mass function of the brown dwarfs/giant planets, we need to conduct more comprehensive surveys for both types of (isolated and companion) ELL-YSOs. It is also important (26) to fill the gap between the very young brown dwarfs at several hundred astronomical units from their companions described in this paper and the close (0.5 to 10 astronomical units) extrasolar giant planets and brown dwarfs around nearby stars recently discovered (27).

References and Notes
5. Molecular cloud is the aggregation of interstellar gas and dust, being one of the coldest and densest components of the interstellar medium, where gas is mostly in the form of molecules.
11. C. Bertout, G. Basri, J. Bouvier, Astrophys. J. 330, 350 (1988). It should be noted that thermal emission from disks might contribute to the K-band flux. This is the reason why we use the J-band and why we can discriminate YSOs from normal stars on the J-H versus K-H diagram.
12. The reddening corrections for the sources detected in this paper range from visual extinction of 0 to 10 magnitudes in Taurus and from 5 to 20 magnitudes in this paper. We also thank C. Packham and M. Merrill for reading the manuscript.
5 June 1998; accepted 6 October 1998

Ages of Prehistoric Earthquakes Revealed by Cosmogenic Chlorine-36 in a Bedrock Fault Scarp at Hebgen Lake
Marek Zreda and Jay S. Noller

Cosmogenic chlorine-36 reveals dates of the multiple prehistoric earthquakes that have occurred on a scarp in the Hebgen Lake fault. Apparent chlorine-36 ages are stratigraphically correct, follow a predicted theoretical pattern, and produce geologically reasonable model ages of 10, 7, 6, 2, 1.7, and 0.4 thousand years ago. This result demonstrates the feasibility of using cosmogenic chlorine-36 to extract paleoearthquake records from bedrock fault scarp.

Verification of long-term earthquake models with field observations requires records that contain multiple, well-dated earthquakes. However, such paleoseismic records are rare because landforms and sediments that record faulting are difficult to identify and are easily buried or eroded; commonly, evidence of earlier earthquakes is obscured by later ones. Bedrock fault scarps are the best evidence of past earthquakes. They are clearly associated with a particular fault, they frequently record multiple earthquakes, and they tend to remain unmodified because of their resistance to erosion. A major disadvantage of bedrock fault scarps is that they have not been datable by numerical techniques with adequate precision and accuracy. Here, we describe an approach to dating prehistoric earthquakes based on the buildup of cosmogenic 36Cl in bedrock scarps exposed during surface faulting, and discuss its application to a limestone scarp on the Hebgen Lake fault (3, 4). Montana (Fig. 1). The technique measures how long the scarps have been exposed to cosmic radiation. Cosmogenic 36Cl is produced by cosmic-ray neutrons and muons that interact with 36K, 40Ca, and 35Cl in materials in the top few meters of Earth’s crust (5–7). Because the production rate of 36Cl (7, 8) and its distribution below the surface (9, 10) are known, the concentration of cosmogenic 36Cl can be used to calculate how long a surface has been exposed to cosmic radiation, that is, to determine its surface exposure age. In the case of a fault scarp, the cosmogenic 36Cl exposure age is the time since the scarp face was suddenly exposed during a large surface-faulting earthquake.

Before faulting, only a small amount of cosmogenic 36Cl accumulates below the surface because of shielding by the overlying rocks. In limestones, this subsurface production is dominated by spallation of 40Ca at depths of <3 m and by negative muon capture by 40Ca below that depth (11). At a depth of 2 m, the total production rate due to spallation and negative muon capture decreases to <10% of that at the surface. This inherent component of 36Cl can be quantified and subtracted from the total measured 36Cl to determine the surface exposure age of the

References and Notes
1. J. D. Kirkpatrick, C. A. Beichman, M. F. Skrutskie, ibid. 476, 1988. It should be noted that thermal emission from disks might contribute to the K-band flux.
5. Supported by Grant-in-Aid for Science Research of Japan. Infrared astronomy at Palomar was supported by a grant from the National Science Foundation. We thank K. Matthews and H. Suto for help with the observations. We also thank C. Packham and M. Merrill for reading the manuscript.
6. M. Zreda, Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ 85721, USA. J. S. Noller, Department of Geology, Vanderbilt University, Nashville, TN 37235, USA.
1097
fault scarp, and thus the age of the earthquake. In a scarp representing multiple earthquakes, then, concentrations of \(^{36}\)Cl will gradually increase from a minimum at the bottom of the face and change abruptly at places representing different slip events (Fig. 2). A sufficient number of samples must be collected to resolve this spatial and temporal pattern of accumulated \(^{36}\)Cl.

We examined a scarp in limestone of the Middle Cambrian Meagher Formation (12) on the Hebgen Lake fault. The last large earthquake (1959, \(M = 7.5\) (3)) produced surface ruptures 34 km long with vertical offsets of up to 6.5 m. On a >12-m-high fault scarp in limestone bedrock, we identified the 2.1-m-high 1959 face and older, progressively more weathered faces toward the top. We collected 21 samples, every \(\sim 0.5\) m, from 0.5 m to >10 m above the bottom of the youngest pre-1959 scarp. In addition, we collected six samples from the freshly exposed 1959 face. The samples were collected, processed, and analyzed using standard methods (13), and apparent \(^{36}\)Cl ages were calculated (14).

Apparent \(^{36}\)Cl ages (those not corrected for \(^{36}\)Cl accumulation below the surface) increase from near zero at the bottom of the scarp to 37,000 years ago (37 ka) at the top (Fig. 3A) (15). With one exception, these ages are in correct stratigraphic order. They form a pattern similar to that predicted by our conceptual model (Fig. 2), with six different sections that correspond to faces exposed by separate earthquakes. These sections have been recognized in the field on the basis of surface characteristics: smoothness, preservation of polish (slickensides), degree of surface pitting, and coloration. The 1959 surface (section 1 in Fig. 3A) is smooth, highly polished, heavily mineralized, and light brown. Lower (younger) pre-1959 faces have a fresh, smooth, unworn weathered appearance, contain well-preserved (section 2) or slightly weathered (section 3) slickensides, and are light beige and gray. Upper (older) faces have progressively deeper and wider weathering pitting. Section 4 has parallel weathering grooves developed along former slickensides. Section 5 has deep weathering pits with no recognizable directional pattern; any former slickensides have been completely obliterated by weathering. The uppermost part (section 6) is similar to section 5 in surface weathering, but it is clearly distinguishable by its much darker color.

Model ages of paleoearthquakes (Fig. 3B) are calculated by correcting the apparent ages for \(^{36}\)Cl that accumulated below the surface before the rupture that exposed the face, in accord with the conceptual model of scarp exposure and accumulation of cosmogenic \(^{36}\)Cl. In the calculations of model ages, geochemical and isotopic data are used together with the locations of the weathering boundaries determined in the field. The data imply that earthquakes occurred 0.4, 1.7, 2.6, 7.0, 20.3, and 23.8 ka. All six model ages are statistically different at the 1\(\sigma\) level (Fig. 3B). However, at the 2\(\sigma\) level, there are overlaps in groups 6 and 5, 3 and 2, and 2 and 1. This resolution problem is due to the short time intervals between earthquakes, combined with difficulties in measuring the extremely low concentrations of stable Cl in the samples (15). An independent age estimate of 2.8 \(\pm\) 1.1 ka has been obtained for a pre-1959 scarp.
D e t e c t i o n o f C e n t i m e t e r - S i z e d M e t e o r i d E n t i t y I m p a c t E v e n t s i n S a t u r n ’ s F R i n g

Mark R. Showalter

Voyager images reveal that three prominent clumps in Saturn’s F ring were short-lived, appearing rapidly and then spreading and decaying in brightness over periods of ~2 weeks. These features arise from hypervelocity impacts by [30-cm]-diameter meteoroids into F ring bodies. Future ring observations of these impact events could constrain the centimeter-sized component of the meteoroid population, which is otherwise unmeasurable but plays an important role in the evolution of rings and surfaces in the outer solar system. The F ring’s numerous other clumps are much longer lived and appear to be unrelated to impacts.

The faint and narrow F ring orbits 3000 km beyond the outer edge of Saturn’s main ring system. It was discovered during the Pioneer 11 encounter in 1979 (1) but was imaged more clearly and extensively by Voyager’s cameras in 1980 and 1981 (2, 3). The Voyager images revealed a variety of peculiar structures within the ring, variously described as strands, kinks, clumps, and “braids.” Many of these structures are now believed to be related to gravitational perturbations by the nearby “shepherding” moons Prometheus and Pandora (4–6), but details of the interactions remain mysterious.

The F ring appears much brighter in forward-scattered than backscattered light, suggesting diffraction by a population of fine dust. Photometric models reveal the dust to be predominantly ~1 μm in size (7). Such fine dust has a brief lifetime of 10^2 to 10^3 years against various drag forces and loss mechanisms (8), so it must be replenished by an unseen population of larger parent bodies.

After Voyager, the F ring was not seen again until 1995, during the crossings of Earth and sun through Saturn’s ring plane. Observers reported a number of new moons near the F ring (9–11); however, with implied radii of ~10 km, these bodies were too large to have escaped detection by Voyager. They have integrated brightnesses comparable to that of the brightest clumps observed by Voyager (10), so clumps provide a much more plausible explanation for these “moons.” The numbers and locations of the clumps changed between observations in May, August, and November of 1995 (9–11), suggesting that they are transient, with lifetimes <3 months.

The 1995 images provided a firmer constraint than the Voyager data set, which merely showed that no major clumps survived for the ~9 months between encounters (12). However, the Voyager data set is much more extensive than any obtainable from the ground, with reasonable resolution and nearly complete longitudinal coverage for periods of

References and Notes

13. Rock samples were collected from top 2 to 5 cm of rock using hammer and chisel. The samples were cleaned of any organic material and encrustations, crushed and ground, and sieved to size fraction 0.1 to 0.00 mm. To remove any meteoric 36Cl, they were leached first in 3% nitric acid for a few minutes and then in deionized water for 24 hours, dried in an oven overnight at 100°C, and placed in sterile plastic bags. Samples for 36Cl were obtained by dissolution of 100 g of purified rocks in sufficient amount of 5% nitric acid mixed with 20 ml of 0.1 M AgNO3. To prevent rapid sample dissolution and minimize possible loss of Cl with released CO2, nitric acid was dispersed slowly (1 ml/min) using a pump. Chloride was precipitated as AgCl (12) and M. G. Zreda, F. M. Phillips, S. S. Smith, Cosmogenic 36Cl Dating of Geomorphic Surfaces (Hydrology Program Rep. 90-1, New Mexico Institute of Mining and Technology, 1990). M. G. Zreda, thesis, New Mexico Institute of Mining and Technology (1994), which was rinsed in deionized water and purified of sulfur with barium nitrate. Chloride was measured by accelerator mass spectrometry [D. Elmore et al., Nature 277, 22 (1979)] at Purdue University. Major elements were determined by x-ray fluorescence or inductively coupled plasma–atomic emission spectrometry, and Cl by the ion-selective electrode method [P. J. Aruscavage and E. Y. Campbell, Talanta 30, 745 (1983)] modified for carbonate rocks.
14. Apparent cosmogenic 36Cl surface exposure ages were calculated using CHLOE software [F. M. Phillips and M. A. Plummer, Radiocarbon 38, 98 (1996)], with spallation production rates of 73.3 ± 4.9 atoms 36Cl/yr.
15. Supported by the Nuclear Regulatory Commission, the Packard Fellowship in Science and Engineering, and NSF. We thank W. Lettis for field assistance, R. Schapiro and D. Robinson for help in sample collection, and two anonymous reviewers for constructive comments.

2 July 1998; accepted 7 October 1998