Magma chamber elongation as an indicator of intraplate stress field orientation: "borehole breakout mechanism" and examples from the Late Pleistocene to Recent Kenya Rift Valley

William Bosworth, Gebel el Zeit Petroleum Company, el Maadi, Egypt

Kevin Burke, Department of Geology, University of Houston, Houston, TX, USA

Manfred Strecker, Department of Geology, Universität Potsdam, Potsdam, Germany

Table of contents

Bosworth, W., Burke, K. and Strecker, M. 2000. Magma chamber elongation as an indicator of intraplate stress field orientation: "borehole break-out mechanism" and examples from the Late Pleistocene to Recent Kenya Rift Valley. In: Stress, Strain and Structure, A volume in honour of W D. Means. Eds: M.W. Jessell and J.L.Urai. Volume 2, Journal of the Virtual Explorer. ISSN 1441-8126 (Print). ISSN 1441-8134 (CD-ROM). ISSN 1441-8126 (On-line at www.virtualexplorer.com.au/VEjournal/Volume2).

Abstract

Quaternary volcanism and faulting in the Kenya rift valley are focused in a narrow zone along the rift axis. Beginning ~1 Ma, large trachytic volcanoes were built within an E-W to ENE-WSW extensional stress field. Volcanic fissures and associated pyroclastic cones were aligned ~N-S, parallel to the maximum horizontal stress (**S_{Hmax}**). Mt. Suswa, a large volcano located ~1°S latitude, collapsed sometime between 240 and 100 ka, and the resultant caldera is elongate N83°E, parallel to the minimum horizontal stress (**S_{hmin}**). At the time of Suswa’s collapse, or shortly thereafter, the regional stress field rotated 45° in a clockwise direction. After ~100 ka, the trachytic volcanoes in the northern rift also began large-scale caldera collapse. The calderas of Kakorinya, Silali, Emuruangogolak and Paka formed at about 92, 64, 38 and 10 ka, respectively (Dunkley et al., 1993). The calderas of these volcanoes are oriented N75°W, N58°W, N56°W and N55°W, progressively rotating toward parallelism with the new N45°W **S_{hmin}**. Likewise, some of the youngest fissures and trains of small-scale cones on the flanks of the northern volcanoes are aligned NE-SW, parallel to **S_{Hmax}**.

We suggest that the magma chambers beneath each of the trachytic volcanoes grew to an elliptical shape by stress-induced spalling of the chamber walls, analogous to the formation of breakouts in boreholes and tunnels. The caldera long axes therefore represent the time-averaged shallow crustal **S_{hmin}** direction during the life of the underlying magma chambers. The actual collapse of the calderas, beginning with Suswa, may have been triggered by the sudden rotation of the stress field, which formed new fracture systems and increased the ease with which magmas could be ejected from flank eruptive centers or fissures. The link between stress field rotation and catastrophic caldera collapse may have implications for geologic risk assessment in the East African rift and other volcanically active areas.

Introduction

One of the most impressive geologic features of the Kenya rift valley is the occurrence of young, often large volcanic centers along its axis (Fig. 1). These are low-angle, multi-vent shield volcanoes composed principally of trachytic and basaltic lavas and pyroclastic deposits (McCall, 1968; Williams et al., 1984; MacDonald, 1987). The larger volcanoes, including Suswa, Paka, Silali, and Emuruangogolak, rise 700-1100 m above the rift valley floor (Randel and Johnson, 1991; Dunkley et al., 1993). Construction of the volcanoes began at less than 2 Ma, with most volcanism younger than ~1 Ma. Slightly before and simultaneous with the building of the large axial volcanoes, the inner rift valley experienced focused subsidence and intense faulting (Baker and Mitchell, 1976; Baker et al., 1978; Dunkley et al., 1993). Most of these faults are parallel to the rift margins, which vary in strike from NNW to NNE. The faults are spatially associated with eruptive fissures, lava domes and pyroclastic cones, reflecting complex interaction between upward movement of lava and structural weaknesses in older rocks. Starting in the Late Pleistocene, and particularly after about 100 ka, the inner rift entered a distinctly different phase of its volcanic history. The most dramatic occurrence of this latest period was the catastrophic collapse of many of the axial volcanoes, producing large, nearly vertically-walled calderas (Fig. 2). This was accompanied by the eruption of large volumes of ring-fracture lavas and pyroclastic material from smaller vents on the flanks of the volcanoes.

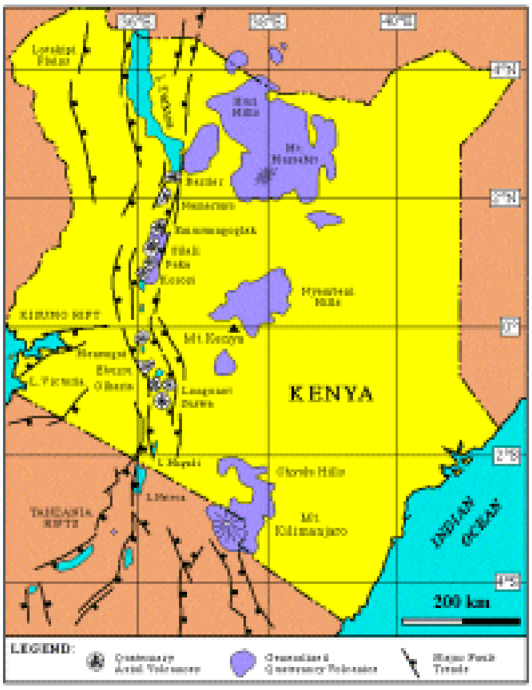

Figure 1. Kenya rift valley and location of Quaternary volcanism (after Baker et al., 1972; Dunkley et al., 1993). Quaternary volcanic activity has been focused along the inner trough of the rift at large volcanic centers (labeled) and at three broad volcanic piles east of the fault-defined rift.

Figure 2. Aerial photograph of the southern rim of the giant collapse caldera at Silali volcano. The caldera measures 5.1 x 7.7 km, with a N58°W trending long axis. The southern caldera wall rises 340 m above the caldera floor.

In general, the Kenya rift valley developed in response to east-west tensional stresses during the late Neogene (Strecker et al., 1990). The present-day minimum horizontal stress (**S_{hmin}**), however, is now oriented NW-SE over most of Kenya (Bosworth et al., 1992). The period of rift valley caldera collapse occurred within a time of rapidly changing shallow crustal stress fields, perhaps indicating a genetic relationship (Bosworth et al., 1996). It is possible that stress fields could also have played a role in triggering the formation of collapse calderas in other continental rifts or in other tectonic regimes. One of the characteristics of several of the Kenya calderas is an elongation in plan view (McCall, 1968). We interpret caldera elongation as a reflection of an elliptical shape in the underlying magma chamber, and will show that the axis of elongation was parallel to the operative **S_{hmin}** as determined from independent stress-field indicators. We therefore suggest that caldera ellipticity was stress-induced, and not controlled by the orientation of pre-existing faults. If this correlation is correct, then the shape of calderas from other geologic settings may be useful as indicators of paleo-stress field orientation.

We will begin with a brief review of the Quaternary volcanic and structural evolution of the Kenya rift valley axis, and then correlate this with temporal changes in the shallow crustal stress field. In conclusion we will propose a mechanical model for caldera elongation that is based on the well-known analysis of a cylindrical hole in an elastic material.

Volcanic and Structural Setting of the Rift Valley Floor

The Neogene Kenya rift was preceded by a period of extension in the Oligocene that is best documented in the north, in a broad area that extends from Lake Turkana west to the Lotikipi Plain (Fig. 1; Morley et al., 1992). Reflection seismic data suggest that an older rift, perhaps an arm of this Oligocene rift complex, underlies the Kenya rift valley at least as far south as the region of the Lake Baringo basin (Mugisha et al., 1997). Volcanism associated with the Oligocene rifting began at about 33 Ma, and continued sporadically in time and space to the present (Zanettin et al., 1983; Morley et al., 1992). Initial extension is interpreted to have begun shortly after the onset of volcanism. In a general sense, both volcanism and structuring in the northern rift shifted to the east through time, and became focused along the position of the modern rift valley by the Middle to Late Miocene (Cerling and Powers, 1977; Morley et al., 1992; Bosworth and Maurin, 1993). This culminated with subsidence of the inner rift trough and the development of closely spaced "grid faults" along much of the rift axis starting at about 2 Ma (Baker, 1958; Baker and Mitchell, 1976; Chapman et al., 1978; Baker et al., 1978, 1988; Dunkley et al., 1993).

After formation of the inner rift trough, large areas were flooded with basalt and trachyphonolite lavas, and pyroclastics with associated trachyte lavas were erupted locally as at Chepchuk (northeast of Lake Baringo) and at Likaiu on the Barrier (south end of Lake Turkana) (Fig. 3; Dodson, 1963; Hackman, 1988; Dunkley et al., 1993). During the Late Pleistocene, starting about 1 Ma, numerous axial shield volcanoes were constructed within the inner trough, establishing the present-day geomorphologic character of the rift.

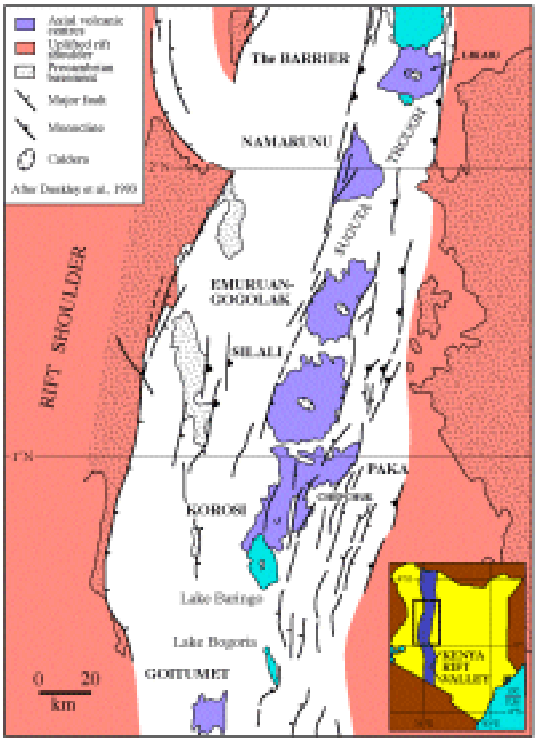

Figure 3. Major faulting and location of axial volcanoes in the northern Kenya rift. After Dunkley et al., 1993.

Caldera Collapse

Most of the Kenya rift axial volcanoes have lost large areas of their summits due to formation of calderas (Fig. 1). Two of the largest calderas are south of the equator at Suswa and Menengai, with areas of approximately 20 and 80 km^2, respectively (McCall, 1968; Williams, 1978; Randel and Johnson, 1991). North of the equator (Figs. 1,3), calderas are the size of Suswa or smaller, but due to less rainfall the details of the volcanically- and structurally-controlled topography are better preserved. Recent detailed structural mapping and geochronologic studies in the north have also established better constraints on the timing of caldera formation, and provided data for interpretation of Pleistocene stress fields (Dunkley et al., 1993).

<u>Northern Volcanoes</u>

The fault patterns, eruptive centers, and ring fractures in the vicinity of Emuruangogolak and Silali illustrate many of the relationships common to the axial volcanoes (Figs. 3,4). Trachyte shield construction at Emuruangogolak began ~1 Ma, followed by a major period of faulting (Dunkley et al., 1993). Trachytic pyroclastic activity and eruption of basalts started at ~200 ka and continued to within the last few hundred years. Caldera collapse occurred between 38±6 ka and 27±5 ka (Dunkley et al., 1993). The caldera is 3.5 x 5.0 km, with a N56°W trending long axis (Fig. 4a). Cause of the caldera collapse has been attributed to withdrawal of the Enababa trachyte lavas (38±3 ka; Ar-Ar) from a high-level magma chamber beneath the summit (Dunkley et al., 1993).

The oldest shield trachytes exposed at Silali are ~225 ka (Dunkley et al., 1993). As at Emuruangogolak, initial construction of the trachyte shield was followed by faulting, pyroclastic deposition, and onset of basaltic volcanism. Caldera collapse occurred between 64±2 ka and 7±3 ka (Dunkley et al., 1993). Dunkley et al. (1993) interpreted the collapse to have formed due to a piston-like movement, triggered by magma withdrawal and lateral dyke injection, resulting in very regular, vertical walls that reach 340 m height (Fig. 2). The caldera measures 5.1 x 7.7 km, elongate in a N58°W direction. Most fissures, faults and volcanic cones are aligned N-S to N10°E, parallel to the rift margins (Fig. 4b). However, a well-developed NE trend is also locally present and is discussed below.

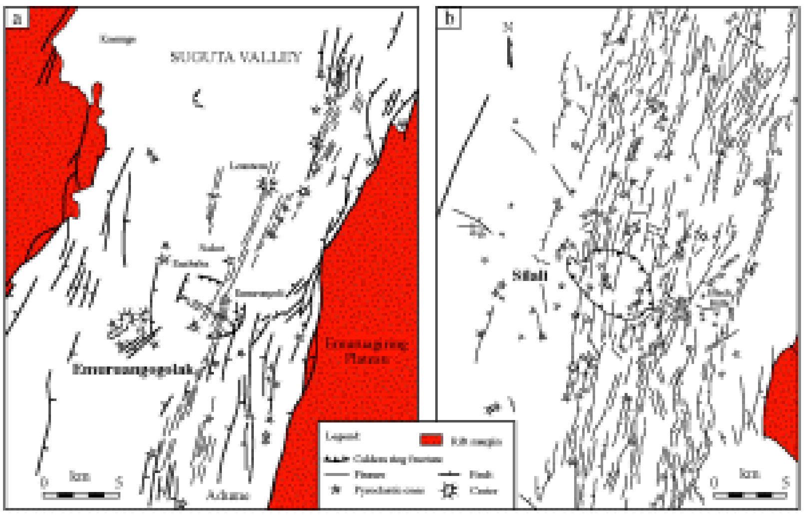

Figure 4. Faults and volcanic structures of Emuruangogolak and Silali volcanoes. After Dunkley et al., 1993. Alignments of pyroclastic cones and small craters have two general trends: 1) parallel to main extensional faults (N-S to NNE-SSW), and 2) NE-SW (less frequent, and found generally in youngest flows).

Timing for the formation of other calderas in the northern rift valley is broadly similar to that of Silali and Emuruangogolak. The slightly elongate N75°W oriented Kakorinya caldera on the Barrier at the south end of Lake Turkana (Fig. 3) formed between 92±2 ka and 58±4 ka, and the caldera at Paka at ~10 ka. (Dunkley et al., 1993). Although the Paka caldera is circular and only about 1.5 km in diameter, it lies along a N55°W trending, fault-bounded ridge together with several smaller craters (Fig. 5). The overall structure of the summit is therefore elongate in an orientation similar to that of the other northern calderas.

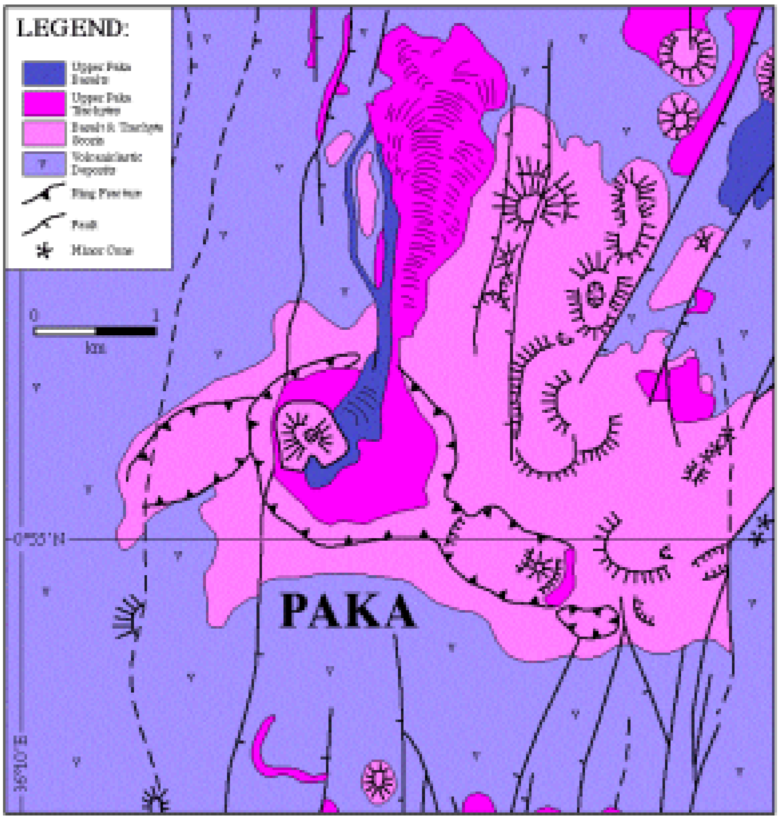

Figure 5. Faults and volcanic structures of Paka volcano. After Dunkley et al., 1993.

<u>Southern Volcanoes</u>

The timing of volcanicity and structuring at Suswa and Menengai is not as tightly constrained as that of the northern volcanoes due to the existence of fewer radiometric age dates. Based on Kenya Topographic Survey maps, the caldera at Menengai is about 7.8 x 12.8 km, elongate parallel to N47°E. McCall (1957) used correlation of ash deposits to interpret that this, the largest caldera in Kenya, formed piecemeal, at about 10 ka or less. More recently, McCall (1968) stated the age of formation to be "probably Upper (Late) Pleistocene." Due to the uncertainties in its age of formation, and our lack of more detailed structural data, we cannot presently include Menengai in our discussion of rift axis caldera and stress field evolution.

Suswa, the most southern of the large caldera-bearing volcanoes, experienced one of the most complicated documented histories of the axial volcanoes (Randel and Johnson, 1991). The main collapse caldera of this cone measures approximately 4.8 x 5.4 km, elongate along a N83°E (N97°W) axis (Fig. 6). Caldera collapse is now known to have pre-dated those of the northern volcanoes. Due to the marked dissimilarity in orientation to the calderas of the northern volcanoes, a brief discussion of Suswa will be important in our attempt to relate volcanic structure to stress field orientation.

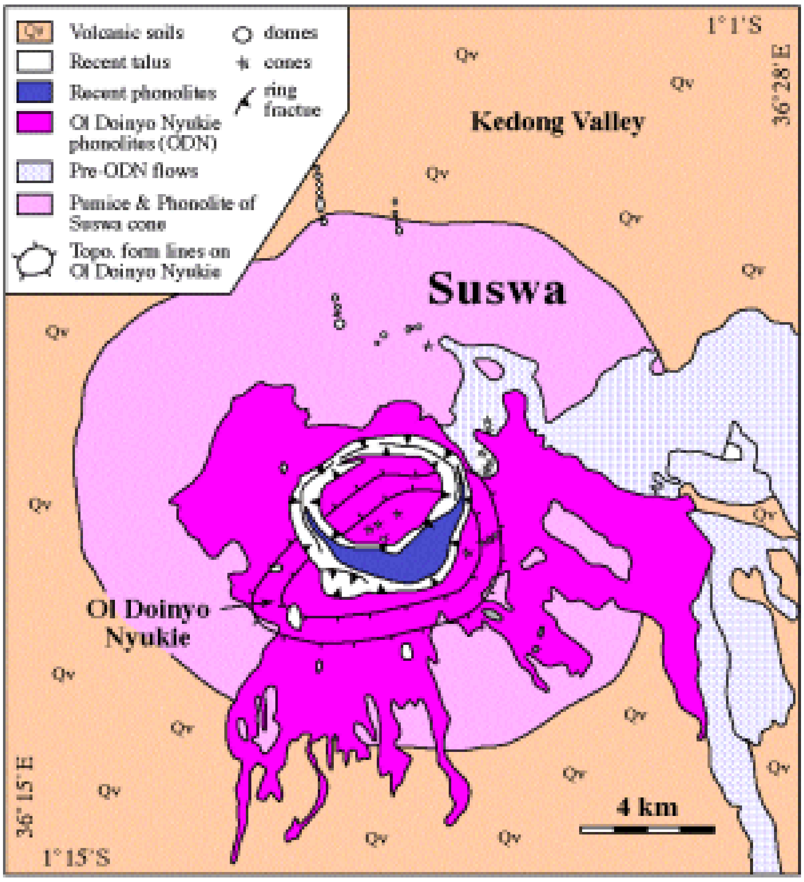

Figure 6. Surface geology of the southern volcano Suswa. Ol Doinyo Nyukie (topographic form shown by lines with small ticks) is a smaller cone built after the initial caldera collapse, which is slightly elongate in a NNE-SSW direction. The Suswa caldera is older than the summit calderas of Emuruangogolak, Silali and Paka shown in Figures 4 and 5.

The main shield of Suswa is composed of trachytes and phonolites that have been dated as 240±10 ka by Baker et al. (1988; Sample KSS-10, K-Ar). Caldera collapse was marked by the eruption of extensive pyroclastics and ring-fracture lavas (Randel and Johnson, 1991). These units are presently undated. Following the formation of the main caldera, additional volcanism occurred within the summit region of the volcano, focused at a new cone, Ol Doinyo Nyukie, located on the southwest rim of the caldera (Fig. 6). Two samples from this Ol Doinyo Nyukie eruptive phase both yielded ages of 100±10 ka (Baker et al., 1988; Samples KSS-18 and KSS-30; K-Ar). Following the formation of Ol Doinyo Nyukie, a second major collapse event occurred, producing an intra-caldera "ring graben", but was not associated with eruption of pyroclastics or lavas (McCall, 1963; Randel and Johnson, 1991). A very recent, minor lava flow was later extruded within the caldera, partially filling the southern part of the ring graben, and a minor fissure-eruption occurred on the south flank of the volcano.

The formation of the main (outer) Suswa caldera is therefore bracketed to have occurred between 240 and 100 ka. Despite this relative imprecision in timing of formation, the ENE-WSW oriented Suswa caldera is clearly older than any of the NW-SE elongate calderas in the north.

Previous Section Home Next Section

Stress Field History

Rows of small vents, cones, domes and collapse pits are common in volcanic terranes. These features are thought to form above feeder dikes. Although dike orientation can be influenced by the orientation of pre-existing faults and other structures, in general the strongest control on dike orientation is the country rock stress field, with intrusion perpendicular to the least principal stress (Nakamura, 1977; Delaney et al., 1986). The surface vents are therefore generally aligned parallel to the local maximum horizontal stress direction ($\mathbf{S_{Hmax}}$). The rift-parallel volcanic vent and fissure alignments in the vicinity of the axial volcanoes suggest that during most of the Pleistocene, the minimum horizontal stress direction ($\mathbf{S_{hmin}}$) was oriented approximately E-W. For example, small cones and domes on the northern flank of Suswa that pre-date caldera collapse are generally aligned parallel to N7°W (Fig. 6). A large number of pyroclastic and lava cone alignments are present in the region of Silali, with an average orientation of N10°E (Fig. 4b). Fault kinematic data from the central rift in the area of the Kinangop Plateau (east of Menengai, Fig. 1) support the volcano-tectonic interpretation of E-W extension during the Late Pliocene to Early Pleistocene (Strecker et al., 1990).

Borehole breakout data are available for several hydrocarbon exploration wells in eastern Kenya and their interpretation suggest that the present-day $\mathbf{S_{hmin}}$ is aligned NW-SE (Bosworth et al., 1992). Vents in the large volcanic shields east of the rift valley at the Huri Hills, Mt. Marsabit, and Nyambeni Hills (Fig. 1) are predominantly aligned NE-SW, also indicating NW-SE $\mathbf{S_{hmin}}$. Uppermost basalts at Mt. Marsabit and the Huri shield have been dated ~500 ka and younger (Brotzu et al., 1984; Key, 1987; Charsley, 1987), demonstrating that this NW-SE $\mathbf{S_{hmin}}$ is a very young stress field orientation. In the region of the eastern border fault of the central Kenya rift, faulting dated at less than ~500 ka yields a similar NW-SE extension direction (Strecker et al., 1990).

At Suswa, small cones in the Ol Doinyo Nyukie phonolites (circa 100 ka; see above), which post-date caldera collapse, are aligned N60°E (Fig. 6). East of Silali caldera, in the Black Hills, very young trachyte lavas (10±2 ka and 4±2 ka; Ar-Ar; Dunkley et al., 1993) display two fissure and cone alignment trends, one N-S to N20°E and the other N50°E (Fig. 4b). The presence of N50°E to N60°E volcanic alignments in the youngest units of the rift axial volcanoes supports the interpretation that a new stress field has manifest itself within the rift valley axis. This places the WNW-ESE to NW-SE trending long axes of the northern axial calderas sub-parallel to $\mathbf{S_{hmin}}$ of this new stress field. As argued by Dunkley et al. (1993), large magma chambers probably existed beneath some or all of the volcano summits prior to caldera collapse. Subjected to non-hydrostatic stress, these chambers would experience variation in shear stress around their walls, and might behave analogously to a tunnel or well-bore under similar circumstances. As discussed below, pieces of the chamber wall are envisioned to spall off to produce a large-scale "borehole breakout" and elongate the chamber in a direction parallel to $\mathbf{S_{hmin}}$. This interpretation would indicate that the NW-SE $\mathbf{S_{hmin}}$ was in effect along the rift axis during the past 100 ka, the period of collapse of the northern volcanoes.

The Late Pleistocene rotation of stress fields was not confined to the vicinity of Kenya. In the northern Red Sea and Gulf of Suez, the regional extension direction shifted from N55°E to N15°E sometime prior to the onset of the Eemian interglacial (circa 125 ka; Bosworth and Taviani, 1996; Bosworth and Strecker, 1997). Although the sense of rotation is opposite, we interpret that these stress field rotations from widely different segments of the Afro-Arabian

Rift System are genetically related and reflect a plate-scale change in continental crustal dynamics.

Previous Section Home Next Section

Home

Magma Chamber Elongation and Caldera Collapse Mechanisms

The state of stress in the wall rock adjacent to a magma chamber will depend upon the pressure of the magma fluid, the actual shape of the chamber, the depth below the surface and density of the overlying rock burden, fluids that may be present within fractures or pore space of the wall rock, and any applied far-field stresses. If, however, the geometry of the magma chamber can be approximated as a fluid-filled cylinder, and assuming the country rock to be elastic, isotropic and infinite, then an exact solution exists for the radial and tangential stresses around the chamber. This is a form of the circular hole problem, considered by Jaeger and Cook (1969) to be "perhaps the most important problem in rock mechanics." It is critical to understanding the stability and failure of tunnels and boreholes. In structural geology, application of the analysis of the distortion of stress fields around circular holes has been applied to problems of solution transfer and "pressure solution" in experimental (Sprunt and Nur, 1977; Bosworth, 1981) and naturally deformed (Engelder, 1982) solid-fluid systems. Failure around vertical boreholes, known as borehole breakouts, has also proven to be one of the most useful indicators of the orientation of the present-day maximum and minimum horizontal stress directions in the shallow crust. In the compilation provided by the World Stress Project (Zoback, 1992; Zoback et al., 1992), 28% of the reliable stress field indicators were from analysis of borehole breakouts.

The recognition of breakouts in wellbores was first made by Cox (1970), and documented by Babcock (1978). Bell and Gough soon interpreted the formation of borehole breakouts as a stress-related phenomenon, and the application of this concept to basin analysis and determination of in-situ stresses was quickly developed in North America (Bell and Gough, 1979, 1982; Gough and Bell, 1981, 1982; Plumb and Hickman, 1985; Zoback et al., 1985; Bell and Babcock, 1986) and Europe (Blümling et al., 1983; Brereton and Müller, 1991). Breakouts take the form of an elongation of the borehole cross-section. They are detected by the use of borehole geometry tools, including 4- and 6-arm dipmeter-calipers, and various electric and sonic formation imaging tools. In practice, breakouts must be differentiated from washouts and drill-pipe wear of the wellbore, which are not stress-induced but also cause departures from hole circularity.

The simplest circular hole case to consider is one in which uniaxial compression of magnitude σ_1 is applied at infinity, perpendicular to the axis of the hole in a radial direction $\theta = 0°$ (Fig. 7a,b). In this case, the tangential stress around the hole will vary from $3\sigma_1$, at $\theta = 90°$, to $-\sigma_1$, at $\theta = 0°$ (Kirsch, 1898; Hubbert and Willis, 1957; Jaeger and Cook, 1969). If a far-field stress σ_2 also exists in the direction $\theta = 90°$, then the tangential stresses become $3\sigma_1-\sigma_2$ and $3\sigma_2-\sigma_1$, at $\theta = 90°$ and $\theta = 0°$, respectively. For many engineering problems, such as an air-filled vertical shaft, these solutions are appropriate. However, in geological examples, the hole is generally filled with a fluid, such as magma or drilling mud, at a pressure p. In this case the tangential stress will vary from $3\sigma_1-\sigma_2-p$ to $3\sigma_2-\sigma_1-p$, with the radial stress at a constant value equal to p. Two modes of failure are possible under these conditions. If $p>3\sigma_2-\sigma_1$, then tensile stresses exist at $\theta = 0°$. If the tensile strength of the hole wall material is exceeded, then a fracture will propagate away from the hole in a direction parallel to σ_1 (hydraulic fracturing; Fig. 7c). In the region of $\theta = 90°$, shear stresses will be at their maximum, and the wall material can undergo compressive shear failure. Detailed ultrasonic televiewer observations in wellbores indicate that the region of failure, or "breakout" (Fig. 7d), is rather broad and flat-bottomed, producing a hole cross-section that is approximately elliptical at its advanced stages of development (Zoback et al., 1985; Hickman et al., 1985). Borehole breakouts are equally common in regions of tectonic shortening, extension and strike-slip faulting.

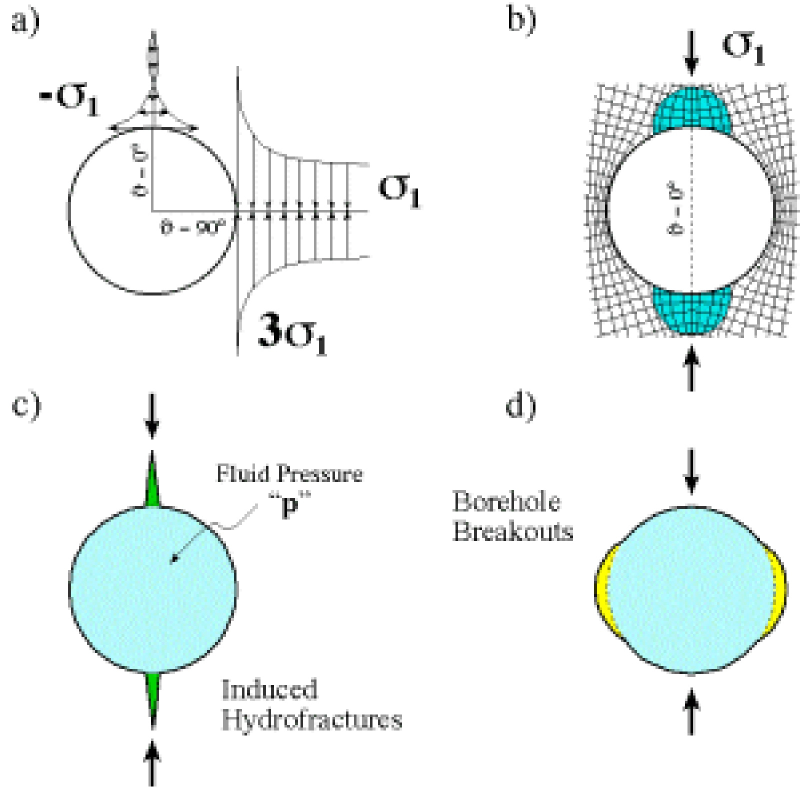

Figure 7. a) State of stress around a fluid-filled cylindrical hole within an infinite, isotropic solid, subjected to far-field uniaxial compression of magnitude σ_1, parallel to $\vartheta = 0°$ (for simplicity, shown with fluid pressure p = 0), b) stress trajectories and region of tensile stress (shaded) for same geometry. Two kinds of failure may occur: c) if the fluid pressure p becomes high enough, the tensile strength of the material will be exceeded and hydrofractures parallel to σ_1 will be induced, d) when p is kept low and σ_1 is increased, the shear strength of the material (in our case a magma chamber wall) will be exceeded, causing spalling that produces a cross-section elongate perpendicular to σ_1. Figure a after Engelder (1982); Figure b after Jaeger and Cook (1969).

The initial intrusion of magma into the earth's crust is, essentially, a large-scale hydrofracturing phenomenon (e.g., Fink and Pollard, 1983). Shallow crustal magma chambers are probably generally emplaced via large-scale dikes or dike swarms. However, many volcanoes are roughly circular in form, and they are capped by summit craters that are also commonly circular. Eroded volcanoes often reveal roughly cylindrical stocks beneath their centers. These lines of evidence suggest that after initial emplacement, the main magma chambers beneath volcanoes evolve into rather equi-axed, or nearly cylindrical bodies, probably by melting and assimilation of adjacent country rock and previously extruded volcanic material. Periodically, as new magmas are forced into an existing chamber, induced hydrofracturing of the adjoining country rock may occur, contributing to flank fissure eruptions or the formation of additional volcanic cones. Whenever the pressure in the magma chamber drops, however, it is more likely that failure of the chamber walls will occur by compressive shear fracturing adjacent to the $\mathbf{S_{hmin}}$ direction. This large-scale breakout process should produce an elliptical cross-section. If the volcano collapses due to the rapid withdrawal of magma, then the resulting caldera should also be elliptical, with its long axis parallel to the regional $\mathbf{S_{hmin}}$. The calderas of Emuruangogolak and Silali have shapes very similar to those reported for borehole breakouts, and this can be attributed to the effects of the Late Pleistocene to Recent stress field that existed in the vicinity of the Kenya rift valley.

Dunkley et al. (1993) have shown that there is little evidence for the existence of older calderas in the northern Kenya rift, and that the post-92 ka calderas in the north, and the slightly older calderas in the south, are a unique feature in the evolution of the rift. This is also the situation in the Ethiopia rift valley, where large calderas are generally confined to silicic volcanoes of the very young, roughly axial Wonji fault belt (Mohr and Wood, 1976). However, large magma chambers should have been present within the axial rift valley at other times in the past. We have suggested that the onset of caldera collapse was triggered by the regional change in stress field (Bosworth et al., 1996). During the early development of the shield volcanoes (~1 Ma to ~200 ka), with S_{hmin} oriented E-W to ENE-WSW, existing rift-parallel fractures were ideally oriented to facilitate lava movement (Fig. 8a). Suswa’s magma chamber was intruded during this time, began to deflate (hence entering into chamber wall compressive failure), and became elongate approximately N83°E. Definitively after ~500 ka, and most probably at 150-125 ka, the regional stress field began to rotate in a clockwise direction, but did not produce immediately visible effects in the volcanic structure of the rift axis (Fig. 8b). The younger (or longer-lived) northern magma chambers, however, began to elongate progressively more toward the NW-SE. The new stress field also favored the formation of NE-SW aligned extension fractures, and reactivated rift-parallel fractures and faults as dextral strike-slip faults (Strecker and Bosworth, 1991). The combination of better fracture interconnectivity plus strike-slip fault movement eventually triggered catastrophic removal of lava from beneath the northern summits, starting at Kakorinya sometime after 92 ka (Fig. 8c).

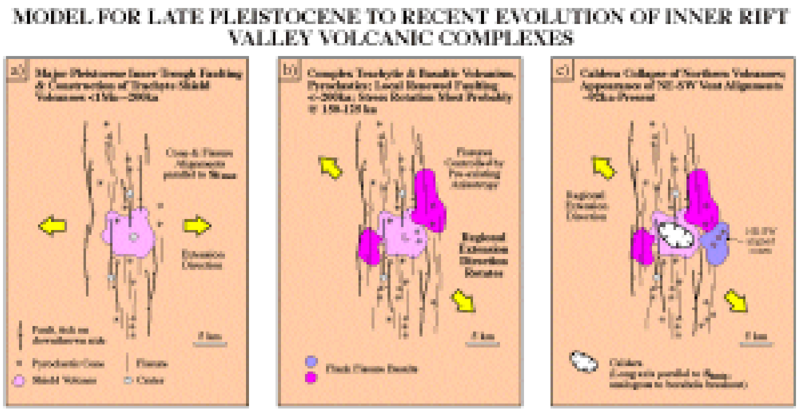

Figure 8. Proposed interaction between Pleistocene regional stress fields and the volcanic evolution of axial shield volcanoes in the northern Kenyan rift valley. Caldera collapse (elongate NW-SE, parallel to S_{hmin}) and development of NE-SW volcanic lineaments (parallel to S_{Hmax}) were caused by ~45° counterclockwise rotation of the regional stress field sometime at about 200-100 ka.

The temporal correlations between volcanism, structuring and stress field orientations are summarized in Figure 9. Kakorinya is elongate parallel to N75°W. The younger calderas at Silali (<64 ka), Emuruangogolak (<38 ka) and Paka (~10 ka) display elongation directions of N58°E to N55°E. The progressive change in caldera orientation, from Suswa to Paka, has followed, with some lag time, the counterclockwise rotation of the regional S_{hmin} direction.

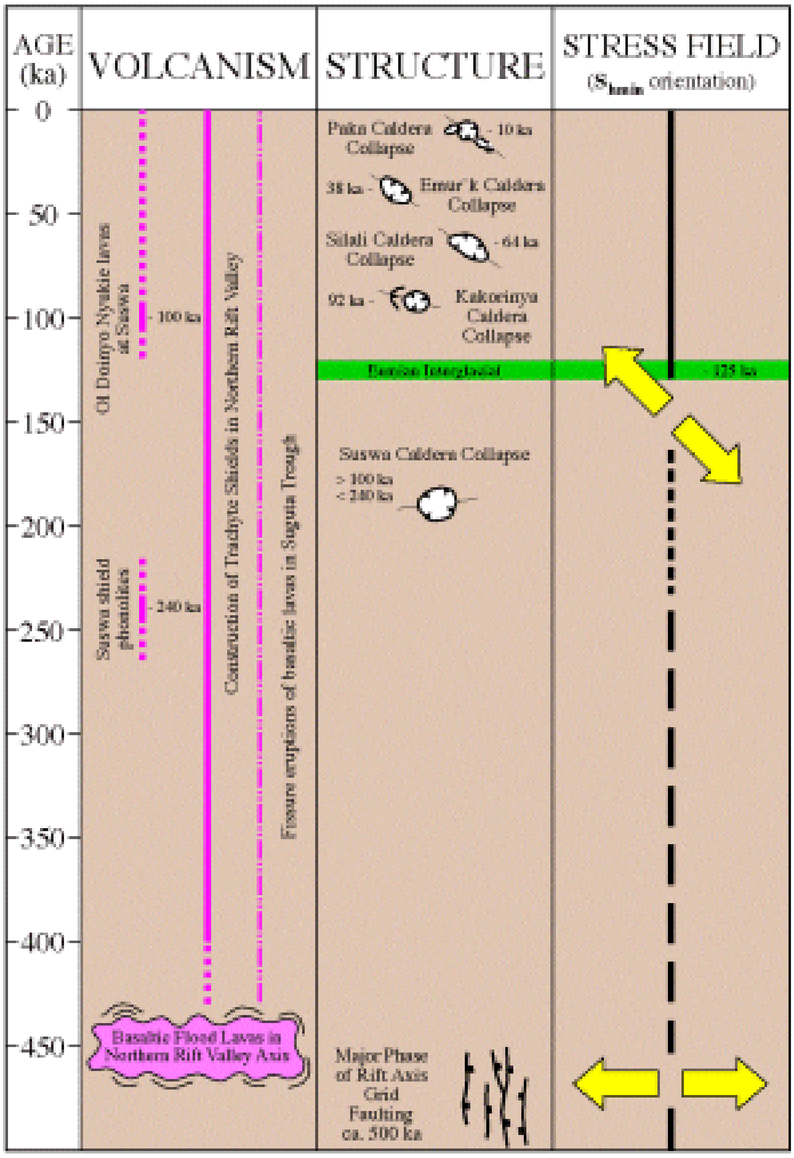

Figure 9. Summary of the timing of volcanic activity, structuring, and stress field evolution in the Kenya rift valley axis. "Eemian interglacial" at ~125 ka marks the minimum age for the establishment of the new Late Pleistocene stress field in the northern Red Sea/Gulf of Suez section of the Afro-Arabian rift system and is shown for comparison with the timing of events in Kenya. Sources of data are given in the text.

Previous Section Home Next Section

Discussion and Conclusions

Our comparison of the Quaternary stress field history and volcanologic evolution of the inner Kenya rift valley suggests that rotation of the regional $\mathbf{S_{hmin}}$ direction, and possibly changes in its magnitude, contributed to the rapid withdrawal of magmas from beneath active volcanoes, and the violent eruption of these magmas from volcanic flanks. This produced large collapse calderas that are sub-parallel to the Late Pleistocene NW-SE $\mathbf{S_{hmin}}$ orientation. We interpret that the caldera elongation reflects a similar shape in the underlying magma chamber, which in turn represents a mechanical response to the presence of non-hydrostatic stresses in the adjacent country rock.

An alternative interpretation to our breakout model is that the sub-caldera magma chambers grew to an elliptical shape due to the presence of pre-existing, NW-SE striking structures or zones of weakness in the older volcanic rift fill and basement ("transverse tension zones" of McCall, 1968). Many structural attributes of the Kenya rift, such as border fault geometry and basin segmentation, have been shown to be at least partially controlled by basement structures (McConnell, 1972; Smith and Mosley, 1993; Hetzel and Strecker, 1994). Dunkley et al. (1993) have identified NW-SE trending shear zones in the Precambrian basement complex of the eastern rift shoulder that project across the rift valley at the position of the Emuruangogolak and Namarunu volcanoes. However, no such corresponding features are known for Paka, Silali, or the Barrier (Kakorinya).

If the orientations of the rift axis calderas were controlled by pre-existing basement structures, then this would fail to explain why the older Suswa caldera formed elongate ENE-WSW, when the extension direction was approximately the same, while the northern calderas are elongate progressively more NW-SE, according to their age of formation. If pre-existing faults or fractures were the dominant factor, then it would seem more likely that calderas should be elongate parallel to the profuse system of rift-parallel structures, or approximately N-S.

As discussed above, aligned minor craters and pyroclastic cones of early to mid-Pleistocene age throughout the rift valley axis are generally oriented ~N-S, whereas in the latest Pleistocene to Recent, NE-SW alignments appear, such as in the Black Hills of Silali. This shows that despite the very strong N-S structural and volcanic fabric of the inner rift, feeder dikes have been forced to change to the new, mechanically most efficient orientation. When borehole breakouts were first recognized in wells in the 1960’s and 1970’s, they were interpreted to represent elongation parallel to joints and fractures intersected while drilling (e.g., Babcock, 1978). However, after detailed observational and theoretical studies, it was established that the elongations are related to the state of stress in the borehole wall, and not to pre-existing fractures (Bell and Gough, 1979; Plumb and Hickman, 1985; Zoback et al., 1985).

Fortunately, the catastrophic Kenya rift valley caldera collapse events occurred during prehistoric times, prior to the colonization of large populations along the rift axis. Detailed studies of Quaternary stress field evolution may help assess the likelihood of future catastrophic magma loss and caldera collapse at other Holocene volcanoes.

Acknowledgments - Funding for travel and field work was provided by SFB 108 and Marathon Oil Company. Discussions with Martin Smith were greatly appreciated. John Platt made helpful comments on the manuscript. Win Means first directed one of the authors (WB)

toward potential uses of the cylindrical hole problem many years ago during his work as a doctoral student.

References

Babcock, E. A., 1978, Measurements of subsurface fractures from dipmeter logs. American Association of Petroleum Geologists Bulletin, v. 62, p. 1111-1126.

Baker, B. H., 1958, Geology of the Magadi area. Geological Survey of Kenya Report no. 42, 81 p.

Baker, B. H., and Mitchell, J. G., 1976, Volcanic stratigraphy and geochronology of the Kedong–Olorgesaile area and the evolution of the south Kenya rift valley. Journal of the Geological Society, London, v. 132, p. 467-484.

Baker, B. H., Crossley, R., and Goles, G. G., 1978, Tectonic and magmatic evolution of the southern part of the Kenya rift valley. *in:* Neumann, E.-R. and Ramberg, I. B., eds., *Petrology and Geochemistry of Continental Rifts*, Reidel, Dordrecht, p. 29-50

Baker, B. H., Mitchell, J. G., and Williams, L. A. J., 1988, Stratigraphy, geochronology and volcano-tectonic evolution of the Kedong-Naivasha-Kinangop region, Gregory Rift Valley, Kenya. Journal of the Geological Society, London, v. 145, p. 107-116.

Baker, B. H., Mohr, P. A., and Williams, L. A. J., 1972, Geology of the eastern rift system of Africa, Geological Society of America, Special Paper 136, 67 p.

Bell, J. S., and Babcock, E. A., 1986, The stress regime of the western Canadian basin and implications for hydrocarbon production. Bulletin of Canadian Petroleum Geologists, v. 34, p. 364-378.

Bell, J. S., and Gough, D. I., 1979, Northeast-southwest compressive stress in Alberta: Evidence from oil wells. Earth and Planetary Science Letters, v. 45, p. 475-482.

Bell, J. S., and Gough, D. I., 1982, The use of borehole breakouts in the study of crustal stress. U.S. Geological Survey Open File Report, n. 82-1075, p. 539-557.

Blümling, P., Fuchs, K., and Schneider, T., 1983, Orientation of the stress field from breakouts in a crystalline well in a seismic active area. Physics of the Earth and Planetary Interiors, v. 33, p. 250-254.

Bosworth, W., 1981, Strain-induced preferential dissolution of halite. Tectonophysics, v. 78, p. 509-525.

Bosworth, W., and Maurin, A., 1993, Structure, geochronology and tectonic significance of the northern Suguta Valley (Gregory Rift), Kenya. Journal of the Geological Society, London, v. 150, p. 751-762.

Bosworth, W., and Strecker, M. R., 1997, Stress Field Changes in the Afro-Arabian Rift System during the Miocene to Recent Period. Tectonophysics, v. 278, p. 47-62.

Bosworth, W., and Taviani, M., 1996, Late Quaternary reorientation of stress field and extension direction in the southern Gulf of Suez, Egypt: Evidence from uplifted coral terraces, mesoscopic fault arrays, and borehole breakouts. Tectonics, v. 15, p. 791-802.

Bosworth, W., Strecker, M. R., and Blisniuk, P. M., 1992, Integration of East African paleo and present-day stress data: Implications for continental stress field dynamics. Journal of

Geophysical Research, v. 97, p. 11,851-11,865.

Bosworth, W., Strecker, M., and Burke, K., 1996, Late Pleistocene caldera collapse at Kenya Rift Valley volcanoes related to a reorientation of the stress field within the past ~500 ka.. EOS, Transactions, American Geophysical Union, Spring Mtg. Abst., p. S274.

Brereton, R., and Müller, B., 1991, European stress: Contributions from borehole breakouts. Philosophical Transactions Royal Society of London, Ser. A., v. 337, p. 165-179.

Brotzu, P., Morbidelli, L., Nicoletti, M., Piccirillo, E., and Traversa, G., 1984, Miocene to Quaternary volcanism in eastern Kenya: sequence and geochronology. Tectonophysics, v. 101, p. 75-86.

Cerling, T. E., and Powers, D. W., 1977, Paleorifting between the Gregory and Ethiopian Rifts. Geology, v. 5, p. 441-444.

Chapman, G. R., Lippard, S. J., and Martyn, J. E., 1978, The stratigraphy and structure of the Kamasia Range, Kenya Rift Valley. Journal of the Geological Society, London, v. 135, p. 265-281.

Charsley, T. J., 1987, Geology of the North Horr area. Kenya Ministry of Environment and Natural Resources Report No. 110, 40 p.

Cox, J. W., 1970, The high resolution dipmeter reveals dip-related borehole and formation characteristics. Transactions, Society of Professional Well Log Analysts, 11th Annual Logging Symposium, p. 1-25.

Delaney, P. T., Pollard, D. D., Ziony, J. I., and McKee, E. H., 1986, Field relations between dikes and joints: Emplacement processes and paleostress analysis. Journal of Geophysical Research, v. 91, p. 4920-4938.

Dodson, R. G., 1963, Geology of the South Horr Area. Report of the Geological Survey of Kenya, n. 60, 53 p.

Dunkley, P. N., Smith, M., Allen, D. J., and Darling, W. G., 1993, The geothermal activity and geology of the northern sector of the Kenya Rift Valley. British Geological Survey Research Report SC/93/1, 185 p.

Engelder, T., 1982. A natural example of the simultaneous operation of free-face dissolution and pressure solution. Geochimica et Cosmochimica Acta, v. 46, p. 69-74.

Fink, J. H., and Pollard, D. D., 1983, Structural evidence for dikes beneath silicic domes, Medicine Lake Highland Volcano, California. Geology, v. 11, p. 458-461.

Gough, D. I., and Bell, J. S., 1981, Stress orientation from oil well fractures in Alberta and Texas. Canadian Journal of Earth Sciences, v. 18, p. 638-645.

Gough, D. I., and Bell, J. S., 1982, Stress orientation from borehole wall fractures with examples from Colorado, east Texas, and northern Canada. Canadian Journal of Earth Sciences, v. 19, p. 1358-1370.

Hackman, B. D., 1988, The geology of the Baringo–Laikipia area. Report of the Mines and Geological Department of Kenya, no. 104.

Hetzel, R., and Strecker, M. R., 1994, Late Mozambique Belt structures in western Kenya and their influence on the evolution of the Cenozoic Kenya Rift. Journal of Structural Geology, v. 16, p. 189-201.

Hickman, S. H., Healy, J. H., and Zoback, M. D., 1985, In situ stress, natural fracture distribution, and borehole elongation in the Auburn Geothermal Well, Auburn, New York. Journal of Geophysical Research, v. 90, p. 5497-5512.

Hubbert, M. K., and Willis, D. G., 1957, Mechanics of hydraulic fracturing. Transactions of the American Institute of Mining Engineers, v. 210, p. 153-168.

Jaeger, J. C., and Cook, N. G. W., 1969, Fundamentals of Rock Mechanics. Methuen and Company, Ltd., London, 513 p.

Key, R. M., Geology of the Marsabit area, Kenya Ministry of Environment and Natural Resources Report n. 108, 42 p.

Kirsch, G., 1898, Die Theorie der Elastizität und die Bedürfnisse der Festigkeitslehre. Zeitschrift VDI, n. 42, 770 p.

MacDonald, R., 1987, Quaternary peralkaline silicic rocks and caldera volcanoes of Kenya. *in:* Fitton, J. G. and Upton, B. G. J., eds., *Alkaline Igneous Rocks*, Geological Society, London, Special Publication, n. 30, p. 313-333.

McCall, G. J. H., 1957, The Menengai Caldera, Kenya colony. Proc. 20th Int. Geol. Cong., Mexico City, Section 1, p. 55-69.

McCall, G. J. H., 1963, Classification of calderas: ‘Krakatoan’ and ‘Glencoe’ types. Nature, v. 197, p. 136-138.

McCall, G. J. H., 1968, The five caldera volcanoes of the central Rift Valley in Kenya. Proceedings of the Geological Society, London, v. 1647, p. 54-59.

McConnell, R. B., 1972, Geological development of the Rift System of Eastern Africa. Geological Society of America Bulletin, v. 83, p. 2549-2572.

Mohr, P. A. and Wood, C. A., 1976. Volcano spacing and lithospheric attenuation in the Eastern Rift of Africa. Earth and Planetary Science Letters, v. 33, p. 126-144.

Morley, C. K., Wescott, W. A, Stone, D. M., Harper, R. M., Wigger, S. T., and Karanja, F. M., 1992, Tectonic evolution of the northern Kenyan Rift. Journal of the Geological Society, London, v. 149, p. 333-348.

Mugisha, F., Ebinger, C. J., Strecker, M., and Pope, D., 1997, Two-stage rifting in the Kenya rift: implications for half-graben models. Tectonophysics, v. 278, p. 63-81.

Nakamura, K., 1977, Volcanoes as possible indicators of tectonic stress orientation–Principle and proposal. Journal of Volcanology and Geothermal Research, v. 2, p. 1-16.

Plumb, R. A., and Hickman, S. H., 1985, Stress-induced borehole elongation: a comparison between the four-arm dipmeter and the borehole televiewer in the Auburn geothermal well. Journal of Geophysical Research, v. 90, p. 5513-5521.

Randel, R. P., and Johnson, R. W., 1991, Geology of the Suswa area. Kenya Mines and Geological Department Report, n. 97, 41 p.

Smith, M., and Mosley, P., 1993, Crustal heterogeneity and basement influence on the development of the Kenya Rift, East Africa. Tectonics, v. 12, p. 591-606.

Sprunt, E. S., and Nur, A., 1977, Experimental study of the effects of stress on solution rate. Journal of Geophysical Research, v. 82, p. 3013-3022.

Strecker, M. R., and Bosworth, W., 1991, Quaternary stress-field change and rifting processes in the East African Gregory Rift. EOS, Transactions of the American Geophysical Union , v. 72, p. 17-22.

Strecker, M. R., Blisniuk, P. M., and Eisbacher, G. H., 1990, Rotation of extension direction in the central Kenya Rift. Geology, v. 18, p. 299-302.

Williams, L. A. J., 1978, Character of Quaternary volcanism in the Gregory Rift Valley. *in:* Bishop, W. W., ed., *Geological Background to Fossil Man*, Scottish Academic Press, Edinburgh, p. 55-69.

Williams, L. A. J., MacDonald, R., and Chapman, G. R., 1984, Late Quaternary caldera volcanoes of the Kenya Rift Valley. Journal of Geophysical Research, v. 89, p. 8553-8570.

Zanettin, B., Justin Visentin, E., Bellieni, G., Piccirillo, E. M., and Rita, F., 1983, Le volcanisme du bassin du nord-Turkana (Kenya): âge, succession et évolution structurale. BCREDP, v. 7, p. 249-255.

Zoback, M. D., Moos, D., Mastin, L., and Anderson, R. N., 1985, Wellbore breakouts and in situ stress. Journal of Geophysical Research, v. 90, p. 5523-5530.

Zoback, M. L., 1992, First and second order patterns of stress in the lithosphere: The World Stress Map Project. Journal of Geophysical Research, v. 97, p. 11,703-11,728.

Zoback, M. L., et al., 1992, World stress map - maximum horizontal stress orientations. Journal of Geophysical Research, v. 97, one sheet color map, 1:40,000,000 scale at equator.