Inflationary versus Crusted-over Roofs of Pyroducts (Lava Tunnels)

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Abstract

Many types of lava caves exist. Of these longitudinal conduits that serve for long-distance, underground, post-eruptional transport of (with a few exceptions) basaltic lavas are the largest and most common. They represent the mechanisms building low-slope (often <2°) shield volcanoes. Originally described from Iceland, these caves were observed actively forming in Hawai‘i and in 1844 were named “pyroducts” (a term taking precedence over the later - post 1940 - term “lava tube” that may incorrectly imply that lava can flow upward like in plumbing tubes). However, formation of pyroducts is still a subject of debate in textbooks.

During recent decades, interest in these transport ducts increased also because of the discovery of long volcanic flows on the Moon, Venus, Mars and Io. The longest surveyed uninterrupted pyroduct is Kazumura Cave (65.5 km) (Hawai‘i, Kilauea Volcano) and the longest duct-supported flow on Earth is the 160 km long Undara flow, site of our symposium. The Hawaiian Speleological Survey has explored and surveyed many other caves on Hawai‘i and elsewhere that allow us to study the formation and evolution of these “pyroducts” from the inside.

Apparently several modes exist: In the “inflationary” mode lava flows grow at their distal tips where hot lava quickly covers the ground in thin sheets. The next advance will lift this sheet up (“inflation”) before forming the next distal surface sheet. The process can be repeated many times, forming a primary roof with several sheets, separated by sheer interfaces (only the first or top sheet displays ropy pāhoehoe surfaces). Another mode is the “crusting over of channels” that appears to have two cases: closure by slab jam and closure by lateral shelf growth.

In the first case shoals, blocks, lavaballs and secondary clasts of already solidified lava form a “log jam” on the surface of a channelized lava flow. This jam is highly porous and not very stable. But since it floats on the channel, it is injected by molten lava from below that form characteristic, upward directed “squeeze balls”. In this way the roof is gaining mass and stability. The high porosity allows air to circulate through the forming roof. It can not only oxidize the lava slabs, turning them reddish, but also freeze-out layers of lining originating from the top of the hot lava in the channel. These layers often show thin lamination and can grow to a thickness of 10 cm or more, also stabilizing the roof. It is conceivable that the roof may break up several times, forming larger agglomerations. Once it is established, it can also be reinforced by later overbank events depositing layers of pāhoehoe on top of the roof. Often this secondary reinforcement is the only stable element in the roof structure while the slab-jam caves-in once the lava below has receded, depriving the roof of its buoyancy.

Closure by lateral shelf accretion, on the other hand, apparently needs a rather calm and steady lava flow and is therefore most probably operating in the formation of secondary roofs inside the downcutting pyroduct and not so much in the formation of primary roofs.

Our investigation shows that, apparently, most of the long Kilauea ducts, including Kazumura, Keala, Ainahou, Keauhou Trail and others, as well as several of the Hualālai Caves, such as Huehue, are of the inflationary type, while the Mauna Loa Kipuka Kaohina Cave System is of the slab-jam type.

Examples of roof sections of some of these caves will be given, illustrating the importance of studying roof structure at pukas and at sites of breakdown in the cave.

1. The problem

Many types of lava caves exist. Of these, longitudinal conduits that serve for long-distance, underground, post-eruptional transport of (with a few exceptions) basaltic lavas, are the largest and most common. They represent the mechanisms building low-slope (often <2°) shield volcanoes. Originally described from Iceland (e.g., Kempe, 2008), these caves were observed actively forming in Hawai‘i and in 1844 (Coan 1844) were named “pyroducts” (a term taking precedence over the later - post 1940 - term “lava tube” that may incorrectly imply that lava can flow upward like in plumbing tubes) (for history of term pyroduct see Kempe 2002; Lockwood & Hazlett 2010). However, the importance and formation of pyroducts is still of debate in geological and volcanological textbooks that turn out to be extremely imprecise - if they mention pyroducts at all:

- Gordon Macdonald & Agatin Abbot (1970) state: "*The feeding rivers of pahoehoe flows quickly crust over and develop more or less continuous roofs, and thenceforth the lava stream flows within a tunnel of its own making.*" (p. 26).
- Ronald Greeley (1987) writes: "*The term 'lava tube' may be defined as the conduit beneath the surface of solidified lava through which molten lava flows. 'Lava channels' however contain non-roofed rivers of lava that frequently develop surface crusts. Many (if not most) lava tubes develop from the roofing of channels. ... the distinction between channels and tubes is made in regard to the roof crust. So long as the crust remains mobile and free-floating on the active flow the structure is regarded as a channel section in which the crust is continuous across the active flow and fixed to the immobile parts of the flow are considered lava tubes. Thus even if the roof collapses when the flow drains the feature is considered to be a lava tube…*" (p. 1590).
- Robert and Barbara Decker (1991) state: *"Beneath the hardened surface of a pahoehoe flow, hot lava still flows rapidly in tunnels that supply the advancing front. These lava tubes form a complex network that transports molten rock from the vent to flow front over ... several km. ... Small lava tubes feeding individual lobes apparently coalesce as the multiple flow lobes pile up and form lava tunnels as much as 10 m in diameter and many km long."* (p. 80).
- Peter Francis (1993) summarized *"Lava tunnels form when the surface of a flow crusts over, while hot lava continues to flow beneath. If the rate of flow is sufficiently fast the flow may erode its way thermally into underlying lava, producing ... distinctive, figure-8-shaped profiles. When the lava supply is cut off, the lava filling the tube drains away ..., leaving behind an empty conduit."* (p. 149).
- Jacque-Marie Bardintzeff (1999) writes: "*An den Rändern des Lavastromes, die schneller als die Strommitte erstarren, bilden sich manchmal richtige „Dämme", die die Lava kanalisieren. Wenn dann auch das Dach des Lavastromes erstarrt, fließt die Lava durch einen Tunnel… . Später kann sie unter ihrer festen Kruste heraus fließen und einen weithin offenen Lavatunnel hinterlassen, ... der mehrere km Länge erreichen kann*." (p. 77). ("At the fringes of the lava flow, that solidify faster than the center of the flow, real dams can sometimes form that channelize the lava. If then also the roof of the lava flow congeals, the lava flows through a tunnel … Later it can flow out from underneath its solid crust leaving a wide open lava tunnel, … that can reach several kilometres in length". Translation by author.)
- Paul Spudis in the *Encyclopedia of Volcanoes* (2000) defines lava tubes as: "*A lava channel that is partly or completely roofed over to enclose the lava stream may form a cave after the flow has cooled*." (p. 697).
- This long-standing theme of "crusting-over of channels" as the origin of pyroducts is still dominant in Jack Lockwood's (Lockwood & Hazlett 2010) chapter, albeit followed by the inflation mode of information: "*On steeper slopes ... pāhoehoe flows are ... fed by well-defined channels… these channels will commonly crust over to form pyroducts. The formation of pyroduct roofs involves two processes: a) narrowing of the channel rims by freezing of lava levees along channel walls, and b) the accretion of plates of crust that are skimmed off channel surfaces .... Once a pyroduct roof segment is established that roof forms a blockage for crustal fragments moving downstream and the roofed-over area will rapidly propagate upstream as more crustal fragments plate onto the pyroduct entrance. Pyroduct roofs are also thickened by new lava that may flow onto them .... Where pāhoehoe flows reach more gentle terrain channel development mostly ceases and is much less important a mode of pyroduct development. Most lava instead is supplied by high pressure inputs beneath inflating crusts (Hon et al. 1994). Such flowage tends to be concentrated along the most efficient pathways which evolve into persistently active pyroducts as eruption continues. ...*" (pp. 140-141).

These statements are derived from watching active lava flows, but they entirely lack the evidence gained from studying lava caves internally.

2. Pyroduct roofs

During the last decades, interest in volcanic surface placement increased also because of the discovery of long volcanic flows on Moon, Venus, Mars and Io. The longest surveyed uninterrupted pyroduct is Kazumura Cave (65.5 km total, 41 km main trunk length) (Hawai'i, Kilauea Volcano) and the longest duct-supported flow on Earth is the 160 km long Undara flow, site of our symposium (Atkinson & Atkinson 1995). The current Kilauea SE-Rift eruption provided ample opportunity to study pāhoehoe flows giving new insight into pyroduct formation. In parallel the Hawaiian Speleological Survey has explored and surveyed hundreds of caves on Hawai'i and elsewhere that allow to study the formation and evolution of pyroducts from the inside. Specifically the study of roof sections is needed if we want to progress in our understanding of pyroduct formation.

It has now become clear that several modes of pyroduct formation exist:

In the "inflationary mode" lava flows grow at their distal tips where hot lava quickly covers the ground in thin sheets. The next advance will lift this sheet up ("inflation") before forming the next distal surface sheet (Hon *et al.* 1994). The process can be repeated many times, forming a primary roof with several sheets, separated by shear interfaces (only the first or top sheet displays ropy pāhoehoe surfaces). Fig. 1 gives an idealized cross-section of a roof of a cave developed by inflation and Fig. 2 gives an interpreted view of a section through an inflationary primary roof of the Huehue Cave, Hawai'i. One of the misconceptions about pyroducts (also expressed in several of the above quotations) is the suggestion

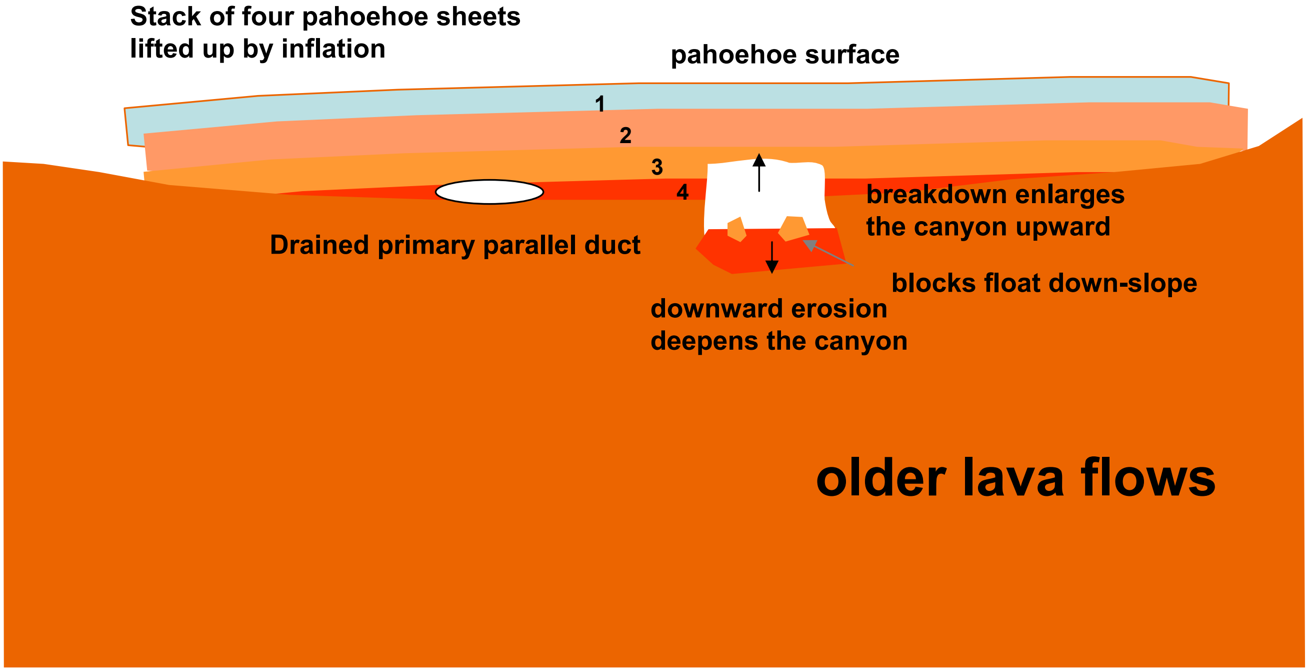

Fig. 1. Sketch of the structure of a primary roof formed by "inflation".

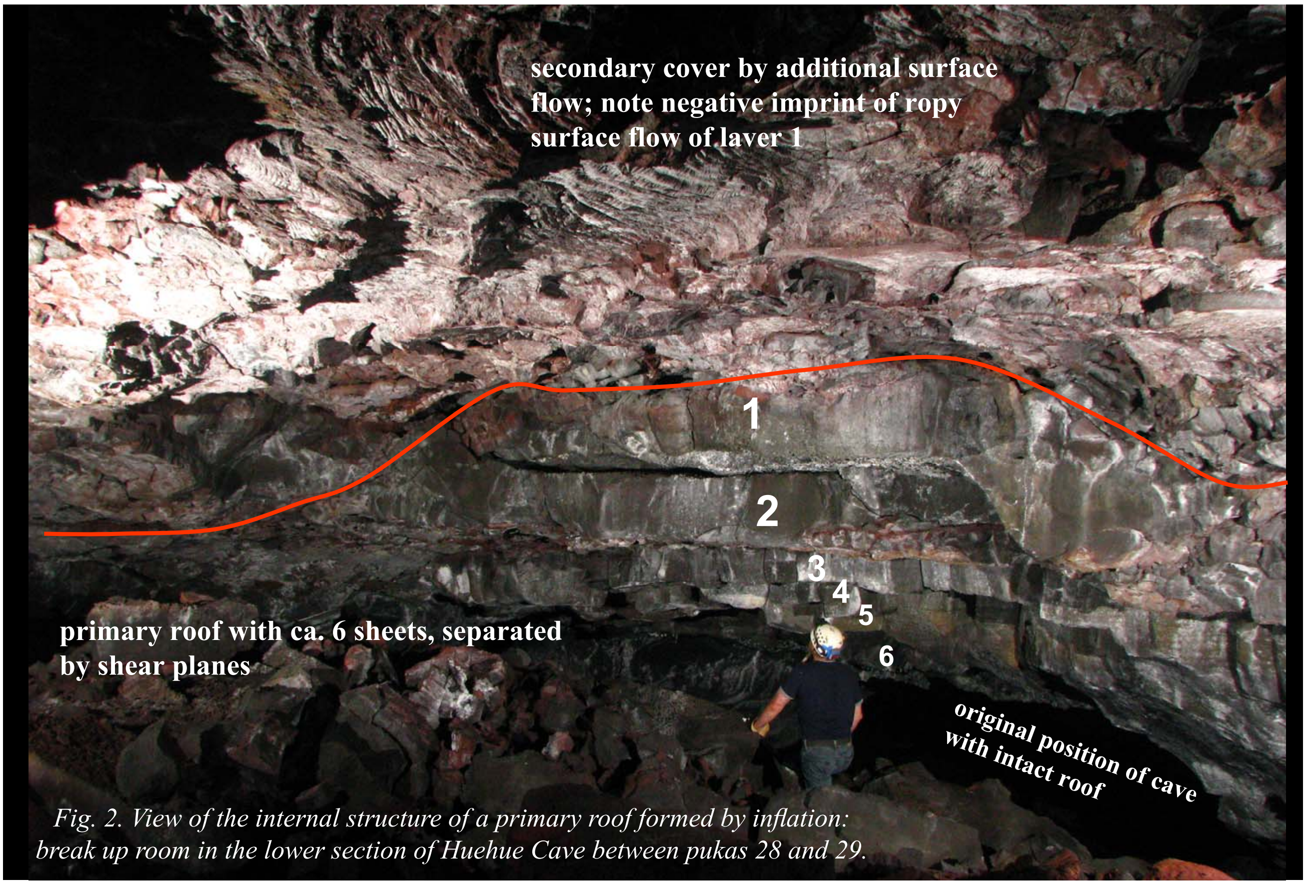

Fig. 2. View of the internal structure of a primary roof formed by inflation: break up room in the lower section of Huehue Cave between pukas 28 and 29.

that caves become only accessible after the "tube has been drained". The study of lava caves has shown that almost all of the caves have already a gas-space above the internal lava river due to massive down-cutting (Allred & Allred 1997; Kempe 1997, 2002; Greeley *et al.* 1998). Thus, even if the residual lava did not drain and solidify inside the caves, we would still be able to access them. It is also a misconception that the roof is upheld by the lava flowing below by buoyancy. Inflationary lava cave roofs hold up because they form low natural vaults with their weight resting on the walls. The internal development of pyroducts has been summarized in Kempe (2002, 2009). Fig. 3 gives some of the features that appear in a typical inflationary cave during its prolonged activity (Kempe 2010).

The so-much-described "crusting-over of channels" mode appears to have two cases: closure by "log jam" and closure by "lateral shelf growth". In the first case slabs, blocks, lavaballs and secondary clasts of already solidified lava form a "log jam" on the surface of a channelized lava flow (Fig. 4). This "jam" is highly porous and not very stable. But since it floats on the channel, it is injected by molten lava from below that forms characteristic, upward directed "squeeze balls" (Fig. 5). In this way the roof gains mass and stability. The high porosity allows air to circulate through the forming roof. It can not only oxidize the lava slabs, turning them reddish, but also freeze-out a lining originating from the top of the hot lava in the channel. This layer shows often thin lamination and can grow to a thickness of 10 cm or more, also stabilizing the roof. It is conceivable that the roof breaks up several times, forming larger agglomerations. Once it is established, it can also be reinforced by later overbank events depositing layers of pāhoehoe on top of the roof. Often this secondary reinforcement is the only stable element in the roof structure while the slab-jam collapses once the lava below recedes, depriving the roof of its buoyancy.

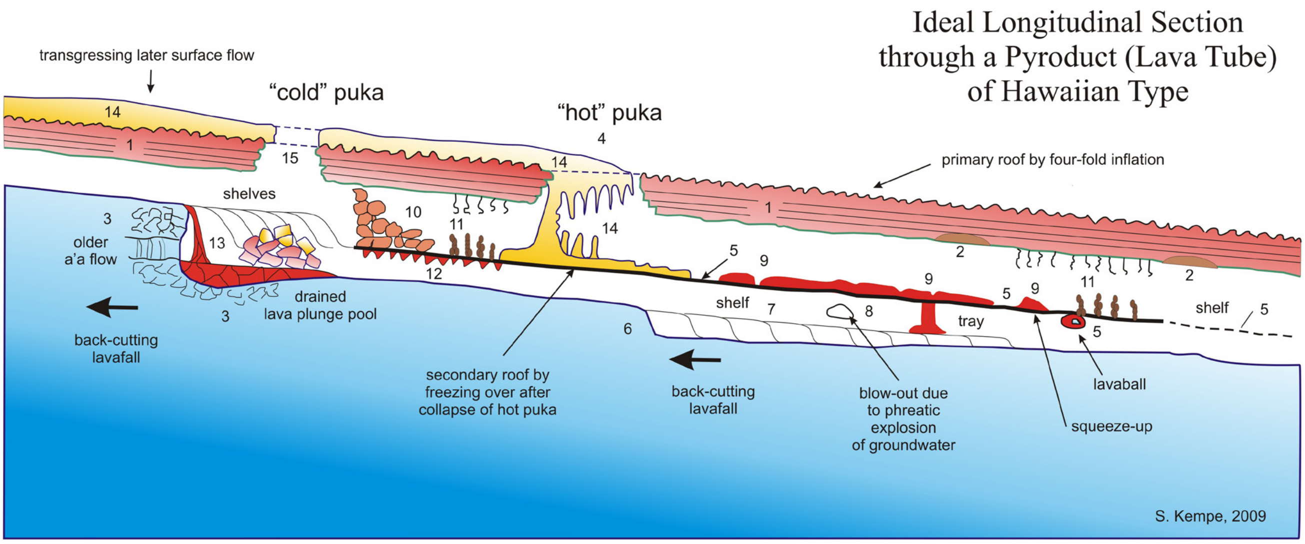

Fig. 3. Scheme of the variety of rock-speleothems tied into the evolution of a lava–pyroduct of Hawaiian type: (1) Primary roof with four inflation layers. (2) Higher passage labyrinth that was drained by the lava while the main thread of flow concentrated into a main channel that cut down into lava of older eruptions below. (3) A back-cutting lavafall has created a large underground canyon and impressive plunge-pools halls. (4) A collapse of the primary roof ("hot puka"; breakdown removed) and consecutively intruding cold air causes solidification of the lava river surface and forms a "secondary roof" (5). (6) Below the secondary roof, erosion continues and a new lavafall cuts the tube further down. (7) Back-cutting leaves curved shelves marking temporary lava fall positions. (8) Where water can enter the tube the thin and hot glazing can be expanded into bubbles, finally bursting. (9) Spills occur from below, reinforcing the secondary ceiling and seeping back through the secondary roof, to be transformed into pendants with horizontal flat feet ("trays"). Other spills form only local "squeeze ups". (10) Boulders derived either by roof or wall collapse or eroded from the floor float on the lava river and become coated spherically. Some are swept onto the secondary roof, blocking its upper end; others may get stranded below that roof. (11) The still hot primary roof extrudes residual melt that drips to the floor, being frozen by intruding cold air to form stalagmitic piles of discrete drips. Further extrusion is forming helictite-like "pig-tails" and cylindrical stalactites. (12) Final subsidence of flow and detachment from ceiling leaves cone-shaped stalactites, often consisting of many layers below ceiling. (13) The lava lake freezes-over, its last lava empties to below causing the crust to collapse. Also, the last bit of flow consolidates at the lava fall, sometimes forming irregular columns. (14) After the cave cooled, a younger flow crossed the cave and marginally flowed into the hot puka, forming a large column, stalactitic curtains and large stalactites. (15) The roof collapses again ("cold puka"; breakdown blocks preserved below), piercing both the primary roof and the later lava overlaying it. Such collapses often occur were a large hall exists underground (Kempe, 2010).

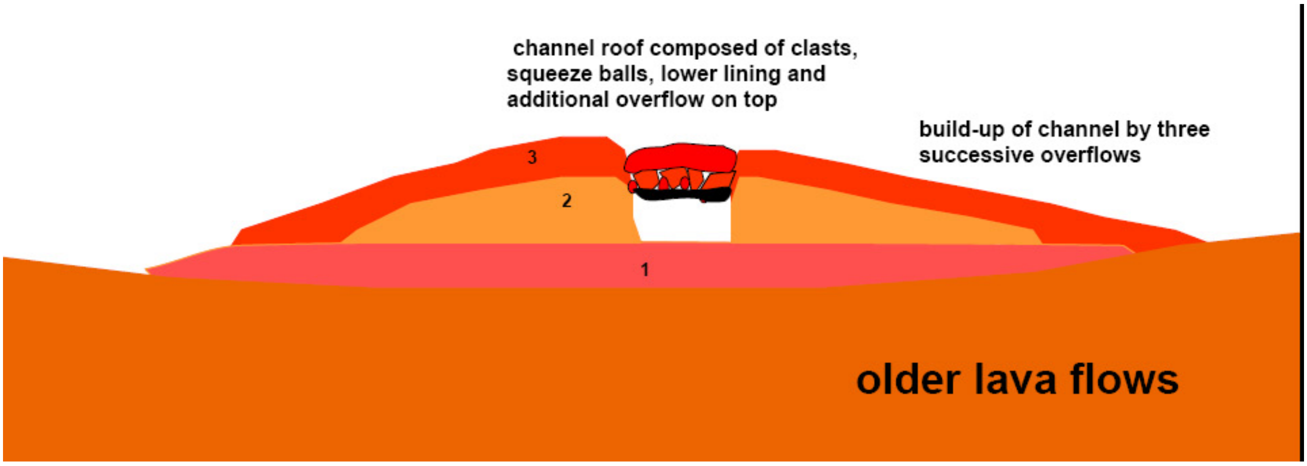

Fig. 4. Scheme of a cross-section through a roof, formed by the crusting-over of a channel by the agglomeration of floating clasts.

Closure by lateral shelf accretion (Fig. 6) on the other hand apparently needs a rather calm and steady lava flow and is therefore most probably operating in the formation of secondary roofs (Fig. 7) inside the down-cutting pyroduct and not so much in the formation of primary roofs.

3. Examples and discussion

Our investigation shows that apparently most of the long Kilauea ducts, including Kazumura, Keala, Ainahou, Keauhou Trail and others, as well as several of the Hualālai caves, such as Huehue, are of the inflationary type. Also all of the pyroducts studied in Jordan are inflation caves, sporting uninterrupted lava

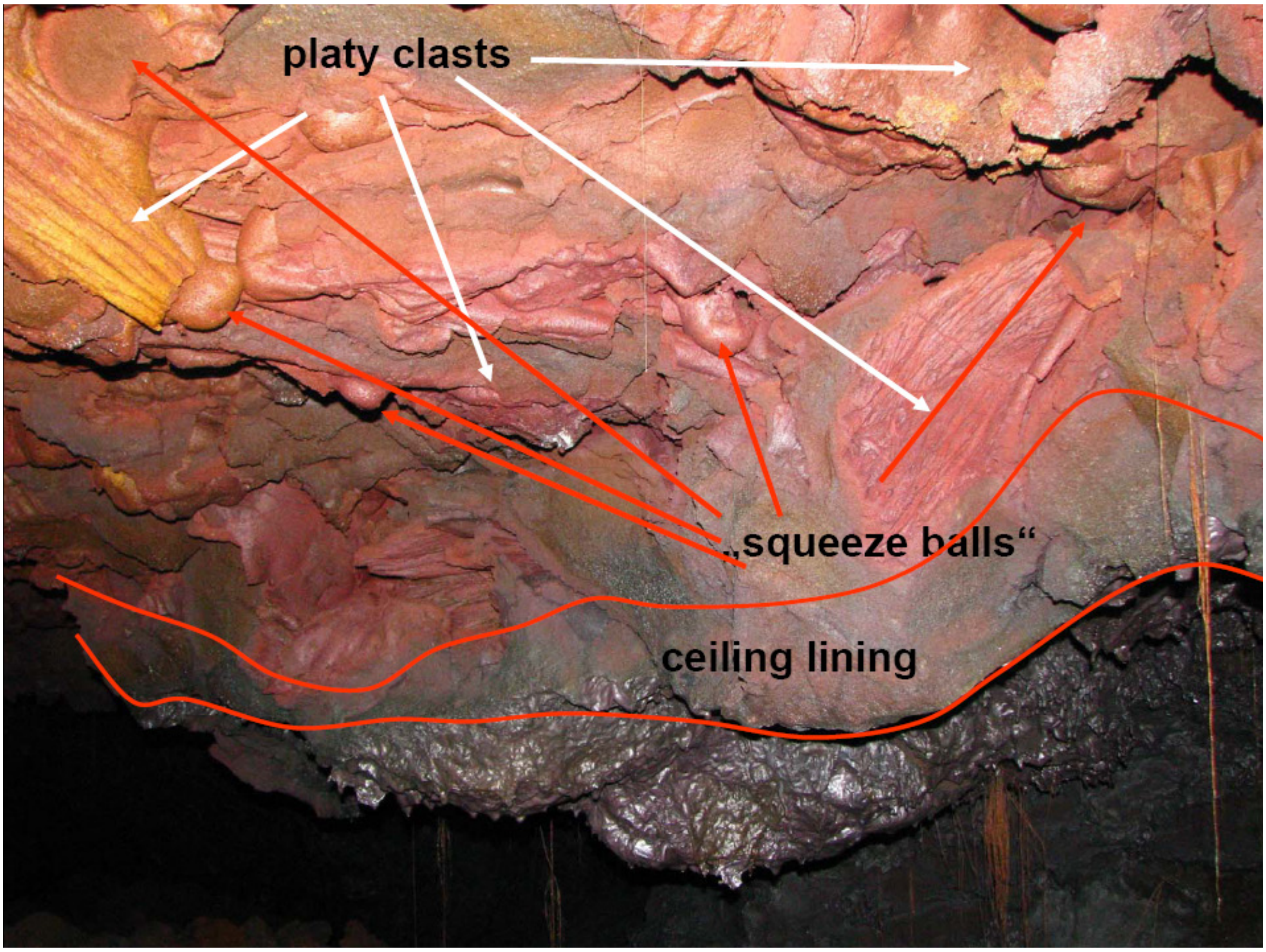

Fig. 5. Structure of a section of roof from Poha Cave, a section of Kula Kai Cavern. Individual slabs have been deposited in various orientations, some of them visibly thin pahoehoe slabs. “Squeeze-balls” were injected from below into the clasts of an agglomerated roof. The high porosity of the roof allowed air ventilation that caused recrystallization of glasses to fine-grained hematite, coloring the surfaces red. Cooling also caused the solidification of a ceiling lining.

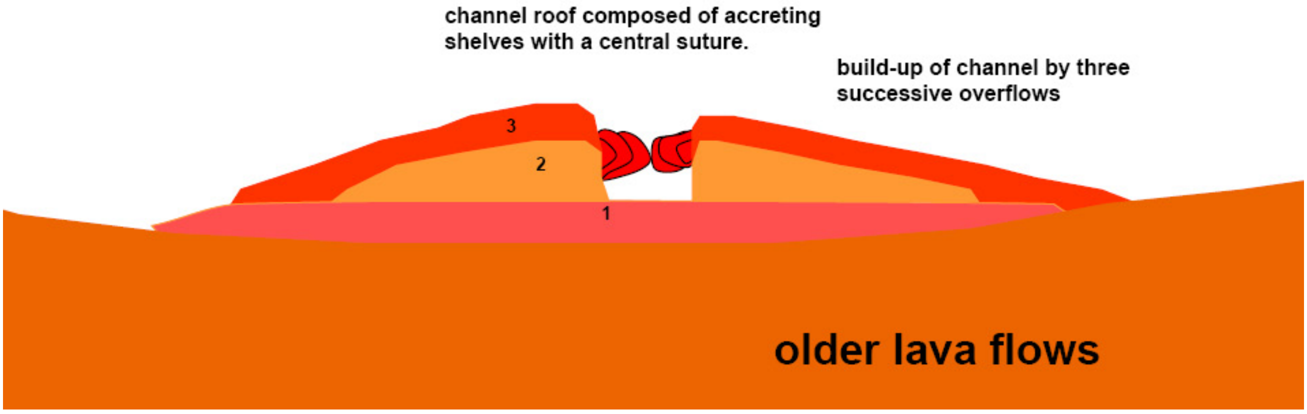

Fig. 6. Scheme of a cross-section through a roof, formed by the crusting-over of a channel by accretion of levees.

Fig. 7. Accretionary lateral shelf growth as part of a secondary ceiling in Lost Brother Cave, Hawai'i.

sheets as roofs (Kempe *et al.* 2006).

Inspection of the Mauna Loa Kipuka Kaohina System (Kula Kai Cavern) in March 2010 by the authors on the other hand showed that it appears to have formed by the crusting-over process of the slab-jam type (Fig. 5). The system is a "multiple-trunked" pyroduct (Kempe 2009) in which passages are produced on top of each other by multiple overflows interconnected with each other also vertically. The source of these overflows seems to be a deep-seated master conduit running NW-SE along the NW border of the system. It is itself not accessible any more. It produced a local flow ridge, that later caused the transgressing 1907 flow to split and to form two tongues on either side of this ridge. From the master conduit multiple flows issued that did not follow the direction of the master down-slope but flowed off the flank of the ridge to the SSE (Fig. 8). Lava was produced so rapidly that the lower, still active passages were buried below newer, younger ones on top. The upper passages must have been drained first and then the older, lower ones that in

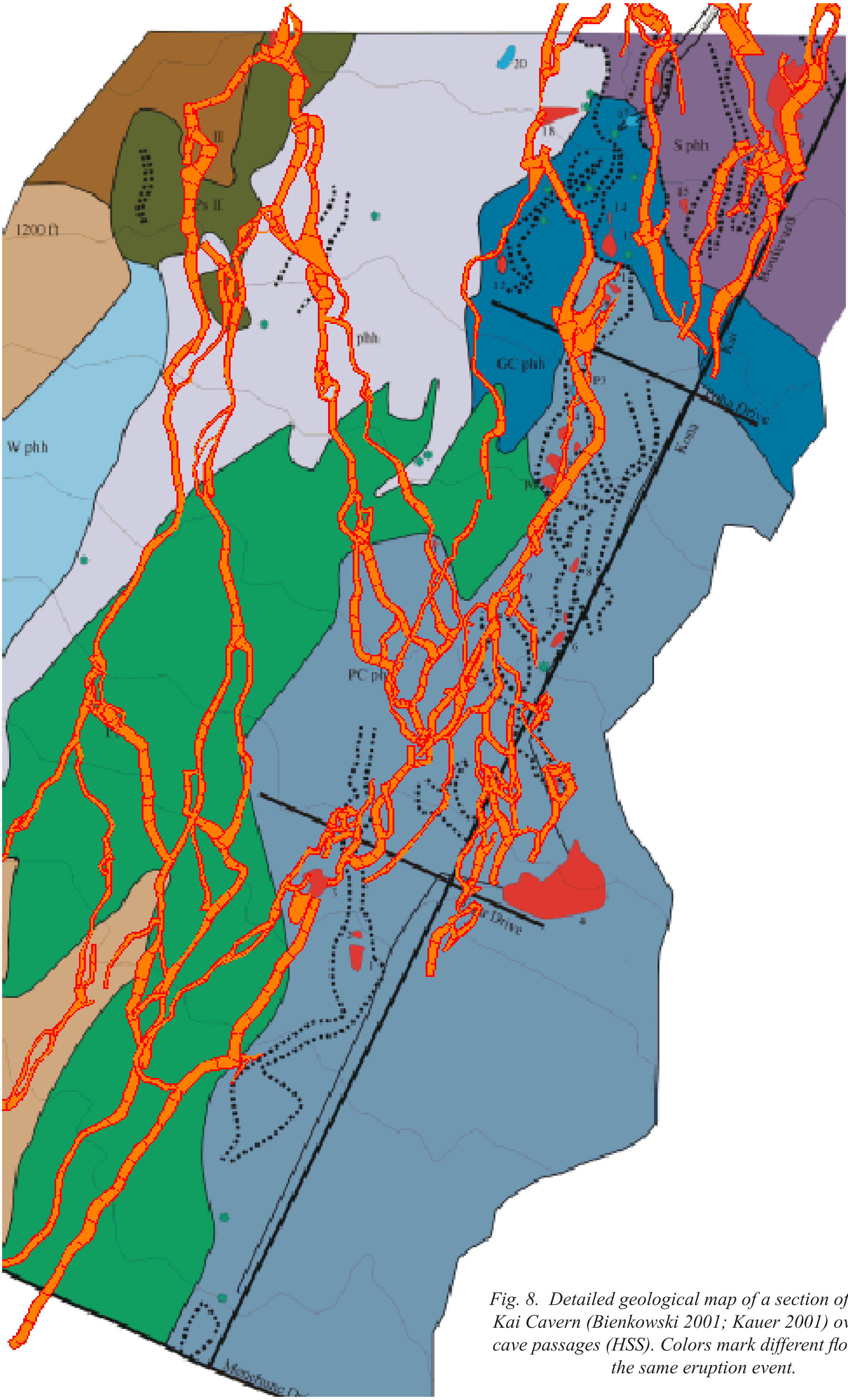

Fig. 8. Detailed geological map of a section of the Kula Kai Cavern (Bienkowski 2001; Kauer 2001) overlaying cave passages (HSS). Colors mark different flows of the the same eruption event.

fact must have been filled up to the ceiling, in contrast to the inflation-type caves in which lava flows mostly with an open surface. Successive overflows produced more surface flows, some of them pahoehoe, others a‘a on top of the existing subterraneous maze. These flows were mapped by Michael Kauer and Robert Bienkowski in 2001 (Fig. 8) yielding a pattern not related with the conduits below due to the processes described above.

A cave with the primary roof formed by lateral growth of levees cannot be named at this time. This process is mostly seen in the formation of secondary ceilings inside the already existing pyroduct.

Certainly more detailed studies of roof structure are needed in many more caves to show what the proportions are between caves formed by inflation and by crusting-over. From the listed examples one can doubt that the majority of caves are formed by the crusting-over process, as suggested by the cited text books.

The statement of Lockwood & Hazlett (2010, p. 140-141; see above): “*On steeper slopes ... pāhoehoe flows are ... fed by well-defined channels... these channels will commonly crust over to form pyroducts. ...Where pāhoehoe flows reach more gentle terrain channel development mostly ceases and is much less important a mode of pyroduct development.*” suggesting that channel- and inflation-derived caves are caused by differences in slope, cannot be substantiated by our observations. Specifically the comparison of the Puhia Pele Channel System (Lerch 1999) with the parallel Huehue Cave (both erupted one after the other in 1801 during the last eruption of the Hualalai, Hawai‘i; Fig. 9), developed side by side with an equal slope profile, shows that slope cannot be the governing factor differentiating between the two cave-forming processes. Alternatively, we suggest that flow rate is the important factor. The transport rate of lava through the Huehue Cave was limited by cross-sections of ca. 2 m^2 while the channel of the Puhia Pele system has a larger cross-section. Flow rate does not say anything about flow duration that may well have been much longer for the Huehue pyroduct than for the Puhia Pele channel.

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References

Allred, K. & Allred, C. 1997 Development and morphology of Kazumura Cave, Hawai‘i. *Journal of Cave Karst Studies,* 59(2): 67-80.

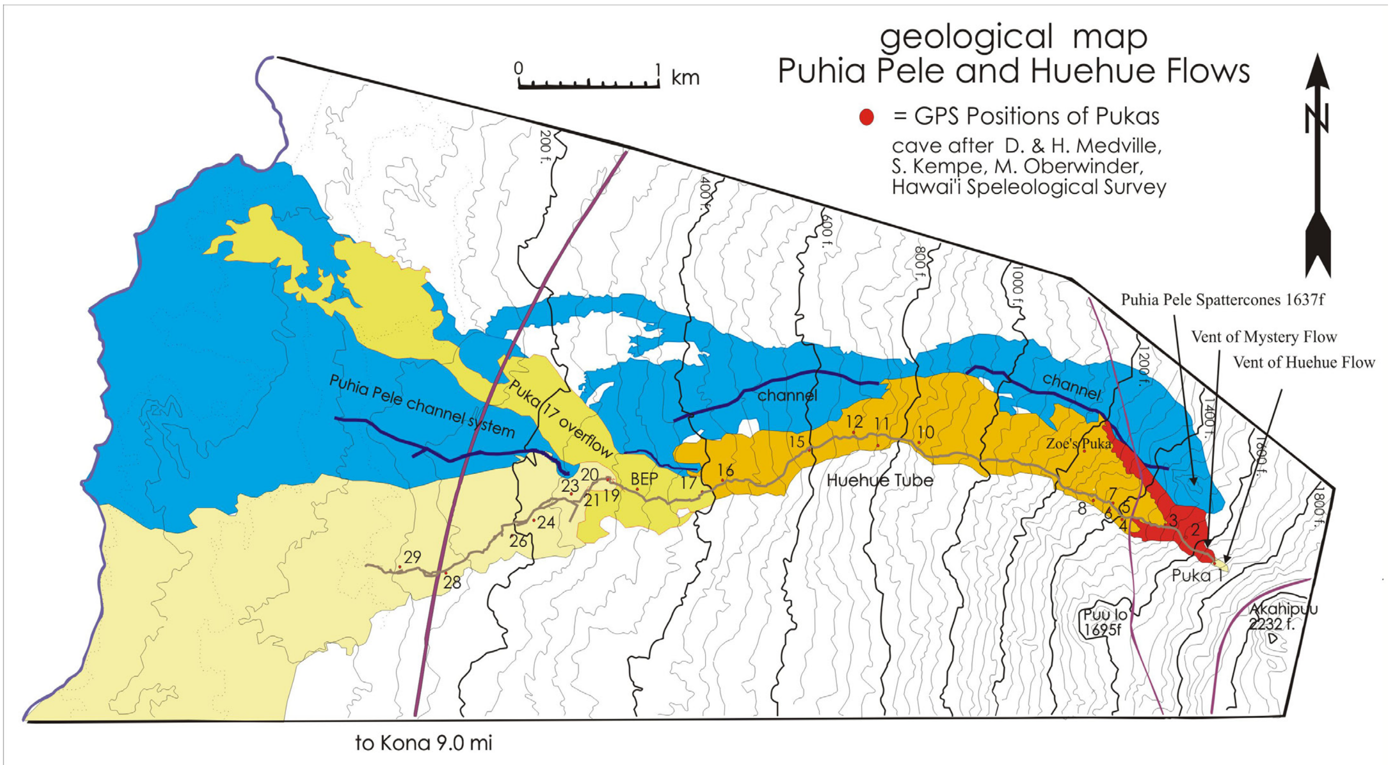

Fig. 9: Map of the flows of the 1801 eruption of the Hualalai. The Puhia Pele vent is marked by steep spatter ramparts and a km-long channel system (blue) while the lava producing the Huehue Cave (and the overlying “Mystery Lava”) oozed out of the mountain side without any specific vents (Lerch, 1999; Kempe et al., 1999; Kempe 2002).

Atkinson, A. & Atkinson, V. 1995 *Undara Volcano and its Lava Tubes.* The Authors: Brisbane, 86 pp.

Bardintzeff, J.-M., 1999: Vulkanologie. F. Enke Verlag: Stuttgart, 280 pp.

Bienkowski, R. 2001 Stratigraphie der Mauna Loa Lavaflüsse des Kanohina Gebietes (Nord), Ocean View, Big Island, Hawaii, USA. Diploma Thesis, FB 11, TU-Darmstadt, unpublished.

Coan, T., 1844 Letter of March 15, 1843 describing the Mauna Loa eruption of 1843. *Missionary Herald,* 1844.

Decker, R.W., & Decker, B.B. 1991 *Mountains of Fire, the Nature of Volcanoes.* Cambridge University Press: Cambridge. 198pp

Francis, P. 1993 *Volcanoes, a Planetary Perspective.* Clarendon Press / Oxford Univ. Press: Oxford. 443.

Greeley, R. 1987 The role of lava tubes in Hawaiian volcanoes. [In] Decker R.W., Wright, T.L. & Stauffer P.H. (eds.) *Volcanism in Hawaii. US Geol. Surv. Prof. Paper* 1350: 1667 pp.

Greeley, R., Fagents, S.A., Harris, R.S., Kadel, S.D., & Williams, D.A. 1998 Erosion by flowing lava, field evidence. *J. Geophys. Res.,* 103 (B11): 27,325-27,345.

Hon, K., Kauahikaua, J., Denlinger, R. & Mackay, K. 1994 Emplacement and inflation of pāhoehoe sheet flows: observations and measurements of active lava flows on Kilauea Volcano, Hawai‘i. *Geol. Soc. Amer. Bull.,* 106: 351-370.

Kauer, M. 2001 Stratigraphie der Mauna Loa Lavaflüsse des Kanohina Gebietes (Süd), Ocean View, Big Island, Hawaii, USA. Diploma Thesis, FB 11, TU-Darmstadt, unpublished.

Kempe, S. 1997 Lavafalls: a major factor for the enlargement of lava tubes of the Ai-la‘au Shield phase, Kilauea, Hawai‘i. *Proc. 12th Intern. Congress of Speleology, La Chaux-de-Fonds, Switzerland* 1: 445-448.

Kempe, S. 2002 Lavaröhren (Pyroducts) auf Hawai‘i und ihre Genese. [In] Angewandte Geowissenschaften in Darmstadt, W. Rosendahl & A. Hoppe (Eds.), *Schriftenreihe der deutschen Geologischen Gesellschaft,* 15: 109-127.

Kempe, S. 2008 Immanuel Kant's remark on lava cave formation in 1803 and his possible sources. *Proc. 13th Intern. Sympos. on Vulcanospeleology, Jeju Island, Korea, 1.-5. Sept. 2008:* 35-37.

Kempe, S., 2009: Principles of pyroduct (lava tunnel) formation. *Proc. 15th Intern. Congress of Speleology, Kerrville, Texas, July 19-26, 2009,* vol. 2: 669-674.

Kempe, S. 2010 Longitudinal section through a lava pyroduct. *Hawai‘i Speleological Survey Nl.,* Spring 2010 #27: 18.

Kempe, S., Lerch, C. & Oberwinder, M. 1999 Channel and cave systems of the Puhia Pele Flow, Hualalai, Hawaii, and its relation to the 1801 (Huehue) Flow. Abstract, NSS Convention 1999, Vulcanospelelogical Session; and *Journal of Cave and Karst Studies,* 62 (April 2000) (1): 42-43.

Kempe, S., Al-Malabeh, A., Frehat, M., Henschel, H.-V. 2006a: State of lava cave research in Jordan. Proc. 12th Intern. Symp. on Vulcanospeleology, Tepotzlán, Mexico, 2-7 July, 2006. *Assoc. for Mexican Cave Studies, Bull.,* 19 and *Socieded Mexicana de Exploraciones Subterráneas Bol.,* 7: 209-218.

Lerch, C. 1999 DGPS Kartierung von Lavakanälen des Hualalai/Hawaii, USA. Diploma Thesis, FB 11, TU-Darmstadt, unpublished.

Lockwood, J.P. & Hazlett R.W. 2010 *Volcanoes, Global Perspectives.* Wiley-Blackwell: Chichester. 541pp.

Macdonald, G.: & Abbott, A.T. 1970 *Volcanoes at Sea, the Geology of Hawaii.* Univ. of Hawaii Press, 441 pp.

Spudis, P. 2000 Volcanism of the Moon. [In] Sigurdsson, H., (ed.) *Encyclopedia of Volcanoes.* Academic Press: San Diego. 1417 pp.