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EVIDENCE AND MANIFESTATIONS OF VOLCANIC ACTIVITY ON MERCURY

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Abstract. *The earliest hints of volcanic activity on Mercury came from observations by the “Mariner 10” mission. And the results of the “MESSENGER” mission provided compelling evidence that volcanism on Mercury played a key role in shaping the planet's surface. Numerous landforms characteristic of volcanic activity has also been identified on Mercury. Evidence of effusive volcanism with lava flows is represented by large smooth plains that can be interpreted as solidified flows of basaltic lava that poured onto the surface. The blade-shaped edges of many lava flows are clearly visible, lava channels and a large shield volcano have been found. Evidence of possible volcanism is evidence of its explosive activity. The age of Mercury's lava surfaces shows that large-scale effusive volcanism ceased about 3.5 billion years ago due to planetary cooling. Then Mercury's crust entered a state of global compression. The discovery of widespread pyroclastic vents and deposits on Mercury has important implications for the volatile content of the planet's bulk and its thermal evolution. The presence of volatile elements, and especially sulfur, is considered a key factor that could contribute to the presence of explosive volcanism on Mercury. The most extensive manifestation of effusive volcanism on Mercury is the formation of smooth plains of large sizes. That is, powerful massive outpourings of relatively liquid lava on Mercury covered vast areas. The geological history of Mercury is the result of a complex interaction between its internal thermal evolution, volcanism processes, and tectonic deformations caused by the global compression of the planet. Mercury's huge core would have played a central role in all of these processes.*

The earliest hints of possible volcanic activity [29] on Mercury were made during observations by the “Mariner 10” mission [2]. However, it was the observations by the “MESSENGER” mission that provided compelling evidence that volcanism on Mercury played a key role in shaping the planet's surface [1, 14]. “MESSENGER” data confirmed the existence of both large-scale lava flows and

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powerful explosive volcanism. Thanks to the presence of high-resolution cameras on the “MESSENGER” spacecraft and spectrometric observations, numerous landforms characteristic of volcanic activity were identified on Mercury [5, 7, 8]. Chemical analysis of materials on the surface of Mercury confirmed their volcanic origin [19, 26].

Evidence of effusive volcanism with lava flows [10, 18] is primarily represented by large smooth plains similar to the so-called lunar seas, which can be interpreted as solidified flows of basaltic lava that poured onto the surface. The images from the MESSENGER spacecraft clearly show the blade-shaped edges of many lava flows (Fig. 1); structures resembling lava channels have also been found on the surface of Mercury. There, it was even possible to identify a rise similar to a large shield volcano, the diameter of which exceeds 100 km. It is located not far from the edge of the Caloris basin. Even more striking evidence of possible volcanism is the signs of its explosive activity [23]. The MESSENGER spacecraft has been able to detect more than a hundred objects that can be interpreted as volcanic vents. They are usually irregularly shaped, often elongated or complex depressions without the raised rim characteristic of impact craters [30]. Their diameters range from 5 to 45 km. Such vents are often located within old impact craters or along the edges around large basins, such as Caloris. This may indicate the possibility of using existing areas of weakened crust for magma ascent. Some of the vents found have associated small cone-shaped elevations.

Thus, the volcanic nature of Mercury's surface features was revealed by NASA's “MESSENGER” mission. It is now known that much of the surface was at some point submerged by lava, sometimes in extremely large eruptions. The age of Mercury's lava surfaces indicates that large-scale effusive volcanism ceased about 3.5 billion years ago due to planetary cooling. Mercury's crust then [4, 11] entered a state of global compression [13], thereby preventing further magma ascent. However, some smaller-scale volcanism continued in zones of crustal weakening, especially in the central regions of impact craters. Much of this late volcanism was highly explosive. There, volatile gases potentially helped magma rise and tore it apart as it entered the near vacuum of the surface. Many of the vents found were surrounded by bright, diffuse deposits of reddish hues. These features were called faculae or “red spots”. They were interpreted as pyroclastic deposits of ash and debris ejected during explosive eruptions. Such deposits could extend tens or even more than a hundred kilometers from the vent. Areas with pyroclastic deposits have also been found where no clear central vent is visible. However, there is a fairly porous relief, which is composed of many small depressions [22].

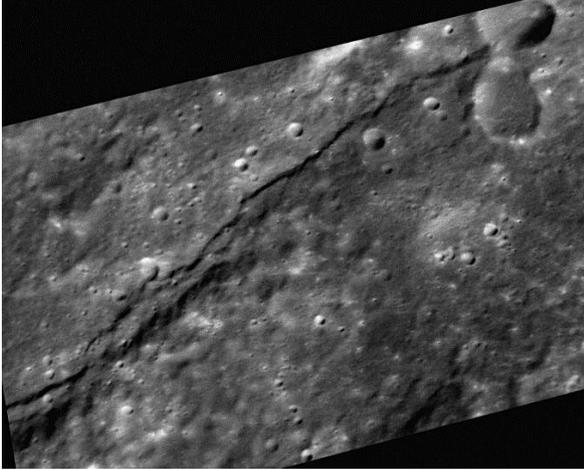


Fig. 1. A common tectonic feature found on Mercury is a ledge, or steep cliff, that runs the entire length of this image, acquired on 12/31/2011

(https://photojournal.jpl.nasa.gov/jpegMod/PIA15325_modest.jpg)

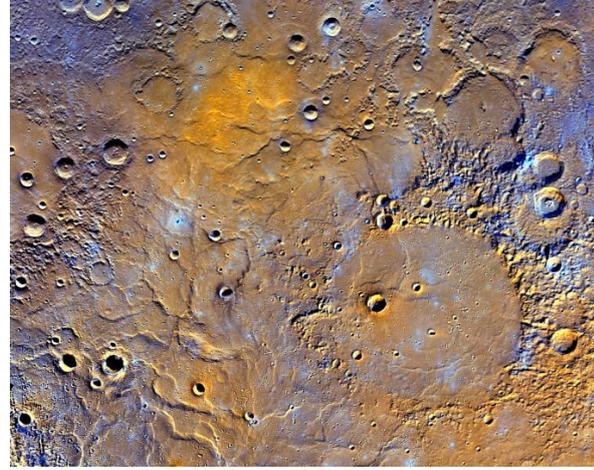


Fig. 2. View of the Northern Volcanic Plains of Mercury in enhanced colors to highlight the different rock types on Mercury's surface

(https://messenger.jhuapl.edu/Resources/Articles/images/NorthernVolcanicPlains_PD_S15_release.png).

The discovery of widespread pyroclastic vents and deposits on Mercury has important implications for the volatile content of the planet's bulk and its thermal evolution. However, the significance of pyroclastic volcanism for Mercury depends on the mechanisms by which the eruptions occurred. Using images obtained by the “MESSENGER” spacecraft, more than 150 locations were found where endogenous pits are surrounded by relatively bright red spectral anomalies with diffuse edges [15]. This appearance was used to identify in images the locations of explosive volcanism. Typically, such locations are concentrated at the edges of impact basins and along some tectonic structures. Such pyroclastic deposits are scattered at distances of up to 150 kilometers from their eruption source. Therefore, such eruptions were most likely caused by relatively high concentrations of volatiles, which correspond to their concentration before the eruption in a shallow magma chamber.

Observations by “MESSENGER” instruments that measured the chemical composition of the surface have independently confirmed the volcanic nature of many plains and deposits on Mercury. These instruments include the XRS X-ray spectrometer and the GRNS gamma-ray and neutron spectrometers. Analysis of the data obtained by these instruments showed that, compared with other terrestrial planets [21, 24], the surface of Mercury as a whole has a unique chemical

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composition. It is characterized by a relatively low content of iron (Fe), aluminum (Al) and calcium (Ca). However, it turned out to be enriched in magnesium (Mg). Large regions with quite different chemical compositions were found on the surface of Mercury. These regions correspond to different geological eras and are large volcanic plains. For example, the plains within the Caloris Basin and the Northern Volcanic Plains have quite specific and different chemical compositions.

Among the most unexpected results was the discovery of significantly higher than expected concentrations of moderately volatile elements, such as sulfur (S), potassium (K), sodium (Na) and chlorine (Cl). For example, the content of sulfur on the surface can be several percent by weight. And this is significantly higher than on the Moon or on Earth. Also contradicting existing models is the high content of potassium on the surface. Because of Mercury's proximity to the Sun, a strong loss of all volatile elements is expected. The presence of these volatile elements, and especially sulfur, is considered a key factor that could contribute to the presence of explosive volcanism on Mercury. Gases released from the magma as it rose to the surface (most likely, these were sulfur compounds such as SO_2 or H_2S) could create significant pressure, which was necessary for the fragmentation of the magma and for the ejection of pyroclastic material over considerable distances [14].

Thus, the chemical composition of the surface measured by the "MESSENGER" spacecraft not only confirmed the volcanic origin of many of the observed landforms [26, 27], but also was able to explain the mechanisms of explosive eruptions, and indicated the composition of Mercury's interior unexpectedly rich in volatile compounds. And the unique chemical composition of individual volcanic plains with a high content of magnesium and a low content of iron, aluminum and calcium – indicated that the magmas from which they were formed were of a special composition, which differed significantly from typical lunar or terrestrial basalts.

These facts may indicate a rather specific composition of Mercury's mantle [25]. It may be poor in feldspars and enriched in magnesium silicates; Mercury may also have some special melting conditions in its interior: for example, high temperature, low pressure or strongly reducing conditions. Such unique geochemistry is likely to be closely related to the general prehistory of the formation of this planet and its huge core. It should be noted that the most extensive manifestation of volcanism on Mercury is the formation of large-scale smooth plains [16, 17]. Data obtained by the MESSENGER mission have conclusively confirmed that these plains are the result of so-called effusive volcanism. That is, powerful massive outpourings of relatively liquid lava on Mercury covered vast territories. Such smooth plains occupy up to 27% of the entire surface of the planet. The largest continuous area of such plains is called the Northern Volcanic Plains

(Fig. 2). They cover an area of more than 6% of the surface of Mercury [6]. The thickness of such lava cover can be significant [3].

In some places, especially within impact basins, it can be several kilometers across. For example, the volume of lava that filled the Caloris Basin is estimated to be 3–5 million cubic kilometers. Counting the impact craters on the surface of these plains has shown that a major phase of large-scale effusive volcanism occurred early in Mercury's history. It peaked between about 4.0 and 3.5 billion years ago. It largely ceased at the end of this period. The enhanced-color view of Mercury's Northern Volcanic Plains highlights the different types of rocks on its surface. The 291 km diameter Mendelssohn impact basin, which was once almost completely filled with lava, is visible on the lower right of this image. Large wrinkled ridges that formed as the lava cooled are visible on the lower left.

Impact craters with rounded edges can also be recognized in this same area. Near the top of the image, a bright orange area is visible, indicating the location of a volcanic vent that is the source of one of the largest pyroclastic deposits on the planet. The north pole in the image is in the lower left corner. The improved colors are created by superimposing images obtained in the 1000 nm filters and in the red, green, and blue channels on top of the first one obtained in the 430 nm wavelength. Such a huge volume of erupted lava in a relatively short period of time indicates that the magma formation rate in Mercury's mantle was quite high in the past [12].

In turn, such facts indicate that once upon a time the planet's interior was much hotter than today's values. And therefore they were capable of their intense melting. Such a large-scale effusive volcanism was a key process that was able to form a significant part of the modern crust on Mercury. And its large-scale termination was an important milestone in the thermal and geological evolution of the planet [9, 20, 28]. Thus, the geological history of Mercury is the result of a complex interaction between its internal thermal evolution, volcanism, and tectonic deformations caused by the global compression of the planet. Mercury's huge core must have played a central role in all of these processes.

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