THE HOLUHRAUN REGION OF ICELAND AS A HIGH-FIDELITY PLANETARY ANALOG SITE FOR ROBOTIC AND HUMAN EXPLORATION. C. W. Hamilton[1], J. R. C. Voigt[2], M. Zanetti[3], S. M. Hibbard[2], P. M. Bremner[3], P. Schroedl[4], and C. D. Neish[5], [1]Lunar and Planetary Laboratory, The University of Arizona, Tucson AZ 85721 USA (chamilton@arizona.edu), [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, [3]NASA Marshall Space Flight Center, Huntsville, AL, USA, [4]Department of Biology, Boston University, Boston, MA, USA, [5]Department of Earth Sciences, University of Western Ontario, London, ON, Canada.

Introduction: Every planetary body is unique in terms of its geology and geological history. Exploration of one planet or moon may therefore inform our understanding of another, but will have limitations as a "simile" when used to compare two inherently unlike things. For instance, a location in the Highlands of Iceland may exhibit some similarities to one or more locations on Mars, but both environments will also differ in fundamental and important ways.

Foucher *et al.* (2021) [1] provide an excellent overview of what they call "functional analogues" to emphasize the importance of defining the specific properties that constitute an analog because there will always be some differences between the analog and the object(s) to which it refers. They further suggest that robust planetary analogs may be established on the basis of one or more of the following criteria: (1) sites used for their planetary analogy; (2) sites used for analogies to mechanical and chemical processes; (3) sites used for their petrological and mineralogical analogy; (4) analog sites of astrobiological interest; and/or (5) engineering analog sites. One could add to this list with other criteria, but these metrics provide a reasonable basis for establishing a useful comparison, or analogy, between a site on Earth and a location on another planetary body.

The Holuhraun region of Iceland provides a high-fidelity planetary analog because it not only meets, but exceeds relevance critera in all five categories described by Foucher *et al.* (2021) [1]. Holuhraun has the strongest relevance for Mars (Fig. 1), but is also pertinent as an analog for other planetary bodies, including the other terrestrial planets (e.g., Venus and Mercury), moons (e.g., our Moon, Io, and Titan), and some asteroids. With appropriate recognition of similarities and dissimilarities between Holuhraun and other planetary environments, it can serve as a valuable functional analog for a broad range of scientific and engineering goals.

Fig. 1. Holuhraun (right) provides an outstanding analog for planetary environments such as Jezero Crater on Mars (left).

Geological Description of Holuhraun: As the body of scientific literature grows for Holuhraun, so do certain assumptions and misnomers. It is therefore critical to recognize that "Holuhraun" is not simply a recently emplaced lava flow field, it is a region that includes a wide range of landforms generated by a variety of different geological processes.

The most recent volcanic eruption of Holuhraun occurred in 2014–2015 and was associated with the Bárðarbunga–Veiðivötn volcanic system [2]. However, this volcanic system has had at least 23 subglacial and subaerial eruptions in the past 1,100 years, including two previous eruptions in the Holuhraun region between 1794 and 1864 [3–5]. The most recent eruption has brought special attention to Holuhraun, but the lava flow field itself has had a complex history, including three large effusive eruptions in the past 229 years.

Volcanoes in the Neovolcanic zone of Iceland typically include a central volcano and two rift zones [6], which are controlled by local stresses in an extensional environment. Consequently, volcanoes that are geographically close to one another can be sourced from completely different magmatic reservoirs. For example, the Holuhraun lava flow field was fed from the Bárðarbunga central volcano, but is adjacent to the northern part of Kverkfjöll's rift system and much closer to the Askja central volcano than to its own magmatic source. Parts of the Holuhraun lava flow field directly overlie older Askja lavas [4] and so it is imperative to consider Holuhraun in a broader context of landscape evolution that involves not one, but three volcanic systems.

Another key component of the Holuhraun region is the underlying sandsheet called Dyngjusandur. This is a glacial outwash plain ("sandur" in Icelandic) that primarily originates from the Dyngjujökull outlet glacier of Vatnajökull. Dyngjusandur is one of the most active dust sources on Earth and is intensively modified by aeolian processes as well as the Jökulsá á Fjöllum river and episodic glacial outburst floods ("jökulhaulps" in Icelandic). Dyngjusandur is also affected by seasonal snowfall and snowmelt. Most researchers visit Holuhraun during the summer and this imparts a strong bias on perceptions of weather conditions throughout the year. For instance, several meters of snow can accumulate in the winter, leading to extensive spring melting and the development of transient lakes that are responsible for moving pumice and other sediments.

Functional Analogs: Differences between Earth's gravity, atmospheric pressure, climate and weather, as well as biology and biogeochemistry all limit direct comparisons between Holuhraun and locations on Mars, but there are numerous aspects that are similar.

1. General planetary analogs. The 2014–2015 Holuhraun eruption was the largest flood lava eruption in Iceland since the 1783–1784 Laki eruption. Thus, it provides valuable insights into volcanic terrains on other terrestrial planets and moons, such as large effusive eruption products in the Northern Plains of Mercury, vast regions of Venus' surface, the lunar mare, and effusive eruption products on Jupiter's moon, Io [7]. Similarities between eruption styles, lava emplacement dynamics, and resulting lava morphologies [8–10] make Holuhraun an important location for testing models and ground-truthing remote sensing observations.

2. Mechanical and chemical analogs. The 2014–2015 Holuhraun eruption was the product of a fissure-fed eruption, which makes it similar to eruption products from fossae on other planetary bodies, such as the Cerberus Fossae on Mars. Fissure-fed effusive eruptions are more typically dynamic than eruptions from longer-lived effusive eruptions from central volcanoes because they exhibit larger fluctuations in time averaged discharge rate. The resulting lava products tend to be highly disrupted by episodic pulses of lava entering into the lava transport system, leading to the formation of "transitional lava types" such as rubbly and spiny lava, rather than traditional ʻaʻā and pahoehoe end-members [9]. Holuhraun's eruption style, effusion rates, emplacement processes, and lava morphologies are therefore comparable to fissure-fed lavas Mars [11, 12] and other planetary bodies [13], despite differences in gravity, atmospheric pressure, and other environmental factors.

3. Petrological and mineralogical analogs. The petrology, mineralogy, and geochemistry of lava units in the Holuhraun region primarily range from olivine tholeiite to basalt and basaltic andesite [3, 4], which provides an excellent analog for primitive magmas erupted on terrestrial planets and moons. Askja also includes more evolved rhyolites [4] that are formed by fractional crystallization, rather than plate recycling, which provides insight into silicic magmas on other planetary bodies, such as the Gruithuisen Domes on the Moon.

4. Astrobiology analogs. Landforms in the Holuhraun region were produced by a combination of volcanic, aeolian, hydrological, and glacial processes, which provide multifaceted parallels to geologically recent volcanic terrains on Mars where floods of lava and water appear to have been erupted from the same fissure systems [14]. Resulting lava–water interactions associated with the 2014–2015 Holuhraun eruption can therefore inform our understanding how fresh volcanic units, including lava-induced hydrothermal systems [15], undergo microbial colonization. Holuhraun therefore offers an analog that can inform our understanding of the habitability of analogous volcanic environments on Mars as well as the biosignatures associated with life in these extreme environments.

5. Engineering analogs. Holuhraun includes barren lava flows and the Dyngjusandur sandsheet, which both provide exceptional operational analogs for the exploration of terrains on Mars, such as Jezero Crater on Mars, which include volcanic and sedimentary units that can be examined using a combination of rovers and unoccupied aircraft systems (UAS).

Holuhraun also represents high-fidelity lunar analog terrain. While aeolian processes are not present on the Moon, its surface morphologies, compositions, and terrain characteristics are similar to lunar mare environments. The broad, relatively flat expanses of sand that embays lava flow units and outcrops in Holuhraun is qualitatively similar in appearance to many regions visited during the Apollo Era, and the geotechnical properties of the sand are similar enough for meaningful rover and astronaut mission operation simulations. Moreover, simply being a vegetation-free environment significantly adds to the "magnificent desolation" of the environment (Aldrin, 1969) and has helped *Apollo* astronauts and the next generation of *Artemis* astronauts to train for lunar missions.

Conclusions: Holuhraun offers one of the best Mars analogs on Earth, with applications to volcanic, aeolian, fluvial, and glacial processes. In addition to providing an exceptional scientific analog, Holuhraun offers an valuable engineering analog for field-testing new technologies and science operations scenarios for a wide range of planetary mission designs—ranging from ongoing missions to *Mars Sample Return*, the *Veritas* mission to Venus, robotic and human exploration of the Moon (e.g., *Artemis*), and can even UAS-based exploration of Titan with *Dragonfly*.

Acknowledgments: This work was supported by NASA PSTAR Grant # 80NSSC21K0011 and authorized by the Vatnajökull National Park Service. C. D. Neish thanks the CSA FAST program for funding.

References: [1] Foucher et al. (2021) *Planet. Space Sci*., 197, 105162, 1–13; [2] Gudmundsson et al. (2016) *Sci.*, 353 (6296), 1–8; [3] Sigmundsson et al. (2014) *Nat.*, 517(7533) 191–195; [4] Hartley et al. (2016) *Bull. Volcanol.* 78(28), 1–18; [5] Mattsson et al. (2016) *Geochem. Geophys. Geosyst.*, 17(8) 2953–2968; [6] Gudmundsson et al. (2000) *Annu. Rev. Earth Planet. Sci.*, 28, 107–140; [7] Byrne (2019) *Nat. Astron.*, 4, 321–327; [8] Pedersen et al. (2019) *J. Volcanol. Geotherm. Res.*, 340, 155–169; [9] Voigt et al. (2021) *J. Volcanol. Geotherm. Res.*, 419, 107278, 1–27; [10] Voigt et al. (2022) *Geology* 50(1), 71–75; [11] Voigt and Hamilton (2018) *Icarus*, 209, 389–410; [12] Keszthely et al. (2000) *J. Geophys. Res.*, 105(E6), 15,027–15,049; [13] Keszthelyi et al. (2004) *Geochem., Geophys., Geosyst.*, 5(11), 1–32; [14] Jaeger et al. (2010) *Icarus*, 205(1), 230–243; [15] Duhamel et al. (2022) *Astrobiology*, 22(10), 1–23.