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Full Length Research Paper

The role of isotope geology in the reconstruction of the Cenozoic history of Kenya

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Geochronology has had a dramatic impact on the understanding of African geology. Consideration of the radiometrically dated geological phenomena in the continent has led to a more complete view of the evolution of Africa. In this paper, the role of isotope geology in constructing the cenozoic history of Kenya is systematically reviewed. The general sequence in the cenozoic volcanics shows a continuous history of rift formation and volcanic activities from mid-Tertiary times. Stable isotope measurements on carbonates have been used to elucidate climatic conditions prevailing at the time of deposition of these materials. Radio-isotopic dates on igneous material have helped to erect an overall time scales for homonid evolution in East Africa. Despite shortcomings in the available ages, isotope geology has played a significant role in the construction of the geological history of Kenya.

Key words: geochronology, isotopes, cenozoic, rifting, volcanism, palaeoclimate, fossils, homonids, reconstruction, evolution.

INTRODUCTION

Since the pioneering work of Holmes (1965), geochronolgy has had a dramatic impact on the understanding of African geology. Consideration of the radiometrically dated geological phenomena in the continent has led, despite shortcomings in the available ages and in knowledge of the geology, to a more complete view of the evolution of Africa.

In this paper, I present a small portion of the much larger picture: the role that isotope geology has played in the elucidation of the history and tectonothermal events in Kenya.

THE RIFT VALLEY SYSTEM

The great East African Rift system has attracted the attention of geologists since the pioneer work of Gregory (1921) for the geomorphological expression, its tectonic significance, and it's associated volcanic igneous activity. The main rift features extend southward from the southern end of the Red Sea through Ethiopia, Kenya and Tanzania in a 3000 km-long fracture, a portion of which is known as the Eastern or Gregory Rift. The Eastern Rift appears to end at about 6°S latitude in Tanzania (Figure 1).

Age of rift faulting

The rift system typically is made up of usually approximately parallel fault zones 50 to 80 km apart, with the downdropped central portion vertically displaced up to 3000 m or more. Not all the rifts have faults on both flanks, and some have tilted blocks defined only by faulting on one side. The fractures themselves are usually normal step faults; they are discontinuous, and offsets and bifurca-tions are frequent (Cahen and Snelling, 1984).

Isotopic ages of lava from the rift have provided age limits for some episodes of rift faulting mainly in the western and southern parts of the Kenya rift. Age determinations have been carried out by K-Ar analyses of whole-rock samples of phonolites, basalts, trachytes and nephewlinites. As a result of K-Ar dating, in conjunction with mapping and paleomagnetic polarity measurements, it has been concluded that the rift was initiated as a downwarp, which was later infilled by melanephelinitic agglomerates, and lavas (15-12 Ma ago). Major faulting (12-7 Ma ago) downthrew these volcanics to the east and flood trachytes (7-5 Ma ago) were erupted onto the newly formed rift floor. Minor faulting and volcanism proceeded the second period of minor faulting (5-3 Ma ago).

Extensive flood basalts (3-2.5 Ma ago) infilled the resulting rift structure. Later subsidiary depressions in the rift floor were infilled by two large prophyritic trachyte flows in the north (the older one 2.1 Ma ago), by flood basalts (2.1-1.7 Ma ago) in the south and by flood trachytes (1.4-0.7 Ma ago) in the east. A period of major faulting (most of it post – 0.6 Ma ago) created much of the

Figure 1. Showing the approximate alignment of major faults of the Eastern Segment of Gregory Rift in Kenya.

present rift topography (Crossley, 1979).

In addition, isotopic evidence shows that the rift structures in southern Kenya developed at about the same time as the formation of the axial trough of the Red Sea. The temporal correlation cannot, however, be taken to indicate similarity in the mechanism of formation of neo-oceanic and continental rifts (Fairhead et al., 1972).

Associated volcanic activity

A particular aspect of the Rift Valley system is the presence of considerable quantities of volcanic rocks extruded as plateau flows, as well as very large central volcanoes, one of which, Mt. Kilimanjaro, rises to 5895 m and forms the highest point in Africa. Many of these volcanoes are still active. Volcanism is not a direct conesquence of rifting, for extensive sectors of the rift system are devoid of volcanic rock and the central volcanoes rarely show a close association with fracture zones.

Many of the larger central volcanoes are characterized by well differentiated volcanic series, whereas the plateau formations are generally more homogenous in composition. Over 100 K-Ar and a few $^{40}Ar/^{39}Ar$ isotopic age determinations have been made on these volcanic formations. As a result, the following sequence of events has been chronicled.

The Kenya rift volcanics were erupted nearly continuously from Early Miocene to Holocene time. Miocene volcanism was mostly of nephelinites, alkali basalts and phonolites. Pliocene activity was trachytic, phonolitic and nephewlinitic in central and southern parts of the rift valley, while contemporaneous basaltic volcanism took place along its whole length. The only extensive rhyolitic activity occurred in northwestern Kenya in liocene times. Late liocene and Quaternary volcanism was mainly trachytic in the rift valley floor and basaltic to the east (Baker et al., 1974). The age of the phonolites and nephewline syenites of Mt. Kenya, has been found to be 3.5 - 2.6 million years. Mt. Kilimanjaro is younger than Mt. Kenya, the maximum age of basalts lying at the north-eastern base being 2.3 million years (Bagdasaryan et al., 1973).

PALAEOCLIMATIC RECONSTRUCTION

Oxygen isotope ratios vary with climatic conditions. Under warm dry conditions, rain water is fractionated as it falls, with the water reaching the ground enriched in the heavier isotope of oxygen. Evaporation of the lake waters will also leave behind the heavier isotope. The $\delta^{18}0$ values thus increase with arid conditions, and conversely, decrease during cool wet periods.

The Plio-Pleistocene sediments of the Koobi Fora region on the eastern shore of Lake Turkana contain a variety of carbonate horizons: molluscs, stromatolites, indurated calcitic sediments and concretions. The stable oxygen isotope ratios of these carbonates are largely unchanged since deposition, and constitute a record of environmental conditions at the time of deposition. Two factors influence these isotope ratios: (1) temperatures, which produce more negative $\delta^{18}O$ values with increasing temperatures; and (2) evaporative concentration of the heavier oxygen isotope in the rainfall and body of the lake, which makes for more positive values of $\delta^{18}O$ under arid conditions (Abell and McClory, 1986).

Using fossil gastropods

The molluscs in the Koobi Fora sediments are almost ubiquitous. Three gastropod species have been selected for use as recorders of environmental conditions in the oxygen isotope ratios of their shells. These three have been chosen because: (1) they occur in shallow water habitats and would be expected to be in good equilibrium with the surrounding water; (2) they are capable of living over a wide range of pH and concentrations of dissolved salts; (3) they frequently inhabit the same sedimentary horizon, and thus provide an intergeneric check on the isotope results, and are thus best suited to give a reasonably continuous climatic record (Abell, 1982).

For palaeoclimatic studies, well-preserved specimens have been selected, whole shells ground to a powder, oxygen isotope ratio measurements made and values reported versus the PDB standard. Values varying over a range of 7‰ have been reported. Excursions towards negative values represent non-evaporative conditions and indicate cool and / or wet climates and brackish to freshwater conditions. Excursions of the oxygen isotope curve toward positive values represent evaporative regimes and indicate dry and / or hot climates and brackish water conditions.

However, values of $\delta^{18}O$ from zero to +2 or 3% have been found in freshwater lakes such as Lake Victoria indicating highly fractionated rainfall rather than brackish lake conditions. This is probably the global or la-titudinal pattern which involves a continuous decrease in $\delta^{18}O$ in precipitation from the equator toward the polar re-gions. It is not some manifestation of the “continental effect” in which the earliest precipitation from a moving air mass is isotopically heavy and later precipitation isotopi-cally light.

Detailed study of samples along the spiral growth structure of the gastropod shells demonstrates that they are sensitive recorders of water temperature during their approximately one year of normal lifetime. This means that the general isotopic ratios of oxygen isotopes in freshwater gastropods can be used to picture overall environment, and detailed studies of individual gastropods used to show seasonality of climate.

The climatic trends recorded in Lake Turkana have some contemporary analogies in Africa. The warm/dry periods which have characterized much of the past at Lake Turkana and which prevail today are also recorded in much the same oxygen isotope ratios in modern gastropods at Lakes Victoria, Edward, Albert and Kivu (Abell, 1982).

Using stromatolites

Compared to other lake indicators, stromatolites are treasure-houses of information. Like most biogenic carbonates, they keep a record of the time gone by (^{14}C, Th/U) but also an isotopic print of the palaeoenvironment of deposition (^{13}C, ^{18}O). In addition, they are valuable because they precisely mark ancient shorelines.

Well developed stromatolites with preserved blue-green algal microfossils are found at different stratigraphic levels in Plio-Pleistocene lacustrine sedimentary deposits of the lake ancestral to modern Lake Turkana. A sequence of these fossil stromatolites has been examined for $\delta^{18}O$ and $\delta^{13}C$ content (Abell et al., 1982). From two to twenty intact and solid interior fragments of stromatolites were collected from each of seven beds.

The intact stromatolites were slabbed with a diamond saw and the slabs then sampled at intervals of 2–5 mm for the isotopic analyses. The fragments were baked at 400-450°C in vacuum for four hours to remove any organic material, and weighed samples (5 – 7 mg) were then dissolved in 100% phosphoric acid on a standard vacuum line to liberate the carbon dioxide. Isotope ratios were measured on a V.G. Micromass 6002 ratio re-cording mass spectrometer, using a second standard for comparison. All isotope ratios were reported vs. PDB.

The stable isotope ratios obtained for oxygen and carbon indicated changing climatic conditions, ranging from a cool, wet climate prior to Ca. 19 Ma to drier, warmer conditions around 1.4 Ma, followed in turn by a somewhat cooler and wetter climate at the end of the Pleistocene.

The basin of Lakes Natron and Magadi, on the Tanzanian-Kenyan border, is one of the lowest points of the east branch of the Rift. Today the two lakes, nearly dried up and covered with a fairly thick crust of trona, receive a small amount of water during the rainy season. However, the basin was occupied by much deeper, if not larger, lakes on several occasions during the Pleistocene. The most recent lacustrine episodes resulted in a nearly continuous belt of algal stromatolites some 50 m above the modern water level.

Three distinct generations of stroma-tolites, occasionally overlapping in stratigraphic position, are observed. The oldest exceeds the limits of the Th/U dating method (greater than 200,000 years); the interme-diate one is dated at about 130,000 years and the most recent between 12,000 and 10,000 years B.P. (Hillaire-Marcel and Casanova, 1987).

The three generations of stromatolites are characterrized by relatively high $\delta^{18}O$ and $\delta^{13}C$ values. These reflect a long residence time for the paleolake water, which would have been favourable to the establishment of an isotopic equilibrium between atmospheric CO and the dissolved inorganic carbon.

Using other carbonates

Oxygen isotope compositions of carbonates are controlled by the oxygen isotope compositions of the formation waters and by temperature. The oxygen isotope compositions of meteoric waters in turn are controlled by climatic factors. Consequently, isotopic analyses of groundwater carbonates provide excellent indicators of climatic conditions prevailing at their time of formation.

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East African waters are abnormally rich in the heavy Isotopes of oxygen and hydrogen. The isotopic data do not fall in a line characteristic of world-wide meteoric water ($\delta D = 8\delta^{18}O + 10$) but are instead on a line characteristic of evaporating waters ($\delta D = 5\delta^{18}O + 10$). This is a result of the fact that the rain partially evaporates as it falls through the dry East African atmosphere. Analyses of five rain waters from Olduvai Gorge and Lake Turkana ranged in D from +4.9 to +26.0 and in $\delta^{18}O$ from –0.4 to +3.5 (Cerling et al., 1977). The δD and $\delta^{18}O$ values of Lake Turkana and Lake Ndutu (west of Olduvai Gorge) are +37.1 and +5.84, and +41.7 and 6.7, respectively. Rain water has the lightest isotopic values of all the waters possibly involved in carbonate formation in this area. Three types of carbonates were analyzed: pedogenic calcretes, pedogenic nodules, and groundwater nodules from lacustrine clays.

Modern waters from East Africa could not produce the relatively low $\delta^{18}O$ values observed in these older sediments unless soil and groundwater temperatures were 35 - 45°C. This is completely unreasonable on the basis of faunal evidence. Therefore the soil and groundwaters from which the older carbonates precipitated, originated from rainfall that was at least 2 - 4 per mil lower in O content than found in modern waters of the region. This is favoured by lower evaporation rates and therefore implies that there was more rain in the past. Moreover, increased humidity might be expected to result in a decrease in temperature, which would cause a further decrease in O values of rainfall and groundwater. These results point to a drastic decrease in rainfall about 1.8 - 2.0 Ma at Lake Turkana and 0.5 - 0.6 Ma at Olduvai Gorge.

Radiocarbon dating of the bulk carbonate fraction from various depth intervals of four piston cores recovered from Lake Turkana resulted in good determinations of sedimentation rates in two of them (Halfman, 1987). Eight of the 15 radiocarbon dates yielded ages between 850 and 3,840 years B.P. In addition, a core-top sample from one of the cores yielded an age younger than 1950 A.D., due to the presence of nuclear bomb radioactivity.

The ages of the samples increased with depth downcore. Sedimentation rates were found to be roughly 0.5 cm/yr., based on the best-fit linear interpolation of the radiocarbon age versus depth in two cores. These rates are at least an order of magnitude larger than the other large lakes of the world, and two to three orders of magnitude larger than the deep sea. The fast sedimentation rates make Lake Turkana an excellent site for high-resolution paleoclimatic study.

HOMINID AND FAUNAL EVOLUTION

At various sites in Northern and Western Kenya, hominid and other faunal remains have been discovered, which have indicated the evolutionary development has been followed back several millions of years with the help of isotope dating.

Northern Kenya

Plio-Pleistocene lacustrine and fluvial sediments of the Koobi Fora formation along the East shore of Lake Turkana in Northern Kenya have become widely recognized because of their rich hominid and artifact assemblages. The Plio-Pleistocene sequences consist of a complex of alluvial fan, fluvial deltaic and lacustrine deposits exposed over an area approaching 2600 km^2. These deposits have been correlated using a series of volcanic tuff deposits, which have been dated by conventional K-Ar and $^{40}Ar/^{39}Ar$ total degassing geochronological methods. Some of these fossils date back as much as three million years and are accompanied by artifacts (stone tools) as old as two million years (Abell et al., 1982).

Western Kenya

The thick sedimentary sequences on Rusinga and Mfangano Islands on Lake Victoria contain a remarkably diverse and abundant Miocene vertebrate fauna, one of the most important in Africa, most notably because of the early hominids which have so far been described: two species of *Limnopithecus*, three of *Proconsul*, and *Kenyapithecus*. K-Ar isotopic ages obtained for associated volcanic rocks in the mammalian localities have been compared tentatively with the dates established for Miocene Land Mammal Ages in North America (Bishop et al., 1969).

DISCUSSION

Under optimum conditions, potassium-argon age determinations carried out on fresh crystal separates or whole-rock samples of igneous rocks should reveal the true age of primary crystallization. In practice, many difficulties arise. Certain minerals may occlude radiogenic argon during growth. These minerals, like rocks enclosing numerous undigested xenoliths of older rocks or minerals will contain excess argon, and age determinations made on them will produce discrepantly high “apparent” ages.

The main source of error in potassium-argon age determination, however, results from loss of radiogenic argon subsequent to crystallization or emplacement and the consequent production of discrepantly low “apparent” ages. Argon loss may be caused by the poor argon retentivity of the individual minerals or fabric of the rock, or it may result from the effects of subsequent events, such as partial recrystallization, tectonic strain, hydrothermal metasomatism, or surface weathering, that tend to release argon from the rock. If all the accumulated radiogenic argon is released from a rock or mineral the true age is said to be “overprinted” by the subsequent event that will be dated by potassium-argon age determination. Partially “overprinted” ages, intermediate between initial crystallization and some subsequent event, are very common.

Tuffs present special geochronological problems. Only rarely is it possible to be certain that all their constituent crystal and rock fragments are juvenile, and that age determination is revealing the true age of eruption. Admixture of quite small quantities of mineral fragments derived from the basement or from earlier volcanics can result in serious overestaimations of the age of tuffs. Again the very nature of pyroclastic deposits makes them especially subject to subsequent hydrothermal alteration, diagenetic changes, groundwater leaching, and weathering, all of which can cause severe argon loss and large reductions in their apparent ages (Bishop et al., 1969).

In dating Tertiary-Quaternary rocks, very small amounts of radiogenic argon must be measured, and this considerably reduces the accuracy of results. In many of the potassium-argon determinations done on the Rift volcanics, duplicate analyses were performed on samples containing less than 10^{-4} mm^3 gm^{-1} of radiogenic argon in order to establish the reproducibility of the measurements (Fairhead et al., 1972).

Anomalous variations in $\delta^{13}C$ and $\delta^{18}O$ were found in some of the stromatolites studied (Abell et al., 1982). The reason was found to be that the particular fragment being analyzed was from the outside or was next to a void in the stromatolite and had been subjected to weathering.

Great biases in age were found in some tuffs when fission-track counting was done only on a few zircons with very low track densities.

Statistical analysis of the results of dating Armenian Neogene-Quaternary volcanics (Bagdasaryan et al., 1973) showed that the maximum possible error in determination of their absolute ages are up to 30 - 35% for the rocks with ages from 0.5 to 2 million years, up to 20 - 25% for rocks with ages from 3 - 5 million years, and not more than 7 - 10% for the rocks with ages from 6 to 12 million years. The accuracy of measurements is, therefore, sufficient for separation of Upper, Middle and Lower Pliocene rocks and Pliocene-Pleistocene rocks.

Conclusion

Isotope geology has played a significant role in the reconstruction of the geological history of Kenya. The ge-neral sequence in the Cenozoic volcanics has been established by systematic mapping, supplemented by isotope age determinations, and shows a continuous history of rift formation and volcanic activity from mid-Tertiary times. Stable isotope ratio measurements on carbonates have been used to elucidate climatic conditions prevailing at the time of deposition of these carbonates.

Radioisotopic dates on igneous material related to fossils and artifacts excavated at hominid sites have enabled anthropologists, aided by stratigraphy and paleomagnetic studies, to erect an overall time scale for hominid evolution in East Africa.

The surface has barely been scratched. With the evolution of isotope geology into a highly diversified discipline, the applications to the solution of the jigsaw puzzle, which is earth history, are numerous.

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