bedroom, kitchen, and bathroom walls. The highest amounts of contamination have generally been observed on wood surfaces, that is, doors or window frames. None of the apartments studied was found to be uncontaminated (*5*).

An evaluation has been made of the dose rate at various positions while the instrument is in operation to ensure that there is no radiation exposure hazard to either the operator or apartment occupant from its use. The operational doses at the distances indicated are as follows: (i) 6 inches (15.2 cm) directly in front of the uncapped source, 25 mr/hr; (ii) 6 inches directly in front of the capped source, background; (iii) 12 inches from the wall surface with the instrument in the operating position against the wall surface, 0.03 mr/hr; and (iv) at the surface of the hollow, wood-lathed, plastered wall directly opposite the source, that is, transmission through the wall with the least amount of attenuation, 0.25 mr/hr.

Since the source is uncapped only when it is pointed at a wall surface, exposure condition (i) is expected not to occur in practice with the instrument in the hands of a trained operator. Condition (iv) is unlikely to occur, but may be considered the "worst possible condition" as far as the apartment occupant is concerned. A 2-minute exposure at this position would produce a total exposure of $0.25 \times 1/30 = 0.0085$ mr. Radiation protection guides in current use allow a cumulative exposure of 500 mr for 1 year to an individual (*6*). An exposure of 0.0085 mr is a negligible fraction of this total. The exposure due to backscatter (0.03 mr/hr) to the operator is also well below radiation exposure limits for occupational exposure.

GERARD R. LAURER
THEO. J. KNEIP, ROY E. ALBERT
Institute of Environmental Medicine, New York University Medical Center, New York 10016
FREDERICK S. KENT*
Environmental Health Services, New York City Department of Health, New York 10013

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* Present address: Office of International Health, Department of Health, Education, and Welfare, Washington, D.C. 20201.

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Final Desiccation of the Afar Rift, Ethiopia

Abstract. *Stable and radioactive isotope studies of ancient corals and mollusks from a fossil atoll in the Afar Rift indicate that final separation of the Afar Depression from the Red Sea occurred not earlier than 32,000 years ago. Desiccation followed within a few thousand years. The events recorded in the Afar Rift illustrate the processes occurring in the incipient stages leading to the formation of an oceanic body by rifting of a continental block.*

The geology of the Afar Depression of Ethiopia is of great interest because it may elucidate the processes that take place during the earliest stages of the formation of an oceanic body by rifting of a continent. The northern part of the depression, as much as 120 m below sea level, is an elongated rift located between the Ethiopian Plateau and the Red Sea (Fig. 1). Between the depression and the Red Sea lie the Danakil Alps, an ancient continental block that was originally part of the Ethiopian Plateau. Separation of the Danakil Alps from the plateau by tensional and rotational movements (*1*) created the depression. As a consequence of these motions, continental crust is missing below the axial zone of the northern Afar Rift (*2*). The depression was an intermittent marine basin until late Pleistocene time (*3*), when it last became severed from the Red Sea, probably by newly formed volcanic structures in the Gulf of Zula area. Final desiccation followed. In this report we attempt to date these events.

During recent expeditions to Afar (*4*), a series of originally submarine volcanoes were discovered (*5*). Among them is a volcanic cone about 50 m high and 500 m wide. This structure, located in the axial zone of the rift at about 13°20′N and 41°00′E (Fig. 1), may be considered a fossil atoll, since it consists of a ring of submarine basaltic pyroclastics capped by molluscan deposits and a well-preserved coral reef. The fossil organisms were evidently living during the time between cessation of volcanic activity and desiccation of the depression. Stable O and C isotope analyses of calcium carbonate from these organisms were done to study the progress of desiccation. Age determinations were made by C^{14} and Th^{230}/U^{234} methods. Procedures and assumptions pertaining to the latter method have been given by Thurber *et al.* (*6*) and Osmond *et al.* (*7*), among others. Results are shown in Table 1.

Sample M-8A, a large pelecypod (probably of the genus *Tridacna*), consists of an outer portion, which is almost pure calcite ($M\text{-}8A_2$) clearly derived from recrystallization of aragonite, and an inner zone, which is pure aragonite ($M\text{-}8A_1$), as determined by x-ray diffraction. Stable O and C isotope analyses and C^{14} dating were performed on both the calcitic and aragonitic parts.

Sample M-8B, a coral probably belonging to the genus *Astracosmilia*, also showed some evidence of recrystallization of calcite from aragonite, but the two crystalline phases could not be physically separated for analysis. This sample was analyzed for both Th and U and for stable O and C isotopes, but not for C^{14} dating.

The O^{18}/O^{16} and C^{13}/C^{12} analysis of the aragonitic, unrecrystallized mollusk sample M-8A gave values that indicate a normal marine environment (Table 1). The recrystallized calcitic portion of the same mollusk (sample $M\text{-}8A_2$), on the other hand, gave an O^{18}/O^{16} composition of +12.2 per mil, which indicates recrystallization in a hypersaline environment. If the relationship between O^{18}/O^{16} composition and salinity discussed by Craig (*8*) obtains, the salinity of this environment can be calculated to have been about 75 per mil. The O^{18}/O^{16} composition of the coral (sample M-8B) is about 5 per mil heavier than usual in unrecrystallized corals (*9*), obviously a result of the

Table 1. Stable and radioactive isotope data on organic carbonate samples from the Afar Depression, Ethiopia. The δO^{18} and δC^{13} values refer to the Chicago standard PDB-1; errors are ± 0.1 per mil. C^{14} errors are 1 σ (samples ML684 and ML664). U^{234}/U^{238} and Th^{230}/U^{234} ratios are activity ratios; U and Th errors are the 0.10 level of significance of radiometric count.

Sample No.	Type	Mineralogy	δO^{18} (per mil)	δC^{13} (per mil)	C^{14} age ($\times$ 1000 years)	U (ppm)	$\frac{U^{234}}{U^{238}}$	$\frac{Th^{230}}{U^{234}}$	$\frac{Th^{230}}{U^{234}}$ age ($\times$ 1000 years)
M-8A_1	Mollusk	Aragonite, unrecrystallized	0.0	+0.9	31.6 ± 0.8	0.50 ± 0.02	1.20 ± 0.08	0.392 ± 0.034	54.0 ± 4.6
M-8A_2	Mollusk	Calcite, recrystallized	+12.2	−0.2	$30.0 + 0.9 - 0.7$	—	—	—	—
M-8B	Coral	Calcite and aragonite	+ 1.6	0.0	—	1.34 ± 0.03	1.12 ± 0.04	0.294 ± 0.017	37.8 ± 2.2

partial recrystallization mentioned above.

In conclusion, the O and C isotope analyses indicate deposition of skeletal material under normal marine conditions, followed by recrystallization during evaporation and increased salinity.

C^{14} analysis dates the formation of the unrecrystallized portion of the mollusk specimen (sample M-8A_1) at 31,600 years ago, and recrystallization as having occurred most probably within about 2000 years (sample M-8A_2 in Table 1).

The Th-U age of the unrecrystallized mollusk sample (M-8A_1) is 54,000 years, which is considerably greater than the corresponding C^{14} age. This is expected because mollusks are often open systems with respect to U migration (*7, 10*). The age obtained for the coral sample (M-8B) is 37,800 years, or about 6,000 years greater than the C^{14} age obtained for the unrecrystallized mollusk sample (M-8A_1). Although corals appear to be generally closed systems with respect to U migration, the amount of recrystallization observed in the sample obviously resulted in some loss of U. Two additional samples were analyzed for Th and U. One showed evidence of original or acquired Th, as indicated by the presence of Th^{232}, which would tend to give a determined age older than actual (determined age was 90,000 years); and the other had a Th^{230}/U^{284} ratio distinctly greater than 1.0, which is clearly undatable and probably resulted from preferential removal of U after emergence. These two samples are not reported in Table 1.

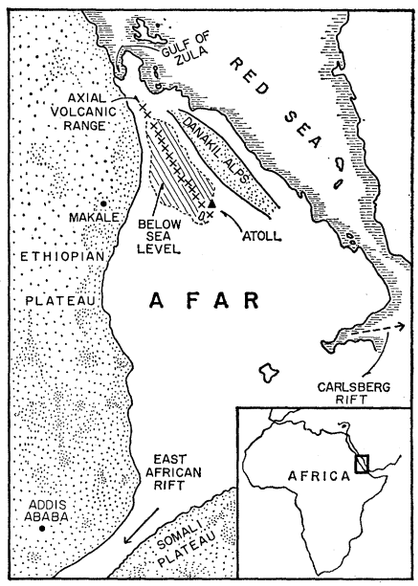

Fig. 1. Map of the Afar region showing the area below sea level and the axial volcanic range.

Because of the large net evaporation rate of the Afar region, growth of marine invertebrates could not have occurred much after the final separation of the region from the Red Sea. Thus, volcanic events responsible for this separation are dated at not earlier than about 32,000 years ago. Within 2000 years, desiccation had proceeded to the point where a substantial portion of the original seawater had evaporated, as indicated by the oxygen isotopic value given by the recrystallized mollusk sample (M-8A_2). Total desiccation might have taken another 2000 years. In any case, final separation of the Danakil Depression from the Red Sea appears to have occurred not earlier than 32,000 years ago, and desiccation to have occurred largely or entirely within a few thousand years.

The evaporite deposits, which carpet the northern Afar Depression to a depth of at least 3 km (*11*) and are evidence of earlier open marine stages in the area (*3*), indicate that northern Afar has been subjected to various episodes of marine transgression alternating with partial or total desiccation. These events are probably caused by the interplay of the tectonic motions associated with the rifting and the injection of basaltic magma along the rift; they illustrate the processes taking place in the incipient stages leading to the birth of an oceanic body by rifting of a continental block. The development of the proto-Atlantic by rifting of Pangea must have occurred along similar lines, as suggested by the existence on the opposite sides of the Atlantic of evaporite deposits contemporary with the opening of the Atlantic rift (*12*).

ENRICO BONATTI
CESARE EMILIANI
GÖTE OSTLUND, HAROLD RYDELL
Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Virginia Key, Miami, Florida 33149

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