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SAUDI GEOLOGICAL SURVEY

NEW PROJECT FOR VOLCANO AND SEISMIC HAZARD ASSESSMENT IN THE BLACK DESERT DEVELOPMENT AT THE RED SEA PROJECT

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A NEW COMPLEX RESEARCH PROJECT ON VOLCANIC, SEISMIC, AND GEOHERITAGE ASPECTS OF HARRAT LUNAYYIR

A new project has been established to develop a complex study of volcanic and seismic hazards in the Harrat Lunayyir, one of the youngest Cenozoic monogenetic volcanic fields in Saudi Arabia, which is located just east of Umluj.

The project is funded by the Red Sea Global (RSG), a wholly-owned subsidiary of the Public Investment Fund of Saudi Arabia (PIF). The company was established to develop and promote an area referred to as the Red Sea Project. This area is envisioned as an international, barefoot luxury destination. A regenerative approach to tourism is applied at every step of its design, development, and operation. Within this project, and following the above-outlined philosophy, a region of approximately 28,000 km^2 is planned to be set up as a new Special Economic Zone (SEZ). This SEZ will have its own regulatory framework based on global leading practices, with a special emphasis on environmental sustainability, business-friendly regulation, and relaxed social norms. The Vision of RSG is to deliver an ambitious regenerative tourism destination that actively enhances the islands along the Red Sea Coast near Umluj, nature, cultural heritage, and lives of those living in surrounding communities while setting new international standards and positioning Saudi Arabia on the global tourism map. The Red Sea Project is envisaged as a barefoot luxury leisure, tourism, and residential destination, underpinned by a commitment to sustainability and aligned with the internationally recognized UN Sustainable Development Goals (SDGs) (https://www.theredsea.sa/en). The Red Sea Project will be a captivating destination offering domestic and international travelers the chance to experience one of the world's last true hidden natural treasures. The Red Sea Project also explores inland regions to develop special niche tourism destinations. These attraction areas allow visitors to engage with the rich geological heritage of one of the youngest nearby volcanic harrats. The Harrat Lunayyir volcanic field, which features valley-confined lava fields and extensive black ash plains south of the destination, has several dormant volcanic cones. It boasts stunning scenery and beautiful vistas of the enormous lava fields. Red Sea Global embraces sustainability and environmental protection protocols. It is committed to setting new standards for sustainable development, pioneering a new partnership between luxury tourism and the natural environment, and achieving a better tomorrow. The RSG believes sustainability is no longer enough and is applying a regenerative approach to tourism.

The Volcano Project (Black Desert) site is located within the Harrat Lunayyir in the Umluj Governorate (Fig. 1), approximately 65 km east of Umluj. The site was observed to have sequences of basaltic lava stacking on top of and next to each other. The development has identified a site (referred to as Option 4 location) for the development of the Volcano Project (Fig. 2). The site was observed to have different mountains and dormant volcanoes, which are attractive for recreational activities.

ABUNDANT CENOZOIC MONOGENETIC VOLCANISM IN WESTERN SAUDI ARABIA

Western Saudi Arabia hosts one of the world's largest alkali basalt provinces that covers a total area of about 180,000 km^2. Volcanic rocks and volcanic edifices normally directly overlie the Precambrian basement complex of the Arabian Shield, part of the western Arabian plate. The province has traditionally been subdivided into 19 regions, each characteristically dominated by eruptive products of coherent lava and less voluminous pyroclastic rocks, mostly mafic in geochemical composition (Coleman and Gregory, 1983; Camp and others, 1991; Camp and Roobol, 1992; Camp and others, 1992). The subdivision, however, is commonly ambiguous both geologically and by the

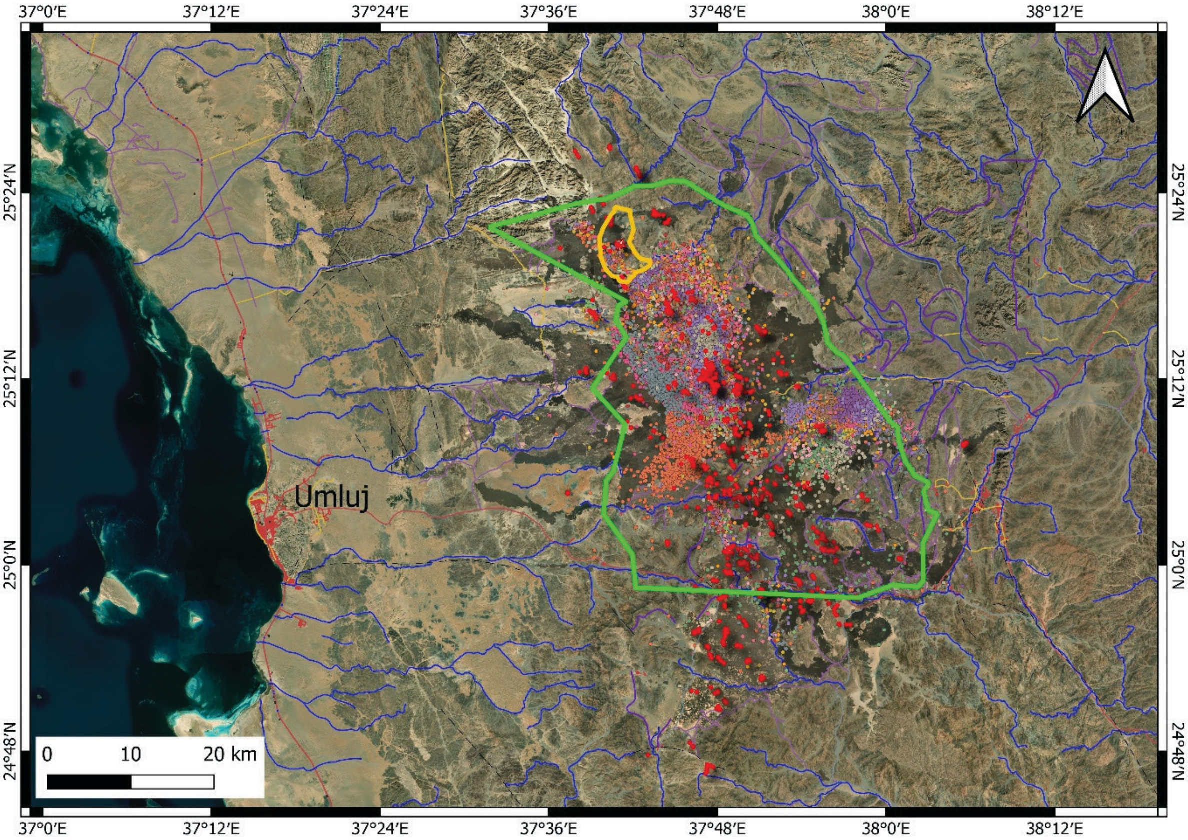
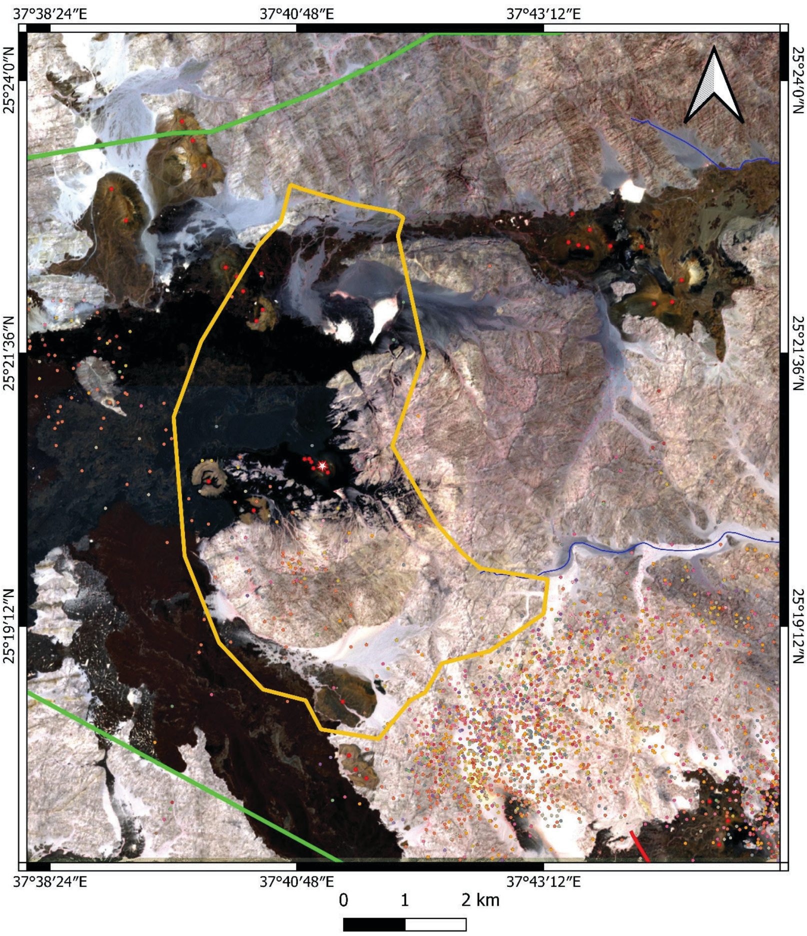


Figure 1. Overview map (Bing Satellite) showing the Red Sea Global project site's broad area (green outline) and its focused development site (yellow outline). Identified volcanic vents are marked with red stars, while the target volcano for geotourism development is marked with white in the yellow-outlined region. The map also shows the larger than M2.5 earthquakes recorded by the SGS seismic network since 2007 (dot colors are coded in the year of occurrence).



usage of local names to specific geographical regions. The subdivision of volcanic fields is also complicated in areas where the number of post-Miocene volcanic edifices is reaching several hundred, such as the Harrat Rahat, as older volcanic edifices are difficult to reconstruct correctly, especially to locate their individual vents. (Runge and others, 2015, 2016). Of the 19 volcanic fields, 13 host dozens of vents and cover significant surface areas. Distinguishing volcanic fields can also pose a problem as large volcanic fields nearby show transitional appearance in the field, and often, putting the boundary between them is not straightforward, such as the case between Harrat Rahat and Khaybar, Harrat Khaybar and Ithnayn, and Harrat Khaybar and Kura for instance (Camp and other, 1991). Extensive geological and geochemical work was carried out in the western Arabian monogenetic volcanic fields in the 1970s to early 1990s (Brown and others, 1989; Camp and others, 1991, 1992; Coleman, 1993), leading to several volcanic source models and hypotheses about the relationship between this type of volcanism and the Red Sea Rift

Figure 2. Close-up view of the focused development area on a Sentinel 2 Satellite False Color Composite image. Note the young lava flows and the remaining ash cover over ridges. Volcanoes are marked by red stars, while the main development site volcano is a white one within the yellow-focused region. Small dots represent earthquakes with a magnitude larger than 2.5 since 2007.

(Camp and others, 1992). While this question is still under debate, it is more and more evident that volcanism generated the harrats due to deep-sourced melt propagation to the surface along basement structures reacted to tectonic stress, allowing small batches of melt to reach the surface periodically (Abdelwahed and others, 2023; Abdelwahed and others, 2024). This style of volcanism is commonly referred to as monogenetic (Smith and Németh, 2017). Dispersed volcanism, which involves deep-sourced magmas such as basalt, is one of the most common types of volcanism on Earth, particularly in intraplate settings. It is among the most challenging types for developing a practical and useful volcanic hazard estimate.

The abundance of monogenetic volcanoes and volcanic fields in western Saudi Arabia suggests fundamental melt generation and transportation processes controlled by various lithosphere structures. The Arabian plate's lithosphere has been commonly modeled from the inversion of P- and S-wave receiver functions (Al-Damegh and others, 2005; Al Amri and others, 2017; Al-Amri and others, 2020). These studies suggest that the Neoproterozoic Arabian Shield has an average crustal thickness of ~40 km. However, towards the Red Sea and the Gulf of Aqaba, the crust thins abruptly to about 23–25 km (Al-Damegh et al., 2005; Almalki et al., 2015). In the northwestern part of the Arabian Shield, which includes the area of Harrat Uwayrid located just north of the study area of Harrat Lunayyir, the crustal thickness varies from 33 to 37 km. In contrast, in the eastern part of the Arabian Platform, where Harrat Hutaymah is located, the crust is much thicker, ranging from 41 to 48 km (Al Amri and others, 2017).

HARRAT LUNAYYIR

Harrat Lunayyir (HL), also known as Harrat Al-Shaqa, is one of the smaller and younger volcanic fields in NW Saudi Arabia. It spans an area of nearly 1750 km^2 and has a generalized structural trend of ~N300 W. It is located on the western edge of the Great Escarpment and is within ~100 km of the Red Sea margin (Coleman and Gregory, 1983). The HL is composed of Cenozoic basaltic flows, without silicic magma (that makes it different from Harrat Khaybar, Kishb, or Rahat) and emplaced along the arc-related plutonic rocks of diorite to tonalite composition with imprints of several cycles of metamorphism and tectonism during Tertiary–Quaternary time. The basement of Harrat Lunayyir comprises amalgamated belts of sedimentary and metamorphic rock units that are delimited by the regional Precambrian Najd Fault System and intervened by numerous basic dykes (Blasband and others, 2000; Stern and Johnson, 2010). The basaltic lava field has two (main) subdivisions, Quaternary and Holocene basaltic flows (Al-Amri and others, 2012; Mukhopadhyay and others, 2013). Using remote sensing techniques, at least three generations of lava flows have been identified in Harrat Lunayyir (HL) (Mogren and others, 2017). Harrat Lunayyir is a continental volcanic field where the composition of lava flows (Fig. 3) and scoria cones (Fig. 4) varies from basanite to alkali olivine basalt to trachy-basalt.

In this volcanic field, at least 50 volcanic cones have been mapped. These are primarily aligned along a NW-SE axis, following the orientations of normal faults (Baer and Hamiel, 2010; Al-Amri and others, 2012; Trippanera and others, 2019). Such volcanic cones are served by deep fissures cutting through the crustal rocks of diorite and tonalitic composition. Two sets of fault systems, which act as feeders, have been identified: (i) a NE-SW trending set, mainly controlled by an older Precambrian fault system that was reactivated during the Tertiary period, and (ii) another set with a NW-SE direction, both of which are somehow related to the rifting and opening of the Red Sea (Mukhopadhyay and others, 2013).

The geodiversity of Harrat Lunayyir is high due to the

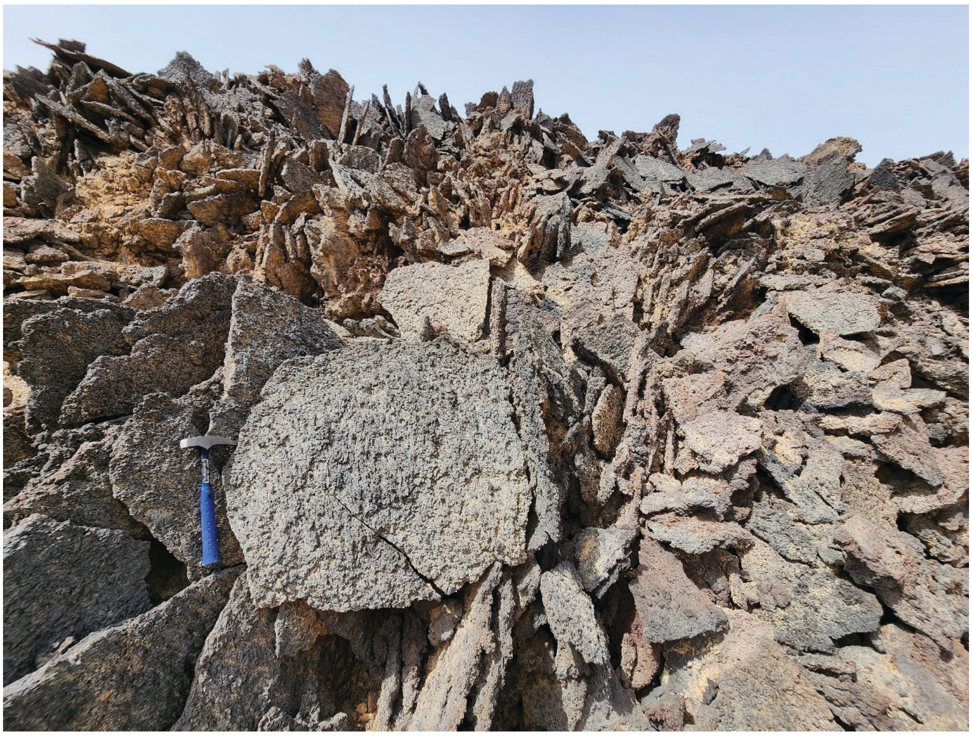


Figure 3. The peculiar slabby pāhoehoe lava flow margin in the center of the target area demonstrates flow complexity and high geoheritage value due to their unique lava flow nature. The hammer is 30 cm long.

complex morphology of rugged basement hills engulfed by extensive lava flows. The basis of the high morphodiversity value is shown well on a geomorphon (Jasiewicz and Stepinski, 2013) map within an appropriate resolution of the region (Fig. 5). Long lava flows are commonly dammed where the accumulation of lava triggers inflation and sudden outbreak, showing complex surface textural diversity of typical transitional pahoehoe lava flows.

Long lava flows in distal areas are commonly disaggregated by surficial processes after their placement. This is common when water from intense rainfall follows the network of lava tubes, gradually breaking down the main bodies of the flows. The field is also remarkable due to the young scoria cones, which likely reached violent Strombolian-style eruptions. These eruptions led to the dispersal of falling ash to a sub-Plinian style and resulted in a substantial amount of ash fall. This ash fall created extensive ash plains, similar to the region where Red Sea Global Development is currently focusing its efforts.

Harrat Lunayyir showed seismic activity suspected to be linked to the presence of some magmatic anomalies still present in the region (Zahran and El-Hady, 2017). This suspicion was confirmed when the region experienced recent seismic unrest, and ground deformation resulted in surface rupture and a fissure formation with clear

Figure 4. Looking into the main development area from the NW toward the main young scoria cone in the middle of it, please note that the ash blanket is partially preserved on the steep Precambrian monzogranite - syenogranite basement ridge.

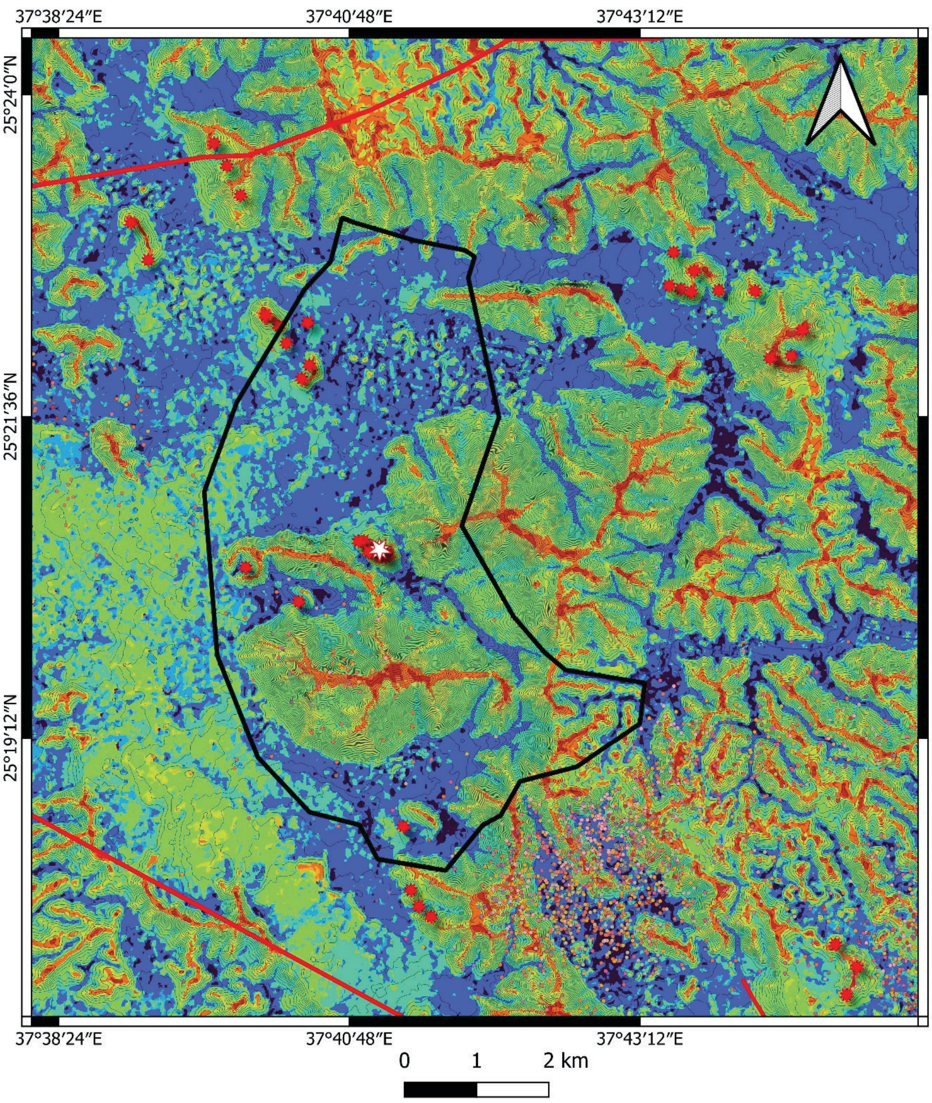


Figure 5. Geomorphon map generated in QGIS Terrain Analysis tool set classifying the landscape elements based on a 12.5 m resolution ALOS-PALSAR digital elevation data. Roughly blue regions represent flat areas, while red zones ridge lines. Contour lines with 10m spacing enhance the topography visually.

fracture zone development nearly 20 km in length in 2009 (Trippanera and others, 2019). This event has been interpreted as a failed eruption where propagating dyke tip never reached the surface and arrested about few hundreds of meters below the surface (Zahran and others, 2009; Pallister and others, 2010; Mukhopadhyay and others, 2013). Since this seismic unrest, the region experiencing elevated seismicity has gradually diminished and shifted its focus toward the northwest.

The Harrat Lunayyir area has been identified as a seismic source zone in recent studies of seismic source zonation in northwestern Saudi Arabia (Al-Arifi and others, 2013; Zahran and others, 2016; Sokolov and Zahran, 2018). This identification has also been added to the recent edition of the Saudi Building Code [https://www.sbc.gov.sa/en/Pages/default.aspx – accessed on 9 May 2024]. A prominent seismic activity has been observed in the Red Sea, in the northwestern, western, and southwestern directions from the study area. This necessitates an appropriate seismic hazard assessment for the area.

THE SAUDI GEOLOGICAL SURVEY CONSULTANCY SERVICES IN GEOHAZARD ASSESSMENT OF HARRAT LUNAYYIR

In response to a need, the Red Sea Global requested a consultancy service from the Saudi Geological Survey in early 2024. This work aims to develop a scientifically validated and evidence-based geohazard assessment, specifically focusing on the Harrat Lunayyir volcanic hazards and the region's seismic hazards. This work includes new and innovative elements. These include providing a data-driven geodiversity assessment of the region and creating an inventory of various geosites, which could be significant for geotourism and geoeducation. This work will develop a geoconservation strategy that will be in good concert with the region's fragile ecosystem and biodiversity, all offering the basics of omnidiversity (a combination of geo and biodiversity elements to a nature diversity view) estimates of the development site (Crisp and others, 2022). The project's geohazard aspects also break out from the traditional probabilistic approach. This is a particularly new development as the volcanic field still has very limited age data of its eruptive events. Their resolution is coarser than the time scale development, such as the Red Sea Global strategic plans in the field might need to be aligned with (decades scale while volcanic recurrence estimated to be in millennial scale at least). This approach will generate a deterministic characterization of volcanic hazards. The documentation of eruptive scenarios will be conducted based on direct field observations. For instance, cataloging the type of volcanic eruption types and styles, their preserved eruptive products, and measurable impacts. In this way, a set of eruption scenarios will be documented and elaborated on in a manual for mitigation if such an eruption occurs. The project will put less emphasis on the location of the most probable future eruption sites. Instead, it will delineate a zone where past eruptions in the entire volcanic field were more abundant and focus on those zones with every possible scenario expected to occur anywhere. The work will provide the most likely eruption scenario, which will be based on geological observations. Additionally, it will evaluate potential models of lava inundation. These models will predict the path of lava flow if a new vent were to open in the target area. The study will also identify regions where safe passage can be guaranteed during lava emission within a specified time frame. In this work, there will be special emphasis on the lava emplacement style and their potential hazard and crisis management. The project will also outline the past seismic activity in the target area and offer a model-based recommendation of what any construction should stand for. This work will also produce a series of maps to visualize the spatial patterns of earthquakes, using existing recordings within the SGS to identify these patterns. Additionally, the study will investigate the specific seismic conditions that must be prepared for should magma segregation and intrusion occur at shallow crustal levels."

As requested, the project will also generate an observation-based geoheritage map to identify areas that can be considered geodiversity and geoheritage hot spots. These areas will be described, and recommendations will be given for developing a realistic geotouristic strategy around them. The geoheritage and geodiversity mapping of the region will provide an asset for the Red Sea Global for future planning and operation.

Prof. Karoly Nemeth, an international expert in volcanology with ample knowledge about monogenetic volcanism and the geoheritage of volcanic regions, led the project. The seismic hazard estimates will be managed by Prof. Vladimir Sokolov, a global expert in seismic hazards, and Prof. Mostafa Toni, who has significant expertise in the impact of seismic hazards on the environment. The project's field of volcanology and Geographic Information System (GIS) management will be organized and overseen by Mr. Abdulrahman Alsowaigh, a research officer for the National Program of Earthquakes and Volcanoes. As the project has deep interdisciplinarity, the outcomes will be extensively discussed by other staff members of the center as well.

REFERENCES CITED

Abdelwahed, M.F., Alqahtani, F., El-Masry, N.N., Aboud, E., El-Hady, S., Faried, A., Abdulfarraj, M., 2024. The role of the Red Sea rift and the inherited geological structures in the seismo-volcanic activity along the rift flanks. Journal of Asian Earth Sciences 260 doi: 10.1016/j.jseaes.2023.105964

Abdelwahed, M.F., Alqahtani, F.A., El-Masry, N.N., El-Hady, S.M., 2023. Insights into the relationship between the Red Sea rift-related structures and the seismo-volcanic activity in Harrat Lunayyir, Saudi Arabia: A seismic tomography study. Journal of Asian Earth Sciences 241:105484. doi: https://doi.org/10.1016/j.jseaes.2022.105484

Al-Amri, A.M., Abdelrahman, K., Mellors, R., Harris, D., 2020. Seismic identification of geothermal prospecting in Harrat Rahat, Northern Arabian Shield. ARABIAN JOURNAL OF GEOSCIENCES 13(8) doi: 10.1007/s12517-020-05300-2

Al-Amri, A.M., Fnais, M.S., Kamal, A.-R., Mogren, S., Al-Dabbagh, M., 2012. Geochronological dating and stratigraphic sequences of Harrat Lunayyir, NW Saudi Arabia. International Journal of Physical Sciences 7(20 [https://doi.org/10.5897/IJPS12.178]):D950EAB19041. doi:

Al-Arifi, N.S., Fat-Helbary, R.E., Khalil, A.R., Lashin, A.A., 2013. A new evaluation of seismic hazard for the northwestern part of Saudi Arabia. Natural Hazards 69(3):1435-1457. doi: 10.1007/s11069-013-0756-1

Al-Damegh, K., Sandvol, E., Barazangi, M., 2005. Crustal structure of the Arabian plate: new constraints from the analysis of teleseismic receiver functions. Earth and Planetary Science Letters 231(3):177-196. doi: https://doi.org/10.1016/j.epsl.2004.12.020

Al Amri, A., Abdelrahman, K., Andreae, M.O., Al-Dabbagh, M., 2017. Crustal and Upper Mantle Structures Beneath the Arabian Shield and Red Sea. In: Roure, F., Amin, A.A., Khomsi, S., Al Garni, M.A.M. (eds) Lithosphere Dynamics and Sedimentary Basins of the Arabian Plate and Surrounding Areas. Springer International Publishing, Cham, pp 3-29. doi: 10.1007/978-3-319-44726-1_1

Almalki, K.A., Betts, P.G., Ailleres, L., 2015. The Red Sea – 50years of geological and geophysical research. Earth-Science Reviews 147:109-140. doi: https://doi.org/10.1016/j.earscirev.2015.05.002

Baer, G., Hamiel, Y., 2010. Form and growth of an embryonic continental rift; InSAR observations and modelling of the 2009 western Arabia rifting episode. Geophysical Journal International 182(1):155-167. doi: http://dx.doi.org/10.1111/j.1365-246X.2010.04627.x

Blasband, B., White, S., Brooijmans, P., De Boorder, H., Visser, W., 2000. Late Proterozoic extensional collapse in the Arabian-Nubian Shield. Journal of the Geological Society 157:615-628. doi:

Brown, G.F., Schmidt, D.L., Huffman Jr, A.C., 1989. Geology of the Arabian Peninsula; shield area of western Saudi Arabia. In: Professional Paper. Reston, VA doi: 10.3133/pp560A

Camp, V.E., Roobol, M.J., 1992. Upwelling asthenosphere beneath Western Arabia and its regional implications. Journal of Geophysical Research-Solid Earth 97(B11):15255-15271. doi:

Camp, V.E., Roobol, M.J., Hooper, P.R., 1991. The Arabian Continental Alkali Basalt Province 2. Evolution of Harrats Khaybar, Ithnayn, and Kura, Kingdom of Saudi-Arabia. Geological Society of America Bulletin 103(3):363-391. doi:

Camp, V.E., Roobol, M.J., Hooper, P.R., 1992. The Arabian Continental Alkali Basalt Province 3. Evolution of Harrat Kishb, Kingdom of Saudi-Arabia. Geological Society of America Bulletin 104(4):379-396. doi:

Coleman, R.C., Gregory, R., 1983. Cenozoic volcanic rocks. U. S. Geological Survey Professional Paper:287-287. doi:

Coleman, R.G., 1993. Geologic evolution of the Red Sea. Oxford Monographs on Geology and Geophysics, 24 [Oxford University Press, New York]:1-186. doi:

Crisp, J.R.A., Ellison, J.C., Fischer, A., 2022. Omnidiversity Consolidation of Conservation Assessment: A Case Study of Tasmanian Coastal Geoconservation Sites. Geoconservation Research 5(1):108-134. doi: 10.30486/gcr.2022.1947195.1099

Jasiewicz, J., Stepinski, T.F., 2013. Geomorphons-a pattern recognition approach to classification and mapping of landforms. Geomorphology 182:147-156. doi: 10.1016/j.geomorph.2012.11.005

Mogren, S., Saibi, H., Mukhopadhyay, M., Gottsmann, J., Ibrahim, E.-K.H., 2017. Analyze the spatial distribution of lava flows in Al-Ays Volcanic Area, Saudi Arabia, using remote sensing. Arabian Journal of Geosciences 10(6) doi: 10.1007/s12517-017-2889-0

Mukhopadhyay, B., Mogren, S., Mukhopadhyay, M., Dasgupta, S., 2013. Incipient status of dyke intrusion in top crust - evidences from the Al-Ays 2009 earthquake swarm, Harrat Lunayyir, SW Saudi Arabia. Geomatics Natural Hazards & Risk 4(1):30-48. doi: 10.1080/19475705.2012.663794

Pallister, J.S., McCausland, W.A., Jonsson, S., Lu, Z., Zahran, H.M., El Hadidy, S., Aburukbah, A., Stewart, I.C.F., Lundgren, P.R., White, R.A., Moufti, M.R.H., 2010. Broad accommodation of rift-related extension recorded by dyke intrusion in Saudi Arabia. Nature Geoscience 3(10):705-712. doi: 10.1038/ngeo966

Runge, M.G., Bebbington, M.S., Cronin, S.J., Lindsay, J.M., Moufti, M.R., 2015. Sensitivity to volcanic field boundary. Journal of Applied Volcanology 4(1) doi: 10.1186/s13617-015-0040-z

Runge, M.G., Bebbington, M.S., Cronin, S.J., Lindsay, J.M., Moufti, M.R., 2016. Integrating geological and geophysical data to improve probabilistic hazard forecasting of Arabian Shield volcanism. Journal of Volcanology and Geothermal Research 311:41-59. doi: 10.1016/j.jvolgeores.2016.01.007

Smith, I.E.M., Németh, K., 2017. Source to surface model of monogenetic volcanism: A critical review. In: Geological Society Special Publication. 446, pp 1-28. doi: 10.1144/SP446.14

Sokolov, V., Zahran, H.M., 2018. Seismic hazard analysis for development of risk-targeted ground-motion maps in the western Saudi Arabia. 16th European Conference on Earthqwuake Engeneering Thessaloniki, Greece(18-21 June 2018):1-12. doi:

Stern, R.J., Johnson, P., 2010. Continental lithosphere of the Arabian Plate: A geologic, petrologic, and geophysical synthesis. Earth-Science Reviews 101(1):29-67. doi: https://doi.org/10.1016/j.earscirev.2010.01.002

Trippanera, D., Ruch, J., Passone, L., Jonsson, S., 2019. Structural Mapping of Dike-Induced Faulting in Harrat Lunayyir (Saudi Arabia) by Using High Resolution Drone Imagery. FRONTIERS IN EARTH SCIENCE 7 doi: 10.3389/feart.2019.00168

Zahran, H.M., El-Hady, S.M., 2017. Seismic hazard assessment for Harrat Lunayyir A lava field in western Saudi Arabia. SOIL DYNAMICS AND EARTHQUAKE ENGINEERING 100:428-444. doi: 10.1016/j.soildyn.2017.06.009

Zahran, H.M., McCausland, W.A., Pallister, J.S., Lu, Z., El-Hadidy, S., Aburukba, A., Schawali, J., Kadi, K., Youssef, A., Ewert, J.W., White, R.A., Lundgren, P., Mufti, M., Stewart, I.C., Anonymous, 2009. Stalled eruption or dike intrusion at Harrat Lunayyir, Saudi Arabia? Eos, Transactions, American Geophysical Union 90(52, Suppl.):Abstract V13E-2072. doi:

Zahran, H.M., Sokolov, V., Roobol, M.J., Stewart, I.C.F., El-Hadidy Youssef, S., El-Hadidy, M., 2016. On the development of a seismic source zonation model for seismic hazard assessment in western Saudi Arabia. Journal of Seismology 20(3):747-769. doi: 10.1007/s10950-016-9555-y