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TORFAJÖKULL, ICELAND – A RHYOLITE VOLCANO AND ITS GEOTHERMAL RESOURCE

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ABSTRACT

Torfajökull in South-Central Iceland occupies a unique position among Iceland´s volcanoes both as regards type of volcanism and structure, but the size and intensity of its geothermal activity is also exceptional. Its geothermal potential is estimated in the range of 1000 MW, two or three times higher than Hengill which comes next. The results of surface exploration carried out in the past 20 years are presented in summary. They were directed towards both the geothermal resource and the volcanology. The two fields of interest complement each other to give a fairly good conceptual model of the area.

1. GENERAL FEATURES

The Torfajökull volcano (1200 m a. sl.) forms a massive, 300–600 m higher than the surroundings. Its eastern half is heavily eroded contrary to the western half where Holocene lavas have been erupted. The eastern area offers the best exposures and allows the development of the volcano to be traced far back. Bright coloured rhyolite is almost the sole rock type there (up to 7 units in a single section) with remnants of hyaloclastite (basaltic) overlying it in places with NE-SW-feeder dykes cutting up through the rhyolite below. The western half is undulating high ground where hyaloclastite, obsidian flows and dark grey ash shed over it from neighbouring volcanoes lend the landscape a blackish hue. Local permanent snow and the fumes from countless steam vents make a contrast and green ribbons of moss along streams bring some live to the scene.

Torfajökull (Figures 1 and 2) developed as a flank zone volcano with rocks of transitional composition (intermediate between tholeiitic and alkalic). In a last stage it was overtaken by a spreading zone propagating to the SW. This change is marked by the eruption of mixed lavas of primarily transitional rhyolite and some tholeiite components.

The hot springs are a very dominant feature in the landscape (Figure 3). They concentrate in certain areas forming wide tracts of steaming ground with mud pots and roaring fumaroles. Judging from their areal distribution and intensity the core of the geothermal field is located around the eruption foci of the centrally erupted Holocene lavas. The high temperature geothermal manifestations occur within a 18 x 12 km caldera. Cold alteration extends beyond it as do tepid and hot springs to the NE and SW, some rich in carbondioxide, probably outflows. The oldest dated rocks are nearly 0.4 million years old. They are superimposed on hydrothermally altered pre-caldera rhyolite and caldera-fill.

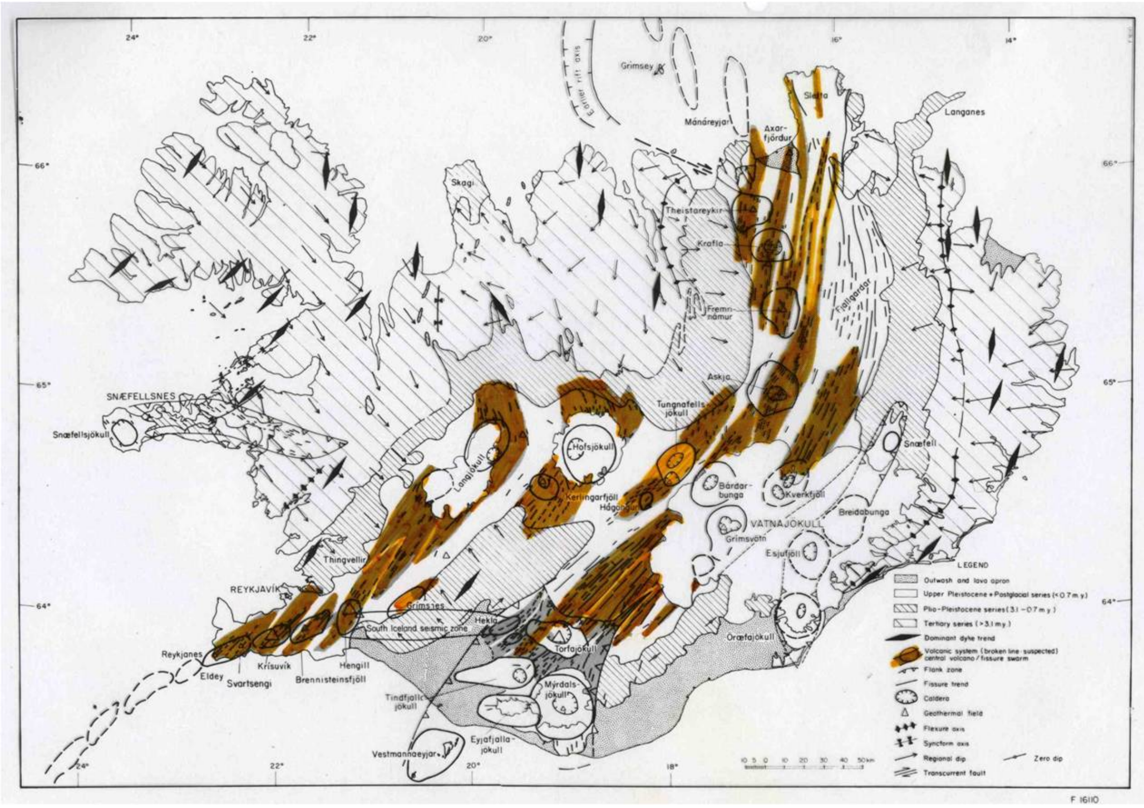

FIGURE 1: Volcanic systems of the active volcanic zones in Iceland. Torfajökull in South Central Iceland is at the intersection of a spreading zone to the north-east, the South Iceland Seismic Zone to the west and a non-rifting flank zone to the south

2. GEOLOGY

Five main groups form the Torfajökull sequence (Figure 2):

1. The oldest group forms a horseshoe shaped rim around the caldera which is open to the west. Its oldest member is less than 800 ka.
2. A caldera collapse followed. It became filled with sediment, tuff, rhyolite breccia and plugs. Resurgence (i.e. uplift of the caldera floor) and a second inner caldera subsidence occurred.
3. Domes erupted from concentric fissures within and around the caldera close to its rim are as old as 300 ka. The youngest member of the group, about 25 km³, was erupted subglacially at about 80 ka.
4. Hyaloclastite (basaltic) erupted below ice from a NE-SW dyke swarm, most intense in the NE but otherwise occurring around a volcanic shadow zone. The shadow zone is underlain by a magma chamber in the central part of the caldera. It is thought to have contracted after the 80 ka event (Figures 2 and 5).
5. Holocene rhyolite lavas, mixed with tholeiite to some degree, erupted on a NE-SW fissure swarm. The tholeiitic component of the lavas indicates that the eruptions were triggered by lateral injection via dykes from a rift zone volcano 80 km distant to the NE (Bárdarbunga in Vatnajökull Glacier) (Figure 10). Three Holocene basaltic eruption fissures transected the western part of the volcano without intersecting the magma chamber.

As to the youngest stratigraphic unit (number 5 above) there have been 8 eruptions in Holocene time (last 11,500 years). The oldest occurred about 9000 years ago, the three youngest about 2000, 1100 and 500 years ago (Figure 4). Six of them erupted rhyolite flows. Some of them had an initial plinian phase which produced widespread air fall ash layers (brown arrows). The eruptions were triggered by tholeiitic injections from the north-east.

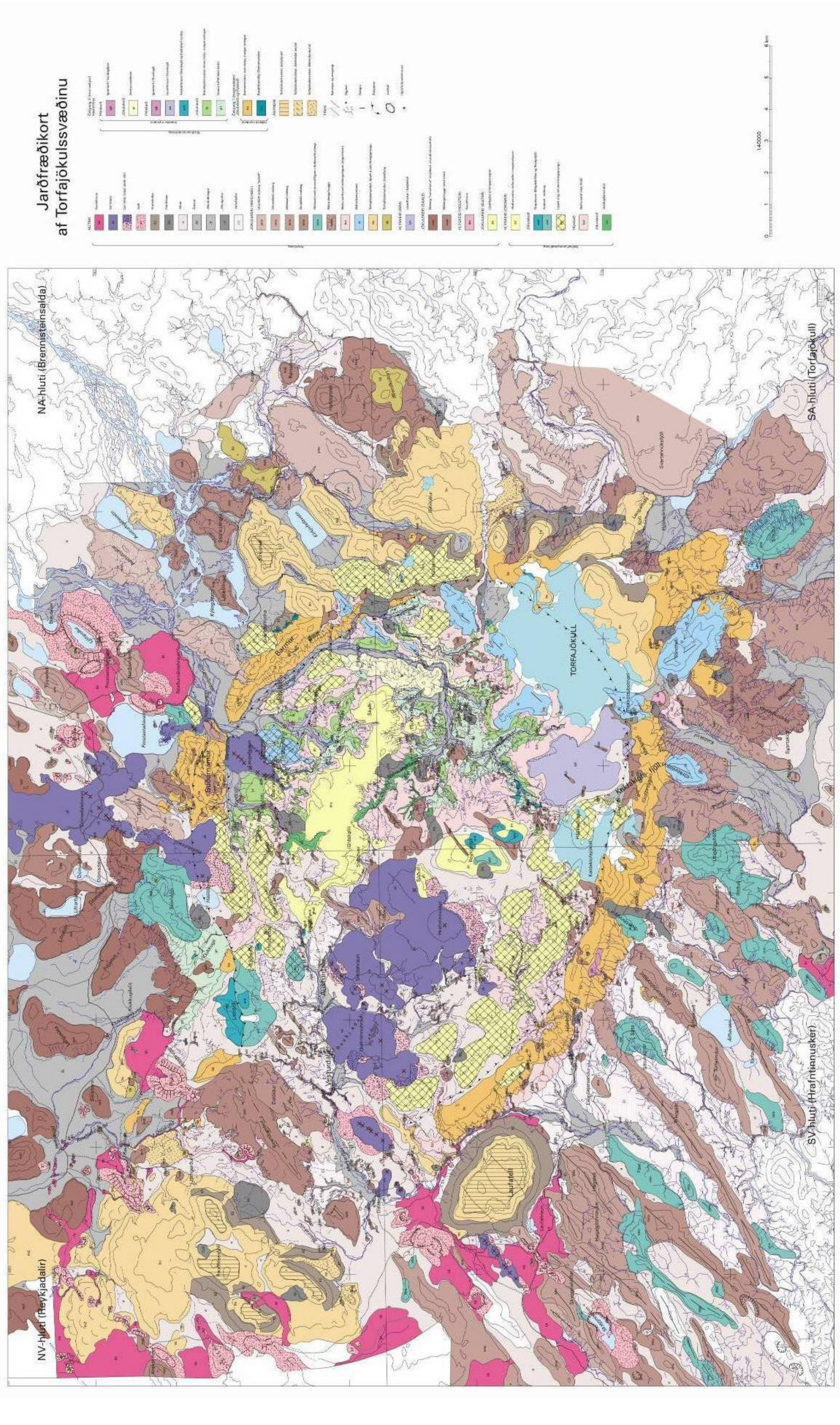

FIGURE 2: Geology of the Torfajökull volcano. The oldest unit crops out in an elliptical narrow zone which encloses the caldera. In Holocene time rhyolite lavas were erupted in the centre of the caldera and mixed lavas near its periphery. Basalt lavas were erupted from NE-SW crater rows further away. The ring fracture rhyolites are shown in pale yellow

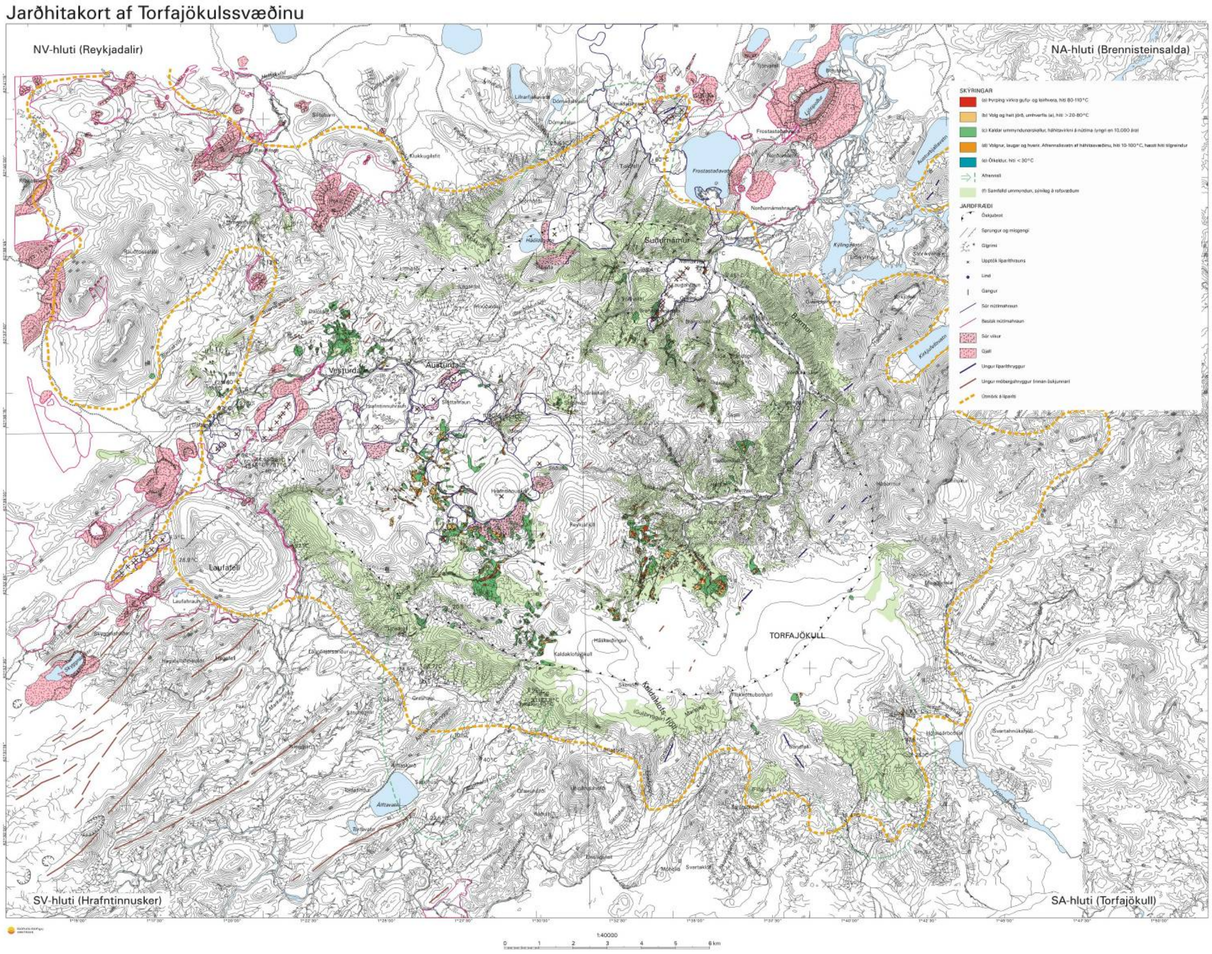

FIGURE 3: Geothermal activity is widespread, mostly as fumaroles inside the caldera. Warm and hot springs are common too around the periphery of young lavas and other permeable formations. CO_2-rich hot springs occur in the east of the caldera and to the SW of it. Alteration is pervasive in the older rock units, much of it cold (light green). Hot ground is extensive around the fumarole fields (dark green)

The most intense thermal manifestations are clearly related to faults and eruption foci of the active NE-SW fissure swarm, in particular within the shadow zone (Figures 3 and 5). There is a marked large offset (right lateral) of the fissure swarm in the SW of the caldera (Figures 2 and 4). The offset segments of the fissure swarm overlap rather than being connected by a transcurrent fault. In the eastern half of the caldera fumaroles concentrate around the youngest domes (most of which erupted under ice) and related fissures.

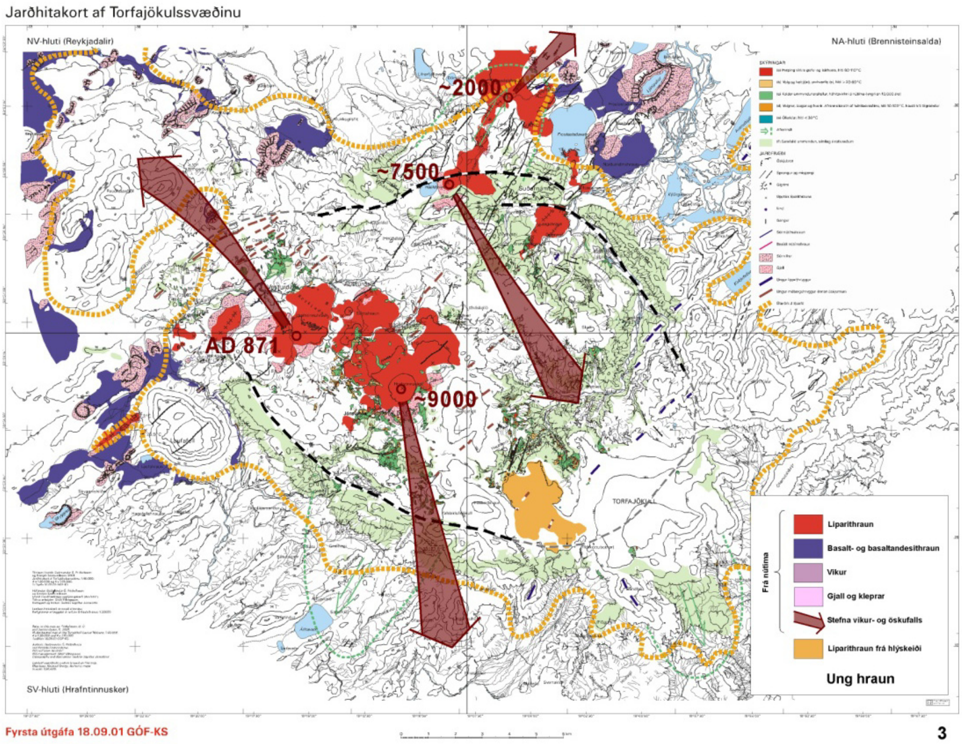

FIGURE 4: Holocene lavas of Torfajökull volcano and plinian phase fall-out of rhyolitic ash which was erupted in the initial stage of the eruptions. Rhyolite (mixed) lavas are red. Basaltic and andesitic lavas are blue. The yellow, stippled contour marks the rhyolite area

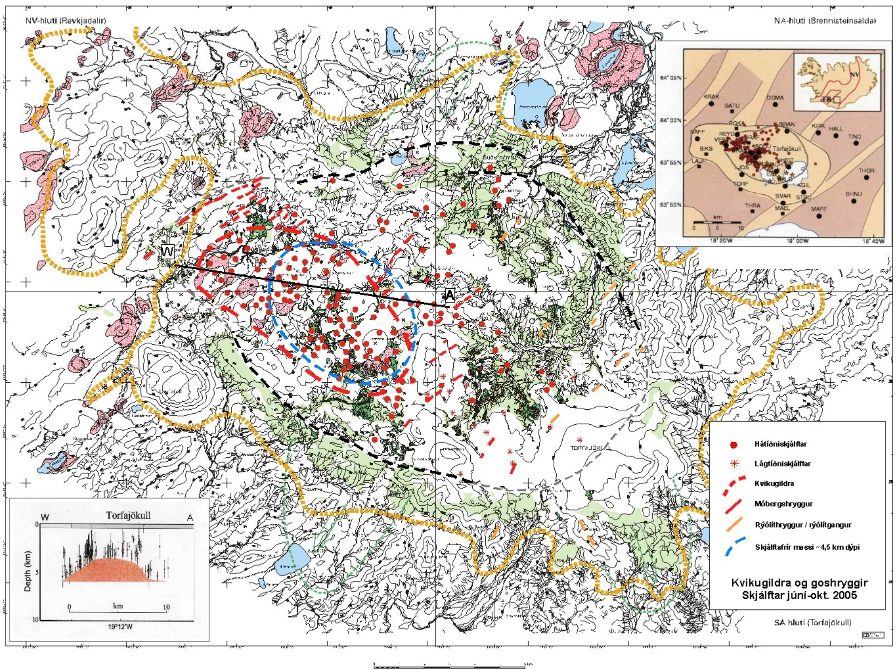

FIGURE 5: A volcanic shadow zone (red hatched contour) where basalt has not erupted is found in the SE of the caldera. It has narrowed with time. Until eruption of the voluminous ring fracture rhyolites about 80 ka it occupied almost the entire caldera. Microearthquakes are common in Torfajökull. Most of them are high frequency earthquakes (the common type which is caused by rock fracturing). They occur in the western part of the caldera. A large, dome-shaped area underneath the shadow zone is void of earthquakes. It is interpreted as ductile (nearly molten?) due to high temperature (blue stippled contour). Low frequency earthquakes (due to movement of fluid, perhaps of pneumatolitic origin) occur in the east of the caldera, extending down to about 15 km depth (stars).

3. GEOCHEMISTRY OF FUMAROLE GASES AND HOTSPRING WATERS

An extensive geochemical survey was made of Torfajökull (Figure 3). Fumarole gases indicate reservoir temperatures of 300-320°C in the entire caldera region. Deep reservoir water (high silica content) occurs in hot springs at the lowest level in the NE. The silica geothermometer indicates a temperature of about 265°C there. The peripheral hot springs are rich in CO_2 suggesting final phase fluxing from cooling intrusions. (Exhumed central volcanoes have a last phase aureole of $CaCO_3$ around them). A peculiarity is a relatively high concentration of methane in fumarole gases in the eastern central part of the caldera. Methane is a volcanic gas which reacts slowly in the rock. It's concentration in geothermal water may therefore be relatively high. The high concentration coincides with the focal area of low frequency earthquakes (Figure 5). It is probably expelled into a pneumatolytic phase from cooling intrusions.

4. GEOPHYSICS

Of geophysical methods resistivity soundings have been applied at Torfajökull specifically to investigate the subsurface thermal structure. Microseismicity has been registered for about 25 years adding significantly to understanding of it´s thermal activity and deep structure. Other methods carried out as part of larger projects include gravity and airborne magnetics. Recently ground levelling (GPS) was added to follow up indications from seismicity of a shallow magma chamber.

The resistivity survey (TEM) revealed a vast prospective area. Resistivity anomalies reveal themselves as high-resistivity bodies below a cap of low resistivity (Figure 6). Those bodies extend well beyond the limits of the caldera. However resistivity does not separate between cold and hot rock in high alteration facies (chlorite-epidote zone). From geological evidence such as cold surface alteration outside the caldera and outflow character of thermal waters the areas outside the caldera are likely to have largely cooled down. The same resistivity structure inside the caldera, on the other hand is likely to define a still hot rock body of chlorite-epidote alteration (gives high resistivity) below 400–500 m depth (Figure 7). There is a correlation between geological structure, alteration zoning, thermal occurrences and resistivity in the eastern part of the caldera. This is expressed in a caldera parallel trend of those features. These conditions may apply also to the western part of the caldera where erosion has not exposed deep outcrops yet. There the fumarole activity is most intense in the area of the Holocene lavas.

Microseismic recordings of over 25 years revealed two types of seismic signals separated also by area. High frequency earthquakes (due to fracturing) occur in the western part of the caldera down to 5 km depth. They concentrate around the shadow zone leaving an aseismic body below 3 km depth underneath it. They are interpreted as being due to a water front encroaching upon and cooling an intrusive body or a magma chamber. Low frequency earthquakes (kind of tremor due to fluid flow) occur in the eastern part of the caldera concentrating about an area of very intense fumarolic activity. Their origin is deeper, from surface to ~15 km depth. Seismologists have explained them as magma movements, a laccolithic intrusion or even as foreboding of an eruption. Ground levelling indicates minor subsidence in the east central caldera, however. Another explanation is more likely: i.e. they originate at the plastic to brittle transition at a critical temperature around a cooling intrusion. Such an intrusion gives off volatiles which may form metal rich solutions and precipitates in fractures, similar to epithermal mineral veins, well known from surroundings of shallow intrusive bodies around the world.

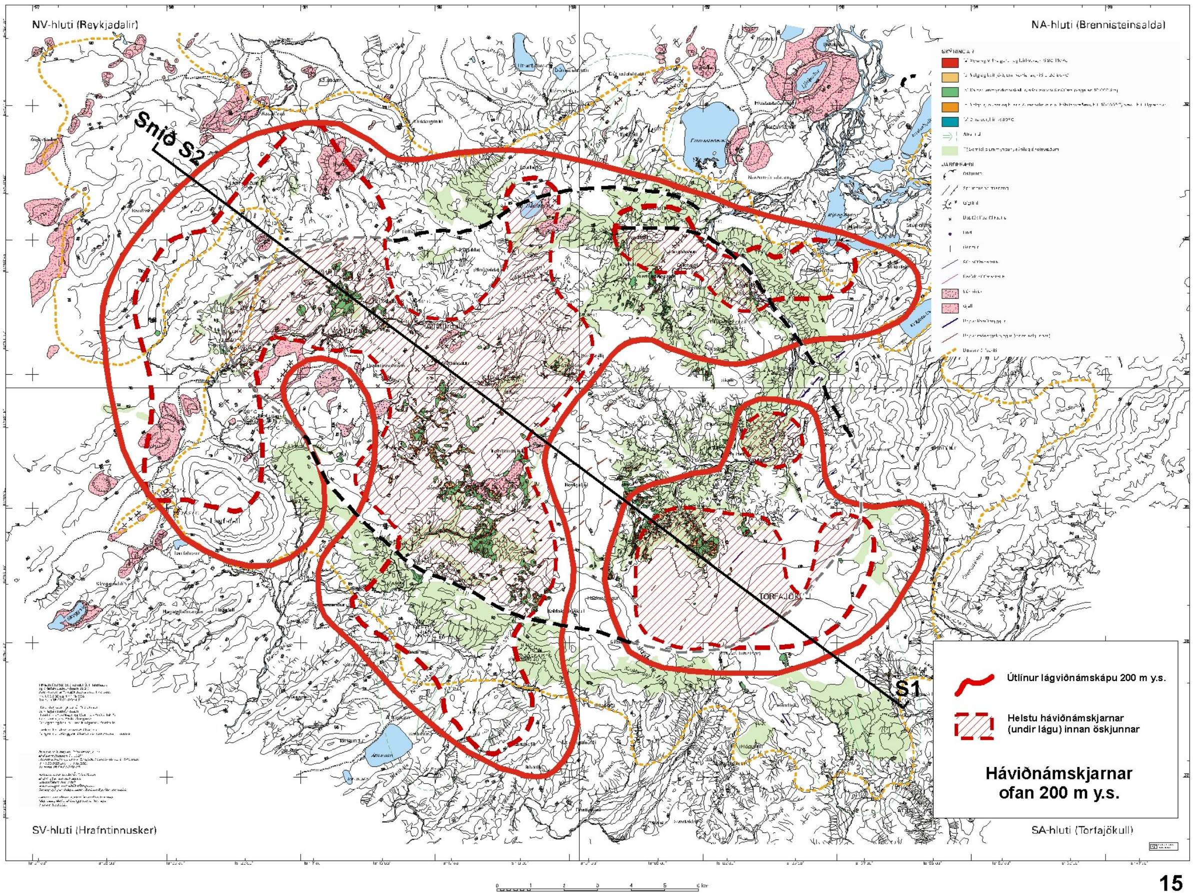

FIGURE 6: Prospective resistivity anomalies reveal themselves as high-resistivity bodies below a cap of low resistivity. They are unlikely to be sufficiently hot for steam production outside the caldera

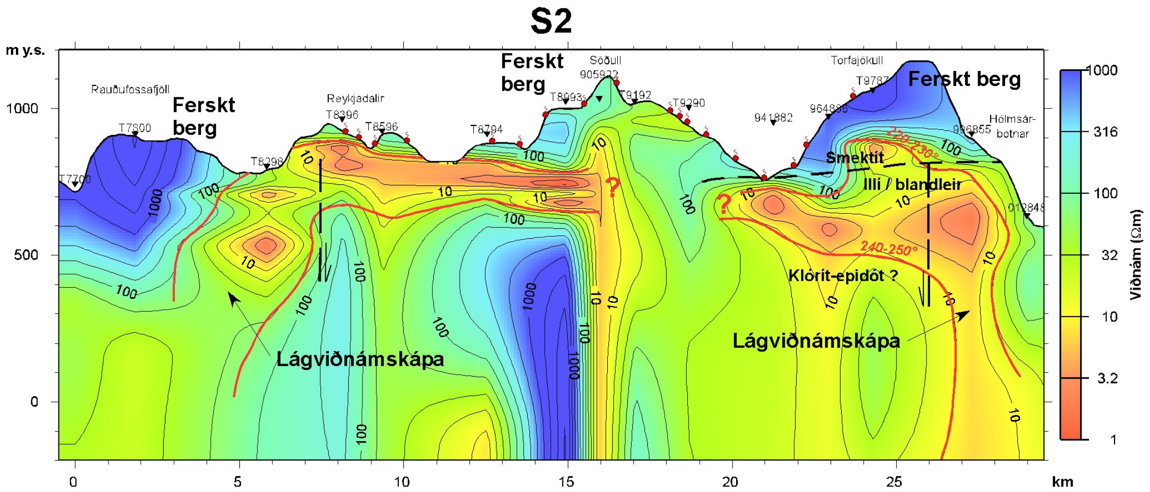

FIGURE 7. East-west section showing resistivity and its inferred correlation with alteration zoning. The alteration of the accessible uppermost few hundred metres gives a tie to conclude about the kind of alteration which causes the resistivity below.

A gravity survey of South Central Iceland shows an extensive gravity low around the Torfajökull volcano and a marked gravity high within it (about 12-14 mgal) correlating with the caldera (Figure 8). The gravity high is interpreted as a heavy rock mass in the roots of the caldera, i.e. basic intrusions which were emplaced at the neutral buoyancy level underneath the lighter rhyolite and basic residuals of crystal fractionation or partially melted crustal material. Most of the time the basaltic melt did not erupt in the caldera region but it did at lower levels close to and around the volcano (Figure 10). The transitional basalt composition of the proximal low level volcanics as against the rhyolites of the central area gives evidence of a layered magma chamber.

An aeromagnetic map (Figure 9) shows low magnetization in areas where rhyolite predominates, especially where altered. Hyaloclastites and their accompanying basalt flows and pillow lavas which occur in the northern part of the young fissure swarm and largely cover most of the rhyolite, show up as strongly magnetized areas. For geothermal purpose the map is not a significant addition. However, it reveals features north and south of Torfajökull that are significant for understanding its position in the frame of South-Central Iceland geology.

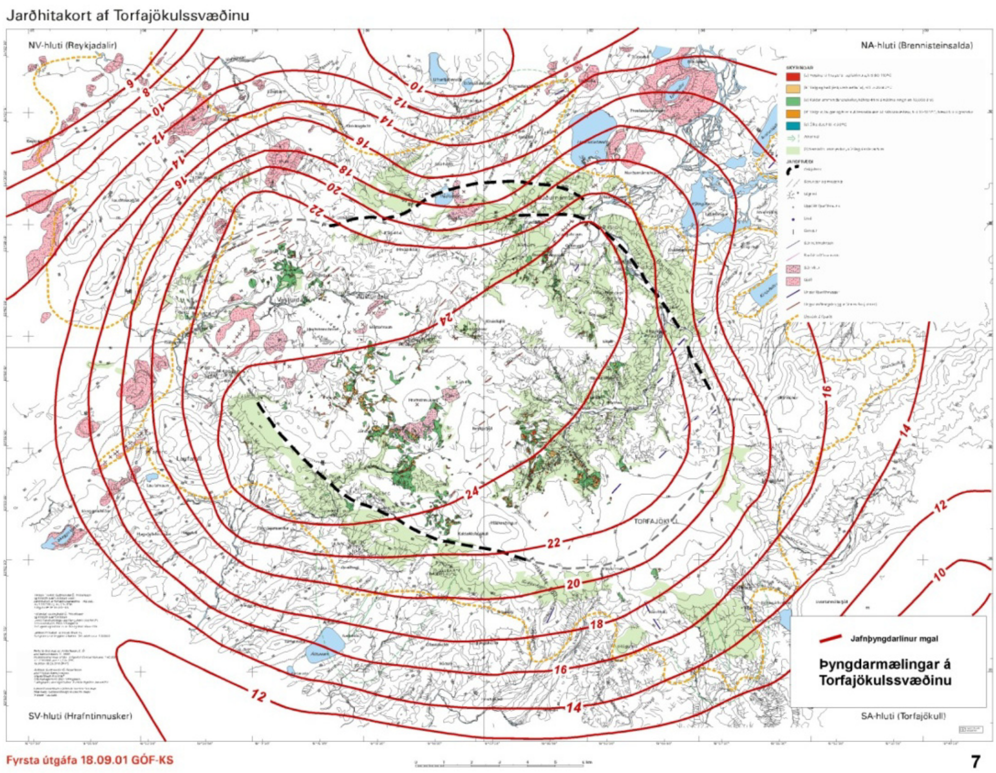

FIGURE 8: A gravity survey of South Central Iceland shows an extensive gravity low around the Torfajökull volcano and a marked gravity high within it (about 12-14 mgal) correlating with the caldera

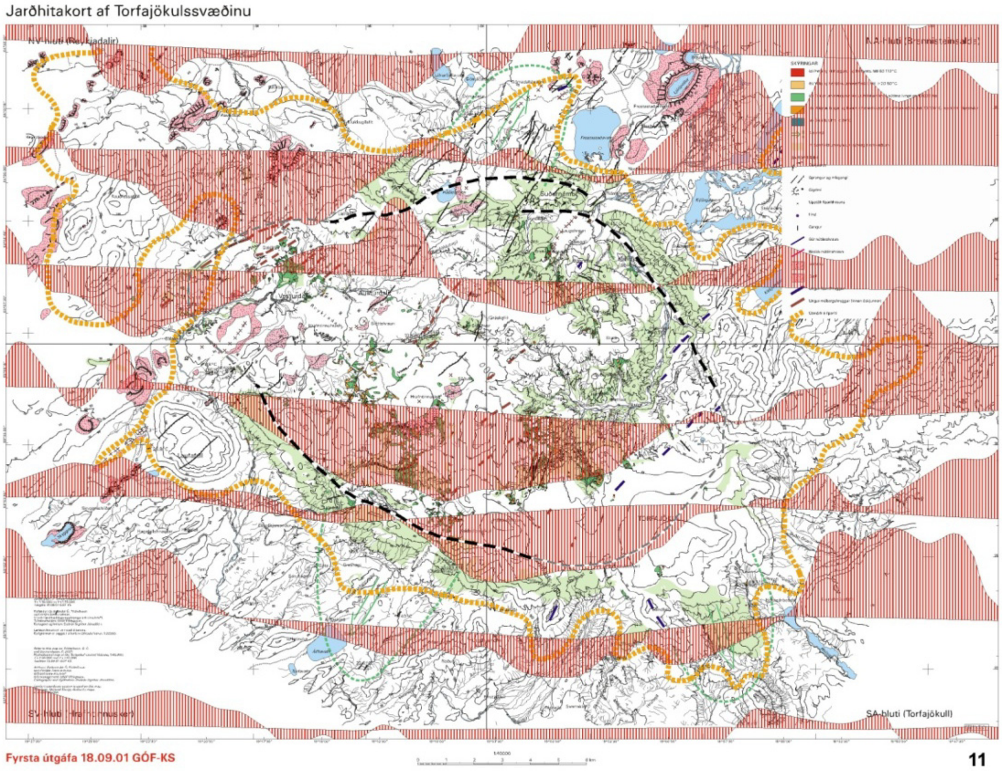

FIGURE 9: An aeromagnetic map shows low magnetization in areas where rhyolite predominates, especially where altered

5. GEOLOGICAL MODEL – DEEP THINKING

The geological structure of Torfajökull is shown schematically in Figure 11. The volcano began as a flank zone volcano on 5-10 million year old tholeiitic crust under a stress field with horizontal max compression (NE-SW). Heat from the mantle plume and a SW-propagating rift zone caused generation of transitional basic magma in the mantle. The magma rose to the LNB-level near the lower (intrusive) and upper (extrusive) crustal boundary forming a magma chamber. This went on during development of the volcano and a thick plug of gabbroic rock formed in the roots of the volcano. It may have developed into a stem-like rock body thus causing the gravity high. A profound revolution occurred in Late Pleistocene, beginning some 100 thousand years ago, when the spreading zone broke across the volcano. The first response was a voluminous eruption of at least 25 km³ of rhyolite on a ring fracture. Partial emptying of the magma chamber was followed by NE-SW fissure eruptions of first transitional basalt from deeper levels of the magma chamber and later mixed volcanics composed of high level lateral intrusions of tholeiite into residual rhyolite magma (small volume as compared to past situations) underneath the centre of the caldera.

This summary is an abridged version of a detailed report (in Icelandic) on the geology and geophysics of Torfajökull by the author compiled from various sources as regards topics other than geology which are largely his own. The figures presented here are from this report (Orkustofnun 2007, in press). They were put together by the author to illustrate a few of the main characteristics of the area, in particular those related to the geothermal phenomena.

Torfajökull was chosen here as an example of a rhyolite volcano. It hosts a powerful geothermal resource as does Olkaria, it´s closest analogue in the Kenya Rift Valley.

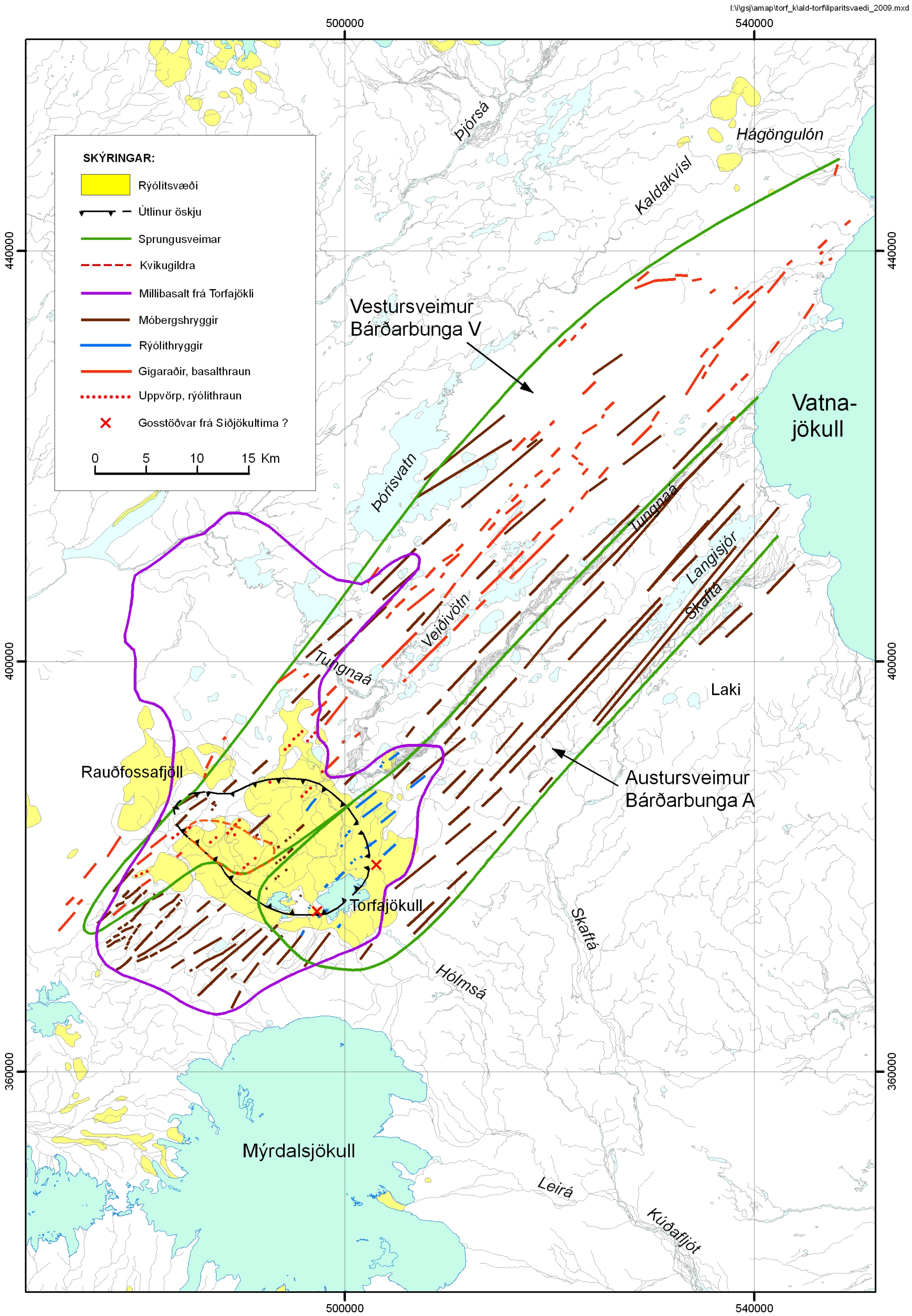

FIGURE 10: Main features of the wider surroundings of Torfajökull. An area of transitional basaltic rocks (violet line) dominates in the area around the rhyolite terrane. A fissure swarm cuts across the volcano. During the Holocene its western half has erupted tholeiite lavas to the northeast of Torfajökull and mixed lavas in the rhyolite area and to the southwest of it. The eastern half of the fissure swarm has not erupted in Holocene time. The Torfajökull caldera is shown and a volcanic shadow zone in the southwest of it.

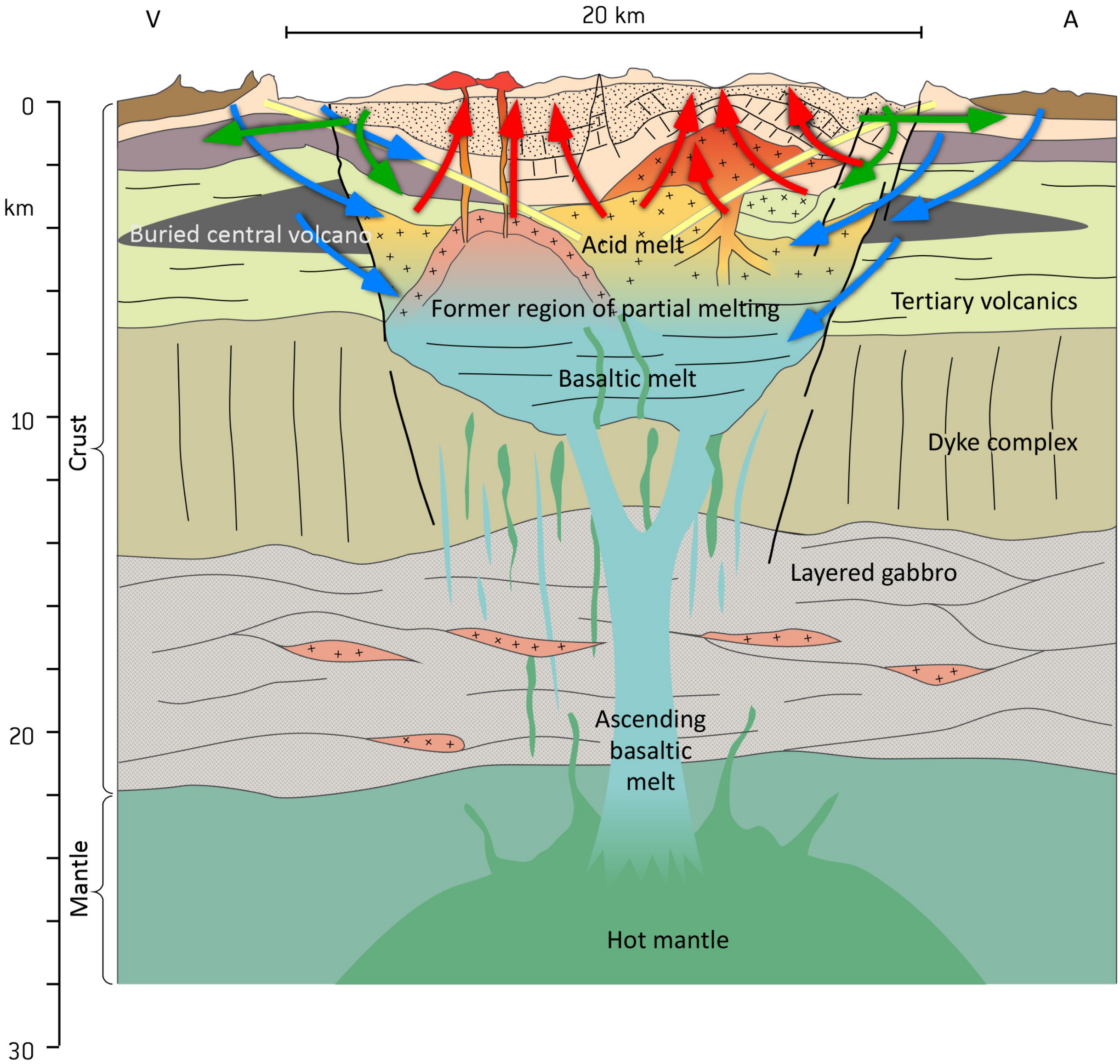

FIGURE 11: Conceptual model of the deeper structure of the Torfajökull volcano