Presented at *Short Course VIII on Exploration for Geothermal Resources,*
organized by UNU-GTP, GDC and KenGen, at Lake Bogoria and Lake Naivasha, Kenya, Oct. 31 – Nov. 22, 2013.

STRUCTURAL GEOLOGY – TECTONICS, VOLCANOLOGY AND GEOTHERMAL ACTIVITY

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ABSTRACT

Discussion will concentrate on rift zone geothermal systems, continental and oceanic, with side look on the hotspot environment. "Volcanology" is contained in the title of this summary/lecture because the discussion will be limited to high-temperature geothermal systems which might as well be called volcanic geothermal systems. The volcanic systems concept is introduced as "a system including the plumbing, intrusions and other expressions of volcanism as well as the volcanic edifice" (Walker 1993). Different types of high temperature geothermal fields occur. Their main characteristics are described including the structures which control their geothermal system. Hotspots are referred to. Many are associated with rift zones (East Africa, Iceland) others are intraplate in continental (Yellowstone) or oceanic (Hawaii) settings. Their magma supply is excessive and they provide a long term thermal high of regional extent.

1. INTRODUCTION

The intrusive part of a volcanic system is most important as a potential heat source for high-temperature geothermal systems (Figure 1). The intrusions form large bodies at a few km depth. They feed a multitude of dykes and sheets underneath a volcanic centre which are relatively shallow and contribute significantly to maintaining and driving geothermal circulation. With increasing distance from the centres dykes become dominant. Concentration of dykes and clustering of volcanic eruptions may occur away from the centre and a geothermal system may develop.

How and why do the intrusions form at preferred levels? Walker´s (1989) ideas about the significance of neutral buoyancy in distributing incoming magma between magma chamber, rift zones, intrusions and surface flow are discussed. Neutral buoyancy is defined as the depth where pressure in the magma (or magma density) equals lithostatic pressure. At this level the magma may form sheet/sill intrusions or may pool to form a large magma chamber. Realize that volcanic edifices may expand nearly as much by growth of subsurface intrusions as by surface outpourings. However, volcano growth is countered by subsidence and collapse.

Calderas as a rule, or at least at some stage, are underlain by a magma chamber. It may be active, ready to erupt, depending on inflow rate and residence time of magma, irrespective of regional tensional stress. Characteristic structures are concentric and radial eruption fissures with radial dykes and cone sheets at depth (Figure 2). Some calderas are more passive. They depend on the regional

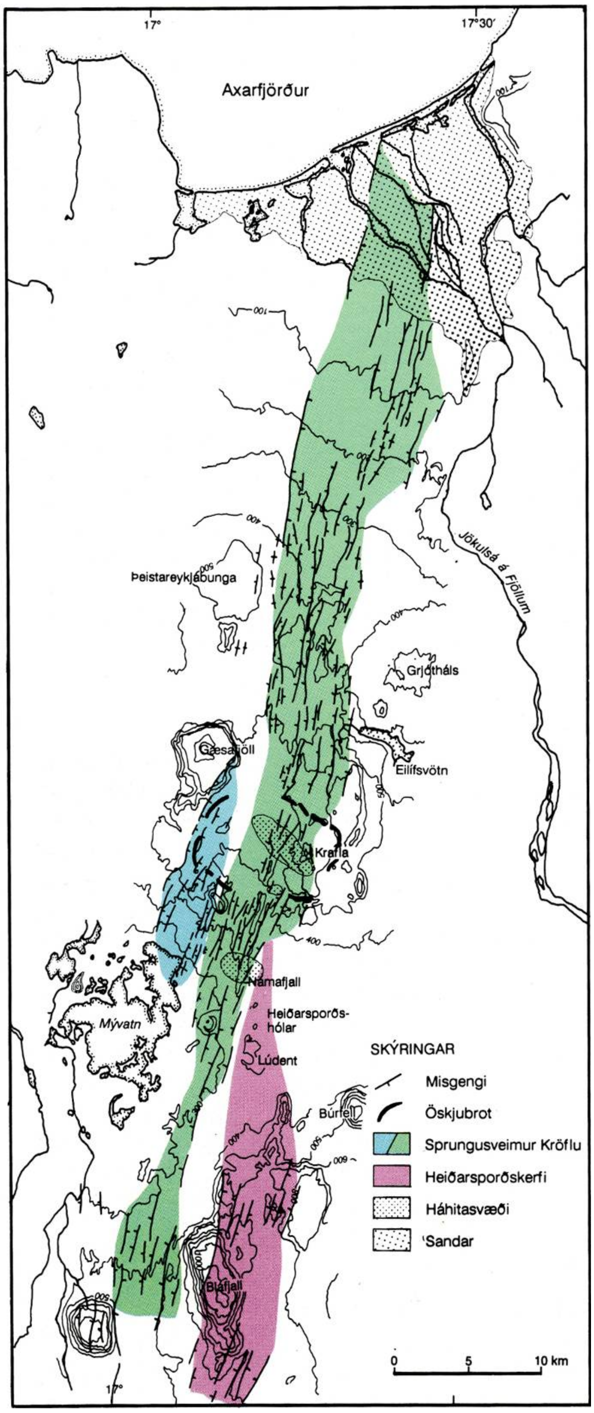

FIGURE 1: Krafla volcanic system. Shield volcano near centre defined by maximum volcanic production (topographical high), silicic rocks, a caldera and geothermal activity. It is transected by fissure swarms totalling over 80 km in length, with aligned basaltic crater rows, faults and ground fissures. Volcanic eruptions extend for about 40 km along the swarm. Non-volcanic faults and fissures (surface expression of dykes) extend far beyond surface volcanism

stress build up for eruptions or triggering by dyke injection from a neighbour volcano. Is Olkaria one such?

So called, volcanic shadow zones define areas within volcanic systems where almost only silicic melts reach the surface, whereas the basaltic melts erupt on the flanks or are emplaced as intrusions at depth. Shadow zones correlate closely with calderas and geothermal manifestations (Figure 3). Olkaria may be an example. Stacking of basaltic intrusions (of relatively high density) below caldera floor may contribute to subsidence.

Types of faults (Figure 4) and gross features of rift zones and fissure swarms are discussed as well as the importance of dyke swarms in controlling underground flow pattern. Listric faults (dip decreases with depth) are a main feature of continental rifts. They are well documented seismically. Planar faults (dip remains constant with depth) also occur. They are nearly vertical in the volcanic part of the fissure swarms. A distinction between listric and planar faults can be seen at the surface as listric normal faults result in rotation of the hanging wall block, whereas planar faults do not. Verticality is indicated by open tension gashes thought to be the surface expression of dykes. En echelon offsets are typical of rift zones.

The volcanic systems are commonly arranged en echelon. Their fissure swarms (defined by faults, open fissures and crater rows) are segmented on a smaller scale in the same fashion. This is prominent where the extension direction is oblique to the rift axis (now easily determined by GPS-network extending on to the marginal blocks) (see e.g. Figure 5 of Iceland).

Dyke swarms may extend over 400 km from their source. An example is the Mull swarm in Scotland and England (Figure 6, left). Fissure swarms which are the surface expression of dykes extend well over 100 km in the rift zones of Iceland and probably also in East Africa. There is a gradation in the dyke and fissure pattern with distance from the source of the magma underneath a central volcano to 1) net dyking, planar and inclined sheets and a wide range of orientations around the source and in the nearest surroundings of the volcano including concentric fissures/faults to 2) dykes, ground fissures and

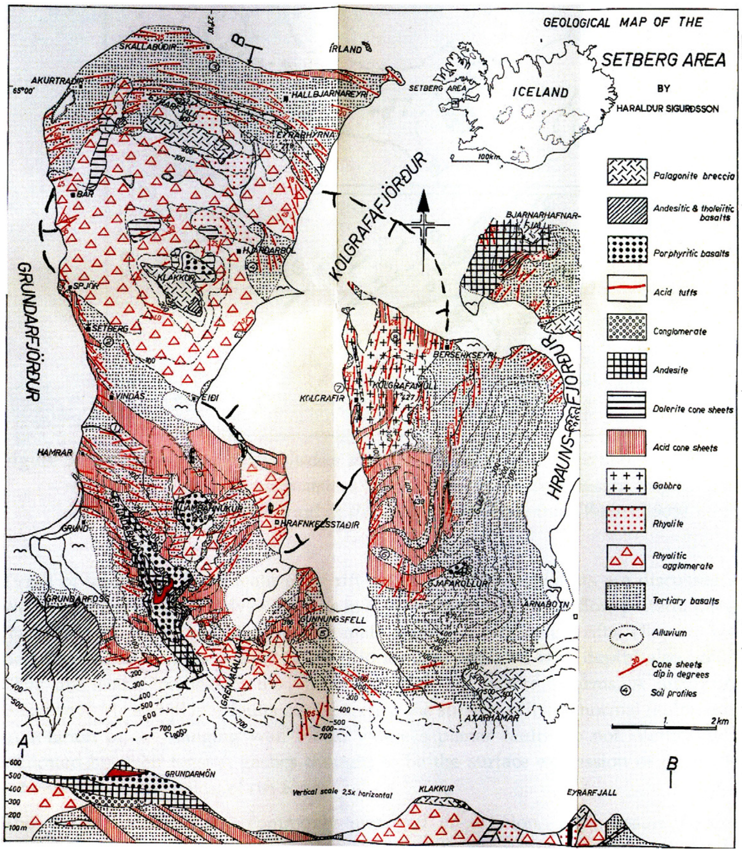

FIGURE 2: Cone sheet swarm of Setberg volcanic centre, West Iceland. The sheets are inclined 25-40° towards a focus at about 3 km depth underneath a caldera, filled with silicic breccia and a gabbro intrusion (Sigurdsson, 1967)

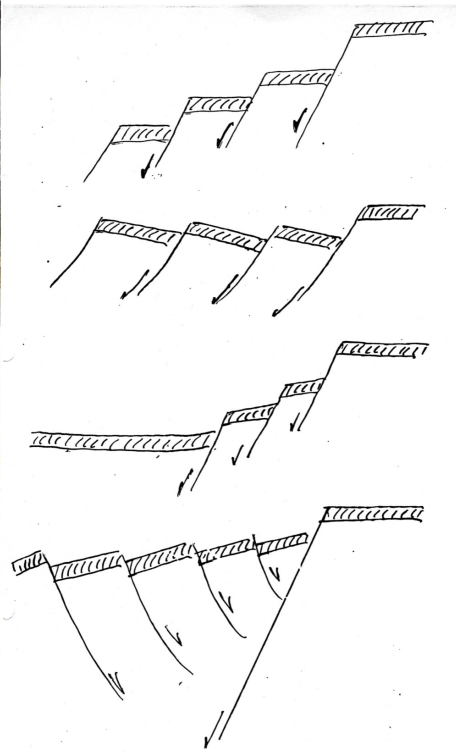

FIGURE 4: Types of normal faults

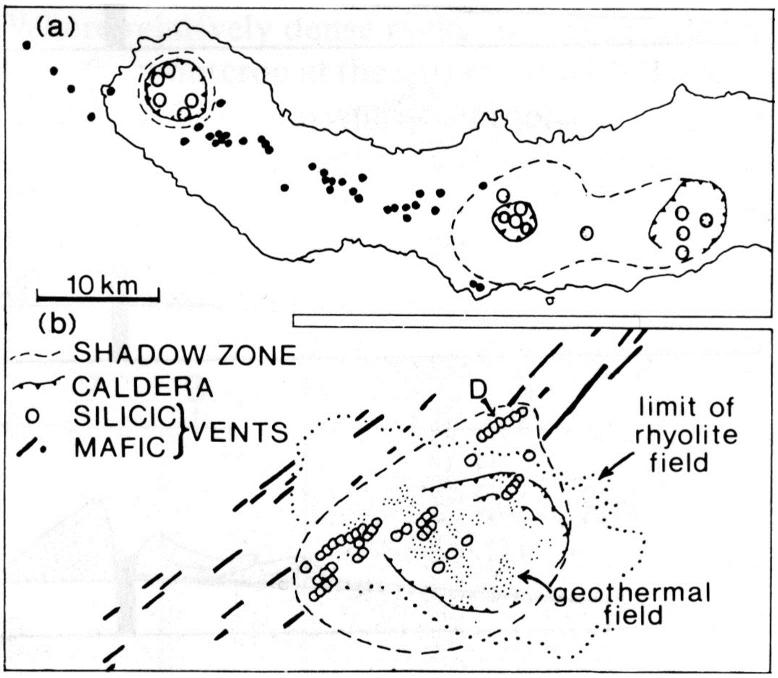

FIGURE 3: Sete Cidades, Azores, and Torfajökull, Iceland. Examples of magmatic shadow zones (where basalt does not erupt) in calderas of rhyolite volcanoes. Magma chambers with silicic melts prevent basaltic magmas from attaining the surface. Such erupt on the adjoining fissure swarms (Walker, 1989)

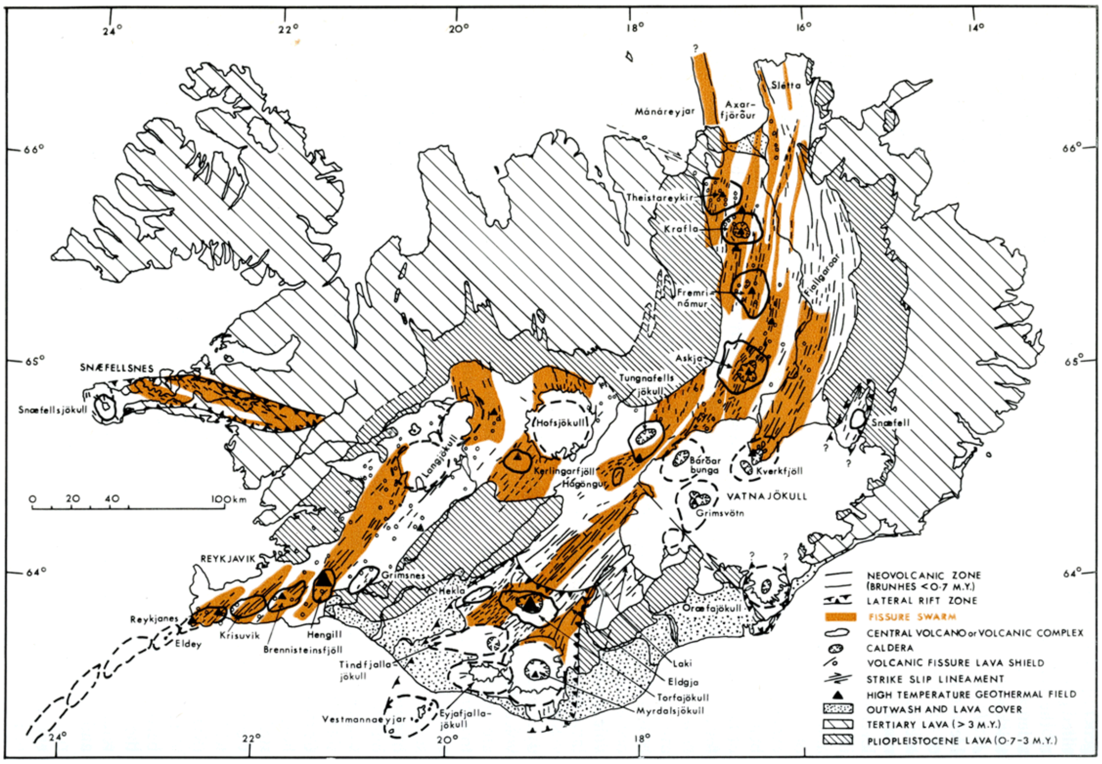

FIGURE 5: Magmatic rift segmentation is reasonably well defined in Iceland. However there are cases where the fissure swarms of volcanic systems overlap and interact: activity of one triggering eruption of another. Differences in petrochemistry help to sort out. This relationship may be more obscure in continental rifts, but little attention has been paid to it so far (Saemundsson, 1978)

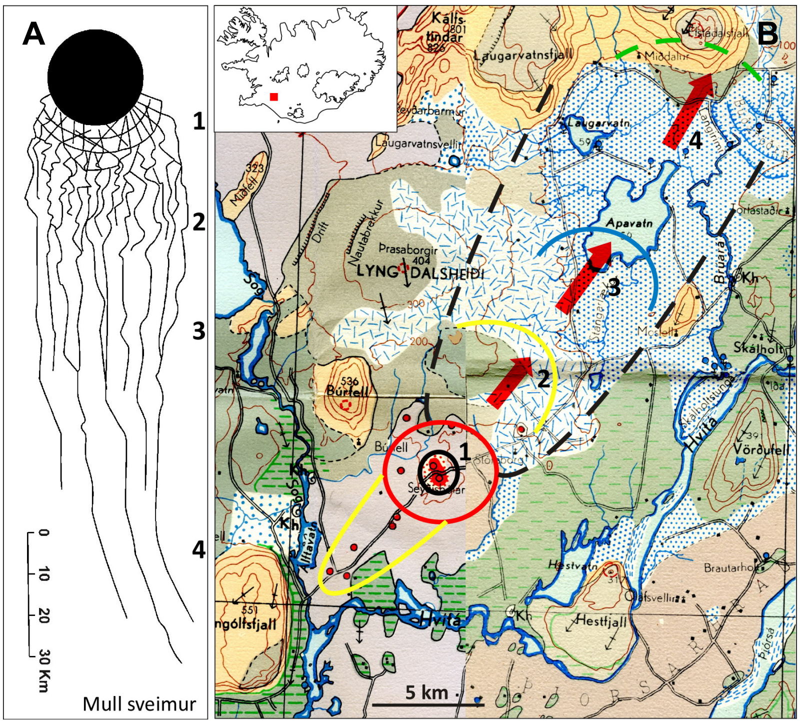

FIGURE 6: A) Variation in trend of the dykes of the Mull dyke swarm. Only 120 km of it are shown including the central and proximal parts. Erosion amounts to 1500-2000 m (Jolly and Sanderson, 1995);
B) Grímsnes volcanic system in South Iceland, shown for surface comparison. Red circle shows the volcanic centre. Yellow lines show how far eruption fissures reach. Blue line how far wide ground fissures reach. Broken green line the approximate outer limit of narrow cracks.
The interpretation is that fracturing is caused by dykes all along the system. They have not reached the surface beyond the yellow line and deepen towards NE. The NE-extension of the system from the centre is about 25 km. Low temperature geothermal systems occur between the blue and green lines.

fissure eruptions becoming more aligned with distance from the volcano to 3) metre scale faults and ground fissures and only rare eruptive fissures to 4) centimetre scale cracks dominating. The gradation correlates with depth to the dykes. They reach the surface only rarely at over 50 km distance from the volcanoes. In the distal part of the swarms where minor fissures on surface indicate propagating dykes they may branch, and not extend higher than about a ½-1km below surface. In Iceland high temperature geothermal systems develop primarily in the source and proximal area. Areas 2) and 3) host low temperature geothermal systems of generally high permeability and rather low temperature whereas the distal areas of type 4) host low temperature geothermal systems often in the range 80-120°C but are of a more restricted fracture permeability. The gradations are indicated for the Grímsnes volcanic system (Figure 6 right) from 1 to 4 and the corresponding subsurface analogies of the Mull swarm.

2. GENERAL ISSUES TO BE CONSIDERED AND KEPT IN MIND

Exploration strategy should be fitted to detect and map the outline of an upwelling geothermal plume and its outflow. Role of geologist is to investigate a variety of features that may shed light on the nature, geological history and present state of the respective geothermal system with emphasis on the central volcanic focus.

Information about the volcanic stratigraphy, structure and rock composition is needed as a basis for interpreting results of geophysical and geochemical surveys, and exploration drilling conducted before drilling of production wells. The volcanic history and mode of eruption needs to be known. This is important also for assessment of volcanic hazard.

2.1 Segmentation of rifts and characteristics of volcanic systems

Look for segmentation of rifts and define volcanic systems by area (from fault trends, crater rows and rock composition). Evaluate volcanic production and mode of eruption. Define rock types. Try to estimate ground movements, vertical and horizontal, their rate – latent creep and/or rifting episodes accompanied by volcanic or intrusive activity. Rifting episodes have been ongoing in the East African Rift since 2005 in Ethiopia (Dabbahu) (Last event occurred in 2009. Rift segmentation and recognition of volcanic systems is widely recognized in Icelandic geology. This may also be applied to the Kenya and Ethiopian rifts, although individual systems have as yet not been well defined.

2.2 How volcanic systems operate

Most magma involved in formation of a volcanic system does not reach the surface but heats a large volume of underground rock. This is difficult to measure, but the volume of evolved (acidic) rocks indicates the degree of partial melting or crystal fractionation, and storage in the crust (before eruptions) underneath the centres. The deeper mafic magma chamber constitutes a large volume which it distributes among sheets (in the central region), dykes in the fissure swarms and gabbros in the roots of the main centres which tend to subside gravitationally.

2.3 Internal structure of volcanic systems

The internal structure of volcanic systems is characterized by dyke complexes in rift zones (deep levels of entire rift zones have been observed in deeply eroded Precambrian terranes). Sheets, dykes and minor intrusions constitute a high percentage of the rock mass at shallow depth (1-3 km) underneath volcanic centres where magma pressure overcomes lithostatic pressure. Larger intrusions (magma chambers) form at greater depth near level of neutral buoyancy (LNB). These act as long term heat sources which also give off volatiles upon solidifying.

2.4 Sheet complexes form in the roots of central volcanoes

Sheet complexes form in the roots of central volcanoes. These are inclined sheets or near horizontal sills, commonly forming coherent sets (Figure 7). From cross cutting relationships it is clear that dyke and sheet intrusions may alternate. Magma injections into roots of central volcano cannot all be accommodated as dykes if extension is slow. Minimum stress orientation then oscillates between horizontal (dykes) and vertical (sheets and sills). Sheets and sills contribute to thickening of the volcanic edifice (mostly balanced by subsidence) which may amount to hundreds to over 1000 metres. They constitute a significant part of the heat source. Their depth is controlled by the LNB (Walker 1989).

FIGURE 7: Cone sheets of Lýsuskard central volcano, W- Iceland, intersecting basalt lavas and their surface breccia (scree covered ledges).

2.5 Calderas

Calderas are a common feature of central volcanoes including shield-volcanoes and stratovolcanoes. These are collapse structures that may be up to 1000 m deep or more. The down dropped block usually consists of the formerly high ground (or volcanic cone). Pre-caldera geothermal alteration may not have reached as high there as it did on the lower slopes of the volcanic edifice. Also calderas tend to fill up within geologically a short span of time. A young caldera may therefore contain a thick pile of rock, as yet little affected by alteration and therefore too permeable for a high temperature system to evolve or become conspicuous. Figure 9 is an example of a shallow caldera showing this feature.

3. IMPORTANT MAPPING FEATURES

3.1 Mapping of geothermal features

Mapping of geothermal features, both active and extinct, is important. As to the active features areal distribution, intensity, size and coherence of fumarole fields or steaming ground, efflorescence minerals and directional trends is quickly assessed. At low levels where hot or boiling springs dominate the same applies except that the deposits from the water must be identified: travertine (tufa) or silica sinter. The first is a bad omen as regards chemistry of reservoir water and temperature the latter a good sign especially if silica sinter is the sole or predominant precipitate. As to the extinct features it is necessary to study the type of alteration (what type of clay, especially transition from smectite to chlorite which is temperature dependant) and its relation to the unaltered rock or soil nearest to it. This may show if the feature became recently extinct (Figure 8).

3.2 Surface geology

Besides plain stratigraphic and tectonic mapping significant features to be defined include volcano type (stratovolcano – shield volcano), dominant rock type (basaltic or acidic), occurrence of acid rocks (lavas, domes, ignimbrite, pumice), caldera whether incremental (Silali) or collapse with related volcanics, (Menengai: ignimbrite flow of ~1000 km² about 8000 or 12.000? years ago), type of basalt eruptions and their structural control such as: unidirectional fissure swarm, radial or circumferential fissures around caldera, central vent eruptions. Hydrothermal and volcanic explosion craters, their age, distribution, size and ejecta. Those indicate nearness to an upflow or a boiling reservoir and are targets for drilling production boreholes. These also constitute a hazard to be assessed properly before siting of surface constructions.

FIGURE 8: Fresh volcanic breccia overlying altered breccia. The altered rock is of low permeability and retains some of the rain water supporting vegetation, whereas most of it percolates rapidly down through the fresh breccia which thus is unfavourable for vegetation in a cold climate

3.3 Life time and development of volcanic systems

Life time of volcanic systems varies from hunderd of thousands to millions of years. It may be assessed from study of well exposed extinct and eroded volcanoes in geologically similar terranes. Development through the nearest geological past and history of activity can usually be found out for at least the last few thousand years. Extension across rift zone during a much longer active period can often be estimated from fault density and throws. With time a preferred stationary intrusion focus would produce an intrusive body, elongated in the direction of stretching (spreading), as calderas also do. Distal parts cool off with time and increasing distance from centre of active magma chamber. CO_2 fluxing of marginal parts of geothermal system is a corollary.

3.4 Permeability

The near surface rocks of a geothermal area are often permeable (lavas and pyroclastics, densely spaced faults). Permeability decreases downwards as alteration progresses and finally secondary permeability may prevail. Directional drilling is best suited to intersect promising targets if the upflow is fracture controlled or to track feed zones for stratabound aquifers.

3.5 Extinct and eroded volcanic centres

It is most informative to study extinct and deeply eroded volcanic centres, the internal volcanic feed system and their hydrothermal aureoles (Figure 9). The alteration zones can be seen with their characteristic secondary minerals. Dyke complexes can be separated by rock type, distribution and relative age relationships. Dense dyke complexes correlate with increase in high-temperature mineralization. Retrograde mineralization towards end of activity is seen as overgrowth by zeolites. Deeper roots of hydrothermal systems (supercritical conditions, beyond depth of drilling) are well known from study of epithermal ore deposits around exhumed intrusive bodies (former magma chambers).

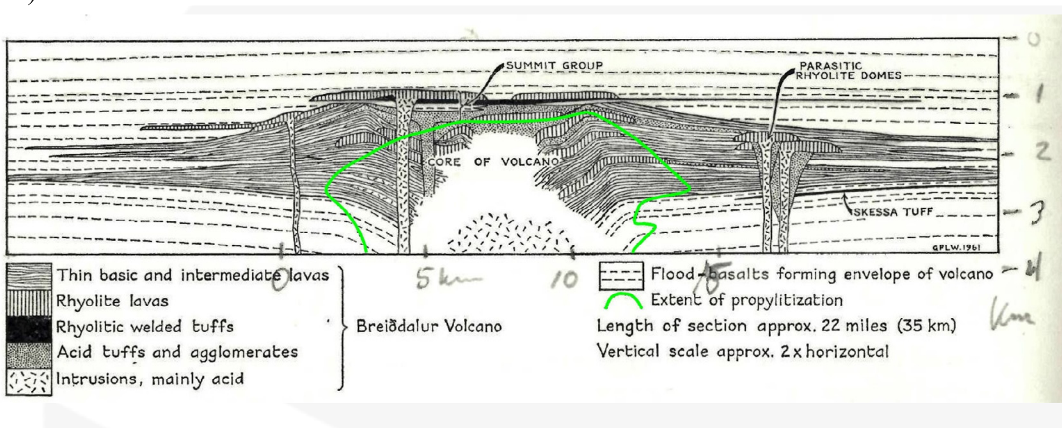

FIGURE 9: Schematic composite section across the Miocene Breiddalur central volcano in East Iceland, long extinct and exhumed by erosion (Walker, 1963). A caldera in the core area of the volcano once hosted a geothermal system of which high-temperature alteration is evidence. Intrusive complex is found in roots of volcano

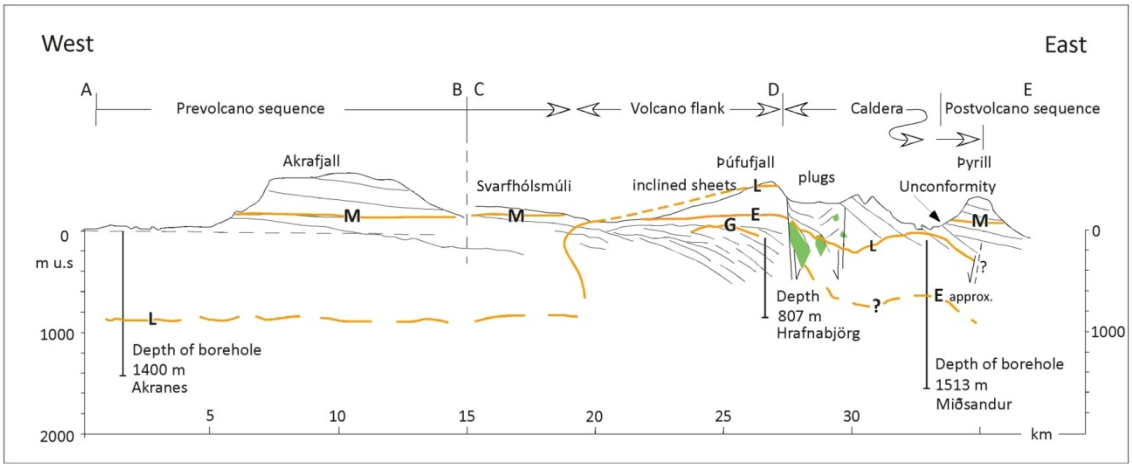

FIGURE 10: Section through the exhumed Pliocene Hvalfjördur central volcano in West Iceland. Flank of volcano is intruded by a multitude of inclined (cone) sheets. The central part has collapsed to form a deep caldera. A geothermal system left its imprint as a high temperature secondary mineral zoning from laumontite to chlorite-epidote and garnet-actinolite. The upper limit of index minerals is marked as L, E and G. The laumontite zone is followed upwards by zeolite zones. M= upper limit of mesolite-scolecite zone. Here the geothermal system did not recover after the caldera collapse.

4. STRUCTURAL FEATURES AND WAYS TO RECOGNIZE THEM

Let us look at large features first that are visible from space or air planes and go on to mapping at ground level. Try to make such features as faults accessible by excavation if they are buried and you think that they are significant.

4.1 Satellite images

Satellite images are useful for overview, however, they lack details. Ground check is needed.

4.2 Air photos

Air photos (stereo pairs) are a very important guide to structures, ground control is a must.

4.3 Mapping

Plain mapping involves: fissures and faults (trend, throw, width, hade, sense of motion, relative age from cross cutting relationships), craters and volcanic fissures (trends, swarming, age relations, explosivity), tilting of the ground (most obvious in antithetic fault zones). Take care on flanks of volcanic edifices where dips are depositional. Mapping of geothermal features in order to recognize directional trends or local concentrations include: mapping of hot and tepid springs, silica or travertine deposits, steam emissions, gas vents, hot ground, efflorescence minerals, alteration (cold or active, local or pervasive, clayey (rock altered beyond recognition of primary rock type) or moderate if original structure of rock is preserved), sliding on clayey slopes may constitute a hazard.

4.4 Faults

Faults are not always topographically distinct unless young or recently activated. Faults are sometimes smoothed out by lava, levelled by erosion, disguised by vegetation, or draped over by scree, pumice or other sediment and only visible in erosive channels, quarries, road cuts or other exposures. Reference markers should be looked for. Various types of faults occur. Normal faults and tension gashes dominate in extensional regimes. Whether listric, planar or vertical depends on whether they are dry or magma generated (the vertical ones). Strike slip faults dominate in fracture zone regimes. Look for riedel shears to determine sense of motion. Normal and strike slip faults both occur in oblique (transtensional) rift zone settings. The two types may be active alternately. Reverse faults occur in Circum Pacific Belt. Volcanic systems in subduction zones may develop fissure swarms which are parallel with the axis of maximum compression.

4.5 Minor faults or fractures

Minor faults or fractures may give a clue to prevailing stress field. Look for striations and riedels on fault surfaces. Helps define stress field. Max. stress axis is near vertical in rift zones. Point source stress develops above inflating magma chambers, causes circumferentially inclined sheets and fissures to form, including volcanic fissures in case of incremental caldera formation (Askja, Iceland, Silali, Kenya).

4.6 Subsurface geology

Look for clues to subsurface geology. Take into account the possibility of low permeability near surface layers (espec. alluvial, lacustrine or mud flow deposits) that might divert water flow laterally.

4.7 Geological hazard factors

Be aware of geological hazard factors such as rock slides, potential flooding, ground fissuring, type and place of volcanic eruptions and their distribution in time. In Krafla and Námafjall, Iceland several boreholes were clogged by basaltic melt during the Krafla volcanic episode in the 1970's. Also the geothermal system was partly rendered unexploitable temporarily by influx of volcanic gases. Two recent examples of fatal disasters can be mentioned (Muffler and Duffield, 1995). In Ahuachapan, El Salvador, a hydrothermal eruption occurred in 1990 resulting in 25 fatalities. At Zunil, Guatemala, a landslide buried a drilling pad and killed 23 people.

5. TYPES OF VOLCANIC GEOTHERMAL SYSTEMS IN RIFT ZONES

Eburru, Kenya – stratovolcano with large geothermal area extending over 15 km N-S. Collapse structure likely. Erupts silicic rocks (trachytes and rhyolites) and subordinate basalts in central area but basalts along fissure swarm to the north. Upflow may be limited to central volcanic area with outflow to north and south. Fissure swarm prominent with faults, and chains of craters.

Hengill, Iceland – shield volcano with large geothermal area extending 12 km NE-SW (surface manifestations). Lacks collapse structure, erupts mainly basalt, but silicic rocks occur in core area. Fissure swarm prominent with crater rows, faults and ground fissures. Main upflow follows dyke zones which fed Holocene and Late Pleistocene basaltic eruptive fissures.

Ahuachapan, El Salvador – complex stratovolcano with fumaroles at higher ground and hot springs at lower ground. Lacks collapse structure. E-W trending volcanic axis within back arc type graben. Aquifer primarily Plio-Pleistocene andesites at about 500-900 m depth in a laterally fed aquifer. Main upflow underneath volcanic ridge.

Olkaria, Kenya– rhyolite volcano with extensive geothermal field within large ring structure. Caldera most likely present now filled up. Eruptives mainly silicic rocks (rhyolitic) – about 13 km³ over about the last 20.000 years. (For comparison Menengai about 50 km³ over about the last 30.000 years). Fissure swarm is evident in the central area and in the northeast where possibly invaded by Eburru swarm?

Torfajökull, Iceland – rhyolite volcano, dead or dormant as an independent (primary) eruption system of its own. Invasion of basaltic magma from a distant volcanic system triggers faulting and mixed rhyolite/basalt eruptions. Last large eruption produced about 25 km³ about 80.000 years ago. Large caldera, gravity high, shadow zone, magma chamber, geothermal area ~140 km² based on surface manifestations.

Asal, Djibouti – close sub-aerial equivalent to oceanic ridge axis geothermal system. Shield volcano with geothermal system in central area and marginally to it in the direction of widening. Numerous NW-SE faults and crater rows. Recharge by sea water. Lessons to be learned from Reykjanes, Iceland? Perhaps drill shallow wells into steam zone which may already exist and become thicker in the future when production from deeper, water dominated part of the system comes about. Drilling into the steam zone will be difficult (to say the least) after it has developed further with pressures around 50-60 bar. Subsurface brine will get saltier with time as boiling off due to drawdown proceeds.

Reykjanes, Iceland – Small geothermal area from surface manifestations (1.5 km²) at centre of volcanic system. Numerous NE-SW faults and crater rows occur. Recharge by sea water. Best feed zones are dyke feeders of eruptive fissures. Boiling reservoir about 300°C. Production of geothermal fluid (corresponding to 100 MW electric) over a period of 18 months caused a drawdown of more than 200 m in the reservoir. Recharge slow despite open faults and fissures, probably due to sealing off of the geothermal reservoir (by anhydrite deposition)? Steaming ground, fumaroles and mud-pools have increased drastically indicating development of a shallow steam zone as a corollary of the drawdown. Such conditions may result in steam explosions if fissures open up. No such have occurred so far in Iceland as a consequence of drawdown. The obvious practice (in Iceland) to avoid disastrous consequences is to drill and exploit the steam zone for power generation.

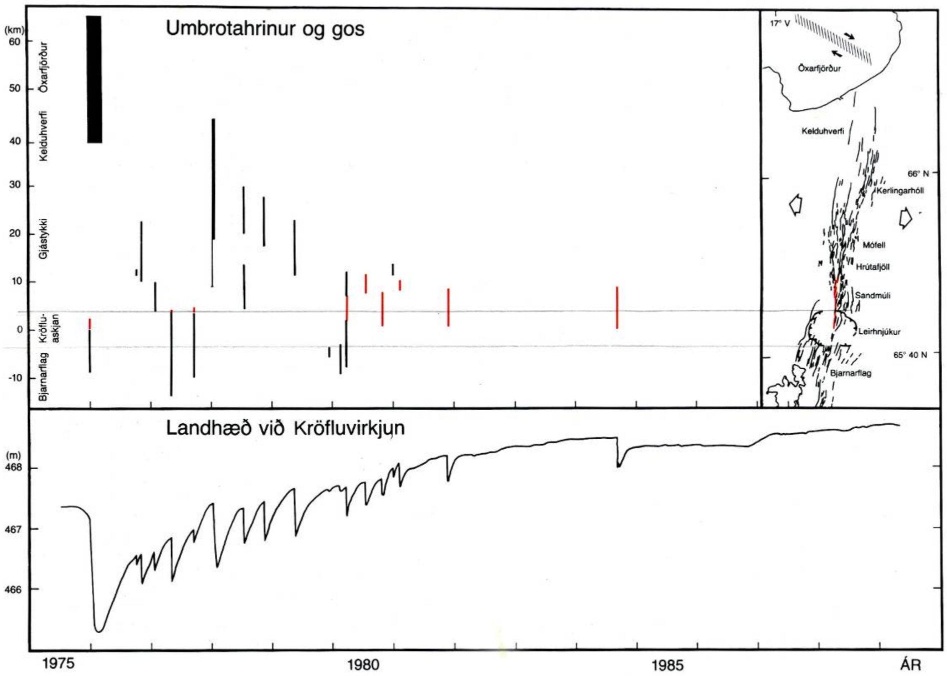

FIGURE 10: Krafla rifting episode of 1975-1984, course of events. Upper diagram: Dyking (black) and eruptive events (red). The bars indicate the part of the fissure swarm which were affected in individual events with reference to the map on the right. Their thickness is proportional to the time each event lasted. Lower diagram: elevation changes with time (Einarsson, 1991)

<u>Krafla, Iceland</u> – activity adjusted to slow spreading (half rate 1 cm/y). Rift episodes (Figure 10) occur at intervals of a few hundred years. Geothermal surface manifestations correlate with a preferred intrusion focus at centre of 8x10 km diameter caldera. Both have been extended in the direction of widening by about 1 km since the caldera formed 110.000 years ago. Magma chamber containing silicic melt in east central part of caldera. Rock composition basaltic to mixed basalt/rhyolite. A rifting episode occurred in 1975-1984. Precursory symptoms were earthquake activity starting a year before and elevation changes. Basaltic magma collected in magma chamber at 3-7 km depth. After filling and residence in magma chamber which took a few months, magma was expelled repeatedly as dyke intrusions with minor eruptions over a period of four and a half years. This was followed by further dyke intrusions and fissure eruptions occurring repeatedly over a period of another four and a half years (Figure 10). A total of about 1 km³ of basaltic magma was estimated to have been erupted and intruded as dykes. The widening of the fissure swarm amounted to max. 9 m on a 70 km segment of the fissure swarm. Geothermal power plant at Krafla produces 60 MW. A part of the geothermal system was contaminated and rendered unexploitable by a volcanic gas flux for about 15 years.

<u>Dabbahu, Ethiopia</u> – stratovolcano underlain by magma chamber. Abundant fumaroles at summit area of volcano extending from there towards north. Silicic rocks form the summit area, basaltic fissure eruptions on prominent fissure swarm. A rifting episode occurred in 2005. Precursory earthquake activity was followed by a minor mixed basaltic/silicic eruption and a major lateral magma flow at about 2-9 km depth 60 km to the SE. The intrusion event lasted less than a week. Dyke volume has been calculated about 2.3 km³. Widening of fissure swarm was about 6 m, with addition of several m throw to pre-existing fault scarps. There have been repeated rifting events after 2005, much less in size. These were not accompanied by inflation and deflation of central area. Possibly the explanation here is that dykes are fed from a lower crustal magma chamber.

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