Cosmogenic Ages for Earthquake Recurrence Intervals and Debris Flow Fan Deposition, Owens Valley, California

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Model exposure ages (beryllium-10, aluminum-26) of boulders on an offset debris flow fan yield an earthquake recurrence interval between 5800 and 8000 ^{10}Be:^{26}Al years for a strand of the Owens Valley fault in California, which last ruptured in an earthquake of moment magnitude >7.5 in 1872. Cosmogenic age estimates for this and several nearby fan surfaces flanking the eastern Sierra Nevada are consistent with stratigraphic relations and suggest that these surfaces were abandoned after 1000, 8000, and 21,000 ^{10}Be:^{26}Al years ago. The wide scatter and nonconcordance of ^{10}Be:^{26}Al ages on an older fan surface suggest that boulder erosion and lowering of the fan surface there have influenced apparent exposure ages.

The east front of the Sierra Nevada rises about 3000 m from the floor of Owens Valley (Fig. 1). Uplift, fluvial down-cutting, and repeated glaciation during the Pleistocene have etched deep canyons into the range front. At the mouths of these canyons, extensive alluvial fans merge into a gently sloping surface bordering the range and extending to the valley center, a distance of up to 10 km. These fans are bouldery and are formed in large part by debris flows (*1*). Near Lone Pine (36° 36′N, 118° 05′W), boulders are commonly granitic, equant, and 2 to 4 m in diameter; the largest exceed 10 m. Fan-building episodes and increased frequency of debris flows have been correlated with deglaciation in the Sierra Nevada (*2*) primarily on the basis of terraces mapped inside equivalently weathered moraines and on arguments regarding the availability of sediment from glacially overdeepened source basins. In this report, we present cosmogenic age estimates for the timing of Sierra Nevada fan aggradation, and we use these estimates to calculate average recurrence intervals for movement on the Lone Pine fault.

Along Lone Pine Creek (Fig. 1), cross-cutting relations and relative weathering criteria distinguish geomorphic surfaces of at least three distinct ages (*3*). The oldest surface, Qg1, is smooth and underlain by heavily weathered granitic boulders; deposits of equivalent weathering intensity appear to underlie much of the bajada. Qg1 likely represents more than one episode of deposition, but we cannot distinguish them reliably at Lone Pine with relative weathering criteria. Boulders on the Qg1 surface are rare, heavily weathered, and primarily aplitic. Fan surface Qg3 has abundant, moderately weathered granitic boulders and distinct boulder levees. Qg4, a terrace of Lone Pine Creek, is the youngest surface on which we collected samples for dating. It is inset as much as 20 m into the Qg3 surface and is covered by large, unweathered granitic boulders. Although the stratigraphic relations among these three surfaces are certain, their relation to a fourth and faulted fan surface 8 km down Lone Pine Creek is ambiguous (Fig. 2). Relative weathering data indicate that the faulted fan is likely younger than the Qg1 and Qg3 fan surfaces (*4*).

The faulted fan has been beheaded by stream capture and is displaced vertically more than 6 m by the Lone Pine fault (LPF), a strand of the Owens Valley fault (OVF), which runs along the valley bottom for more than 100 km and in several places cuts the Los Angeles aqueduct (Fig. 2). In 1872, the OVF ruptured for a distance of 100 ± 10 km, generating an earthquake of estimated moment magnitude 7.5 to 7.7 (*5*). During this event, right-lateral, oblique slip on the LPF broke the fan surface. Observations from trenches (*4*) suggest that three events are recorded by colluvial wedges in the adjacent graben; this observation is supported by scarp morphology as well as desert-varnish rings (*4*) and weathering

Table 1. Isotopic data, Lone Pine Creek debris fans.

Sample	^{10}Be (10^5 atoms g^{-1})*	^{26}Al (10^5 atoms g^{-1})*	^{10}Be model age† (10^3 years)	^{26}Al model age† (10^3 years)
		Surface Qg1		
LPF-2	22.64 ± 0.75	111.23 ± 9.94	97.3 ± 21.2	77.7 ± 19.2
LPF-20	27.45 ± 1.07	90.04 ± 5.10	125.7 ± 28.1	67.8 ± 15.7
LPF-1	10.45 ± 0.41	45.73 ± 2.85	45.5 ± 9.6	32.7 ± 7.2
AHI-1	17.28 ± 0.62	95.70 ± 5.48	88.8 ± 19.2	79.7 ± 18.8
AHI-14	25.11 ± 0.74	75.84 ± 4.12	127.9 ± 28.4	63.7 ± 14.6
AHI-16	20.13 ± 0.62	101.54 ± 7.01	103.9 ± 22.7	84.4 ± 20.4
Average			98.2 ± 30.1 (12.3)	67.3 ± 18.8 (7.7)
		Surface Qg3		
LPF-16	9.46 ± 0.38	54.83 ± 5.62	37.2 ± 7.8	35.3 ± 8.4
LPF-17	5.34 ± 0.25	31.47 ± 2.26	21.1 ± 4.4	20.4 ± 4.5
LPF-18	5.34 ± 0.25	35.34 ± 4.11	21.1 ± 4.4	22.9 ± 5.5
LPF-19	5.04 ± 0.26	32.92 ± 2.69	22.8 ± 4.8	24.5 ± 5.5
LPF-8	4.68 ± 0.21	27.51 ± 2.42	21.2 ± 4.4	20.5 ± 4.6
LPF-9	5.56 ± 0.26	27.21 ± 3.00	25.2 ± 5.3	20.3 ± 4.8
AHI-5	5.54 ± 0.45	28.33 ± 3.15	29.1 ± 6.4	24.3 ± 5.8
Average			25.4 ± 6.0 (2.3)	24.0 ± 5.3 (2.0)
		Surface Qg4		
LPF-3	0.25 ± 0.07	1.82 ± 0.48	1.1 ± 0.4	1.3 ± 0.4
LPF-5	0.23 ± 0.16	3.20 ± 0.48	1.0 ± 0.7	2.3 ± 0.6
LPF-6	0.22 ± 0.09	4.59 ± 0.74	1.0 ± 0.4	3.3 ± 0.9
LPF-7	0.37 ± 0.24	2.72 ± 0.37	1.6 ± 1.1	2.0 ± 0.5
LPF-4	0.23 ± 0.29	1.14 ± 0.10	1.1 ± 1.3	0.8 ± 0.2
Average			1.2 ± 0.3 (0.1)	2.0 ± 1.0 (0.4)
		Faulted fan		
LPF-11	1.64 ± 0.19	11.74 ± 1.26	11.5 ± 2.7	13.5 ± 3.1
LPF-12	1.16 ± 0.10	6.78 ± 0.85	8.2 ± 1.8	7.8 ± 1.9
LPF-13	1.52 ± 0.14	9.44 ± 1.57	10.7 ± 2.4	10.9 ± 2.9
LPF-14	2.54 ± 0.19	14.78 ± 2.15	17.8 ± 3.8	17.0 ± 4.3
LPF-15	1.41 ± 0.13	8.10 ± 1.21	9.9 ± 2.2	9.4 ± 2.4
Average			11.6 ± 3.7 (1.6)	11.7 ± 3.6 (1.6)

*Propagated uncertainties include blank and carrier, total Al (5%), and total Be (2%). †Assuming sea level, high latitude production rates of 6.03 (^{10}Be) and 36.8 (^{26}Al) atoms g^{-1} year^{-1} (±20%). Altitude-latitude corrections are according to (*15*) assuming all production by nucleons. Values in parentheses for the average model ages are standard errors of the mean. Propagated uncertainties include stated uncertainty in isotopic abundance and 20% uncertainty in production rates.

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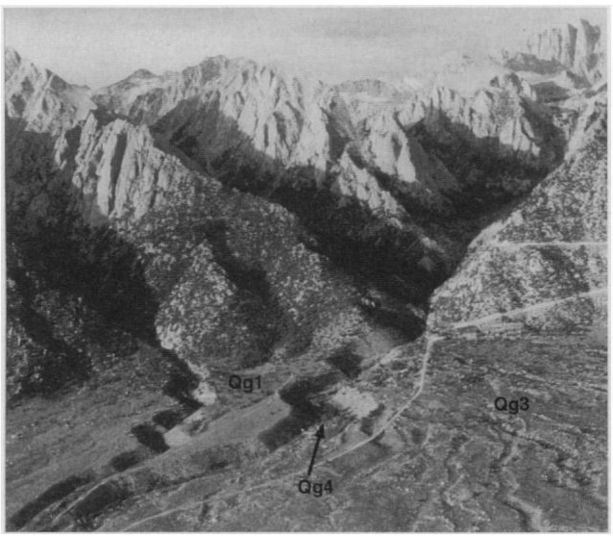
zones on a large (4-m) boulder (sample LPF-14) exposed in and above the fault scarp. The first faulting event recorded by sediments in the graben probably occurred before the faulted fan was beheaded by stream capture, which prevented further deposition (*4*).

Both the actual and average recurrence intervals of ground-rupturing earthquakes on the LPF had been difficult to determine because, until this study, neither the offset fan surface nor the faulting events had been dated directly (*6*). Previously, recurrence intervals (5000 to 10,500 radiocarbon years) were calculated by assigning the faulted fan a minimum, late glacial age of 10 ka (thousand years ago) and by assuming that the fan, because it does not preserve a shoreline of Pleistocene Lake Owens, was younger than radiocarbon-dated shoreline tufa (21,000 ± 1300 radiocarbon years, sample USGS-609) (*4*). To estimate the age of the faulted fan surface and to investigate the utility of in situ–produced cosmogenic isotopes for dating debris flow fan surfaces, we collected and analyzed 23 samples from granitic boulders on four fan surfaces near Lone Pine (*7*). To calculate model ages from measured isotope abundances, we used currently accepted isotope production rates, which may be 10 to 20% too high (*8–10*). Because production rates of ^{10}Be and ^{26}Al remain uncertain, we interpret isotope abundances as model ages propagating a production rate uncertainty of ±20% (*10*).

Our isotopic data provide a direct estimate of the timing of boulder deposition and abandonment of the faulted fan and allow calculation of average recurrence intervals for ground rupture on the LPF (Table 1). Model ^{10}Be:^{26}Al ages (assuming no isotopic inheritance and no boulder erosion) for five boulders on the faulted fan range from 8.0 to 17.4 ka with a mean exposure age of 11.7 ka. The ^{10}Be and ^{26}Al model ages are well correlated (Fig. 3), suggesting that the variability in ages is not due to analytic uncertainties, but rather mainly reflects differing amounts of isotope inheritance from predeposition exposure to cosmic rays, effects of exposure geometry, boulder erosion, and time-transgressive deposition on the fan surface. Although we cannot chose confidently one explanation over another, we favor the latter explanation for three reasons: (i) The Qg4 data indicate isotope inheritance is minimal, (ii) the sampled boulders are not heavily weathered (*4*), and (iii) the boulder with the lowest average ^{10}Be:^{26}Al exposure age (LPF-12; 8.0 ka) is located at the margin of the youngest abandoned channel (LPC-2), which was probably active after the first faulting event (*4*), whereas desert-varnish rings show that the boulder with the oldest ^{10}Be:^{26}Al average exposure age (LPF-14; 17.4 ka) is located near an older abandoned channel and records all three faulting events (*4*).

There are various ways to calculate a recurrence interval for ground rupture on the LPF assuming that faulting recurs at characteristic, regular intervals. At the simplest, if the fan surface age were taken to be the average age of the boulders on it (11.7 ka, n = 5) and the fan has been offset by three events (*4*), then the average recurrence interval would be 5850 years; however, the faulted fan is composed of debris flows emplaced over a period of time and therefore has no single age. Lubetkin and Clark (*4*) pointed out that three faulting events ruptured the southern, older portion of the fan near boulder LPF-14 (17.4 ka) from which we calculate an average recurrence interval between 5800 to 8700 years. To the north, the fault scarp offsets the last active channel of Lone Pine Creek on the faulted fan and only two events are preserved there. LPF-12 (8.0 ka) was deposited or exposed on the margin of this channel (LPC-2) after the first faulting event but before the fan was abandoned and the second and third faulting events occurred (*4*), yielding an average recurrence interval between 4000 and 8000 years. Conservatively, the average earthquake recurrence interval on the Lone Pine fault is the outer limits, 4000 to 8700 ^{10}Be:^{26}Al years; however, 5800 to 8000 years is the range of recurrence intervals consistent with the dating at both sites.

The recurrence intervals we have calculated are similar to those previously calculated (*4*); however, our calculations are more robust because we estimated the age of the fan surface directly. Our dating also suggests that deposition on the faulted fan continued through the late Pleistocene before early Holocene stream capture and abandonment of the faulted fan <8000 ^{10}Be:^{26}Al years ago (LPF-12). This finding is consistent with radiocarbon dates on charcoal (610 ± 70 ^{14}C years ago, sample QL-4361; 4030 ± 60 ^{14}C years ago, sample TO-1666) which indicate that Holocene fluvial activity and fine-grained debris flows have deposited material on the Qg5 or modern fan (Fig. 2). Cosmogenic dating of the Qg4 surface and radiocarbon dating of the Qg5 fan suggest that debris flow activity and fan deposition continued through the Holocene and that the debris flow that



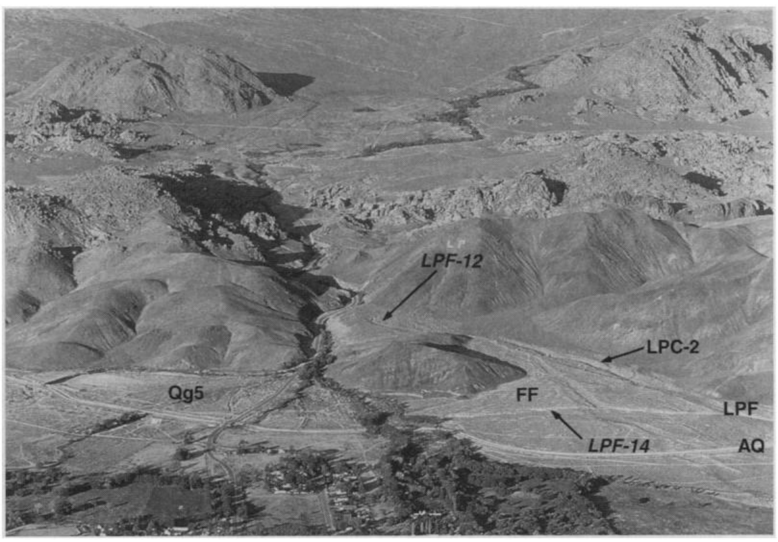


Fig. 1 (left). Oblique aerial photo looking west toward the east front of the Sierra Nevada and over fan surfaces Qg1, Qg3, and Qg4 of Lone Pine Creek. Lone Pine Creek is inset into surface Qg4. The road paralleling Lone Pine Creek indicates scale. **Fig. 2 (right)**. Oblique aerial photo of Alabama Hills west of Lone Pine, California. A faulted and beheaded late Pleistocene fan is on the right (FF). On the left is the active, Holocene fan (Qg5). Sample sites LPF-12 and LPF-14 and the abandoned channel, LPC-2, are identified with arrows. LPF, Lone Pine fault scarp; AQ, Los Angeles aqueduct. Houses and roads indicate scale. View to west.

blocked the Los Angeles aqueduct at Olancha during the summer of 1990 is not an isolated geologic hazard in Owens Valley. However, the relatively small volume of unweathered boulders on Owens Valley fans and the deep incision of Lone Pine Creek suggest that the rate of Holocene debris flow deposition is lower than during the Pleistocene.

The three other fan surfaces have consistent relative and cosmogenic ages. Using the five samples from unweathered debris-flow boulders on the youngest, inset Qg4 surface, we have demonstrated that cosmogenic isotope abundances can be measured successfully in late Holocene samples. Our results indicate that deposition on the Qg4 surface ceased about 1000 years ago. The discordance between some Qg4 ^{10}Be and ^{26}Al ages may reflect inheritance from prior exposure, preferential radiogenic or muonogenic production of ^{26}Al, or errors in blank correction for these very low-level samples. The low isotopic abundances measured in samples from the Qg4 surface suggest that for boulders on debris flow fans in Owens Valley, isotopic inheritance from cosmic ray exposure before deposition on the fan is probably minimal ($\leq$2.0 ka). This lack of significant prior exposure contrasts with apparent inheritance for clasts sampled from predominately fluvial fans in Death Valley, 100 km east (*11*).

The extensive Qg3 surface (mean ^{10}Be:^{26}Al age, 25 ka) represents the end (by 21 ka) of an earlier depositional period and provides a maximum limiting age for the deep fan-head incision of Lone Pine Creek, after which boulders could no longer be deposited on the Qg3 surface (Fig. 1). The clustering of six of the seven ages suggests that erosion by fire spalling has been minimal or similar among boulders (*12*). The single boulder with the higher exposure age (LPF-16; 36 ka) lies farther from the fan axis and closer to the mountain front than all other samples and may represent either an earlier episode of fan deposition or an isolated rockfall from the Sierran escarpment. Isotopic measurements on the Qg3 surface suggest that late Pleistocene, Sierra Nevada debris-fan surfaces likely preserve a consistent age signal and that a significant source of bouldery debris (extensive glaciation?) was available to supply material for deposition on the Lone Pine fans between 21 and 26 ka.

The magnitude and variety of model exposure ages calculated for boulders on the Qg1 surface are consistent with the oldest relative age of this surface, the degree of postdepositional surface lowering, and the magnitude of boulder weathering. The discordance of Al and Be ages (age ^{10}Be > age ^{26}Al) is consistent with a scenario in which sampled boulders were exposed to cosmic radiation, then buried by debris flows and re-exhumed by fan surface lowering (Fig. 3). During burial, more of the relatively short-lived ^{26}Al would decay than would the longer lived ^{10}Be. The large range of model exposure ages on this surface probably represents differing times of boulder burial and exhumation, differing rates of boulder erosion after exhumation, and perhaps the time-transgressive nature of fan deposition. The Qg1 boulder with the lowest isotopic abundance (LPF-1) is coarse grained, heavily weathered, and stands <1 m above the fan surface. The remaining boulders plot on a line trending away from Be and Al correlation, suggesting differing exposure and burial histories (Fig. 3). Cosmogenic data can be used to suggest that deposition on Qg1 began before 128 ka (AHI-14), presuming none of the sampled boulders inherited ^{10}Be or ^{26}Al from cosmic ray exposure before deposition.

Current uncertainties in cosmogenic isotope production rates prevent meaningful comparison of our estimates for the timing of fan surface abandonment with global climate records such as δ^{18}O measured in ice and deep-sea sediments. The paucity of ^{10}Be and ^{26}Al measurements on samples from Sierra Nevada moraines precludes us from understanding the temporal relation between moraine and fan deposition. Taking existing data at face value, it appears that the cessation of fan deposition lags moraine deposition consistent with field stratigraphic evidence. Earlier ^{10}Be and ^{26}Al dates from latest Pleistocene moraines at Pine Creek (*11*), 120 km north of Lone Pine (13.8, 13.9, and 17.5 ka), suggest that these moraines predate the abandonment of the Lone Pine faulted fan and postdate abandonment of the Qg3 surface. Because boulders on the Qg1 fan surface appear to have complex burial and exposure histories, correlation with older Pine Creek moraine samples (95 and 115 ka) is not meaningful. Lastly, our model ages for fan aggradation can be compared with the only extensive cosmogenic data set published so far for Sierra Nevada moraines (*13*). From revised ^{36}Cl production rates, exposure ages of boulders from three nested moraines at Bloody Canyon, about 200 km north of Lone Pine, average 16.0, 17.3, and 36.7 ka (*14*). The two younger moraines predate abandonment of the faulted fan and postdate deposition on the Qg3 surface. The oldest moraine appears to predate abandonment of the Qg3 surface.

We have demonstrated that Sierra Nevada alluvial fans preserve a datable record of fan surface activity and abandonment. Better production rate estimates and more cosmogenic measurements of samples from moraine and fan surfaces may reveal the temporal relation between fan and moraine deposition and let us fully exploit these terrestrial archives of climate change.

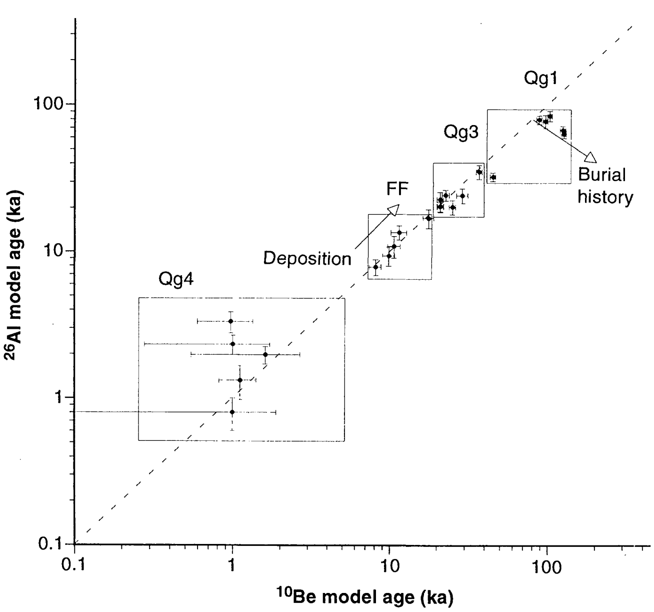


Fig. 3. Scatter plot of ^{10}Be and ^{26}Al ages. Samples from each fan surface are boxed and identified. FF, faulted fan. Error bars (1σ) include propagated counting statistics, blank and carrier correction, and total Al and Be abundance, but no uncertainty in production rates. Arrows show the likely time-transgressive nature of boulder deposition on the FF surface and differing burial and exposure histories of boulders on the Qg1 surface.

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4. L. Lubetkin and M. Clark, *Geol. Soc. Am. Bull.* **100**, 755 (1988). The age of an alluvial fan surface is difficult to define because deposition on most fans takes place over an extended period of time. For example, an exposure in the head of the faulted fan in the Alabama Hills shows numerous strata, the lower of which are heavily weathered, indicating that initial deposition on the faulted fan probably occurred before the late Pleistocene. The distance to the fan from the range front (8 km) suggests that only the largest and least viscous debris flows could travel far enough to reach the faulted fan. Considering these observa-

tions, the faulted fan was most likely built by many episodes of deposition over thousands to tens of thousands of years. For the three youngest fans, we have used the youngest average ^{10}Be:^{26}Al age as a limit for fan surface abandonment, cognizant of the limitations imposed by small sample sizes (which causes overestimate of the limit), boulder erosion (causes underestimate), and the assumption of no isotope inheritance at deposition (causes overestimate). A minimum duration of fan deposition can be estimated from the distribution of boulder ages; however, such an estimate is a function of analytic precision, the age distribution of boulders cropping out on the fan surface, and the number of boulders sampled and analyzed. If more samples are collected from any single fan surface, the apparent duration of deposition should generally increase as the likelihood of sampling boulders from the tails of the age distribution increases.

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6. Thermoluminesence (TL)–derived ages at Lone Pine were not useful for determining recurrence intervals because the TL system appeared not to have been reset to zero during erosion and transport of material from the scarp to the adjacent graben. No organic material suitable for radiocarbon dating has been found in four trenches dug so far across the LPF and adjacent graben; it is likely that the highly oxidizing environment destroyed most organic material.
7. Quartz was separated [C. P. Kohl and K. Nishiizumi, *Geochim. Cosmochim. Acta* **56**, 3583 (1992)] and ^{10}Be and ^{26}Al were isolated by cation exchange after HF dissolution at the University of Vermont. We measured isotopic ratios at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory. Measured ratios, corrected for blanks and carrier, ranged from 15×10^{-15} to 1989×10^{-15} and 52×10^{-15} to 3509×10^{-15} for $^{10}Be/Be$ and $^{26}Al/Al$, respectively. Isotope production, as a function of altitude and latitude, is scaled for nucleon abundance (*15*); for samples reported here, production is 2.4 to 4.2 times that at sea level.
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10. New radiocarbon data from the Sierra Nevada suggest that ^{10}Be and ^{26}Al calibration sites (*9*) are about 20% older than originally believed (13,000 to 14,000 calendar years ago versus 11,000 calendar years ago); thus, ^{10}Be and ^{26}Al production rates at sea level and high latitude may be up to 20% lower than the previously accepted values of 6.03 and 36.8 atoms g^{-1} $year^{-1}$, respectively (D. H. Clark *et al.*, *Geol. Soc. Am. Abstr. Programs* **26**, A447 (1994); D. Clark *et al.*, *Quat. Res.*, in press). This finding is supported by ^{10}Be and ^{26}Al data from the Laurentide terminal moraine in New Jersey (*8*). If production rates are revised downward, our model ages will increase by similar percentages. In addition to uncertainties in average production rates, changes in geomagnetic field strength have probably caused instantaneous production rates at Sierra Nevada altitudes and latitudes to vary over the duration of boulder exposure on the fan surfaces. Because production-rate calibration was performed on late Pleistocene surfaces (*9*), exposure ages could be overestimated by 10 to 15% for samples from the Qg1 surface, first exposed during a period of relatively high isotope production, and underestimated by a similar magnitude for samples from the Qg4 surface, which were exposed in part during a period of high field strength and consequently low production rate. We interpret isotope abundances as ages using 20% uncertainty in production rates propagating the following uncertainties: 10%, age of calibration surface (*9*); 6%, abundance variance in calibration samples (*9*); 10%, variation in magnetic field strength over time (*9*); 10%, altitude and latitude correction (*15*); 5%, muon contribution to production; and 5%, geomagnetic latitude of the sample over time. All in situ cosmogenic ages cited in this report are in ^{10}Be, ^{26}Al, and ^{36}Cl years which reflect an uncertain and nonlinear stretching of the calendar time scale.
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16. We thank J. Turner for assistance in sample preparation, C. Massey, D. Clark, K. Whipple, and K. Campbell for field assistance, and the staff at the Center for Accelerator Mass Spectrometry (Lawrence Livermore National Laboratory), in particular, J. Southon, for assistance in making the isotopic measurements. TL measurements made by G. Berger. Reviews by M. Clark and M. Pavich greatly strengthened this manuscript. Supported by NSF grant EAR 9004252 and 9396261, U.S. Geological Survey grant 14-08-001-G1783, and the University of Vermont (P.R.B.), and by NSF grant EAR 9004252 and the Geology program at the National Aeronautics and Space Administration (A.R.G.).

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Lithoautotrophic Microbial Ecosystems in Deep Basalt Aquifers

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Bacterial communities were detected in deep crystalline rock aquifers within the Columbia River Basalt Group (CRB). CRB ground waters contained up to 60 μM dissolved H_2 and autotrophic microorganisms outnumbered heterotrophs. Stable carbon isotope measurements implied that autotrophic methanogenesis dominated this ecosystem and was coupled to the depletion of dissolved inorganic carbon. In laboratory experiments, H_2, a potential energy source for bacteria, was produced by reactions between crushed basalt and anaerobic water. Microcosms containing only crushed basalt and ground water supported microbial growth. These results suggest that the CRB contains a lithoautotrophic microbial ecosystem that is independent of photosynthetic primary production.

The existence of microorganisms in the deep terrestrial subsurface has been noted for decades (*1*); viable microorganisms are present at depths as great as several thousand meters below the surface, in broadly variable physical and chemical settings (*2*). Nutrient flux at such depths is usually very low because of limitations of sediment chemistry and hydrology. The few measurements of in situ metabolic rates from these systems are the lowest recorded, which indicates that although microorganisms are active at such depths, they function in Earth's most oligotrophic environments (*3*). Most reported subsurface communities are ultimately, though indirectly, dependent on photosynthesis for energy; they either use remnant organic carbon deposited with sediments or use dissolved oxygen as a metabolic terminal electron acceptor. As nutrients are exhausted from sediments, the enclosed microbial population should become extinct. Here, we report evidence for an active, anaerobic subsurface lithoautotrophic microbial ecosystem (SLiME) within the CRB that appears to derive energy from geochemically produced hydrogen. SLiMEs should persist independently of photosynthetic products.

The CRB is a series of Miocene tholeiitic continental flood basalts that formed 6 to 17 million years ago and cover >163,000 km^2 (*4*). In our study area (Fig. 1), the CRB is 3 to 5 km thick. With increasing depth, the age of the water in confined aquifers between basalt flows increases (ages may exceed 35,000 years), as does the lateral distance to recharge. Shallow ground waters are low-sulfate, low-chloride bicarbonate solutions of moderate pH (generally 7.5 to 8.5), with calcium as the dominant cation. At depth, sodium and chloride predominate, and pH varies from 8 to 10.5 (*4, 5*). Sulfate concentrations are below 0.5 mM even at depth, except in geographically restricted zones where sulfate concentrations may exceed 2.0 mM. The igneous rocks in the study area contained little organic carbon, yet we found relatively high populations of anaerobic microorganisms within aquifers hundreds of meters below any sedimentary interbeds (*6*).

To identify the electron acceptors and electron donors to which CRB communities are adapted (*7*), we investigated the metabolic capabilities of bacteria from eight aquifers. We measured the population sizes of bacteria capable of dissimilatory Fe(III) reduction (DIRB), sulfate reduction (SRB), methanogenesis (MB), fermentation (FB), or acetogenesis (AB). We also compared numbers of organisms that could grow on simple organic compounds (heterotrophs) with numbers of organisms that could grow with H_2 as the sole electron donor (autotrophs). The aquifers were sampled (*8*) through a series of preexisting wells (Fig. 1). The results of geochemical measurements (Table 1) were consistent with microbiological measurements (Table 2). DIRB were present only at low numbers, FB were com-

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