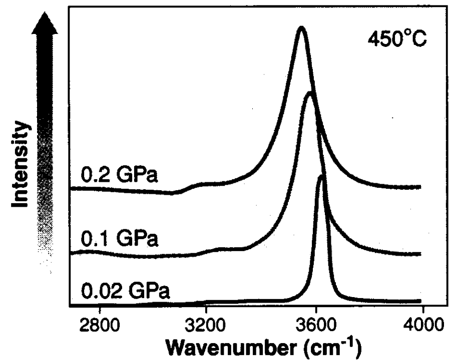
certainties. In rare cases, spectra are recorded on the mineral completely or heavily enriched in the rarer heavy isotope. For example, Gillet *et al.* (*4*) did this for calcite and were able to carry out a detailed mode assignment. With spectral data over a large pressure and temperature range, they demonstrate convincingly the importance of carrying out anharmonic calculations in order to derive thermodynamic parameters (specific heat, coefficient of thermal expansion, and so on) that agree with the measured values over geologically interesting *P-T* ranges.

Spectral data on geological materials over an important range of both pressure and temperature conditions are still quite limited. The situation is changing fast since the construction of a number of high-temperature, high-pressure cells with windows: diamond anvil and optical cells. High-quality spectroscopic data (see figure) are measured in situ under the working conditions, typically <35 GPa and <2000 K (*7–9*).



Variation of the Raman spectra of water with pressure varying from 0.02 to 0.2 GPa at 450°C in an optical cell (*8*). At constant pressure, the frequency of the maximum intensity increases along with temperature. Such *P-T* frequency changes are input data to the model calculations.

The interpretation of the small variations in the isotopic composition of natural materials depends on the application of high-precision fractionation factors derived from spectroscopic data and calculations, empirically or experimentally, and how they vary with thermodynamic parameters. Pressure is a variable that now must be taken into account, at least for hydrogen isotopes, in fluid-bearing systems at low to moderate pressures, such as those that occur in the oceanic crust and the middle to upper continental crust. Further studies will define more precisely the limits of these pressure effects. The significance of pressure variations on interphase isotopic fractionations under mantle conditions (>1 GPa) is another direction that merits further exploration.

References

1. T. Dreisner, *Science* **277**, 791 (1997).
2. V. B. Polyakov and N. N. Kharlashina, *Geochim. Cosmochim. Acta* **58**, 4739 (1996).
3. S. D. Mineev and V. A. Grinenko, abstract, *V. M. Goldschmidt Conference* (1996), vol. 1, p. 404.
4. P. Gillet *et al., Geochim. Cosmochim. Acta* **60**, 3471 (1996).
5. R. N. Clayton *et al., ibid.* **39**,1197 (1975).
6. H. C. Urey, *J. Chem. Soc. (London)* **1947**, 562 (1947).
7. R. J. Hemley *et al., Science* **237**, 605 (1987).
8. J. D. Frantz *et al., Chem. Geol.* **106**, 9 (1993).
9. P. Gillet *et al., Geophys. Res. Lett.* **20**, 1931 (1993).

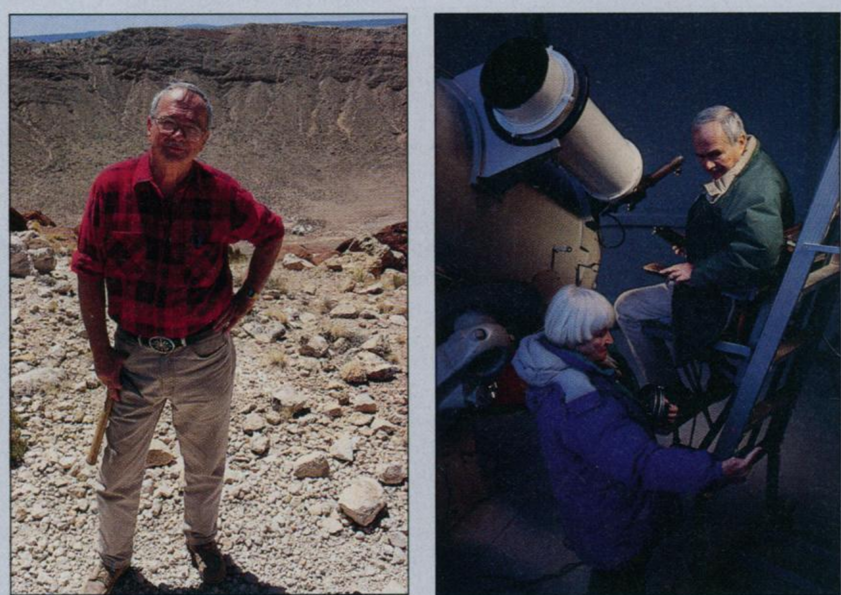
RETROSPECTIVE

Eugene M. Shoemaker (1928–1997)

Susan W. Kieffer

The life of a renowned leader in the science community was lost on 18 July 1997, when Eugene M. Shoemaker was fatally injured in an auto accident in Australia. Gene was doing field work on the impact craters that he so much enjoyed exploring. His field partner, astronomy colleague, and wife, Carolyn, survived the accident.

Gene leaves many legacies that will benefit scientists and humankind for generations to come. He, with Carolyn, formulated and conducted a sky survey of nearly two decades duration in which they discovered and cataloged earth-crossing asteroids and comets. This survey culminated in the codiscovery, with David Levy, of Comet Shoemaker-Levy, which provided a spectacular display of impacts into the jovian atmosphere in 1994. The whole world—scientists and nonscientists alike—gained new insights into the dynamics of comets, the phenomenon of impact, and the planetary science of Jupiter.



PHOTOS: G. MARULLO

At Meteor Crater, Arizona, and with Carolyn Shoemaker at Palomar Observatory.

Gene led the creation of planetary science as a discipline distinct from astronomy by bringing fundamental geologic principles to the mapping of the planets. Starting in the 1960s, he used geologically well-known principles of stratigraphy to interpret the ancient and modern histories of the planets of the solar system. He helped create an alliance between NASA and the U.S. Geological Survey (USGS) with the formation of the Branch of Astrogeology in the USGS and guided a major program of mapping the planets using geologic techniques to interpret remote sensing data. Early involvement in the unmanned Ranger and Surveyor programs evolved into scientific leadership in the manned Apollo program. He helped train astronauts in geologic principles for their visits to the moon and was involved in interpretation of the lunar rocks

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MARINE GEOCHEMISTRY

A New Look at Old Carbon

Katherine H. Freeman

The burial of organic carbon in marine sediments is a key control for the global inventory of carbon on Earth's surface and is a principal control for carbon dioxide concentrations over geologic time scales. For example, an increase in the rate of organic carbon burial is thought to be at least one cause of the relatively low CO_2 levels and cool climate experienced on Earth since the Neogene. Although the quantitative importance of carbon burial in Earth's climate system is well recognized, the precise mechanisms by which organic carbon is preserved in sediments are not as well known. The work by Eglinton *et al.* (*1*) reported on page 796 of this issue provides a powerful approach to understanding the biogeochemical processes that create, destroy, and preserve organic matter in ocean sediments.

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In the Black and the Arabian seas, sources of organic matter include algae, many groups of bacteria, and vascular plants in the surrounding land areas. Grazing organisms and bacteria degrade, alter, and remake organic matter during its transport through the water column and upon deposition at the sediment surface, yielding a highly modified composition of organic matter relative to the starting materials. In addition, decay processes in marine environments impact the ^{14}C contents of organic matter, with differing influences on amino acids, carbohydrates, and lipids (*2*).

The intensity of the biological production and decay reactions can vary both geographically and temporally. For example, the strongly seasonal monsoon winds in the Arabian Sea alter physical circulation in the basin, causing upwelling of nutrient-rich waters, which then drive phytoplankton production. This in turn changes the oxygen content of the underlying waters and results in a shift in the environment for bacteria and other consuming organisms. Such factors make it difficult to resolve the history and quantify the processing of organic matter preserved in sediments.

Molecular structures and ^{13}C contents

when they were returned to Earth. His lunar studies culminated in 1994 when, as science team-leader of Project Clementine, he led the acquisition of new photographs of the lunar south pole region, previously ill-documented.

Gene applied his creative, but disciplined, imagination to propose interpretations of phenomena on other planets never seen in our terrestrial experience. He was a key member of the team that proposed that the plumes on Io, a satellite of Jupiter, were geysers and volcanoes venting from sulfur and sulfur dioxide reservoirs. He was on the team that proposed that the plumes on Triton, a satellite of Neptune, could be degassing nitrogen from a solid-state greenhouse of nitrogen ice, and he was involved in many projects interpreting the geology of both the rocky and icy satellites. No planet in the solar system escaped his observant eyes, and every piece of data was integrated into his constantly evolving vision of the origin and evolution of the solar system.

Gene unraveled the geologic history of many parts of the southwestern United States, particularly in Arizona. He loved the Hopi Buttes, Meteor Crater, and Grand Canyon country. Thirty-five years after his careful mapping and interpretation of the processes of eruption of the diatremes of Hopi Buttes was published in 1962 with C. H. Roach and F. M. Byers, it still provides the basic model for our understanding of these features and their relatives, the diamond-bearing kimberlites. He introduced many of us to the geology of the Grand Canyon on river-rafting trips to explore the rocks, to teach us about the rates of processes revealed in the side-canyons, and to educate us in the history of exploration of the Southwest. His desire to understand and document the geology of the Southwest led to the establishment of a major paleomagnetic facility at Flagstaff.

He pioneered the documentation of impact craters, especially Meteor Crater, Arizona, which was his intellectual home. Gene loved to be in the field mapping. It was almost incidental to him that he developed the theoretical concepts for interpretation of impact by drawing on analogies between chemical and nuclear explosions and impact processes. With E. C. T. Chao and B. M. Madsen, he was first to discover the natural occurrence of coesite, at Meteor Crater. Shoemaker and Chao solved the controversy about the origin of the Ries basin in Germany by finding coesite in the rocks there. The theoretical concepts, the petrologic discoveries, and the careful field mapping in the 1950s and 60s paved the way for acceptance of impact as an important geological process on Earth. Decades later these discoveries and concepts became crucially important in the unfolding of ideas about the K/T extinctions.

For his work, Gene received nearly every award given in the geosciences, including the Arthur L. Day Medal of the Geological Society of America for his application of physics and chemistry to geological problems, the U.S. National Medal of Science in 1992, and the Bowie Medal of the American Geophysical Union in 1996 for outstanding contributions to fundamental geophysics and unselfish cooperation in research. He was elected to the U.S. National Academy of Sciences in 1980.

In addition to his scientific legacy, there are the memories that those of us who knew him will always treasure: of the warm, twinkling humanness, the unfailingly generous spirit, the intellectual honesty and generosity, the romance and love in his eyes for Carolyn, and the unflagging enthusiasm for life and its unfolding. The life has ended but the magic lives on in our hearts.

Online Appreciations

- Several pages have been placed on the Web in commemoration of E. M. Shoemaker. His colleagues at the USGS have written an article describing his life and have included several photos at http://www.flag.wr.usgs.gov/USGSFlag/Space/Shoemaker/
- The Lowell Observatory has several articles of reflection on his life at http://www.lowell.edu/lowell/eugene/geneshoemaker.html
- The Goddard Space Flight Center provides a brief article on the discovery that made him famous: http://nssdc.gsfc.nasa.gov/planetary/comet_body.html