yielded a high-precision age of 1108 ± 16 ^{14}C yr before A.D. 1950 (QL-4623), which corresponds to a 95% confidence interval between A.D. 885 and 990 (3). This interval probably includes the time when the dated culms lived. Culms of modern *S. maritimus* at Puget Sound live less than 1 year and rarely stand dead for more than 2 years. By analogy, the dated culms lived within 3 years of the abrupt subsidence that killed the *S. maritimus* and that coincided, within months, with deposition of the sand sheet.

24. Oceanic tsunamis produced sand sheets along the southern Washington coast 300 and 1400 to 1900 years ago (*10, 11*)—times when little or no sand accumulated at our Cultus Bay and West Point sites.
25. Laboratory numbers, from greatest to least age: Beta-51806, -48232, and -48231; USGS-3090; Beta-51805. Ages calculated with an assumed δ^{13}C value of −25 per mil except for USGS-3090 (1040 ± 35 ^{14}C yr B.P.), which was calculated with a measured value of −26.8 per mil. Use of this measurement reduced the age by about 30 ^{14}C yr relative to the age that would have been obtained for a value of −25 per mil.
26. As in (*25*): Beta-50841, -49193, -52626, -52627, -52625, -49614, -49196, -52539, and -49194; QL-4623; Beta-51890 and -49615. Only ages for peat (P) and bulrush stems (S) were adjusted for the measured δ^{13}C value.
27. We thank D. Drake, K. Sharp, I. Khilfeh, and T. Gunstone for hospitality; B. Benson, S. Palmer, J. Bourgeois, L. Amidon, P. Atwater, P. Bierman, R. Bucknam, D. Clark, A. Eipert, B. Eipert, E. Eipert, C. Graff, B. Hallet, K. Hoppe, K. Nimz, D. Perkins, M. Reinhart, J. Shulene, R. Waitt, K. Whipple, and T. Yelin for field help; E. Hemphill-Haley and S. Cooke for fossil identifications; P. Reimer, M. Stuiver, and P. Wilkinson for high-precision radiocarbon dating; F. Bardsley for drafting; and R. Bucknam, D. Swanson, J. Bourgeois, A. Dawson, R. Waitt, and two anonymous referees for reviews.

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Paleoearthquakes in the Puget Sound Region Recorded in Sediments from Lake Washington, U.S.A.

Robert E. Karlin and Sally E. B. Abella

Holocene sediments in Lake Washington contain a series of turbidites that were episodically deposited throughout the lake. The magnetic signatures of these terrigenous layers are temporally and areally correlatable. Large earthquakes appear to have triggered slumping on the steep basin walls and landslides in the drainage area, resulting in turbidite deposition. One prominent turbidite appears to have been deposited about 1100 years ago as the result of a large earthquake. Downcore susceptibility patterns suggest that near-simultaneous slumping occurred in at least three separate locations, two of which now contain submerged forests. Several other large earthquakes may have occurred in the last 3000 years.

Recently, there has been increasing concern that the Pacific Northwest may be subject to infrequent great earthquakes caused by subduction of the Juan de Fuca plate under North America (*1–3*). The Puget Sound region itself is also seismically active, and occasional large earthquakes have occurred in recent times, such as the magnitude 7.1 Olympia earthquake in 1949 and the magnitude 6.5 Seattle earthquake in 1965 (*4, 5*).

The history of earthquake activity in Puget Sound has been difficult to decipher because the area lacks traditional morphologic indicators such as well-defined fault scarps from which the timing and areal extent of past earthquakes can be interpreted. Perhaps one of the most promising ways of assessing paleoseismicity is to study continuously deposited sedimentary sequences in lakes and fiords, where basin topography might be conducive to slumping and associated turbidite activity during a major earthquake. In addition to slumping from the sides, such bodies of water might also contain evidence of large changes in sediment input caused by earthquake-induced landslides in the drainage basin. Of course, seismically induced changes must be differentiated from changes due to climatic influences (floods, lake level variations) and nonseismic geotechnical effects (delta overloading and slope failure).

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Lake Washington, bounding the eastern side of Seattle, lies in a steep-sided glacially sculpted valley. The oligotrophic lake averages about 34 m deep and has a subdued W-shaped cross section with marginal elongate troughs 3 to 4 m deeper than in the center of the lake (*6*). The lake sediments consist of a thick sequence of blue glacial clay of indeterminate thickness that is overlain by 7 to 17 m of Holocene limnic peat or gyttja with a basal radiocarbon age of 13,400 years before the present (yr B.P.) (*6, 7*). The limnic section contains the Mazama ash with a radiocarbon age of ~6850 yr B.P. and distinctive post-1916 A.D. laminations that serve as key marker beds. The sediments are anoxic (*8*), so sediment disturbance due to bioturbation is minimal. The lake contains three sunken forests (Fig. 1) that were emplaced by massive block slides with trees still in growth position. The submergence of the forests, lying at the north and south ends of the lake, was originally dated at about 1160 ^{14}C yr B.P. (*9*), and more recently, by high-resolution dates on rings of standing drowned trees (*10*).

Sediments from a series of gravity and piston cores taken throughout the lake contain a record of quasi-periodic sedimentary disturbances that may represent turbidity flows or rapid changes in mass flux from the drainage area. Here we report sedimentologic and paleomagnetic analyses of a suite of ten 3-m-long gravity cores that span the last 3000 years and discuss spatial and temporal patterns of sedimentation that constrain the timing, sources, and causes of these disturbances.

Because the magnetic properties of sediments are sensitive to small changes in the concentration and grain size of magnetic minerals, measurements of magnetic susceptibility (χ) are an extremely useful remote sensing technique for correlating cores and rapidly identifying lithologic and textural changes. As shown in Fig. 1, susceptibility profiles (*11*) of the cores show a high degree of intercore correlation. The shape, position, and magnitudes of the χ peaks are in close agreement for all cases, and several features can be traced across the lake. The magnetic spikes appear to define terrigenous clay and silt layers, which signify short, intense periods of rapid mud accumulation. One interval at 10 to 30 cm is probably the clay and silt layer deposited as a result of the 3 m lowering of the lake level and opening of the Lake Washington Ship Canal in 1916 A.D. (*6, 12*).

Another dominant susceptibility peak at 80 to 110 cm is present in all cores. The peak is sharp at the base and gradational toward the top, a pattern suggestive of a turbidite because hydraulic sorting causes upward fining and concentration of the heavy magnetic minerals in the coarse basal layer. X-radiographs show a distinctive opaque layer 8 to 10 cm thick at this depth. Visual examination and detailed grain-size analyses on TT195 cores 8, 14, and 15 confirm that the layer shows graded bedding and thus has the characteristics of a distal turbidite.

The χ intensities for the horizon at 80 to 110 cm shows a distinctive dependence on location. Magnitudes are highest in the northern and southern cores and lowest in the central cores. A lone exception to this trend is in the core (TT195-5 gc) taken on the western edge of the central basin by Madison Park. This overall pattern suggests that there were multiple detrital sources for

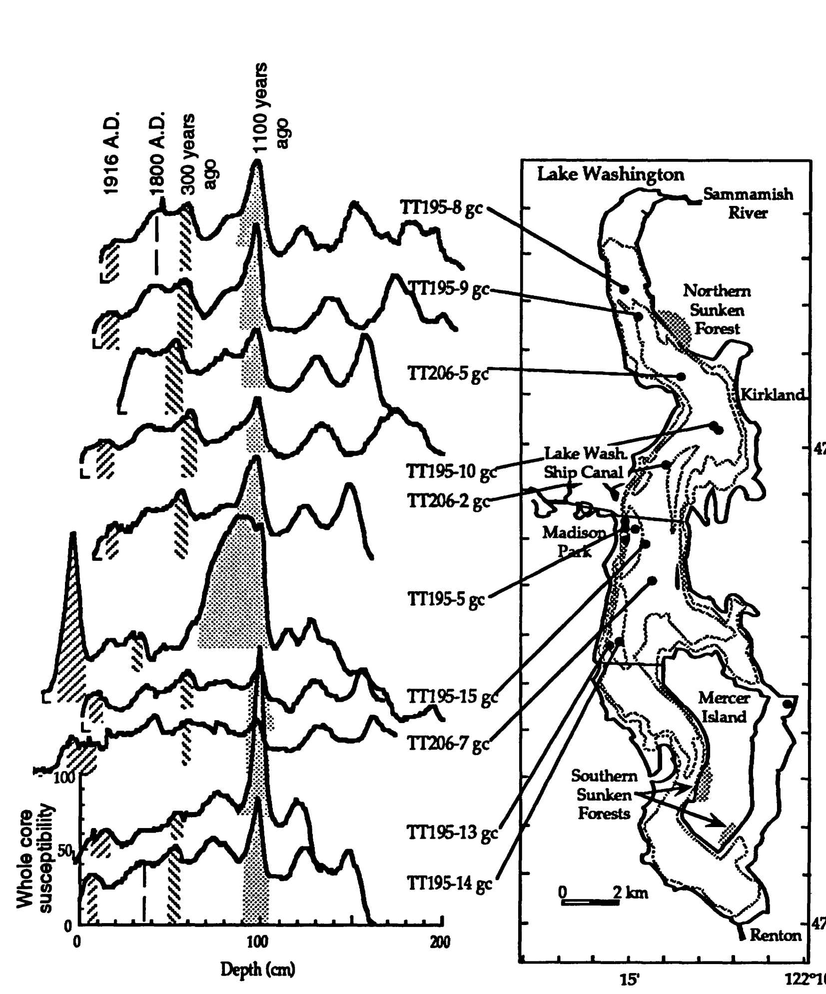

Fig. 1. Whole core magnetic susceptibility profiles of gravity cores from cruises TT195 and TT206B, and a location map of Lake Washington showing core sites and the sources of the sunken forest blocks off Kirkland and Mercer Island. Susceptibilities are given in 10^{-5} cgs units. The horizons with ages of 1916 A.D., 300 years ago and 1100 to 1200 years ago are shown as patterns on the profiles. Depths on the map are contoured at 20-m intervals.

a single event, such as landslides occurring nearly simultaneously in both the northern and southern portions of the basin as well as in an areally restricted zone near Madison Park. The lower relative amplitude of the peak in core 8 than in core 9 suggests that the turbidite layer originated at the sunken forest near Kirkland rather than from the mouth of the Sammamish River in the northernmost end of the lake.

To better delineate the nature of the sediments, major element chemistry (*13*), loss on ignition (LOI), petrography, and grain-size analyses were done on core 8. In general, the sediments are a mixture of diatoms and clay with varying amounts of silt- to sand-sized mineral grains. Volcanic glass is rare, and discrete ash layers are not observed; thus, the magnetic peaks are not of volcanic origin. With the exception of the turbidite at 80 to 110 cm, silt layers are not visibly discernible; however, textural variations are evident petrographically, and density bands up to 2 cm thick are present on the x-radiographs.

As shown in Fig. 2, the χ profiles vary directly with Al_2O_3 content and inversely with the loss on ignition (LOI) of the samples, which is an indication of organic matter content. The contents of Al_2O_3 and other terrigenous components also vary inversely with SiO_2 content. These relations confirm that the sediments are a mixture of two components consisting of (i) detrital aluminosilicates and (ii) biogenic silica (diatoms) and organic matter. These patterns also strongly suggest that the susceptibility variations were produced by increases in terrigenous flux to the lake and concomitant decreases in the biogenic and organic content. Magnetic measurements and scanning electron microscopy on magnetic separates indicate that the dominant magnetic minerals are detrital magnetite and paramagnetic clay. Grain size analyses indicate that the anomalous intervals are enriched in the silt-sized fraction. Such behavior is consistent with episodic turbidity flows or other rapid changes in terrigenous flux. The increased sediment flux occurs over a relatively large depth interval; this relation suggests that more than just local slumping has occurred. The drainage basin must have been subject to longer term disequilibrium, such as landslides followed by erosion, fluvial removal, and eventual drainage re-equilibration.

To determine the ages of the magnetic features, radiocarbon dates on cores 8 and 14 were obtained on the organic fraction from four horizons plus a 4-cm interval just below the base of the turbidite layer at 80 to 110 cm (*14*). In addition, an interval 6 cm below the base of the turbidite layer was dated in core 15.

Age-depth profiles (Fig. 2) show essentially linear sedimentation rates below 35 cm of 51 cm per thousand years (kyr) in core 8 and 55 cm/kyr in core 14. The apparent surface intercepts are misleading because several studies have shown that sedimentation rates in the lake increased after deforestation and urbanization accelerated in the 1880s (*15–17*). Radiocarbon ages of lacustrine sediments are often anomalously old because of dead carbon in the system that arises from the age, recycling, and decomposition time of vascular plant material and inorganic carbon before burial. To estimate this reservoir age, we identified three historical horizons in cores 8 and 14: (i) the 1916 A.D. horizon, on the basis of magnetic signatures and characteristic laminae above this interval; (ii) an *Alnus* (alder) pollen increase that occurred circa 1880 A.D. (*12*); and (iii) a change in the diatom population of *Aulacoseira sp.* at about 1800 A.D. The estimated raw radiocarbon age of the 1800 A.D. horizon is 953 ^{14}C yr B.P. in core 8 and 848 ^{14}C yr B.P. in core 14. These ages suggest that the reservoir age is between 700 to 800 years relative to a 1950 A.D. ^{14}C datum. This result is consistent with an estimated reservoir age of 650 years determined by comparing ^{210}Pb and ^{14}C ages of box-cored sediments from the lake (*16, 17*).

We established chronologies for cores 8 and 14 by fixing the three historical horizons and assuming that sedimentation rates deeper in the core were 51 cm/kyr and 55 cm/kyr, respectively. We determined calibrated age ranges at a 1σ level by assuming that the reservoir age was 750 years (Fig. 3). Sedimentation rates remain the same regardless of whether ^{14}C ages or the best calibrated age estimates are used. Combination of the 1σ end points of the calibrated dates yields an estimated uncertainty of ± 5 cm/kyr in the absolute sedimentation rates.

As a consistency check, the ratio of accumulation rates of core 8 to core 14 based on radiocarbon dating is 0.9, which is identical to the slope of the depth-depth curve established by matching magnetic features in the χ profiles. This result suggests that sed-

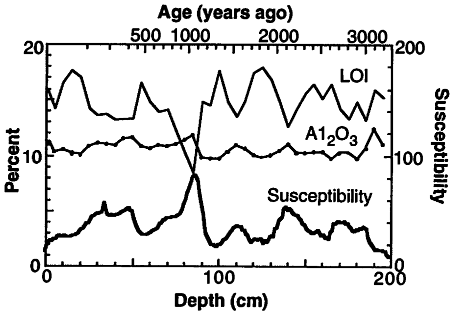

Fig. 2. Profiles of whole core magnetic susceptibility, Al_2O_3 contents of ashed samples, and loss on ignition values for core TT195-8 gc plotted against depth (lower axis) and age in years before 1990 A.D. (upper axis). Note the close correspondence between susceptibility and Al_2O_3 content and their inverse relation with LOI, which is a measure of organic content.

imentation throughout the lake has been essentially uniform for the last 3000 years and that the same episodic disruptions are found at both core locations.

The base of the turbidite layer at 80 to 110 cm for cores 8, 14, and 15 yielded corrected individual radiocarbon ages of 1050 ± 108, 1100 ± 108, and 1200 ± 192 ^{14}C yr B.P., respectively (*18*). The corresponding calibrated age ranges are 950 to 1110, 970 to 1200, and 970 to 1340 calendar years ago, respectively, at a 1σ level (Fig. 3). The mean age is 1117 ± 142 ^{14}C yr B.P. (960 to 1265 years ago). Assuming linear sedimentation rates were linear before 1800 A.D., the base of turbidite layer occurs at 1100 to 1200 ^{14}C yr B.P. in both cores 8 and 14.

These results are similar to the age of the submergence of the three forests in the northern part of the lake and off Mercer Island. We postulate that the magnetic high in the various cores is a silt band associated with the huge block slides that created the sunken forests. We attribute the magnetic peak to dilution of the normally non-magnetic biogenic sediment grains of magnetite and paramagnetic clay associated with an increased flux of terrigenous material. The sudden slumping may have caused huge seiches (large amplitude oscillations in lake level) and turbidity currents that deposited the layers throughout the lake. A similar pattern of seiching and turbidity flows was reported in Kenai Lake, Alaska, as a result of the 1964 Alaskan earthquake (*19*).

The increases in aluminosilicate accumulation rates could be caused by climatic factors such as increased precipitation or severe floods. We consider these mechanisms less plausible for several reasons. (i) Pollen and organic geochemical analyses done on piston cores from Lake Washington (*7, 20*) show that the climate has been stable for the last 6000 years and the region has been heavily forested. Thus, erosion in the drainage basin and lake productivity should tend to maintain a steady state. (ii) The drainage area of Lake Washington is unusual in that sediment input from the Cascades before 1916 A.D. first entered Lake Sammamish before arriving in Lake Washington by way of the small Sammamish River. Lake Sammamish thus acted as a settling pond buffering Lake Washington from episodic pulses of sedimentation originating in the High Cascades. (iii) Increased nutrient input during the modern flood season in winter and spring stimulates biogenic productivity in the lake and should result in increased organic accumulation during times of enhanced fluvial input. This pattern is contrary to what is observed. Indeed, sediment trap data from the severe winter floods in 1990 and 1991 (*22*) suggest that winter storms cannot produce anywhere near the amount of sediment needed to explain the observed thickness and distribution of the terrigenous layers.

Enhanced terrigenous fluxes could also be caused by pulses of erosion in the drainage basin from forest fires. Major fires should result in increased fluxes of organic matter as well as enhancements in pollen from disturbed species such as alder. Neither the LOI variations (Fig. 3) or pollen profiles (*7*) support this scenario.

The susceptibility records from throughout the lake are suggestive of a correlation of Lake Washington disturbances with events observed elsewhere. In addition to the event about 1100 years ago, other possible events occur at 300 to 400, 1600 to 1700, 2200 to 2400, and 2800 to 3100 years ago (Fig. 3). The event about 300 years ago, in particular, is synchronous with probable coseismic submergence of marsh grass and trees along the Washington coast (*24, 28*). The interval from 2800 to 3100 years ago roughly corresponds with three periods of landsliding deduced from the dating of drowned trees in the lake (*10*).

Given the dating uncertainties, the event about 1100 years ago is of the same age as a major subduction earthquake that caused rapid submergence of marsh peats (*23–25*) along the Oregon-Washington coast. This event also coincides with another postulated earthquake which may have caused faulting on the Olympic Peninsula (*26*), coseismic platform uplift and tidal marsh submergence around Puget Sound (*21*), and a possible tsunami near Seattle (*27*), presumably resulting from movement on the nearby Seattle Fault (*21*). The available data does not allow us to determine which earthquakes caused the disturbances in Lake Washington or whether subduction zone and upper plate seismicity were somehow coupled. Nevertheless,

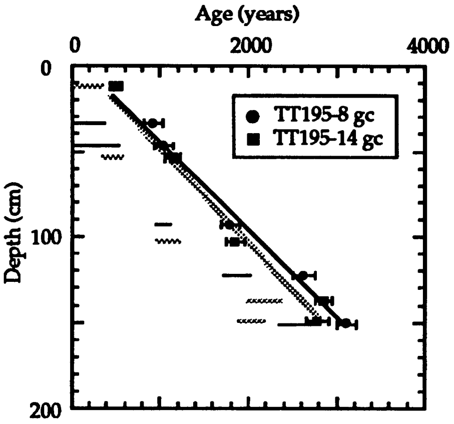

Fig. 3. Age-depth profiles showing raw radiocarbon ages (in ^{14}C yr B.P.) and dating uncertainties for cores TT195-8 gc (solid circles) and TT195-14 gc (solid squares) as well as their corresponding calibrated age ranges (in years ago).

the accumulated evidence is beginning to point to a number of near-simultaneous events throughout the region about 1100 years ago that are most simply explained by major seismic activity.

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Prehistoric Rock Avalanches in the Olympic Mountains, Washington

Robert L. Schuster, Robert L. Logan, Patrick T. Pringle

Rock avalanches blocked streams in the Olympic Mountains southwest of Puget Sound during the past few thousand years. Limiting radiocarbon ages indicated that three or four of six avalanches occurred from 1000 to 1300 years ago or shortly thereafter. Most of the dates were from the outer preserved rings of trees drowned behind avalanche dams. These three or four avalanches may be coeval not only with one another but also with abrupt tectonic deformation in western Washington. No rock avalanches in the Olympic Mountains are known to have resulted from storms or earthquakes during the past century. The avalanches strengthen the case that a large prehistoric earthquake occurred in the Puget Sound region.

Prehistoric earthquakes in western Washington have been inferred from features that suggest abrupt uplift (*1*), abrupt subsidence (*2, 3*), and tsunamis (*2, 3*). Although all of these features are consistent with earthquake-induced deformation, none of them demonstrates seismic shaking. Seismic shaking could be recorded by rock avalanches, which can be triggered by large earthquakes (*4*). We found 11 large prehistoric rock avalanches in mountains southwest of Puget Sound. We propose that at least three of these avalanches represent strong shaking in western Washington, and that this shaking may have accompanied abrupt vertical tectonic movement in the region.

The 11 rock avalanches are in the southeastern Olympic Mountains. All of the avalanches consist primarily of large boulders derived from Tertiary basalt, which is widespread on the south, east, and north sides of the range (*5*). Five of the avalanches blocked streams and produced small lakes (300 to 800 m long) in which trees died. The dams were 10 to 20 m high and as much as 300 m long.

Radiocarbon ages were obtained from plant remains associated with six of the rock avalanches (Table 1). At Jefferson Lake, Lower Dry Bed Lake, Spider Lake, and Lena Lake [see figure 1 of (*1*)], we dated the outer 10 to 30 rings preserved in bark-free trunks of separate standing dead trees (snags) that protrude from the lakes at times of low water (Fig. 1) (*6*). For each snag, we assumed that the dated rings predated the avalanche by no more than 100 years. The assumption is based on the belief that the trees died within a year of being drowned behind a rock-avalanche dam and on circumstantial evidence that the trunks have lost fewer than 100 external rings to postavalanche decay and erosion. At the Hamma Hamma River, we dated detrital wood and charcoal in lacustrine deposits behind a now-breached avalanche dam, and at Lake Cushman we dated stumps from a quarry in an avalanche (*7*).

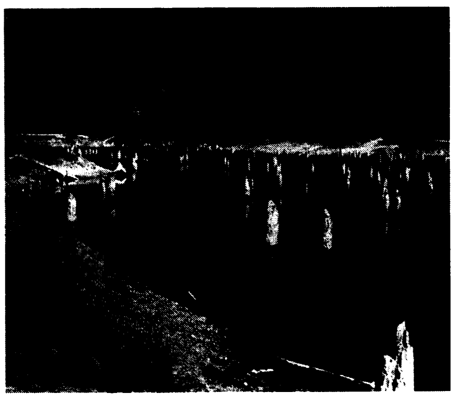

Fig. 1. Drowned snags extending above surface of Spider Lake at low-water level, September 1992.

The radiocarbon ages show that three or four of the six avalanches may have happened at the same time. The ages for the snags at Jefferson, Lower Dry Bed, and Spider Lakes overlap one another at or near 1 standard deviation. Snags at Lena Lake yielded somewhat greater ages; either the avalanche there is somewhat older or the dated snags have lost more rings than assumed. The other two avalanches yielded ages that are distinctly older (Hamma Hamma River) or younger (Lake Cushman). The weighted mean of the radiocarbon ages from Jefferson, Lower Dry Bed, and Spider lakes (1197 ± 23 ^{14}C years before the present) corresponds to a calibrated (approximately calendric) age in the range 1000 to 1300 years ago (*8*).

Three points suggest that strong shaking triggered most or all of the six avalanches, whatever their ages: (i) The basalt that avalanched is not known to have failed historically, either during storms or during the largest 20th-century earthquake at Puget Sound, which occurred in 1949 with a magnitude of 7.1 and a hypocentral depth of 54 km [(*9*); epicenter shown in figure 1 of (*1*)]. (ii) Worldwide, earthquakes triggered 29 of 71 rock ava-

Table 1. Radiocarbon ages (*13*) of wood and charcoal associated with rock avalanches in the Olympic Mountains

Avalanche location*	Sample (Beta-)	Age (^{14}C yr B.P.)
Lake Cushman (*7*)	50539	400 ± 50
	50540	420 ± 50
Jefferson Lake	42123	1150 ± 50†
	42124	1210 ± 50†
Lower Dry Bed Lake	50544	1180 ± 50
Spider Lake	50550	1260 ± 50
	50602	1180 ± 60
Lena Lake	32671	1340 ± 50†
	32672	1300 ± 50†
Hamma Hamma River (*7*)	50598	2900 ± 60
	39798	2960 ± 80†

*See figure 1 of (*1*). †$\delta^{13}C$ not measured. Age normalized to assumed $\delta^{13}C$ of −25 per mil.

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