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The distribution of earthquakes and volcanoes along the East African Rift system

The pattern of earthquake epicentres for the period 1904 to 1993 is compared with the distribution of 615 Cenozoic volcanoes in the East African Rift system. Holocene volcanism occurs mostly within the rift valleys while the pre-Holocene volcanoes are more scattered and extend beyond the confines of the rift. Pre-Holocene volcanism is also more extensive, reaching south through Mozambique and Zimbabwe. Most of the volcanoes, of all ages, are associated with the eastern branch of the rift system. In contrast, the western branch appears to be far more seismically active than its eastern counterpart, although most of the epicentres postdate 1963. In general, teleseismic earthquake epicentre data for 1904 through 1993 (noting the short time period) and Holocene volcanism show no apparent simple relationship except for the Ethiopian Rift.

Although the axis of the eastern branch of the rift system is thought to be an incipient, accreting plate margin between the Nubia and Somali plates (Girdler and others, 1969), the boundary between the plates is complex: at the northern end is the Afar triple junction with the Arabian plate to the northeast and the Nubia and Somali plates to the west and south; south of Afar, the Ethiopian Rift is covered with volcanic rocks which become less continuous in Kenya. Further south, in Tanzania, the single rift becomes several branching rifts. In addition, the eastern and western branches seem, at least in part, to enclose another plate, with Lake Victoria near its middle. Some sectors are more active than others at the present time and some have, undoubtedly, been more active in the past. The episodic nature of seismic activity and the segmentation of the rift, produce

Introduction

The East African Rift system was first recognised as a continental rift system in the last century (Suess, 1891; Gregory, 1896, 1921). Extensive coverage by satellite remote sensing offers a unique opportunity to study its major tectonic and geological features. Whilst imagery from the rift system has been discussed by Mohr (1974), who presented lineament maps using imagery from the first Landsat satellite (ERTS-1), no previous study has used newer data and covered the entire East African Rift system from the Red Sea southwards. There has been no extensive comparison of the seismicity with distribution of volcanoes which dominate much of the landscape in the region. The distributions of teleseismic events and volcanoes are discussed here, as they offer some insight into rifting processes. The rift is usually defined by its geomorphic expression, i.e. opposite-facing scarps across a graben-type structure and by general topographic uplift of the shoulders and margins (figure 1).

Figure 1 Location of major features along the East African Rift.

Figure 3 Coverage of various satellite remote-sensing imagery used in the location of volcanoes.

Figure 4 Holocene and pre-Holocene volcanoes of East Africa. Locations of Holocene volcanoes from Simkin and others (1981, 1989) and McClelland and others (1989).

show clear evidence of eruptions within the past few thousand years (e.g. uneroded volcanic ash cones, eruptive products overlying glacial debris, or young unvegetated lava flows in regions where revegetation should be rapid). As individual volcanoes may remain intermittently active for millions of years, some volcanoes which we have classified as Holocene were also active prior to the Holocene, and were also grouped with the pre-Holocene volcanoes. The remaining 96 per cent of the volcanoes classified as pre-Holocene, show no evidence of activity during the last 10 000 years. As it is virtually impossible to determine the age of volcanic activity using remotely sensed data alone, we relied on published data based on geochronology and historical accounts. The Holocene volcano data are from Simkin and others (1981); McClelland and others (1989); Geothermal Reconnaissance Study (1987); and from various SEAN (Seismic Event Alert Network) Bulletins. Data for pre-Holocene volcano locations are largely from satellite images. Other volcano data were obtained from detailed maps, publications by the International Association of Volcanology data sheets (Richard and Neumann Van Padang, 1957), and databases of the US Defense Mapping Agency. Volcanoes were readily located on the TM and MSS scenes. A database was created with latitude, longitude, country, volcano name, type, and age with reference, if known. Three prominent geographic features were used to georeference each remote-sensing scene. The location of the centre of the volcanic feature is accurate to 0.04° of latitude (about 4 km) on the imagery. Parasite cones and domes associated with major shield and composite volcanoes were not recorded. However, isolated cones and domes with basal diameter exceeding 0.5 km were included. Volcanic features were characterised as shields, composite cones, cinder (scoria) cones, or domes.

The locations of all the volcanoes are shown in figure 4; Holocene volcanoes are shown in figure 5b and pre-Holocene in figure 5c. There are 516 pre-Holocene and 99 Holocene volcanoes. Of the Holocene volcanoes, Nyamuragira and Nyiragongo in Zaire, Rungwe and Kieyo in Tanzania, Erte Ale in Ethiopia, and Ol Doinyo Lengai in northern Tanzania have erupted during the past decade.

Comparison of volcano and epicentre distributions

Under the assumption that the epicentre distribution has not changed much over the last 10 000 years, a comparison can first be made of the epicentre locations and the location of Holocene volcanoes (figures 5a and b), and how each of these relate to the rift structures.

The spreading axis of the Gulf of Aden shows the seismic activity and topographic expression characteristic of the mid-ocean ridge system; however, oceanographic surveys are not sufficiently detailed to show whether or not volcanoes exist on the ocean floor. This is not so for the southernmost Red Sea which has (from south to north) the volcanic islands of Perim, Great and Little Hanish,

Zukur, the Zubair Group, and Jebel At Tair (Gass and others, 1965, 1973; Girdler, 1973). Figure 5a shows that the epicentres seem to trend north on both sides of the Danakil block, i.e. in the southern Red Sea and in Afar between Nubia and the Danakil block; from about 16°N they continue mostly along the axis of the Red Sea. In northern Ethiopia, between 11° and 15°N a line of youthful volcanic cones, the Erta Ale range, strikes northwest-southeast and is clearly visible on satellite imagery. Seismic activity is largely confined to this range; the Gulf of Tadjoura and its land extension; and western Afar (the Nubia scarp). The Ethiopian Rift, stretching southwest from Afar at about 10°N , 40°E to about 6°N is a well-developed rift with an almost continuous line of Holocene volcanic centres along the valley floor and some seismicity. It is this section which appears to be most like the accreting margin of the mid-ocean rift system. In contrast to the flat-lying Afar, this whole region, excluding the rift valley itself, is mountainous and elevated for some 560 km to the west and 330 km to the east of the rift axis (figure 1). From about 6°N to Lake Turkana (4°N), the regional topography and well-defined rift disappear, though the presence of volcanoes and seismicity suggest that there is some continuous rift structure. This may be connected with interference from the Mesozoic Central African rift system (Jorgensen and Bosworth, 1989), which crosses the East African Rift system in this locality. An east-west topographic profile at about 2°S , crossing the western branch of the rift system, Lake Victoria, and the eastern branch would lead one to think that the two branches are due to similar, tensional processes. However, the eastern and western branches of the rift bordering the 'Victoria plate' exhibit some strongly contrasting characteristics. Both branches, except for the southern end of the eastern branch, show rift valley topography. However, the western branch has few volcanic centres. The eastern branch has volcanoes where the rift valley topography is well developed, but terminates at about 3°S , where basin-and-range-type faults are prominent over a wider area. The rule seems to be that volcanoes form only near a rift valley, or graben. The presence of Holocene volcanoes indicates a nearby rift, though the converse is not neces-

Figure 5a above left Locations of earthquake epicentres; ISC (from January 1963 to May 1991) NEIS (June 1991 to April 1993) and various agencies (see text) data (1904 to December 1963).

b above Locations of Holocene volcanoes from Simkin and others (1981, 1989) and McClelland and others (1989).

c left Locations of pre-Holocene volcanoes.

sarily true. Seismicity, abundant in the entire western branch and in the southern end of the eastern branch, seems to be related to the volcano frequency, i.e. teleseismicity is low where the volcanicity is high and vice-versa. Near the southern end of the eastern branch, in northern Tanzania, there is a wide distribution of epicentres, but these are not continuous with the western branch, which is defined by Lakes Tanganyika, Rukwa and Malawi. Seismic activity on the eastern shoulder of these rifts is much less than to the west. South-west-trending bands of epicentres extend from the western branch at about 6°S, 7.5°S, and 10°S. This seismic activity is more intense than along the Ethiopian rift, or the Kenya Rift, and seems to be related to propagating rift structures (Girdler, 1983, 1985, 1991). The pre-Holocene volcanoes (figure 5c) are much more widespread than those of the Holocene. Afar is densely covered and the trend continues through Ethiopia and Kenya. The symmetry of these about the Ethiopian rift is striking; they essentially form a broad band extending 200 km either side of the rift axis. This trend continues southwards past the Lake Turkana region, along the Kenya Rift and stops in northern Tanzania, as do the Holocene volcanoes (cf. figures 5b and c). An important feature of the pre-Holocene volcanoes (figure 5c) is the tendency to form two north-south lines in Kenya, with one of these 100-150 km east of the Kenya Rift. Other studies of volcanism along the Kenya Rift indicate that volcanism has migrated

toward the rift since the Miocene (Girdler and others, 1969; Baker and others, 1972; King, 1978; Bellieni and others, 1986). Initially diffuse volcanism evolved in a similar manner along the Ethiopian rift (Mohr, 1983); as summarised by Chorowicz and others (1987), volcanism may have accompanied narrowing of the eastern branch (rifts) with time. All volcanism along the western branch is strikingly lower than along the eastern branch. Volcanic activity along the western branch was also scattered prior to the Holocene (figure 5c) and became very much less during the Holocene.

Magma volumes and 'off-axis' volcanism

Differences in volcanism along the eastern and western branches have been summarized (see Mohr, 1982). There are magmatic volume differences between the eastern branch and the western branch. Estimated eruptive volumes for the eastern branch are 144 000 km³ in Kenya (Williams, 1972) and 345 000 km³ in Ethiopia (Baker and others, 1972; Mohr, 1982). The western branch which has few volcanoes has been described as magmatically 'dry'. Figures 5b and c show that fewer than ten of the Cenozoic volcanoes are situated near the western branch. Volcanism has been restricted to the rift basins of the western branch for the past 10 Ma (Ebinger, 1989). A similar pattern of volcanism generally applies to the older Kenya Rift, although 'off-axis', Pliocene–Holocene volcanism is seen on the eastern shoulder 100–150 km from the rift axis (figure 5b). Interest in 'off-axis' volcanism is accentuated by the alignment of the imposing volcanoes, Kenya, Marsabit, and Kilimanjaro, the last being the largest in Africa. The cause of 'off-axis' volcanism has been the subject of considerable debate (Suess, 1891; Girdler and others, 1969; Bosworth, 1987; Morley, 1988; Ellis and King, 1991). Typically, the volcanoes analysed have been the enormous, late-Cenozoic volcanoes: Marsabit, Kenya, and Kilimanjaro. Our data indicate, however, that approximately 20 pre-Holocene volcanoes may be classified as 'off-axis' (figure 5c). Lithospheric thinning was suggested as an explanation for the symmetrical locations of large shield volcanoes on opposite flanks of the Kenya Rift (Girdler and others, 1969; Searle 1970; Brown and Girdler, 1980) whilst Bosworth (1987) invoked thinning with intersecting detachment faults. The symmetry is lost, however, if the smaller volcanic sites are included in the analysis. Problems also arise from the Miocene age of Mount Elgon (west of the Kenya Rift) relative to proposed detachments (Morley, 1988). The 'off-axis' linear trend in figure 4 suggests that volcanism was concentrated along older structures parallel to the Kenya Rift. Although these older structures may have been important for allowing magma to erupt (Smith and Mosley, 1993; Dawson, 1992), the reason for the concentration of magma east of the Kenya Rift remains unresolved. Hackman and others (1990) have suggested that the development of Plio-Pleistocene multicentred shields east of the Kenya Rift indicates an eastward shift in the manifestation of tensile stress. This could explain the 'off-axis' volcanism, but may conflict with the observed Holocene volcanism within the Kenya Rift, the focusing of volcanism into the Kenya Rift with time, and the observations indicating the whole of east Africa is associated with NW–SE extensional stress (Fairhead and Girdler, 1971).

Concluding remarks

Earthquake epicentres for 1904 through 1993 and spatial and temporal data for 516 pre-Holocene and 99 Holocene volcanoes extending along the entire East African Rift system have been presented. These indicate that pre-Holocene volcanism was much more scattered compared with Holocene volcanism, which is mostly focused in the rift valleys. 'Off-axis' volcanism along the Kenya Rift occurred at approximately 20 volcanoes scattered along the entire length of the rift, suggesting fracture-controlled magma conduits. Cross-correlation of teleseismic earthquake epicentre data for 1904

through 1993 (noting the short time period) and Holocene volcanism, show no simple relationship except for the Ethiopian rift.

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Listings of the volcanoes with locations (latitudes and longitudes) and simple descriptions may be obtained from the first author. □

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