CONTRASTING STYLES OF VOLCANISM AND RIFTING

[1]BARRY, T. L., [2]KAMPUNZU, A. B., [3]RASSKAZOV, S., [3]IVANOV, A. and [2]ZHAI, M. [1]Liverpool University, Liverpool, Britain; [2]University of Botswana, Gaborone, Botswana; [3]Institute of Earth's Crust, Irkutsk, Russia.

Summary

It has long been recognised that continental rifting is associated with a compositional spectrum of igneous rocks. Whilst some oceanic basins record spatial and temporal variations of composition of volcanic rocks from pre-continental rift stages up to passive margins, the relationship between continental rifting and volcanism is poorly understood. Arguments of '***active***' versus '***passive***' rifting have sometimes tended to cloud interpretations of intraplate continental volcanism, rather than clarify, especially where timing of rifting and volcanism are poorly constrained.

Rifts can be characterised by crust about 25-35 km thick with significant thinning taking place in the lower part of the crust. Active rifts are associated with the active uprise of asthenosphere by starting plumes which cause regional crustal doming and subsequent fracturing of the crust. Lithospheric thinning in active rifts may be several times wider than the rift zone. In the passive rift setting, large-scale stresses exert force upon the lithosphere, causing it to fracture and allowing the passive uprise of asthenosphere. Uplift in the passive rift setting is confined to faulted near-surface regions and rift shoulders. Lithospheric thinning is confined to the rift zone.

In terms of volcanism produced in the active and passive settings, passive rift systems show that the onset of volcanism occurs after the initiation of rifting, whereas the opposite characterises active rift systems. Active rifting is marked by relatively large volumes of magma when considered at a regional scale and early volcanism is dominantly by shallow mantle sources. In contrast, passive rifts produce only small volumes of magma especially during the earliest stages of development and initial mantle melts are derived from deep mantle sources. An additional point about passive rifting is that clastic sedimentation is thought to exceed the rate of volcanism. These differences are shown to reflect different dynamics between the asthenosphere and lithosphere.

Introduction and general characteristics

The two end-member models for ***active*** and ***passive*** rifting describe volcanism as either directly linked to starting mantle plumes or as a minor subsidiary consequence of lithospheric extension, respectively. To address this debate, we selected two of the best examples of intra-plate rifting for a detailed comparative study of the dynamics of asthenosphere and lithosphere during the earliest stages of continental rifting. This comparison relies on petrological and geochemical characteristics of mafic volcanic rocks and their mantle xenoliths. The two rifts are the East African Rift System (EARS) and the Central and East Asian Rift (CEAR).

The EARS is located far from any convergent plate margin and its development has been linked to starting plumes impinging on the base of the lithosphere (e.g. George et al., 1998). The EARS is the longest modern rift system in the world, being over 6500 km in length. It includes two main branches (Fig. 1): the eastern branch includes Afar, Ethiopia and Kenya rifts whereas the western branch comprises of a large number of rift basins hosting several lakes (e.g. Albert, Tanganyika). The volume of lavas poured out in these two branches is estimated to be at least 700 000 km^3 in the eastern branch versus ca. 100 000 km^3 in the western branch (e.g. Kampunzu and Mohr, 1991). The volcanic activity started in the Eocene, around 40 Ma in the eastern branch (e.g. Baker et al., 1996) and during the Miocene, ~ 20 Ma in the western branch (e.g. Ivanov et al., 1998; Kampunzu et al., 1999). In both branches, the earliest lavas pre-date the onset of rifting and are commonly continental tholeiites (e.g. Mohr and Zanettin, 1988; Kampunzu and Mohr, 1991; Ivanov et al., 1999). The full spectrum of mafic lava associations include transitional, alkaline and ultra-alkaline lavas sometimes associated with carbonatites (e.g. natrocarbonatite at Oldoinyo Lengai). Major central volcanoes topped with large calderas are known in several volcanic provinces (e.g. Virunga, NE Tanzania, Kenya, etc). Geophysical data indicate that both branches are seated on top of a very broad (>1000 km wide) asthenospheric uprise.

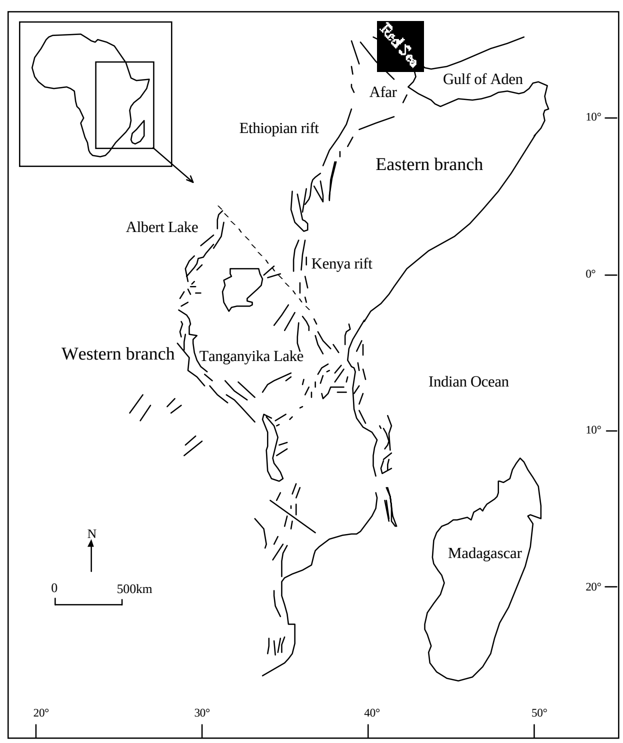

Figure 1. A map of the East African Rift System (EARS).

The second intra-plate rift example is the CEAR, located within a broad zone involving the collision between Eurasia and India since the early Palaeogene, beginning around 55 Ma (e.g. Molnar and Tapponnier, 1975; Treloar and Coward, 1991). The origin of this rift system is more ambiguous than the EARS and has been attributed to lithospheric responses to collision (Molnar and Tapponnier, 1975) or to a mantle plume, as in the case of the East African rift system (e.g. Logatchev et al., 1978). In contrast to the EARS, geophysical studies show the existence of spatially restricted, narrow, deep conduits in the upper mantle which are unable to explain the size of the CEAR. Therefore, whilst CEAR may not be fully classified as a passive rift, neither does it fall within the active rift category. Indeed, there may be combined effects within the entire rift zone, and remains a subject for debate (e.g. Logatchev et al., 1983). The CEAR system extends over 3000 km (up to a maximum of ~6000 km) and mainly comprises the dominant Baikal rift segment, the Stanovoy-Okhotsk belt, the Tan-Lu fault system through China and the Hobsogul-Mongolian area (Fig. 2; e.g. Barry and Kent, 1998). Cenozoic rifting is thought to have begun around 30-35 Ma (Logatchev and Zorin, 1992), with the earliest faulting likely to have occurred in the Baikal area. Rifting is still active along the Tunka segment of the Baikal rift zone, as well as along the margins of Lake Baikal. Numerous volcanic provinces are associated with this overall region of rifting and faulting, namely the Vitim and Hamar-Daban (Baikal); Udokan (Stanovoy); and Hobsogul –Hangai volcanics in Mongolia. In close association with the CEAR province is the Tancheng-Lujian (Tan-Lu) deep fault of NE China. This fault system is elongated in a NNE-SSW direction and passes through the Bo Hai Sea. To the north, the Tan-Lu fault has two branches which extend into Russia. In close proximity to this fault system are numerous Cenozoic volcanic provinces e.g. Hannuoba, Kuandian, Changbaishan.

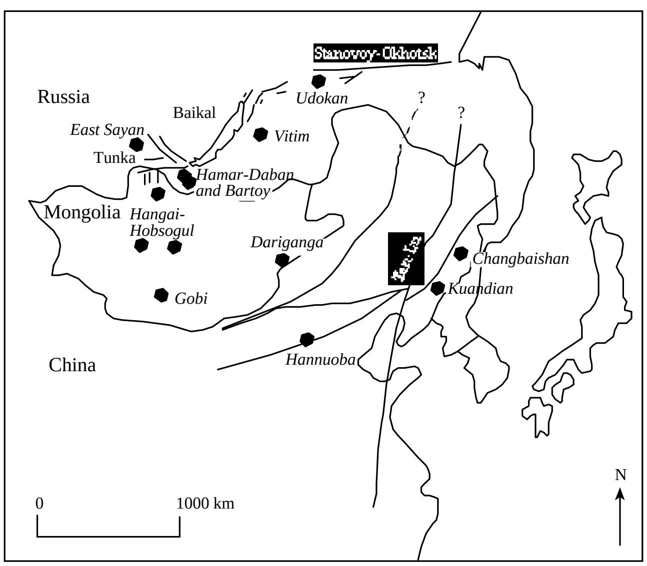

Figure 2. A map of the Central and East Asian Rift; a complex of numerous large faults and volcanic provinces. Volcanic provinces written in italic.

Most of the volcanic rocks from these regions are flat-lying lavas with occasional strombolian cones. There are few distinct stratovolcanoes (one reported from central Mongolia; Kepezhinskas, 1979). The total volume of lavas erupted from Russian and Mongolian volcanic provinces is considered not to exceed ~15 000 km^3. The total volume of volcanic rocks erupted in China is currently unknown, as there are considerable quantities buried beneath clastic sediments. However, it is estimated that CEAR is less than one-third the size of EARS. In the Baikal rift zone, volcanism initially began in the East Sayan area ~25 Ma and possibly at a similar time elsewhere, in the Hobsogul and Hamar-Daban regions. Volcanism did not begin until ~14 Ma in the northeastern region of Udokan.

TIMING OF RIFTING RELATIVE TO VOLCANISM

Age progression of volcanism is a key tool in determining hotspots/mantle plume relationships e.g. Hawaii. In the case of EARS there is a broad trend in the age of volcanism from north to the south but, because the African plate was almost stationary during the Cenozoic, this age polarity cannot be attributed to the displacement of the plate above a hotspot. Instead, it marks a north to south polarity of opening of the EARS (nb. on a local scale there can be age progression from south to north). In the case of CEAR the relationship is less obvious. For example, the oldest volcanism in Mongolia, occurs in the southern Gobi region (Fig. 2; Barry et al., subjudice). Later Cenozoic volcanism occurs in the far north, around Hobsogul, but the most recent volcanism is situated in the central region, around the Hangai district. The earliest volcanism in the Baikal area is ~25 Ma (Rasskazov, 1994). In two volcanic provinces close to the flanks of Baikal rift zone, Udokan and East Sayan, there is westward migration of volcanic activity. It is not clear what the origin of this migration is though, as it is not apparent elsewhere and migration of the crust is unknown.

On a regional scale, volcanism in the EARS was initiated early (pre-rift). For example, in the western branch of the EARS, tholeiitic basalts exposed in the Virunga, Bukavu, Mwenga-Kamituga and Rungwe volcanic provinces were emplaced between 20 and 10 Ma, whereas associated rifting is younger than 10 Ma. On a similar scale in the region of the CEAR, volcanism is generally late (syn-rift). All of the volcanism in the Baikal area occurs either within smaller rifts away from the main Baikal depression, or 100’s km away, on the rift shoulders. A detailed study in Mongolia revealed that rifted valleys were always infilled by volcanic sequences rather than clastic sedimentary sequences (Barry, unpublished data).

GEOCHEMICAL RELATIONSHIP TO RIFT SETTING

Mafic and ultramafic rocks (SiO_2 <53 wt% and MgO >5wt%) of tholeiitic, alkaline and ultra-alkaline composition enable us to define key differences between these two rift examples.

In the EARS, shallow-originating magmas are the first to be erupted. The earliest lavas in some volcanic provinces are quartz-tholeiites, e.g. in the Bukavu volcanic province. They are overlain by olivine-tholeiites and transitional basalts. Most of these earliest saturated basalts pre-date the onset of rifting. Younger lavas are alkaline basalts emplaced during the earliest stages of rifting and are then followed by olivine tholeiites, more depleted in incompatible elements than their earlier homologues (Kampunzu and Mohr, 1991). The early saturated quartz-tholeiitic compositions are evidence that early volcanism was produced from a relatively high degree of partial melting at shallow depth. This is interpreted as the rapid ascent of hot fertile asthenosphere, which fosters variable degrees of partial melting at all levels, and allows shallower magmas to be erupted early in the volcanic activity of the region. As time progresses, the magmas appear to come from a deeper source, with more input from a garnet-bearing source. In the Bukavu and Mwenga-Kamituga volcanic provinces, Zr/Y ratios increase with time during early stages of volcanism (Kampunzu and Kanika, unpublished data). In contrast, in many of the CEAR volcanic provinces, deep-originating magmas are the first to be erupted e.g. Udokan in Russia and Tariat in Mongolia and is reflected in decreasing Zr/Y ratios, during early stages of magmatism, with a return to high Zr/Y ratios in the most recent volcanism (Barry et al., subjudice). This is inferred as the slow progressive uprise of asthenosphere which influences melting at depth, dominantly in the presence of garnet.

Geochemical features distinguish mafic rocks from each of these rifts, e.g. Ce/Pb ratios in the EARS is in the range for OIB/MORB (25±5) whereas highly variable ratios and low values (<15) are common in several areas of the CEAR (e.g. Hsu and Chen, 1998; Barry et al., 1999). Lithospheric mantle beneath the EARS was strongly affected by metasomatism (e.g Lloyd et al., 1991). Amphibole-bearing mantle xenoliths are frequent, as well as more rare phlogopite-clinopyroxenite mantle xenoliths from Toro-Ankole which also includes carbonate minerals (e.g. Lloyd et al., 1991). These xenoliths show evidence of a strong metasomatic event in the lithospheric mantle, inferred to be the source of these xenoliths. However, evidence from CEAR also shows that numerous volcanic provinces have been strongly affected by metasomatism (e.g. Ionov et al., 1992b, 1994). Amphibole-bearing, as well as anhydrous peridotites are found in the Bartoy volcanic field (Fig. 2) and are commonly LREE enriced (Ionov et al., 1992b). Within Mongolia, in the Dariganga Plateau (Fig. 2), a volcanic province not obviously associated with rifting, 'melt blebs' attest to chemical disequilibrium caused by an influx of metasomatic fluids, shortly before eruption (Ionov et al., 1994; Wiechert et al., 1997).

Thus, metasomatism is common to both rifted regions, suggesting that mantle metasomatism is not controlled by the mantle dynamics or the process of rifting (cf. active versus passive rifting).

Conclusions

It appears from geochemical and temporal studies, that two large rift provinces, the East African Rifts (EARS) and the Central and East Asian Rifts (CEAR) can be compared, providing information about the conditions and relationships of volcanism to rifting. Mafic and ultramafic rocks (SiO_2<53 wt.% and MgO>5%) of tholeiitic, alkaline and ultra-alkaline composition enable us to define key-differences between these two types of rifts. At a regional scale, volcanism is initiated early (pre-rift) in the EARS whereas it occurs late (syn-rift) in the CEAR. The earliest magmas to reach the surface in the CEAR are from a deep source, indicating slow progressive uprise of the asthenosphere. Whilst the EARS shows the converse, marked by the rapid ascent of the asthenosphere which fosters higher degrees of partial melting at all levels allowing magmas from shallower depths to reach the surface first. Ce/Pb in the EARS is in the OIB/MORB range (25±5) whereas highly variable and low values (<15) are common in areas of the CEAR.

References

Baker, J., Snee, L. and Menzies, M., 1996. A brief Oligocene period of flood volcanism in Yemen: implications for the duration and rate of continental flood volcanism at the Afro-Arabian triple junction. Earth and Planetary Science Letters, 138: 39-55.

Barry T. L. and R. Kent, 1998. Cenozoic magmatism in Mongolia and the origin of Central and East Asian basalts. In: Flower, M., Chung, S.-L., Lo, C.-H., Lee, T.-Y., (Eds.) Mantle dynamics and plate interactions in East Asia, AGU Monograph, Geodynamics Series, 27: 347-364.

Barry, T. L., Saunders, A. D., Kempton, P. D., Windley, B. F., Pringle, M. S. and Davies, G., 1999. Petrogenesis of Mongolian Cenozoic volcanism: evidence from Hangai and the Gobi, IGCP 400, 'Geodynamics of continental rifting: Baikal' abstract.

Barry, T. L., Saunders, A. D., Kempton, P. D., Windley, B. F., Pringle, M. S., Davies, G., Dorjnamjaa, D. and Saandar, S. subjudice. Petrogenesis of Cenozoic basalts in Mongolia; evidence for contribution from a hydrous lithospheric source.

George, R., Rogers, N., and Kelley, S., 1998. Earliest magmatism in Ethiopia: evidence for two mantle plumes in one flood basalt province. Geology, 26: 923-926.

Hsu, C.N. and Chen J.C., 1998. Geochemistry of late cenozoic basalts from Wudalianchi and Jingpohu areas, Heilongjiang province, northeast China. Journal of Asian Earth Sciences, 16: 385-405.

Ionov, D. A., Kramm, U. and Stosch, H. –G., 1992b. Evolution of the upper mantle beneath the southern Baikal rift zone: a Sr-Nd isotope study of xenoliths from the Bartoy volcanoes. Contrib. Min. Petrology, 111: 235-247.

Ionov, D.A., Hofmann, A.W. and Shimizu, N., 1994. Metasomatism-induced melting in mantle xenoliths from Mongolia. Journal of Petrology, 35: 753-785.

Ivanov, A.V., Rasskazov, S.V., Boven, A., Andre, L., Maslovskaya, M.N. and Temu, E.B., 1998. Late Cenozoic alkaline-ultrabasic and alkaline basaltic magmatism of the Rungwe province, Tanzania. Petrology, 6: 208-229.

Ivanov, A. V., Rasskazov, S. V., Boven, A., Punzalan, L., Brandt, I. S., Brandt, S. B., and Fernandez-Alonso, M., 1999. Timing of late Cenozoic volcanic activity and rift basin formations in the Rungwe province of Tanzania substantiated by K-Ar and $^{40}Ar/^{39}Ar$ dating. IGCP 400, 'Geodynamics of continental rifting: Baikal' abstract.

Kampunzu, A.B., Bonhomme, M.G. and Kanika, M., 1998. Geochronology of volcanic rocks and evolution of the Cenozoic Western branch of the East African Rift System. Journal of African Earth Sciences, 26: 441-461.

Kampunzu, A.B.and Mohr, P.,1991. Magmatic evolution and petrogenesis in the East African Rift System. In: Kampunzu, A.B. and Lubala, R.T. (Eds) Magmatism in Extensional Structural Settings. Springer Verlag, Heidelberg, Germany: 85-136.

Kepezhinskas, V. V., 1979. Cenozoic alkalic basalts of Mongolia and their deep-seated inclusions (in Russian). Nauka, Moscow. 311 pp.

Logatchev, N. A. and Florensov, N. A., 1978. The Baikal system of rift valleys. Tectonophysics, 45: 1-13.

Logatchev, N.A. and Zorin, Y.A., 1992. Baikal rift zone: structure and geodynamics. Tectonophysics, 208: 237-286.

Logatchev, N. A., Zorin, Yu. A., and Rogozhina, V. A., 1983. Baikal rift: active or passive? – Comparison of the Baikal and Kenya rift zones. Tectonophysics, 94: 223.

Lloyd, F.E., Huntingdon, A.T., Davies, G.R. and Nixon, P.H., 1991. Phanerozoic volcanism of southwest Uganda: a case for regional K and LILE enrichment of the lithosphere beneath a domed and rifted continental plate. In: Kampunzu, A.B. and Lubala, R.T. (Eds) Magmatism in Extensional Structural Settings. Springer Verlag, Heidelberg, Germany: 23-72.

Mohr, P. and Zanettin, B., 1988. The Ethiopian Flood Basalt province. In: MacDougall, J.D., Continental Flood Basalts. Kluwer, Dordrecht, The Netherlands: 63-110.

Molnar, P. and Tapponnier, P., 1975. Cenozoic tectonics of Asia: effects of a continental collision. Science, 189:419-426.

Rasskazov, S.V., 1994. Magmatism related to the eastern Siberia rift system and the geodynamics. Bulletin Centres Recherche Exploration-Production Elf Aquitaine, 18: 437-452.

Rasskazov S., Ivanov A., Boven A. and Andre L., 1997. Late Cenozoic reactivation of the early Precambrian Aldan shield: trace element constraint on magmatic sources beneath the Udokan ridge, siberia, Russia. Proceedings of the 30th International Geological Congress, Part 15, VSP.

Treloar, P. J. and Coward, M. P., 1991. Indian plate motion and shape – constraints on the geometry of the Himalayan orogen. Tectonophysics, 191: 189-198.

Whitford-Stark, J. L., 1987. A survey of Cenozoic volcanism on mainland Asia. Geol. Soc. America Sp. Paper no. 213, pp.74.

Wiechert, U., Ionov, D. A. and Wedepohl, K. H., 1997. Spinel peridotite xenoliths from the Atsagin-Dush volcano, Dariganga lava plateau, Mongolia: a record of partial melting and cryptic metasomatism in the upper mantle, Contrib. Min. Petrology. 126: 345-364.