oufi, et al., 2008). This high resistivity continuous display that as elongated anomalous on profiles A1, A2, and A3 at depth layers 8, 13,94, and 19,24 m, clearly indicate the limitations for these caves across road Umm El-Quttein in trends NE to SW direction of the investigated area (Fig.5).

IP data was plotted on log-log graph, based on interpretation of the relationship apparent resistivity (ρ_a) with chargeability (*M*), and normalized chargeability (*Mn*), that derived from IP parameters at depth layer 8.32 from below the surface (Fig.6 and 7). The resistivity decreasing with increase the chargeability (*M*) which suggests introducing to fracture features; located between stations 710 to end the profile (Fig.6). This relationship is correlated with normalized chargeability (*Mn*) that has values over than 0.120092 mS/m. This illustrating that the dense basalt layer is affected by highly fractured which almost filled with clay or carbonate sediments. Figure (7), display the relationship between increasing the resistivity with decrease the (*M*) and decrease the (*Mn*) values less than 0.006169 mS/m, between stations 500 to 530 m. This indicates to closely the lava cave that may influence with secondary mineralized.

To identify the engineering properties for these caves, where made IP interpretation using inversion models are shown in Figures (8, 9, and 10). These models were created to support interpretations of the IP data. Figure (8) shows the inverse models of apparent resistivity (ρ_a), chargeability (*M*), metal factor (*MF*) pseudosections, respectively. Profile A1 (Fig.8), yield to accurate interpretation of IP inverse model.

Resistivity data shows a high resistivity values in the top layer grater than 1172 Ohm-m, and located between stations 640 to 660 m as labeled (A).

Fig.5: *2-D IP resistivity mapping at different depth levels*



The geological model for this profile is interpreted that the lava cave collapsed (Al-Howa) which has depths ranges from 1.71 to 12.6 m. Anomaly (B) shows low resistivity zone with less than 44.1 Ohm-m. This anomaly correlated with (*M*) data values about of 7.67 to 13 mV/V,and has (*MF*) values grater than 1791 mV/Ohm-m. This anomaly indicates that the fractures of dense basalt layer are filled with solid minerals from carbonate sediments or clay which reached to 27 m depth. Anomaly (C) shows in the top surface of low resistivity values less than 19.4 Ohm-m. This anomaly indicates to Wadi Quis that affected by unconsolidated sediments, and reached a depth to 13 m. The vesicular basalt shows at anomaly (G) with high resistivity values about of 516 to less than 1172 Ohm-m, and extending a depth from 15 to 27 m.

Profile A2 across in NW to SE, and extending on the lava strike is shown in Figure (9). The anomaly (A) shows high resistivity values over than 10246 Ohm-m in the near surface and located between stations 520 to 540 m. This anomaly feature represents the extent of lava cave (Al-Howa) that extending to depth 12.7 m, and across the road Umm El-Quttein.

A lower resistivity around 303 to less than 93.8 Ohm-m occurs between stations 490 to 520 m as labeled (B).This anomaly is correlated with the (*M*) values; which have been values around 13.3 mV/V. This relationship indicates to a change in surface conduction due to the fracture zone of dense basalt layer; which has high (*MF*) values over than 1592 mV/Ohm-m, and depth ranges from 12.7 to 22 m.This anomaly attribute to materials in dense basalt layer could be filled with clay or carbonate sediments.Figure (7), display the relationship between increasing the resistivity with decrease the (*M*) and decrease the (*Mn*) values less than 0.006169 mS/m, between stations 500 to 530 m. This indicates to closely the lava cave that may influence with secondary mineralized.

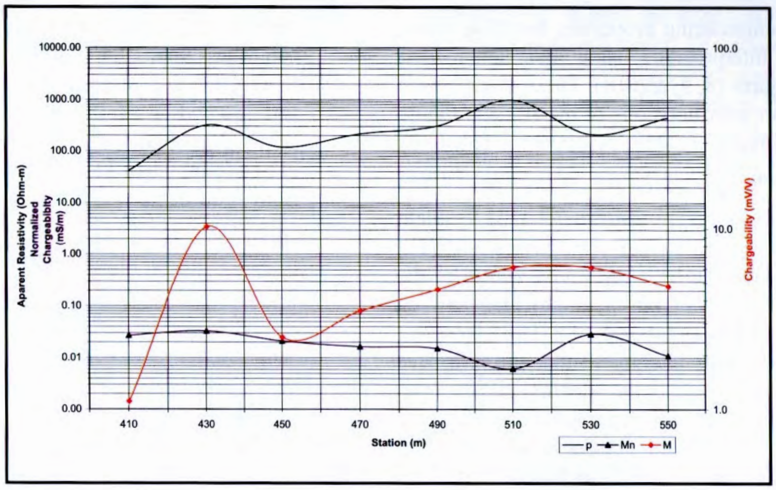


Fig.6: Interpretation of resistivity (ρ_a), chargeability (M), and normalized chargeability (Mn) curves derived from the IP parameters for profile A1.

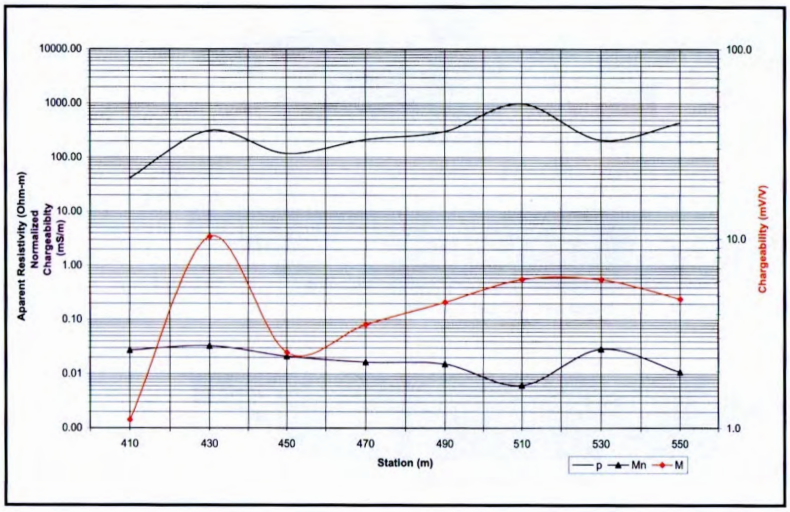


Fig.7: Interpretation of resistivity (ρa), chargeability (M), and normalized chargeability (Mn) curves derived from the IP parameters for profile A2.

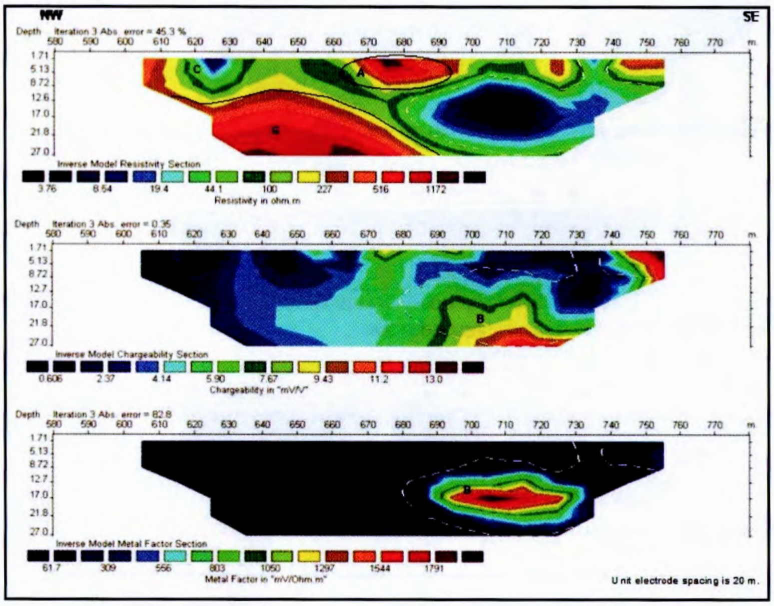


Fig.8: 2-D IP resistivity model at A1 profile: (a) inverse model resistivity; (b) inverse model chargeability; (c) inverse model metal factor.

To identify the engineering properties for these caves, where made IP interpretation using inversion models are shown in Figures (8, 9, and 10). These models were created to support interpretations of the IP data. Figure (8) shows the inverse models of apparent resistivity (ρ_a), chargeability (*M*), metal factor (*MF*) pseudosections, respectively. Profile A1 (Fig.8), yield to accurate interpretation of IP inverse model. Resistivity data shows a high resistivity values in the top layer grater than 1172 Ohm-m, and located between stations 640 to 660 m as labeled (A). The geological model for this profile is interpreted that the lava cave collapsed (Al-Howa) which has depths ranges from 1.71 to 12.6 m. Anomaly (B) shows low resistivity zone with less than 44.1 Ohm-m. This anomaly correlated with (*M*) data values about of 7.67 to 13 mV/V, and has (*MF*) values grater than 1791 mV/Ohm-m. This anomaly indicates that the fractures of dense basalt layer are filled with solid minerals from carbonate sediments or clay which reached to 27 m depth.

Anomaly (C) shows in the top surface of low resistivity values less than 19.4 Ohm-m. This anomaly indicates to Wadi Quis that affected by unconsolidated sediments, and reached a depth to 13 m. The vesicular basalt shows at anomaly (G) with high resistivity values about of 516 to less than 1172 Ohm-m, and extending a depth from 15 to 27 m.

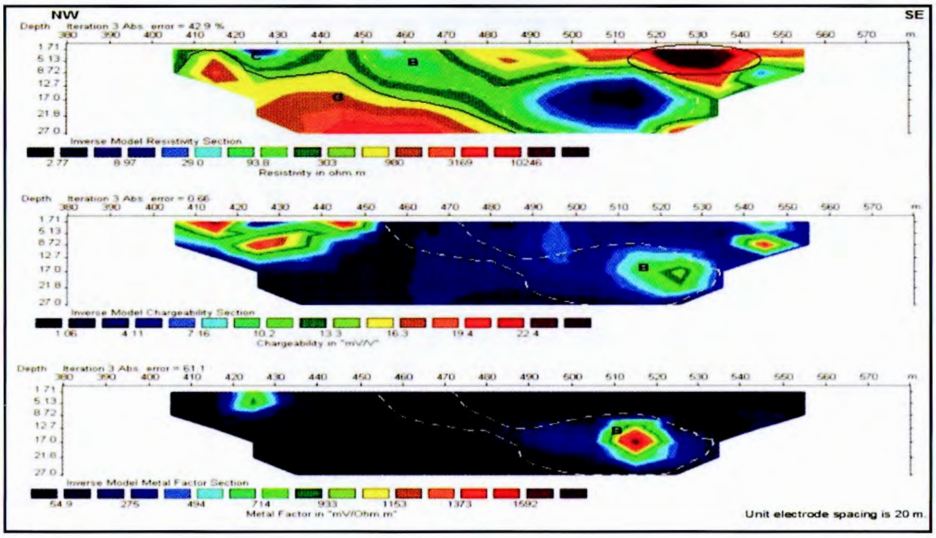


Fig.9: *2-D IP resistivity model at A2 profile: (a) inverse model resistivity; (b) inverse model chargeability; (c) inverse model metal factor.*

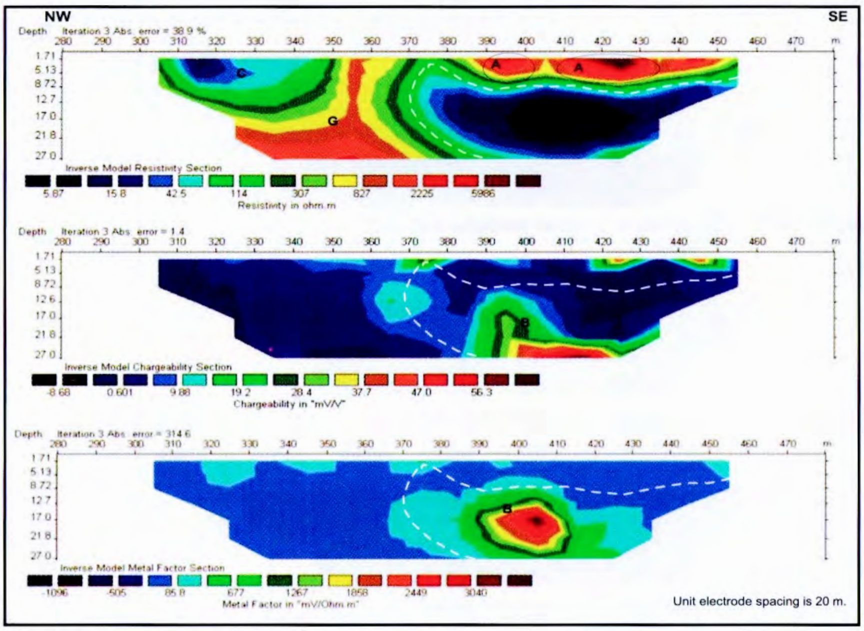


Fig.10: *2-D IP resistivity model at A3 profile: (a) inverse model resistivity; (b) inverse model chargeability; (c) inverse model metal factor.*

Profile A2 across in NW to SE, and extending on the lava strike is shown in Figure (9). The anomaly (A) shows high resistivity values over than 10246 Ohm-m in the near surface and located between stations 520 to 540 m. This anomaly feature represents the extent of lava cave (Al-Howa) that extending to depth 12.7 m, and across the road Umm El-Quttein. A lower resistivity around 303 to less than 93.8 Ohm-m occurs between stations 490 to 520 m as labeled (B). This anomaly is correlated with the (*M*) values; which have been values around 13.3 mV/V. This relationship indicates to a change in surface conduction due to the fracture zone of dense basalt layer; which has high (*MF*) values over than 1592 mV/Ohm-m, and depth ranges from 12.7 to 22 m. This anomaly attribute to materials in dense basalt layer could be filled with clay or carbonate sediments. This interpreted indicates that increase a quantity of mg % in this layer which consist of olivine, plagioclase, clinopyroxine, calcite, quartz, iron oxide minerals (Khalil, 1991; Al-Malabeh, 1994; Ibrahim et al., 2001). Wadi Quis shows in the top layer with low resistivity of less than 29 Ohm-m as labeled (C) and occur underlying of vesicular basalt layers that located between stations 410 to 470 m; with resistivity values of 980 to less than 3169 Ohm-m, as label (G). This anomaly extending a depth from 8.72 to 27 m; and has (*M*) values around 22.4 mV/V.

The lava cave anomaly show high resistivity values grater than 5986 Ohm-m, and extending a depth to 8.72 m as label (A) on profile A3 (Fig.10). Thin layer fracture of sediments shows underlying the cave with decreasing in resistivity with less than 114 Ohm-m; (*M*) values about of 28.4 mV/V, and has high (*MF*) values grater than 2449 mV/Ohm-m as labeled (B). This layer suggests that filled with clay or spread carbonate sediments, which has been a depth from 12.7 to 22 m. While in the top surface at NW of profile A3 (Fig.10) reveal a Wadi Quis with decrease in resistivity value with less than 42.5 Ohm-m as labeled (C), and extending a depth to 8.72 m that bearing by unconsolidated sediments. The source of this Wadi is results from recharges and precipitation falling over the study area and from Jabal Druze. For more accurate interpretation shows the vesicular basalt layer as anomaly (G) with resistivity values of 827 to less than 2225 Ohm-m. This layer has depth may reach to 27 m.

Figure (11) illustrate the distribution of resistivity that corresponding with the lava caves at 8.32 m depth. The interpretation of IP resistivity (Fig.11) suggests that the lava caves have several interconnected form tunnels toward N21°E direction, and increase and decrease in width with increasing thickness of the investigated area. Geometric survey for the lava caves outcrop were given by Kempe et al., (2006), and combined with interpretation results of VLF-EM technique (Al-Oufi et al., 2008). In Figure (11) we an estimate a total length of lava caves investigated approximately of 1600 m; a volume of 28,800 m^3, but considering a dimension of 3×6 m at profile A1. The volume of caves or tunnels may increase to 48,000 m^3 with a dimension of 3×10 m at profile A3. This is display that the volume of caves may be a little bigger to southward direction of the study area. These caves showing that sub-parallel to the last phases of youngest eruptive flows strike in trends NE to SW direction; which distinguished between very negative anomalies had obtained from interpretation results of VLF-EM measurements (Al-Oufi et al., 2008). This interpretation of IP mapping is detect the result of potential hazard environment to road Umm El-Quttein overlying the extent of the lava caves, between depth levels 8.32 and 19.42 m below the surface (Fig.5;11).

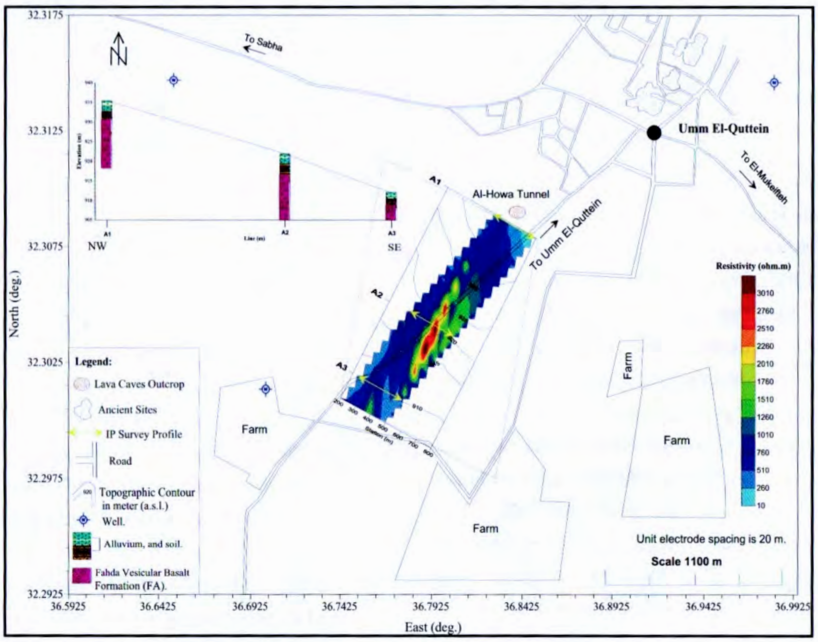


Fig.11: *Resistivity map at 8.32 m depth over road Umm El-Quttein, and showing the high resistivity distribution that may correspond with the lava caves.*

6. Conclusions

Under characterization assessment of the lava caves in NE Jordan; were reconnaissance investigation using IP imaging survey with time-domain method, in order to identify their extent, depths, and geometric properties of potential hazard environment which producing collapse features overlaying of road Umm El-Quttein. The investigation results were conducted and can be recognized on presence of lava caves associated mineralized fractures in dense basalt layer. To obtain information on rocks quality; the IP parameters were analyses, including of apparent resistivity (ρ_a), chargeability (*M*), and metal factor (*MF*). The amount of chargeability depends on the content on the mineralized of the rocks and the specific surface area. IP parameters assist in identification of the IP anomalous and lead to relationship between structure features and IP measurements. An IP imaging results from mapping profiles A1, A2, and A3; display that a good elongated anomalous of high resistivity more than 3010 Ohm-m were identified in the top surface, and have the same orientation. This indicates likely is related to the lava caves and extends toward N21°E direction that near ancient sites across road Umm El-Quttein. This interpretation indicates that the cave body filled with air and has depth levels ranges between 8.32 and reached a maximum to 19.24 m. These anomalous may suggests that the lava caves resulted by lava sheets which have been sub-parallel to the last phases of youngest eruptive flows as described by Al-Oufi et al., (2008). For more accurate interpretation of IP measurements show the profiles occurrence of anomalous of lava caves with depths not exceed of 12.7 m as marked in the inverse model resistivity pseudosections. The IP resistivity, (*M*), and (*MF*) are correlated with open fractures of dense basalt layer, ranges between 303 to less than 93.8 Ohm-m; (*M*) values ranges between 13.3 and 28.4 mV/V, and increasing in the (*MF*) values from 1791 to more than 2449 mV/Ohm-m. These anomalous suggest that the basalt rocks are highly fractured and filled with clay or carbonate sediments, which indicate to increasing content of mg % that attribute to mineralized fractures in the basalt layer. The vesicular basalt layers were recognized that characterized by high resistivity around 827 to less than 2225 Ohm-m which represent of B6 flows. The lava caves indicate to significant their locations in our study and results are display that road Umm El-Quttein may constitute a risk environment due to extent for these caves; such as sudden collapse features. The IP technique is rapid and economical for mapping the extents of lava caves and determines their edges locations in a shallow subsurface and most accurate that reflect interpretation of the subsurface structures. This technique is new used in Jordan on the basalt environmental.

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Investigation on the Vegetation and the Characteristic of Lava by Observing the Structure of Tree Molds in Higashi-Usuzuka-Minami Lava Flow at Mt Fuji

by

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Abstract

Tree molds are a record of both vegetation and interaction phenomena between lava flow and standing trees. The observation of tree mould diameter distribution can predict the vegetation succession phase at the eruption time and estimate the interval from the former eruption of lava flow if one piled up another. The diameter distribution study of 398 tree molds of Higashi-Usuzuka-Minami lava flow ejected on the southern flank of Mt.Fuji shows 1000 to 1200 years lapse after the former eruption of Kotengu lava flow. This lapse was compared with the recent tephra study and C14 dating(Kotengu-Lava flow: 2120±40y BP, Higashi-Usuzuka-Minami Lava flow: 1190±40y BP) and consistent with them.

By observing also the structure of tree mold, lava flow characteristics such as lava thickness, flow speed, flow direction etc., can be deduced. Here, the speed and viscosity of the basaltic lava flow of Higashi-Usuzuka-Minami were estimated by upposing that all the tree of diameter below the minimum diameter of the existing tree has been thrown down with collision of lava flow. From this diameter, the speed of lava flow was estimated as about 4m/sec. Substituting the slope angle, lava flow thickness and density of lava to the simple slope flow equation, the viscosity of lava can be obtained. The estimated viscosity was about 4000 poise, which seems to be reasonable as a viscosity of low fraction silica content basaltic.

1. Introduction

Tree molds are a record of both vegetation and interaction phenomena between lava flow and standing trees. The observation of tree mold diameter distribution can Predict the vegetation succession phase at the eruption time and estimate the interval from the former eruption of lava flow if one piled up another. The diameter distribution study of 398 tree molds of Higashi-Usuzuka-Minami lava flow ejected on the southern flank of Mt.Fuji has been investigated from the view points from the botanical aspect and the hydrodynamic aspect. It is well known that the tree molds could predict the lava flow direction and velocity (Tsuya,1971; Lookwood and Williams 1978).

2. Botanical Aspect and Analysis

The total number investigated in the Higashi-Usuzuka-Minami lava flow by Kensuke Ogawa (Ogawa1986) is 482, among these, the total number for the standing tree moulds are 433, the total number for inclined tree moulds is 49. Among the 433 standing tree molds, 398 are investigated for this study. Fig 1 shows the representative tree molds for inclined tree molds and the standing tree molds.

Fig.1 *Inclined tree mold (left) and Standing tree mold (right).*

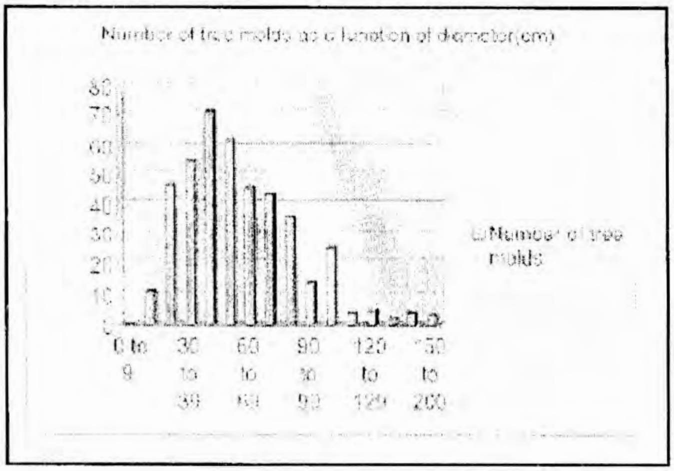

Fig.2 : Number of the tree mold distribution by diameter.

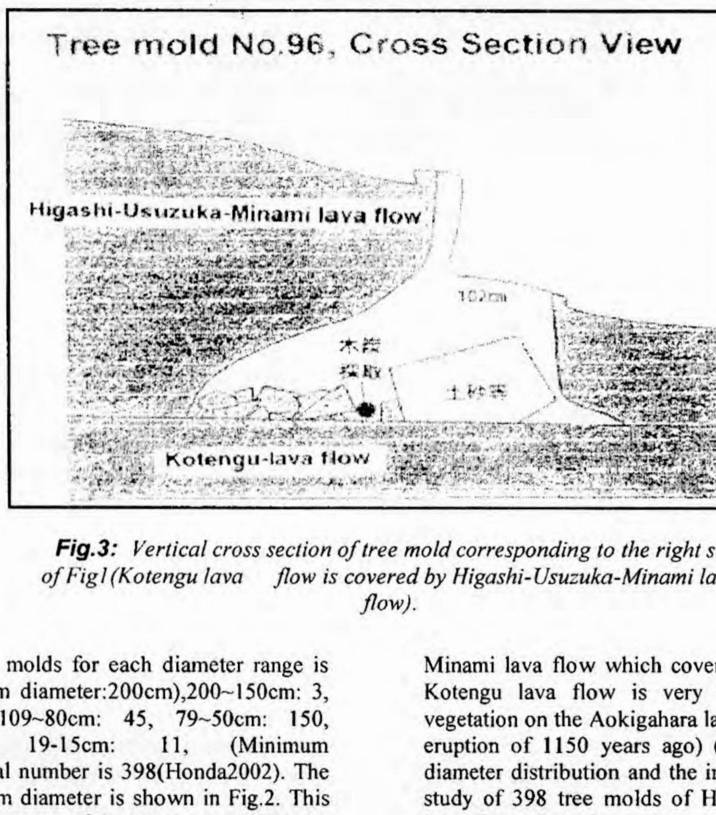

Fig.3: *Vertical cross section of tree mold corresponding to the right side of Fig1(Kotengu lava flow is covered by Higashi-Usuzuka-Minami lava flow).*

Number of the tree molds for each diameter range is classified (Maximum diameter:200cm),200~150cm: 3, 149~110cm: 17, 109~80cm: 45, 79~50cm: 150, 49~20cm: 172, 19-15cm: 11, (Minimum diameter:10cm).Total number is 398(Honda2002). The distribution per 10cm diameter is shown in Fig.2. This distribution of the diameter of the tree is very similar to the diameter distribution of the present vegetation on Aokigahara lava flow studied by T. Kobayashi (Kobayashi 1988).

Aokigahara lava flow has been ejected at AD 864 which are registered in the official historical document of the government that period.

Also, the vegetation aspect such as the kind of trees which can be observed in the inner surface configuration of the tree mold of the Higashi-Usuzuka-Minami lava flow which covers the vegetation on the Kotengu lava flow is very similar to the present vegetation on the Aokigahara lava flow(vegetation after eruption of 1150 years ago) (Honda, 2002). So, the diameter distribution and the inner surface observation study of 398 tree molds of Higashi-Usuzuka-Minami lava flow ejected on the southern flank of Mt.Fuji predicts 1000 to 1200 years lapse after the former eruption of Kotengu lava flow if it is base on the study on the vegetation on the Aokigahara lava flow.

This lapse was compared with the recent tephra study and C14 dating (Takada and Kobayashi, 2007): Kotengu lava flow: 2120±40y BP, Higashi-Usuzuka-Minami Lava flow: 1190±40y BP). This means the about 1000 years interval between these two eruptions. The lapse is consistent with this vegetation study.

3. Hydrodynamic Aspect and Analysis

By observing also the outer structure of tree mold, lava flow characteristics such as lava thickness, flow speed, flow direction etc., can be deduced. Here, the speed and viscosity of the basaltic lava flow of Higashi-Usuzuka-Minami were estimated by supposing that all the tree of diameter below the minimum diameter of the existing tree has been thrown down with collision of lava flow. From this diameter (about10cm), the speed of lava flow was estimated.

The flow around the tree(cylinder model) is depending on the Reynolds number: $Re=\sigma Ud/\mu$, where σ : density of lava, U : flow velocity of lava, d : diameter of cylinder (tree), μ : viscosity of lava, L:height of lava flow. Generally, the Reynolds number of the slow flow of lava is in the range of 1~10.

The force acting on the cylinder (tree) is shown as the resistive force:$F= CDA(\rho U2/2)$,where CD:coefficient of resistance, A = dL:projected cross section.

From the resistive force, the bending moment and stress acting on the cylinder (Bending moment : $M=L2W/2$, where $W=F/L$, and bending stress : $\sigma=M/Z$) can be deduced.

As the bending strength of living tree is σ=200Kg/cm2, and the coefficient of cross section :

$Z=(\pi/32)d3$, the diameter d of living tree resistive to the lava can be determined by velocity and thickness of lava : $d=LU(8CD\rho/\pi\sigma)1/2$,where,L=1m, d=10cm, σ=200kg/cm2

As generally CD=2 for this kind of flow of low Reynolds number、U=4m/sec can be deduced.

Then, by using the equation of Newtonian fluid flowing down on the slope, viscosity:$\mu=(\rho\cdot g\cdot \sin\alpha\cdot H2)/2U$ can be obtained, where μ :viscosity of lava, g :gravity acceleration, α:slope angle ,9 degree for Higashi-Usuzuka-Minami lava flow,H:thickness of lava flow(1m),U:velocity of lava flow, ρ:density of lava(2.5).

Substituting the slope angle, lava flow thickness and density of lava to this simple slope flow equation, the viscosity of lava can be obtained. The estimated viscosity was about 4000 poise, which seems to be reasonable as a viscosity of low fraction silica content basaltic. The location of the tree molds is very near to the eruption point, the temperature might be around 1200-1100°C.

4. Summary and future work:

- The observation of tree mould diameter distribution could predict the vegetation succession phase at the eruption time and estimate the interval from the former eruption of lava flow if one piled up another.

- By observing also the individual structure of tree mould, lava flow characteristics such as lava thickness, flow speed, flow direction and viscosity, etc., can be deduced.

- The influence of the successive lava flow for other lava flows in Mt Fuji such as Obuchi-marubi lava flow, etc., will be studied in future.

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A History of Human Exploration and Occupation of the Lava Caves of the Zuni-Bandera Volcanic Field, New Mexico, USA

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Abstract

In the high desert of New Mexico's Zuni-Bandera Volcanic Field (ZBVF) there are hundreds of volcanoes and lava caves. These caves have been occupied, explored, mined and even bombed over the past 10,000 years. Many of these caves contained large perennial ice accumulations. The Native Americans used the caves for ice, water, protection, religious ceremonies and food storage, primarily from 7500 BC to 1130 AD. Prehistoric Native American artifacts are still being discovered in the caves today. Under law, these artifacts are repatriated to the Native Americans.

Europeans (Spanish conquistadors) first entered the region in AD 1540. However, the first scientific exploration of the ZBVF did not began until the conclusion of the Spanish-American War in AD 1850, when surveying commenced for the first transcontinental railway. During World War II scientific exploration ceased as the ZBVF became a conventional bombing range. In 1945 the ZBVF was almost selected as the site for the first atomic bomb test.

The Space Race of the 1960s sparked an interest in lunar rilles (pyroducts). Scientists subsequently turned to the ZBVF to study terrestrial pyroducts. During the same period, the National Speleological Society (NSS) began exploring the caves of the ZBVF.

In 1987 the ZBVF became protected as a El Malpais National Monument and Conservation Area. The National Park Service (NPS) has completed two comprehensive surveys of the lava caves of the region, in 1988 and 1994-1997. The NSS has continued to survey the caves under the NPS, but currently all caves in the ZBVF are closed pending further characterization of the devastating bat disease *White Nose Syndrome*. The rugged terrain means that large areas have not yet been explored. The future of cave exploration in the ZBVF is unclear at the present time.

Introduction

In the high desert of New Mexico, in the southwestern United States, is the Zuni-Bandera Volcanic Field (ZBVF) and hundreds of volcanoes and lava caves and "ice caves" (Fig.1). The caves have a rich history of occupation, exploitation, and exploration dating back almost 10,000 years. Native Americans have been using the caves for thousands of years. The caves attracted the attention of Europeans only about two centuries ago. Before then, the Spanish called the Zuni-Bandera Volcanic Field "el malpais" – the badlands. During the past 100 years the caves have been bombed with high explosives, narrowly avoided a nuclear blast, explored by rocket scientists, mined for guano and gravel, and finally protected as a National Monument (Fig. 2). This is the history of the Zuni-Bandera lava caves.

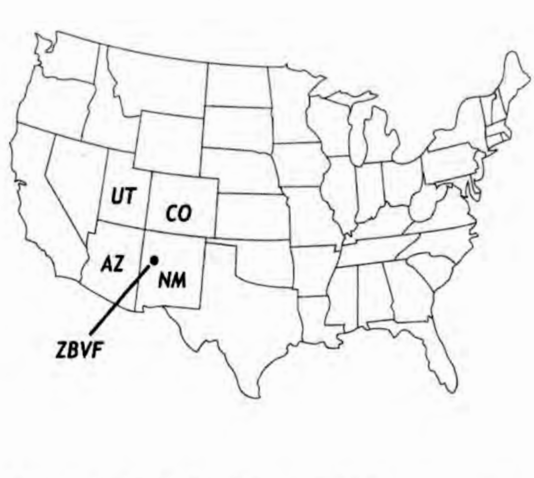

Fig 1: The Zuni-Bandera Volcanic Field, New Mexico, USA.

Fig. 2: The high desert environment of the Zuni-Bandera Volcanic Field. This is the view looking northeast towards the sandstone bluffs from the vicinity of El Calderon crater. (Photo by Harry A. Marinakis).

Paleo-Indian Period

The earliest known people to visit the ZBVF date to the Paleo-Indian period (before 7500 BC). Paleo-Indians were big-game hunter-gatherers who crossed over the Bering land bridge from Asia at the end of the last glaciation. Recent archeological investigations near the lava beds by the University of New Mexico unearthed a stone projectile point, identified as a Midland point, that is thought to be 10,000 years old (Doleman, 1990). It is not known if Paleo-Indian actually used the caves because their lifestyle left little evidence for archeological analysis (Fig. 3).

Southwestern Archaic Period

The transition from the glaciation to a more arid environment forced the people of the Southwestern Archaic period (7500 BC to AD 200) to rely more heavily upon cultivated plants and adopt a more settled lifestyle. Only a couple of Archaic sites have been found near the Zuni-Bandera lava beds (Doleman, 1990). Approximately 3,000 years ago, these Archaic farmers witnessed an extensive eruption from McCarty's Crater that sent lava streaming 65 kilometers across their farmland. Today the Navajo still refer to the ZBVF as Yeii Tso Bidilth Ninigheezh - "where Big Monster's blood congealed," a reference to a Navajo myth in which Big Monster was slain by the War Twins on nearby Mount Taylor (Crumpler, 1982; Holmes, 1989).

The Anasazi

The Anasazi were probably the first to regularly use the ice caves of the ZBVF (Holmes, 1989; Doleman, 1990; and Marshall, 1991). The Anasazi civilization was a great society that flourished in the Colorado Plateau and San Juan Basin from AD 1 to AD 1130. Their socio-political hub was centered 80 miles north of the ZBVF at Chaco Canyon. At its zenith between AD 1100 and AD 1130, the Anasazi nation was a network of roads and hundreds of small farming communities extending over a 1300,000-square kilometer area (Magnum, 1990; Fagan, 1991). Many of these small settlements surrounded the ZBVF.

Within the lava beds themselves, researchers located more than 60 Anasazi campsites (Carlton, 1988). The bulk of these sites are near ice caves. Generally, these campsites are nothing more than simple rock shelters or circular walls of stone.

The primitive nature of these camps suggests that the Anasazi utilized the ice caves only sporadically, for example, during religious ceremonies. Large charcoal and ash deposits in most of the ice caves suggest that the Anasazi also melted the perennial ice for water. They dug shallow wells in at least two caves. Archaeologists used the abundant and characteristic black-on-white pottery fragments at these sites to demonstrate that ice cave utilization peaked during the Pueblo II phase (AD 950 to AD 1125) (Doleman, 1990; Marshall, 1991). Physical and climatic evidence suggests that cave ice accumulations were significantly more extensive at that time.

Fig. 3: Common findings in many caves in the Zuni-Bandera Volcanic Field: ice, ash and Anasazi pottery shards. (Photo by Harry A. Marinakis) .

After AD 1130, the Anasazi civilization rapidly declined. The reasons for this decline are not known, but many archaeologists point to multiple factors, including tribal or religious warfare. Whatever the cause, the final culminating event was a fifty-year drought cycle and subsequent crop failures. This drought is thought to have been precipitated by the Anasazi themselves through widespread deforestation of the region (Fagan, 1991). Tree ring analysis from logs in the Anasazi ruins and trees from the surrounding mountains suggests that the Anasazi were traveling further and further away from their settlements to collects logs for construction.

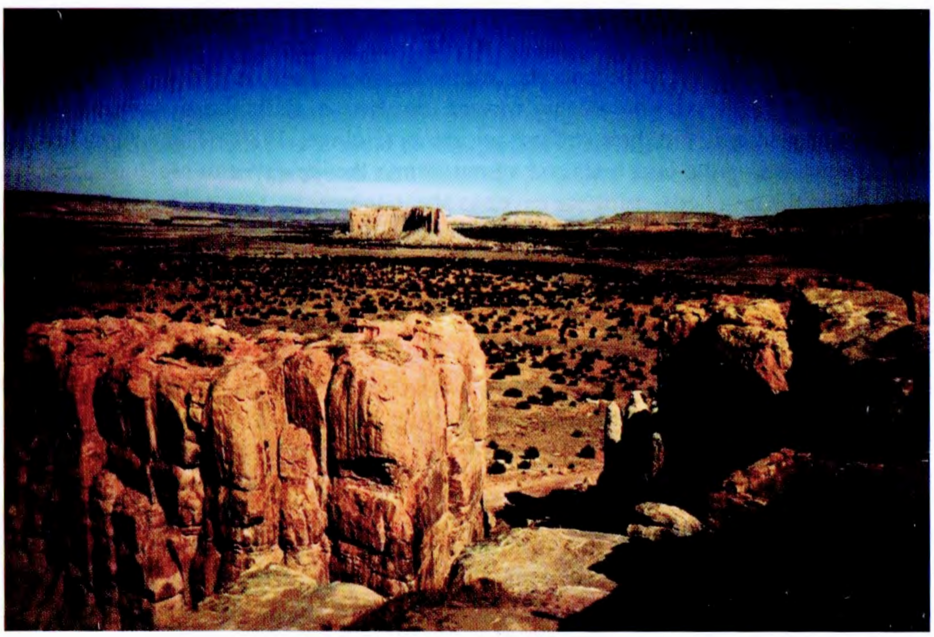

Fig. 4: A view from "Sky City," Acoma Pueblo. (Photo by Harry A. Marinakis).

Fig. 5: The remains of a bighorn sheep trap in a lava cave in the Zuni-Bandera Volcanic Field. (Photo by Harry A. Marinakis).

Fig 6 Mount Taylor mesa, circa 1877. Panorama from the eastern side, showing numerous volcanic necks. (Photo by Clarence Dutton, courtesy of the U.S Geological Survey.).

Pueblo Phase

Eventually the Anasazi completely abandoned Chaco Canyon and migrated to other regions. By AD 1200 new socio-political nuclei developed as people aggregated into fortified settlements of large pueblos that housed thousands of people. The modern pueblos near the ZBVF at Acoma, Zuni, and Laguna are examples of these settlements. Acoma Pueblo is also called "Sky City" because it was built on top of an easily defended mesa. The defensive nature of these pueblos is seen as further evidence that war may have played a pivotal role in the collapse of the Anasazi society (Fig. 4). The Acoma people, and to a lesser extent the Zuni and Laguna peoples, utilized the ZBVF for physical and spiritual sustenance as did their Anasazi ancestors (Holmes, 1989). The Acoma herded sheep and cattle in the fields surrounding the lava beds and ventured into the ice caves to replenish their water. They hunted Bighorn sheep in the lava beds, using the caves as sheep traps.

The Zuni harvested piñon nuts from seasonal camps near the lava beds and collected water from the caves. The ice caves also continued to be important religious sites. Then, in the sixteenth century, a new religion appeared that nearly destroyed the Pueblo way of life: Roman Catholicism. utilized the ZBVF for physical and spiritual sustenance as did their Anasazi ancestors (Holmes, 1989). The Acoma herded sheep and cattle in the fields surrounding the lava beds and ventured into the ice caves to replenish their water. They hunted Bighorn sheep in the lava beds, using the caves as sheep traps.

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European Invasion

Roman Catholic conquistadors, led by Francisco Vásquez de Coronado, first traveled in the area that is now New Mexico in the year AD 1540 (Powers et al., 1990 and Magnum, 1990). These Spanish explorers, and nearly all other Europeans who followed, saw "el malpais" as nothing more than an obstacle to their conquest for land and minerals.

Native Americans who got in the way were brutally dispatched. In 1598, Don Juan de Oñate slaughtered 800 residents of the Acoma pueblo (two-thirds of the population at that time) and then severed the left foot of all surviving men. War raged between the Spaniards and Native Americans off and on for three centuries. Often the Native Americans took refuge from the conflict by retreating into the lava caves of the ZBVF, which they stocked with provisions (Powers et al, 1990).

Westward Expansion

The lava beds and ice caves of the ZBVF received little interest by Europeans until the conclusion of the Mexican-American War in 1848. After the territory of Nuevo Mexico was conceded to the United States, Americans began the first systematic investigations of the ZBVF (Magnum, 1990). The first to explore the region were reconnaissance officers of the United States Topographical Engineers. Their goals were to scout the territory for military advantage and to establish communication routes between the forts (Dutton, 1885).

Other reconnaissance parties soon followed. In the early 1850s, a reconnaissance party led by Lieutenant A. Whipple and his accompanying by geologist Joules Marcou briefly explored the region on the ZBVF in search of suitable route for a transcontinental railway (Dutton, 1885). The next decade brought a flux of westward-bound settlers, many of whom got no closer to the Pacific Ocean than Grants, New Mexico. The settlers were protected from Navajo raids by U.S. Army soldiers stationed nearby at Fort Wingate. In 1873 another American survey party passed through the area, led by Lieutenant G.M. Wheeler of the now-famous Wheeler Survey.

In 1884, the newly formed U.S. Geological Survey sent an officer to the area that is now known as the Zuni-Bandera Volcanic Field of northern New Mexico. That officer was Clarence Dutton, a very well traveled and experienced geologist. Dutton wrote of his assignment:

"The topographic parties which had been engaged in mapping Northwestern New Mexico had just brought back accounts of some striking features in the vicinity of Mount Taylor, and these awakened so much interest that the Director was of the opinion that a single season could be spend with advantage in studying them... I was ordered to New Mexico to see what was there."

Clarence Dutton (Fig. 7) spent the summer of 1884 in the miserable heat of the Zuni-Bandera Volcanic Field. He wrote: "Even the sagebrush, the ashy bloom of the desert elsewhere, resents the scorching summer and refuses to stay, and the cacti, vengeful and repellant everywhere, here assume a still more cruel and misanthropic mien."

Dutton explored the volcanic landscape, the "malpais" as the Mexicans called it, and even mapped the McCarty's lava field. His final report, "Mount Taylor and the Zuñi Plateau" was published in the 6th Annual Report of the U.S. Geological Survey (Dutton, 1885). Dutton's report has become a geologic classic and it laid the foundation for modern geology concepts. In fact, it was Dutton who used the Hawaiian term "pahoehoe" to describe ropy lava.

During the 1880s the population of Grants swelled by the thousands when the Atlantic and Pacific Railroad built a railway line that sliced through the northern edge of the ZBVF. During the summer, these workers wantonly quarried ice from the largest ice cave in the lava beds, a cave that came to be known as the Grants Perpetual Ice Cave (Magnum, 1990).

Ice quarrying at the Grants Perpetual Ice Cave continued into the 1940s. The local population was interested in protecting the ice cave, but the United States government was not interested (Magnum, 1990). The owner of the ice cave developed a tourist attraction at the ice cave, and ice mining permanently ceased (Fig. 8).

The local efforts to preserve the Grants Perpetual Ice Cave were nearly thwarted by the far-reaching global events of World War Two. In the spring of 1944, Manhattan Project physicist K.T. Bainbridge was searching for sites for the first atomic bomb test. The ZBVF, already in use as an Army Air Corps conventional bombing range, was on his final list of three potential sites (Bainbridge, 1976 and U.S. Department of Energy, 1994). In his search for a test site, Bainbridge had numerous scientific and military requirements. He felt that any potential test site had to be flat to minimize terrain effects on the blast The weather needed to be consistently good with little haze and wind so that the optical sensors could operate properly. The site had to be far from ranches and other settlements to avoid contamination of civilians. The area had to be securable by military police. Finally, the test site needed to be close to Los Alamos Laboratory to minimize time lost to travel. Bainbridge narrowed his list of potential test sites to eight locations. In the order specified by Bainbridge himself (Bainbridge, 1976), these sites were:

1. Tularosa Valley, New Mexico
2. Journada del Muerto ("Journey of Death") Valley, New Mexico
3. Desert training area, Rice, California
4. San Nicolas Island, California
5. Zuni-Bandera Volcanic Field near Grants, New Mexico
6. Area near Cuba, New Mexico
7. Sand bars off the Texas coast
8. San Luis Valley, Colorado (Great Sand Dunes National Monument)

Bainbridge and his entourage made several trips to the proposed test sites. Their survey included automobile trips and low-altitude flights. Eventually they narrowed the list to three locations:

1. Journada del Muerto Valley, New Mexico
2. Desert training area, Rice, California
3. Zuni-Bandera Volcanic Field near Grants, New Mexico

Major General Leslie R. Groves, Manhattan Project's military commander, rejected the ZBVF because of the sizable local Native American population. General Groves did not want to have to deal with the problematic Secretary of the Interior Harold Sickles over the issue of Indians (Groves, 1962). General Groves also rejected the desert training area in California because he did not want to have to deal with the base's "disagreeable" commander, General George S. Patton (Szasz, 1984). Thus, the atomic bomb test site was established further south in the Journada del Muerto Valley, New Mexico. The nuclear weapon was detonated there on July 16, 1945, sparing the ZBVF from a nuclear blast.

The Space Program

The first scientific investigations of the ZBVF caves actually began as a spin-off of the Apollo expeditions to the Moon. President Kennedy's special message to Congress on May 25, 1961 heralded the beginning of the most important scientific endeavor accomplished by mankind. He said, "I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to the earth."

The manned space missions of Redstone, Gemini and Apollo are well known to all. Less appreciated are the lunar-exploration missions of Ranger, Surveyor and Lunar Orbiter that were conducted along with the manned space flights.

These unmanned explorations a'a rubble provided the detailed understanding of the Moon's gravitational fields and surface characteristics that, in the end, permitted the safe landing of Apollo 11 in the Sea of Tranquility on July 21, 1969.

The spacecraft of the Ranger program (1961-1965) were designed to take close-up images of the lunar surface with a resolution of 5 meters. Simply designed, they were programmed to fly straight down and impact the moon's surface, taking photos all the way down. The spacecraft of the Surveyor program (1966-1968) were designed to test the ability to land safely on the moon. Once landed, the spacecraft tested lunar soil mechanics and took close-up photos of the lunar surface. The spacecraft of the Lunar Orbiter program (1966-1967) were designed to completely map the lunar surface at a resolution of 2 to 18 meters. The maps were used to choose landing sites for the Apollo missions.

It was during the course of these unmanned space missions that the Ranger and Lunar Orbiter cameras revealed the first detailed photos of the rilles on the lunar surface. These rilles were thought to be lunar pyroducts. Lunar rilles had been known since the 1684 discovery of Hyginus Rille by Christian Huygens. However, the lunar rilles were unlike anything known on the earth in terms of size and morphology, even when accounting for differences in gravity and chemical composition. Lunar rilles approach a'a rubble size of the Grand Canyon (Cruikshank et all, 1972). So keen was the interest in rilles that the astronauts of Apollo 15 actually landed at the Hadley Rille in 1971.

Geologist Kent Carlton conducted the first exhaustive inventory of ZBVF caves in 1988 under a contract with the National Park Service. Starting with geologic maps, topographical maps, and aerial photographs, Carlton explored most of the region first by helicopter and later by foot. Much of Carlton's work was solo. In documenting his work in the Outlaw area (Fig. 11), Carlton wrote that he explored the caves "alone with all the hazards, real and imagined, that caving without a backup entails." In his final report, 1988 Lava Tube System Resource Inventory Report, Carlton identified about 100 caves in the ZBVF.

Fig. 7: The Grants Perpetual Ice Cave. (Photo by Harry A. Marinakis).

Fig. 8: The Grants Perpetual Ice Cave. (Photo by Harry A. Marinakis).

Lunar Rilles and Terrestrial Counterparts

Scientists turned their attention to pyroducts on Earth to better understand their lunar counterparts. Cruikshank et al (1972) wrote, “Much can learned about the probable formation of small-scale structures on the lunar surface by first-hand observations of active terrestrial lava flows, pit craters, lava lakes, and other phenomena, purely from a dynamic morphological point of view. Physical studies of terrestrial volcanoes, considered with a view toward lunar problems, will surely give us an even more valuable insight into the origin and evolution of the small-small topography of the moon.” Scientists explored pyroducts in the ZBVF, Hawaii, Oregon, Washington and Kenya and wrote dozens of papers explaining lava tube formation.
Gerard Kuiper, Chief Scientist of Ranger program and father of modern planetary science, was particularly interested in the similarities between the lunar rilles (Fig. 9) and the pyroducts of the Zuni-Bandera Volcanic Field (Elston et al, 1987).

Kuiper asked the scientists Hatheway and Herring to investigate the pyroducts of the Zuni-Bandera Volcanic Field. In their 1970 paper titled "Bandera Lava Tubes of New Mexico, and Lunar Implications," Hatheway & Herring mapped and characterized the major pyroducts and caves in the ZBVF. Their work was followed by that of Causey (1971), Maxwell (1986), Andrew (1995) and Cascadden (1997).

The National Park Service finally became interested in the ZBVF during the late 1960s. After nearly three decades of negotiation with New Mexico state agencies and local landowners, El Malpais National Monument was created on December 31, 1987 (Magnum, 1990). Additional lands around the ZBVF were incorporated in the El Malpais National Conservation Area and the El Malpais Wilderness Area.
Cavers were active in the ZBVF long before its inclusion into the national park system. Members of the Southwestern Region of the National Speleological Society (SWR-NSS) and Albuquerque's Sandia Grotto have been exploring the lava caves for many decades. Exactly how and when the lava caves were discovered by cavers is not known. The location of many caves was common public knowledge. For instance, it is said that during the 1960s and 1970s, anyone could drive into any petrol station in Grants to get directions to Truckett's Guano Cave (now known as El Calderon Bat Cave). Similarly, detailed information about ZBVF lava caves was common Grotto knowledge. However, both present and past SWR-NSS members consistently identify three people as being important in the history of ZBVF caving: Victor Polynak, Michael Goar, and Cyndi Mosch.

Victor Polynak probably knows the ZBVF better than anyone else. Formerly a resident of Grants during the 1960s and 1970s, Polyak was perhaps the first caver to extensively explore the ZBVF and he is credited with discovering many of the region's finest caves. Michael Goar and Cyndi Mosch have also been two of the most productive cavers in ZBVF. Together they spear-headed efforts that produced some of the first survey maps of major lava caves. Some of these superb maps include Brewer's Cave (1989), Navajo Ice Cave (1989), Junction Cave (1990), and Braided Cave (1995).

Goar and Mosch also conducted extensive and detailed exploration of the Hoya de Cibola System in the ZBVF. Crawling through tight passage and breakdown, they made difficult connections between caves to establish the Braided System (Fig.10) as the longest segmented cave system in the ZBVF cave inventory (over 2,700 meters of cave pasageway).

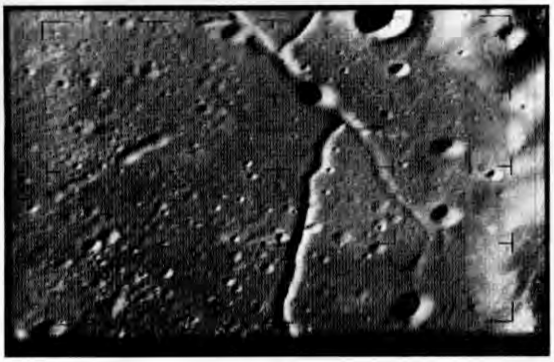

Fig. 9: *Lunar rilles, as photographed by a Ranger spacecraft. (Photo courtesy of NASA.).*

In August 1997, this author completed a follow-up cave inventory project through the National Park Service, with support from the Boy Scouts of America, the Southwestern Region of the NSS, the Sandia Grotto in Albuquerque, and other cavers and scientists. In addition to discovering new caves, this project integrated, augmented, and refined all available cave data.

Despite these cave inventory projects of Carlton (1988) and Marinakis (1997), vast areas of the ZBVF still have very little record of exploration, and dozens of caves have still not been entered. Cave exploration has been limited by the inferior roads within the ZBVF, the long hikes (often 10-15 kilometers round-trip) and the inherent difficulty in locating caves in the wilderness. The Monument's rocky and muddy thoroughfares are major impediments to anyone who does not own a four-wheel-drive truck. Some of the caves are too far from the road to explore in a single day, but the high temperatures and lack of water make back-packing very difficult. Furthermore, only skillful backcountry navigators are able to negotiate the rugged and confusing terrain of lava beds.

During the past decade, the National Park Service continued to partner with the National Speleological Society to explore and map the caves. Then, in 2006, the disease White Nose Syndrome was discovered in bats in numerous caves in New York. The mortality rate was as high as 90 percent in some areas. The disease was subsequently identified in hundreds of other caves across the northeastern United States. Each month more and more infected caves are identified. In order to prevent the spread of the disease, the federal government closed most caves within its jurisdiction. These closures also apply to the caves of the Zuni-Bandera Volcanic Field. There was so much more to explore in the ZBVF, but cave exploration has been suspended indefinitely. Perhaps if Nose Syndrome can become better understood then the caves will be re-opened. Until then, it appears that the story of cave exploration in the ZBVF has suddenly and unexpectedly ended.

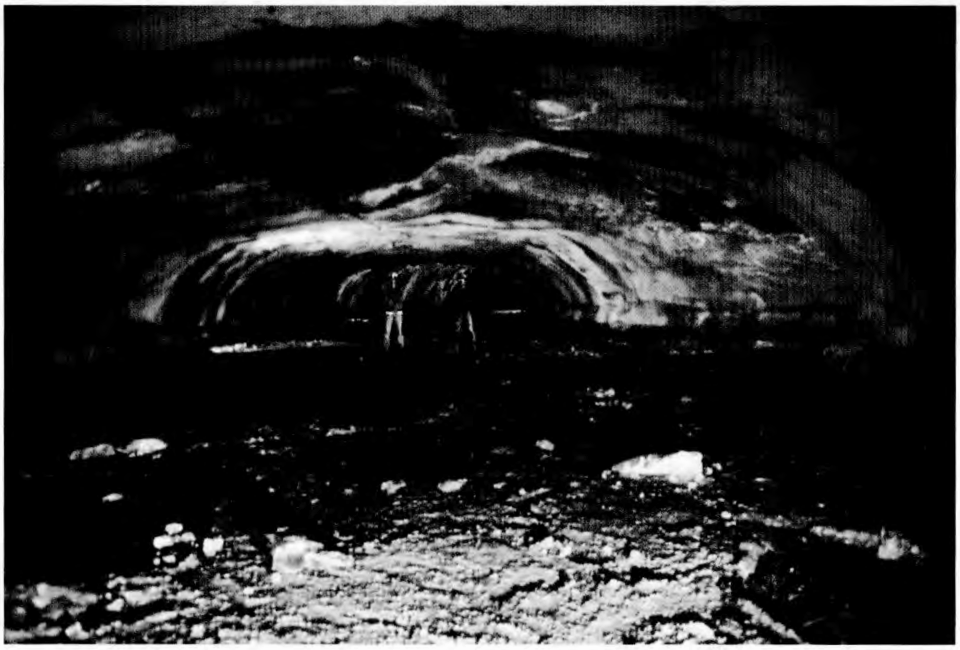

Fig. 10:: Braided Cave. (Photo by Harry A. arinakis).

Photo 11: Outlaw Cave. (Photo by Harry A. arinakis).

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