Multi-disciplinary Monitoring of the 2014 Eruption of Fogo Volcano, Cape Verde

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ABSTRACT

The Fogo volcano, located in the Cape Verde Archipelago (offshore Western Africa), is a complete stratovolcano system. It is the most recent expression of the Cape Verde hotspot, that has formed the archipelago. The summit reaches ~2830m above sea level, and raises 1100m above Chã das Caldeiras, an almost flat circular area (approximately 10 kilometers in the north-south direction and 7 kilometers in the east-west direction.

The last eruption of Fogo started on November 23, 2014 (~10:00UTC) on a subsidiary vent of the main cone, after 19 years of inactivity. C4G (Collaboratory for Geosciences), a distributed research infrastructure created in 2014 in the framework of the Portuguese Roadmap for Strategic Research Infrastructures, collaborated immediately with INMG, the Cape Verdean Meteorological and Geophysical Institute with the goal of complementing the permanent geophysical monitoring network operated in Fogo island. The INMG permanent network is composed of seven seismographic stations and three tiltmeter stations, with real-time data transmitted.

This network started to detect pre-event activity on October 2014, with earthquakes occurring at depths larger than 15 km. These events led to a first volcanic warning to the Cape Verdean Civil Protection Agency. On the basis of increased activity, INMG issued a formal alert of an impending eruption to the Civil Protection Agency, about 24 hours before the onset of the eruption. The Copernicus Emergency Management Service was also activated and several maps of lava flows advance and general site information were produced, based on Earth Observation, to facilitate crisis management.

Although the eruption caused no casualties or personal injuries due to the warnings issued, the lava expelled by the eruption (which last until the end of January) destroyed the two main villages in the caldera (~1000 inhabitants) and covered vast areas of agricultural land, causing very large economic losses and an uncertain future of the local populations.

The C4G team installed a network of seven GNSS receivers and nine seismometers, distributed by the entire island. The data collection started on 28th November 2014, and continued until the end of January 2015. The mission also included a new detailed gravimetric survey of the island, the acquisition of geological samples, and the analysis of the air quality during the eruption. We present here a detailed description of the monitoring efforts carried out during the eruption.

This monitoring effort carried out at the request and in collaboration with INMG, was made possible by an emergency financial support provided by Fundação para a Ciência e Tecnologia* (Portuguese National Science Foundation), *Portugal.

FOGO VOLCANO

Fig. 1 – Location of Fogo Volcano, Cape Verde

Fogo is an active stratovolcano that had 28 eruptions since the initial settlement around 1500AD, with average time intervals of 20 years. Its present main geomorphological features results from a large lateral collapse, which occurred between 123 and 62 Ka. Partial infilling of the collapse scar has produced a nearly horizontal flat plateau, known as Chã das Caldeiras (Fig. 2). On the eastern side of Chã das Caldeiras rises the summit cone Pico do Fogo (28m asl). The flanks of Fogo outside the lateral collapse scar display numerous volcanic vents, concentrated in radial zones, which form a modified triple rift geometry. The distribution of dikes in the cliff of the collapse scar – the Bordeira - replicates these preferential directions: NNS, SSE and a broader sector towards the West. According to historical records, until 1725 most of the eruptions occurred through the Pico do Fogo summit, although more recent mapping indicates that some of these also involved eruptions on flank fissures in the northwest and southeast. After the 1785 eruption until now the summit of Pico do Fogo has been inactive. The six subsequent eruptions occurred inside the collapse scar, mainly through N-S fissures, that are arranged in a pattern that suggest that the feeding dikes follow the trends of the NNE and SSE rift zones at greater depth, except the two last eruptions (1995 and 2014), which were fed by the western rift zone.

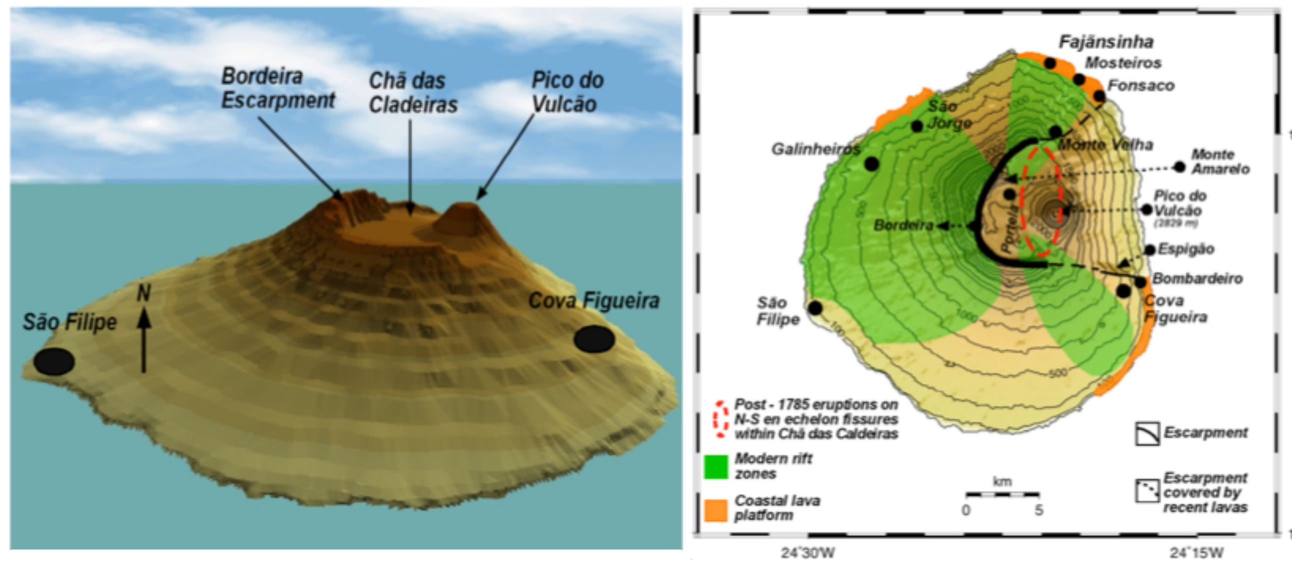


Fig. 2 – Main geomorphological and structural features of Fogo: (left) Perspective view from the south; (right) Topographic map of Fogo showing also the rift zones.

FOGO 2014 ERUPTION

During the pre-eruptive period the seismic activity was dominated mainly by events of hydrothermal origin. Early October there was a change and the activity was dominated by very weak and deep seismic volcano-tectonic events. On the 4th October a 2.5 magnitude event was recorded, and it was located at about the middle of the island at 15 km (bsl) deep, and the first alert was issued. On the 21st November, two days before the beginning of the eruption, a very shallow VT swarm started (when the alert level was raised to 3), and reached a peak on the 22nd about 23h00 (UTC) (and the alert level was change to 4). The hypocenters of the events of the swarms were located at about the middle of the island between and 5 and 3 km (bsl) deep. During the eruption only very few VT events were recorded. At ~09h00 (UTC) of the 23rd November, volcanic tremor started to be recorded, but until there no LP were recorded. The amplitude of the volcanic tremor reached a maximum (Fig. 3) at the beginning of the eruption at 11h15 (UTC), and then it decreased exponentially. In the following days it was good indicator of the state of the eruption as the effusion rate was correlated with some delay in time with the amplitude of the volcanic tremor.

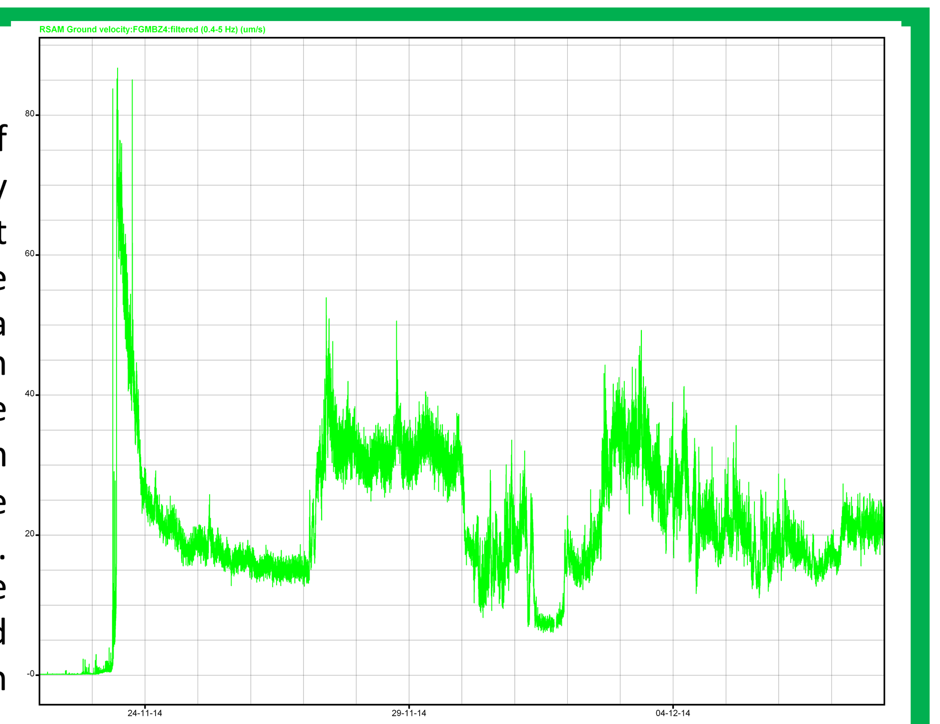
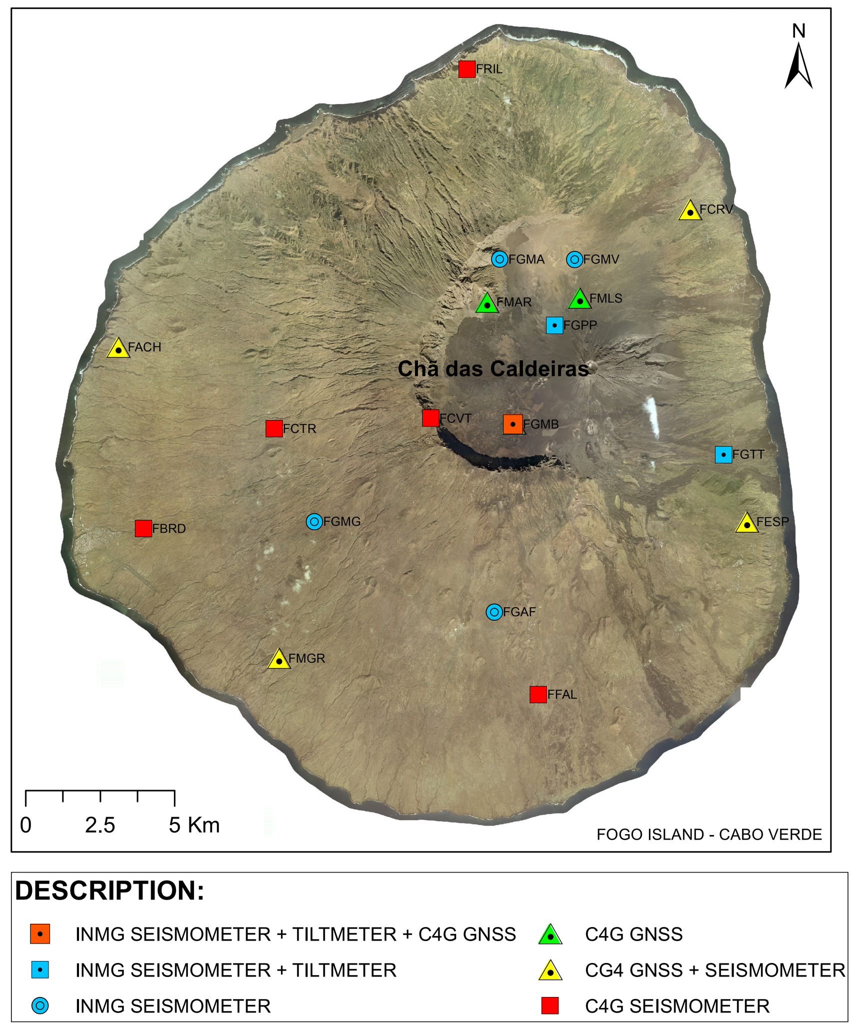


Fig. 3 – RSAM of the filtered between 0.4 and 5 Hz vertical component of seismic signal recorded at FGMB station (which is closest station to the eruptive vent). The vertical units are um/s and horizontal are days.

C4G MONITORING OF 2014 FOGO ERUPTION

C4G received a request of collaboration from INMG to assist the instrumental observation of the ongoing eruption few days after the begin of the eruption. The request was readily accepted, and FCT exceptionally funded a mission to Fogo to collect geological, seismic, geodetic, and geochemical data. These rich datasets offer a unique opportunity to image the active plumbing system and eruptive behavior of Fogo.



Field monitoring of the eruption effusive and explosive activity and respective vents; lava flows rock sampling for petrological and geochemical studies.

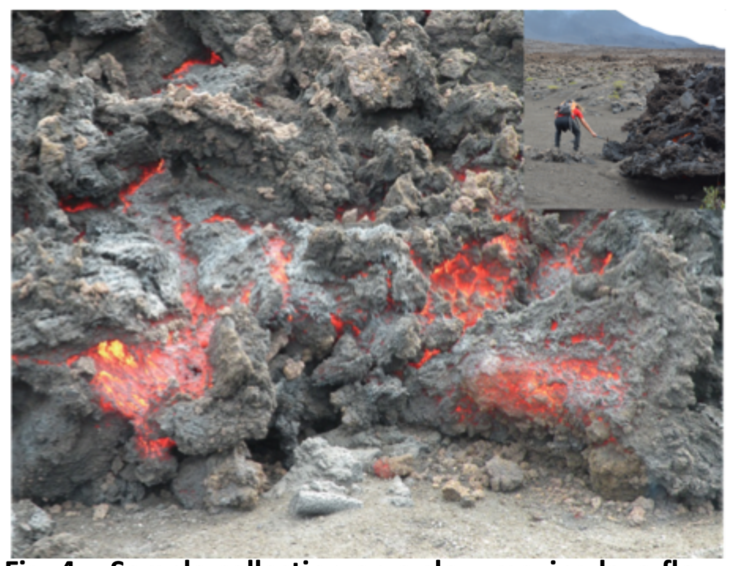


Fig. 4 – Sample collection on a slow moving lava flow front (5 Dec).

The pool of C4G seismometers (provided by IPMA and Univ. Évora) were installed in order to optimize the existing INMG network. The C4G GNSS receivers (provided by University of Beira Interior) were installed in a geodetic network created in 1999.

Fig. 6 – Distribution (above) and details (below) of the seismic and geodetic networks installed during the eruption.

Air quality monitoring and outdoor dusts collection in eleven of Fogo island main villages. The locations were selected on an effort to monitor the island and understand the impact of the 2014 eruption on the population's health.

Fig. 5 - Air quality monitoring portable equipment: (a)PM10 sampler, (b) dust track aerosol monitor, and (c) CO, CO2, TVOCs, temperature and humidity analyzer.

THE FIRE PROJECT

As a consequence of the mission to Fogo, C4G has promoted the submission of a large collaborative project to the latest (end of January 2015) FCT call for scientific projects: FIRE (Fogo Island volcano: multi disciplinary Research on 2014 Eruption). This project counts with a large team of Portuguese and Cape Verdean scientists, many of whom have a distinguished track record of work on Fogo and other volcanic systems. The project is the first joint scientific venture of the C4G community, serving as catalyzer of integration between scientists and research groups within C4G, and between C4G and its strategic partners (61 researchers from Portugal and Cape Verde Institutions).

This project aims the improvement of volcanic hazard assessment and risk mitigation strategies for Fogo, in partnership with the competent authorities. This mission will be achieved through:

1. Improvement of the scientific knowledge of the plumbing system, through geological, morphostructural and geochemical investigations, complemented by microgravity surveying and seismic tomography;
2. Thorough characterization of the 2014 eruption dynamics, through the analysis of the associated seismicity data and geodetic signature, complemented with field observation and remote sensing data;
3. Lava flow modelling with a new digital elevation model derived with a UAV (drone), for a range of possible vent locations, associated with a probability density function derived from the previous eruptive history.

The project's activities converge into the following 3 transversal themes:

i) volcanic structure (Past);
ii) eruption dynamics (Present);
iii) strategies for risk mitigation (Future).

The results that feed into the three transversal themes are obtained through disciplinary tasks that facilitate in depth knowledge exchange. In order to achieve the proposed goals, we rely on a variety of techniques spanning the fields of physical volcanology, geological mapping, remote sensing, seismology, space geodesy & gravimetry, igneous petrology & geochemistry, geochronology, palaeomagnetism, and numerical modeling.

Besides contributing to hazard assessment, the anticipated results will also contribute to a holistic understanding of the Fogo volcano and of ocean island volcanoes in general. Notably, improved knowledge of the Fogo system will allow insight into the trigger mechanisms behind volcanic extreme events (low probability, high impact): In pre-historical times, Fogo generated several highly explosive (plinian) eruptions, and it was also the site of a catastrophic flank collapse that triggered a devastating giant tsunami (~73 kyrs ago).

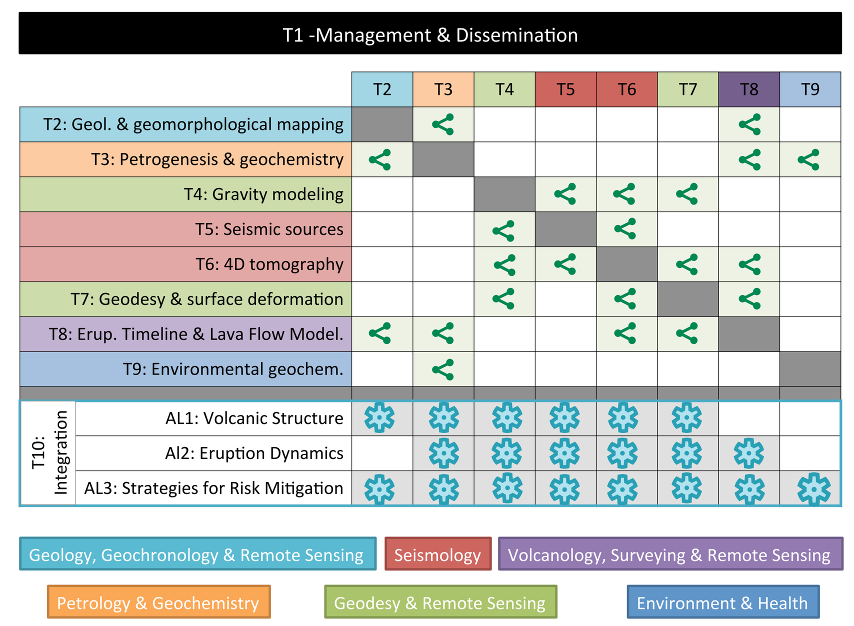


Fig. 7 – FIRE multi-disciplinary project (submitted to FCT)

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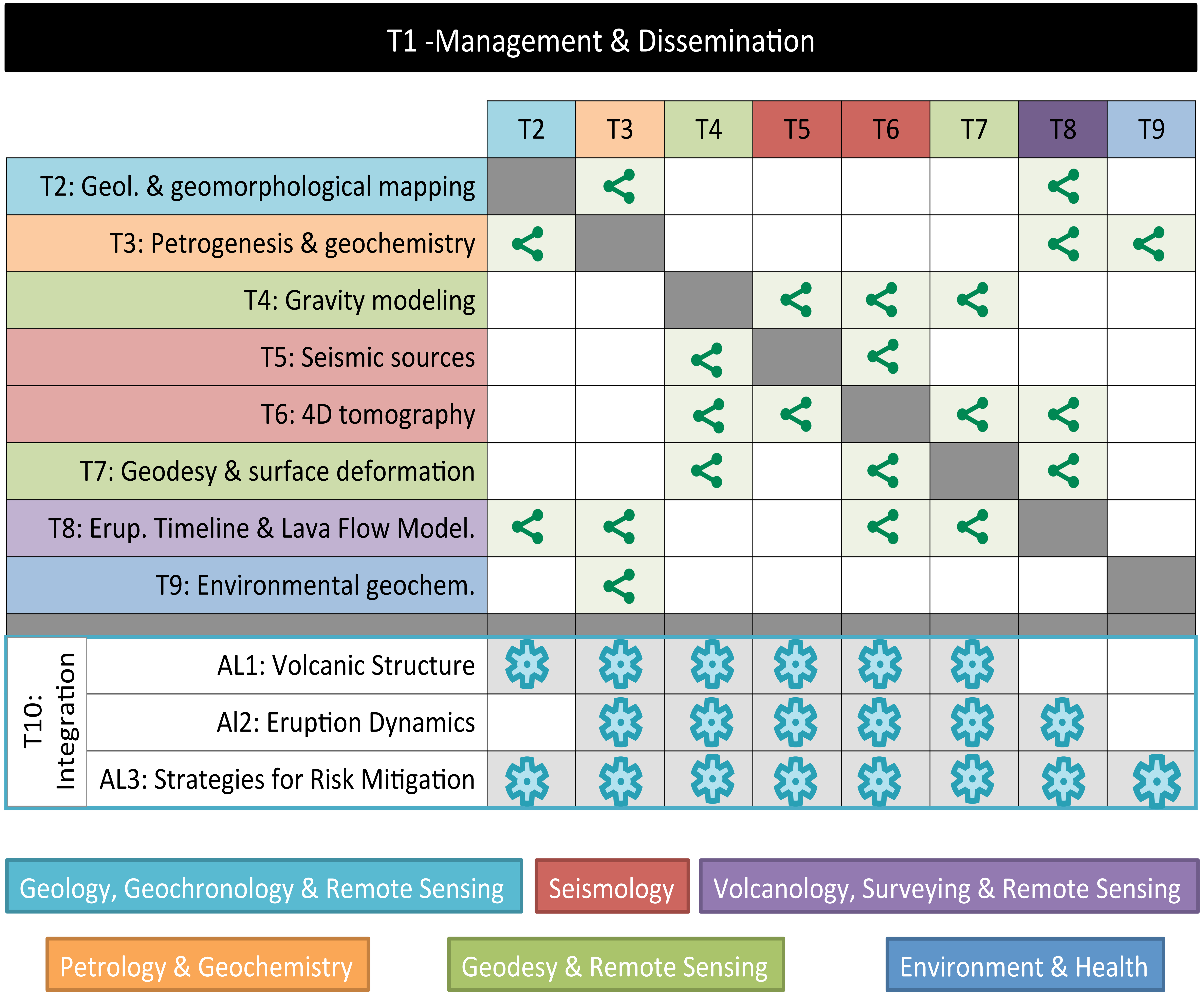

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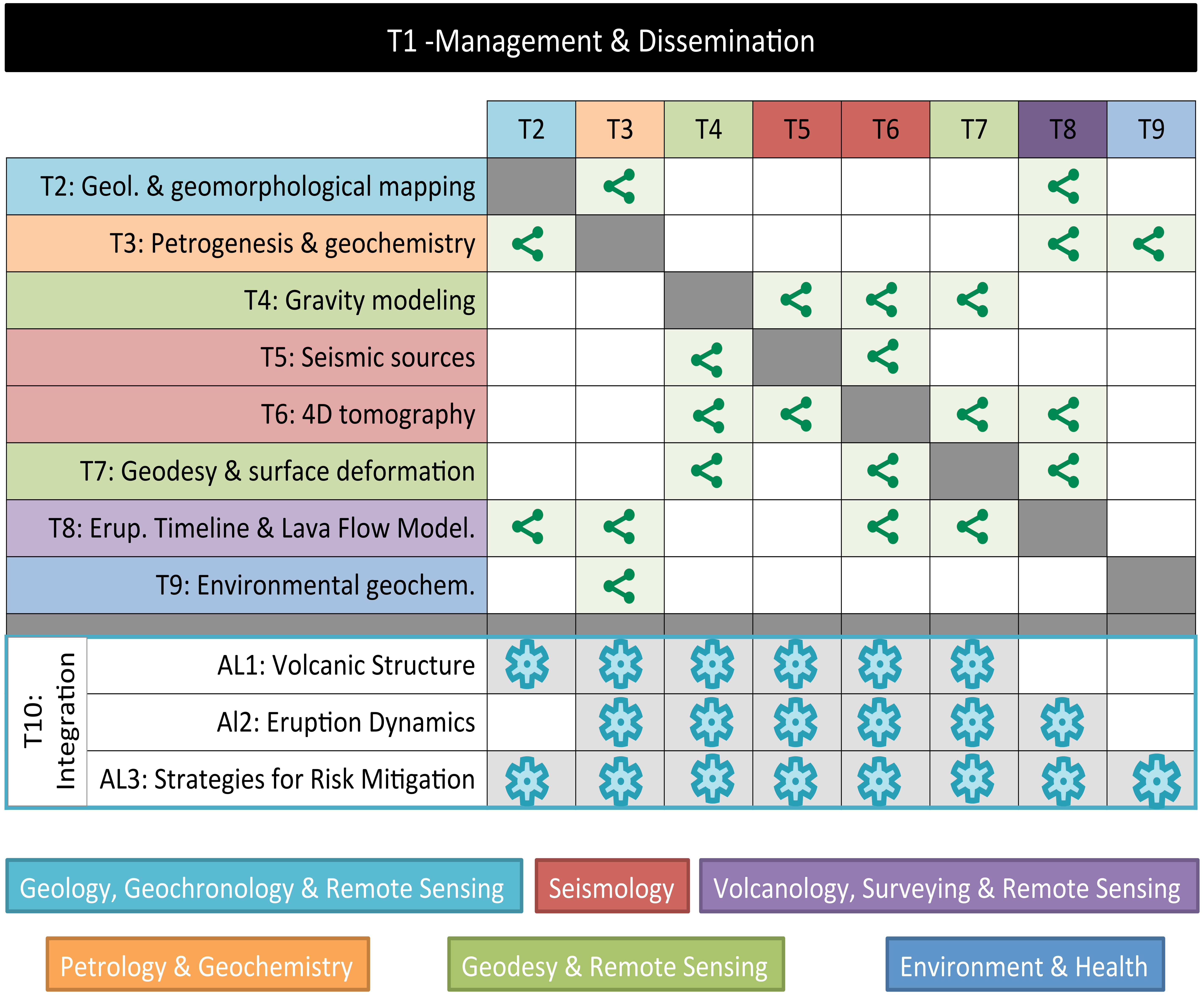

Task 1 - Management & Dissemination (Rui Fernandes)

Task 2 – Morphostructural evolution of the Fogo Island (José Madeira)

Task 3 - Petrogenesis and geochemistry of the 2014 eruption products (João Mata)

Task 4 - Computation of a density model using gravity (Machiel Bos)

Task 5 - Seismic sources (Fernando Carrilho)

Task 6 - Using Ambient Noise towards 4D Monitoring and Imaging (Graça Silveira)

Task 7 - Surface Deformation using Space Geodesy (Rui Fernandes)

Task 8 - Eruption Timeline and Lava Modelling (Ricardo Ramalho)

Task 9 - Geochemistry of volcanic ash plumes: Implications for air, soil and surface water quality and for human health (Carla Candeias)

Task 10 - Scientific integration and hazard assessment (João Fonseca)