to an oven-dry basis. In the chemical analyses of water, forest floor, and mineral soil we followed well-established procedures, using a Technicon Auto Analyzer for colorimetric determinations (NH_4^+, NO_3^-, Cl^-, SO_4^{2-}, and PO_4^{3-}) and an atomic absorption spectrophotometer for the analyses of metal cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+).

9. Forest floor composite samples were collected before and after fires at each of 110 randomly located semipermanent plots. The sample area totaled about 80 ha of the treatment watershed.
10. W. L. Pritchett, *Properties and Management of Forest Soils* (Wiley, New York, 1979).
11. W. A. Hough, *U.S. For. Serv. Res. Pap. SE-187* (1978).
12. L. J. Metz, *Soil Sci. Soc. Am. Proc.* **18**, 335 (1954); C. G. Wells and C. B. Davey, *ibid.* **30**, 399 (1966).
13. J. R. Jorgensen and C. G. Wells, *ibid.* **35**, 806 (1971); H. J. Lutz, *U.S. Dep. Agric. Tech. Bull. 1133* (1956); S. M. Old, *Ecol. Monogr.* **39**, 355 (1969).
14. Composite mineral soil samples were collected from three soil depths at each of 110 semipermanent plots before fires and again after fires and about 15 cm of rainfall (a 2- to 3-month interval). Soil sampling was organized in a randomized complete block design with blocks (7-ha burning compartments), soil horizons, and fire as main effects and fire and horizon interaction effects as potential sources of variation of experimental importance.
15. Wells sampled two types of ground water: ground water flow through surface soils and ground water from subsoils (at 10- to 15-cm and at 30- to 35-cm soil depths, respectively). Prefire concentration means for individual wells were used as covariates in an analysis of covariance, since they markedly improved the precision of fire-test models for most chemical constituents. Rainfall was above average during the postburn sampling period.
16. F. H. Bormann, G. E. Likens, D. W. Fisher, R. S. Pierce, *Science* **159**, 882 (1968); P. L. Johnson and W. T. Swank, *Ecology* **54**, 70 (1973).
17. C. W. Ralston, D. A. Binstock, P. van Nguyen, in *Proceedings, Florida's Water Resources—Implications for Forest Management* (Resources Report No. 6, University of Florida, Gainesville, 1979), pp. 77–82.
18. Supported by cooperative research grants from the Southeastern Forest Experiment Station, U.S. Department of Agriculture Forest Service, and Duke University. Partial support for manuscript preparation was received from Oak Ridge National Laboratory, U.S. Department of Energy, under contract W-7405-eng-26 with Union Carbide Corporation. We thank O. G. Langdon, J. E. Douglass, J. E. Henderson, and W. P. LeGrande, members of the U.S. Forest Service. We also thank more than 15 graduate students of the School of Forestry and Environmental Studies, Duke University, and especially D. A. Binstock and Phu van Nguyen. Publication No. 1739, Environmental Sciences Division, Oak Ridge National Laboratory.

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Salt Diapirs Bordering the Continental Margin of Northern Kenya and Southern Somalia

Abstract. *The presence of newly discovered diapirs of presumed salt origin is documented for the continental margin of northeastern Kenya and southeastern Somalia. These structures are probably a manifestation of a significant thickness of Lower Jurassic evaporites deposited during the rift and early-drift stages of the separation of Madagascar from the African continent.*

The proximity and parallelism of salt formations to continental margins and their presence at conjugate locations on both sides of the mid-ocean ridges have led several investigators to believe that the deposition of salt is related to processes active during the very early separation of the continents (*1*). In this report we document the presence of newly discovered diapiric structures that border the continental margin of northeastern Kenya and southeastern Somalia. We believe that these structures are salt diapirs on the subsided continent and on the embryonic ocean floor created during the separation of Madagascar from the mainland of Africa.

Salt deposits have been inferred on the basis of geophysical measurements beneath the sea floor of many rifted or passive continental margins and have in some instances been confirmed by drilling (*1*, *2*). Often, these deposits appear on seismic reflection profiler records as prominent diapiric structures. In places, they border the margins at conjugate locations on both sides of the mid-ocean ridges; for example, salt diapirs are observed on seismic reflection profiles on the continental margins of the South Atlantic Ocean north of the Rio Grande Rise–Walvis Ridge complex (*3*) and bordering the conjugate margins of Morocco and Nova Scotia (*1*, *4*) and of the Red Sea (*5*). Similar salt deposits have been inferred on the Atlantic continental margin of the United States as well as its predrift location off northwestern Africa (*6*).

Cruises 3618 and 3619 of R.V. *Vema* (see Fig. 1 for navigation) were devoted to studying the evolution of the western Somali Basin and East African continental margin by the use of geophysical techniques (multichannel seismic reflection, seismic refraction, gravity, magnetics, and echo sounding). Implicit in this study were the kinematics of the Madagascar-Africa separation.

Investigators have proposed several reconstructions for the fit of Madagascar in the Gondwana supercontinent (*7*). The weight of paleomagnetic evidence (*8*), physiographic evidence (*9*, *10*), and inferences from gravity measurements (*11*) strongly suggests that Madagascar moved south from northeastern Kenya and southeastern Somalia (Fig. 1). If this is correct, the margin bordering most of Kenya and Tanzania was created by the transform motion of Madagascar along Africa; the margin of northeastern Kenya and southeastern Somalia was formed by the rifting and drifting of Madagascar from Africa. The ship's track for the first of the two cruises was planned to determine the structures associated with the separation of Madagascar from the African continent. A major discovery of this cruise was the observation of a diapir field located on the continental margin of northeastern Kenya and southeastern Somalia. The diapiric structures are observed only on that portion of the continental margin formed by the rifting of Madagascar from Africa; they are not observed on the transform margin. Figure 1 shows the relative motion of Madagascar from Africa, based on the poles and rotations given by Bunce and Molnar (*10*), together with the location of the zone of diapiric structures as observed on seismic reflection records.

A typical crossing of the rifted section of the margin showing the diapirs is given in Fig. 2. The tops of the diapirs are covered, in general, by sediments with thicknesses between ~ 0.50 and ~ 0.75 second of the two-way travel time (~ 450 to ~ 675 m, based on a sediment velocity of 1.80 km/sec deter-

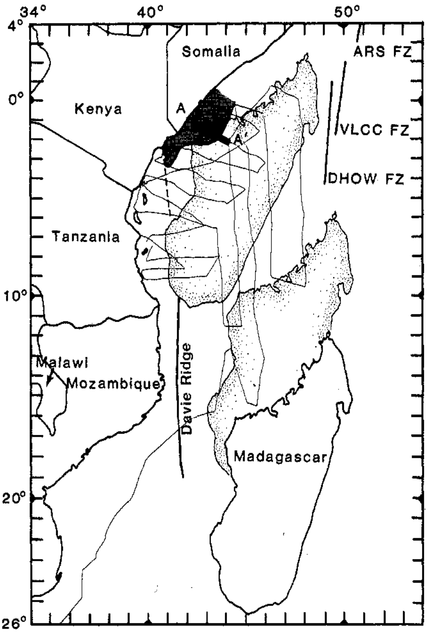

Fig. 1. Map of the study area. Madagascar is rotated back to its prebreakup position adjacent to East Africa according to the parameters of Bunce and Molnar (*10*). The track lines of R.V. *Vema* cruises 3618 and 3619 are shown as thin solid lines. Davie Ridge, the fracture zones (*FZ*) of Bunce and Molnar (heavy solid lines), and the gravity high (dashed line) are marked. The evaporite province is cross-hatched. Profile *A–A′* appears in Fig. 2.

mined by sonobuoy wide-angle reflection methods). The synclines between diapirs together with the arching and thinning of the strata overlying the diapirs suggest that the structures are indeed intrusive (*12*). The absence of residual gravity or magnetic anomalies above individual diapirs, together with compressional seismic wave velocities in the range of 3.5 to 4.2 km/sec beneath the tops of the diapirs, indicates the sedimentary, as opposed to igneous, nature of the structures (*13*). In some cases the intensity of deformation between the intrusive structures is greatest at depth and decreases upward, suggesting contemporaneous deposition and halokinesis (Figs. 2 and 3). Dissolution of the evaporites and associated faulting may account for the depression in the sea floor observed above the easternmost diapir in Fig. 3 (*14*). Coherent reflections from the interiors of the diapirs are absent, and diffraction patterns occur on the flanks of the structures; both observations strongly suggest that the diapirs are cored by evaporites. Furthermore, the tectonic setting—restricted or closed circulation basin—as derived from the marine magnetic anomaly pattern (*13*), and the occurrence of diapirs along only the rifted part of the margin, imply that these diapirs represent the movement of salt. We cannot rule out that the diapirs are of shale origin; presently only drilling could accomplish that. The age of the presumed salt movement has yet to be determined; however, the arching and thinning above the diapirs in the Middle to Late Tertiary section (Fig. 3) suggests the continuation of deformation into Neogene time.

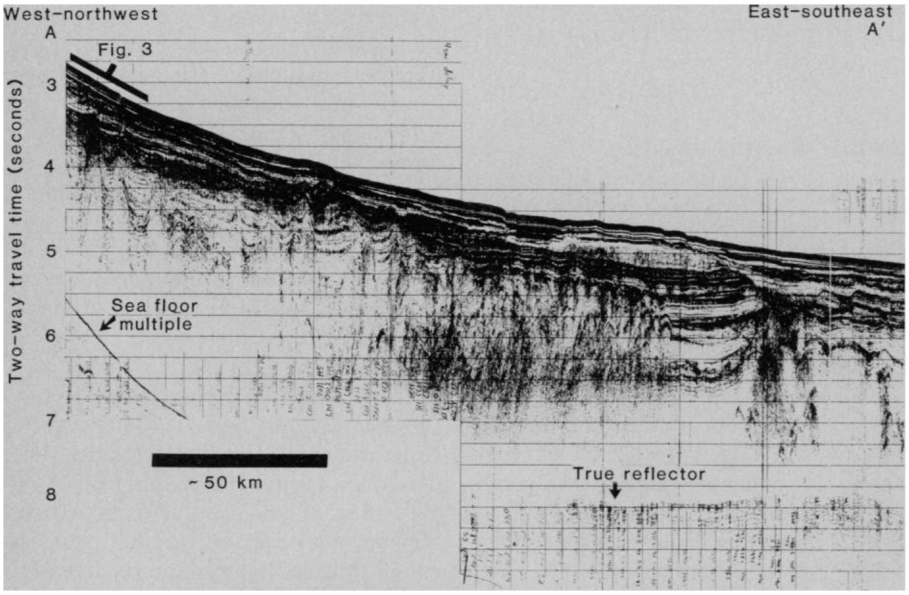

Fig. 2. Single-channel seismic profile of line *A–A′* (see Fig. 1 for location). Note the individual diapirs in the western segment of the profile, grading into an intensely deformed zone seaward. Still farther to the east is a buried channel of probable Late Miocene age, with underlying deformation (*14*).

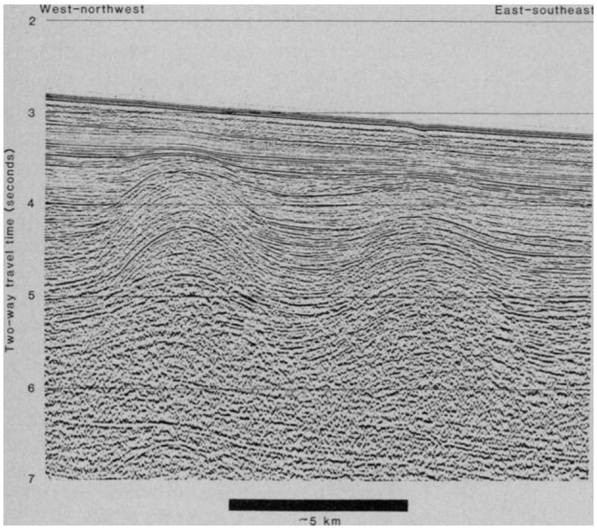

Fig. 3. Two distinct diapirs (see Figs. 1 and 2 for location), as they appear on 12-fold stacked nonmigrated multichannel seismic records. The sediment deformation becomes more intense with depth between the two diapirs. The depression in the sea floor directly above the easterly diapir is possibly the result of salt dissolution.

In addition, we observe a zone of very intense structures on the downslope sections of the profiles (Fig. 2). We are able to trace a reflector beneath this deformed zone at a depth of ~ 8 seconds of two-way travel time. We do not know at present the origin of this zone; it is probably a large slump or gravity slide that may have been initiated by salt movement farther upslope. The possibility cannot be excluded that some diapiric structures are present within this zone of deformation.

On the basis of magnetic anomaly identifications in the western Somali Basin, we believe the age of the presumed evaporites to be Early Jurassic (*13*). Deep Sea Drilling Project site 241, situated seaward of the diapirs (*15*), bottomed ~ 1.8 seconds of two-way travel time above acoustic basement in Upper Cretaceous clays and siltstones. The oldest sediments recovered by drilling in the coastal region off southeastern Somali and northeastern Kenya were ~ 3 km of mid–Upper Jurassic to Lower Cretaceous marine shales (*16*). None of the coastal wells here have penetrated sediments older than mid–Late Jurassic, and no evaporites have been encountered. However, about 3 km of evaporites of Permian (?) to Early Jurassic age have been drilled in an isolated graben bordering the transform margin of coastal Tanzania (*17*).

We believe that the fit of northern Madagascar to Africa such as that proposed by Bunce and Molnar (*10*) provided the restricted basin environment necessary for evaporite deposition. Unless there has been a ridge crest migration leaving all the evaporites on the African side, one would expect to see similar diapiric structures bordering northern Madagascar. It has been suggested that such ridge crest migrations occur during the initial separation stages of other areas (*18*). We did not observe diapiric structures on our track lines off northern Madagascar; the ship may not have approached close enough to the coastline to permit us to observe them, if indeed they are present. Drilling onshore and offshore in the northern Madagascar region through the entire Mesozoic section has not penetrated evaporites (*19*).

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References and Notes

1. G. Pautot, J. M. Auzende, X. Le Pichon, *Nature (London)* **227**, 351 (1970); K. Burke, *Geology* **3**, 613 (1975).
2. P. Rona, *An. Acad. Bras. Cienc.* **48**, 265 (1976).
3. L. W. Butler, *Geol. Soc. Am. Bull.* **81**, 1079 (1970); T. R. Baumgartner and T. H. van Andel, *ibid.* **82**, 793 (1971); R. Leyden, W. J. Ludwig, M. Ewing, *Bull. Am. Assoc. Pet. Geol.* **55**, 2161 (1971); R. Leyden, G. Bryan, M. Ewing, *ibid.* **56**, 682 (1972); P. D. Rabinowitz, *J. Geophys. Res.* **77**, 6327 (1972); G. Pautot, V. Renard, J. Daniel, J. Dupont, *Bull. Am. Assoc. Pet. Geol.* **57**, 1658 (1973); R. Leyden, H. Asmus, S. Zembruscki, G. Bryan, *ibid.* **60**, 196 (1976); J. Mascle and V. Renard, *An. Acad. Bras. Cienc.* **48**, 179 (1976).
4. M. J. Keen, *Can. J. Earth Sci.* **7**, 1561 (1970); L. H. King and B. MacLean, *Marit. Sediments* **6**, 1 (1970); N. L. McIver, *Can. J. Earth Sci.* **9**, 54 (1972); Y. Lancelot *et al.*, *Initial Reports of the Deep Sea Drilling Project* (Government Printing Office, Washington, D.C., 1980), vol. 50.
5. S. S. Ahmed, *Bull. Am. Assoc. Pet. Geol.* **56**, 707 (1972); G. M. Friedman, *ibid.*, p. 1072; J. D. Lowell and G. J. Genik, *ibid.*, p. 247; R. G. Coleman, in *The Geology of Continental Margins*, C. A. Burk and C. L. Drake, Eds. (Springer, New York, 1974), p. 743; R. B. Whitmarsh *et al.*, *Initial Reports of the Deep Sea Drilling Project* (Government Printing Office, Washington, D.C., 1974), vol. 23.
6. P. A. Rona, *Nature (London)* **224**, 141 (1969); K. O. Emery, E. Uchupi, J. D. Phillips, C. O. Bowin, E. T. Bunce, S. T. Knott, *Bull. Am. Assoc. Pet. Geol.* **54**, 44 (1970); P. A. Rona, *ibid.*, p.129; W. S. Olsen, *ibid.* **58**, 1191 (1974).
7. A. L. DuToit, *Our Wandering Continents* (Oliver and Boyd, Edinburgh, 1937); M. F. J. Flower and D. F. Strong, *Earth Planet. Sci. Lett.* **7**, 47 (1969); J. B. Wright and P. McCurry, *ibid.* **8**, 267 (1970); G. Flores, *Trans. Geol. Soc. S. Afr.* **73**, 1 (1970); A. G. Smith and A. Hallam, *Nature (London)* **225**, 139 (1970); J. R. Heirtzler, in *Antarctic Research*, L. O. Quam, Ed. (AAAS, Washington, D.C., 1971), p. 667; D. H. Tarling, *Nature (London)* **229**, 17 (1971).
8. M. W. McElhinney and B. J. J. Embleton, *Earth Planet. Sci. Lett.* **31**, 101 (1976); ______, L. Daly, J. P. Pozzi, *Geology* **4**, 455 (1976).
9. J. R. Heirtzler and R. H. Burroughs, *Science* **174**, 488 (1971).
10. E. T. Bunce and P. Molnar, *J. Geophys. Res.* **82**, 5305 (1977).
11. P. D. Rabinowitz, *ibid.* **76**, 7107 (1971); R. A. Scrutton, *Earth Planet. Sci. Lett.* **39**, 84 (1978).
12. F. Trusheim, *Bull. Am. Assoc. Pet. Geol.* **44**, 1519 (1960); R. S. Bishop, *ibid.* **62**, 1561 (1978).
13. M. F. Coffin and P. D. Rabinowitz, *Eos* **62**, 298 (1981); P. D. Rabinowitz, M. F. Coffin, D. A. Falvey, *ibid.*, p. 297; P. D. Rabinowitz and M. F. Coffin, in preparation.
14. H. H. Lohmann, *Bull. Am. Assoc. Pet. Geol.* **63**, 2097 (1979).
15. R. Schlich, F. Aubertin, J. Delteil, L. Leclaire, P. Magnier, L. Montadert, P. Patriat, P. Valery, *C. R. Acad. Sci.* **275**, 1331 (1972); E. S. W. Simpson *et al.*, *Initial Reports of the Deep Sea Drilling Project* (Government Printing Office, Washington, D.C., 1974), vol. 25.
16. M. D. Beltrandi and A. Pyre, in *Sedimentary Basins of the African Coasts*, G. Blant, Ed. (Association of African Geological Surveys, Paris, 1973), part 2, p. 159; R. Walters and R. E. Linton, in *ibid.*, p. 133; M. Kamen-Kaye and S. U. Barnes, *Oil Gas J.* **76/31**, 80 (1978).
17. P. E. Kent and J. T. O. Perry, in *Sedimentary Basins of the African Coasts*, G. Blant, Ed. (Association of African Geological Surveys, Paris, 1973), part 2, p. 114.
18. B. P. Luyendyk and E. T. Bunce, *Deep-Sea Res.* **20**, 537 (1973); S. Cande and P. D. Rabinowitz, Paper 3268, *Proc. Offshore Tech. Conf.* (1978), p. 1869; P. D. Rabinowitz and J. LaBrecque, *J. Geophys. Res.* **84**, 5973 (1979).
19. R. Brasseur *et al.*, *Inst. Pétrole Rev.* **14**, 3 (1959); H. Wories, personal communication.
20. We thank the officers, crew, and scientists on the R.V. *Vema* for their assistance in gathering the data. We express special thanks to W. C. Robinson for maintaining the multichannel seismic system. We thank J. Mutter and J. Ladd for critically reviewing the manuscript. This work was supported under National Science Foundation grant OCE 79-19389 (Office of Oceanography). This is Lamont-Doherty Geological Observatory Contribution No. 3271.

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Carbonyl Sulfide and Carbon Disulfide from the Eruptions of Mount St. Helens

Abstract. *Ash from the massive 18 May 1980 eruption of Mount St. Helens readily gave off large amounts of carbonyl sulfide and carbon disulfide gases at room temperature. These findings suggest that the sulfur that enhances the Junge sulfate layer in the stratosphere after volcanic eruptions could be carried directly to the upper atmosphere as carbonyl sulfide and carbon disulfide adsorbed on ash particles from major volcanic eruptions.*

The eruptions of Mount St. Helens have provided a unique opportunity to study the sequence of volcanic events that precede and follow the massive dacitic explosions of volcanoes. We report here our studies of gases emitted directly by the volcano and those adsorbed on the ash particles. It has been demonstrated that the Junge sulfate layer in the stratosphere is enhanced after volcanic eruptions (*1*). It has been suggested that the SO_2 from volcanic eruptions is the source of sulfur for this sulfate layer (*2*, *3*); however, we have found that volcanic ash releases COS and CS_2 but no SO_2 or H_2S at room temperatures, which may be another significant mechanism for the transport of sulfur from volcanoes to the stratosphere. The idea that the nonvolcanic COS and CS_2 might be a source of the sulfate layer has been suggested by several investigators (*4*, *5*). Hobbs *et al.* (*6*) observed that H_2S [~ 1 part per million (ppm)] was the dominant sulfur gas close to the ash plume of the major 18 May and 25 May 1980 eruptions at 3 to 5 km. Small amounts of COS and CS_2 were also observed. The flux of SO_2 increased dramatically only after 25 May, and SO_2 became the dominant gas after the 13 June eruption. These results, together with ours, suggest that SO_2 may not be the major sulfur-containing gas emitted from the volcano until after the major explosive eruption. Thus COS and CS_2, adsorbed on ash, may be more important contributors of volcanic sulfur to the stratosphere.

We collected volcanic ash both before and after the major eruption of Mount St. Helens on 18 May 1980, and from a light aircraft we collected air samples of the volcanic emissions. The air was collected in stainless steel flasks, with inert internal surfaces (rendered inert by the SUMMA process), reaching pressures of 1.35 to 2.0 atm. The trace gases studied were found to be stable in the containers and were analyzed within a few hours after collection. The gases emitted by the volcano underwent great dilution by ambient air before we could collect them, and so we measured $CFCl_3$ (F-11) and CF_2Cl_2 (F-12) in all the samples to obtain an estimate of the dilution factor. If we assume that F-11 and F-12 are entirely man-made, the dilution factor D is equal to $(1 - r)^{-1}$, where r is the ratio of the F-11 concentration in the plume sample to that in ambient air.

The ash samples, collected at several distances from the mountain, were sealed in the field in airtight 2- and 4-liter stainless steel cylinders fitted with Nupro SS-4-H-4 bellow valves. We used this arrangement of valves to first desorb trace gases from the walls of the containers under vacuum and then to purge the containers with a synthetic contaminant-free zero air at 150° to 200°C in the laboratory before filling them in the field with volcanic ash. Samples processed in this way have proven to be free of contaminants as compared to samples casually collected in plastic bags or glass jars. In addition to the direct analysis of the gases in the headspace above the ash in the field samplers, 100-g samples were removed and transferred to similarly cleaned 1.5-liter Pyrex flasks fitted with graded seals to Nupro SS-4-H-4 valves. All the samples were pressurized to 1.0 atm with dry synthetic air and were allowed to stand for at least 4 days before being analyzed. The COS and CS_2 were measured by gas chromatography–mass spectrometry (GC-MS) isothermally at 0° and 100°C, respectively, on a glass column (0.64 cm by 2.7 m) packed with 10 percent OV-101 on Chromosorb W. We made quantitative measurements on 5-ml samples, using single-ion monitoring at mass-to-charge ratio (m/e) 60 for COS and m/e 76 for CS_2. Additional GC-MS scans were made on larger air samples (~ 500 ml) concentrated by a cryotrap. In this case the samples were injected onto the column at 20°C, and then the temperature was raised at 8°C per minute to 150°C. The COS and CS_2 were measured independently with a flame photometric detector (FPD-GC), which was also capable of measuring H_2S, SO_2, and dimethyl sulfide. The CS_2 was measured with an electron-capture detector (EC-GC) in the analysis of the halocarbons present in the samples.

The results of the air analyses are shown in Table 1. The absence of any CS_2 in the majority of these events and in