Estimating the age of formation of lakes: An example from Lake Tanganyika, East African Rift system

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ABSTRACT

Age estimates for ancient lakes are important for determining their histories and their rates of biotic and tectonic evolution. In the absence of dated core material from the lake's sedimentary basement, several techniques have been used to generate such age estimates. The most common of these, herein called the reflection seismic-radiocarbon method (RSRM), combines estimates of short-term sediment-accumulation rates derived from radiocarbon-dated cores and depth-to-basement estimates derived from reflection-seismic data at or near the same locality to estimate an age to basement. Age estimates from the RSRM suggest that the structural basins of central Lake Tanganyika began to form between 9 and 12 Ma. Estimates for the northern and southern basins are younger (7 to 8 Ma and 2 to 4 Ma, respectively). The diachroneity of estimates for different segments of the lake is equivocal, and may be due to erosional loss of record in the northern and southern structural basins or to progressive opening of the rift. The RSRM age estimates for Lake Tanganyika are considerably younger than most prior estimates and clarify the extensional history of the western branch of the East African Rift system.

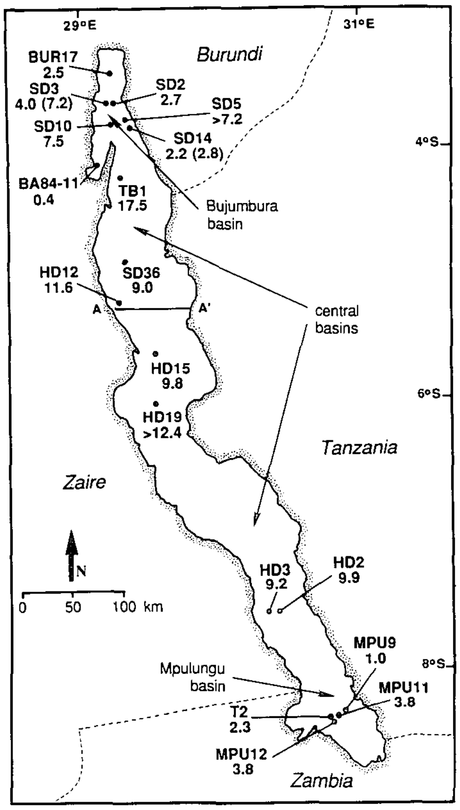

Figure 1. Location map of core sites included in this study. Lower numbers below core-site designations (described in more detail in Table 1) are RSRM age estimates from silt compaction model. RSRM age estimates from shale compaction model are from 10% to 20% higher (see Table 1). For sites SD3 and SD14, two age estimates given are based on varying sediment-accumulation rates discussed in text and Table 1. Note cluster of older values in central regions of lake and consistently younger age estimates at north and south ends. Cross section A-A' is location of seismic line shown in Figure 3.

INTRODUCTION

Speculations about the ages of ancient lake basins have figured prominently in debates over many issues, from rates of evolution in endemic species flocks (Brooks, 1950; Coulter, 1991) to the history of rift tectonism (Ebinger, 1989). Much of this discussion has been stymied by the absence of adequate outcrops or cores that penetrate basement (Rosendahl and Livingstone, 1983). As a result, indirect methods have been used to estimate ages for specific lakes. Four methods have figured prominently in these efforts. (1) Assessment of the regional tectonic setting of the lake basin can establish a maximum age of lake formation (Ebinger, 1989). (2) Comparison of a lake's extant species with related taxa found outside the lake through various methods can establish a minimum age of faunal divergence (Brooks, 1950; Coulter, 1991). (3) A deterministic model of basin evolution can be compared with a particular rift's stage of tectonic evolution. The geohistory of basins with good biostratigraphic age control is used as a standard for estimating the age of a modern lake at a particular stage of infilling (J. LeFournier et al., unpublished). (4) The combination of radiocarbon-derived accumulation-rate data from Holocene sediment and estimates of sediment thickness derived from reflection-seismic studies can produce an age estimate for a basin's fill (e.g., Tiercelin and Mondeguer, 1991).

Here we apply the reflection seismic-radiocarbon method (RSRM) to estimate the basal age of Lake Tanganyika, the largest of the African rift lakes (Fig. 1). We also examine the assumptions required for this method, given the known relation between structure and sedimentation in the African Rift (Rosendahl et al., 1986; Rosendahl, 1987; Johnson and Ng'ang'a, 1990; Scholz and Rosendahl, 1990).

The age of Lake Tanganyika has been debated since the turn of the century (Coulter, 1991, and references therein). Attempts to apply RSRM are dependent upon ^{14}C-based estimates of sediment-accumulation rate, which first became available for the lake in the 1960s and 1970s (e.g., Livingstone, 1965; Degens et al., 1971; Hecky and Degens, 1973). Recent seismic-reflection surveys and regional tectonic investigations have shown that the lake is segmented into several discrete half-grabens containing up to 4 km of sediment (Degens et al., 1971; Rosendahl et al., 1986; Ebinger, 1989; Scholz and Rosendahl, 1990; Tiercelin and Mondeguer, 1991). On the basis of these data, Patterson (1983) estimated a minimum age of 18.6 Ma for the Kigoma basin of the lake. Subsequent attempts to estimate the lake's age using similar data bases have produced similar ages ranging from 15 to 25 Ma (Rosendahl and Livingstone, 1983; Morley, 1988; Tiercelin and Mondeguer, 1991), with one notable exception (5–6 Ma; J. LeFournier et al., unpublished).

Two fundamental problems exist with the longer estimates. The first relates to the assumptions used in the calculations of duration of sedimentation, the second relates to alternative evidence for the tectonic history of the basin. The first problem arises because the two data required to make an age estimate (a rate and a thickness) have normally been derived from different localities. Previously, authors who have used RSRM have applied sediment-accumulation rates estimated from various basinal piston-coring localities to the maximum stratal thicknesses, which are usually found near faulted basin margins (Rosendahl et al., 1986). The assumption is that deep-water sediment-accumulation rates throughout Lake Tanganyika are invariant or at least do not vary in a systematic fashion. Yet both Degens et al.'s (1971) variable sediment-accumulation-rate data (sediment-focusing related to depth) and the pattern of thickening of seismic sequences toward faulted basin margins have provided unequivocal evidence that this cannot be true. Half-graben basins, as a consequence of their mode of formation and development of accommodation space, in the long run must accumulate sediments at a higher rate within their zones of maximal subsidence.

METHODS

We estimated sediment-accumulation rates from published ^{14}C data (summarized in Tiercelin and Mondeguer, 1991). All ^{14}C dates except HD15 were derived from bulk organic matter. For each ^{14}C-dated core, we based accumulation-rate estimates on the oldest date obtained from the core to reduce errors caused by the inverse correlation between estimated sediment-accumulation rate and duration (Sadler, 1981). In cores with more than one ^{14}C-dated horizon, the sediment-accumulation rates calculated for intermediate core intervals between ^{14}C-dated horizons were consistently greater than the sediment-accumulation rates calculated from the oldest ^{14}C-dated horizon. Therefore, our calculated sediment-accumulation rates provide a conservative (i.e., maximum) RSRM age estimate. In the cases of cores HD12 and HD3, our rate estimates came directly from Hecky and Degens (1973). For the two cores (SD3 and SD14) in which there is an inversion in ^{14}C age calculations (i.e., an older age was obtained from a stratigraphically higher horizon), we used both inverted ages to make two RSRM estimates. Radiocarbon dates from cores SD5 and SD19 represent minimum ages; therefore, RSRM estimates from these sites are minimum estimates.

We calculated total stratal thicknesses at each core locality from interval velocities along 24-fold seismic reflection profiles. We obtained interval velocities from rms velocities using the Dix equation (Dix, 1955) for the upper 2 s of sedimentary section. Additional assumptions included horizontal layering and no lateral velocity variations within the field of the velocity scans. Interval velocities within the sedimentary section ranged from 1480 to 3000 m/s. We assumed interval velocities of 3000 m/s for the deeper parts of the section on the basis of refraction studies in analogous basins in Lakes Malawi and Baikal (Ding, 1991). We calculated thickness estimates to the Nyanja event, a high-amplitude and well-defined two- to three-couplet reflector that is widespread in Lake Tanganyika and is interpreted to be prerift basement (Tack and DePaepe, 1983; Rosendahl, 1988). We estimated the uncompacted thickness of each sedimentary column following the methods of Sclater and Christie (1980). The degree of mechanical compaction is highly dependent upon lithology, which in this case is unknown below maximum core penetration, although seismic facies analysis suggests that all core sites are dominated by fine-grained deposits such as muds and diatom oozes. Therefore, we have made two calculations for uncompacted thickness; the first was based on an assumption of a sediment pile with 100% shale, the second with 100% siltstone. These two lithologies compose the majority of each core; therefore, the calculated values give reasonable maximum and minimum sediment thicknesses for each locality. These values were subsequently used to calculate a maximum and minimum RSRM age for each site.

RSRM AGE ESTIMATES

Core number, locality, depth, uncompacted thickness, sediment-accumulation rate, and RSRM age estimates are compiled in Table 1. The wide range of estimates, between 0.40 Ma and either 20.50 Ma (from the compaction model assuming 100% shale) or 17.49 Ma (assuming 100% siltstone), suggests that the initiation of sedimentation within the structural basins of Lake Tanganyika was highly diachronous, although only one estimate fell within the range of 15 to 20 Ma proposed by earlier authors.

The oldest estimates are from the central structural basins of the lake (Fig. 1). In this area we obtained estimates of between 10.44 and >13.50 Ma (100% shale model) and 8.99 and 12.40 Ma (100% siltstone model). A single, anomalously old estimate (20.50 Ma from 100% shale or 17.49 Ma from 100% siltstone models) for locality TB1 probably resulted from fault repetition, as inferred from the seismic data. Estimates for the Bujumbura (northern) basin are consistently younger than those of the central basins and show considerable variation, although a maximum "plateau" value of 7 to 8 Ma is evident. The single estimate we made from Burton's Bay (locality BA84-11) is considerably younger than any other estimate in the lake. Our estimates for the southern end of the lake (Mpulungu basin) are also considerably younger (maximum age estimates ~4 Ma) than those from the central parts of the lake.

There are some reasons for examining more carefully the structure of these estimates. RSRM age estimates showed great variation in water depths of <600 m (Fig. 2A). It is significant, however, that all of the deep-basinal sites (>600 m depth) yielded RSRM estimates within the modal range. Sediment-accumulation rates are extremely variable and do not correlate with water depth throughout the entire lake (Fig. 2B). This is clearly the result of differential patterns of sedimentation and erosion in different basins and does not invalidate the conclusions of Degens et al. (1971), that accumulation rates within a single basin are dependent on depth focusing.

TABLE 1. LOCATIONS AND WATER DEPTHS USED IN THIS STUDY PLUS DATA USED IN RSRM CALCULATIONS

Core	Location[†]	Water depth (m)	Core depth of ^{14}C age (m)	^{14}C age (yr B.P.)[§]	Sediment accumulation rate (mm/yr)	Sediment column thickness (m)	Decompacted sediment thickness (m) silt	Decompacted sediment thickness (m) shale	RSRM age (Ma) silt	RSRM age (Ma) shale
BA84-II	B basin (BFS11)	70	5.1	2700	1.84	630	730	790	0.40	0.43
MPU9	M basin (BFS18)	450	9.5	22,950	0.41	350	390	410	0.95	1.01
SD14[*]	B basin (BFS11)	230	5.2	11,640	0.45	830	990	1090	2.20	2.43
MPU12	M basin (BFS18)	422	10.0	25,650	0.39	1190	1500	1680	2.30	2.58
T2	M basin (BFS18)	440	10.3	15,900	0.65	1200	1500	1680	2.31	2.59
BUR-17	B basin (BFS9)	~200	5.7	6850	0.83	1560	2050	2330	2.47	2.81
SD14[*]	B basin (BFS11)	230	4.8	13,200	0.36	830	990	1090	2.76	3.03
SD2	B basin (BFS10)	325	5.2	5980	0.86	1750	2350	2690	2.74	3.13
MPU11	M basin (BFS18)	418	9.1	23,210	0.39	1190	1500	1680	3.85	4.31
SD3[*]	B basin (BFS10)	320	4.3	13,280	0.32	1030	1270	1410	3.96	4.41
SD3[*]	B basin (BFS10)	320	3.1	17,577	0.18	1030	1270	1410	7.20	8.02
SD5	B basin (BFS11)	223	5.5	>30,000	<0.18	1050	1300	1450	>7.22	>8.05
SD10	B basin (BFS10)	275	4.8	34,795	0.14	870	1050	1160	7.51	8.29
SD36	C basin (BFS13)	1245	4.9	12,740	0.38	2390	3420	3970	8.99	10.44
HD3[#]	C basin (BFS17)	1300	NP	NP	0.40[#]	2540	3680	4270	9.19	10.69
HD2	C basin (BFS17)	1380	2.5	6350	0.39	2630	3850	4480	9.86	11.48
HD15	C basin (BFS13)	1180	1.9	3750	0.51	3280	5020	5880	9.83	11.52
HD19	C basin (BFS14)	660	2.0	>28,200	<0.07	740	870	950	>12.40	>13.58
HD12[#]	C basin (BFS13)	1190	NP	NP	0.50[#]	3690	5790	6800	11.58	13.60
TB1	B basin (BFS11)	520	8.2	28,270	0.29	3310	5070	5950	17.49	20.50

[*] Estimates from cores with stratigraphic-age inversions.

[†] Basins refer to bathymetric basins labelled on Fig. 1.; B=Bujumbura; C=central; M=Mpulungu. BFS and number=the border-fault segment of Ebinger (1989).

[§] ^{14}C ages are conventioal radiocarbon age estimates.

[#] No supporting depth or age information was provided in the original document; only sediment-accumulation rates were given (Hecky and Degens,1973). NP=not provided.

DISCUSSION

RSRM age estimates for Lake Tanganyika obtained from coring sites are significantly younger than RSRM estimates made earlier by authors who used maximal sediment accumulations along border faults. Collectively, the Lake Tanganyika estimates support a maximum age for the lake of 12 Ma, although both northern and southern ends may be significantly younger. Taking into consideration Sadler's (1981) demonstrated inverse relation between sediment-accumulation rate and the duration of accumulation, it could be argued that the age estimates are too low, and that the earlier suggestions of an age of 15–20 Ma are reasonable. However, Sadler's (1981) data for small basinal seas (his Fig. 4, which best compares to Lake Tanganyika in terms of size and sedimentation rates) show little if any drop in sedimentation rates over the time span between 1 and 1000 ka. Sadler (1981) noted that the changes in rates of sediment accumulation for long-lived lake basins are comparable to those "seen in biogenic and terrigenous sediments accumulating below wave base" (Sadler, 1981, p. 578; i.e., comparable to his small basinal sea or abyssal trends). No data exist on attenuation of sediment-accumulation rates over the time span 1–1000 yr for Lake Tanganyika. However, Pilskaln and Johnson (1991) have shown that in similar environments in Lake Malawi there is a remarkably high completeness of the stratigraphic record over equivalent time intervals. Individual lamination thicknesses were measured for deep-basinal sediments from Lake Malawi; estimated durations from 1-mm-thick laminae couplets over intervals of up to 9 m of laminated sediments correspond closely to ^{14}C age determinations over the same interval (Pilskaln and Johnson, 1991, Table 2).

The deep-basinal sediments of large meromictic rift lakes like Malawi or Tanganyika display extremely high degrees of stratigraphic completeness; it is difficult to displace such sediments as a consequence of both their topography and isolation from wind-driven circulation. Erosion in shallower parts of the lake must result in enhanced accumulation in deep water. This accounts for the great variability in rates observed in shallower water environments simultaneous with their uniformity in deep water. Thus, decreases in completeness in the marginal parts of a deep rift lake must result in increasing completeness (and higher net-accumulation rates) in deeper environments. This hypothesis is supported by seismic studies from both Lake Tanganyika and Lake Malawi (Rosendahl, 1988; Scholz, 1989).

The depth cutoff between shallower water variability and deeper water uniformity (~660–1180 m) corresponds to a proposed lake-level drop of 600 m during the Pleistocene (Scholz and Rosendahl, 1988). If a 600 m drop did occur, regions shallower than 600 m would have inevitably undergone significant sedimentation-rate shifts during such lake-level fluctuations and, as Tiercelin et al. (1989) showed, probable erosional episodes. Regions deeper than 900 m (i.e., at least 300 m deep during a 600 m lake-level fall) would have remained deep-water environments and, given the smaller size of the remaining lake basins, would have been below the zone of wind-induced mixing (Fig. 3). The greatest stratigraphic completeness is likely to be found in these areas. Given the uniformity of rate estimates from the deeper parts of Lake Tanganyika, it is likely that the most accurate age estimates also come from these areas. Figure 2B indicates that age estimates of 9 to 12 Ma (all with rate estimates of ~0.5 mm/yr) for the central basins have the highest likelihood of accuracy of all measurements calculated *in* this study.

The cores from the Bujumbura (northern) and Mpulungu (southern) basins are all from water depths of less than 600 m, and these regions may have undergone periods of nondeposition or erosion. Therefore, RSRM age estimates for the northern and southern basins may be too low, underestimating the age of these basins. However, for the Bujumbura basin, our maximum age estimates of 7.51 Ma (siltstone compaction model) or 8.29 Ma (shale model) are in close concordance with available independent tectonic evidence. Ebinger (1989) showed that the Ruzizi basin at the north end of Lake Tanganyika became active prior to 6.5–5 Ma, on the basis of interbedded volcanic-sedimentary sequences overlying metamorphic basement. Elsewhere in the region, no demonstrably early or middle Miocene fossils have been recovered from within the Lake Tanganyika basin, although Neogene sedimentary deposits are commonly exposed (Tack and DePaepe, 1983; Pasteels et al., 1989). K/Ar dates from the Tanganyika region within the South Kivu basin and the Rungwe volcanic field (north of Lake Tanganyika; Tiercelin and Mondeguer, 1991) are also mostly late Miocene–Holocene. Older dates (cf. 20 Ma in South Kivu and 30–40 Ma in the Rungwe volcanic field) are clearly anomalous with respect to the bulk of volcanic activity in the region. In addition, both Burton's Bay (core locality BA84-11) and the extreme southern end of the lake are at present seismically active rift segments (Fairhead and Stuart, 1982). It is interesting to note that the pattern of RSRM age progression correlates very closely with magnitude of extension across Lake Tanganyika calculated from Project PROBE seismic

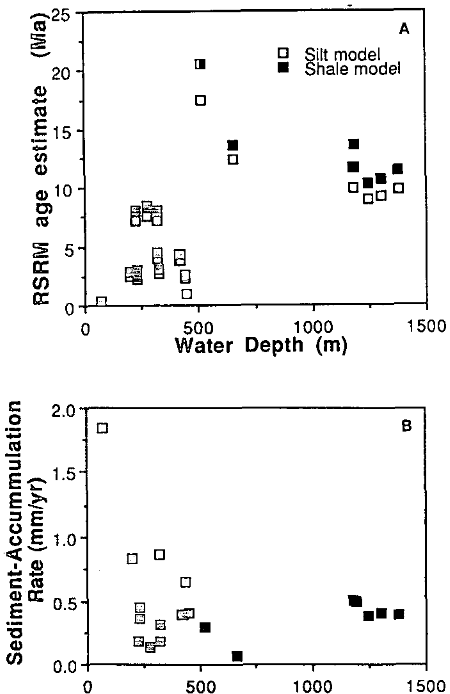

Figure 2. A: RSRM age estimates vs. water depth for 100% siltstone and 100% shale compaction models. Note consistency of RSRM age estimates for water depths greater than 600 m, maximum likely depth of previously inferred Pleistocene lake-level lowstands. Date of 17.5 (20.5) Ma is suspect because of fault repetition. B: ^{14}C-based sediment-accumulation-rate estimates vs. water depth. Note clustering of deep-water sediment accumulation rates, suggesting relatively continuous accumulation below maximum mixing depths during periods of lake-level lowstands.

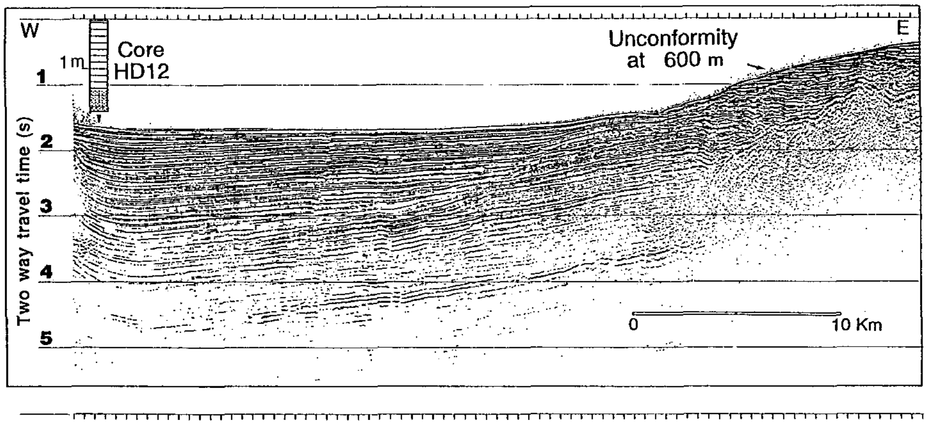

Figure 3. Multifold seismic line 8338 (position shown as section A-A′ in Fig. 1) with nearest projected position for core HD12. Horizontal lines are laminated diatom ooze; patterned area is silty-sandy turbidites. Note continuous, rhythmic character of deep-water acoustic stratigraphy (particularly near HD12 core location), suggesting high stratigraphic completeness, compared with discontinuous, variable-amplitude character of shallow-margin reflectors above 600 m unconformity.

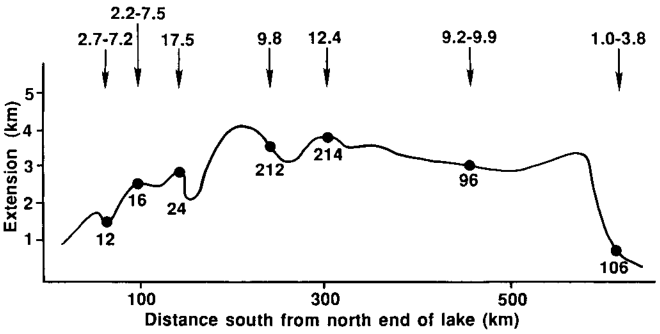

Figure 4. Plot of extension estimate along rift axis (from Morley, 1988) and corresponding RSRM age estimates. Curved line represents estimate of extension in dip direction along rift strike, assuming purely east-west extension. Numbers above curved line give RSRM age estimates. Solid circles represent location of seismic lines used in this study and are referenced by numbers below circles to Rosendahl (1988). Note that older RSRM ages occur consistently in regions of greater extension. Only ages calculated from seismic lines in common with Morley's (1988) data are shown, and age ranges indicate that two or more cores existed along same seismic line.

data by Morley (1988). Although his results are controversial (Scott et al., 1989), the similarities between older RSRM ages and greater extension are intriguing (Fig. 4). The central basins exhibiting the oldest RSRM ages have undergone between 3 and 4 km of extension, whereas the Bujumbura basin underwent only 1–3 km of extension, and the Mpulungu basin underwent <1 km of extension.

A late Miocene age for Lake Tanganyika imposes significant restrictions on both rifting and evolutionary processes. Discussions on subjects as diverse as the rates of coevolution in Tanganyikan endemic species flocks (West et al., 1991) and controversies concerning extensional rates and rift-propagation models (Morley, 1988; Scott et al., 1989) depend on accurate age estimates. Border-fault formation and volcanism on the eastern side of northern Lake Kivu (Ebinger, 1989), subsidence adjacent to border faults of Lake Rukwa (Wescott et al., 1991; Morley et al., 1992), and formation of the central basins of Lake Tanganyika all began in the late Miocene; intervening regions may exhibit younger ages. Verification of this, or any lake's, age must ultimately await deep drilling, an exciting prospect for all scientists concerned with the history of rift basins.

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