Memorial to Warren B. Hamilton
1925–2018

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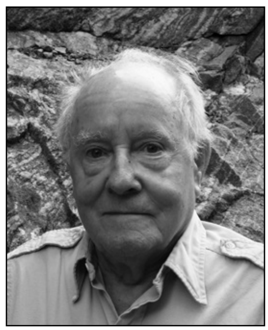

Warren B. Hamilton, a widely traveled geologist formerly of the U.S. Geological Survey (USGS) and Colorado School of Mines, whose work integrated observational geology and geophysics into planetary-scale syntheses, died peacefully at his home in Golden, Colorado, on 26 October 2018. His wife and lifelong companion, Alicita, who travelled with him through 90 countries, passed away three years before him. They are survived by a daughter and two sons (Kathryn Harhai; James and Lawrence Hamilton), six grandchildren (Sarah, Dave, Laura and Richard Hamilton; John and Kat Harhai), and six great-grandchildren.

Warren's early-career insights, before the advent of plate tectonics, include recognizing the need for continental mobility to explain the geology of the southern hemisphere and western United States. Following an International Geophysical Year expedition to Antarctica, his 1960 paper in *Geological Survey Research* gave the Transantarctic Mountains their name. Subsequent field work covered every part of the globe, including a major new synthesis of Indonesian geology (1969–1979). In all of these studies, he sought to understand local rocks in terms of their dynamic evolution and how that connected with processes operating up to global and billion-year scales. Eventually, this broad vision extended beyond Earth itself, leading to new interpretations of other terrestrial planets.

Warren's work earned recognition and honors including election to the National Academy of Sciences and the Penrose Medal of the Geological Society of America. When he received the Career Contribution Award of the GSA Structural Geology and Tectonics Division, the citation by Keith Howard spoke to his collegiality as well.

> "Warren's communication skills—on field trips, informal contacts, hundreds of lectures, and many visiting professorships and distinguished lectureships—have stimulated and influenced large numbers of students. He has served as a visiting scientist in many countries, and he has been a charismatic mentor, guide, and friend to countless colleagues and students. Colleagues come to him as a sounding board on subjects ranging from giant Precambrian impact structures to environmental policy. Though he is never one to coddle or mince words

> at work with which he disagrees, Warren is outgoing, generous with his time, and a helpful tutor to those with whom he comes in contact. His crisp, power-packed collegial letters enjoy their own celebrated reputation."

Away from work, Warren was a warm friend and devoted family man with a self-effacing sense of humor. He passed along his curiosity, love of nature, and a sense of life as an adventure to his children and grandchildren, and he continued to hike with them in the Colorado Rockies well into his 90s.

Born in Los Angeles in 1925, Warren enrolled in 1943 at the University of California, Los Angeles (UCLA), and joined the Naval Reserve Officers Training Corps. In 1945, he became a commissioned officer in the U.S. Navy and soon afterward was assigned to the new aircraft carrier *Tarawa*. Released from active duty in 1946, he returned to school under the G.I. Bill, subsequently earning graduate degrees in geology from the University of Southern California (MSc, 1949) and UCLA (PhD, 1951). In the course of these studies, Warren became convinced that continental drift had occurred in the geological past. This concept was dismissed—even ridiculed—by almost all geoscientists at the time. Holding strongly to scientific observations while undeterred by peer pressure, Warren stuck to what he knew had to be.

After a year teaching at the University of Oklahoma (1951–1952), Warren accepted a job as full-time researcher with the USGS in Denver. His initial projects involved field and laboratory studies of the Great Smoky Mountains in Tennessee and the Salmon River country in western Idaho. The Tennessee rocks had metamorphosed from deep-sea sandstones and shales. Those in Idaho had crystalized deeper than most of the Sierra batholith. These and other diverse experiences, including a trip through the Precambrian geology of northern Ontario, began building the vast first-hand knowledge and sense of interconnections that would inform all his future work. The Mojave Desert north of Blythe, California, was virtually unexplored geologically when, in 1958, Warren launched the field work that would reveal the Grand Canyon succession of sedimentary strata in drastically thinned, contorted form.

In September of 1958, Warren accepted a sudden invitation to lead a National Science Foundation–supported two-man geological expedition departing the next month to Antarctica as a component of the International Geophysical Year. From the Navy logistical base at McMurdo Sound, he and fellow USGS geologist Phil Hayes were dropped off by helicopter or Twin Otter for four extended camping trips. During the first of these, after their plane left them high on Taylor Glacier, Warren and Phil found that they had been given kerosene instead of the white gas their cookstove required. They improvised an outdoor kerosene stove using an open pan with a sock for a wick, but for 10 days could eat and drink little more than what they melted or thawed out by body heat at night. It was a miserable time but, as Warren recalled, "We accomplished excellent geologic studies." He realized that the Antarctic geology they saw accorded not with then-conventional stablist assumptions, but with the older continental drift–based predictions of South African geologist Alexander Du Toit. Warren's subsequent travels in Australia and South Africa, along with further trips to Antarctica in 1963 and 1964, confirmed that conclusion in his mind. Although continental mobility was still rejected by most scientists, and its explanation in terms of plate tectonics was some years away, like the earlier geniuses Alfred Wegener and Arthur Holmes, Warren recognized that evidence could not be reasonably explained any other way.

The plate tectonic revolution arrived in the late 1960s when paleomagnetic and oceanographic data essentially swept away all doubt. Warren's view of the western United States fit spectacularly into this framework. In 1966, he and Bradley Meyers explained:

> "The structure of the western United States is here described and interpreted in terms of a tectonic system in which the California region is moving rapidly northward past the continental

interior. Structures of extremely varied superficial aspect can be viewed within the moving framework of this tectonic system as manifestations of a single pattern of continental motion."

In this view, refined shortly thereafter by Atwater's classic 1970 analysis, western North America acts as a wide, soft, boundary zone between the rigid Pacific and North American plates. Such plate boundary zones are now recognized worldwide, having been confirmed over decades by every new terrestrial and space-based surveying technology that has emerged.

In 1969, Warren was invited to conduct a U.S. State Department–sponsored tectonic analysis of the Indonesia region, where petroleum exploration was getting under way. Indonesian dynamics proved more complex than the regions he had previously studied, with multiple interacting plates whose boundaries changed shape and moved relative to one another. Synthesizing observations from onshore geology and offshore geophysics brought him to a new understanding of plate dynamics in which his thinking once again diverged from the mainstream. While most others saw plate motions as driven from below, by hot material circulating in an undifferentiated mantle, Warren saw a fractionated mantle with plate movements controlled from above, as the cooled, sinking lithosphere of subducting plates pulled overriding plates away from spreading centers. In Warren's schema, hinges roll back into the subducting plates, and their slabs sink broadside rather than sliding down inclined slots as simplistically drawn in textbooks. The Indonesian work resulted in many published papers and maps and a high-profile USGS monograph published in 1979.

Beyond Indonesia, Warren traveled globally in the 1970s through early 1990s, studying the Phanerozoic evolution of continental crust (541 Ma to present). He saw much evidence for plate tectonic processes similar to those occurring today. But conversely, in much older rocks he saw no such evidence, an anomaly that he would explore later. Publications from this period include papers on the mechanism of Laramide deformation, Cretaceous and Cenozoic history of northern continents, Paleozoic strata of the Mojave, crustal extension of the Basin and Range Province, detachment faulting in Death Valley, plate tectonics and island arcs, subduction systems, magmatism, and problems with terrane analysis. He traveled not only for research but also to share what he had learned, through five visiting professorships and many short courses and lectures.

On retiring from the USGS in 1995, Warren took a new position as Distinguished Senior Scientist in the Department of Geophysics at Colorado School of Mines. The scope of his writing broadened further, now drawing on decades of field work and research around the world to challenge conventional views in papers such as "Archean magmatism and deformation were not products of plate tectonics" (*Precambrian Research*, 1998) or "The closed upper-mantle circulation of plate tectonics" (*AGU Geodynamics Series*, 2002). His 2003 paper in *GSA Today*, "An alternative Earth," summarized a basket of heterodox but coherent ideas: Earth accreted fast and violently, fractionated irreversibly in the early Archean, and plate tectonics started much later. Subduction is driven by the plates themselves, hinges roll back into subducting plates and slabs sink broadside. Overriding plates advance at the same rate; an Antarctica-fixed framework depicts "absolute" plate motions that make kinematic sense, whereas hotspot and no-net-rotation frames do not. Plumes from the deep mantle, subduction into the deep mantle, and bottom-up convective drive do not exist. Later papers developed these themes further, presenting corrections, new evidence, and details as his ideas evolved. Publications include "Plate tectonics began in Neoproterozoic time, and plumes from deep mantle have never operated" (*Lithos*, 2011), and "Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust" (*Tectonophysics*, 2013).

If the evidence for mantle plumes was tenuous on Earth, applying the conjecture to other planets, with different assumptions in each case, struck Warren as highly improbable. On Venus, a landscape saturated with thousands of small to giant circular structures, typically rimmed depressions that would elsewhere be seen as impact features, had instead become interpreted largely in terms of plumes, antiplumes, and other endogenic processes with no terrestrial or planetary analogues. Warren's contrarian papers, "Plumeless Venus preserves an ancient impact-accretionary surface" (GSA Special Paper 388, 2005) and "An alternative Venus" (GSA Special Paper 430, 2007) presented radar imagery and topographic, magnetic and geophysical evidence for a tectonically inactive Venus, its ancient craters variably modified by erosion or by sedimentation from long-vanished seas.

Warren synthesized his ideas about Earth and Venus, also bringing Mars and Earth's Moon into view, in an epic 2015 paper whose thesis is contained in its title: "Terrestrial planets fractionated synchronously with accretion, but Earth progressed through subsequent internally dynamic stages whereas Venus and Mars have been inert for more than 4 billion years" (GSA Special Paper 514, 2015). One argument advanced in this paper is that the famous Martian volcanoes are not plume products or even endogenic volcanoes; instead these broad, circular, single-peak structures represent impact-generated melt constructs. Warren proposed that ancient impactors on both Venus and Mars sometimes hit transient seas, and water- or ice-saturated ground, altering their footprints. And if Earth, Venus, and Mars had all received oceanic quantities of water through icy bombardments around 4 Ga, as some evidence suggests, he reasoned that the Moon must have done so as well—giving rise to its own short-lived seas.

His 2015 paper was the last published before Warren's death, but it did not mark the end of his writing. Over the next three years and into his final month, he worked toward an even broader synthesis that would represent a culmination of his career: "Toward a myth-free geodynamic history of Earth and its neighbors." He knew this project was a race against time, but refused to take shortcuts in the painstaking work. Time won that race, just barely. Warren passed away leaving behind a manuscript of more than 39,000 words, which he judged to be 95 percent complete—with "all the hard parts" done. Colleagues, friends, and family have picked up this legacy and carried it the last steps. The great man's final paper will be published posthumously in 2019.

SELECTED BIBLIOGRAPHY OF WARREN B. HAMILTON

1956 Geology of the Huntington Lake Area, Fresno County, California: California Division of Mines and Geology Special Report 46, 25 p. + map.

1956 Precambrian rocks of Wichita and Arbuckle mountains, Oklahoma: Geological Society of America Bulletin, v. 67, p. 1319–1330, https://doi.org/10.1130/0016-7606(1956)67[1319:PROWAA]2.0.CO;2.

1957 Polymetamorphic rocks of Blue Ridge near Old Fort, North Carolina: American Journal of Science, v. 255, p. 568–573, https://doi.org/10.2475/ajs.255.8.568.

1960 New Interpretation of Antarctic Tectonics: U.S. Geological Survey Professional Paper 400-B, p. 379–380.

1961 Origin of the Gulf of California: Geological Society of America Bulletin, v. 72, p. 1307–1318, https://doi.org/10.1130/0016-7606(1961)72[1307:OOTGOC]2.0.CO;2.

1961 Geology of the Richardson Cove and Jones Cove Quadrangles, Tennessee: U.S. Geological Survey Professional Paper 349-A, 55 p. + map.

1962 Late Cenozoic structure of west-central Idaho: Geological Society of America Bulletin, v. 73, p. 511–516, https://doi.org/10.1130/0016-7606(1962)73[511:LCSOWI]2.0.CO;2.

1963 Antarctic tectonics and continental drift, *in* Munyan, A.C., ed., Polar Wandering and Continental Drift: Society of Economic Paleontologists and Mineralogists Special Publication, v. 10, p. 74–93, https://doi.org/10.2110/pec.63.01.0055.

1963 Metamorphism in the Riggins Region, Western Idaho: U.S. Geological Survey Professional Paper 436, 95 p. + map.

1963 Overlapping of late Mesozoic orogens in western Idaho: Geological Society of America Bulletin, v. 74, p. 779–787, https://doi.org/10.1130/0016-7606(1963)74[779:OOLMOI]2.0.CO;2.

1964 The origin of high-alumina basalt, andesite, and dacite magmas: Science, v. 146, p. 635–637, https://doi.org/10.1126/science.146.3644.635.

1964 (with Meyers, W.B.) Deformation Accompanying the Hegben Lake Earthquake of August 17, 1959: U.S. Geological Survey Professional Paper 435, p. 55–98.

1965 Diabase Sheets of the Taylor Glacier Region, Victoria Land, Antarctica: U.S. Geological Survey Professional Paper 456-B, 71 p. + map.

1965 Geology and Petrogenesis of the Island Park Caldera of Rhyolite and Basalt, Eastern Idaho: U.S. Geological Survey Professional Paper 504-C, 37 p. + map.

1965 (with Pakiser, L.C.) Geologic and Crustal Cross Section of the United States along the 37th Parallel: U.S. Geological Survey Map I-448.

1966 Origin of the Volcanic Rocks of Eugeosynclines and Island Arcs: Geological Survey of Canada Paper 66-15, p. 348–356.

1966 Formation of the Scotia and Caribbean Arcs: Geological Survey of Canada Paper 66-15, p. 178–187.

1966 (with Myers, W.B.), Cenozoic tectonics of the western United States: Reviews of Geophysics, v. 4, p. 509–549, https://doi.org/10.1029/RG004i004p00509.

1967 Tectonics of Antarctica: Tectonophysics, v. 4, p. 555–568, https://doi.org/10.1016/0040-1951(67)90019-4.

1967 (with Krinsley, D.) Upper Paleozoic glacial deposits of South Africa and southern Australia: Geological Society of America Bulletin, v. 78, p. 783–800, https://doi.org/10.1130/0016-7606(1967)78[783:UPGDOS]2.0.CO;2.

1967 (with Meyers, W.B.) The Nature of Batholiths: U.S. Geological Survey Professional Paper 554-C, 30 p.

1968 Cenozoic climatic change and its cause, *in* Mitchell, J.M., ed., Causes of Climatic Change: Boston, Massachusetts, American Meteorological Society Meteorological Monographs, v. 8.

1969 Mesozoic California and the underflow of Pacific mantle: Geological Society of America Bulletin, v. 80, p. 2409–2430, https://doi.org/10.1130/0016-7606(1969)80[2409:MCATUO]2.0.CO;2.

1969 The volcanic central Andes—a modern model for the Cretaceous batholiths and tectonics of western North America, *in* McBirney, A.R., ed. Proceedings of the Andesite Conference: Oregon State Department of Geology and Mineral Industries Bulletin, v. 65, p. 175–184.

1969 Reconnaissance geologic map of the Riggins quadrangle, west-central Idaho: U.S. Geological Survey Map I-579.

1970 Bushveld Complex—Product of Impacts? *in* Vissler, D.J.L., and Von Gruenewaldt, eds., Symposium of the Bushveld Igneous Complex and Other Layered Intrusions: Geological Society of South Africa Special Publication 1, p. 367–379.

1970 The Uralides and the motion of the Russian and Siberian platforms: Geological Society of America Bulletin, v. 81, p. 2553–2576, https://doi.org/10.1130/0016-7606(1970)81[2553:TUATMO]2.0.CO;2.

1972 The Hallett Volcanic Province, Antarctica: U.S. Geological Survey Professional Paper 456-C, 62 p.

1974 (with Myers, W.B.) The nature of the Boulder batholith of Montana: Geological Society of America Bulletin, v. 85, p. 365–378, https://doi.org/10.1130/0016-7606(1974)85<365:NOTBBO>2.0.CO;2.

1974 Earthquake map of the Indonesian region: U.S. Geological Survey Map I-875C.

1977 Subduction in the Indonesian region, *in* Talwani, M., and Pitman, W.C., eds., Island Arcs, Deep-Sea Trenches and Back-arc Basins: American Geophysical

Union Maurice Ewing Series, v. 1, p. 15–31.

1978 Mesozoic tectonics of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Paleogeography Symposium 2, p. 33–70.

1979 Tectonics of the Indonesian Region: U.S. Geological Survey Professional Paper 1078, 345 p. + map.

1981 Plate-tectonic mechanism of Laramide deformation: University Wyoming Contributions to Geology, v. 19, no. 2, p. 87–92.

1981 Tectonic map of the Indonesian region: U.S. Geological Survey Map I-875-D, 2nd ed., revised.

1981 (with Kröner, A., Moorbath, S.E., and Windley, B.F.) Crustal evolution by arc magmatism: Royal Society of London Philosophical Transactions, Series A, Mathematical and Physical Sciences, v. 30l, no. 1461, p. 279–291, https://doi.org/10.1098/rsta.1981.0111.

1982 Structural evolution of the Big Maria Mountains, northeastern Riverside County, southeastern California, *in* Frost, E.G., and Martin, D., eds., Mesozoic-Cenozoic Tectonic Evolution of the Colorado River Region, California, Arizona, and Nevada: San Diego, California, Cordilleran Publishers, p. 1–27.

1983 Cretaceous and Cenozoic history of the northern continents: Annals of the Missouri Botanical Garden, v. 70, p. 440–458, https://doi.org/10.2307/2992082.

1983 (with Stone, P., and Howard, K.A.) Correlation of metamorphosed Paleozoic strata of the southeastern Mojave Desert region, California and Arizona: Geological Society of America Bulletin, v. 94, p. 1135–1147, https://doi.org/10.1130/0016-7606(1983)94<1135:COMPSO>2.0.CO;2.

1987 Crustal extension in the Basin and Range Province, southwestern United States, *in* Coward, M.P., Dewey, J.F., and Hancock, P.L., eds., Continental Extensional Tectonics: Geological Society of London Special Publication 28, p. 155–176, https://doi.org/10.1144/GSL.SP.1987.028.01.12.

1987 Plate-tectonic evolution of western United States: Episodes, v. 10, p. 271–276.

1987 Mesozoic geology and tectonics of the Big Maria Mountains region, southeastern California: Arizona Geological Society Digest, v. 18, p. 33–47.

1988 Detachment faulting in the Death Valley region, California and Nevada, *in* Carr, M.D., and Yount, J.C., eds., Geologic and Hydrologic Investigations of Potential Nuclear Waste Disposal Site at Yucca Mountain, Southern Nevada: U.S. Geological Survey Bulletin 1790, p. 51–85.

1988 Laramide crustal shortening, *in* Schmidt, C.J., and Perry, W.J., Jr., eds., Interaction of the Rocky Mountain Foreland and the Cordilleran Thrust Belt: Geological Society of America Memoir 171, p. 27–39, https://doi.org/10.1130/MEM171-p27.

1988 Tectonic setting and variations with depth of some Cretaceous and Cenozoic structural and magmatic systems of the western United States, *in* Ernst, W.G., ed., Metamorphism and Crustal Evolution of the Western United States: Prentice-Hall, p. 1–40.

1988 Plate tectonics and island arcs: Geological Society of America Bulletin, v. 100, p. 1503–1527, https://doi.org/10.1130/0016-7606(1988)100<1503:PTAIA>2.3.CO;2.

1989 Crustal geologic processes of the United States, *in* Pakiser, L.C., and Mooney, W.D., Geophysical Framework of the Continental United States: Geological Society of America Memoir 172, p. 743–782, https://doi.org/10.1130/MEM172-p743.

1990 (with Clift, P.D., Robertson, A.H.F., Dewey, J.F., Gass, I.G., Curry, G.B., Harris, N.B.W., and Şengör, A.M.C.) On terrane analysis: Royal Society of London Philosophical Transactions A, Mathematical, Physical and Engineering Sciences, v. 331, 511–522, https://doi.org/10.1098/rsta.1990.0086.

1994 Subduction systems and magmatism, *in* Smellie, J.L., ed., Volcanism Associated with Extension at Consuming Plate Margins: Geological Society of London Special Publication 81, p. 3–28, https://doi.org/10.1144/GSL.SP.1994.081.01.02.

1998 Archean magmatism and deformation were not products of plate tectonics: Precambrian Research, v. 91, p. 143–179, https://doi.org/10.1016/S0301-9268(98)00042-4.

2002 The closed upper-mantle circulation of plate tectonics, *in* Stein, S., and Freymueller, J.T., eds., Plate Boundary Zones: American Geophysical Union Geodynamics Series, p. 359–347, https://doi.org/10.1029/GD030p0359.

2003 An Alternative Earth: GSA Today, v. 13, p. 4–12, https://doi.org/10.1130/1052-5173(2003)013<0004:AAE>2.0.CO;2.

2005 Plumeless Venus preserves an ancient impact-accretionary surface, *in* Foulger, G.R., Natland, J.H., Presnall, D.C., and Anderson, D.L., eds., Plates, Plumes, and Paradigms: Geological Society of America Special Paper 388, p. 781–814, https://doi.org/10.1130/0-8137-2388-4.781.

2007 Earth's first two billion years—The era of internally mobile crust, *in* Hatcher, R.D., Jr., Carlson, M.P., McBride, J.H., and Martínez Catalán, J.R., eds., 4-D Framework of Continental Crust: Geological Society of America Memoir 200, p. 233–296, https://doi.org/10.1130/2007.1200(13).

2007 Driving mechanism and 3-D circulation of plate tectonics, *in* Sears, J.W., Harms, T.A., and Evenchick, C.A., eds., Whence the Mountains? Inquiries into the Evolution of Orogenic Systems: A Volume in Honor of Raymond A. Price: Geological Society of America Special Paper 433, p. 1–25, https://doi.org/10.1130/2007.2433(01).

2007 An alternative Venus, *in* Foulger, G.R., and Jurdy, D.M., eds., Plates, Plumes and Planetary Processes: Geological Society of America Special Paper 430, p. 879–911, https://doi.org/10.1130/2007.2430(41).

2011 Plate tectonics began in Neoproterozoic time, and plumes from deep mantle have never operated: Lithos, v. 123, p. 1–20, https://doi.org/10.1016/j.lithos.2010.12.007.

2013 Evolution of the Archean Mohorovičić discontinuity from a synaccretionary 4.5 Ga protocrust: Tectonophysics, v. 609, p. 706–733, https://doi.org/10.1016/j.tecto.2013.08.009.

2015 Terrestrial planets fractionated synchronously with accretion, but Earth progressed through subsequent internally dynamic stages whereas Venus and Mars have been inert for more than 4 billion years, *in* Foulger, G.R., Lustrino, M., and King, S.D., eds., The Interdisciplinary Earth: A Volume in Honor of Don L. Anderson: Geological Society of America Special Paper 514, p. 123–156, https://doi.org/10.1130/SPE514.

2019 Toward a myth-free geodynamic history of Earth and its neighbors, invited paper in preparation for Earth-Science Reviews.