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1. INTRODUCTION

A geological survey was carried out in Mauritius Island in January 2012 by ELC-Electroconsult in the framework of the project “Preliminary Study of Geothermal Potential in Mauritius” for the Ministry of Energy and Public Utilities of the Republic of Mauritius.

In January 2012, an Inception Report was subsequently presented.

This report presents and discusses the data collected in the field and the main conclusions of geothermal relevance, derived from the analysis of the geological and volcanological information.
2. REGIONAL GEOLOGICAL BACKGROUND

A comprehensive synthesis of Mauritius geology has already been presented in the Inception Report (ELC-Electroconsult, 2012). In order to better frame the relevant information regarding the geothermal resources development, in the following it may be useful to recall some basic lines.

Located at about 20°17’S / 57°33’E in the south-western Indian Ocean, some 1800 km south of Seychelles archipelago and 900 km east of Madagascar eastern coast, the Island of Mauritius is a dryland culmination of a huge submarine relief, the Mascarene Plateau. This regional-scale morphological feature, overprinting the submarine topography of the Indian Ocean, lies entirely within the Africa plate, is aseismic and is largely made of volcanic rocks, at least in the uppermost crust layers. The pattern of this structure, well depicted in Figures 2.1-2.2, exhibits a huge, elongated, arched rise with a nearly flat top. The plateau and the adjacent basins also show a micro-relief made up by several scattered guyots and sharply cut by large, linear fractures.

Figure 2.1. Excerpt from LANDSAT photomosaic in Google Earth visualization, showing the very complex submarine topography of the western Indian Ocean. The arc-shaped Mascarene Plateau is highlighted in paler tones of blue, east of Madagascar. The yellow circle encloses the islands of Réunion, on the left, and Mauritius, on the right (both volcanic islands are shown in Figure 2.2)

The geology of Mauritius Island and the surrounding sea areas of the Indian Ocean and the role played in geodynamic evolution have been tackled in several scientific work. The available papers, albeit of general character, also provide indirect information about the geothermal characters of this area.

The morphological/physiographic features are identified thanks to a number of scientific missions started with the Deep Sea Drilling Project and the Integrated Ocean Drilling Program. Both surveys focused on data collection and interpretation for improving the knowledge on the plate dynamics, the occurrence of natural resources, geohazards and climate
changes. These data and subsequent studies on volcanology, petrology, geophysics, and geochemistry, led to frame the geology Mauritius within the regional scenario and to better define the volcanic evolution.

As a matter of fact, the volcanism and the oceanographic features of this area can be better understood when referred to the local- and regional-scale plate tectonics (i.e. WILSON, 1963) is combined with the mantle plume model (i.e. MORGAN, 1971). The plate motion over an almost stable hotspot (at present likely located beneath Réunion) explains the volcanic evolution of the area. Such a hotspot is known to have produced in the past a huge amount of in the Deccan Traps of India, in the outstanding islands alignment of the Chagos-Maldives-Laccadive Ridge System, and in the scattered guyots of the Mascarene plateau (see Figure 2.3). In other words, the hotspot-related (plume-related) volcanism started about 66 - 68 Ma in Deccan and at present is active on Réunion. Geological data indicate that Mauritius crustal block is drifting toward NE, at a speed of around 24 mm per year, and that the plume-related volcanism rejuvenates towards SW.

Figure 2.2  Detail of the former image, showing the islands of Réunion and Mauritius (after Google Maps). The smaller island without toponyms, indicated by the white arrow, is Rodrigues, on a roughly E-W trending fracture zone (see Figure 4.1)

Figure 2.2 simply shows the seafloor topography without any information about tectonics and other geological features. The relationship between topography and tectonics of this area will be shown in Section 4. The seafloor topography east of Mauritius and south of Rodrigues is much more complex, due to a dense net of fractures. The eastern side of Mauritius is facing a long, rectilinear trench, whereas west of this lineament, Mauritius and Réunion seem to share the location on the same NNE-SSW trending oceanic crustal block. This agrees with the common interpretation of the two islands sharing a similar volcanic evolution. Some minor NNE-SSW trending alignments (ridges and fractures) which link the two islands are observable across and in between them.
Figure 2.3 Morphology of the Indian Ocean with enhanced and shaded relief, showing the geographic elements mentioned in the text. For some elements the geological age (in Ma) is indicated: 1 Madagascar; 2 Seychelles; 3 Mascarene Plateau; 4 Southwest Indian Ridge; 5 Central Indian Ridge; 6 Southeast Indian Ridge; 7 Chagos (49 Ma); 8 Lakshadweep (60 Ma); 9 Deccan Traps (66-68 Ma); 10 Ninety East Ridge (43 Ma to the south, up to 81 Ma to the north). The Ninety East Ridge, mostly made of tholeiite lavas, is an approximately 5,000 km long seamount chain, acting as a major divide between Western and Eastern Indian Ocean, and was identified by the Deep Sea Drilling Project survey.

Mauritius climate can be classified as tropical oceanic during the rainy season (November to April). The average annual rainfall of the whole island is 2,180 mm. The value in the inner high plateau exceeds 4,000 mm per year, and the minimum value below 700 mm is recorded along the western coast. The annual average temperature ranges from 23 °C at sea level to about 18-19 °C at the highest elevation; the annual average potential evaporation is 1,670 mm (with a maximum value in January) and the observed value was 1,330 mm (data set from 1957 to 1980: United Nations, 1989, unpublished report by).

Due to the climate conditions, the volume of annual water infiltration (approximately 10% of the annual rainfall) is estimated to be approximately 400 million cubic meters. Hot and humid climate obviously favours a strong and fast weathering of the rocks (especially the less compact volcanic deposits, like agglomerates, scoriaceous layers, cinder/spatter pyroclastic falls etc.), besides important erosion along the drainage network.
3. THE LITHOSPHERE BENEATH MAURITIUS

The evolution of the Mauritius volcanic complex basement is very intriguing. As reported in by Moore et al. (2011), and references therein, (i) Mauritius erupted through an oceanic crust, created about 60-65 Ma (Palaeocene) by sea-floor spreading of the Central Indian Ridge, and (ii) the thickness of oceanic lithosphere is approximately 75 km. The fully oceanic nature of the crust beneath the superficial cover of younger basaltic lavas remains however rather controversial, due to the presence, even if still unknown in extension, of continental fragments in the detachment area between India and Madagascar (Figure 3.1).

On the basis of deep geophysical data, Hammond et al. (2012) propose a model of lithosphere beneath the Seychelles, which may be extended southwards, in the Mascarene Plateau, involving a stratified upper mantle with exceptionally low S-waves velocities, covered with a mafic lower crust and an upper continental crust.

Besides the spectacular outcrops of granitic rocks in the Seychelles (Hammond et al., 2013; Torsvik et al., 2001), detrital zircons were observed by Torsvik et al., 2013 as grains from basaltic sands in Mauritius beaches eroded from lavas including xenocrysts. The ages of these zircons is split in two main groups (Paleoproterozoic and Neoproterozoic, respectively) and the authors' interpretation of Mauritian zircons is that they trace a granitic source beneath the basaltic sea-floor. Zircons were assimilated from fragments of an ancient continental
lithosphere, and were brought to the surface by plume-related lavas. On the basis of gravity data inversion, TORSVIK et al., 2013 also speculate that Mauritius belongs to an anomalously thick crust block, which extends northwards up to the Seychelles (ibidem). Hence, volcanic rocks of Mauritius and the adjacent Mascarene Plateau might overlie a Precambrian microcontinent, called 'Mauritia' (ibidem); on the basis of reinterpretation of marine geophysical data, it has been proposed that 'Mauritia' was separated from Madagascar and fragmented into a ribbon-like configuration by a series of mid-ocean ridge jumps during the opening of the Mascarene ocean basin, between 83.5 and 61 Ma. The plume-related magmatic deposits have since covered 'Mauritia' and other possible continental fragments.

Such interpretation is consistent with the results of geophysical surveys, both seismic and gravimetric, described in HAMMOND et al. (2013), which confirm the presence of a huge wedge of continental crust (~ 30 km thick, but with a relatively high velocity lower crustal layer) beneath the Seychelles Plateau. This 'granitic' crustal block thins southwards down to ~ 1 km over a distance of ~ 50 km, which agrees with the plate tectonics model of Seychelles being located at the edge of the Deccan plume, prior to its separation from India (Figure 3.1).

MOORE et al. (2011) consider the present location of the pre-Mauritius shield volcano at an approximate depth of 7,500 m below sea level, as a consequence of sinking of the oceanic crust beneath the mass of the volcano itself (which gave rise to some 3 km depression compared with the adjacent non-deformed seafloor, see Figure 3.2). This has to be considered for the correct interpretation of volcanic edifice volume and overall morphology.
4. MAURITIUS VOLCANISM AND MORPHOLOGY

Information on stratigraphy, geological age, and volcanic evolution of Mauritius is provided by several papers, like e.g. McDougall and Chamalaun (1969), Baxter (1972), Nodha et al. (2005), Paul et al. (2007), Debaityoti et al. (2007); a synthetic overview was recently published by Moore et al. (2011). The morphological features are presented in detail by Saddul (2002); additional information is provided in Giorgi et al. (1999), Dymen et al. (2012). The morphotectonics of the whole Mascarene archipelago is thoroughly analyzed by Hantke and Scheidegger (1998).

Mauritius is located approximately 220 km ENE of the island of Réunion, which hosts one of the most active volcanoes of the world, the Piton de la Fournaise. Both Réunion and Mauritius are huge shield-type volcanic complexes rising from the adjacent sea floor at a depth around 4,500 m below sea level (Figures 3.2 and 4.1). The two islands are rather comparable in size (2,512 km², Réunion, and 1,860 km², Mauritius), but their maximum elevation is far different. The two summits of Réunion exceed 2,000 m elevation above sea level (namely Piton des Neiges, 3,069 m, and Piton de la Fournaise, 2,631 m), whereas the highest peak of Mauritius (Piton de la Petite Rivière Noire) reaches just 828 m a.s.l.

Although morphological evidence (both satellite imageries/aerial photographs and field observations during the inception mission) is not very clear, probably due to the pre-Quaternary age of the episode, a huge caldera in the central part of the island is inferred in most geological studies (e.g. Giorgi et al., 1999; Dymen et al., 2012; Moore et al., 2011). The existence and the significance of the central caldera as a relevant volcanic feature for geothermal research are discussed at the end of this chapter. Such episode should have substantially lowered the original height of Mauritius volcano edifice.

In any case, Réunion consists of two joined volcanoes, so Moore et al. (2011) presume Mauritius may have never been as large as Réunion. The approximate volume of Mauritius shield volcano calculated (ibidem) by means of topographic profiles is about 75,000 km³. In any case, Mauritius Island is just a minimal part of the mainly submerged volcano edifice, and its basement is inaccessible for direct geological survey and remains partly unknown, besides some punctual information from scattered oceanographic drillings. It is worth to mention that Réunion deserved much more investigations than Mauritius Island aimed at assessing and monitoring the volcanic hazard. Concerning the assessment of geothermal resources, the dryland volume of rocks where to search for a possible geothermal reservoir appears to be rather limited and the thickness of rocks, which may be actually drilled by any future deep borehole, is made of volcanic deposits only, predominantly made up of mafic lavas (described later).

Mauritius shows a more mature morphology than Réunion, but Quaternary volcanism in its central part can be recognized; some volcanic landforms and rocks in Nouvelle Découverte area were described as recent (Giorgi et al., 1999), and future eruptions are still considered possible, although not probable (Moore et al., 2011). Hence, a heat source needed for the formation of a geothermal system can be in principle found in Mauritius. However, the presence of a shallow magmatic chamber was considered as doubtful in the Inception Report, based on the data collected to date. The volcanic evolution and the overall geodynamic setting
suggests that possible active volcanism, might be fed along deep-seated fracture zones. This, in general, is considered as an unfavourable condition, even if it does not exclude the possibility to find a suitable heat source.

**Figure 4.1** Sketch-map of dryland and sea-floor topography redrawn after SADDUL (2002), showing the ratio between dryland and submarine parts of Réunion and Mauritius volcanic edifices rising from the abyssal plain, besides some important fracture zones.
Réunion was more thoroughly investigated from the geothermal point of view, and some interesting data are provided in DEMANGE et al. (1989) and WOHLETZ and HEIKEN (1992). In particular, a deep exploration geothermal well was drilled in Salazie Cirque (a caldera in the central part of Réunion Island, north of Piton des Neiges), attaining a depth of 2,108 m and encountering a temperature of 192 ±8 °C.

After the geochronology revision by MOORE et al. (2011), the oldest rocks belonging to the building phase of Mauritius shield volcano are dated at 8.9 Ma. In any case, due to its geographic setting and location, the deepest volcanic rocks of Mauritius are actually very difficult to reach, as a consequence of crustal sinking favoured by thermal heating and induced by the weight force of the progressively growing volcano on the seafloor, as sketched in Figure 4.2.

![Figure 4.2 General scheme of evolution stages, controlling the growth and morphology of oceanic shield volcanoes, after Letourneur L. (2008) - Structure and Dynamics of Plumbing Systems of Oceanic Shield Volcanoes: An Example from Réunion Island. PhD Thesis, University of Göttingen, Germany. The red star is a ‘possible-to-reach’ location for lithological sampling, which does not correspond to the lowest (most ancient) volcanostratigraphic unit.](image)

The stratigraphy of the three series of volcanic rocks, separated by reddish paleosols, is described Chapter 5. Petrological and geochemical investigations on many rock samples indicate an evolution from silica-saturated early products to silica-undersaturated younger volcanic deposits.

Compared with Réunion, Mauritius does not show large volcanic edifices as relevant landforms. The dryland area is roughly elongated along a NNE-SSW trend. The highest elevations model a discontinuous chain of reliefs with a similar NNE-SSW trend, along the western side of the island; lower reliefs up to 480 m a.s.l. are scattered in the eastern side, especially close to the small cove of Mahébourg (Figures 4.3 and 4.6).
By comparing their location with the geological sketch-map in Figure 4.4, these elevations are made of the most ancient rocks and thus represent the remains of the original huge shield volcano. The central part of the island may be considered as a slightly irregular plateau, roughly aligned with the only small offshore morphological platform at the NNE end of the island (bounded by -200 isobath and including small islets and guyots, as shown in the Schema Structural annexed to the publication by GIORGI et al., 1999 (Figure 4.5).

The eastern and western coastal sides greatly differ from each other. This is immediately observable in the topographic maps and aerial photographs, but has been much more clearly defined by new sets of data collected by means of oceanographic cruises in the Mascarene Islands.

The eastern coastal zone shows rather gentle slopes and its profile keeps a similar inclination in the nearest sub littoral zone, giving rise to a wide coastal plain except for the area of ancient volcanic outcropping. This convex shoreline corresponds to a rather regularly circular shape, corresponding to a radius of ~33 km (Figure 4.5). On the contrary, the western coastal zone is irregular but roughly rectilinear by comparison with the opposite one and appears to be abruptly truncated. The submerged relief of the sub littoral zone is correspondingly steep. These morphological features, combined with volcanological observations, suggested the large, catastrophic flank collapse of western Mauritius, as hypothesized by DYMENT et al. (2012).

![Figure 4.3 Relief visualization of Mauritius Island after Google Maps](image)

**Figure 4.3** Relief visualization of Mauritius Island after Google Maps
Figure 4.4 Geological sketch-map of Mauritius showing the three main lithostratigraphic groupings, after MOORE et al. (2011). Younger Series volcanic rocks (in pale brown) are commented in Chapter 5. Sampling sites (surface and drill holes) of Moore et al 2001 are also shown.
The flank collapse proposed in DYMÉNT et al. (2012) is certainly capable to strongly influence the volcanic evolution of Mauritius island and may be the cause of the rejuvenated volcanism (MOORE et al., 2011) at the origin of the Intermediate Series described in Chapter 5, after the first important episode of volcanic quiescence. The collapse and the subsequent volcanic...
events are clearly linked. Figure 4.5 shows the roughly NNE-SSW alignment of volcanic centers (in red), more recent than the inferred collapse, being sub-parallel to the western coast, which should correspond to the collapse scar.

The central area of Mauritius concentrates the most interesting features for investigating the geothermal potential. The aforementioned recent volcanic centers constitute a clear volcanic axis which seems to continue below sea level, in the submerged reliefs on the upper right corner of Figure 4.5. They are briefly commented and described in GIORGi et al. (1999): the 1:50,000 geological map and accompanying notes show and describe them as small dome-like edifices (ranging in height between 30 and 80 m above the adjacent topography, that is not as absolute elevation), with small craters still clearly recognizable. The most important of these centers are Alma Hill and Bar Le Duc-L'Escalier, in the Nouvelle Découvert-Plaine des Roches area in the 'central plateau' (Figure 4.6). From these centers some lava flows, somewhere vesicular or very scoriaceous and often strongly fractured (hence prone to a fast chemical alteration in the tropical climate of the island) were emitted. These flows are classified as “late volcanic lavas” and geochronologically attributed to Pleistocene (GIORGi et al., 1999). Most common products are pale gray, aphyric hawaiites (olivine basalts with relatively high content in sodium, with an intermediate composition between alkali basalt and mugearite). Lava tunnels up to 1 km long are also observed, indicating a very low viscosity and probably an inflated typology (see i.e. GLAZE and BALOGA, 2013) of the involved volcanic lava flows. More information is provided in Chapter 5.

The aforementioned Nouvelle Découvert-Plaine des Roches area was already considered as a main target for investigations aimed at defining the geothermal potential during the Inception Mission. A thorough description of this area is found in SADDUL (2002). Due to the approximately central position in the Island of Mauritius, this area is receiving the highest amount of rainfall (thus being the recharge zone of the main Mauritian aquifers) and is substantially located inside the caldera rim inferred by most authors. It has however to be noted that no sharp counter-slopes along circular or lobe-shaped rims can be identified and the inland ’plane’ is actually a very gently steeping slope, regularly dipping toward the eastern coast, dissected by an almost regular radial pattern of drainage, at least between Rivière du Rempart and Rivière du Poste de Flacq (Figure 4.6). The very young appearance of volcanic landforms and deposits is emphasized in SADDUL (2002), especially in Bar Le Duc-L’Escalier volcanic system. This is reliably considered (ibidem) to be the location of the last volcanic manifestation of Mauritius shield volcano, on the basis of the overall morphology of the volcanic center itself and of the surrounding area. On the slopes of Bar Le Duc-L'Escalier boreholes CH 89 and CH 291, CH 90 and a Gradient Well, GW, are located. The relevant results from three of these boreholes (CH 89, CH 90 and the GW) are summarized in Chapter 6.

The morpho-structural features of Mauritius are both roughly rectilinear (belonging to the different fracture systems) and sub-circular (linked to volcanic collapse episodes). The latter are referred to the aforementioned caldera. Figure 4.6 is a Digital Terrain Model (DTM) visualizations after the NASA's Shuttle Radar Topography Mission - STRTM (JARVIS et al., 2008), which clearly show the morphological difference between an external 'ancient' Mauritius (where most of Older Series outcrops concentrate, as indicated in Figure 4.4), heavily eroded, and the 'younger' central 'plateau', which actually corresponds to
a rather regular and rounded ridge, approximately NNE-SSW trending. This ridge looks clearly overlying the circular feature of the caldera rim. The two areas, 'external' Mauritius and inner plateau, can be sketched as two morphological units corresponding to the Older Series volcanic evolution stage, and the Intermediate + Younger one, respectively. The two are separated by a discontinuous and irregular divide that is the trace of the inferred caldera rim. The continuity of such caldera is truncated or masked/buried under the blanket of volcanic deposits (probably mixed with minor amount of epiclastics). The only evident segment is observed to the north, where a clear counter-slope on the southern side of a set of reliefs, made of Older Series, is recognizable. In the DEM (Figure 4.6) these reliefs show a mature morphology and a still recognizable radial pattern which well corresponds to a coherent set of remnants of the shield volcano (pre-dating the Intermediate and Younger Series). Besides the aforementioned northern segment, is difficult to recognize the continuity of the caldera rim, especially toward the east. Toward the west, some lobes can be identified, but the overall continuity of the caldera is hard to recognize anyway. This is partly due to the interference of the ascertained effects of gravitational slope deformations, which gave rise to a set of roughly NNE-SSW faulted steps, and to the masking effect of recent volcanic deposits. The bulk mass of the island seems to be transversally divided by a roughly E-W alignment, from immediately north of Grand Port Bay (on the eastern coast) to a small and narrow cove immediately south of Plaine St. Pierre (on the western coast), crossing the southern slope of Bambou Mountain Massif, the northern slope of Mt. La Grave, and south of Trou aux Cerfs small edifice (a typical spatter cone as clearly suggested by its morphology and described in GIORGI et al., 1999). South of this E-W lineament, other lobe-shaped minor features, attributable to a secondary calderic collapse, are found, but hardly fit in the overall geometry of the main one. The morphology confirms the similar interpretations in GIORGI et al. (1999) and SADDUL (2002), which substantially postulate a polycentered, polycyclic caldera evolution. In any case, the southern part of Mauritius, south of the E-W lineament, besides including in a clearly eccentric location the highest elevation of the island (Piton de la Petite Rivière Noire, 828 m a.s.l.), shows the most ancient and mature morphology, which underwent a strong erosion, in the south-west corner beneath the younger volcanic edifice culminating at 678 m a.s.l. (Curepipe Point). In any case, based on the morphology, a progressive shift of volcanic activity along the NNE-SSW trend, toward NNE may be inferred. What is sure is the very eccentric (and NNE-shifted) location of the youngest volcanic centers (SADDUL, 2002), that is Bar le Duc - L'Escalier.

As for the rectilinear features (lineaments sensu O'Learly et al., 1976), besides the obvious N 20° E main 'volcano-tectonic' alignment which crosses almost the whole island (except for the southernmost part), some important systems are recognizable. The lineaments were identified by analyzing, on the base of the DTM (Figure 4.6), the morphology of (i) crest lines; (ii) river valleys and secondary features in the drainage network; (iii) the reliefs physiographic and structural pattern. Such interpretation is aimed at providing a global information on the main structural elements, which are expected to feed and control the possible geothermal systems. This information has to be considered as unsophisticated, rudimentary (since lacking of an adequate in-the-field validation by means of structural analysis in measurement stations), but basic and useful.
Figure 4.6 Rectilinear and circular/sub-circular lineaments drawn on the Digital Terrain Model - DTM of the Island of Mauritius (JARVIS et al., 2008). Most of toponyms mentioned in the text are plotted on the map.

As for the rectilinear features (lineaments sensu O’Learly et al., 1976), besides the obvious N 20° E main ‘volcano-tectonic' alignment which crosses almost the whole island (except for the southernmost part), some important systems are recognizable. The lineaments were identified by analyzing, on the base of the DTM (Figure 4.6), the morphology of (i) crest lines; (ii) river valleys and secondary features in the drainage network; (iii) the reliefs physiographic and structural pattern. Such interpretation is aimed at providing a global information on the main structural elements, which are expected to feed and control the possible geothermal systems. This information has to be considered as unsophisticated, rudimentary (since lacking of an adequate in-the-field validation by means of structural analysis in measurement stations), but basic and useful.

The aforementioned dense set of lineaments around E-W, transversally cutting the whole island, stands out as a main family but is not scattered over the whole island surface. It is
followed by a secondary one, less dense and continuous, sub-parallel and slightly curvilinear (ranging around N 80° E), crossing the eastern coast close to Mahébourg. This lineaments system can be compared with the structural trend of the Rodrigues Fracture Zone (Figure 4.7). Another location of this system is immediately north of Mauritius, cutting the littoral platform sustaining the islets of Île Ronde and Île Plate.

![Figure 4.7](image)

**Figure 4.7** Topography and tectonics of Indian Ocean including Mascarene Islands, showing the main fault zones (after HANTKE and SCHEIDEGGER, 1998)

On the western side of the island, the normal faulting (roughly NNE-SSW trending), partly triggered or re-activated by the gravity, is clearly visible through several, slightly curvilinear westward downthrown steps. Other lineaments, less numerous, range around N-S and NE-SW.

By comparison, the interpretation by HANTKE and SCHEIDEGGER (1998) is reported in Figure 4.8 that summarizes their interpretation, which considers two main morphostructural alignments; (i) a trench-like depression trending N 145° E from Port Louis area (on the western coast) to Mahébourg area (on the eastern coast), and (ii) a very broad basin trending N 70° E from Flic-en-Flac to Post de Flacq. The N 20° E trending ridge (and volcanic axis) is considered as a reactivation of a transform fault which affects Mauritius and cut the crust south-east of Réunion. By combining the rose diagram maxima of joints strike, river valleys and crest lines on the whole Mauritius, the prevailing N 157° E to N 160° E and N 66° E to N 77° E global trends are well defined and should be due to a common neotectonic control.

Since the roughly N 70° E trending morphostructural element is crossing the N 20° E tectonic-volcanic alignment closely south of Bar le Duc - L’Escalier, the structural setting of this young volcanic area (Figure 4.8) seems to be a favorable factor for geothermal research.
Figure 4.8  Topography/tectonics of Mauritius (after HANTKE and SCHEIDEgger, 1998). Black dots are structural measurement locations; double lines are the main lineaments. Red triangle is the approximate location of Bar Le Duc - L’Escalier volcanic complex.
5. STRATIGRAPHY: GENERAL OVERVIEW OF MAURITIUS VOLCANIC AND SEDIMENTARY UNITS

The most complete and updated information about the volcanic deposits, their petrology, geochemistry and geochronology, based on analyses of a representative set of rock samples, collected from both boreholes previously drilled by Mauritius Water Resources Unit and outcrops in different parts of the island, is provided in MOORE et al. (2011).

The bulk mass of Mauritius Island is made of volcanic rocks only and sedimentary rocks may be found just in very narrow belts of coastal deposits and as thin and discontinuous Quaternary units, like slope and colluvial deposits or filling material of topographic depressions and plains, eventually mixed with epiclastic deposits made of reworked volcanic material. The thin layers of paleosoils and weathered rocks fragments as in-situ deposits on erosion surfaces could be referred to sedimentary rocks, mixed with epiclastic, and have been recognized in the boreholes. Moreover, the borehole logs are somewhere mentioning the presence of layers made of sand and loose materials. This is of doubtful interpretation, since these layers may actually correspond to strongly altered rocks, interbedded as layers and/or lenses within much harder lavas, where a complete core recovery is difficult.

As for the type of alteration, it is worth to outline that only in-situ chemical alteration due to weathering processes (i.e. oxidized layers) was actually observed in any sample or outcrop. No hydrothermal alteration linked to hot fluids was observed and no relevant hot springs with evidences of important chemical exchange between the fluids and the host rocks were found in the whole area investigated during the Inception Mission.

Regarding the rock types which are expected to be found in the boreholes, Mauritius is a giant shield volcano, hence it is chiefly made of a sequence of lava flows, with clearly subordinate layers of pyroclastic deposits, and hence the most common rocks constituting the borehole cores are various types of basalts.

A very important issue is outlined by MOORE et al. (2011), regarding the timing of the volcanic episodes in Mascarene islands, related to a regular plate motion above an almost stable hotspot, and compared with other volcanic island chains like i.e. the Hawaii and Samoa in the Pacific Ocean. In particular, Mauritius is the penultimate island along the so-called Réunion hotspot track, but the geological age of its volcanism disagrees with the simple model of volcanic chains with the progressive growth and extinction of volcanoes after drifting apart from their magma source (the hotspot). In fact, detailed geochronological data allow to identify phases of volcanic activity renewal, after very long-lasting hiatuses (which may last up to 1.2 Ma: MOORE et al., 2011). Mauritius shows an excellent example of such volcanic evolution, since two well separated episodes of rejuvenescent volcanism have been identified, and the volcanic products of the last phase are very important in volume and cover more than 75 % of the whole dryland area (see Figure 4.3).

The available information about stratigraphy is recalled at the beginning of Chapter 4. Previous and useful studies on volcanic rocks stratigraphy are those by SIMPSON (1950) and BAXTER (1972); more information is also provided in SADDUL (2002). The first studies recognized three distinct episodes of volcanic activity, separated by probably long periods of volcanic quiescence and subsequent erosion. BAXTER (1972) proposed the Older,
Intermediate, and Younger Series as shown in Figure 4.3. McDougall and Chamalaun (1969) defined the Older Series as the first volcanic growth stage of the shield volcano (spanning a 7.9 to 4.73 Ma time), cropping out in few places as a remnant mostly covered with younger deposits. These outcrops are well observable due to their sharp morphological relief, suggesting a typical relief inversion due to a probably sharp contrast in hardness and compactness of volcanic rocks. As clearly shown in the geological map (Giorgi et al., 1999), the outcrops corresponding to the Older Series are located in the peripheral part of Mauritius, outside the rim of the inferred caldera structure, and the Younger Series almost regularized the previous topography as a cover. As a whole, the oldest volcanic rocks seem to make a bulk mass, more hard and thus prone to brittle deformation (certainly triggered by both tectonics along the several fracture zones of the adjacent sea floor, and above all by gravity, as suggested by the huge flank collapse hypothesized in Dyment et al., (2012).

Paul et al. (2007) further distinguished the Older Series in two subunits: an early 'primitive' series (corresponding to samples collected exclusively in borehole cores below 45 m depth) and a later differentiated series with different geochemical and petrological 'signature'. Based on the interpretations by the specialists of Mauritian Water Resources Unit, Paul et al. (2007) reported that “Below approximately 100 ft. depth --that is, about 30.5 m-- the Older Series are present in all the boreholes”. However, this simple remark is based on a visual classification of rock types in the core record, and seemingly lacks a detailed reconstruction of individual stratigraphic variations. As a matter of fact, a true and reliable volcano-stratigraphic marker within the rather monotonous sequence of Mauritius was not found.

The most relevant results and interpretations as described in Moore et al. (2011) are as follows:

- The geological age of the earliest known volcanism on Mauritius is extended back in time from 7.9 Ma (of previous dating) to 8.9 Ma. Probably, an already formed volcano edifice on the seafloor was already present before 9 Ma, but authors were not able to provide more precise information due to the lack of available samples from beneath the lowest investigated volcanic layers (Older Series).

- At the end of the shield-building stage, a first important hiatus interrupted the volcanic activity between 4.7 and 3.5 Ma, thus representing an exceedingly long lapse of time of 1.2 Ma. The end of this hiatus roughly corresponds to the timing of flank collapse episode inferred by Dyment et al. (2012).

- Based on new geochronological data, the age of Intermediate Series ranges between 3.5 and 1.7 Ma. The actual extension of Intermediate Series outcrops is smaller, compared with the mapping by Giorgi et al. (1999), hence Figure 4.3 (after Moore et al., 2011) substantially revised the shape and reduced the size of such unit, by attributing part of the outcrops to the overlying, younger unit. This Series is the first episode of rejuvenescent volcanism.

- Outcrops of true Intermediate Series only occur in the southwestern part of the island and elsewhere are covered with the widespread products of Younger Series. Several boreholes crossed volcanic rocks which can be referred to Intermediate Series, buried by the Younger Series ones.
• The volcanism producing the Intermediate Series was interrupted again by the second hiatus, between 1.7 and 1.0 Ma.

• The Younger Series can locally be thicker than previously interpreted (up to exceed 200 m) and so, these volcanic rocks attributed to the last rejuvenescent phase in Mauritius volcanic evolution have a relatively important volume, which has been estimated in at least 35 km³, that is approximately 0.05 % of the total volume of shield volcano.

• The youngest reliable ages of Mauritian volcanic rocks are 0.031 and 0.040 Ma and the reconstructed eruption frequency in the last 400 ka suggests that future eruptions on Mauritius dry land are still possible. In such a case, the most probable eruptive centers are the ones in the central part of the island, along the already mentioned NNE-SSW trending volcanic axis (see Figure 4.3 and related comments), where some young vents already produced lava flows long enough to reach the sea.

The aforementioned hiatus certainly produced the erosion surfaces, covered with the paleosoils somewhere observed in the drilling as layers, 1 to 2 m in thickness, rich of reddish clay and strongly oxidized, loose to weakly cemented materials, generally described as laterites. This is for sure the only certain kind of stratigraphic marker which is possible to find and easily interpret in the core record. It should be also considered however, that minor paleosoils can commonly be found as preserved layers within a volcanostratigraphic sequence of lava flows, especially under tropical climate. The texture of any lava flow (blocky, jointed due to cooling, scoriaceous) can greatly affect the core recovery, if drilling parameters are not the most adequate in order to obtain the maximum in terms of complete record and less disturbed samples.

The most common lithological types among Mauritius lavas are alkali basalts, with some samples more tholeiitic, and a general trend from normatively silica-saturated lavas of the Older Series to slightly silica-undersaturated lavas of Intermediate and Younger Series is described in MOORE et al. (2011). Besides the exact geochronology and the name of volcanostratigraphic units, both often undergoing revisions after new data, the volcanic rocks of Mauritius can be usefully resumed as proposed in SADDUL (2002), on the basis of the aforementioned references and some additional ones (i.e. PERRaud, 1982). This summary, which can be a useful guide for the interpretation of the wells stratigraphy of next chapter, is referring again to the 'classical' partition in three main groups (Older, Intermediate, and Younger, respectively) but separates the most ancient (lower) group into two units (the older 'Breccia Series' and the overlying “Old Lava Series”), as described hereinafter.

The Breccia Series is the deepest geological unit which has been crossed in the drillings, corresponding to a relative basement, and consists of alternating brecciated lava flows (alkali basalts and oceanites), volcanic ashes and reddish-ochre tuffs.

The Old Lava Series are prevailing lava flows, 5 to 30 m thick, mostly made of picrite basalts, olivine basalts and subordinate hawaiites, interlayered with subordinate beds of volcanic “agglomerates”. Together with the Breccia Series, this unit built at least the directly known part of Mauritius shield volcano and underwent an important erosion phase.

As a rare example of magmatic evolution, some endogenous domes and plugs made of trachyte (i.e. Piton du Milieu, Mt. La Selle, and Mt. Camizard) are also described in SADDUL.
These trachytes and accompanying trachyandesites are confirmed in Moore et al. (2011) and represent a volcanic episode slightly more alkaline at the end of the Older Series volcanism. Based on the interpretation of these two lower units belonging to the Older Series as the product of an early phase of volcanism, followed by a long hiatus or volcanic quiescence which in Pliocene gave rise to important subaerial morphogenetic processes, the Old Lava Series should be covered with deposits of reworked / weathered / eroded volcanic to epiclastic materials, debris etc., in all favorable locations as topographic depressions, and even onto gentle-dipping slopes of volcanic edifices. These weak or loose materials may be found in irregularly thick layers in drilling cores too.

The Early Series (Intermediate Series of the other authors) is related to a volcanism rejuvenescent phase since around 3.5 Ma, initially explosive (volcanic 'agglomerates' in beds up to 40 m thick) and later quiet (lava flows made of compact olivine basalts, up to 10 m thick, relatively massive and sometimes with columnar jointing). The lava flows were emitted along fissures and volcanic vents, with an inferred maximum thickness of 300 m. The volcanism giving rise to this Early Series is considered as stopped at around 2 to 1.7 Ma (Saddul, 2002), which substantially agrees with the new age constraints in Moore et al. (2011). Another lava flows yielding episode at around 0.7 Ma is attributed to this unit (ibidem), but this disagrees with the latest geochronological dating (which, in contrast, should include such episode in the Younger Series). Anyway, the lava flows described in Saddul (2002) consists of low-viscosity olivine-rich basalts emitted from a roughly NNE-SSW alignment of some 25 vents in the central part of Mauritius Island, showing well preserved cones and summit craters. At the end of this phase explosive activity occurred, forming some thick layers of tuffs.

The Recent Series (Younger Series of the other authors) mostly produced olivine basalts. The youngest flows were emitted from the L’Escalier volcano, in Plaine des Roches area, and show a well preserved pahoehoe morphology and a highly vesiculated texture, with the advance of thin growth lobes deforming a rapidly cooling crust inflated by high pressure of volatiles. This kind of lava flow is highly efficient in preserving the original heat and allows to transport lava over great distances, favoring the formation of lava tunnels.

As a final remark, the Intermediate and Younger Series (including the aforementioned Early Series and Recent Series by Saddul, 2002), that is the whole volcanic products of the rejuvenescent phase, are described as essentially impossible to distinguish in the field from a petrographical point of view, except for the older volcanic products tendency to be more weathered (Moore et al., 2011), which cannot be an absolute criterion. Given the similarities in composition and eruptive style, it is appropriate to consider the two Series a single, long-lasting episode of volcanism, interrupted by a relatively short hiatus (ibidem).

From a practical point of view, this means an objective difficulty in describing and distinguishing, from the drilling cores, different volcanostratigraphic layers in a rather monotonous sequence.
6. STRATIGRAPHIC DATA

During the Inception Mission information from the drilled wells were collected. Many wells were drilled in Mauritius at different locations, but most of them were aimed at water supply, and thus are quite shallow.

As already indicated in the Inception Report, the most promising area for focusing the investigations aimed at the geothermal potential evaluation of Mauritius Island is the region of Novelle Découverte, and the young domes and volcanic vents nearby. This area is located in the central part of the island and lies inside the rim of the inferred caldera structure.

By considering the location and the maximum depth, stratigraphy data from two coreholes in the Novelle Découverte area, were analyzed. Data from third hole, Gradient Well (BH1226), specially drilled since May 25th, 2013 in the course of the present project, were also analysed. The gradient well is located at 416 m a.s.l on the ENE flank of Bar Le Duc - L’Escalier polygenic volcano. The two coreholes, both located on the eastern flank of the volcano, are CH 89, at 448 m a.s.l., and CH 90, at 360 m a.s.l. The lithology and stratigraphy of these wells, with core recovery and stratigraphic log description, are in Annex 1, based on the data, which are available and considered as reliable.

The stratigraphic information available from the wells spans from 213 m depth in CH 90 to 270 m in BH1226. CH 89 reaches a depth of 225 m. The gradient well BH1226 latter was actually drilled up to a 432 m depth, but from 270 m to the hole bottom a seemingly monotonous sequence of “breccia” is described, which corresponds to the lowermost unit in the stratigraphic scheme by SADDUL (2002), discussed in the former chapter. In the available stratigraphy of BH1226, layers of both “breccia” (volcanic agglomerate ?) and basaltic lavas are described as alternating, but besides that, no important information about volcanic or petrographic features is provided.

A tentative correlation, based on the presence of the laterite layers (most likely attributed to paleosols, linked to the previously mentioned long-lasting hiatuses in volcanic activity and subsequent erosion phases), is presented in Annex 2. It is worth to mention however, that some discrepancies are noted among the data set of wells stratigraphy, and the identification (and subsequent location) of the laterite layers may be not univocal.

Unfortunately, the target depth of the Gradient Well was not achieved. A depth of 500 m was planned to avoid influences of shallow cold aquifers on the measured temperatures and provide reliable information of the true deep thermal gradient.

As a whole, the lavas which make up the bulk of Mauritius shield volcano are rather impervious materials due to their very low primary permeability (linked to porosity). The laterite layers (and, in general, the zone of strongest chemical alteration) are even less permeable. The breccia-textured and strongly scoriaceous layers (besides the subordinate layers of pyroclastic falls and non-welded tuffs) have plenty of voids and pores, but these are not contiguous enough to provide a relevant primary permeability. In any case, their total volume is clearly minor than the volume of lava flows.
Due to this general features, the only possibility to encounter good (secondary) permeability, able to drive water filtration toward depth, is controlled by tectonic and/or gravitational brittle deformations, yielding fractures of adequate opening and persistence.

The general geodynamic setting of the Mascarene Plateau including the Island of Mauritius, added to the mechanical characteristics of the hard and compact lavas which constitute the huge shield volcano, certainly favor both tectonic- and gravity-driven brittle deformation, triggering the development of important fracture systems. The roughly NNE-SSW trending alignment of volcanic vents and morphotectonic features in the central part of Mauritius is an obvious example of such fracture systems, deep enough to control both volcanism and water circulation.
7. SUMMARY AND RECOMMENDATIONS

The main conclusions of geothermal relevance, derived from the analysis of the geological and volcanological information, can be summarized as it follows:

- Mauritius and the nearby Réunion volcanism are fed by the same magmatic source, as demonstrated by the chemical features of the erupted lavas, with the only difference in the activity status Mauritius, which at present is quiescent.

- These similarities lead to a possible comparison of the geothermal potential of the two islands; in Réunion, some research projects carried out in the late 1980s found temperatures as close as 200 °C at about 2100 m depth.

- Both islands correspond to the minor dry land area of typical, huge polygenic shield volcanoes built on “basaltic” oceanic seafloor and have similar features to other hot-spot related, shield volcanoes in oceanic environment, like e.g. the Hawaiian volcanoes.

- In Mauritius, the total volcano height above its submarine base surface can be estimated to be 7,500 m. This estimated height does not simply correspond to the elevation difference between the maximum height of 828 m asl and the depth of the surrounding ocean floor of 4,500 m bsl, but results from geophysical investigations and it is considered as due to gravity-driven sinking of the seafloor beneath the mass of volcano edifice. The dry land part of the volcano edifice is minimal, compared with the submarine one.

- The volcano volume was estimated to be 75,000 km³. As a shield volcano, the ratio between height and radius of the edifice itself (without considering its basement) suggests a very gentle steeping slope of the landform as a whole. As any shield-type volcano, Mauritius is mostly made of lava flows.

- Volcanic type and overall morphology of Mauritius determine a general outward dipping of the main volcanostratigraphic discontinuities. This feature should be considered in any hydrogeological model.

- Most of the literature (papers, reports and geological maps of Mauritius) claims the presence of a caldera structure in the central part of the island. However, this is hardly recognizable, as neither sharp counter-slopes, nor sub-circular depressions within a visible rim can be clearly identified in the topographic surface. In any case, the caldera should be pre-Quaternary in age and thus probably partly erased by recent morphogenetic processes.

- By contrast, a huge flank collapse cutting the western side of the island is deemed as very probable. Such catastrophic episode is considered as capable to trigger the volcanic rejuvenation after the last long-lasting activity hiatus. On the other side, large-scale slope instability processes of this huge volcanic edifice (above all if in an oceanic location) are very important from the geological hazard point of view.

- Important fracture systems are observed anyway, as an unavoidable result of the combination of rigid rock types (i.e. “basaltic” lavas) and their geodynamic context,
characterized by extensional to strike-slip tectonics and subsequent faulting and fracturing.

- Any geodynamic model of Mascarene Plateau, based on multi-disciplinary research involving substantial oceanographic data, is highlighting a dense set of (probably deep-seated) fractures scattered around and between gigantic fracture zones. This should be considered as a favorable, regional-scale geological factor.

- Mauritius shield volcano is considered as still capable to produce eruptions (last episodes are dated at about 40 ka), hence a volcanic source of heat may exist. Nevertheless, the heat source is probably not a shallow magmatic chamber, but volcanism seems likely to be fed by deep fracture zones.

- The limited interaction / exchange (thermal, chemical, etc.) between the (probably) deep heat source and the infiltrating waters seems to be indicated by the total absence of geothermal manifestations (like e.g. steaming grounds, hot springs etc.).

- The most reliable water recharge should correspond to seawater infiltration in the prevailingly submerged mass of the shield volcano, whereas rainfall and related infiltration in the dry land are clearly subordinate.

- Any available information on geology, petrology, volcanology etc. confirms the Novelle Découvert area in the central plateau as the primary target site for further investigations aimed at defining the geothermal potential.

In conclusion, based on the results of the geological study, the stratigraphic and structural conditions of the Mauritius Island appear to be favourable, pointing to the presence of intense and recent tectonic activity, which may guarantee widespread fracturing and hence adequate permeability of the lavic formations. This positive indication is counterbalanced by the geovolcanological framework, hinting at a likely large depth of any potential heat source: such a negative aspect is also reinforced by the complete absence in the island of hydrothermal manifestations which would witness the existence of a shallow thermal anomaly.
8. REFERENCES


Annex 1 - Coreholes Stratigraphy
Annex 2 - Tentative Stratigraphic Correlation
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