A NEW SESSION OF THE ESA PANGAEA TRAINING PROGRAM FOR ASTRONAUTS IN LOFOTEN, NORWAY: AN EXCEPTIONAL PLANETARY ANALOGUE FOR THE LUNAR HIGHLANDS. F. Sauro[1,2], M. Massironi[3], K. Kullerud[4], R. Pozzobon[3], H. Hiesinger[5], S.J. Payler[1], L. Bessone[1]: [1]Directorate of Human and Robotics Exploration, European Space Agency, [2] Miles Beyond Srl, [3]University of Padua, Dipartimento di Geoscienze, [4]Norwegian Mining Museum, [5]Institut für Planetologie [3]Institut für Planetologie, Westfälische Wilhelms-Universität Münster

Introduction: PANGAEA (Planetary Analogue Geological and Astrobiological Exercise for Astronauts) is a field training course of the European Space Agency (ESA) that seeks to address the topics of geological and astrobiological planetary exploration [1]. Four editions of the training have been implemented since 2016, with a fifth edition ongoing in 2022-2023. In total, 10 astronauts from ESA, NASA and Roscosmos and additional 5 non-astronaut trainees including space engineers, EVA and operation specialists have taken the course. Although portions of PANGAEA are taught in classrooms, developing independent field skills in analogue geological environments is a key part of the training. In order to perform the training in geological environments with relevant analogies to future mission locations, the PANGAEA team initially selected three European analogue sites: 1) the Permian terrains of the Dolomites (Italy) for teaching fundamentals of geology and the geology of Mars; 2) Ries crater in Germany for impact cratering processes and lithologies on the Moon and Mars, 3) the island of Lanzarote in the Canary archipelago for volcanism on Earth, Moon and Mars.

In the view of future Artemis missions to the lunar highlands, in 2019 PANGAEA started the evaluation of an additional training site, the Flakstadøy intrusive complex in the Lofoten archipelago, Norway, as a potential analogue to the geological settings of the lunar primary crust. After a first dry run of the training the same year with astronaut Matthias Maurer (ESA), the site was officially included in the PANAGEA training program during the 2021-2022 edition, with trainees astronaut Kate Rubins (NASA) and Andreas Mogensen (ESA).

Fig. 1. *ESA astronaut Matthias Maurer, examines an anorthosite boulder during the Lofoten session dry runs in 2019.*

Geological settings and analogies with the lunar highlands: Lofoten, is an archipelago in northern Norway inside the Arctic Circle (Fig. 2). The archipelago is composed of Meso- to Neoarchaean gneisses, which were intruded by an extensive magmatic suite of anorthosite-mangerite-charnockite-granite about 1.8-1.7 Ga ago [2]. These old magmatic suites, including the Flakstadøy basic complex, are made up of anorthosites, gabbros, norites, troctolites and orthopyroxene bearing monzonite and granites (i.e., mangerites and charnockites), and originated in the deep crust of the Baltica continent before its merging into the Rodinia supercontinent at 1300-1000 Ma [3, 4]. The processes in which these features formed, though fractional crystallization of a deep magmatic chamber and diapiric uprising of anorthositic mushes followed by intrusions of margerites and charnockites [5, 6], are similar to the formation of the lunar primordial crust, where the Fe-anorthositic rocks segregated from the early magmatic ocean, and were followed by younger intrusions of Mg- and alkali- suites.

The Rodinia break-up at 750 Ma with the formation of the Iapetus Ocean, followed by its closure during the Caledonian orogenesis (Pangaea supercontinent, 420 Ma), as well as the more recent opening of the north Atlantic Ocean (about 56 Ma), allowed the exhumation of the ancient Precambrian rocks in Lofoten archipelago. In this way, this basement crustal segment defines an emerged horst bounded to the east by thrust nappes of the Scandinavian Caledonides, in a similar setting to the Western Gneiss Region of South Norway.

Quaternary glaciations and the limited vegetation means that these rare rocks are well exposed and can be observed and studied across a broad area. They provide some of the best outcrops of lunar highland analogue rocks in the world [5] and present excellent opportunities for traverses exploring magma-genesis processes.

Traverses and activities with the astronauts: The 4th session of PANGAEA in Lofoten is dedicated to the complex topic of magma differentiation and magmatic intrusions with a specific focus on lunar primary crust. This include lessons and discussions on what has been discovered from the Apollo samples about the origin of lunar highlands. In order to achieve practical skills in rock identification of the most important intrusive suits that could be present on the Moon, astronauts are trained on the recognition of the fundamental intrusive minerals and their assemblages both by eye and with optical lenses and portable microscopes. Using the two ternary diagrams QAP (quartz-alcaline feldspar-plagioclase) and PPO (plagioclase-pyroxenes olivines), trainees are provided with a simple schematic classification methodology that can be used for describing lithologies and outcrops. Once they have acquired these basic skills through a set of theoretical lessons and practical exercises, the astronauts start a series of three traverses, both guided and self-directed [1]. The mountains around the village of Nusfjord in particular allow trainees to cross the entire intrusive complex and observe contacts (either intrusive and tectonic) between several units. The astronauts can explore and analyse transitions from pure anorthosites to Mg-suites including norites, troctolites, and all intermediate members, and alkali suites, including mangerites and charnockites. Traverses are planned using spectral images acquired by satellites, allowing trainees to plan traverse routes across areas of different mineralogical compositions. Once in the field, focus is given to the observation of unit relationships, including peculiar processes like magma mingling, assimilation and fertilization happening in the magmatic chamber. After each traverse, geological maps previously obtained through spectral image analysis are refined using the information gathered by the astronauts during the traverses. Finally, all the information acquired is put in the context of the magma ocean hypothesis and related back processes on the Moon.

Open questions and conclusions: The magmatic complex of Flakstadøy is a beautiful example of a massif-type anorthosite body [6]. Studying this terrestrial analogue for the magma-ocean anorthosites of the Moon can provide important additional information about magma mingling and fertilization through different magmatic pulses which formed the Mg-Suite rocks similar to those found during the Apollo program. Several scientific questions at the site remain unanswered by the scientific community, and their discussion and further investigation is a source of additional motivation and engagement for the astronauts and scientists involved in this specific training session.

In summary, for the PANGAEA training objectives, this location enables more advanced training on the topic of magma differentiation and igneous mineralogy on the Earth and Moon. In addition, the long period of geological history exposed in the area can be compared and linked to what was observed at the other training sites during PANGAEA to provide a holistic view into Earth and the Moon's geological evolution. A new edition of the Lofoten session is planned for the summer 2023 with the participation of ESA and NASA astronauts.

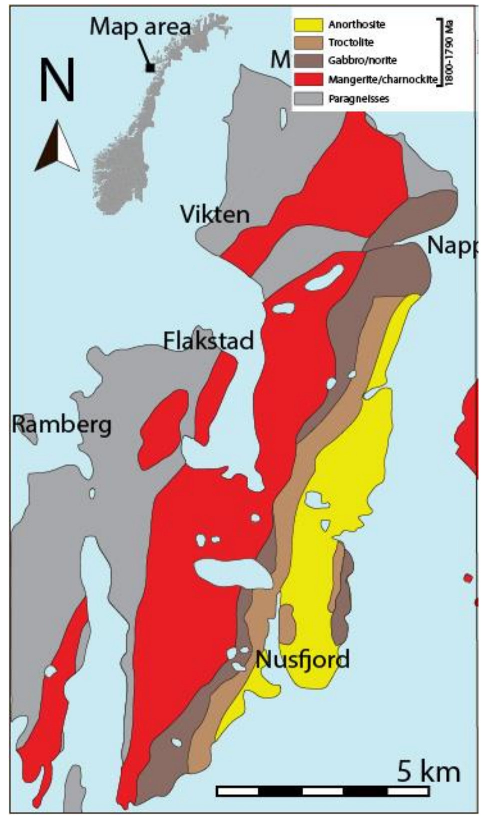

Fig. 2. *Geological map of the* Flakstadøy basic complex showing the sequence of mangerite/charnokite suites and anorthosite/Mg-Suites (modified from [4]).

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