Range fires: A significant factor in exposure-age determination and geomorphic surface evolution

Paul Bierman, Alan Gillespie
Department of Geological Sciences, University of Washington, Seattle, Washington 98195

ABSTRACT

Physical weathering of rock (spalling), removal of adhered rock varnish, and diffusive loss of noble gases are accelerated by heating in range fires, a dramatic and widespread geomorphic process that must be considered when samples are collected for determining surface exposure ages or for measuring in situ production rates of cosmogenic isotopes. Exposure ages and production rates will be minima if the effects of spalling and/or the effects of accelerated diffusive loss of gaseous isotopes such as He and Ne are not considered. To minimize the effect of fire-induced diffusive loss, samples for noble-gas analysis should be collected 5–10 cm below the rock surface or from outcrops that are unlikely to have been heated by fire. In addition, by determining the concentration of in situ produced cosmogenic isotopes of different half-lives, the magnitude of spalling loss (site-specific erosion rate) can be constrained for each sample.

INTRODUCTION

Forest and range fires occur over much of the world and have been noted as an important factor in rock weathering by Blackwelder (1927), Birkeland (1984), Burke and Birkeland (1979), Gillespie (1987), and Evenson et al. (1990). Attention has been focused on forest fires; range fires have received little study as agents of physical weathering.

Fire affects rock in several ways. (1) Uneven heating and thermal expansion, in concert with the vaporization of endolithic moisture, induce spalling, the loosening and removal of large pieces of the rock surface. (2) Intense heating increases the rate of thermal diffusion significantly and causes accelerated loss from the rock of gases such as Ar, He, and Ne. (3) Heating causes microfracturing of rock and could cause the loss of Cl-rich fluid from inclusions; F. Phillips (1990, personal commun.) believes much of the ^{36}Cl measured for exposure-age determination resides in inclusions.

Understanding the nature and rate of physical weathering caused by fire is becoming more important as the use of exposure-age determination methods increases. For example, the chemistry and ^{14}C content of rock varnish have been used to date geomorphic surfaces (e.g., Dorn, 1989; Harrington and Whitney, 1987), and the concentrations of cosmogenic isotopes produced in situ (^{3}He, ^{26}Al, ^{10}Be, and ^{36}Cl) have been used to calculate exposure ages (e.g., Phillips et al., 1990) and to determine empirically isotope production rates (Kurz et al., 1990; Cerling, 1990). When calculating ages or production rates it has often been assumed that boulder surfaces are "original" (have not eroded since deposition) and that isotopes have not been lost by thermal diffusion or release from fluid inclusions. This paper presents field observations and initial model results which suggest that these assumptions may be invalid in areas prone to range fires.

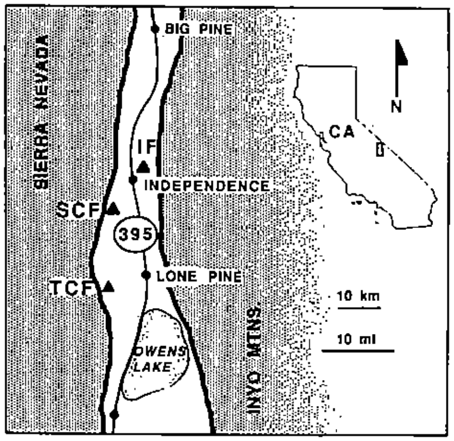

Figure 1. Location of fires discussed in text: IF = Independence fire, TCF = Tuttle Creek fire, SCF = Symmes Creek fire.

METHODS

Observations at Fire Sites

We observed several range fires on the bajada and floor of Owens Valley, a semiarid region between the Sierra Nevada and White-Inyo ranges in southeastern California (Fig. 1). We began observing the Independence and Tuttle Creek fires shortly after ignition. At Independence, we were close enough to the fire to estimate the size and speed of the flame front at several locations and to examine burned areas immediately after the flame front passed. We studied the effects of a third fire, Symmes Creek, by interviewing eyewitnesses and visiting the site within five weeks of the burn.

Following the Tuttle Creek fire of March 31, 1989, and again in October 1989, February 1990, and March 1990, we observed the nature of rock spalling, the condition of vegetation, and evidence of sediment transport in the burned area (Fig. 2). Seven spalled granodiorite boulders were first photographed in April 1989 and rephotographed in October 1989. On April 2–3, 1989, we installed more than 150 erosion pins at two plots (30 × 50 m) within the burned zone (Fig. 3). We have been monitoring these pins during field visits.

Modeling of Fire Effects

We modeled the effects of fire on the concentration of cosmogenic isotopes produced in situ. This necessitated estimating the temperature and spalling histories of a typical boulder. From these data, diffusive losses and concentration profiles of cosmogenic isotopes were deduced.

Figure 2. Granodiorite boulder 36 h after fire at Tuttle Creek. Surface of boulder is darkened by soot from adjacent vegetation; light areas have spalled. Some spall scars are lightly covered by soot, indicating that spalling occurred during fire.

515

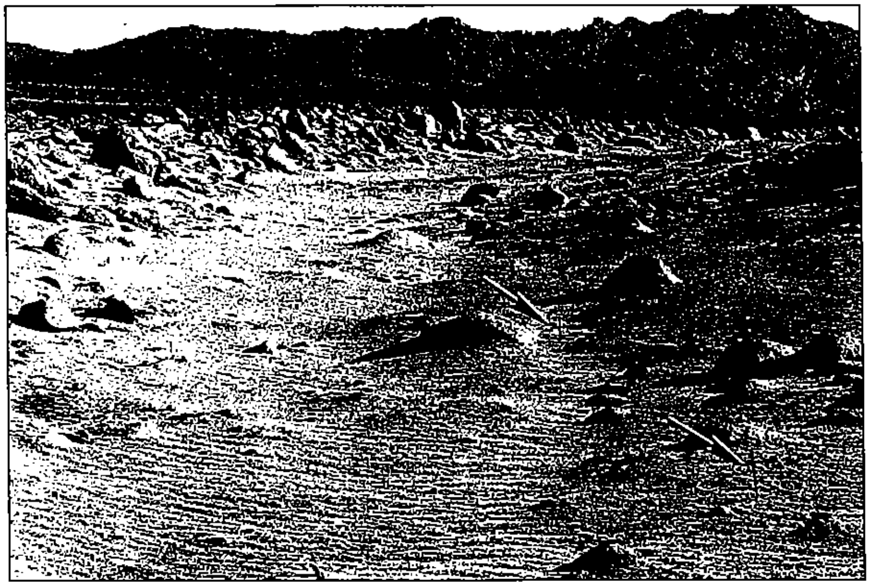

Figure 3. Eolian ripples formed in grus and charcoal within 36 h of Tuttle Creek fire. Mean size of material = 0.3 cm, wavelength of ripples = 10–15 cm, amplitude of ripples = 1–2 cm. Arrows indicate erosion pins.

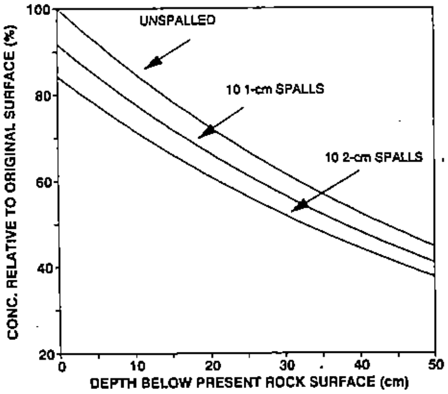

Figure 6. Model results showing relative concentration of ^{3}He produced in situ as function of depth and several geologically reasonable spall thicknesses (1- or 2-cm spalls recurring 10 times). Period of time represented depends on spall frequency; it is probably about 100 ka for Owens Valley granodiorite.

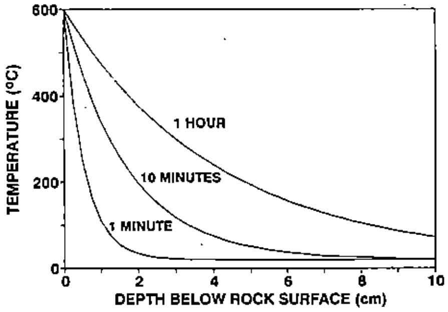

Figure 4. Predicted maximum temperature profiles in granitic boulder exposed to 600 °C fire for different lengths of time. Model results based on cyclical heating equation (Carslaw and Jaeger, 1959, p. 65) and thermal diffusivity of granite = 0.1 cm s^{-2}.

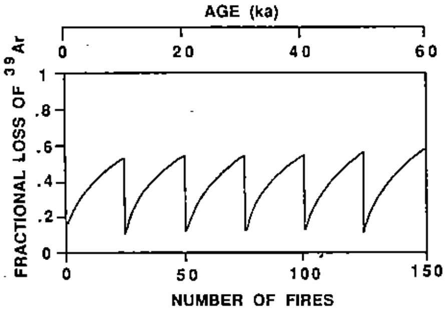

Figure 5. Model results showing predicted fractional loss of ^{39}Ar (produced by neutron irradiation) from boulder surface as function of cumulative fire exposure. Spalling is taken to occur every 25 fires or 10 ka, removing layer depleted in Ar and exposing "fresh" rock at boulder surface. Characteristic diffusion constant = 245 s^{-1}, activation energy = 30.9 kcal/mol, maximum temperature = 600 °C, time of maximum heating in each fire = 300 s.

We estimated maximum boulder temperature (Fig. 4) as a function of depth, using an equation for cyclical heating and a thermal diffusivity for granite presented in Carslaw and Jaeger (1959, p. 65). Diffusive gas loss was estimated by using standard methods of diffusion modeling (Gillespie et al., 1982, 1989). To generate Figure 5, we assumed a recurrence interval for fires in the Owens Valley of about 400 yr (Teensma, 1981), a rock-surface temperature of 600 °C maintained for 300 s, and, at a given locality, a spall every 25 fires. On the basis of our present knowledge, these are reasonable assumptions for Owens Valley.

The depth dependence of the in situ cosmogenic isotope production rate, P_z, was modeled using information provided by Lal (1987) and Kurz (1986).

$$P_z = P_0 e^{-kz}, \qquad (1)$$

where P_0 = production rate at rock surface (atoms/g/yr), k is a density-dependent scaling factor (1.61×10^{-2} cm^{-1} or 165 g/cm^{-2} for basalt density of 2.66; calculated from Kurz, 1986), and z is shielding depth below rock surface (in centimetres). To generate Figure 6, we modeled the effect of ten spalling episodes, each of which removes a specified surface thickness of rock. Each spalling episode is spaced equally in time, and each is preceded and followed by an equal period of cosmic-ray exposure.

RESULTS

Observations at Fire Sites

The Independence fire (0.8 km^2, March 9, 1990) burned in a saltbush (atriplex) and rabbitbrush (crysothamnus) community below the bajada on the fine-grained fluvial and lacustrine sediments of the valley floor. It was fanned by 2.2–4.4 m/s (5–10 mph) winds. The flame front was 5–15 m wide and 2–10 m high. This fire, and others observed in Owens Valley, began at a point and spread as an irregular flame front. We estimated that the dwell time for the fire in any one area was 3 to 5 min. Within the burn, there were numerous areas of unburned vegetation.

The Tuttle Creek (3.2 km^2, March 31, 1989) and Symmes Creek (48.6 km^2, July 2, 1985) fires burned on bouldery debris-flow fan surfaces from sage-floored piñon woodland (pinus, artemisia, coleogyne, and purshia) to desert scrub. We estimated that winds during the Tuttle Creek burn ranged from 5 to 10 m/s (12–25 mph) with higher gusts. Katabatic winds during the Symmes Creek fire were probably two or three times stronger close to the mountains. At Tuttle Creek, the flame front was narrow and varied in height as wind speed and direction changed. On the basis of the size and duration of the Tuttle Creek fire, we estimate that dwell time for the fire at any one area was 2 to 4 min, although heating was likely more intense and of longer duration near individual trees. From reports of the Symmes Creek fire, we estimated dwell time for any one area to be about 6 min.

We examined granitic boulders affected by the Symmes and Tuttle Creek range fires and observed that, on some of the boulders, nearly half of the rock surface had spalled (Fig. 2). At Tuttle Creek, less than 5% of the boulders in the burn area spalled. However, boulders adjacent to the charred remains of trees and large bushes were more heavily darkened by soot and more frequently damaged by spalling than boulders isolated from vegetation. This observation indicates that the extended and perhaps more intense heating caused by the presence of burning trees and sagebrush increases the probability that a particular boulder will spall.

Our observations suggest that most granodiorite spalls are between 0.5 and 3 cm thick, cover an area between 50 and 200 cm^2, and shatter into grus or smaller pieces of rock. Photographs, taken during the 12 months since the burn occurred, suggest that most spalling occurred during or immediately after the fire.

Within 36 h after the Tuttle Creek fire had been extinguished, grus and charcoal had been moved by the wind and shaped into bedforms (Fig. 3). Similar effects were noted in 1988 by K. Whipple (1990, personal commun.) at the 1985 Symmes Creek burn. Although the surface at Tuttle Creek was devegetated, erosion pins indicated little net movement of sediment during the six months after the Tuttle Creek fire, despite unusually heavy thunderstorm activity during August 1989.

Boulder Temperatures During Fires

The temperature of boulders during range fires is not well known. Measured temperatures on an exposed rock surface, reported by Gillespie et al. (1989), provide an estimate of 700 °C for a campfire that was not forced-draft. Zschaechner (1985) reported that maximum temperatures recorded by temperature-sensitive paint placed in sagebrush-fueled fires ranged from 540 to 980 °C. Observations by fire fighters suggest that the most extreme temperatures in range fires occur during brief, intense fire storms, characterized by tornado-like winds. After passage of such vortexes at night, exposed rocks are incandescent (T. Willhoite, 1985, personal commun.), implying temperatures in excess of about 650 °C. Such fire storms were common in the range fires we have observed.

Dwell times for range fires are also poorly constrained, but our observations and other eyewitness accounts suggest that they are typically short (<6 min) in brush and probably less than 1 h in piñon-juniper communities. Such short heating times produce significant temperature changes only near the boulder surface (Fig. 4).

Modeled Loss of Noble Gas by Fire-enhanced Thermal Diffusion

The fractional loss of gasses from near-surface rock increases with the cumulative number and severity of fires the rock has experienced, until the rock spalls. After spalling, depleted rock is lost and fresh rock, from which gas has not yet been strongly depleted, is exposed at the boulder surface (Fig. 5). Model results suggest that isotope concentration (and consequently the exposure age) measured from a sample collected at the rock surface will depend strongly on the time within the fire-spalling cycle at which the sample was collected.

Figure 5 depicts diffusion calculations for ^{39}Ar created by neutron irradiation in microcline (Gillespie, 1987). Although these calculations and the pattern shown in the figure are generally applicable to other gaseous isotopes present at the rock surface, the magnitude of diffusive loss will differ greatly among isotopes and will be controlled by the properties of the specific gas, its siting in the mineral lattice, the effective grain size and composition of the mineral phase in which the gas resides, and the depth from which the sample was collected. Detailed modeling (to be published elsewhere), based on data presented in Trull (1989), suggests that cosmogenic ^3He in quartz may be particularly susceptible to such fire-induced loss.

Modeled Effect of Spalls on Isotope Concentration

The production rate for cosmogenic isotopes is highest at the rock surface and decreases exponentially with depth as cosmic rays are absorbed by overlying rock (equation 1, Fig. 6). When a rock spalls, material with the highest concentrations of cosmogenic isotopes is lost and material deeper in the rock effectively moves toward the rock surface and is thus exposed to a greater flux of cosmic rays. By iteratively solving for the production rate as a function of depth and summing total cosmic-ray exposure, our modeling indicates that a total surface lowering of 10 cm (accomplished in ten 1-cm spall events spaced equally in time) will result in a surface ^3He content or an apparent exposure age more than 90% that of an unspalled rock. A 20-cm lowering by 2-cm spalls will result in a surface ^3He content $\sim 83\%$ that of an unspalled rock.

These results are independent of the actual spalling frequency. In fact, the frequency with which any one area on a boulder spalls is not well determined. For the recurrence interval and spalling frequency we believe to be reasonable for Owens Valley, Figure 6 represents about 100 ka. For the spalling frequency reported by Evenson et al. (1990) for Pinedale, Wyoming, Figure 6 would represent about 10 ka. Our estimate of spall frequency for granodiorite in Owens Valley is based on two lines of evidence. (1) Between 3% and 5% of the boulders in the Tuttle Creek fire actually spalled. On these boulders, between 5% and 50% of the surface area was lost. (2) Striated surfaces, although scarce, can still be found in Owens Valley on morainal and alluvial boulders of late Tioga age (10–15 ka).

Because the rate of boulder erosion determines the integrated cosmic-ray exposure history of any sample now at the boulder surface, the maximum concentration of any cosmogenic isotope is limited by the erosion rate (Nishiizumi et al., 1986; Lal, 1988, equation 15). Therefore, the concentration of ^{36}Cl measured by Phillips et al. (1990) can be used to constrain empirically the maximum erosion (spalling) rate of granodiorite boulders in Owens Valley. Our calculations indicate a maximum erosion rate of between 2 and 4×10^{-4} cm/yr on moraines identified as Older Tahoe age by Phillips et al. (1990). Such rates correspond to, at most, a 1-cm spall every 2.5 to 5 ka. Actual erosion rates are lower than these maxima because the calculation assumes steady-state erosion over the time period for which isotope concentration approaches secular equilibrium; in the case of ^{36}Cl, greater than 1 m.y.

IMPLICATIONS

Our observations suggest that range fires are an important geomorphic agent in semiarid Owens Valley and presumably over much of the Great Basin and other regions prone to range fires. The range fires we observed moved rapidly; a narrow flame front heated soil and rocks in most locations for only several minutes. The presence of unburned vegetation within burned areas indicates that the intensity of heating is spatially heterogeneous.

The intensity of boulder spalling, presumably a proxy for heating intensity and perhaps duration, correlates with the density of vegetation and also varies greatly over the burn surface. Because vegetation density is a function of climate, the frequency, intensity, and effect of range fires has certainly varied spatially and temporally during the Pleistocene.

Range fires influence the physical evolution of geomorphic surfaces in semiarid regions. By removing vegetation and accelerating the physical weathering of granitic boulders, fire is important in the production of grus and its distribution by wind. Repeated range fires may account for the severely weathered state of boulders on older (>25 ka) geomorphic surfaces in Owens Valley (Fig. 7). Observations made by J. B. Adams (1990, personal commun.), by Blackwelder (1927), by E. Evenson (1990, personal commun.), and by us indicate that other rock types, including basalt, andesite, and obsidian, also spall during range fires.

It is important to note that each spall removes all rock varnish adhering to the spalled material. In order to date accurately a geomorphic surface by analysis of varnish radiocarbon or measurement of varnish chemistry, the sampled rock surfaces must never have spalled. The apparent high frequency with which granitic rocks spall indicates that varnish dating of older geomorphic surfaces in locations such as Owens Valley (Dorn et al., 1987, 1990) and elsewhere, where repeated fires and numerous spalling events have occurred, is probably not reliable. Therefore, rock-varnish dates should not be used to establish numerical chronologies or define stratigraphic units (e.g., Dorn et al., 1990), unless it can be proven that spalling has never occurred on either the surfaces to be dated or on the surfaces used for calibration.

Accurate interpretation of cosmogenic-isotope concentrations produced in situ requires knowledge of both the history and magnitude of (1) rock-surface lowering and (2) loss of gaseous nuclides produced in situ by thermal diffusion. This characterization is important both when isotope concentration data are used to calibrate production rates and when they are used to model exposure ages. Isotope losses cannot be corrected systematically because their magnitude depends on the heating and spalling (erosion) history of each sampled rock.

Rates of rock-surface erosion may be calculated by measuring the concentration of multiple isotopes having different half-lives (Lal, 1988; Nishiizumi et al., 1986). By measuring isotopes of different half-lives in single samples, we are currently determining the stability and lowering rates of granitic landforms and boulders. This multiple-isotope approach could be used to calibrate more accurately production rates by selecting for calibration only samples for which low erosion rates have been measured.

The magnitude of diffusive loss from an individual sample is extremely difficult to quantify accurately and precisely; yet, our work shows that diffusive losses are probably commonplace in many regions where exposure-age techniques are being applied. Uncertainty related to diffusive loss may be minimized by selecting specific mineral and isotope systems and by collecting samples from sites at which heating has been minimized.

Figure 7. Partly varnished boulder on older (marine oxygen isotope stage 4?) alluvial-fan surface near Lone Pine, California. Darkest areas are mafic xenoliths. Light areas have recently spalled and are covered by little or no rock varnish. Characteristic pattern of physical weathering is probably determined by differential resistance to fire-induced spalling.

Despite the pitfalls we have illustrated, exposure-age determination methodologies are potentially useful tools for understanding geomorphic systems. Dating methods based on the in situ production of cosmogenic isotopes are much less sensitive than rock varnish to effects of spalling. Boulders that have lost 10 to 20 cm of their surface in multiple spalling events should still provide geologically useful minimum exposure dates if isotope production rates are well known (Fig. 6). By choosing minerals such as olivine, for which diffusive loss of noble gases is thought to be minimal (Kurz, 1986), or by comparing the concentration of metallic and gaseous cosmogenic isotopes in separate aliquots of the same sample, more reliable production rates and ages could be calculated. Because the intensity of range-fire heating falls off more rapidly with depth than the production rate of cosmogenic isotopes, the effect of fire can be minimized by collecting samples from at least 5–10 cm below the rock surface. Alternatively, samples for exposure dating could be collected from outcrops or climatic zones not affected by fire.

REFERENCES CITED

Birkeland, P.W., 1984, Soils and geomorphology: New York, Oxford University Press, 372 p.

Blackwelder, E., 1927, Fire as an agent in rock weathering: Journal of Geology, v. 35, p. 134–140.

Burke, R.M., and Birkeland, P.W., 1979, Reevaluation of multiparameter relative-dating techniques and their application to the glacial sequence along the eastern escarpment of the Sierra Nevada, California: Quaternary Research, v. 11, p. 21–51.

Carslaw, H.S., and Jaeger, J.C., 1959, Conduction of heat in solids: London, Clarendon Press, 510 p.

Cerling, T.E., 1990, Dating geomorphic surfaces using cosmogenic ^{3}He: Quaternary Research, v. 33, p. 148–156.

Dorn, R.I., 1989, Accelerator mass spectrometry radiocarbon dating of rock varnish: Geological Society of America Bulletin, v. 101, p. 1363–1372.

Dorn, R.I., Turrin, B.D., Jull, A.J., Linick, T.W., and Donahue, D.J., 1987, Radiocarbon and cation-ratio ages for rock varnish on Tioga and Tahoe morainal boulders of Pine Creek, eastern Sierra Nevada, California, and their paleoclimatic implications: Quaternary Research, v. 28, p. 38–49.

Dorn, R.I., Cahill, T.A., Eldred, R.A., Gill, T.E., Kushko, B.H., Bach, A.J., and Elliot-Fiske, D.L., 1990, Dating rock varnish by the cation ratio method with PIXE ICP, and the electron microprobe: International Journal of PIXE, v. 1, p. 157–195.

Evenson, E.B., Gillespie, A.R., and Stephens, G.C., 1990, Extensive boulder spalling resulting from a range fire at the Pinedale type locality, Freemont Lake, Wyoming: Geological Society of America Abstracts with Programs, v. 22, no. 7, p. A110.

Gillespie, A.R., 1987, ^{40}Ar-^{39}Ar "exposure" ages of geomorphic surfaces: The effect of range fires: Eos (Transactions, American Geophysical Union), v. 68, p. 1286–1287.

Gillespie, A.R., Huenke, J.C., and Wasserburg, G.J., 1982, An assessment of ^{40}Ar-^{39}Ar dating of incompletely degassed xenoliths: Journal of Geophysical Research, v. 87, p. 9247–9257.

Gillespie, A.R., Budinger, F.E., and Abbot, E.A., 1989, Verification of prehistoric campfires by ^{40}Ar-^{39}Ar analysis of fire-baked stones: Journal of Archaeological Science, v. 16, p. 271–291.

Harrington, C.D., and Whitney, J.W., 1987, Scanning electron microscope method for rock-varnish dating: Geology, v. 15, p. 967–970.

Kurz, M.D., 1986, In situ production of terrestrial cosmogenic helium and some applications to geochronology: Geochimica et Cosmochimica Acta, v. 50, p. 2855–2862.

Kurz, M.D., Colodner, D., Trull, T.W., Moore, R.B., and Obrien, K., 1990, Cosmic ray exposure dating with in situ produced ^{3}He: Results from young Hawaiian lava flows: Earth and Planetary Science Letters, v. 97, p. 177–189.

Lal, D., 1987, Production of ^{3}He in terrestrial rocks: Chemical Geology, v. 66, p. 89–98.

——1988, In situ produced cosmogenic isotopes in terrestrial rocks: Annual Reviews of Earth and Planetary Science, v. 16, p. 355–388.

Nishiizumi, K., Lal, D., Klein, J., Middelton, R., and Arnold, J.R., 1986, Production of ^{10}Be and ^{26}Al by cosmic rays in terrestrial quartz in situ and implications for erosion rates: Nature, v. 319, p. 134–136.

Phillips, F.M., Zreda, M.G., Smith, S.S., Elmore, D., and Kubik, P.W., 1990, A cosmogenic chlorine-36 chronology for glacial deposits at Blood Cañon, eastern Sierra Nevada, California: Science, v. 248, p. 1529–1531.

Teensma, P., 1981, Sagebrush (artemisia tridentata nutt.) and fire in Owens Valley, CA [M.S. thesis]: Eugene, University of Oregon, 74 p.

Trull, T., 1989, Diffusion of Helium isotopes in silicate glasses and minerals, implications for petrogenesis and geochronology [Ph.D. thesis]: Cambridge, Massachusetts Institute of Technology, 399 p.

Zschaechner, G.A., 1985, Studying rangeland fire effects: A case study in Nevada, *in* Sanders, K., and Durham, J., 1985, Rangeland fire effects: Proceedings of a Bureau of Land Management Symposium, Nov. 27–29, 1984: Boise, Idaho State Office, U.S. Department of Agriculture, Bureau of Land Management, p. 66–84.

ACKNOWLEDGMENTS

Supported by U.S. Geological Survey Grant 14-08-001-G1783 and National Science Foundation Grant EAR-9004252 to Gillespie and Bierman, and American Association of Petroleum Geologists and University of Washington graduate research fund grants to Bierman. We thank M. Watkins, P. Shippert, and R. Stockman for assistance in the field and T. Willhoite for discussions of chaparral and forest fires. We also thank G. Spaulding, T. Dunne, E. Evenson, and R. Burke for reviews and F. Bardsley for figure drafting.

Manuscript received July 24, 1990
Revised manuscript received January 22, 1991
Manuscript accepted February 3, 1991