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***Mars Sample Return Analogue Sample Library:
Introduction to Collection Catalogue
with Sampling Details***

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Based on field reports provided by field work teams



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1. Purpose of the MSR ASL rock collection and library

Since February 2021, NASA's Perseverance rover has been exploring Jezero Crater, conducting in-situ analyses to study the planet's geology and ancient habitability. A key objective of Perseverance is to lay the groundwork for Mars Sample Return (MSR). The rover is collecting and sealing samples in tubes, preparing them for eventual retrieval and transport to Earth for detailed analysis.

Following this collection phase, NASA and ESA are leading the Mars Sample Return campaign, which seeks to retrieve, receive, curate, and analyze these Martian samples in laboratories with a level of precision that cannot be achieved through remote observations alone.

To ensure the successful curation and handling of the returned samples, extensive research and development efforts are underway, guided by the goals of the Sample Receiving Project. These efforts focus on several key areas:

- Testing methods for safely opening sample tubes
- Evaluating imaging and sterilization protocols
- Assessing the impact of various analytical techniques on the samples

In further, research and development activities are necessary to maximize the scientific return from these martian samples. These include:

- Developing new technologies to enhance analytical capabilities for working with returned samples
- Improving the interpretation of data collected by Perseverance on Mars

As an ambitious and complex mission, the success of MSR also depends on strong public engagement and collaboration across a wide range of scientific and technical disciplines. This makes public outreach and science communication essential components of the project.

To support both research and outreach efforts, it is critical to have access to analogue rocks that closely resemble the samples cached by Perseverance. The **Mars Sample Return Analogue Sample Library (MSR ASL)** provides a curated selection of natural samples that match key characteristics of the samples collected by the rover. The primary goal of the MSR ASL is to ensure broad access to these analogue materials for the scientific community.

Depending on the intended research or development activity, different properties of the analogue samples may be prioritized, including but not limited to geophysical, geochemical, geomechanical, organic, and mineralogical characteristics. All samples in the MSR ASL are systematically characterized based on these properties.

Currently, the MSR ASL contains five lithologies that serve as analogues for the samples collected by Perseverance during the Crater Floor and Delta Front campaigns. The primary goal of the current acquisition to MSR ASL is to provide analogues for engineering purposes.

2. Samples collected by Perseverance

As for the time of writing, Perseverance rover was exploring regions labelled as Margin Campaigns and three earlier campaigns: Crater Floor, Delta Front and Upper Fan have been completed. MSR ASL in its current stage includes lithologies analogous to the two first performed campaigns: Crater Floor and Delta Front.

Crater Floor samples represent a suite of likely petrogenetically related igneous rocks emplaced as lava flows and intrusions mostly postdating the delta and displaying variable degrees of aqueous alteration (e.g., Udry et al., 2022; Simon et al., 2023).

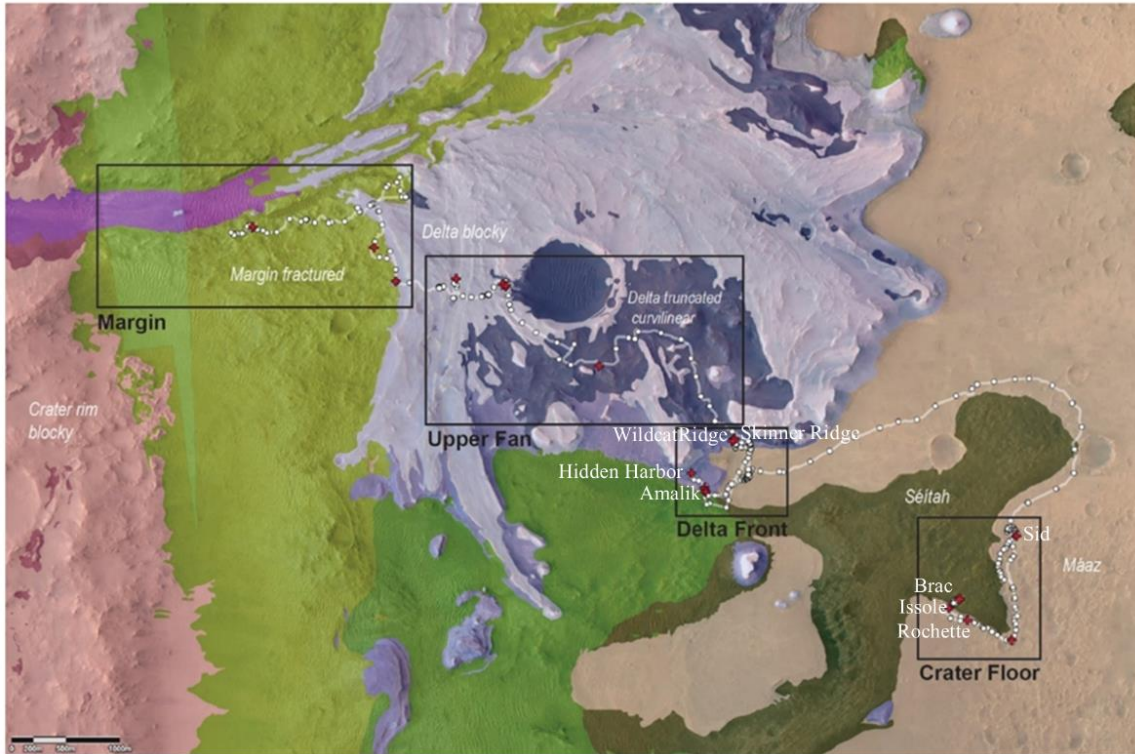


Figure 1. The path taken by NASA's Perseverance Mars rover during the first 1,100 sols (martian days) of its mission at Jezero crater; superimposed on a geologic map after Stack et al. (2020). Rover traverse and waypoints are shown with white line and dots, respectively. Sampling locations are marked with red crosses and labeled with the names. Labeled black boxes show approximate extent of each campaign. (Herd et al., 2024).

The intrusive samples link to Séítah formation and were sampled at Brac and Isole. Based on texture and mineralogy, they represent olivine cumulate (Liu et al., 2022).



Figure 2. Abrasion patches and Watson camera images of cores sampled from Séítah formation at a) Brac and b) Isole.

Second observed formation is Máaz composed of lava flows and sampled at Rochette (Lower Máaz) and Sid (Upper Máaz). Cached rocks represent holocrystalline augite basalt (Farley et al., 2022), although the Lower and Upper Máaz differ in textures and in plagioclase crystal sizes.



Figure 3. Abrasion patches and Watson camera images of cores sampled from Máaz formation at a) Rochette and b) Sid.

Delta Front samples represent fluvial to deltaic sediments formed by the transport and deposition of materials from the Jezero watershed. The samples include fine-grained, sulfate- and carbonate-bearing mudstones (Benison et al., 2024; Stack et al., 2024) sampled at Amalik, Skinner Ridge and Wildcat Ridge.



Figure 4. Abrasion patches and Watson camera images of cores sampled from sediments at the delta front. a) carbonate-cemented basaltic sediments from Amalik. b and c) carbonate-sulfate-cemented basaltic sediments from Skinner Ridge and Wildcat Ridge, respectively.

Additionally, one sample of loose regolith was cached at Hidden Harbor.

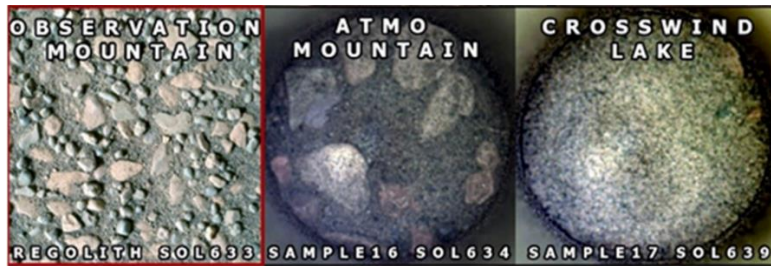


Figure 5. Abrasion patch and Watson camera images of loose regolith cached from the delta front at the Hidden Harbor.

3. Selected terrestrial analogue sites and sampling details

To support the activities for which MSR ASL was created, analogue rocks are required that match the properties of the samples cached by Perseverance as closely as possible. These properties include, and are not limited to, geophysical, geochemical, geomechanical characteristics, as well as organic content and mineralogical composition.

While many locations on Earth contain rocks that meet the necessary mineralogical and textural criteria, additional factors were considered when selecting samples for MSR ALS. These factors include the accessibility of relevant material for sampling and its available quantity.

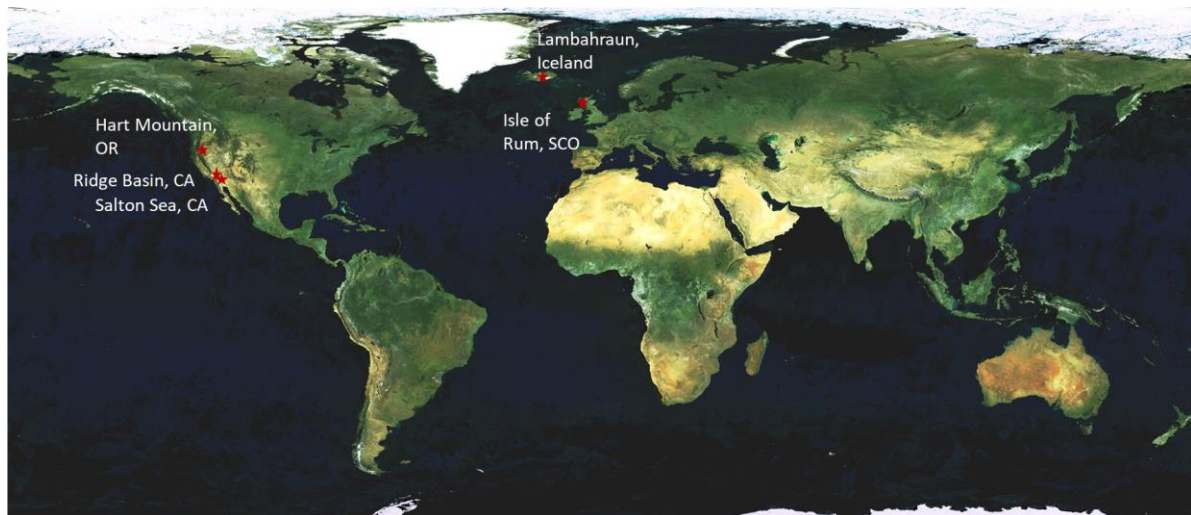


Figure 6. Location of the sites selected for sampling as analogues to Crater Floor and Delta Front Perseverance tubes. Isle of Rum in Scotland – analogue for samples collected from Séítah formation; Hart Mountain, Oregon – analogue for samples from Máaz formation; Ridge Basin, California and Salton Sea, California – analogues for delta sandstones and mudstones collected in Delta Front Campaign and Lambahraun, Iceland – analogue for regolith sample from Delta Front.

By balancing both scientific and logistical considerations, and focusing on obtaining material relevant for engineering tasks, sampling was conducted at the following sites to collect lithologies representative of the materials cached by Perseverance in its first two campaigns (Thiessen et al., 2024; Siebach et al., in preparation):

- 1) Olivine peridotite from Isle of Rum as an analogue to Séítah formation sampled at Brac and Issole (Coulettes and Malay tubes).
- 2) Aphyric and plagioclase-phyric basaltic lavas from Hart Mountain as analogues to Máaz formation sampled at the aphyric Rochette outcrop (corresponding tube Montdenier) and at the Sid outcrop (corresponding tube Atsah).

- 3) Ridge Basin sandstones with carbonate cement as an analogue to Delta Sediments sampled at Amalik outcrop and corresponding Mageik tube
- 4) Salton Sea fine-grained sandstones containing sulfate and carbonate cement as an analogue to Delta Sediments sampled at Skinner Ridge and Wildcat Ridge outcrops, and corresponding Skyland and Bearwallow tubes.
- 5) Basaltic sand from Lambahraun, Iceland as an analogue to regolith sampled in Delta Front at Hidden Harbor and corresponding Crosswind Lake tube.

3.1. Isle of Rum (Scotland) peridotites – Analogues to Brac and Issole sampling

The aim of sampling at Isle of Rum was to collect wehrlitic peridotite previously characterized (Hepworth et al., 2018, Hepworth et al., 2020) and proposed to be a suitable analogue for Séitah olivine cumulates.

Sampling at Isle of Rum was conducted in July 2023. Field work was led by Lydia Hallis (University of Glasgow, UK) and assisted by Helen Williams (University of Cambridge, UK), Simon Matthews (University of Cambridge, UK), John Bridges (University of Leicester, UK) and Mariek Schmidt (Brock University, Canada).

3.1.1. Sampling Site

The field team visited outcrop at Harris Bay and sampled wehrlite belonging to formation of Transitional Member of Western Intrusion of Rum. The transitional member is a ~50 m thick layered peridotite body, and upper ~5 m of the formation is dominated by wehrlitic peridotite (Hepworth et al., 2018).

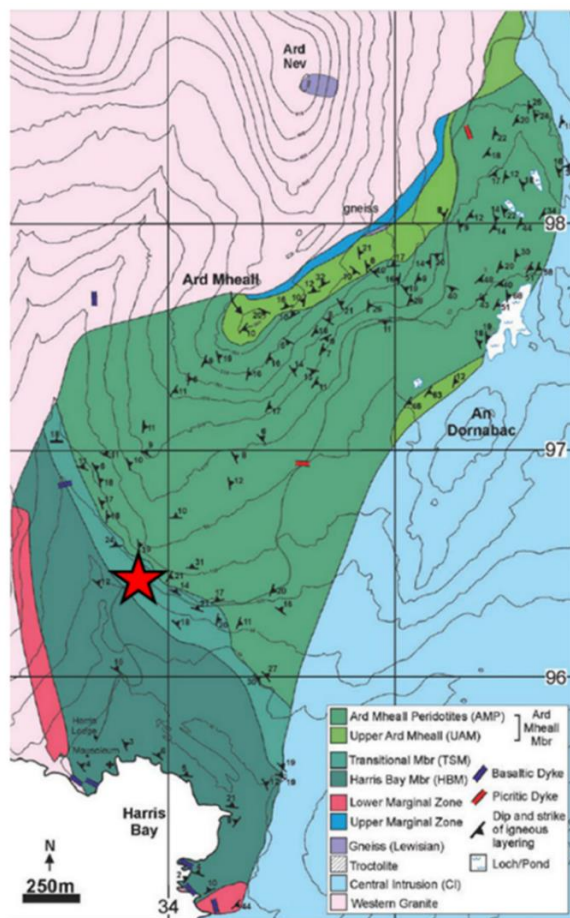


Figure 7. Geological map of the Western Layered Intrusion of the Isle of Rum (after Hepworth et al., 2018) and location of the sampling point marked by the star.

Multiple blocks of wehrlite were present by the side of the road. They looked freshly exposed, perhaps were removed from the cliff-forming unit during road construction.

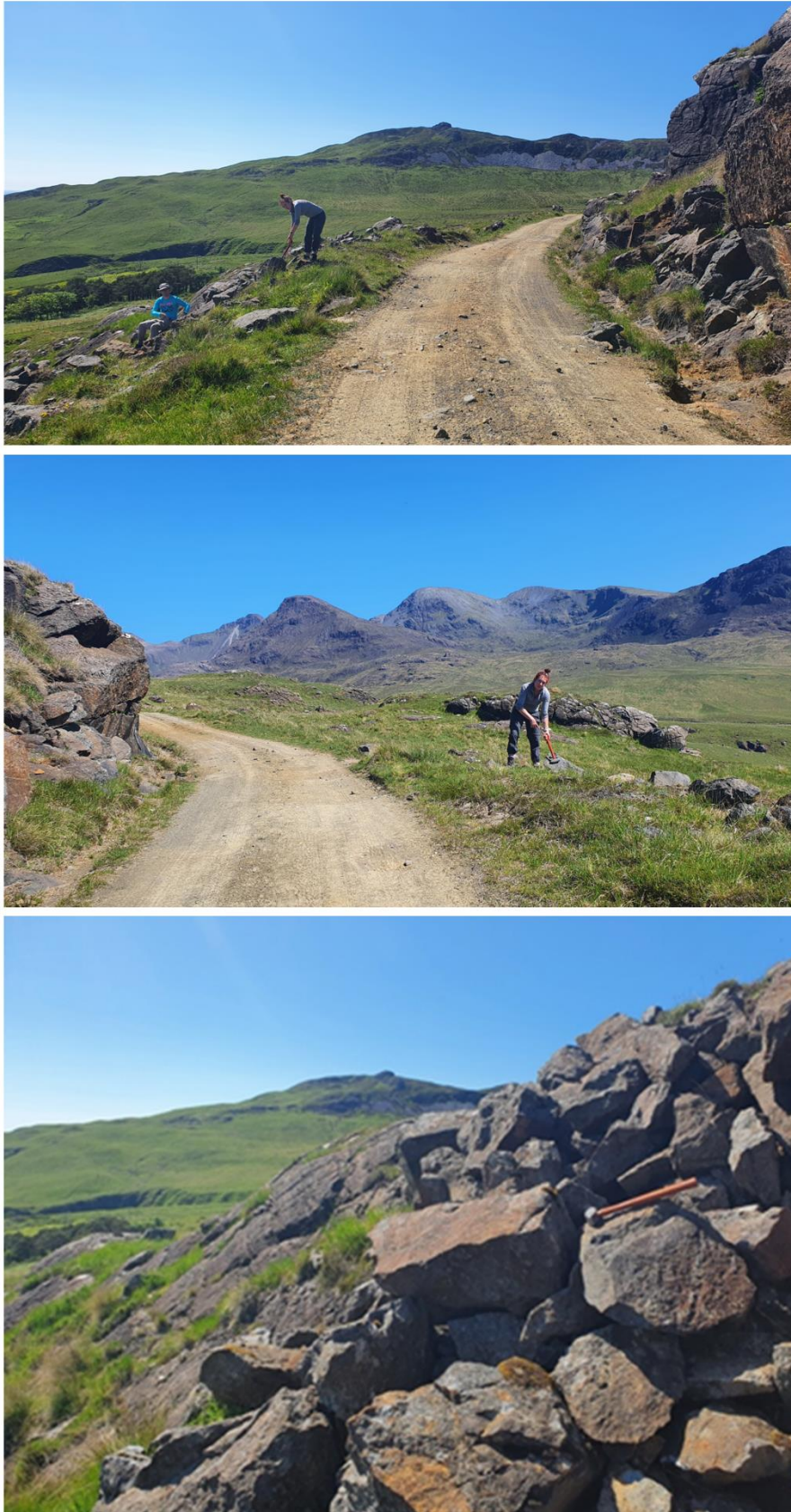


Figure 8. Outcrop at Harris Bay, where sampling for MSR ASL was conducted. Photo credit: Members of the field team.

One individual large block was selected and lifted from the outcrop. Subsequently it was broken down by sledgehammers into smaller (portable, lower than 100 kg in mass) pieces. In total, ~300 kg of wehrlite was collected on the site.



Figure 9. Wehrlite block selected for sampling. a and b) Block in its original location in the outcrop at Harris Bay. c and d) Block after fragmentation to portable pieces. Photo credit: Members of the field team.

3.1.2. Samples Available in the MSR ASL Collection

Sampling at Rum allowed for accession to MSR ASL of more than 40 individual specimens (labelled as RUM) that range in mass from 97 kg to 400 g. Total mass of samples is more than 280 kg. For details of each sample and associated images, see the Sample Catalogue in separate document [\[link\]](#).

At the mesoscopic scale, the hand specimens represent wehrlite, with olivine, clinopyroxene, minor plagioclase as well as chromium-spinel and sulfides in accessory amount. Olivine is altered to iddingsite, mostly along crystal fractures and boundaries.

Samples have a poikilitic texture with clinopyroxene enclosing olivine. Olivine crystals commonly share grain boundaries. Olivine has maximum grain size of 3 mm. The distribution and modal content of plagioclase is heterogeneous even within individual samples (6–10% by volume).



Figure 10. Mesoscopic image of the available sample of wehrlite sampled at Isle of Rum. 1 cm grid for scale.

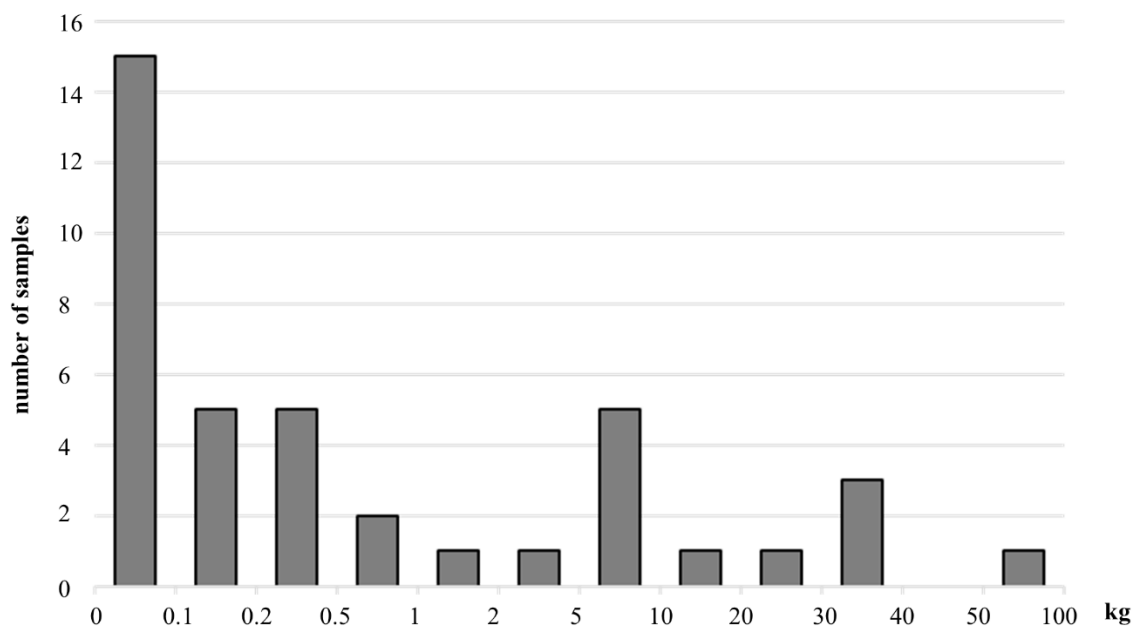


Figure 11. Quantity of RUM samples in binned size ranges.

3.2. Hart Mountain (Oregon) augite basalts – Analogues for Máaz formation

The aim of sampling at Hart Mountain was to collect holocrystalline basaltic lava with plagioclase and augite, proposed to be a suitable analogue for Máaz augite-bearing basalts.

Sampling at Hart Mountain was conducted in October 2023. Field work organization was led by Mariek Schmidt (Brock University, Canada), who was not able to attend the sampling itself. The field work team consisted of Nicole Moore (Pomona College, USA), Anita Grunder (Oregon State University, USA), Lori Shiraishi (Jet Propulsion Laboratory, USA), Josh Labrie (Brock University, Canada) and Lynn Robinson.

3.2.1. Sampling Site

The field team visited outcrop at Hart Mountain and sampled basaltic lavas belonging to Steens Mountain formation (Camp et al., 2013).

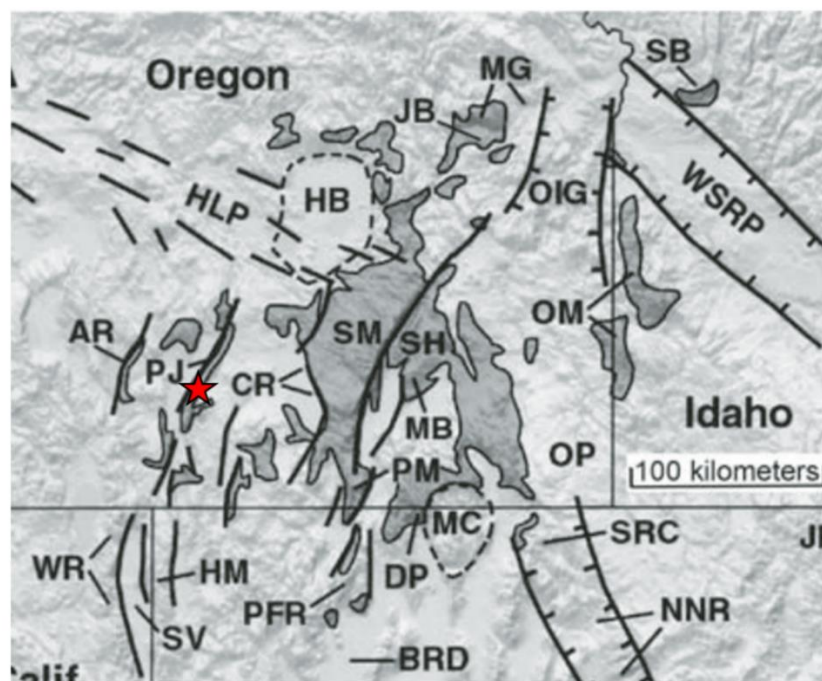


Figure 12. Location map of Steens Mountain basalt exposures in southeastern Oregon, northern Nevada, southwestern Idaho and northeastern California (Camp et al., 2013). Location of sampling site indicated by the red star.

The outcrop is located along a road cut. Two textural types of basalt are exposed in the place: aphyric in the lower part of the outcrop and plagioclase-phyric basalt, overlying the former. The two textural types are separated by a thin red soil weathering horizon.

Samples were collected from talus along the outcrop. In lower parts of the hill, aphyric basalt was exposed and pieces were sampled there. Up the hill, plagioclase-phyric basalt was exposed at the base of a road cut, allowing for sampling of phyric material.

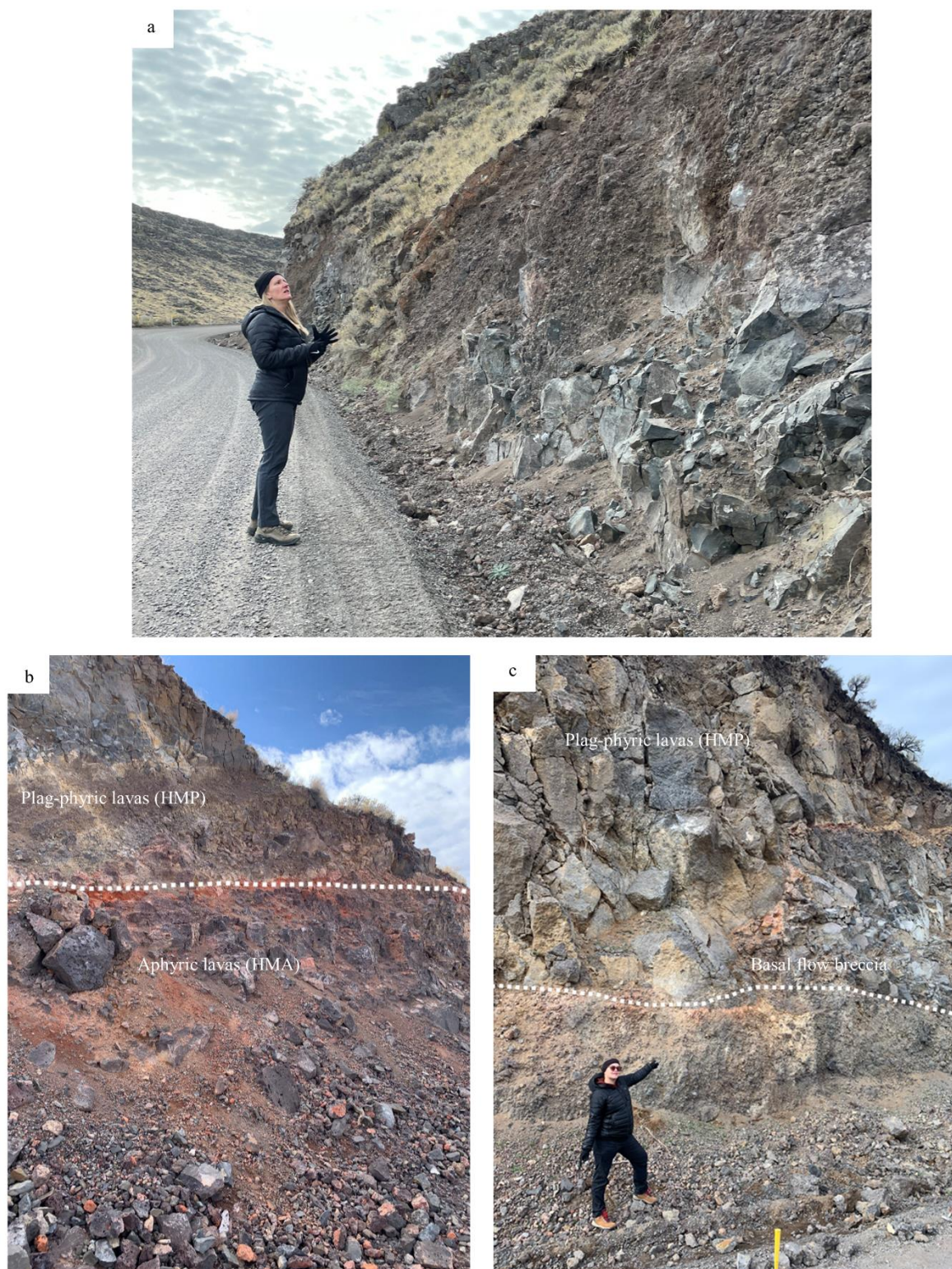


Figure 13. Outcrop at Hart Mountain, along which sampling was done. a) roadcut at Hart Mountain with exposed Steens Basalt lava flows. b) talus from where aphyric samples were collected. Above the red weathering horizon, plagioclase-phyric basalt is present. Further along the outcrop, plagioclase-phyric lava is cropping out at the level of road cut. c) 2 m thick basal flow breccia is exposed at the base of roadcut and is overlain by massive, at least 6 m thick plagioclase-phyric lava. Credit: Members of the field team.

Samples were selected from talus at the base of road cuts. Rock hammers were used to fragment and chip away friable material where necessary.



Figure 14. The specimens of Hart Mountain basalts at the collection site. a and b) Largest blocks of plagioclase-phyric basalt. c) All selected aphyric basalt specimens. d) All selected plag-phyric basalt specimens. Credit: Members of the field team.

3.2.2. Available Samples

In total, >350 kg of samples was collected at Hart Mountain and provided to MSR ASL. More than 40 individual specimens having aphyric texture (labelled as HMA) are available in the MSR ASL collection and they range in mass from 20 kg to 160 g. In total, the mass of aphyric basalt samples is more than 175 kg. For details on each sample, see the Sample Catalogue [\[link\]](#).

At the mesoscopic scale, the hand specimens of aphyric basalts (HMA) appear fine-grained, with the grain size below 1 mm. The rocks are composed of olivine, augitic pyroxene and plagioclase. They contain ilmenite and magnetite in groundmass and as inclusions in feldspar. Olivine is altered to iddingsite.

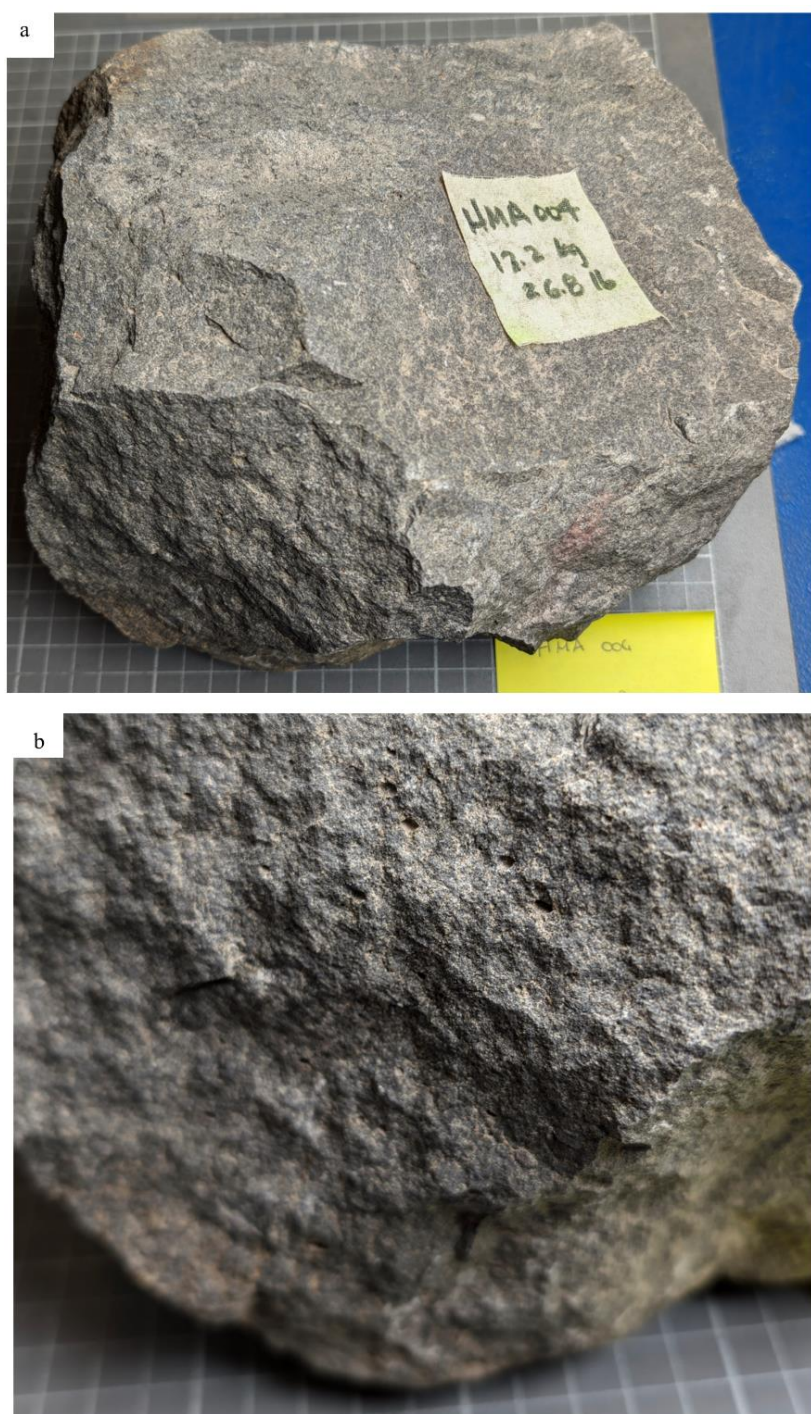


Figure 15. Mesoscopic image of the available sample of aphyric basalt sampled at Hart Mountain (HMA). 1 cm grid for scale.

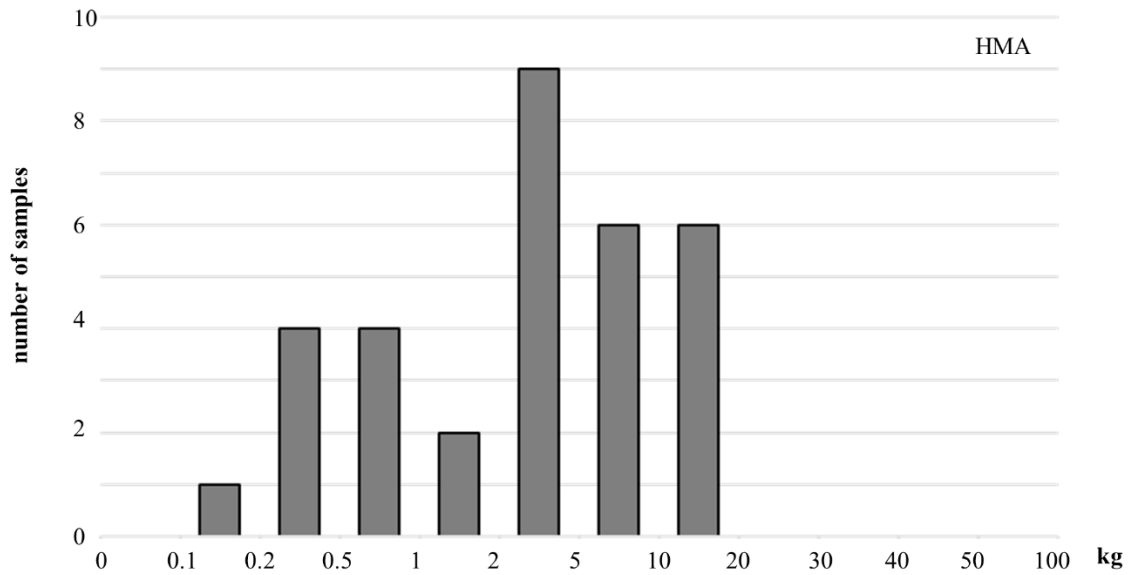


Figure 16. Quantity of HMA samples in binned size ranges.

35 samples having plagioclase-phyric texture (labelled as HMP) are available and those range in mass from 21 kg to 100 g. In total, the mass of plagioclase-phyric basalt samples is more than 170 kg. For details on each sample, see the Sample Catalogue [\[link\]](#).

The hand specimens of plagioclase-phyritic basalts (HMP) are composed of olivine, augitic pyroxene and plagioclase. They are texturally distinct from HMA specimens in being massive. Additionally, the HMP samples contain olivine with sizes up to 2 mm, enclosed as inclusions in plagioclase and as glomerocrysts. Plagioclase crystals have sizes up to 2 cm.

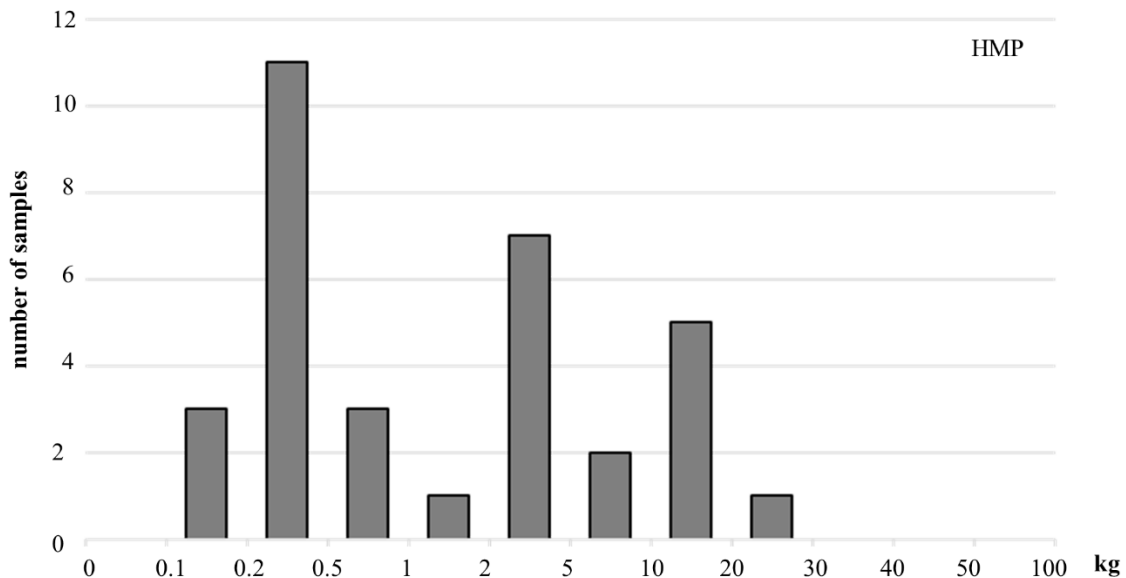


Figure 17. Quantity of HMP samples in binned size ranges.

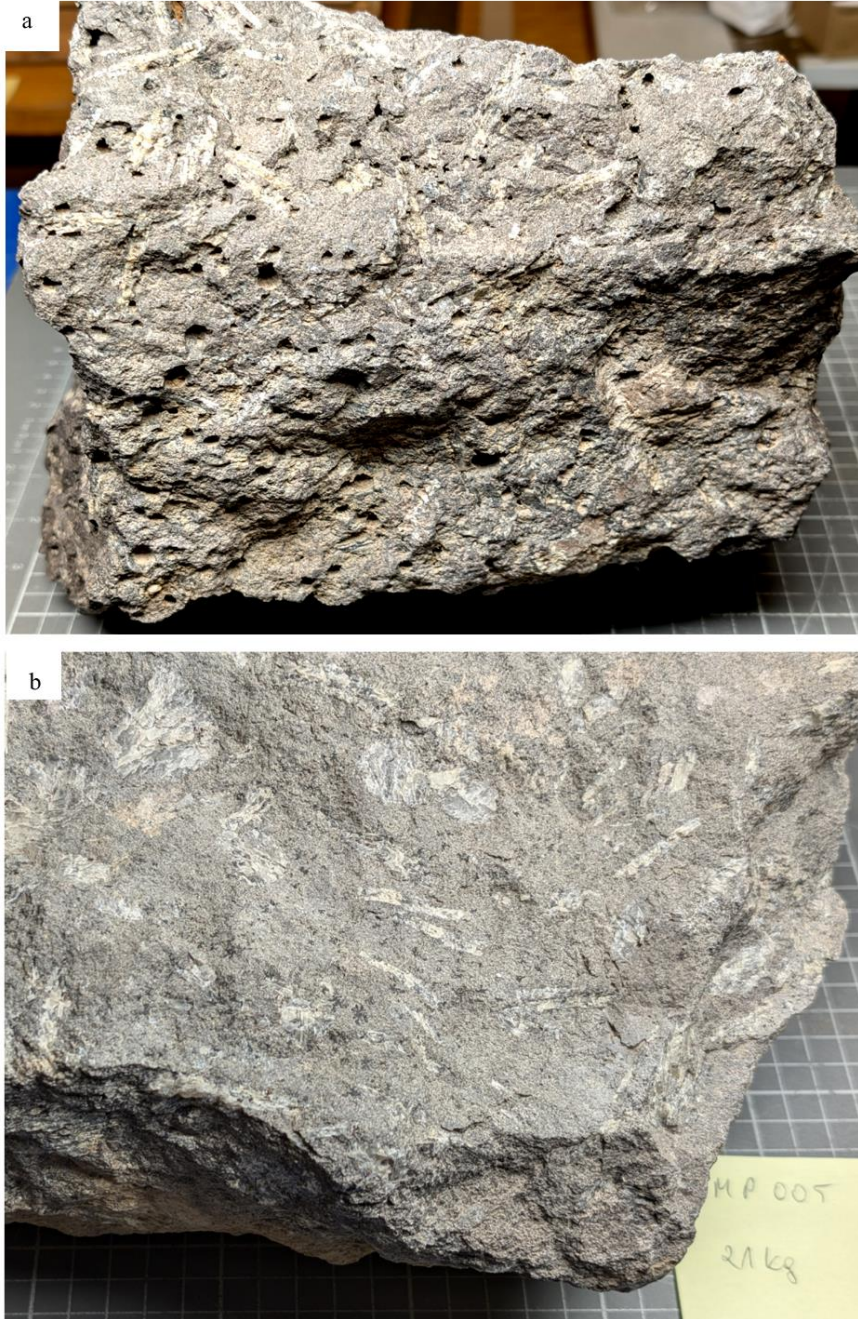


Figure 18. Mesoscopic image of the available sample of plag-phyric basalt sampled at Hart Mountain (HMP). 1 cm grid for scale.

3.3. Basaltic sand from Lambahraun (Iceland) – Analogue for basaltic regolith

The aim of sampling in Lambahraun was to collect basaltic sand, an analogue for basaltic regolith cached in Delta Front at Hidden Harbor. Sand from Lambahraun was previously characterized by Baratoux et al. (2011) and Mangold et al. (2011) and shown to have mineralogical composition and grain size distribution well matching properties of Atmo Mountain and Crosswind Lake Perseverance samples.

Sampling at Lambahraun was conducted in June 2023. Field work was led by Elizabeth Rampe (NASA/Johnson Space Centre, USA) and assisted by Michael Thorpe (NASA/Goddard, USA), Ryan Ewing (Texas A&M University, USA), Teresa Fornaro (INAF, Italy), Daniel Leeb (Iceland Space Agency), Gunnar Gudjonsson (Iceland Space Agency) and Fiona Thiessen (European Space Agency).

3.3.1. Sampling Site

The field team visited the site at Lambahraun, located in front of Lambahraun volcano and Langjökull glacier. The location was known from earlier studies of Baratoux et al. (2011). The exact sampling point was selected based on field reconnaissance and observation of the sand sheet.

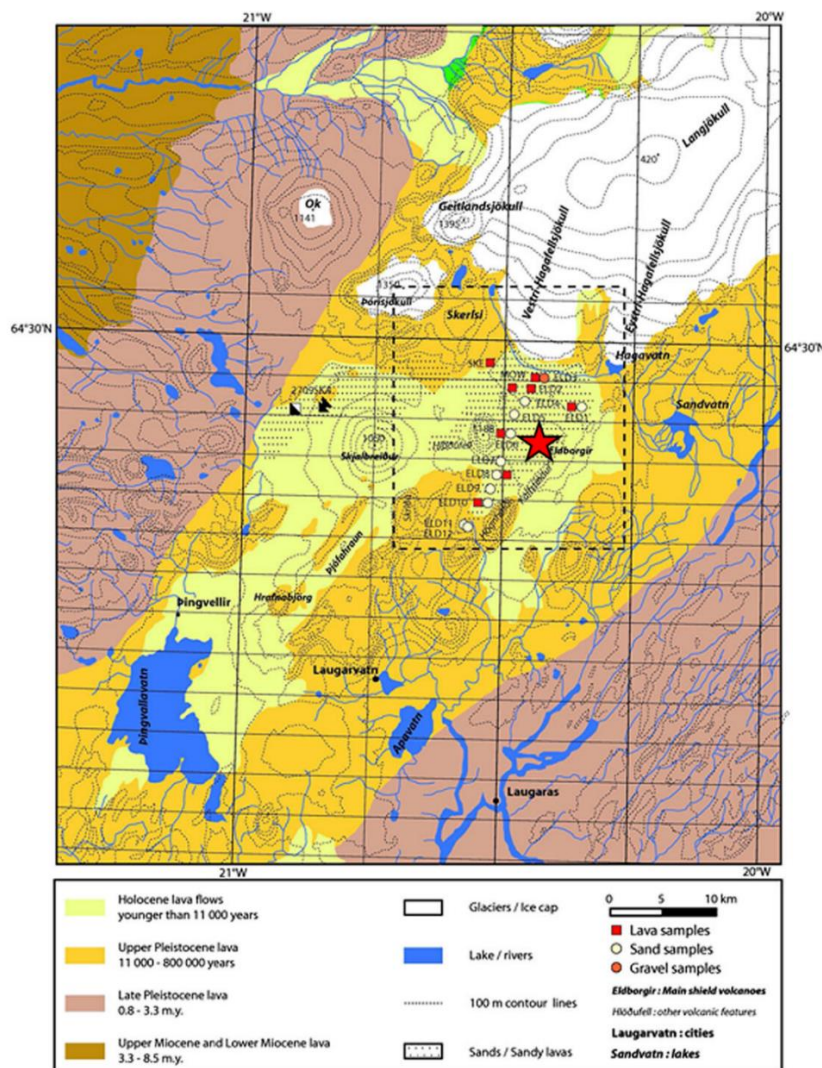


Figure 19. Context map for sampling site at Lambahraun (Baratoux et al., 2011). Sampling site indicated by the red star.

Existing sand sheet and sand dunes were observed by the field team. Sampling was conducted from a sand sheet on the windward side of a climbing sand dune. Granule lag on surface was observed in places, as well as wind ripples.



Figure 20. Sampling site at Lambahraun. a) landscape overview with Lambahraun shield volcano visible in background and relationship of climbing sand dune and sand sheet selected for sampling. b) Close-up view of sand sheet. Area marked with square is enlarged in fig. c. c) Structures of sand sheet: granule lag and wind ripples on the surface. d) Sand sheet surface. Credit: Members of the field team.

For sampling, the field site was segmented into a grid with 11 x 2 cells, and ~20 kg of sand was sampled in each cell across the grid. Samples were collected with a shovel from the upper layer (~5 cm depth from the surface), in order to include the coarse lag and sand.

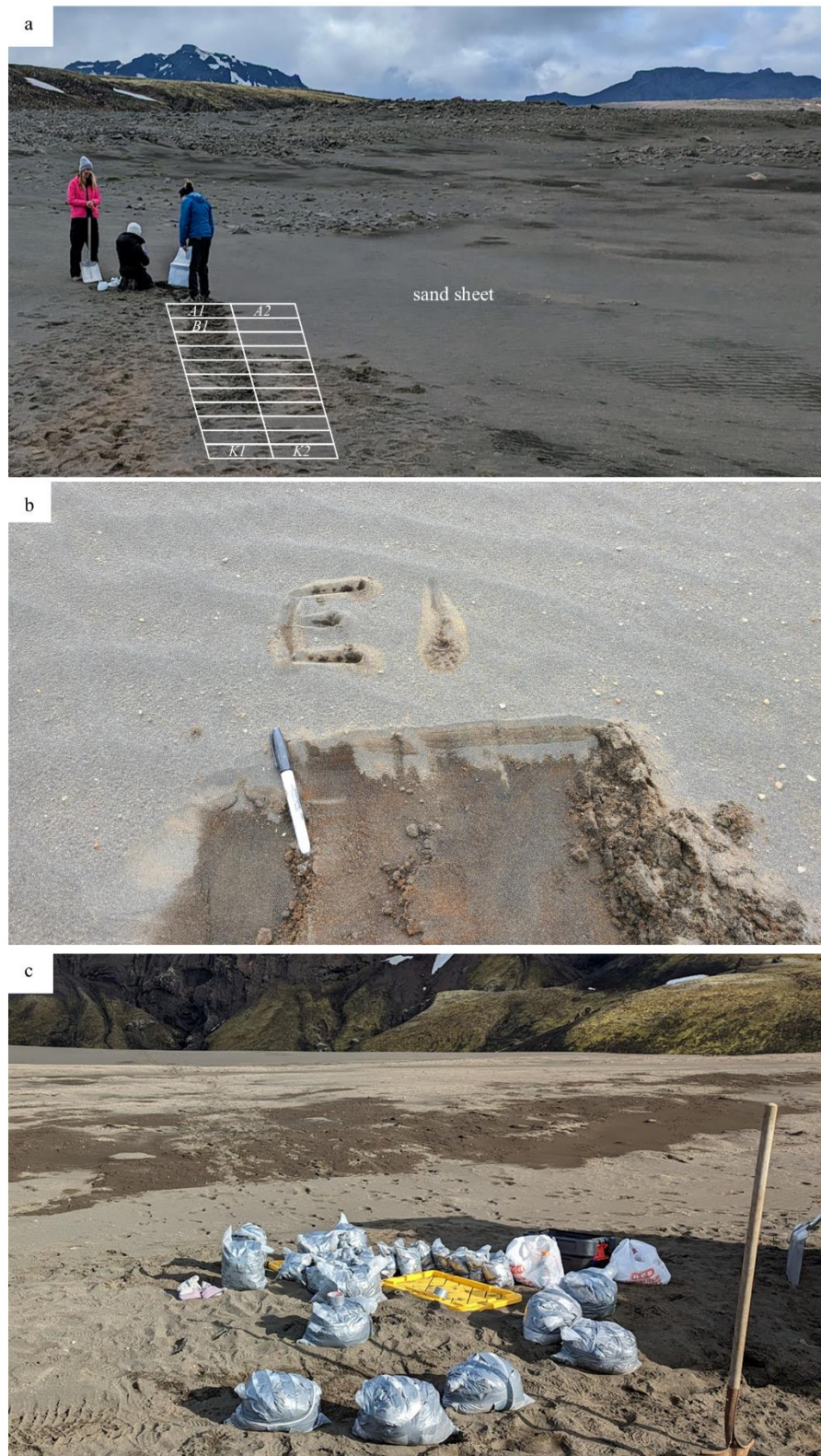


Figure 21. Sampling strategy at Lambahraun and collected material. a) Concept of grid for sampling, note that exact location of cells in the field may be slightly different. b) Close-up view of an example cell sampled, showing stratification within first 5 cm from the surface. c) Collected sand in bags. Credit: Members of the field team.

3.3.2. Available Material

In total, 335 kg of sand was collected from the location and provided to MSR ASL. Information about sample locations within the sampling grid is retained, even though the material across the grid was intended to be uniform. The modal grain size (fine- to medium- grained) is 125 to 350 μm . The sand appears well sorted and well rounded. It is primarily composed of basaltic lithic fragments, mixed with mafic glass and green grains of olivine. Granule lag is coarser grained; grains range from 2 to 4 mm in size. Among larger grains, volcanic pumice is present.



Figure 22. Mesoscopic image of Lambahraun sand (LAM) available in MSR ASL. Ruler for scale.

3.4. Salton Sea (California) sandstones – Analogues for sulfate-carbonate cemented sediments from Delta Front

The aim of sampling of Salton Sea Sandstone was to acquire a material cemented with sulphate-carbonate, aimed to be an analogue for cores Hazeltop and Bearwallow collected at Wildcat Ridge in the Delta Front of Jezero. In this area, carbonate- and gypsum-containing sandstones and mudstones are exposed (Markowski, 2016).

Sampling was conducted in May 2023 on the North Shore of Salton Sea, Durmid Hills. Field work was led by Kirsten Siebach (Rice University, USA) and assisted by David Beaty (NASA-JPL, USA), Lori Shiraishi (NASA-JPL), Errin Dalshaug (NASA-JPL), Maryoyo Brounce (UC Riverside, USA) and Jen Humphreys (UC Riverside).

3.4.1. Sampling Site

The field team visited the site at Durmid Hills, located adjacent to the southernmost tip of San Andreas fault and to modern Salton Sea. Multiple exposures of gypsum-rich sandstones and mudstones are known from this area (e.g. Kirby et al., 2007; Markowski 2016), and they formed in evaporitic deltaic environment, in episodic arid lakes (Kirby et al., 2007).

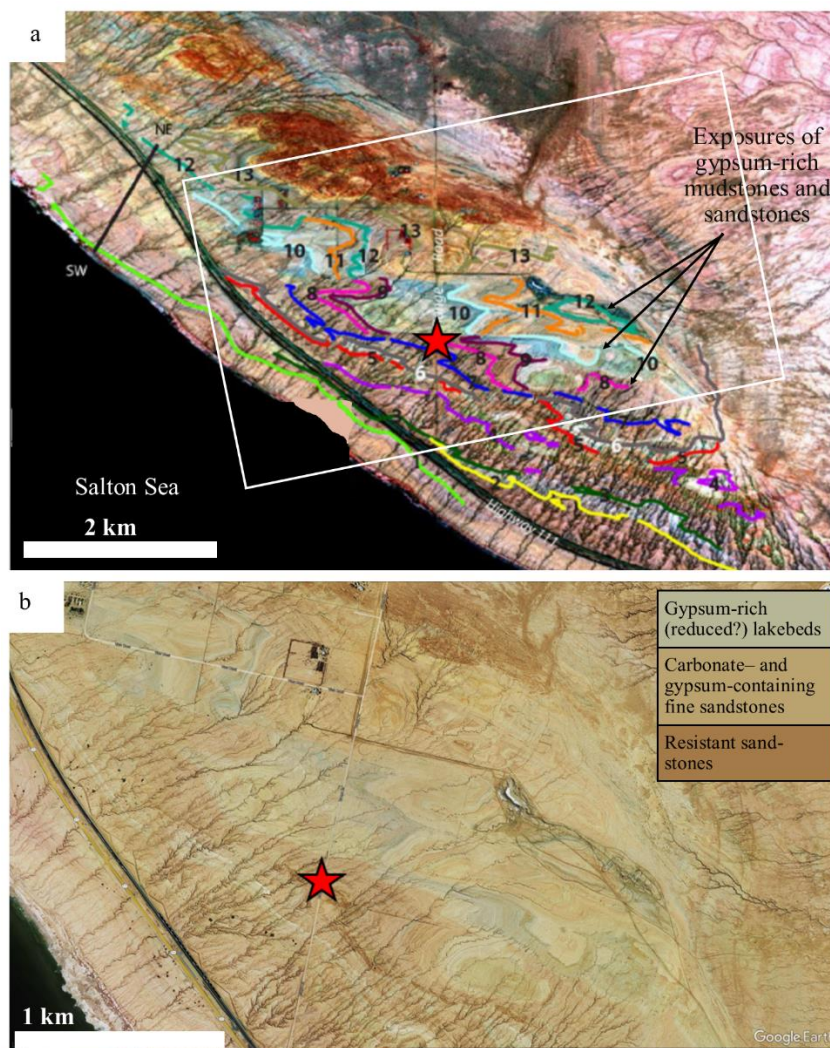


Figure 23. Context map for sampling site at Salton Sea/Durmid Hills. a) simplified geologic map of Durmid Hills from Markowski (2016), in which exposures of gypsum-rich mudstones and sandstones are indicated. Exposure indicated by blue line relates to Brawley Formation, the strata targeted for sampling. White rectangle – area shown in fig. b. b) Google Earth map with enhanced color, showing greenish, gypsum-rich lakebeds and pinkish, more oxidized carbonate- and sulfate-containing finegrained sandstones. Rocks expose best in gullies. Sampling site indicated by red star.

In the area, sandstones and mudstones may contain various content of sulfates. The sampling site was selected among carbonate- and gypsum-containing sandstones, identified from aerial photos by their pinkish color, as opposed to greenish gypsum-dominated mudstones.

Sampling was conducted from a steeply dipping siltstone-sandstone beds exposed in washed beds and gullies close to road. Large portion of rocks in the exposure were too fragile to allow for sampling. The sandstone interval sampled was resistant enough to enable sampling of decimeter-sized blocks.



Figure 24. Sampling site at Salton Sea/Durmid Hills. a) Landscape view. b) View of sedimentary layers from the bottom of a gully. The yellowish sandstone interval to the left of the image was sampled. Most of layers were too friable for sampling. Photo credit: Members of the field team.

The sampled interval appeared rather homogeneous. It underwent positive acid test, implying presence of carbonates in cement. The presence of sulfates is inferred from existence of veins and from the fact that adjacent layers exhibit textures characteristic to evaporitic sulfates. While sampling areas with visible fracture-filling or sparry gypsum were avoided. Samples were separated from the outcrop using rock hammer.

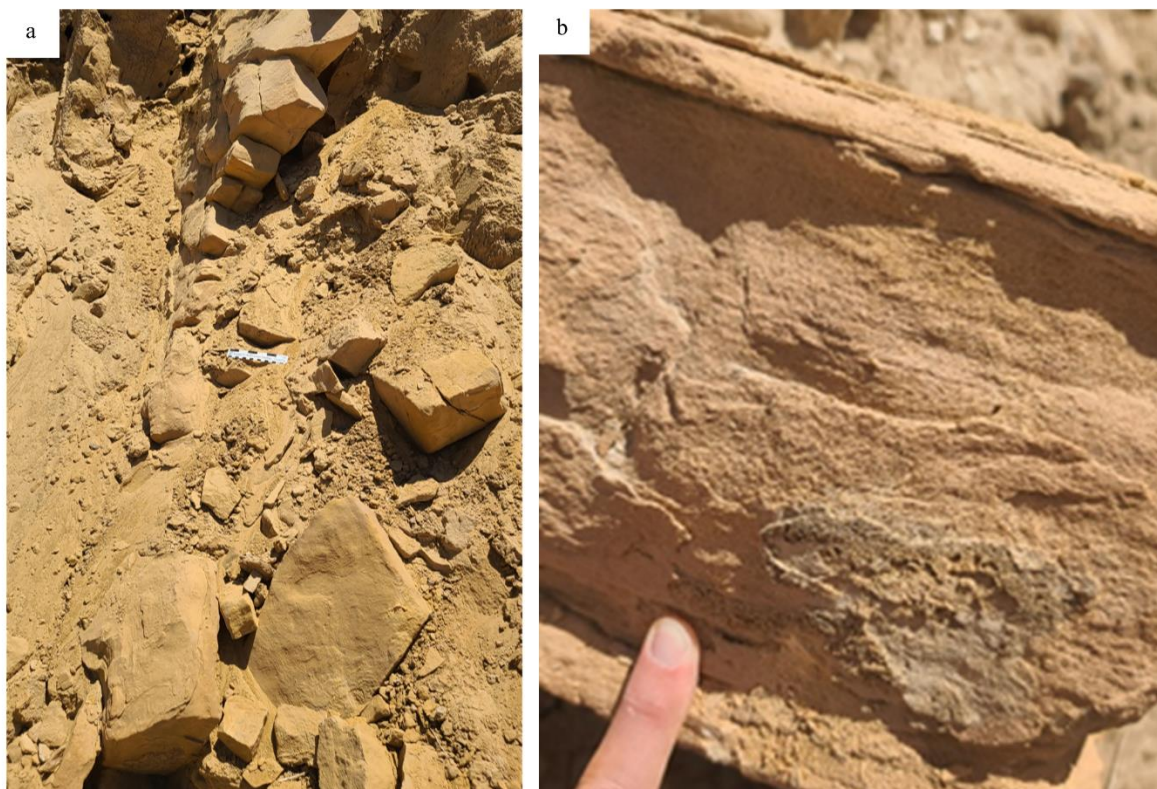


Figure 25. a) Close up photo of the sampled interval. b) example sample collected in the field Photo credit: Members of the field team.

3.4.2. Available Samples

Sampling at Salton Sea led to the accession of more than 30 individual specimens (labelled as SSS) that range in mass from 21 kg to 100 g. In total, the sample mass in the MSR ASL exceeds 100 kg. For details of each sample and corresponding images, see the Sample Catalogue in a separate document [\[link\]](#).

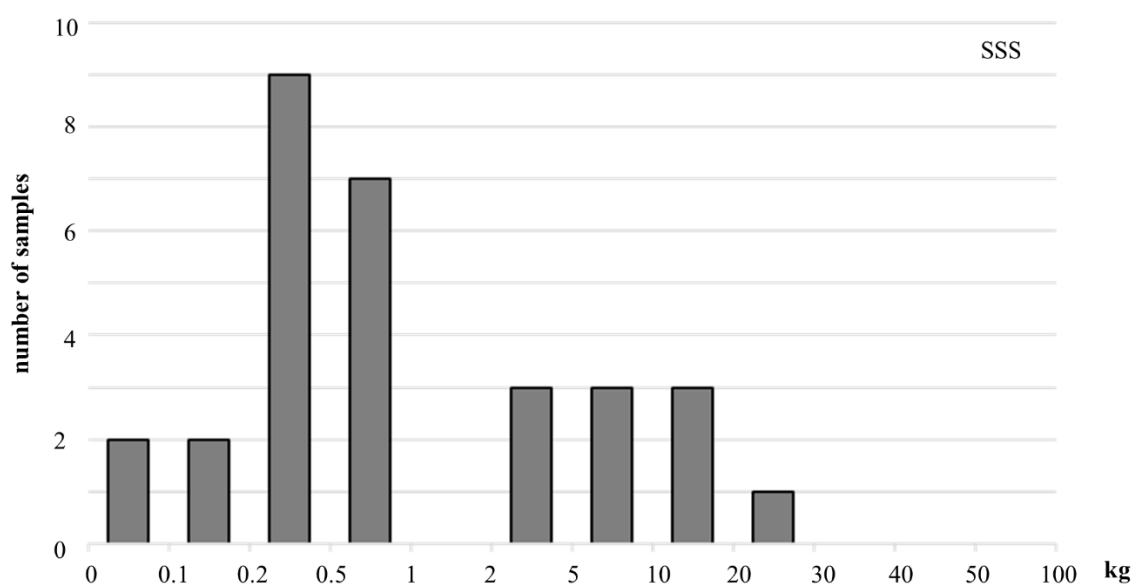


Figure 26. Quantity of SSS samples in binned size ranges.

At the mesoscopic scale, the hand specimens represent sandstone composed of subangular-rounded clasts principally composed of quartz. Feldspar and opaque minerals are present too, as well as a significant amount of cement. This cement must be dominated by carbonates; sulphates are likely also present.

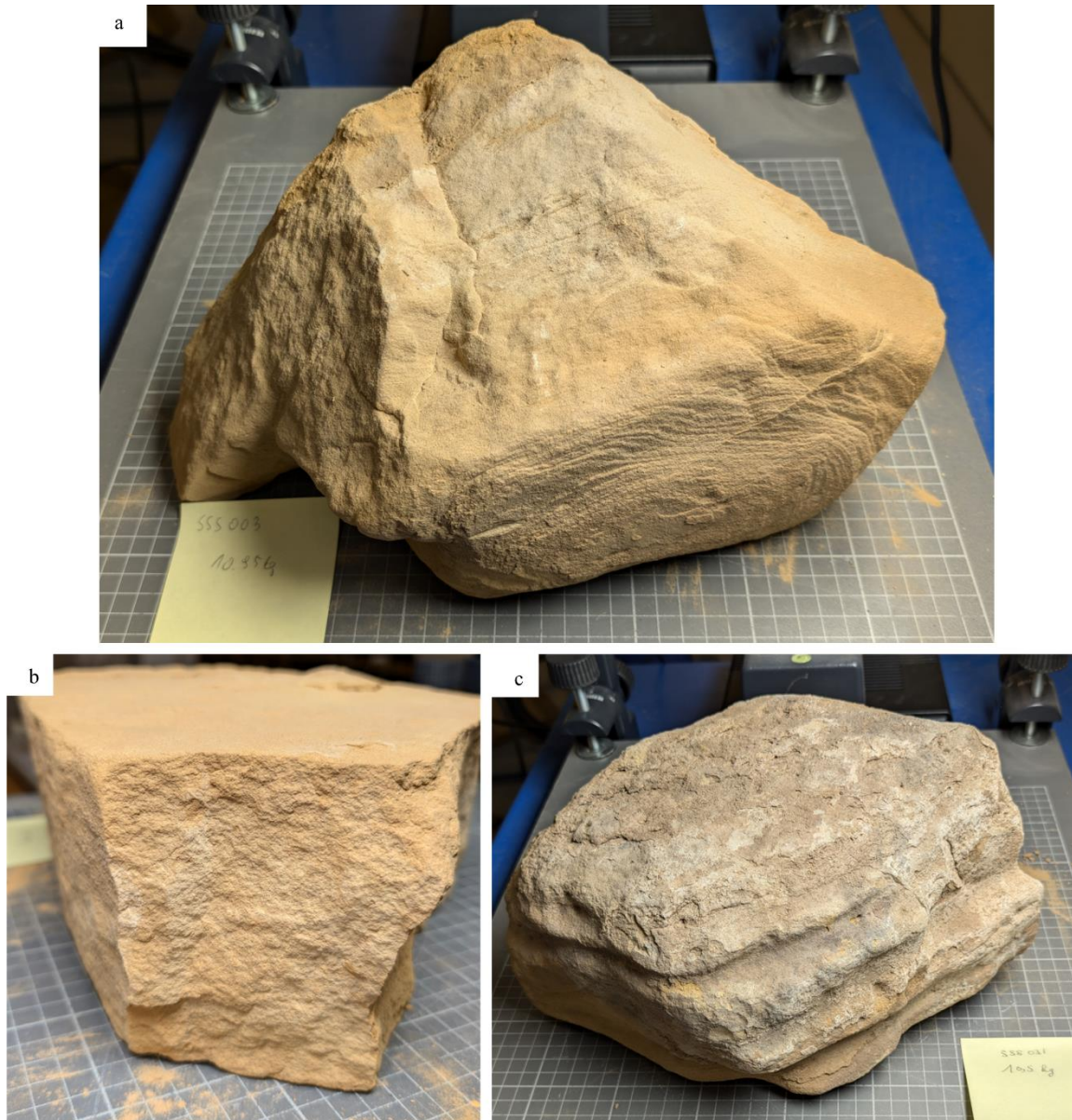


Figure 27. Mesoscopic images of the available sample of sandstones from Salton Sea (SSS). 1 cm grid for scale.

3.5. Ridge Basin (California) Sandstones - Analogues to carbonate-cemented sediments from Delta Front

The aim of sampling of Ridge Basin Sandstone was to collect material cemented with carbonate, an analogue for cores Shuyak and Mageik collected at Amalik in the Delta Front of Jezero. Ridge Basin contains well-studied and well-preserved fluvial, deltaic, and lacustrine/marine sediments comprised of clasts of arkoses and lithic arkoses with minor carbonates, deposited in Transverse Ranges of southern California (Crowell, 2003).

Sampling was conducted in May 2023. Field work was led by Kirsten Siebach (Rice University, USA) and assisted by David Beaty (NASA-JPL, USA), Lori Shiraishi (NASA-JPL) and Errin Dalshaug (NASA-JPL).

3.5.1. Sampling Site

The field team visited site at Piru Gorge, where multiple authors (Crowell and Link, 1982; Crowell, 2003) reported outcrop of planar-laminated sandstone of Peace Valley formation. This sandstone was targeted and identified from Google Earth photos, followed by field inspection.

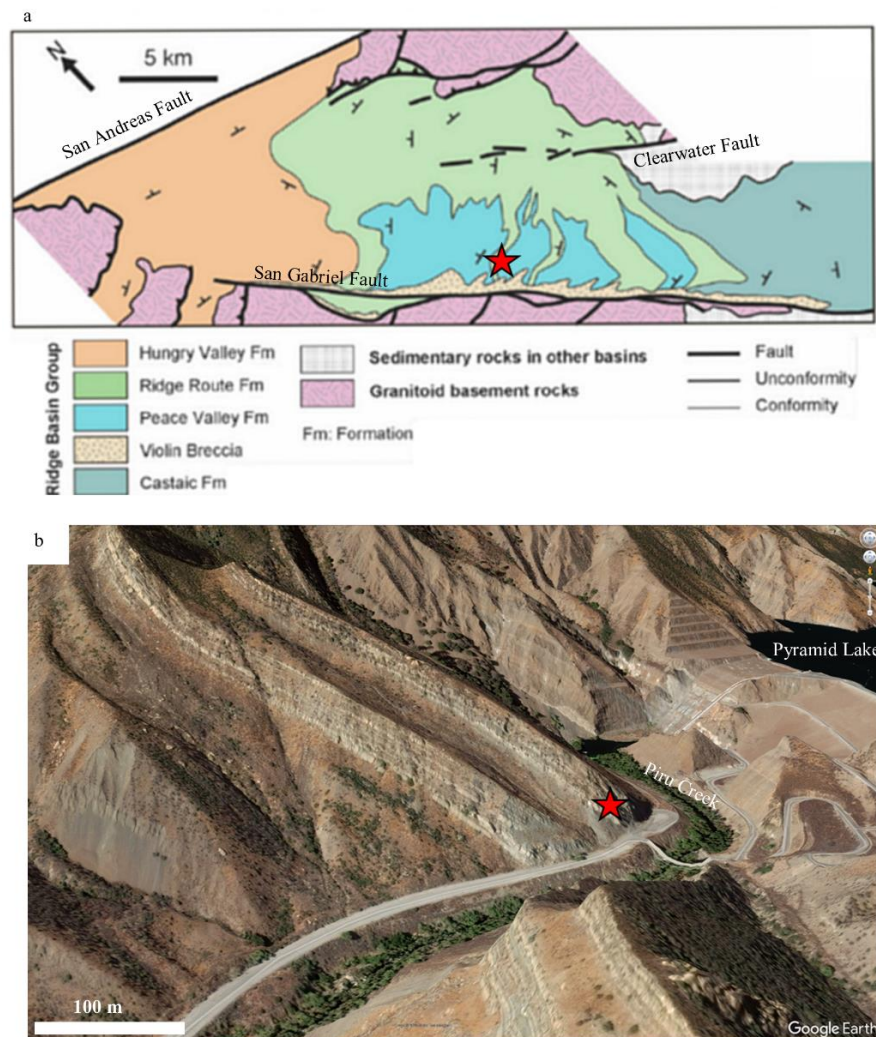


Figure 28. Context map for sampling site at Ridge Basin. a) simplified geologic map of the Basin after Crowell and Link (1982) and Itoh (2013), in which exposures formations of Ridge Basin Group are located. Piru Gorge is part of Peace Valley fm. b) Google Earth map with enhanced color, showing outcrop of Piru Gorge. Approximate location of sampling site indicated by red star.

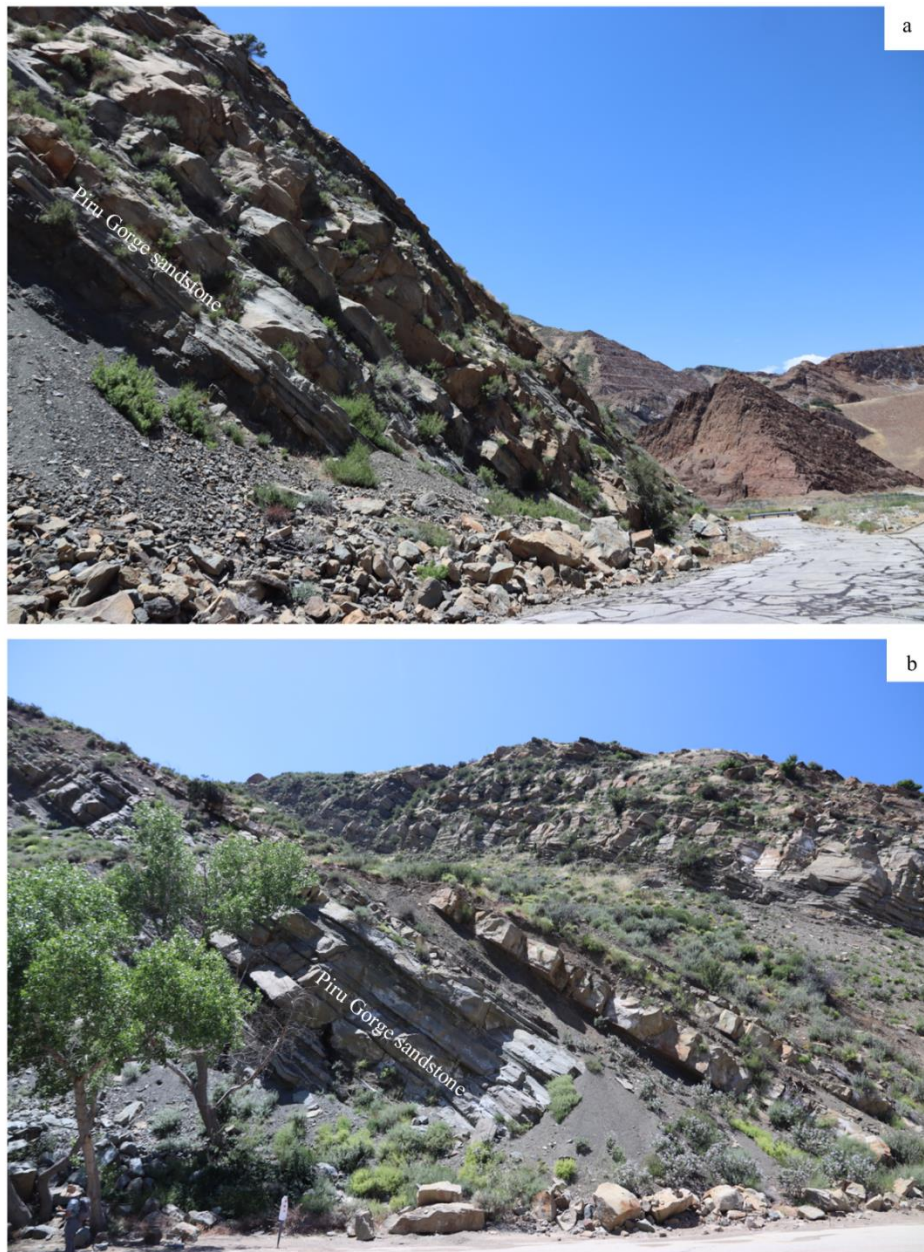


Figure 29. Sampling site at Ridge Basin. Landscape views from different angles showing exposure of Piru Gorge Sandstone. Photo credit: Members of the field team.

The interval chosen for sampling is represented by grey, well-sorted fine sandstone. It is located stratigraphically above fine-grained siltstone and an interval revealing soft sediment deformation. Acid test showed that carbonates are minor in the rock; however, some carbonates appeared to be recrystallizing on surfaces.

For sampling, float rocks were collected from the ground immediately adjacent to the cliff face that contains the facies of interest. Fragments that showed planar lamination resembling those seen in the outcrop were collected. To avoid weathered surfaces and to produce portable pieces, encountered rocks were broken with hammers.

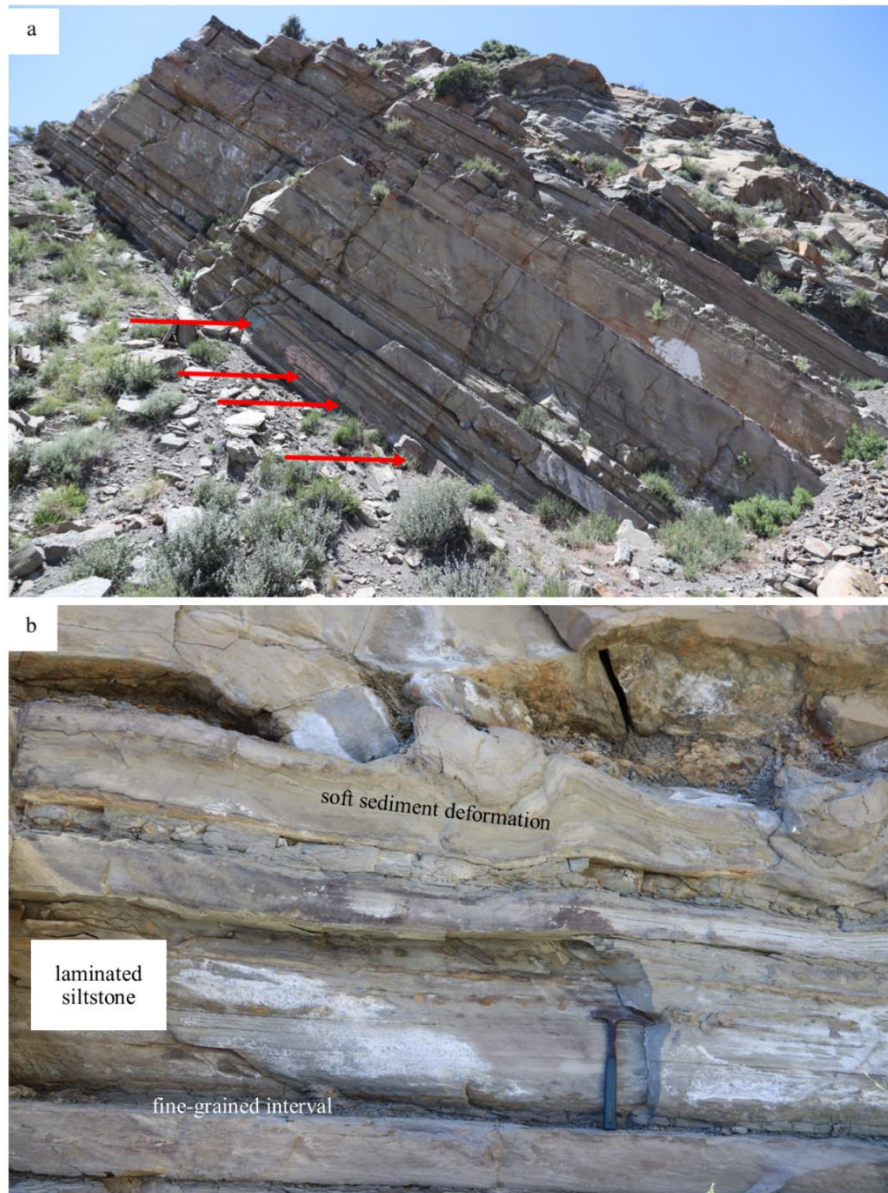


Figure 30. a) Close up photo of the sampled interval marked by red arrows. b) Close up view of the sedimentary textures that served for identification of the interval to sample.

3.5.2. Available Samples

Sampling at Ridge Basin led MSR ASL to the accession of more than 30 individual specimens (labelled as RBS) that range in mass from 30 kg to 100 g. In total, mass of samples exceeds 120 kg. For details of each sample and corresponding images, see the Sample Catalogue in a separate document [\[link\]](#).

At the mesoscopic scale, the hand specimens represent sandstone composed of subangular and subrounded clasts of quartz and feldspar. The sandstone is laminated, and darker laminae are rich in biotite and phyllosilicates. Some carbonates are present in intergranular spaces.



Figure 31. Mesoscopic images of the available sample of sandstones from Ridge Basin (RBS). 1 cm grid for scale.

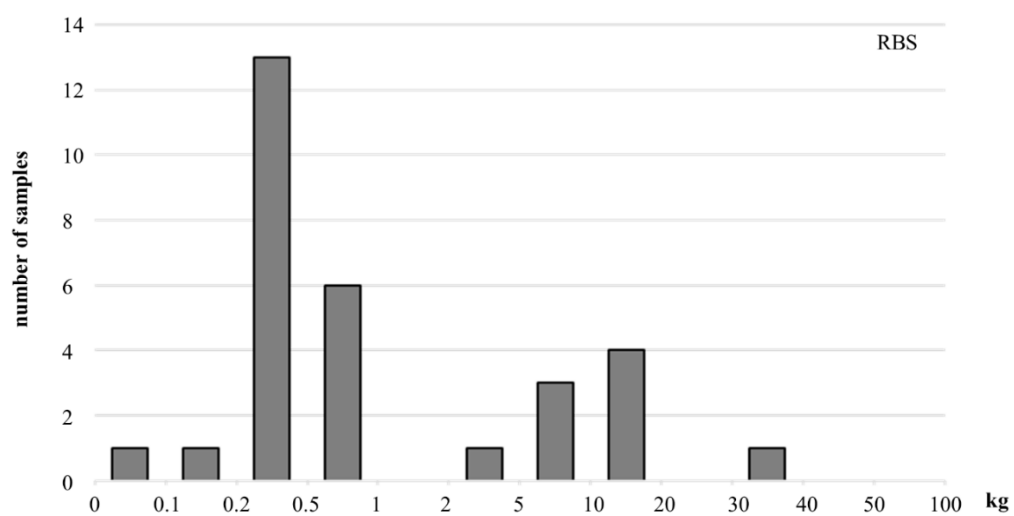


Figure 32. Quantity of RBS samples in binned size ranges.

4. References

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