PERMEABILITY IN GEOTHERMAL SYSTEMS ASSOCIATED WITH CONTINENTAL RIFTS

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SUMMARY - Continental rifts form mainly as half grabens with a border fault system down one side. Heat flow is highest in the centre of the half graben, but deep recharge is likely to be mainly associated with the border fault system. A volcanic centre must therefore form on the edge of the half graben or crosscutting permeable structures must exist for a significant geothermal system to form. Alternatively where there is permeability in pre-rift rocks, a geothermal system may form where they intersect the border fault system. Cross cutting structures can form in rifts where there has been a change in tectonic forces. This is the case in the East Africa rift where basement faults have been reactivated as NW strike slip faults which have produced associated tensional features. Where there is permeability in pre-rift rocks, permeable targets at depth are where the pre-rift permeable feature intersects the border fault system. Where there are strike slip faults, the associated tensional features are the targets at depth, otherwise normal faults parallel to the rift are the main target.

1. INTRODUCTION

Following on from a discussion of how to predict the orientation of permeable structures in geothermal fields related to subduction zones at convergent margins (Bogie, 2000) this paper discusses the potential for permeability at depth in geothermal fields found in the divergent tectonic environment of continental rifts (Ruppel, 1996).

2. GENERAL FEATURES OF CONTINENTAL RIFTS

2.1 Mechanisms of Rift Formation

There are three established mechanisms for the formation of continental rifts. They are deformation produced by the collision between continental plates, the collision between a subduction zone and a spreading ridge and heat build-up beneath a continent (Mareschal, 1983).

Rifts produced by crustal deformation due to the collision of continental plates are known as impactogens. They form in the deformation zone of the larger colliding plate where it has curved in response to collision with a smaller plate. As the zone of curvature has to stretch to geometrically accommodate its formation, rifts form at the maximum point of stretching, producing thinning of the crust and the development of a mantle bulge. These are also described as passive rifts in that they are formed by changes in crustal geometry rather than being the result of deeper processes.

The second type of plate collision is that between an actively spreading ridge and a subduction zone. This terminates both the spreading and the subduction leaving a slabless window beneath the overriding plate, the open space created is filled by a mantle bulge producing a high heat flow, updoming of the crust and consequent rifting. If the collision between the spreading ridge and the subduction zone is oblique, a wide slabless zone can be formed and a much wider area of rifting can form in comparison to the two other types of rifting. Since the rifting is being initiated by changes in the mantle it must be regarded as active rifting.

The third type of continental rift forms due to the fact that there is no ready mechanism for direct heat release fiom the mantle through a continent in comparison with oceanic environments where heat fiom the mantle is mainly released along mid ocean ridges. Heat build up, particularly that associated with mantle hotspots, beneath a continent produces a bulge in the upper mantle due to a combination of convective upward movement of lighter material, including partial melts, and the expansion of material through heating. This bulge is transferred to the crust where there is the formation of a dome as a result of expansion fiom heating, and introduction of melts in response to the upwardly moving mantle bulge. The dome eventually becomes gravitationally unstable and splits to form a rift. The extreme case of this process occurs at a mantle hot spot, with the formation of a triple junction with three separate rifts at angles of 120". Typically two of the rifts continue on to form active spreading centres and the third becomes a failed arm or aulacogen. These are called active rifts (Burke 1977).

2.2 The Structure of Rifts

Continental rifts only rarely form a simple graben structure but usually form in segmented crescentshaped half grabens, usually with alternating directions of polarity, thus giving the rift a sinuous trace along its length (Figure 1).

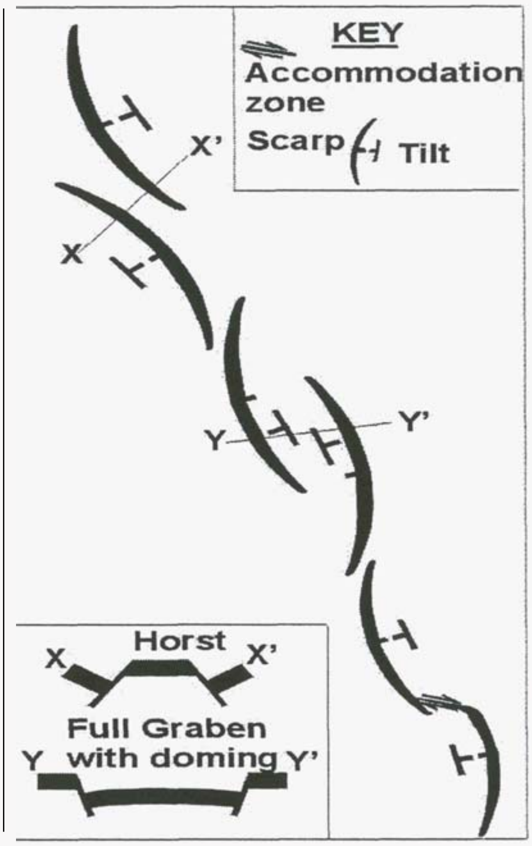

Figure 1: Diagram illustrating how half grabens make up a rift with the formation of horsts, full grabens and accommodation zones (not to scale).

This segmentation also provides allowance for the curve of the earth's crust such that cross cutting tensional structures are not common. Re-existing major basement structures may influence the geometry of the rift. There can be overlap between the half grabens. Where the overlap is back to back a horst is formed between the two half grabens, alternatively when the overlap is front to front a full graben is formed with updoming within the graben (Kusznir et al., 1995). Where half graben segments form with opposite polarities but with no overlap an accommodation zone in the form of a strike-slip fault can form between them.

Half grabens have a border fault system on one side and a ramping margin on the other (Figure 2). The movement on the border fault system is a combination of footwall uplift and gravitational sliding, the footwall uplift being produced by isostatic flexure (Kusznir et al., 1995). The gravitational sliding is not restricted to one fault surface but takes place on a series of parallel faults to produce a set of rider blocks that produce a border fault system rather than a single fault. The main deep fault is listric, decreasing in dip with depth. This main fault is not necessarily continuous along strike, but can be segmented with a relay ramp between segments, thus giving the half graben its curvature; further parallel faults can propagate from the relay ramps. As the rift forms it fills with a combination of mass-flow deposits from the rift scarps, lacustrine and fluviatile sediments, and any products of rift volcanism. The sedimentary units usually have a threefold stratigraphy (Katz, 1995). The basal unit is a fluvial deposit, which passes relatively abruptly into a generally deep-water lacustrine unit, which in turn is gradually replaced by shallow-water lacustrine and fluvial deposits. These will be intercalated with, and close to volcanic centres, completely replaced by, volcanic units.

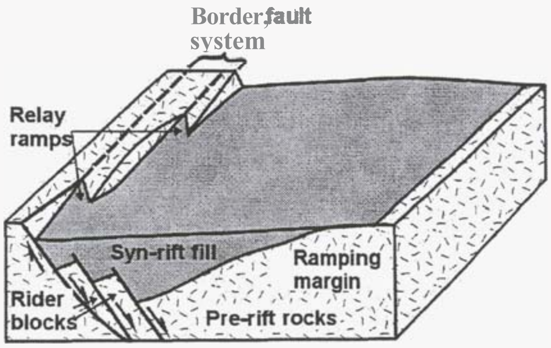

Figure 2: Block diagram indicating the features of a half graben rift (not to scale).

Volcanic centres can form associated with continental rifts. The volcanism is usually bimodal with basaltic compositions predominating over differentiates that include peralkalline rhyolites or trachytes. More silica undersaturated rock suites can be present and more rarely carbonatites and kimberlites can be found.

3. DEVELOPMENT OF GEOTHERMAL SYSTEMS IN RIFTS

Geothermal system development in continental rifts can vary according to the pre-rift geology. Where the pre-rift rocks are crystalline basement with low primary permeability they act to contain the system within the rift. If however pre-existing aquifers are present within the pre-rift rocks, these can play an active part in the system. They can provide deep recharge and where they are tilted and intersect border fault systems with the appropriate geometry they can form upflow zones, as has been modelled for the systems of the Basin and Range (McNitt, 1999). The following discussion is limited to the former situation where low permeability basement makes up the pre-rift rocks. As detailed above rifts can be divided into four structural settings: horsts, half grabens, accommodation zones and grabens. Horsts occupy the smallest portion of the rift and unless there is pre-rift permeability are unlikely to host geothermal systems because they lack vertical permeability. The half grabens that make up much of the length of a rift have a border fault system to provide vertical permeability. There can also be semi-parallel normal faulting within the rift basin. The listric nature of the main border fault limits the depth to which associated permeability can be expected as this is likely to decrease the flatter the fault dips, although providing there is lateral permeability, water within the fault could spread laterally into the rift fill.

There are however some impediments for forming an exploitable geothermal system in half graben settings. The first is that a lake may occupy the side closest to the scarp of the half graben and any associated geothermal system may not be easily accessible by drilling. The second is that possible continuation of faults propagating from relay ramps may mean that the border fault system is recharged from the high elevation scarp and the border fault system will mainly contain down-flowing cold waters. Thirdly unless perturbed by the presence of a volcanic centre the area of highest heat flow is in the centre of the rift (Morgan, 1982) above the area of thinnest crust not at the border fault system. Therefore for a significantly sized high temperature system to form requires that recharge down the border fault system moves laterally into the rift and is heated. This requires either significant continuous horizontal permeability or a volcanic centre with an associated shallow heat source in close proximity to the border fault system. Intra-rift lakes may also have potential as sources of recharge, but this may be limited by low permeability sediments accumulated at the lakes bottom.

If old lake sediments are present as rift fill these are also unlikely to be permeable and are likely to be in direct contact with the border fault system, blocking lateral movement of water. Deeper fluvial sediments may be more permeable but be in contact with the more shallow dipping parts of the main fault where it has less permeability. It is only if there is a lateral permeability in the form of cross cutting structures with a permeable volcanic pile and associated heat source in the immediate vicinity of the border fault system that a large hot system is likely to develop. If lateral permeability is not present a deep circulation system of limited size and temperature localised within the border fault system may form. However, such a system may have the potential for significant mass flow given the driving force of the hydraulic head between the top of the scarp and the floor of the rift. The presence of lacustrine sediments may also complicate geothermal exploration because they can be clay rich and produce a low resistivity signature that can be misinterpreted as representing a geothermal system.

Accommodation zones, because of their strike slip nature, have the potential to form pull-apart basins with potentially high permeability with a predictable orientation (Bogie, 2000). However, they are likely to be found only over a small part of a rift and are short in comparison to arc-parallel strike-slip faults, with proportionally less potential for bends to develop to form pull-apart basins. Otherwise they would be good sites for the development of a geothermal system.

Full grabens, formed by the overlap of two half grabens offer a good setting for the development of exploitable geothermal systems within rifts. This is because in addition to having two border fault systems to provide recharge, the dome that forms in the graben can deform to give a high density of parallel structures along the centre of the graben where the heat flow is highest. Cross-cutting structures are of considerable importance because they allow recharge waters potentially present within the border fault system to flow towards areas of highest heat flow nearer the centre of the graben, without being impeded by any low permeability rift fill. To form cross-cutting structures may require tectonic changes. These and the parallel rift faults can also provide vertical permeability in the centre of the graben, enhancing convection and allowing surface features to form. This general picture may be complicated by the distribution of volcanic centres within the graben. These do not always form in the exact centre of the graben and the presence of shallow magma chambers beneath them may provide localised areas of high heat flow. As in half grabens the presence of a volcanic pile and associated heat source close to the boundary fault systems will be advantageous in forming large hot systems.

4. CURRENT CONTINENTAL RIFTS

The global locations of currently active continental rifts are shown in Figure 3. The Lake Baikal rift (Keller et *al.*, 1995) and the Rhine Graben (Segnor et *al.*, 1978) are examples of impactogens forming in response to the orogens that have produced the Himalayas and the Alps respectively. Although they have associated hot springs, the lack of significant magmatic activity within the rifts makes it unlikely that they will have associated geothermal systems suitable for power generation, and this may possibly be a general feature of passive rifts.

The Basin and Range area of the western United States was initially a back arc basin. It was then further extended following the collision of the East Pacific rise with the subduction zone between the Farallon and North American plates that has converted the convergent margin to a transform along the San Andreas Fault (Atwater, 1970). There is much early volcanism associated with the

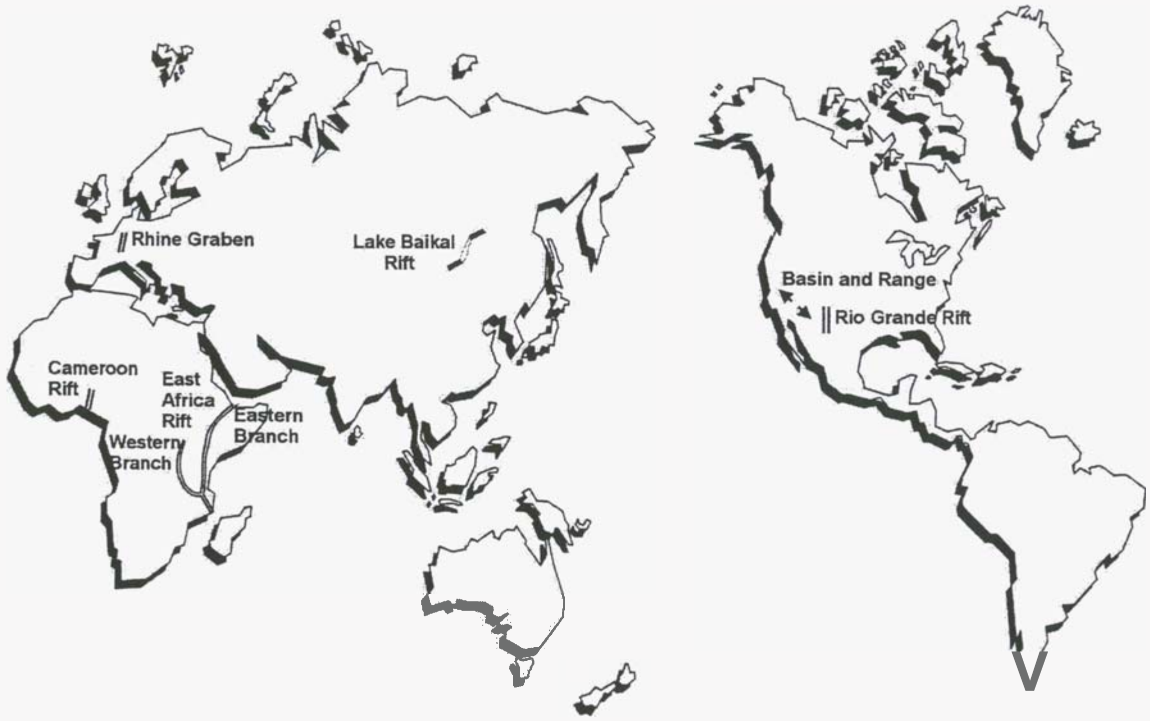

Figure 3: Current continental rifts of the earth.

formation of the Basin and Range, but more limited Recent volcanism. There is a close magmatic association with only three of 15 developed geothermal systems. This lack of close magmatic associations has been attributed to the presence of deep tilted aquifers in the pre-rift geological sequence. These provide deep recharge waters that are heated by the elevated geothermal gradient and upflow at suitable intersections with border fault systems (McNitt, 1995). Thus a close association with volcanic centres is not required.

The Rio Grande Rift has had significant associated magmatism and has current hot spring activity. Much of the geothermal activity there to date has been only utilised for direct use (Witcher, 1995). However, where the Jemez volcanic lineament (Keller et al., 1991) crosses the Rio Grande Rift's western border the Baca geothermal field, within the Valles caldera, is found. Successful high enthalpy wells have been drilled, but the field has not been developed (Nielson and Hulen, 1983).

The largest continental rifts on the earth are found in Africa. The Cameroon line of volcanoes related with the older Benue trough has associated active volcanism (Fitton, 1980) and warm springs, although it is best known for the Lake Nyos CO_2 eruption disaster (Kling et al., 1987). More active rifting occurs along the East African Rift. It has an Eastern and Western branch (Figure 3). Both are regarded as failed arms with the centre of the triple junction for the Eastern rift at the Afar hotspot with two actively spreading arms forming the Red Sea and the Gulf of Aden. The active rift arms of the Western branch are considered to have formed the Madagascar Strait. The Eastern branch is more volcanically active and the Western branch is more seismically active. The Eastern branch also has two major domes, the Ethiopian dome and the Kenyan dome. This may reflect strong hot spot activity associated with the great African plume (Kerr, 1999) and explain why it is so volcanically active. The greater amount of volcanic activity makes the Eastern branch the more interesting in terms of geothermal potential. The volcanic activity occurs both within the Eastern branch and along its flanks, the latter including the very large volcanic edifices of Mt. Kenya and Mt. Kilimanjaro. Numerous thermal areas are found along the rift, mostly associated with volcanic centres. Prospects have been drilled in Kenya, Ethiopia and Djibouti, with the Olkaria field in Kenya and Aluto Langano field in Ethiopia developed. The hot springs along the Western branch are less commonly associated with volcanic centres. The Songwe River prospect in Tanzania, in a volcanic centre where the Eastern and Western Branches intersect, is considered to be the best geothermal prospect associated with the Western branch (Hochstein, 2000).

The most studied part of the Eastern Branch is that which runs through Kenya (Smith and Mosely, 1993; MacDonald et al., 1994). It is divided into three segments, with the northern Turkana segment a series of half grabens underlain by the Proterozoic Mozambique mobile belt. The central segment is a full graben underlain by the boundary between the mobile belt and the Archean Tanzanian craton and the southern segment is an east facing half graben underlain by the craton. The segmentation is considered to be a result of this change in basement geology, as is the style of volcanism. Silica-undersaturated magmatism of the carbonatite-kimberlite-nephelinite association occurs where there is cratonic crust. Mildly alkali basalt-trachyte-peralkalline rhyolite magmatism dominates in areas of thinned crust to the north. In between both are found. This may have some effect upon the potential for the development of exploitable geothermal systems in that shallow magma chambers suitable as heat sources are likely to better developed where rocks of the alkali basalt-trachyte-peralkalline association form differentiated series.

There was a major tectonic change in East Africa approximately 100, 000 years ago. Changes in the rift geometry of the Red Sea changed the least principal stress from an east-west orientation to a northwest orientation (Smith and Mosely, 1993). As a consequence, the north-south faults of the rift now have a combined normal and oblique slip movement, depending upon their proximity to northwest fractures. Northwest striking basement faults have been reactivated as strike slip faults, northeast to east striking faults have been produced as tensional features and calderas formed after 100, 000 years are elliptical, with the long axis striking to the northwest (Boswell et al., 2000).

In terms of permeability at depth the northeast to east striking tensional features are of the most interest. They will mainly be produced in association with the northwest strike-slip faults, rather than being reactivated basement faults as there are few faults of this orientation mapped in the basement (MacDonald et *al.*, 1994). These features can be seen at the Olkaria field (Omenda, 1998), north-west striking faults and a northwest orientated ring fracture are mapped. The ENE striking Olkaria fault, a major locus for geothermal production can be interpreted as a tensional feature produced in response to reactivated movement on north-west strike-slip faults. A predictive model for other good geothermal prospects in the East African Rift, where the rift has a general north-south trend, can be established on this basis. Good geothermal prospects should be above the mobile belt or the transition zone towards the craton but not on the craton itself. They should be associated with a volcanic centre with differentiated volcanics that is intersected by a reactivated NW basement fault. Geothermal prospects that met these criteria are Olkaria, possibly southern Longonot, Eburru and Emuruangogolak (Figure 4). The Arus-Bogoria prospect fits the structural criteria but does not have an associated differentiated volcanic centre.

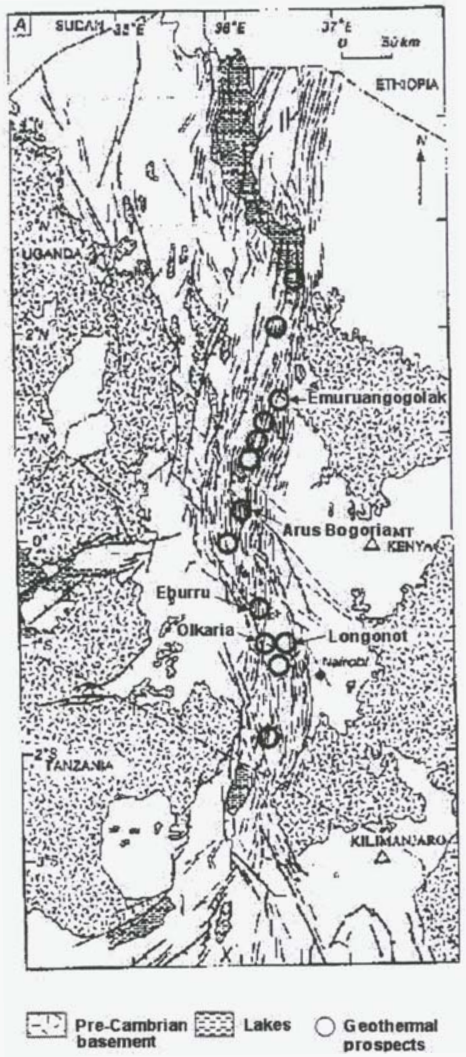

Figure 4: Geothermal prospects in Kenya. Geological base map from Smith and Mosely (1993), prospect locations from Omenda (2001).

5. TARGETING PERMEABILITY AT DEPTH

As can be seen from the proceeding discussion, there is significant local variation between continental rifts, and therefore strategies for targeting permeability at depth must also be locally specific. In the Basin and Range and possibly the Rio Grande Rift pre-rift rocks are important hosts of geothermal systems, and prime targets are the intersection of border fault systems and aquifers in the pre-rift rocks.

In the Kenya section of the East African Rift, strike-slip faulting is now important and the principles discussed for targeting permeability related to strike-slip faulting (Bogie, 2000) can be applied. These are to target associated tensional faults in a manner that obtains the greatest possible length of intersection of the well and the fault. If crosscutting strike-slip faults are absent the main targets at depth will be rift parallel normal faults which should be drilled in a manner that maximizes intersection with the fault as discussed by Bogie (2000).

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