Notes

INTRODUCTION

1. Ewen A. Whitaker, "Galileo's lunar observations and the dating of the composition of 'Sidereus Nuncius,'" *Journal for the History of Astronomy* 9 [1978]:155–69.

2. Fisher 1945, 104; Dietz 1946, 360. Ewen Whitaker has researched the origin of the lunar use of the terms *terra* and *maria* and found that the notion that the dark areas are seas and the light areas are lands like those of Earth seems to have been common among the ancient Greeks.

3. What to call the "objects" is a problem. *Meteor* really refers to an atmospheric phenomenon—a shooting star. *Bolide* was often used in the older literature, but its most common English meaning is "a large bursting meteor." Purist meteoriticists define *meteorite* as a "cosmic rock" that they have found, so by this definition meteorites did not form lunar craters. *Meteoroid* is a technically more precise term for the cosmic objects, but *oid* means "not quite" and is usually used for smallish objects. Ralph Baldwin (1963, 113) tells us not to worry and just go ahead and use *meteorite.* This book, however, also uses more general terms such as *projectile, impactor,* and *impacting object.*

4. Albritton 1963; Gould 1989.

5. L. B. Ronca, "Selenology vs. geology of the Moon, etc.," *Geotimes* 9, 9 (May–June 1965):13.

6. The planets: Mercury, Venus, Earth, Mars. The satellites: Moon, Phobos, Deimos, Io, Europa, Ganymede, Callisto, Mimas, Enceladus, Tethys, Dione, Rhea, Iapetus, Miranda, Ariel, Umbriel, Titania, Oberon, and Triton. Jupiter, Saturn, Uranus, Neptune, and Titan have also been imaged but their solid surfaces were not seen.

7. Many synonyms for *aeon* are given in the literature. One often sees b.y. (billion years). However, billion means a million million (10^{12}) in British English and the Continental European languages, which use thousand million or milliard for 1,000,000,000 (10^9). Giga-year (Gy) and, worse, giga-annum (Ga), are sometimes used, but as Ross Taylor (1982, 57) observed, they are typical of terms designed by committees. The

number 10^9, or 1,000,000,000, is unambiguous, but I do not like numbers. Hence aeon, a nice, short, easy-to-write term suggested by Harold Urey.

CHAPTER 1. A QUIET PRELUDE (1892 – 1957)

1. Histories of early lunar investigations include Baldwin 1949, 1963; Shoemaker 1962a; Green 1965; Kopal and Carder 1974; Marvin 1986; and Hoyt 1987.

2. Davis 1926; Pyne 1980; Yochelson 1980; Hoyt 1987.

3. Pyne 1980; the story of the earthquake is on pp. 211, 228–31.

4. Hoyt 1987, 31–72; Shoemaker 1962a; Farouk El-Baz, "Gilbert and the Moon," in Yochelson 1980, 69–80; Mark 1987.

5. Cited by Davis 1926, 176, and called to my attention by M. Charles Gilbert (no relation).

6. Gilbert 1893. Gilbert also presented his findings orally at least three times (Hoyt 1987, 56, 374) including on 10 December 1982 as the retiring president of the Philosophical Society of Washington.

7. Richard A. Proctor, *The Moon: Her motions, aspect, scenery, and physical condition* (London: Longmans Green, 1873); see Hoyt 1987. I have seen Asterios described alternatively as brothers and as father and son.

8. Shaler 1903. Geologist Shaler's exhaustive lunar investigations spanned a third of a century and damaged his eyes, yet produced few results recognized today as correct.

9. Pyne 1980.

10. Hoyt 1987.

11. Gilbert 1896.

12. Committee on Study of the Surface Features of the Moon included astronomers W. S. Adams, F. G. Pease, Edison Pettit, and H. N. Russell; mathematical physicist P. S. Epstein; and geoscientists J. P. Buwalda, A. L. Day, and F. E. Wright (the chairman). See F. E. Wright, "The surface features of the moon," *Scientific Monthly* 40 (1935):101–15. A later review by F. E. Wright, F. H. Wright, and Helen Wright, in Middlehurst and Kuiper (1963, 1–56), gives the status of lunar knowledge at the time of its writing and includes work done since the committee's dissolution and the death of Fred Wright in 1954.

13. The late William Hoyt tells both stories with great understanding and thorough documentation in his excellent book (Hoyt 1987).

14. Patrick Moore, "The turbulent life of E. J. Opik," *Sky and Telescope* 71 (1986):149; George Wetherill, "Ernst Julius Öpik (1893–1985)," *Icarus* 66 (1986):193–94.

15. See Baldwin 1963.

16. Hoyt 1987, 197–98.

17. A. L. Wegener, "Die Aufsturztheorie der Mondkrater" (The impact theory of Moon craters), *Sirius* 53 (1920):189–94. A longer 1921 paper is "The origin of lunar craters," *The Moon* 14 (1975):211–36, translated by A. M. Câlal Sengör.

18. A biographical sketch of Gifford and extended excerpts from his papers are given by Hoyt 1987, esp. 204–8. Reference to Hoyt's book will spare readers a search for 1924

issues of the *New Zealand Times, New Zealand Journal of Science and Technology* (7:129–242), or the *Hector University Bulletin.*

19. Baldwin (1963, 14) singles out the Meteor Crater study by astronomer Forest Ray Moulton (1872–1952) as "amazingly modern." Baldwin concluded that cratering efficiency depends on kinetic energy, which equals $\frac{1}{2}mv^2$, where m is the mass and v is the velocity. Öpik, however, insisted that the proper measure was *momentum* ($= mv$). Mass is essentially unlimited in Solar System objects; the largest asteroid, Ceres, is nearly 1,000 km across and would demolish the Moon if it hit. Impact velocities near the Earth and Moon are typically 16–20 km per second but can be much higher.

20. *Impact* is now the term most commonly used to describe what happens when an object from space strikes a planet. However, at least one early proponent of this origin for lunar and terrestrial meteorite craters, meteoriticist L. J. Spencer of the British Museum ("Meteorites and the craters on the Moon," *Nature* 139 [1937]:655–57), did not think the term was adequate. He thought it suggested a nonexplosive mechanical effect, as does the term *percussion.* For example, he stated that Wegener said the craters formed "merely" by impact.

21. Barrell 1924; also *Smithsonian Institution Report* 1928 (1929):283–306.

22. See, for example, Spencer, "Meteorites and the craters on the Moon"; Baldwin 1949; Nininger 1952. The newly identified craters were at Odessa, Texas; the appropriately named Campo del Cielo, Argentina; Kaalijärv (Ösel Island), Estonia; Henbury, Australia; and Wabar, Arabia.

23. Nininger (1952) gives the 1936 date for the idea (p. 306). However, he seems first to have published it in 1943 in *Sky and Telescope* 2, 4:12–15 and 2, 5:8–9. Earlier, he says, someone he does not name had suggested that *volcanoes* throw tektites from the Moon to the Earth.

24. J. D. Boon and C. C. Albritton, Jr., "Meteorite craters and their possible relationship to 'cryptovolcanic' structures," *Field and Laboratory* 5 (1936):1–9; "Meteorite scars in ancient rocks," *Field and Laboratory* 5 (1937):53–63; "The impact of large meteorites," *Field and Laboratory* 6 (1938):56–64.

25. Green 1971.

26. Pyne 1980, 175. Of course, Gilbert was referring to Spurr's terrestrial work.

27. Daly 1946. Daly insisted on writing "craters" in quotes because to him the term meant volcanic craters. In 1947 he suggested an impact origin for the Vredefort structure in South Africa (*Journal of Geology* 55:125–45).

28. I believe that any scientist familiar with the Moon who has read Baldwin's books would agree with this statement. For example, see Hartmann 1972, 312; French 1977, 69; Chapman and Morrison 1989, 45–47.

29. Conversation with Baldwin's daughter, Pamela, in San Francisco, July 1990.

30. Baldwin 1942, 1943.

31. Baldwin 1978. Baldwin presented this paper as the Meteoritical Society's banquet address in Sudbury, Ontario, in August 1978. Although titled "An overview of impact cratering," it gives a lengthy account of Baldwin's career.

32. R. B. Baldwin, *The deadly fuze* (San Raphael, Calif.: Presidio, 1980). *Fuze* is the military term for the device that operates to detonate a shell or other explosive; a *fuse* is the device that breaks electrical circuits.

33. Baldwin 1949, 63.

34. Ibid., 202.

35. Hoyt 1987, 357–60.

36. Baldwin 1949, 132.

37. Ibid., 153–54.

38. Ibid., 37.

39. An appropriate occasion to mention this parallel was during my presentation of the citation for the G. K. Gilbert Award of the Geological Society of America to Baldwin at the annual meeting in San Antonio on 11 November 1986. The award was established by the GSA's Planetary Geology Division to honor outstanding contributors to planetary geology. The citation and reply (*Bulletin of the Geological Society of America* 99 [1987]:150–53) contain biographical and career information supplementing that given here; see also Baldwin 1978.

40. Baldwin 1949, 47. In San Francisco in 1982, geochemist Ross Taylor told me that this Serenitatis example was what convinced him at the beginning of his lunar career in the late 1960s that the Moon could be successfully analyzed stratigraphically.

41. Ibid., 158–60. A favorite example of the endogenists demolished by Baldwin is the crater "chain" in the south-central lunar highlands consisting of Ptolemaeus, Alphonsus, Arzachel, Purbach, Regiomontanus, and Walter (north to south), no two of which are the same age.

42. Ibid., 210–13. Baldwin was obviously impressed with the magnitude of the events he had deduced, and his prose gets quite colorful in these pages. The "800 miles" (1,300 km) is the present diameter of the Imbrium topographic basin measured between the mountainous border arcs.

43. Ibid., 178–99; Baldwin 1963, 2, 201–10, 240–45; Fielder 1961, 14, 31–45; Markov 1962, 1–53; Kopal 1962, 1–98.

44. Fielder 1961, 34–35.

45. Baldwin 1963, chap. 11.

46. Brush (1982) favors the train trip version, and Baldwin (personal communication) the scientific meeting version. The rest of this section draws material from Brush's paper.

47. Interview with Epstein, September 1989, at Caltech (where he has been since 1952).

48. Urey 1951, 1952, 1962; "Observations on the Ranger photographs," in Hess, Menzel, and O'Keefe 1966, 3–21.

49. Urey 1962, 489.

50. Ibid., 484; S. G. Brush, "Early history of selenogony" (note), in Hartmann, Phillips, and Taylor 1986, 11.

51. Biographical and historical information about Shoemaker in this and other chapters is taken from lengthy interviews taped on 19 August 1970 (Flagstaff, for USGS personnel), 17 March 1984 (Houston, for W. David Compton), and 25 June 1987 (Flagstaff, com-

memorating [with a nine-month delay] the twenty-fifth anniversary of the Branch of Astrogeology); from many personal conversations over the years; and from Shoemaker 1981.

52. Shoemaker 1962a. This landmark paper includes all his crater studies discussed in this section and is one of his great works of the early 1960s.

53. William Walden Rubey (1898–1974), who contributed in major ways to a number of important geologic topics (for example, thrust-fault mechanics and oceanic geochemistry), kept up with developments in lunar exploration and served on a number of committees, including the Planetology Subcommittee of the Space Science Steering Committee (OSSA) when I was also on it (1969–1970). He was also the first (temporary) director of the Lunar Science Institute in Houston.

54. D. P. Cruikshank, "20th century astronomer," *Sky and Telescope* 47 (1974):159–64; Carl Sagan, "Gerard Peter Kuiper (1905–1973)," *Icarus* 22 (1974):117–18. Both Sagan and Cruikshank were Kuiper's students. Most of the details about Kuiper included here are from Whitaker 1985. See also Bettyann Kevles, "A pioneer of planetary science," *Planetary Report* 9, 3 (May–June 1989):18–21.

55. Coincidentally, Kuiper and Bok ended up as the directors of the two astronomical institutes of the University of Arizona: the Lunar and Planetary Laboratory (see chapter 2) and Steward Observatory, respectively. Because of a maritime tradition requiring astronomy for navigation and timekeeping, and despite its low elevation and overcast skies, the Netherlands has produced an astonishingly large number of eminent astronomers.

56. Claire Patterson, "Age of meteorites and the earth," *Geochimica et Cosmochimica Acta* 10 (1956):230–37. Preliminary results of this landmark study were available to Urey and Kuiper in 1953 and 1954. Patterson's value of 4.55 ± 0.07 aeons, based on isotopes of lead in meteorites, is still widely accepted as Earth's age.

57. H. C. Urey, "Some criticisms of 'On the origin of the lunar surface features,' by G. P. Kuiper," *Proceedings of the National Academy of Sciences USA* 41 (1955):423–28, followed by Kuiper's reply ("The lunar surface—further comments") on pp. 820–23.

58. Whitaker 1985.

59. Middlehurst and Kuiper 1963, 57–89.

60. D. W. G. Arthur, "The classification of the smaller lunar craters," *Journal of the British Astronomical Association* 64 (1954):127–32, 154, wherein Arthur astutely supported the impact origin of lunar craters from their size-frequency distribution. In Kopal and Mikhailov (1962, 317–24) he opined that few faults existed on the Moon, contrary to the opinions of supposedly better-educated geologists and astronomers.

61. A. V. Khabakov, in Markov 1962, 247–303, and map; Kurd von Bülow, "Tektonische Analyse der Mondrinde" (Tectonic analysis of the Moon's crust), *Geologie* 6 (1957):565–609; Firsoff 1959; Fielder 1961, 1965.

62. The camp was the subject of a public television series in about 1987. No one knew quite what to do with these people. They were from enemy countries and yet did not threaten North American security. So they were placed in this not uncomfortable camp, given leave privileges, and left to pursue their intellectual interests. I have never seen mention of this interlude in biographical entries for Gold, but he appeared in an interview on the PBS program.

63. Gold 1955; T. Gold, "Evolution of mare surface," *PLSC* 2 (1971):2675–80. See also chapter 18.

64. Hackman is introduced in chapter 2. He told me this incident in January 1970.

65. Martin Gardner, "The unorthodox conjectures of Tommy Gold," *Skeptical Inquirer* 11 (Fall 1986):21–24; also see follow-up letters in the spring 1987 issue. Gold once told Charles Wood that this was the reason he did not willingly abandon his ideas.

66. Baldwin 1963, 351. The quote referred to crater rays but was generally applicable.

CHAPTER 2. THE QUICKENING PACE (1957 – 1961)

1. Gatland 1981; Baker 1982; McDougall 1985.

2. Hall 1977; Koppes 1982; Burrows 1990.

3. Alter 1967, 1968, esp. 216.

4. Just before his death in 1965 Bucher accepted strong evidence shown to him by Shoemaker as proving the meteorite origin of Meteor Crater and refuting his (Bucher's) "cryptovolcanic" concept (John F. McCauley, conversation with the author, San Francisco, October 1990).

5. Three colloquia were held in 1958, four in 1959, two each in 1960 and 1961, and one each in 1962 and 1963; the last was on 6–7 May 1963. I thank Gene Shoemaker for loaning me his complete set of a limited edition of the proceedings, which were published by North American's Space and Information Systems Division (the new name of the Missile Division and the home since 1959 of Jack Green) and which contain a rare record of the scientific and engineering thinking of the early Space Age.

6. Davies kindly sent me reprints of his quite ingenious orbiter camera study, an update of which he patented in 1964. See M. E. Davies, "Lunar exploration by photography from a space vehicle," in *Proceedings of the Tenth Astronautical Congress* (London, 1959) (Vienna: Springer, 1960), 268–78.

7. Burrows 1986.

8. Newell 1980; Levine 1982; McDougall 1985, 157–76, 195–96.

9. Newell's (1980) memoirs are a rich source of inside information and viewpoints on the trials and tribulations of the space program.

10. The story of the Space Task Group is told by Baker (1982) and, very entertainingly and fully, by C. Murray and Cox (1989).

11. Woods 1981. The excitement of preparing what now seems to have been a primitive space shot, Pioneer 1, is described in the *National Geographic*'s sunny style by A. C. Fischer, Jr., in "Reaching for the Moon," *National Geographic* 115 (1959):157–71.

12. Newell 1980, 258–73; Koppes 1982, 134–60.

13. Whitaker 1985.

14. Kuiper 1959. The same volume contains one of many enunciations by Gold of his dust-transport notion.

15. The story of the atlas's construction is told by Whitaker (1985).

16. Histories of the Department of Defense mapping: Kopal and Carder 1974; St. Clair, Carder, and Schimerman 1979; Greeley and Batson 1990, chap. 2. AFCRL also

started in 1958 to fund a program for measuring cast shadows to determine lunar elevations that would be used on the ACIC charts. This program was conducted at the University of Manchester, England, under the direction of Zdeněk Kopal. Elevations of many points were printed on the charts and were also used to derive contours (which, however, are reliable only in local areas).

Technically, a *chart* is used for navigation, while *map* is a more general term for a two-dimensional portrayal of a region. However, most lunar charts fit this definition of chart only by stretching a point. Presumably they were so named because they were made by the Aeronautical Chart and Information Center, which was accustomed to making charts for airplane navigation. The 1:1,000,000 scale of the LACs was chosen because that was the scale of the Aeronautical Chart Series, 1,800 of which map the Earth's surface.

17. Stereophotogrammetry involves putting two photographs of the same area taken from different angles into a plotter, viewing them stereoscopically, and drawing contours around hills and in valleys with a gadget that makes a dot which seems to stay at the same elevation. No topographically accurate map has yet been made of the entire lunar near side, not to mention the whole Moon.

18. Whitaker 1985.

19. Hall 1977. I am not sure whether Hall coined the term. Sky scientists study particles and fields, and the less material they can see, the better.

20. Newell 1980.

21. Robert Jastrow, "The exploration of the Moon," *Scientific American* 202, 5 (May 1960):61–69; Jastrow 1981; Jastrow 1989, 7–14; Newell 1980, 237.

22. I am indebted to John O'Keefe for sending me, in May 1988, copies of his memos and letters and also an account of his memory of the events of the critical years 1959 and 1960. See also Hall 1977, 14–24. The lunar working group was parallel to two working groups on sky science also established by Newell. At various times it also included such prestigious members as geologist-oceanographer Maurice Ewing of Columbia University's Lamont-Doherty Geophysical Observatory, astronomer-physicist Gordon MacDonald of UCLA, and biologist and Nobel laureate Joshua Lederberg. Newell also visited JPL sometime in mid-January 1959 (Newell 1980, 262).

23. At about this time a "Prospector" mission consisting of a rover and a sample returner, landed by separate Saturns, was proposed to follow the Surveyor land-and-stay missions but was not funded.

24. Newell 1980, 262–64. In fact, the first clear U.S. success in Solar System exploration was Mariner 2's flyby of Venus in December 1962.

25. S. S. Dolginov, E. G. Eroshenko, L. I. Zhuzgov, and N. V. Pushkov, "A study of the magnetic field of the Moon," in Kopal and Mikhailov 1962, 45–52; Ness 1979.

26. Barabashov, Mikhailov, and Lipskiy 1961; Kopal and Mikhailov 1962, 3–44.

27. Shaler 1903, 4, 15. Shaler correctly predicted that except for the fewer maria, the far side was the same as the near side, because he observed crater rays that converged on the far side.

28. A. V. Khabakov, in Markov 1962, 248.

29. E. A. Whitaker, in Middlehurst and Kuiper 1963, 123–28.

30. Wilkins and Moore 1961, 14.

31. Ordway and Sharp 1979, 439–41; McDougall 1985, 198. MSFC was officially dedicated as such in July 1960.

32. McCauley 1967a; Mutch 1970; Wilhelms 1970; Wilhelms and McCauley 1971; Varnes 1974; Guest and Greeley 1977; D. E. Wilhelms, in Greeley and Batson 1990, chap. 7.

33. This history was pieced together from telephone interviews in June 1989 with Whitmore, William E. Davies, and Annabel B. Olson, and an in-person interview with a close associate of Mason's, Helen Foster. See also H. L. Foster, "Memorial to Arnold Caverly Mason (1906–1961)," *Bulletin of the Geological Society of America* 73, 8 (1962): P87–P90. Mason was on active duty with the Corps of Engineers between 1943 and 1947, joined the Military Geology Branch in 1947, and obtained his Ph.D. from the University of Illinois in 1955.

34. R. J. Hackman, "Photointerpretation of the lunar surface," *Photogrammetric Engineering* (June 1961):377–86 (presented orally March 1961).

35. Hackman and Mason 1961.

36. R. S. Dietz, "Shatter cones in cryptoexplosion structures (meteorite impact?)," *Journal of Geology* 67 (1959):496–505, probably contains the first mention of the term *cryptoexplosion.* The defining paper for astroblemes is R. S. Dietz, "Meteorite impact suggested by shatter cones in rock," *Science* 131 (1960):1781–84; see also Dietz, "Astroblemes," *Scientific American* 204 (1961):2–10. Dietz said that *bleme* (*blema*) more specifically refers to the kind of wound formed by a thrown object. He summarized his work on astroblemes and the general status of terrestrial crater investigations in Middlehurst and Kuiper 1963, 285–300. He was not the discoverer of shatter cones but took the lead in demonstrating and publicizing their importance as indicators of impact shock. The account of the Sierra Madera trip given here is from a telephone conversation with Dietz in August 1990.

37. Those who knew Mason with whom I have spoken (see n. 33) cannot pinpoint the cause of his suicide. In January 1970 Hackman told me that it was due to a disparaging remark Shoemaker made to Mason — but Hackman blamed a lot of things on Shoemaker. Annabel Olson recalled a dispute between Hackman and Mason over senior authorship of the *Engineer Special Study* (1961), which Hackman won. Helen Foster said that Mason had never settled on a definite career goal and was therefore sensitive about his priority in one he finally could identify as his. But also, he seems to have suffered from a general depression and had long-standing family problems.

38. E. M. Shoemaker, "Impact mechanics at Meteor Crater, Arizona," USGS open-file report (1959).

39. Hoyt 1987, 357–63. The Coon Mountain debate had begun to flag the importance of shock waves in the 1930s. Very early, Baldwin (1943) also referred to shock waves, but his writings stress the explosion-like effect.

40. E. M. Shoemaker, "Penetration mechanics of high velocity meteorites, illustrated by Meteor Crater, Arizona," *International Geological Congress Report, XII Session (Norden),*

pt. 18 (1960):418–34. An expanded and more accessible report by Shoemaker is in Middlehurst and Kuiper 1963, 301–36.

41. Baldwin 1949, 32, 41, 208.

42. G. P. Kuiper, "The Lunar and Planetary Laboratory," *Sky and Telescope* 27 (1964): 4–7, 88–92; Kuiper, "The Lunar and Planetary Laboratory and its telescopes," *LPL Communications,* no. 172, 9 (1972):199–247; Whitaker 1985.

43. Whitaker 1985. For a few days Kuiper used the name Planetary Physics Laboratory of the Institute of Atmospheric Physics (IAP), but on 1 February 1960 he changed it to the present name, though still under the IAP. By summer 1961 LPL had become independent of IAP, though it was located in IAP quarters until late 1962. In late 1966 LPL moved into its present quarters in the Space Sciences building, funded by NASA and dedicated in January 1967. The Kitt Peak National Observatory ended up being operated not by Kuiper but by a consortium of universities, the Association of Universities for Research in Astronomy (AURA).

44. Kuiper et al. 1960. Each of the 44 fields into which the lunar near side was divided (which do not coincide with the 44 LAC fields) was covered by four to seven photographs, each taken under different lighting conditions and all printed at the same scale of 1:1,370,000. A total of 230 17-by-21-inch sheets was issued in a large box. The photographs of a given area were also usually taken at different librations and can therefore be viewed stereoscopically with the specially constructed stereoscopes designed by Hackman (see n. 34).

45. Arthur and Whitaker 1960. The atlas was printed in December 1960. Orthographic coordinates (a grid that treats the Moon like a disk at an infinite distance) were added to the same photographs as those used in Kuiper et al. 1960, and two versions (one commercial and one for the sponsoring U.S. Air Force) have a latitude and longitude grid as well.

46. Combined references: D. W. G. Arthur, A. P. Agnieray, C. R. Chapman, R. A. Horvath, R. H. Pellicori, T. Weller, and C. A. Wood, "The system of lunar craters," *LPL Communications* 30, 40, 50, 70 (1963–66); D. W. G. Arthur, A. P. Agnieray, and R. H. Pellicori, *Lunar designations and positions* [4 charts] (Tucson: University of Arizona Press, 1964–65). LPL more recently polished and newly summarized the nomenclature in Andersson and Whitaker 1982, a definitive catalog. Ewen Whitaker called this the "NASA Catalog of Lunar Nomenclature" to distinguish it from the rival, and actually more official, IAU system, which substitutes a clumsy system of individual crater names for the lettered designations (Mädler system) used in the LPL-NASA catalog. Leif Andersson was a promising young scientist who died prematurely before the catalog was published.

47. J. A. O'Keefe, "Origin of tektites," *Nature* 181 (1958):172–73. He had previously written a one-page paper suggesting that glass beads could explain the surge of brightness at full moon characteristic of lunar rays ("Lunar rays," *Astrophysical Journal* 126 [1957]:466) and considered tektites to be a plausible explanation for such beads. I thank O'Keefe for calling this historical background of his tektite hypothesis to my attention. I am furthermore deeply indebted to him for the key role he played in getting NASA contract

money for the Survey, thus providing me with gainful and mostly enjoyable employment for 24 years.

48. In a letter to Robert Strom dated 9 April 1963, Urey wrote, "I hope you will do all you can in standing up to these tektites from the moon people." Urey's objection was based partly on his opinions about the Moon's composition and partly on the unlikelihood of hitting small spots on the Earth from the Moon. I thank Strom for sending me copies of his correspondence with Urey.

49. I thank Dan Milton for tracking down the report of the meeting by the secretary of the Geological Society of Washington (USGS geologist John Hack). Arnold Mason and Robert Jastrow also spoke, and Paul Lowman and William Pecora attended and commented on Shoemaker's paper in addition to O'Keefe. About 10 standees were included in the crowd of about 303, in contrast to a usual attendance of about 90 at GSW meetings that year.

50. This account combines the recollections of O'Keefe (letter dated 12 May 1988) and Stieff (interview at his home in Maryland, October 1988).

51. This figure was current in the late 1970s and I doubt that it has been augmented since.

52. O'Keefe and Stieff do not remember the nature of the obstacle. Shoemaker has said that it consisted of the chief of the relevant NASA astronomy program, Nancy Roman, because Roman's father had been in the USGS and had felt mistreated in some way. In a letter to me dated February 1991, however, Roman said that on the contrary, her father greatly enjoyed his Survey association and that she did not remember passing judgment on the proposal.

53. L. Coes, Jr., "A new dense crystalline silica mineral," *Science* 118 (1953):131–33.

54. Nininger 1956, 50, 154.

55. This account is based on letters to me from Chao dated May 1989 and a contemporary journal article by Chao: "Natural coesite—an unexpected geological discovery," *Foote Prints* 32, 1 (1960):25–32. Recollections by O'Keefe, Stieff, and Shoemaker are also incorporated here, but Chao's memory of the coesite discovery seems to be the most complete. Events were not quite as described by W. T. Pecora, "Coesite craters and space geology," *Geotimes* 5, 2 (1960):16–19, 32.

56. Pecora, ibid. Coesite was hard to make in the laboratory and in nature. Pecora visited Coes in his laboratory and found that his success in making it and numerous other minerals was due to his systematic, dogged persistence. He worked without fanfare and was humble about his achievements.

57. Anonymous, "Significant discovery by U.S.G.S.," *Geotimes* 5, 1 (1960):37; Chao, Shoemaker, and Madsden 1960. Brian Skinner confirmed Chao's discovery and had some synthetic coesite made for comparison by F. T. Boyd.

58. Baldwin 1949, 108–12; Dietz, "Meteorite impact suggested." Dietz suggested that the Ries and the nearby "kryptovulkanisch" Steinheim were formed by a "double holocaust" and not along a major tectonic lineament, as had been proposed for them and some nearby diatremes by most of the local experts.

59. Suevite (*Suevit* in German) is from the Latin name for the people and region

called Schwaben (Swabia). Suevite makes limp-looking forms appropriately called *Flädele,* referring to a local spiced pancake that is cut into noodles.

60. Shoemaker and Chao 1961. The paper was presented orally in March 1961 (I do not know by which author) to a joint symposium held by the Geophysics Laboratory of the Carnegie Institute of Washington (sponsor, Philip Abelson) and the Lawrence Radiation Laboratory (sponsor, Wilmot Hess). The NASA sponsor was Gordon J. F. MacDonald.

61. Shoemaker 1962a. Besides the Copernicus and Ries studies, this landmark paper includes Shoemaker's work on maars, nuclear craters, Meteor Crater, and shock processes in general.

62. For example, Chao 1974, 1977.

63. Later, Daniel Milton ("Astrogeology in the 19th century," *Geotimes* 14 [1969]:22) pointed out a nineteenth-century Russian precedent for the use of the term *astrogeology* in geological science.

64. "Astrogeologic Studies Group Semi-Annual Progress Report, August 25, 1960–February 25, 1961," USGS informal report (March 1961). (Henceforth abbreviated as ASSPR; annual reports are ASAPR). The USGS makes abundant use of the "open files," which include reports that are complete to the temporary satisfaction of the author but not to the satisfaction of the exacting Survey editors, who are not bothered by the passage of years before formal publication. Almost all of the lunar research done by the Survey in the early 1960s was buried in these "gray" reports. This book, especially chapters 3 and 4, disinters those which deserve to see the light of day once again.

65. The second semiannual report was dated February 26, 1961–August 24, 1961, and was printed in March 1962.

66. The mare thickness study by Marshall (based on burial of craters, a method still in use) appears on pp. 34–41 of the first semiannual report but, along with a photometric study of the Kepler region, was accidentally omitted from the table of contents. Marshall's report was published formally in the *1961 USGS Annual Report,* USGS Professional Paper 424-D:D208–D211. (Unlike the open-file "gray" Astrogeology ASSPRs and ASAPRs, these Survey annual reports are formal publications.)

67. The meeting was the occasion for many other Moon-related papers in addition to Shoemaker and Chao's paper on the Ries coesite and Shoemaker and Hackman's on the stratigraphic scheme (*Bulletin of the Geological Society of America* 71:2093–2113). For example, Mason and Dietz discussed the subjects this book has identified with them, and Paul Schlichta of JPL made the important point about geology's value in extrapolating data from limited points on the surface.

68. Shoemaker and Hackman 1962. The same volume (Kopal and Mikhailov 1962) contains other papers on subjects then in the forefront of research, including the Soviet rocket exploration of the Moon (3–52), selenodesy (55–115, including Arthur and Whitaker), the ACIC mapping (117–29), the Alphonsus "eruptions" (263–87), and the nature of the surface, including radio observations (475–565, including Gold).

69. Mutch 1970, 37.

70. "Interplanetary correlation" was presented at the Seventh Annual Meeting of the American Astronautical Society, Dallas, Texas, 16–18 January 1961, and was originally

released in 1961 as a 30-page open-file report of the U.S. Geological Survey. It was formally published (Shoemaker, Hackman, and Eggleton 1962) in the proceedings volume of the meeting.

71. Baker 1982, 24–25. Charters wrote one of the earliest widely circulated papers on impact cratering: A. C. Charters, "High-speed impact," *Scientific American* 203 (1960):128–40.

72. Don Gault received the G. K. Gilbert Award of the Geological Society of America in 1987 and recorded the early history of the experiments in *Bulletin of the Geological Society of America* 99:986–87, following Ron Greeley's citation.

73. R. E. Eggleton and E. M. Shoemaker, "Breccia at Sierra Madera, Texas," *1961 USGS Annual Report,* USGS Professional Paper 424-D (1961):151–53. Carl H. Roach had been one of the people in the field camp at Hopi Buttes who told Shoemaker about Sputnik. For some years his project within the branch was a study of impact-induced thermoluminescence.

74. H. G. Wilshire, T. W. Offield, K. A. Howard, and David Cummings, *Geology of the Sierra Madera cryptoexplosion structure, Pecos County, Texas,* USGS Professional Paper 599-H (1972), and earlier papers cited therein, which were written to fill the gap before the professional paper finally worked its way through the USGS mill. Rebound of central peaks is discussed in chapter 1 of this volume, and Baldwin 1949, 146–52; Baldwin 1963, 118–20. Dietz and Baldwin agreed with each other and argued against Shoemaker about the rebound origin of peaks (personal correspondence kindly provided by Baldwin). Shoemaker was influenced by Meteor Crater, which is too small to have a rebound peak. He resisted the rebound origin of Sierra Madera for a long time, which caused him to underestimate the Sierra Madera crater's size and thus the impact rate on the Earth and Moon.

75. Abe Silverstein suggested the name Apollo in early 1960 and no one objected. See Brooks, Grimwood, and Swenson 1979, 7–16; Baker 1982, 55–58.

76. Leonard Mandelbaum, "Apollo: How the United States decided to go to the Moon," *Science* 163 (1969):649–54; Logsdon 1970 (the primary source); Baker 1982, 80–94; McDougall 1985, 301–24; C. Murray and Cox 1989, 70–73 for Webb specifically; Trento 1987.

77. Brooks, Swenson, and Grimwood 1979, 7–31; C. Murray and Cox 1989, 57–69.

78. A NASA memo to that effect appeared on the very day of Kennedy's speech (Hall 1977, 114). The schedule of spaceflights as envisioned in mid-1961 was given by JPL scientist A. R. Hibbs, "The national program for lunar and planetary exploration," *JGR* 66 (1961):2003–12.

79. Philip E. Abelson, "Manned lunar landing," *Science* 140 (1963):267; Hall 1977, 128, 158, 182, 201–2; Newell 1980, 149, 208–9, 290–92, 381–87, 398–411; McDougall 1985, 389–97; Koppes 1982, 113–33.

CHAPTER 3. THE EARTHBOUND VIEW (1961 – 1963)

1. "NASA moved decisions through the system with a speed that today seems unbelievable" (C. Murray and Cox 1989, 83–84).

2. Aldrin and McConnell 1989, 77–78. The Rangers are discussed further in chapter 5 of this volume.

3. *Transactions of the International Astronomical Union* (Proceedings of the Eleventh General Assembly, Berkeley, 1961), 11B:234–35 (New York: Academic Press). The south-up orientation was still permitted for illustrations tied to telescopic use, but east and west were no longer to be used on such illustrations.

4. After the Lunar Orbiter missions, Kuiper, Whitaker, and Arthur devised the name Mare Annulatum (Ringed Sea) for Mare Orientale, but the IAU did not accept the change.

5. Sheehan 1988.

6. Hartmann 1981. Hartmann thought the rings were probably first noticed either by himself or by L. H. Spradley, who was in charge of photography for an atlas of rectified photographs that was another major contribution by LPL (Whitaker et al. 1963). The atlas's rectified views of large areas have remained unique and useful despite the availability of spacecraft photographs.

7. Hartmann and Kuiper 1962. The term *basin* is also discussed in later reviews by Stuart-Alexander and Howard (1970), and Hartmann and Wood (1971).

8. Baldwin 1949, esp. 40–45.

9. Hartmann and Kuiper 1962. Urey and other scientists criticized LPL for this in-house publication (Newell 1980, 127; Hartmann 1981, 88); however, Kuiper felt that no better outlets for the publication of LPL's many lunar and planetary investigations were available, at least before 1962 when the first Solar System journal, *Icarus*, began publication. Also, Kuiper was an artist at heart according to Charles Wood, and wanted to control the design as well as the speed of his lab's publications.

10. Hartmann 1981.

11. Ibid., 89.

12. Shoemaker and Hackman 1962. This paper was written by Shoemaker, but in January 1970 in Washington, Hackman told me that he was the one who worked out the Archimedes relation and the basin-mare time gap. The significance of Archimedes is also described in a paper authored by A. Mason and Hackman in the same volume.

13. A. Mason and Hackman 1962, 303. Hackman told me that it was he, and not Mason, Shoemaker, or anyone else, who first realized that the upland flank of Imbrium was more highly cratered than Mare Imbrium but less highly cratered than typical uplands.

14. The quote is from Baldwin 1963, 6.

15. Markov 1962.

16. Fielder 1961; Kuiper and Middlehurst 1961.

17. OSS and a parallel Office of Manned Space Flight (OMSF) under Brainerd Holmes replaced the earlier Office of Space Flight Development headed by Abe Silverstein.

18. Newell 1980, 205–14, 438; pp. 434–37 give the board's membership through 1972; Compton 1989, 30–31.

19. Space Science Board, National Academy of Sciences 1962. Earlier in 1962 Hess had taken over chairmanship of the Space Science Board from geophysicist–electrical

engineer Lloyd Berkner. The only scientists who then were full members of the board and who had performed Moon-related work (of whom I am aware) were astronomer-physicist Gordon J. F. MacDonald of ULCA and chemist-meteoriticist Harrison Brown of Caltech. Only in the reports' appendixes are there a few references to geologic matters, written by the Working Group on Lunar and Planetary Research, which included names that remained familiar during the later active period of lunar science: Edward Anders, Tom Gold, Harry Hess (chairman), Gene Shoemaker, Fred Whipple, and Don Wise. Philip Abelson, editor of *Science* and an opponent of the Apollo program, was also a member of the working group.

20. Brooks, Grimwood, and Swenson 1979, 61–86; Baker 1982, 144–57; Aldrin and McConnell 1989, 89–107.

21. The libration points lie 60° away from the Moon along its orbit, positions where the gravitational forces of the Moon and Earth are in balance with the centrifugal orbital forces of the particles. The calculations were published by Giuseppe Lagrange in 1776.

22. "ASAPR August 1961–August 1962" (April 1963), pt. A, 64–67. All ASAPR (annual) and ASSPR (semiannual) Astrogeologic Studies progress reports are "open file" gray literature reports of the U.S. Geological Survey. The first six, with their actual dates of appearance in parentheses: "ASSPR August 1960–February 1961" (March 1961); "ASSPR February 1961–August 1961" (March 1962); "ASAPR August 1961–August 1962" (April 1963); "ASAPR August 1962–July 1963" (May 1964); "ASAPR July 1963–July 1964" (November 1964); "ASAPR July 1964–July 1965" (November 1965). Non-USGS scientists, including Charles Wood of LPL, also attempted unsuccessfully to photograph the clouds.

23. Trento 1987, 49–51.

24. Compton 1989, 18–23, 30–31.

25. This was Shoemaker's wording in an interview with W. D. Compton. However, Holmes hired Shoemaker's friend Manfred Eimer in an advisory role to OMSF like that of Shoemaker at OSS.

26. Edison Pettit and Seth B. Nicholson, *Astrophysical Journal* 71 (1930):102–62. They found temperatures of −153°C in the center of the dark hemisphere to 134°C in the center of the full moon.

27. Either Don Lamar or Paul Merifield gave me this crucial information; I cannot remember which. Lamar and Merifield went into private consulting together and worked on lunar problems for a while.

28. Kopal 1962; Kopal and Mikhailov 1962.

29. Baldwin 1963. Robert Dietz and John J. Gilvarry reviewed the book before publication. Baldwin kindly sent me copies of his correspondence from the review and revision period in 1962.

30. Ralph Baldwin, telephone conversation, September 1990.

31. Reviews of shock mineralogy and petrology in the 1960s include Chao 1967; French and Short 1968.

32. D. J. Milton and F. C. Michel, *Structure of a ray crater at Henbury, Northern Territory, Australia,* USGS Professional Paper 525-C (1965):C5–C11; Milton 1968a.

33. A current reference list about terrestrial craters is given in chapter 18, The Vanish-

ing Mysteries. See also J. H. Freeberg, "Terrestrial impact structures—a bibliography," USGS *Bulletin* 1220 (1966); Freeberg, "Terrestrial impact structures—a bibliography 1965–68," USGS *Bulletin* 1320 (1969); Hoyt 1987; and Mark 1987.

34. The current (1989) number of known meteorite craters is 120. I thank Richard A. F. Grieve of the Geological Survey of Canada, one of the geologists most active in investigating the Canadian Shield craters, for compiling these numbers for me.

35. Hartmann 1963, 1964. Now I am convinced that all of the radials were formed by secondary impacts, except scarps that cut the maria, such as the Straight Wall, Rimae Cauchy, and a few others. Recently I found a letter I wrote in February 1963 to Paul Merifield in which I said that the fault origin for the sculpture did not seem right. I wish I had stuck to that opinion.

36. Albritton 1967; Chapman and Morrison 1989, 29–39. A kind of uniformitarian thinking is useful in lunar geology. The present is the key to the past in the sense that degraded features probably once resembled fresh features of the same size and origin; for example, smooth doughnut-like craters that once looked like Copernicus.

37. Mason and Hackman 1962, 303.

38. "ASAPR August 1961–August 1962" (April 1963), 19–31.

39. Marshall 1963. In 1964 Hal Masursky told me that Marshall wanted to map the hummocky deposit as ejecta of Letronne but was pressured by Shoemaker and Eggleton to call it Apenninian. Shoemaker says that Marshall could not see any difference in the hummocky units because of poor photos. Imbrium ejecta did get as far as Letronne, but, in my opinion, created secondary craters, not hummocky deposits there. Letronne is a post-Imbrium crater, as Marshall may have thought.

40. "ASSPR February 1961–August 1961" (March 1962), 132–37.

41. J. J. Gilvarry, "Origin and nature of the lunar surface features," *Nature* 188 (1960):886–91. He calculated a moonwide water depth of about 1 km (about what is now calculated on more evidence for Mars), and even deeper in the low-lying maria. He thought the basin rings and shelves marked the retreat of this life-rich sea! Chapters 8, 9, and 11 give additional references. To Gilvarry, the organics explained Kozyrev's claimed detection of carbon (see chapter 5) without recourse to volcanism.

42. Urey 1962, 495. Urey still insisted, however, that the existence of high lunar mountains was inconsistent with extensive volcanism. He was partly right; the mare basalts are thin and owe their low elevation largely to the impact basins they occupy.

43. C. S. Ross and R. L. Smith, *Ash-flow tuffs: Their origin, geologic relations, and identification,* USGS Professional Paper 366 (1961).

44. J. A. O'Keefe and W. S. Cameron, "Evidence from the Moon's surface for the production of lunar granites," *Icarus* 1 (1962):271–85.

45. J. H. Mackin, "Origin of lunar maria," *Bulletin of the Geological Society of America* 80 (1969):735–48.

46. P. D. Lowman, "The relation of tektites to lunar igneous activity," *Icarus* 2 (1963):35–48.

47. O'Keefe and Cameron, "Evidence from the Moon's surface." Laccoliths were first described by G. K. Gilbert, who called them laccolites.

48. W. S. Cameron, "An interpretation of Schröter's Valley and other lunar sinuous rills," *JGR* 69 (1964):2423–30.

49. As usual, Gilvarry ("Geometric and physical scaling of river dimensions of the Earth and Moon," *Nature* 221 [1969]:533–37) supported his argument quantitatively, by showing that lunar and terrestrial "rivers" obey the same scaling laws.

50. The lava-tube hypothesis was advanced in the mid-1960s by Strom and Kuiper, as discussed in chapter 5, but did not achieve wide acceptance at that time.

51. "ASAPR July 1963–July 1964" (November 1964), 52–66.

52. More than a third of the pages in just the main reference works that we used in the early 1960s and that have been cited above (Baldwin 1949, 1963; Fielder 1961; Kuiper and Middlehurst 1961; Kopal 1962; Kopal and Mikhailov 1962; Markov 1962) are devoted to the surficial material and its microstructure. Most of these works review the background and history of the investigations; see especially Baldwin 1963, 248–86.

53. Baldwin 1949, 22.

54. Baldwin 1963, 281–82.

55. Gilvarry ("The nature of the lunar maria," *Astrophysical Journal* 127 [1958]:751–62) rejected lava because dust was established by the observations of Pettit and Nicholson. Ernst Öpik knew at the same time that the existence of Gold-type dust did not exclude the presence of underlying lava.

56. J. R. Platt, "On the nature and color of the moon's surface," *Science* 127 (1958):1502–3; Baldwin 1963, 262.

57. Donald E. Gault, Eugene M. Shoemaker, and Henry J. Moore, "Spray ejected from the lunar surface by meteorite impact," *NASA Technical Note* D-1767 (1963). Here is another example of an important paper buried in the gray literature, although some of it appears in Salisbury and Glaser (1964, 151–63).

58. Salisbury and Glaser 1964; a paper by Salisbury and his colleague Vern G. Smalley in that book (411–43) contains the essence of the model. Jack Salisbury also initiated and contributed heavily to the bibliographies of lunar and planetary research published between 1960 and 1968 as AFCRL Special Reports 40, 55, 67, 82, and 92, and in quarterly issues of *Icarus* between 1969 and 1975.

59. That the Soviet space establishment was antigeology at this time was confirmed to me by Russian geologist A. T. Basilevsky in Houston, March 1988.

60. The later sample-return Lunas landed in an eastern equatorial zone.

61. Harold Urey's choices as of 19 June 1961 are listed by Brooks, Grimwood, and Swenson 1979, 125. Urey did not participate further in the selection of landing sites, though he liberally criticized the choices of those who did.

62. Shoemaker 1962b. A brief account of the fieldwork appeared in "ASSPR February 1961–August 1961" (March 1962), 74–78.

63. This matter of how to describe scales is a persistent annoyance. Technically, "small" scales are those that are small mathematically; that is, they have a large denominator, such as 1:5,000,000 (1/5,000,000). The problem is that such maps cover large areas, whereas maps having "large" scales, such as 1:5,000, cover small areas. The present book tries to get around this terminology problem, but reader beware.

64. In August 1962 ACIC published an experimental chart at the scale of 1:2,000,000 that included the four 1:1,000,000-scale LACs of the Lansberg region. Shoemaker's geologic map of the Copernicus quadrangle described in chapter 2 was the first one made in the Lansberg region, followed by Hackman 1962 (Kepler, LAC 57), Marshall 1963 (Letronne, LAC 75), and Eggleton 1965 (Riphaeus Mountains, LAC 76). This first Copernicus map was never published in color except as an illustration in the November 1963 issue of *Fortune,* whose cover bears Hackman's Kepler map. A completely new version was later published by Schmitt, Trask, and Shoemaker (1967).

65. Sullivan 1962, 89.

66. "ASSPR August 1960–February 1961" (March 1961), 42–44. The final word on albedo, or at least final enough for my taste, was published by Pohn and Wildey (1970).

67. J. Van Diggelen, "A photometric investigation of the slopes and heights of the ranges of hills in the maria of the Moon," *Bulletin of the Astronomical Institutes of the Netherlands* 11 (1951):283–89; D. E. Wilhelms, "ASAPR August 1962–July 1963" (May 1964), pt. D, 1–12. Mathematical justification and elaboration of the technique is given by: Kenneth Watson, *Photoclinometry from spacecraft images,* USGS Professional Paper 599-B (1968); W. J. Bonner and R. A. Schmall, *A photometric technique for determining planetary slopes from orbital photographs,* USGS Professional Paper 812-A (1973).

68. The Menlo Park USGS geologists included Edgar Bailey, Max Crittenden, Dwight Crowder, Dick Hose, Blair Hostetler, Porter Irwin, George Schlocker, G. I. Smith, and Bob Wallace.

69. T. L. Powers, B. T. Howard, and R. F. Fudali, "An analysis of the value of a lunar logistic system. Part I. An operations research study of a strategy for locating lunar landing sites" (informal Bellcomm memo, 14 March 1963). Nine years later the Bell System published a formal retrospective. I thank Farouk El-Baz for providing me with a copy of this key document (Cappellari 1972), which is the most authoritative published account of the technical and scientific rationale for Apollo site selection. See also Levine 1982, 88–92.

70. Brooks, Grimwood, and Swenson 1979, 127–28.

71. Newell 1980, 291; Levine 1982, esp. 246; Compton 1989, 23–25.

72. J. A. Greenacre, "A recent observation of lunar color phenomena" [with a supplementary note by John S. Hall], *Sky and Telescope* 26 (December 1963):316–17. Similar observations a month later and follow-up reports appear in the January 1964 issue of *Sky and Telescope.*

73. This list is partly from memory and partly from the branch monthly report for November 1963. I was definitely there, though my name is not listed in the report, as it was not when I entered on duty. These monthly reports, which were assembled in haste and with great reluctance, are therefore not reliable records. The reporting requirement finally ended, to general relief, in 1977 at the instigation of Mike Carr, the branch chief from 1974 to 1979.

74. Archimedes and the plains were assigned to the Archimedian and Apenninian Series, respectively, in "ASSPR February 1961–August 1961" (March 1962), 114–16; and by Hackman (1966). The Archimedian-Apenninian split is detectable within the

classic paper by Shoemaker and Hackman (1962) as two different ways of explaining what "Imbrian system" means, with and without Archimedian units. (Capitalization of formal geologic terms such as System, Series, Period, and Formation began to be required in 1961.)

75. Our revisions conformed to a new (1961) code of stratigraphic nomenclature devised for North American geology under the leadership of Hollis Hedberg. The code separates the concepts of rock and time units and so allows for changed age assignments, as happened to our mare units, without causing collapse of the whole stratigraphic scheme. See McCauley 1967a; Mutch 1970; Wilhelms 1970, 1987; and Greeley and Batson 1990, Chap. 7.

76. The pre-Nectarian and Nectarian systems replaced the pre-Imbrian (Stuart-Alexander and Wilhelms 1975). I formalized a distinction between the Lower and Upper Imbrian series that had been made informally on many maps (Wilhelms 1987).

77. One who thinks the importance of nomenclature has been overblown is W. K. Hartmann, "Review of 'Planetary Landscapes,' by Ronald Greeley," *Icarus* 72 (1987): 235–36.

78. Eggleton is the geologist most closely identified with the Fra Mauro Formation. The name first appeared in print in a "gray" report: "ASAPR August 1962–July 1963" (May 1964), 46–63. It first appeared formally on his assigned 1:1,000,000-scale quadrangle map (Eggleton 1965). ACIC's provisional name for the Riphaeus LAC (76) had actually been Fra Mauro, though with the common misspelling "Frau."

79. Hackman 1966.

CHAPTER 4. PREPARING TO EXPLORE (1963 – 1965)

1. Newell 1980, 292. Nolan also personally told John O'Keefe the same thing in about 1965 at dinner in the Saville Club in London (letter to me from O'Keefe dated 12 May 1988).

2. Memo dated 24 April 1963 from Nolan to Gilruth.

3. King 1989; Compton 1989, 41–54. After complex negotiations and disputes in Congress, NASA, and the Space Science Board (chronicled in these references), construction of LRL was begun in the summer of 1966.

4. *Houston Chronicle,* 19 October 1963. The Gemini-Apollo distinction was abandoned, but 7 of the 14 did fly Apollo lunar missions: Bill Anders (Apollo 8), Gene Cernan (Apollos 10 and 17), Buzz Aldrin and Mike Collins (Apollo 11), Alan Bean and Dick Gordon (Apollo 12), and Dave Scott (Apollo 15). Earth-orbiting Apollo missions were flown by 3 others: Walt Cunningham and Donn Eisele (Apollo 7, with Mercury astronaut Schirra), and Russell (Rusty) Schweickart (Apollo 9, with Scott and "Gemini" astronaut Jim McDivitt). Cunningham and Schweickart were civilians when selected. Charlie Bassett, Roger Chaffee, Ted Freeman, and C. C. Williams died in accidents before the Apollo 11 landing.

5. Slayton had been chosen to fly the Mercury 7 mission in 1962 but was replaced by Scott Carpenter when the hypercautious and influential space physicians found a

minor heart irregularity. The doctors treated Slayton and relented in 1972, so that he flew on the joint Apollo-Soyuz mission with the Soviets in July 1975.

6. The early training is described by R. R. Gilruth, "The making of an astronaut," *National Geographic* 127 (January 1965):122–44; King 1989; Compton 1989, 32, 62–63.

7. E. D. Jackson, A. H. Chidester, M. F. Kane, and D. E. Wilhelms, "Effectiveness of the unmanned lunar program in Apollo landing site selection," *Technical Letter Astrogeology* 2 (1964); D. J. Milton and D. E. Wilhelms, "Scientific goals of extended lunar exploration," *Technical Letter Astrogeology* 4 (1964).

8. In 1965 the three divisions of Astrogeologic Studies embraced the following studies. Lunar investigations: stratigraphy and structure, geologic cartography, photometry, polarimetry, and infrared investigations; crater investigations: the solid state, shock phases, impact metamorphism, terrestrial impact structures, and impact experiments; cosmic chemistry and petrology subdivision, based in the Washington offices of the USGS: tektites, meteorites, cosmic dust in the atmosphere and space, and general chemical investigations.

9. Aeronutronic was actually a division of the Philco Corporation, a subsidiary of Ford.

10. The map was finally completed by Newell Trask and published as Schmitt, Trask, and Shoemaker 1967. Gerry Schaber, George Ulrich, and John M'Gonigle were the only other manned-studies geologists who completed 1:1,000,000-scale lunar maps for publication (USGS Maps I-602, I-604, and I-702, respectively).

11. Newell 1980, 284.

12. "ASAPR August 1962–July 1963" (May 1964), 86–98.

13. I now call the Southeast basin the Mendel-Rydberg basin because I like to name a basin after two superposed craters if it contains no named mare or is not itself given a craterlike name (e.g., Apollo).

14. Witness the testimony of Homer Newell, who was in a position to know (Newell 1980, 212–13): "The complacent assumption of the superiority of academic science, the presumption of a natural right to be supported in their researches, the instant readiness to criticize, and the disdain which many if not most of the scientists accorded the government manager, particularly the science manager, were hard to stomach at times." And: "[Administrator] Glennan could not restrain an outburst of indignation at the arrogant presumptuousness of the scientists."

15. "ASAPR July 1964–July 1965" (November 1965), 63–80.

16. "ASAPR August 1962–July 1963" (May 1964), 64–73 (Titley); "ASAPR July 1963–July 1964" (November 1964), 85–89 (Titley and Eggleton); "ASAPR July 1964–July 1965" (November 1965), 3–12 (Trask). The official authorship of the final published maps (like that of many others) did not fully match reality: N. J. Trask and S. R. Titley, *Geologic map of the Pitatus region of the Moon,* USGS Map I-485 (LAC 94) (1966); S. R. Titley, *Geologic map of the Mare Humorum region of the Moon,* USGS Map I-495 (LAC 93) (1967).

17. Wilhelms 1984, 1987.

18. "ASAPR July 1964–July 1965" (November 1965), 35–43. Unlike many of our results in the 1960s, some of these were published: Carr 1966 (see chapter 7, Meanwhile Back at the Office).

19. R. T. Dodd, Jr., J. W. Salisbury, and V. G. Smalley, "Crater frequency and interpretation of lunar history," *Icarus* 2 (1963):466–80.

20. Trask and Titley, *Map of the Pitatus region.*

21. "ASAPR July 1963–July 1964" (November 1964), 1–16; "ASAPR July 1964—July 1965" (November 1965), 13–28.

22. "ASAPR July 1963–July 1964" (November 1964), 17–27.

23. I proposed the name Cayley in "ASAPR July 1964–July 1965" (November 1965), 13–28, then defined it formally when I joined Elliot Morris in preparing the published version of the Julius Caesar quadrangle (Morris and Wilhelms 1967). The type area of the Cayley Formation is in that quadrangle near the totally unrelated crater Cayley. Just how far beyond that area the name applies was never made clear.

24. See chapter 3, The Imbrium Basin.

25. "ASAPR July 1963–July 1964" (November 1964), 17–27.

26. "ASAPR August 1962–July 1963" (May 1964), 74–85.

27. "ASAPR July 1964–July 1965" (November 1965), 115–22.

28. "ASAPR July 1963–July 1964" (November 1964), 102–34.

29. Ibid., 42–51. Of course, the valley and Cobra Head were known to "selenologists," not discovered by Henry. The Aristarchus Plateau had long been known for its distinct brownish color in the telescope and was known as "Wood's Spot."

30. See chapter 1, Interlude and n. 61; Baldwin 1963, 385–89 (constituting one entire chapter, which Baldwin correctly felt covered the grid adequately).

31. S. K. Runcorn, "Convection in the Moon," *Nature* 195 (1962):1150–51; and Runcorn, "Primeval displacements of the lunar pole," *Physics of Earth and Planetary Interiors* 29 (1982):135–47.

32. "ASAPR August 1962–July 1963" (May 1964), 33–45.

33. "ASAPR July 1965–July 1966" (December 1966), 235–305; Wilhelms 1970.

34. "ASAPR August 1962–July 1963" (May 1964), 33–45.

35. J. M. Saari, R. W. Shorthill, and T. K. Deaton, "Infrared and visible images of the eclipsed Moon of December 19, 1964," *Icarus* 5 (1964):635–59. Kopal wanted to establish a cooperative effort between Egypt and the University of Manchester. Shorthill had conducted similar observations of an eclipse on 5 September 1960, and he continued the work after Saari committed suicide in January 1971. Numerous papers have pursued (not to say milked) the subject further, including a particularly perceptive and definitive review by Boeing scientist D. F. Winter (1970).

36. Many preliminary versions of the maps and other reports of this work were prepared, but as usual the formal published report (Rowan, McCauley, and Holm 1971) appeared after the need had passed.

CHAPTER 5. THE RANGER TRANSITION (1964–1965)

1. The technical history and political background of Ranger are given in detail in Hall 1977.

2. Ibid., 379.

3. A popular account describing the details of mission operations and the spacecraft is by H. M. Schurmeier, R. L. Heacock, and A. E. Wolfe, "The Ranger missions to the Moon," *Scientific American* 214 (1966):52–67.

4. See chapter 2, The Challenge; Hall 1977, 112–23.

5. Hall 1977, 53–62; Woods 1981. The time- and energy-consuming dispute between JPL and NASA Headquarters and within JPL about the relative importance of scientific and engineering instrumentation for Ranger is described by Hall, Koppes (1982, 116–33), and Burrows (1990, 94–123).

6. Hall 1977, 128–37, 181, 412–13. The letters and memos were exchanged in October and November 1962. Nicks (1985, 76–77) found the anti-imaging bias "curious" and helped squelch it.

7. Purists insist that the pictures obtained from Ranger and other robotic spacecraft (except the later Zonds) were not photographs because they were transmitted electronically and not recorded on film until the electronic signals got back to Earth. Kuiper and others sometimes called them the Ranger "records." I don't care, but I make a half-hearted attempt in this book to draw the distinction between images and photographs. The term *pictures* covers all bets but is usually considered insufficiently dignified for scientific use.

8. Hall 1977, 176–82.

9. Ranger block 3 carried six television cameras made by RCA. Each was equipped with a shutter (unusual in television cameras) that would allow an image to fall briefly on a specially made sensitive Vidicon image tube. There were four so-called P cameras that could be exposed in only 2 msec (1/500 of a second) and partially (P) scanned and read out in only 0.2 sec, so they could get as close as possible and transmit what they saw up to the last possible moment before impact; an image area less than 3 mm on a side on the Vidicon was read out. The fully scanned (F) images (11 mm on a side) of the two large-format cameras (A and B; exposed in 5 msec and read out in 2.5 sec each) would show the regional context of the P-camera views. The six cameras were mounted together in a cluster and their fields of view overlapped.

10. Hall 1977, 223–33.

11. Ibid., 202–22.

12. Koppes 1982, 151–56.

13. Hall 1977, 240–55; Newell 1980, 268–69.

14. In my 1987 professional paper I incorrectly gave the impact date as 1 August GMT (Wilhelms 1987, 12).

15. More complete atlases were published of Ranger 7 photographs than of those from any other lunar or planetary mission (NASA 1964, 1965a, 1965b).

16. Heacock et al. 1965; pp. 7 and 8 contain a summary, and each of the experimenters authored separate sections. The present section is based on this report except as noted.

17. I thank Andrew Chaikin for telling me of this quote.

18. Letters from Urey to Strom, 28 February 1963; and Strom to Urey, 18 March 1963, courteously sent to me by Bob Strom in 1988.

19. Shoemaker 1964. In Mike Carr's original paper presenting these results ("ASAPR August 1962–July 1963" [May 1964], 9–23) he also reported that Eratosthenes does have at least one ray (northwest of the crater) and cast additional doubt on the ray = young idea by pointing out dark craters that are obviously superposed on rays of Copernicus.

20. In quantitative terms, the parts of a size-frequency curve representing craters smaller than 1 km were steeper than the rest of the curve.

21. E. M. Shoemaker, in Heacock et al. 1965, 116–27.

22. In 1962 and 1963 Henry Moore had predicted mathematically what the limiting crater diameters of the steady state would be for surfaces of a given age and what the size-frequency plots of craters smaller than these diameters would look like (a cumulative log-log plot would always slope at minus 2; "ASAPR August 1962–July 1963," [May 1964], pt. D, 34–51). Craters smaller than the limiting diameter of the steady state display the entire range of morphologies from superfresh to barely visible, including Kuiper's "collapse" craters. The extreme levels of degradation are usually not reached for craters larger than the limiting diameter.

23. Heacock et al. 1965, 59.

24. G. P. Kuiper, "The moon and the planet Mars," in *Advances in earth science*, ed. P. M. Hurley, 21–70 (Cambridge, Mass.: MIT Press, 1966).

25. Hall 1977, 281–84.

26. Ibid., 290. Urey complained about the lack of nesting. JPL showed that the terminal maneuver could have achieved the nesting and prevented the smearing, but the experimenters, acting like engineers, were afraid to try the maneuver and also wanted the stereoscopy obtainable from overlapping frames.

27. Ewen Whitaker and Henry Moore reported such observations, in NASA Manned Spacecraft Center 1972, secs. 29I and 29J.

28. E. M. Shoemaker and H. J. Moore II, "ASSPR February 1961–August 1961" (March 1962), 93–105.

29. Among other things, Herring made good drawings of the limb regions of the Moon that are revealed only under favorable librations. These were published in *LPL Communications* 4, 9, 19, 44, 45, and 66 (1962–65).

30. Heacock et al. 1966.

31. Green 1971. In 1959 Jack moved from the Chevron Research Corporation in La Habra, California, to manage the geosciences laboratory of North American Aviation in Downey, California. In 1965 he moved to Douglas Aircraft's Advanced Research Laboratories in Huntington Beach, California, and in 1970 to California State University at Long Beach.

32. Green 1965; this is a large but often overlooked collection of papers with lasting value that were presented at the conference. Both sides of the crater argument (which Green refers to as Hookes and Spurrs) are represented.

33. Heacock et al. 1966, 302–35.

34. Hall 1977, 296–98.

35. Alexander Solzhenitsyn, *The gulag archipelago* (New York: Harper and Row, 1974), 480–84. I thank Paul Spudis for calling my attention to this reference.

36. Richardson 1961, 67–77; N. A. Kozyrev, in Kopal and Mikhailov 1962, 263–87. Kozyrev also claimed a more massive eruption in October 1959. He could not establish its composition, though, and other astronomers were more impressed by the seeming reliability of the 1958 spectrum.

37. Baldwin 1963, 417–18.

38. Hall 1977, 299.

39. Carl Sagan, "Some mysteries of planetary science," *Planetary Report* 8, 3 (May–June 1988):12–16.

40. NASA 1966a, 1966b; see Heacock et al. 1966, 363–82.

41. Heacock et al. 1966.

42. Brush 1982 (an excellent biography of Urey stressing his views on lunar origin).

43. Whitaker 1985, 48–49.

44. Strom 1964. Strom claimed grid advocate Firsoff as a second inspiration besides Baldwin, and Clark Chapman has told me that grid advocate Fielder exerted an influence over LPL's lunar work second only to Baldwin in the mid-1960s.

45. Heacock et al. 1966, 181, 271–75.

46. Robert G. Strom, telephone conversation, October 1988.

47. Heacock et al. 1966, 252–63.

48. Baldwin (1965, 137) was even more emphatic; referring to 1829 and Franz von Paula Gruithuisen's mention of a meteoritic origin, he concluded, "The 136-year-old argument is over."

49. NASA and the IAU sponsored the Goddard conference. The conference proceedings appeared in Hess, Menzel, and O'Keefe 1966. These volume editors were the conference's organizers. Wilmot Hess, a physicist, was chief of Goddard's Laboratory for Theoretical Studies; Donald Menzel was a solar astrophysicist who nevertheless was president of IAU Commission 17, devoted to the Moon; O'Keefe is described in chapter 2. Urey, Shoemaker, Kuiper, Whitaker, and Gold led off the proceedings, and 71-year-old Ernst Öpik summarized them. The number of earth and sky science papers was about equal. Craters and the surficial material dominated all three conference sessions, and astronomers outnumbered geologists at all three, possibly for the last time at a lunar conference.

50. In a conference contribution only loosely related to Ranger, NASA-Ames engineer Don Gault, geologist Bill Quaide, and geophysicist Verne Oberbeck reported on experiments with a new (1965) gas gun designed by Gault. They also reported on missile impacts at the White Sands Missile Range (barely mentioning the collaboration of Henry Moore, who had initiated the program; see Moore 1976). Among the findings at Ames and White Sands were that although most oblique impacts create circular craters, they *can* create elliptical craters and asymmetric ray patterns under certain combinations of target properties and projectile trajectories. In a panel discussion Tom Gold, Gene Shoemaker, and Fred Whipple agreed that double and aligned lunar craters, which had seemed to support the endogenists' concepts, could have been created by primary impacts.

51. Heacock et al. 1965, 12. The "NASA-LPL" telescope, a 61-inch (1.55-m) reflector in the Catalina Mountains north of Tucson, began operation in October 1965.

52. Kopal and Carder 1974.

53. Formally published maps (abbreviated titles): Ranger 7: USGS, *Bonpland H*, USGS Map I-693 (1971; 1:100,000); Spencer R. Titley, *Bonpland PQC*, USGS Map I-678 (1971; 1:10,000). Ranger 8: Newell J. Trask, *Sabine DM*, USGS Map I-594 (1969; 1:50,000); P. Jan Cannon and Lawrence C. Rowan, *Sabine EB*, USGS Map I-679 (1971; 1:5,000). Ranger 9: Michael H. Carr, *Alphonsus*, USGS Map I-599 (1969; 1:250,000); John F. McCauley, *Alphonsus GA*, USGS Map I-586 (1969; 1:50,000). See also McCauley 1969 (*Moon probes*), which gives a good feeling for the state of lunar science at the time.

54. Trask 1972. Sun angles for Rangers 7, 8, and 9 were 23.2°, 14.7°, and 10.4°, respectively. Despite some success at stereoscopic photography, photogrammetry did not work well because the metric qualities of the television imagery were poor and the geometry was peculiar.

CHAPTER 6. BACK AT THE MAIN EVENT (1965)

1. Brooks, Grimwood, and Swenson 1979, 151–52; Pellegrino and Stoff 1985, 49–51. I imagine Gold is not amused by being called a geologist in the latter book; he scorned geologists although he thought he understood geology. The large footpads were not needed against Gold's dust or ice, but they turned out to be useful in preventing excessive leaning on the Moon's rough surface.

2. Accounts of the Soviet manned program are given by Oberg 1981; Baker 1982; Osman 1983; Furniss 1985; Bond 1987; and Wilson 1987.

3. Brooks, Grimwood, and Swenson 1979, 56–57, 181, 381–84. The recommendation to terminate this Saturn-Apollo test series after 10 tests and to skip the effort to man-rate the Saturn 1 was made by Bellcomm and accepted by George Mueller in fall 1963 as a way of tightening the schedule and saving money. Immediately afterward came Mueller's all-up decision mentioned in chapter 3, November 1963; also see Brooks, Grimwood, and Swenson 1979, 130.

4. Baker 1982, esp. 167–264.

5. Brooks, Grimwood, and Swenson 1979, 182–83; Schirra 1988, 154.

6. The original membership of SOUC: program director Benjamin Milwitzky (OSSA) and project representative Victor Clarke (JPL) from Surveyor; program director Lee Scherer (OSSA) and spacecraft manager Israel Taback (Langley Research Center) from Lunar Orbiter; program director Samuel Phillips (OMSF), mission operations director Everett Christiansen (OMSF), William Lee (MSC), and William Stoney (MSC) from Apollo; and Oran Nicks, Willis Foster, and Urner Liddell (chairman, Planetology Subcommittee of the Space Sciences Steering Committee) from OSSA (Compton 1989, 39–40. 77–80).

7. Brooks, Grimwood, and Swenson 1979, 185; Compton 1989, 39–40, 77–80. Original membership of the ASSB: Phillips, John Claybourne (Kennedy Space Center), Christiansen, Cortright, Lee, Stoney, and Ernst Stuhlinger (Marshall Space Flight Center).

8. Green 1971.

9. Cunningham 1977, 244–45. Although this book contains many attitudes I find

disagreeable, I recommend it as an excellent source of dirt on the astronauts (the title is, of course, sarcastic). Incidentally, Walt's official first name is Ronnie, but I never heard anybody except his friend Rusty Schweickart call him that, and then in jest.

10. Brooks, Grimwood, and Swenson 1979, 179–80; Newell 1980, 209–10; Compton 1989, 55–72.

11. A reference, of course, to the well-known and good book by Tom Wolfe (1979), which first appeared serialized as "Post-orbital remorse" in *Rolling Stone* between 4 January and 1 March 1973.

12. O'Leary 1970, 212–17; Cunningham 1977, 249.

13. The committee was called the Manned Space Science Coordinating Committee. Foster's division, which Shoemaker initiated, is described in chapter 3, November 1963. Later in 1965, when Bill Pecora became director of the USGS, Verl (Dick) Wilmarth (see chapter 4, The Ground Support) left the USGS and replaced Foster.

14. NASA 1965c; Lewis 1974, 37–40; Compton 1989.

15. Clark Chapman, written communication, 1990; the new name of MIT's geology department under Press became Department of Earth and Planetary Sciences, a type of change undergone by many other American geology departments in the 1960s and 1970s.

16. Other geoscience attendees at Falmouth included Isidore Adler, Edward Chao, Clifford Frondel, Paul Gast, Martin Kane, William Kaula, Elbert King, Robert Kovach, Marcus Langseth, Richard Lingenfelter, James Sasser, Gene Simmons, Charles Sonett, Robert Speed, and Jack Trombka.

17. Apparently the term ALSEP originated in January 1966, when seven instruments and the corresponding experimenter teams were tentatively chosen (Compton 1989, 80–85). The ALSEP was contracted to the Bendix Corporation in March 1966.

18. Conversation with Jack McCauley, November 1988.

19. The large-scale geologic maps published in color as USGS "I maps" were: 6 Ranger postmortems, described in chapter 5 (1969 and 1971, scales 1:5,000–1:250,000); 12 maps of potential early Apollo sites, described in chapters 10–12 (1969–72, scales 1:100,000 and 1:250,000, USGS Maps I-616–I-627); 8 maps (four packages) for Apollos 14–17, described in chapters 13–17: Eggleton and Offield 1970; Carr, Howard, and El-Baz 1971; Milton and Hodges 1972; Scott, Carr, and Lucchitta 1972 (scales 1:25,000, 1:50,000, and 1:250,000); and 3 "scientific" maps of potential but unused landing sites at 1:250,000: West 1973; Howard 1975; Pike 1976.

20. In his review of this chapter, Jack McCauley noted that he had been told that Urey had helped terminate the staff.

21. Brooks, Grimwood, and Swenson 1979, 188; Newell 1980, 285; Levine 1982, 175–76, 245–46; Compton 1989.

22. The general geologic rationale for site selection is described in chapters 3 and 4, Picking the Landing Sites. Surveyor and Lunar Orbiter site selection is described in detail in chapters 8 and 9. See also Cappellari 1972, and Compton 1989.

23. Cappellari 1972.

24. MSC's plans started to jell in late 1963 (I have an early summary working paper

bearing the horrible date of 22 November 1963). They devised a launch-to-splashdown mission plan called the reference trajectory that envisioned 10 potential landing sites spaced along the Apollo zone (Compton 1989, 33–34). As later chapters show, this remained the basic number and layout of sites almost until the missions began. One site called Area IV in the November 1963 working paper was close to the actual Apollo 11 landing site.

25. Only three monthly postponements could be tolerated after the propellant was loaded into the launch vehicles and spacecraft (about two weeks before launch) because the propellant began to degrade the propellant systems after about 110 days.

26. I refer to the landing of Apollo 11 in 1969 and to the landing of Viking 1 on Mars in 1976.

27. Lipskiy 1965. Astronomer Yurii Lipskiy of the Shternberg State Astronomical Institute in Moscow was the scientific spokesman for many of the Soviet missions.

28. Wilson (1987) believes Zond 3 was intended as a Mars mission, as was its unsuccessful twin, Zond 2 (launched November 1964), but when troubles developed it was used for the Moon rather than wait two years for the next Mars window. It kept on going and was last heard from (Wilson believes) in March 1966 when it was 153.5 million km away. Zond 1 was directed at Venus (April 1964).

29. Lipskiy 1965. The term *thalassoid* never caught on in the West. The continuing confusion about the terms *basin, mare, mare basin,* etc., make me wish that it had.

30. Hartmann 1964.

31. "ASAPR July 1964–July 1965" (November 1965), 3–12.

32. Ibid., 13–28.

33. Ibid., 29–34, and map supplement. J. A. Keith is listed as coauthor on the map. Jim was an able student who did most of the dirty work of scribing the plastic sheet from which the map was made, all the while applying his geologic knowledge to figure out what Newell and I wanted to show.

34. Very young indeed; activity was reported at Medicine Lake in September 1988.

35. Aldrin 1973.

36. Glen 1982.

37. Collins 1974. I consider this the best book written by an astronaut (despite his not totally favorable comments about the geology training on pp. 72–75).

38. Borman 1988, 101.

39. Ibid., 85–89.

CHAPTER 7. THE GLORY DAYS (1966)

1. NASA's appropriation peaked at $5.25 billion in fiscal year 1965 (1 July 1965–30 June 1966), about $17 billion in 1990 money. In fiscal year 1966 it dropped to $5.175 billion, but expenditures peaked at $5.933 billion (Levine 1982, 179–209). For fiscal year 1967 NASA requested $5.58 billion; President Johnson cut the request to $5.012 billion; Congress finally appropriated $4.968 billion (Brooks, Grimwood, and Swenson 1979, 189).

2. The three men in Voskhod 1 apparently were crammed in at the behest of propaganda-hungry Premier Khrushchev, whose meddling helped get him dismissed (Aldrin and McConnell 1989, 108–11).

3. Baker 1982; Borman 1988, 109–51; Schirra 1988, 158–70. The Schirra-Stafford mission was often called Gemini 6A because the original attempt to launch spacecraft 6 had foundered on the failure of the intended rendezvous target Agena to reach orbit.

4. Oberg 1981; see also Ordway and Sharpe 1979.

5. Lipskiy 1966. Different maps give slightly different coordinates for the landing point, and confusion reigned for a long time after the landing. Lipskiy's coordinates are 7.13° N, 64.37° W.

6. Minchin and Ulubekov 1974.

7. The Soviets concentrated on Mars and Venus in the four years after Luna 3. However, Wilson (1987) also tentatively lists two Lunas (1960A and 1960B) in April 1960.

8. Kosmos 60 did not go beyond Earth orbit in March 1965, the month of Leonov's space walk and Ranger 9. Luna 5 crashed on the Moon in May. Luna 6 missed the Moon by 160,000 km in June, a month before Zond 3 flew by successfully on its way to Mars (see chapter 6, Zond 3 and the Orientale Crater Chain). Luna 7, launched on the eighth anniversary of Sputnik 1, crashed in October. Luna 8 crashed near the Luna 9 landing point in December. No two references I have seen agree on the crash points of Lunas 5 and 7.

9. Lipskiy 1966; USSR Academy of Sciences 1966.

10. Not knowing what the Moon and planets really look like, early space artists like Bonestell (1888–1986) exaggerated their imagined exotic, unearthlike properties.

11. Lipskiy 1966; Thomas Gold and B. W. Hapke, "Luna 9 pictures: Implications," *Science* 153 (1966):290–93 (an excellent example of frantic adherence to a preconception); L. D. Jaffe and R. F. Scott, "Lunar surface strength: Implications of Luna 9 landing," *Science* 153 (1966):407–8; D. E. Gault, W. L. Quaide, V. R. Oberbeck, and H. J. Moore, "Luna 9 photographs: Evidence for a fragmental surface layer," *Science* 153 (1966):985–88; E. M. Shoemaker, R. M. Batson, and K. B. Larson, "An appreciation of the Luna 9 pictures," *Astronautics and Aeronautics* 4 (1966):40–50, which includes the reconstruction of many technical details of the mission.

12. For this comparison densities are calculated as if they were not increased by pressures due to depth, which are greater for Earth than for the Moon.

13. Baldwin 1963, 407.

14. The Soviets had launched a spacecraft on 1 March 1966 in an apparent earlier attempt at lunar orbit, but it was stuck with the consolation-prize name Kosmos 111, and not Luna 10 (Woods 1981; Hart 1987).

15. Adler and Trombka 1970, 9–10, 56–58; Surkov 1990, 187–93. Surkov is the chief of planetary exploration, Vernadsky Institute, Moscow. Luna 10 also attempted to measure the lunar magnetic field (Russell 1980), carried infrared, solar-plasma, and meteorite-particle sensors (Hart 1987), and broadcast the "Internationale" from the Moon.

16. In 1945 Rollin Chamberlin (a rabid opponent of continental drift) commented on the absence of lunar folded mountains and therefore of geosynclines and lateral stresses.

His thoughtful paper (Chamberlin 1945) illustrates the primitive state of knowledge about both Earth and Moon at the time.

17. P. D. Lowman, "The relation of tektites to lunar igneous activity," *Icarus* 2 (1963):35–48; and Lowman "Composition of the lunar highlands: Possible implications for evolution of the Earth's crust," *JGR* 74 (1969):495–504.

18. Marvin 1973a; Glen 1982; R. M. Wood 1985; W. Glen and H. Frankel, "The jubilee of plate tectonics," *Eos* (10 May 1988):583–85.

19. R. M. Wood 1985. Wegener's quite serious lunar work is referenced and briefly described in chapter 1, Interlude. Taylor proposed that Earth's continents were set in motion by its capture of the Moon.

20. Vladimir Beloussov (d. 1992) and many other Russian geologists vigorously resisted the plate tectonics model.

21. McCauley 1968. Jack gave the talk on which the paper was based in October 1967 in Anaheim, California. The three features are described in chapters 9 and 10.

22. Luna 11 returned data for 34 days. Neither it nor Luna 10 transmitted pictures, though Luna 11 may have attempted to do so (Hart 1987). Luna 11's perilune (lowest point in orbit) was 160 km, compared with the 350 km of Luna 10. Purists considered *perilune* to be an unacceptable linguistic hybrid and preferred *pericynthion,* referring specifically to the Moon, or *periapsis,* applicable to any center of gravity. Corresponding terms for the highest point of an orbit are *apolune, apocynthion,* and *apoapsis.* But most people used *perilune* and *apolune* for simplicity.

23. Luna 12 transmitted data for 86 days, thus lasting into 1967.

24. Carr 1966. Before 1967 our lunar geologic map areas had to be called regions rather than quadrangles. Mary Rabbit, who ran the USGS editing den in Washington, saw that some of our maps were not rectangular. Of course, terrestrial maps bounded by longitude and latitude lines are not rectangular at high latitudes either, but "regions" it had to be until Mary retired.

25. McCauley 1967b (LAC 56).

26. McCauley 1967a. Other attendees mentioned in the present book included Robert Dietz, Audouin Dollfus, Gilbert Fielder, Thomas McCord, Richard Pike, Keith Runcorn (an organizer from the host institution), Harold Urey, and John Wood.

27. D. E. Wilhelms, "ASAPR July 1965–July 1966" (December 1966), pt. A, 235–305; Wilhelms 1970.

28. Scott and Trask 1971. Newell Trask helped with the igneous petrology of this appropriately named field area.

29. H. J. Moore, *Geologic map of the Seleucus quadrangle of the Moon,* USGS Map I-527 (LAC 38) (1967). I think the mare Luna 13 landed on is at least as young as Eratosthenian (Wilhelms 1987, pl. 10A). (*Note:* When I looked at this volume to see how I had mapped the spot, I found that the positions of Seleucus and Briggs were reversed on plate 9A.)

30. Van Dyke 1964; Logsdon 1970; McDougall 1985; Compton 1989.

31. Newell 1980, 212–13, 222.

32. O'Leary 1970; Compton 1989, 135–36.

33. Compton 1989, 32–33, 54, 86–88, 275. Homer Newell also considered MSC

arrogant, though he did not exclude other centers from this assessment; see Newell 1980, 245–46.

34. After the allegedly frivolous word "excursion" was dropped from lunar excursion module (LEM), LM continued to be pronounced "lem." The building of the LM is described in two books with the same main title *Chariots for Apollo:* Brooks, Grimwood, and Swenson 1979 (part of the NASA History Series and an excellent and authoritative overall summary that includes not only the LM but also the other modules); Pellegrino and Stoff 1985 (a lively, anecdote- and quote-rich account of the construction of the LM by the Grumman Aerospace Corporation that conveys like no other book I know how intensively and devotedly Americans built the spacecraft that carried their astronauts safely and successfully to the Moon). Unlike LM, the letters of CSM were pronounced separately as "see-ess-em." Everyone at all acquainted with the space program knew and used LM and CSM, but CM for command module was used more rarely.

35. The 2 in AS-201 refers to a Saturn IB; a 1 in the same position refers to a Saturn 1, and a 5 to a Saturn 5. These AS numbers are about the only unambiguous element in Saturn nomenclature. A request by the astronauts' widows to call the mission Apollo 1 was accepted even though it followed three AS tests. George Low suggested renumbering AS-201, AS-202, and AS-203 as Apollos 1A, Apollo 2, and Apollo 3, respectively, but this was not done. The next successful test was called Apollo 4 for reasons that are clear to no one I know. So there were Apollos 1 and 4 but no Apollos 2 and 3. See Brooks, Grimwood, and Swenson 1979, 231–32.

36. Borman 1988, 172. Borman was the first person to enter the burned-out spacecraft. The next fatalities of American astronauts in a spacecraft fell within one day of the nineteenth anniversary of the Apollo 1 fire, when the shuttle *Challenger* exploded on 28 January 1986.

CHAPTER 8. SURVEYOR AND THE REGOLITH (1966 – 1968)

1. A good account of the development and operations of the Surveyor program is given by Oran Nicks (1985), an aeronautical engineer who joined NASA in 1960 and became director of lunar and planetary programs under Newell in OSSA in 1961. Nicks was an early supporter of Shoemaker's efforts to include geology in the lunar program.

2. Kloman 1972; Koppes 1982, 173–80.

3. Newell 1980, 270.

4. Surveyor Project Staff, *Surveyor project final report. Part 1. Project description and performance,* JPL Technical Report 32-1265 (July 1969), 2:17–18.

5. The approach camera was not removed from Surveyors 1 and 2 despite the discovery that there would not be enough radio bandwidth to transmit pictures during terminal descent. An attempt was made to take a picture with the Surveyor 1 approach camera after landing but the camera did not respond. Anyway, its telephoto lens was focused on infinity. I thank Ray Batson for this bit of lore, as well as for many other comments and corrections to this chapter.

6. The camera was a Vidicon that could be scanned to produce pictures with either

200 or 600 lines (compared with the 525 lines of the American system of commercial television). It was mounted at a 16° tilt to provide a good look at the footpad and pointed at a mirror that moved horizontally and vertically. The focal length could be adjusted to provide narrow-angle (6.4°) or wide-angle (25°) fields. The off-vertical mounting of the camera caused the horizon to look wavy in panoramic mosaics.

7. Don Gault, conversation in Palo Alto, California, in July 1989. The scene of Gold's lambasting was a meeting at NASA Headquarters.

8. Nicks 1985, 128.

9. The study is reported anonymously in a 38-page unpublished document dated July 1965 and attributed only to "Surveyor Television Investigations."

10. J. F. McCauley, H. E. Holt, E. C. Morris, J. T. O'Conner, L. C. Rowan, and Alan Filice, "Surveyor landing site recommendations," in "Lunar Orbiter: Image analysis studies report," USGS informal report prepared for NASA/MSC (May 1965–January 1966), 49–65. JPL-er Filice, who also prepared a lunar terrain map, died not long after this work was done.

11. Engineering and operational aspects of the missions are summarized by L. D. Jaffe and R. H. Steinbacher, Introduction to "Surveyor final reports," *Icarus* 12 (1970): 145–55, and are described in detail in each Surveyor mission report (part 1, mission description and performance). These are NASA-JPL Technical Reports having the following numbers and dates: Surveyor 1, 32-1023, August 1966; Surveyor 3, 32-1177, September 1967; Surveyor 5, 32-1246, March 1968; Surveyor 6, 32-1262, September 1968; Surveyor 7, 32-1264, February 1969.

12. Different sources give different exact numbers of pictures for each mission and the total, so I round off to the nearest thousand throughout. Following are the Surveyor photographic atlases: USGS (1968) *Catalog of Surveyor 1 television pictures,* NSSDC (National Space Science Data Center) 68-10; *Surveyor 1 mission report. Part 3: Television data,* NASA-JPL Technical Report 32-1023 (November 1966); *Surveyor III mission report. Part 3: Television data,* NASA-JPL Technical Report 32-1177 (November 1967); R. M. Batson, R. Jordan, and K. B. Larson, *Atlas of Surveyor 5 television data,* NASA SP-341 (1974).

13. Surveyor summary literature: L. D. Jaffe, "The Surveyor lunar landings," *Science* 164 (1969):774–88; Surveyor Program 1969; "Surveyor final reports," *Icarus* 12 (1970):145–232. See also McCauley 1969.

14. L. D. Jaffe, "Surveyor 1: Preliminary results," *Science* 152 (1966):1737–50 (reports the first five days after landing).

15. If I added another significant figure, I would have to hedge, because different methods of determining coordinates on the Moon did not agree (and still do not in most regions). A useful lunar rule of thumb is that 1° latitude = 30 km, a figure also valid for longitude near the equator. Thus, an error of 0.01° is equivalent to 300 m, not worth worrying about unless you are going to land a later mission next to a Surveyor.

16. See chapter 7, Luna 9, and appendix 1. The number of unsuccessful predecessors to Luna 9 (at least seven) was less well known in 1966 than it is today.

17. During the Surveyor 1 mission, over 165 mosaics with a total of about 8,000

individual pictures were completed. The figures for Surveyor 3 were 90 mosaics of 4,500 pictures, and for Surveyor 5, 180 mosaics with over 9,000 pictures. An equal number of improved, annotated mosaics was constructed after each mission.

18. The name Mare Insularum refers to the many islands of terra material in the mare. At a nomenclature meeting Hal Masursky said, "Well, there can only be one ocean on the Moon" (Procellarum). To prove him wrong, I suggested that a large expanse with a lot of terra islands be named Oceanus Insularum. The suggestion was adopted officially by the IAU in its 1976 meeting in Sydney, though with a change from Oceanus to Mare. I'm not sure whether it was all worth the trouble.

19. Building of SFOF was approved in July 1961. It was placed in operation in July 1964 in time for Ranger 7.

20. Nicks 1985, 137–40. Roberson later became one of our NASA contract monitors.

21. Turkevich's principal collaborators were James Patterson of the Argonne National Laboratory and Ernest Franzgrote of JPL.

22. Conversations with Masursky in June 1987 and Gault in July 1989.

23. J. J. Gilvarry, *Nature* 218 (1968):336–41. Gilvarry also maintained that the particle size distribution observed by Surveyor 1 fit sediments better than impact materials.

24. Shoemaker (letter to author, December 1988) clearly remembered Fra Mauro as the leading candidate for Surveyor 6, but the only memoranda mentioning it that I have seen refer to its consideration for Surveyor 7.

25. In NASA terminology, *programs* are usually long-lasting, broad, and multifaceted efforts run from headquarters, whereas a *project* is usually the share of a program run from a field center like JPL.

26. This is Shoemaker's assessment (letter to author, December 1988). He supposed that Homer Newell, Newell's deputy Oran Nicks, and Surveyor program manager Ben Milwitzky (an aeronautical engineer, like Nicks) made the decision to send Surveyor 6 to the maria and Surveyor 7 to a potentially hazardous science site.

27. Sandford Brown, "How we're solving the mysteries of the moon," *Saturday Evening Post* (5 June 1968):32–42.

28. The detailed scientific results of the five successful Surveyor missions were reported in essentially the same words at least twice and often three times. One form was in each Surveyor mission report (part 2, science [or scientific] results). These are NASA-JPL Technical Reports having the same numbers as part 1 (see n. 11) but different publication dates: Surveyor 1, 32-1023, September 1966; Surveyor 3, 32-1177, June 1967 (plus a 24-page addendum including a nonconformist paper by Jack Green); Surveyor 5, 32-1246, November 1967; Surveyor 6, 32-1262, January 1968; Surveyor 7, 32-1264, March 1968. The second form was the NASA Special Papers (SP) listed in this book's bibliography: Surveyor Program 1966, 1967a, 1967b, 1968a, 1968b, 1969. The third form was the formal journal paper, felt by many scientists to be the only genuine medium of publication (Newell 1980, 128).

29. Each report but one by Shoemaker's team listed the authorship as E. M. Shoemaker, R. M. Batson, H. H. Holt, E. C. Morris, J. J. Rennilson, and E. A. Whitaker; Morris was listed first in the Surveyor 6 reports. In an example of the redundancy cited

in the previous note, the regolith was named in two papers by these authors: *Television observations from Surveyor III,* NASA-JPL Technical Report 32-1177 (1967), pt. 2:9–67; and in Surveyor Project 1967a, 9–59.

30. The term *soil* is partly synonymous with *regolith* but correctly refers only to fine particles and not rocks.

31. Non-NASA journal publications that include these results: Shoemaker et al. 1969; E. M. Shoemaker and E. C. Morris, "Geology: Physics of fragmental debris," in "Surveyor final reports," *Icarus* 12 (1970):188–212.

32. See Surveyor 6 and Surveyor 7 reports cited above (n. 28). Block size also depends on the cohesiveness of the substrate material and of previously quarried blocks in the regolith, which get broken into smaller fragments. Because regoliths are formed through repetitive reworking, the volume of a regolith is far less than the cumulative volume of the craters that generated it.

33. See chapter 5, The First Closeups.

34. E. C. Morris and E. M. Shoemaker, "Geology: Fragmental debris," in "Surveyor final reports," *Icarus* 12 (1970):173–87.

35. See Surveyor 3 and 7 reports cited above (n. 28).

36. J. H. Patterson, E. J. Franzgrote, A. L. Turkevich, W. A. Anderson, T. E. Economou, H. E. Griffen, S. L. Grotch, and K. P. Sowinski, "Alpha-scattering experiment on Surveyor 7: Comparison with Surveyors 5 and 6," *JGR* 74 (1969):6120–48; A. L. Turkevich and same coauthors, in Surveyor Project 1969, 271–350; Adler and Trombka 1970.

37. A. L. Turkevich, "Comparison of the analytical results from the Surveyor, Apollo, and Luna missions," *PLSC* 2 (1971):1209–15.

38. E. D. Jackson and H. G. Wilshire, "Chemical composition of the lunar surface at the Surveyor landing sites," *JGR* 73 (1968):7621–29. Wilshire had been with me at Berkeley in 1952–1953 and had worked with Carl Roach in Denver before coming to Menlo Park in summer 1967.

39. Shoemaker announced his compositional calculations in reports of his television experiment team and of a peculiar team called Lunar Theory and Processes headed by Don Gault and including scientists from many disciplines: J. B. Adams, R. J. Collins, G. P. Kuiper, H. Masursky, J. A. O'Keefe, R. A. Phinney, and E. M. Shoemaker, in "Lunar theory and processes," in NASA-JPL Technical Report 32-1264 (1968), pt. 2:267–313; R. A. Phinney and same coauthors, *JGR* 74 (1969):6053–80; "Lunar theory and process: Discussion of chemical analysis," *Icarus* 12 (1970):213–23. Shoemaker believed this mixed team was assembled by Surveyor program manager Ben Milwitzky as a consolation prize for scientists whose instruments had to be thrown off the originally planned "real" Surveyors.

40. Ibid.

41. Wilhelms and McCauley 1971.

42. Shoemaker 1962b; see chapter 3, Picking the Landing Sites, Round 1.

43. See chapter 12.

44. Koppes 1982, 180. The cost of the launch vehicles adds to the $469 million (in 1966 dollars).

CHAPTER 9. THE VIEW FROM LUNAR ORBITER (1966 – 1967)

1. Byers 1977. This excellent report is the source for points of technical information given in this chapter where no other references are cited. Unfortunately, it was not published formally and, I believe, is now obtainable only from the NASA Scientific and Technical Information Facility. I am indebted to Jeff Moore of Arizona State University, Tempe, for letting me use his copy.

2. Nicks 1985, 141–56. The books by Nicks (1985) and Newell (1980) testify to the annoyances caused by rivalries among the centers (JPL-Goddard, Ames-Goddard, Langley-Lewis) and between the centers and headquarters.

3. Byers (1977) credits Edgar Cortright, deputy director of OSSA, with convincing his boss, Homer Newell, to press on with the new Orbiter and also for recommending that Ranger block 5 be dropped. Block 5 was canceled in December 1963 (see chapter 5).

4. Nicks 1985, 141.

5. Byers 1977. The tracking was also welcomed as a means of checking the Apollo navigational computers.

6. Ibid. Boeing likes the capital in "The" and the abbreviation TBC.

7. Israel Taback, LOPO's spacecraft manager, written communication, 1989.

8. Kloman 1972.

9. Details of the spacecraft and photosystem are given by Boeing engineers Levin, Viele, and Eldrenkamp (1968) and by Oran Nicks (1985, 149–52). Tim Mutch wrote his fine book during and soon after the Orbiter missions and included detailed information about them (Mutch 1970, 40–47).

10. The stories in this paragraph are from a conversation with Norm Crabill in San Francisco, July 1989.

11. L. C. Rowan, "Recommendations for Lunar Orbiter Mission A," in "Lunar Orbiter: Image analysis studies report," USGS informal report prepared for NASA/MSC (May 1965–January 1966), 67–69 (the same report contained the recommended Surveyor sites; see chapter 8).

12. The green horrors were called Astrogeology Technical Letters between 1962 and 1967 and Interagency Reports thereafter.

13. The terrain types: dark mare, other mare, mare ridges, mare rays, deformed crater floors, crater rims, sculptured highlands, and two other upland types (Rowan, McCauley, and Holm 1971).

14. Planetology Subcommittee of the OSSA Space Science Steering Committee (memo from committee chairman Urner Liddell dated 5 November 1965, cited by Byers 1977). Masursky and Rowan made the presentation to the subcommittee.

15. M. J. Grolier, "Lunar Orbiter mission-A: Preflight evaluation of site A-3," *Technical Letter Astrogeology* 15 (1966). Site A-3, centered at latitude 0.3° north, longitude 24.8° east, overlaps with a Surveyor target circle 100 km in radius called site 9-100 and lies just south of the concentric 25-km and 50-km Surveyor circles.

16. Some additional improvements were made late in the mission by the expedient of lowering the perilune still further to 40.5 km to see if the V/H would work. Although it

did not, the increased lighting of the surface permitted exposures at 1/100 sec, reducing the smear somewhat. Other possible shutter speeds were 1/50 and 1/25 sec. Orbiter deliberately used "slow" film to prevent fogging by radiation. For simplicity and because of navigational uncertainty, all Orbiter 1 prime sites were shot in bursts of 16 frames in the fast mode.

17. Nicks 1985, 154–55.

18. *New York Times,* 7 October 1966. Each Orbiter carried 80 m of 70-mm film.

19. Lunar Orbiter Photo Data Screening Group 1966.

20. Levin, Viele, and Eldrenkamp 1968. The Bimat, a chemical-soaked web developed by Eastman, was pressed onto the film in a processor and delaminated after processing and before drying.

21. Lunar Orbiter Photo Data Screening Group 1967a. Both sites had been considered prime; the Cayley site was 2P-4 and the crossed-ray site 2P-10.

22. Lunar Orbiter Photo Data Screening Group 1967a, appendix B.

23. W. L. Quaide and V. R. Oberbeck, "Thickness determinations of the lunar surface layer from lunar impact craters," *JGR* 73 (1968):5247–70; V. R. Oberbeck and W. L. Quaide, "Genetic implications of lunar regolith thickness variations," *Icarus* 9 (1968): 446–65.

24. Orbiter 2 press release dated 20 November 1966. The "spires" are at 4.5° N, 15.3° E, on frame H-61, framelets 383 and 384. The press release said they were natural.

25. The inclination in degrees is about the same as the maximum latitude range of the spacecraft in degrees. Oblique photography can extend the latitude range of the photo coverage.

26. Frames 181–212, sites 3P-12a, b, and c.

27. Apollo orbited east to west, opposite to the Moon's rotation (retrograde), whereas the orbits of Lunar Orbiter were posigrade, west to east.

28. The numbers of the spacecraft themselves are different from either the prelaunch letters or the postlaunch numbers. For example, the Lunar Orbiter 1 mission was flown by spacecraft 4, and my favorite mission, Lunar Orbiter 4, was flown by 7. There were also nonflight test (1) and display (C) models, and a sixth spacecraft that was not used.

29. The Surveyor 3/Apollo 12 landing site, at about 3° S, 23° W, is within Orbiter site 3P-9.

30. Lunar Orbiter Photo Data Screening Group 1967b.

31. Although they orbited in opposite directions (see n. 27), both Lunar Orbiter and Apollo arrived at the Moon while the terminator was advancing east to west across the near side with the sunlit area to its east ("sunrise terminator"). Therefore shadows inside craters, for example, are usually on the east wall (the right, when photos are oriented with north at the top; but see n. 33). Rather than try to remember what "east" and "west" mean on the far side, the user can orient Orbiter and Apollo photographs by remembering that the sunlit area of the Moon and the shadows inside craters are on the left in far-side photos oriented with north at the top. So the usual rule is: near side right, far side left.

32. Pohn also was advising LOPO about shutter speeds, on the basis of hand-colored preliminary copies of his new albedo map (Pohn and Wildey 1970). Some exposures

were wrong, however, because the construction of the map made bright points and lines appear as large patches. A better practice would have been to let the points and lines be overexposed, properly exposing the rest of the Orbiter 4 footprint. The map was more useful for Orbiter 5, where the bright and dark patches occupy larger percentages of each frame.

33. The recovery photographs were taken obliquely. By the time perilune was near the west (Orientale) limb, apolune had worked its way around to near the east limb, so the recovery photography took place from high altitude and at the opposite Sun illumination from the rest of the near-side photography.

34. See chapter 6, Woods Hole and Falmouth. AAP was sometimes considered to mean Advanced Apollo Program.

35. Actually, a distinction was made between sites intended for AAP and those for "pure science."

36. Nicks 1985, 144–45, 156.

37. Lunar Orbiter Photo Data Screening Group 1968.

38. The eight sites and their geologic mappers, 1:100,000 scale first/1:25,000 scale second: Mare Tranquillitatis: 2P-2 (Michael Carr/Don Wilhelms); 2P-6 (Maurice Grolier, both scales). Sinus Medii: 2P-8 (Lawrence Rowan/Newell Trask, the team leaders were assigned to what was thought the most important site). Oceanus Procellarum: 2P-11 (Howard Wilshire/Newell Trask); 2P-13 (Spencer Titley, both scales in 1967); 3P-11 David Cummings/Mareta West and Jan Cannon), 3P-12 (Terry Offield/Jerry Harbour); 3P-9 (Howard Pohn/Stephen Saunders and Tim Mutch). Maps at both scales were prepared for all eight sites in 1967. All except site 2P-11 were updated in 1968 and 1969, with some changes in authorship, as discussed in chapter 10.

39. Byers 1977.

40. Oran Nicks, telephone communication, September 1989.

41. Mutch (1970, 44–47) gives an amusing account of this problem. The framelets are sections into which the film was divided for scanning by a spot of light in the spacecraft. Each framelet measures 1.8 by 39.5 cm in the original ground reconstructions.

42. Reproductions of mediocre quality are in Bowker and Hughes 1971; and Gutschewski, Kinsler, and Whitaker 1971. Coverage data are given in the final supplements to Kuiper's lunar atlas (Kuiper et al. 1967); the Orbiter information is compiled in a booklet that is easier to obtain than the atlas itself, which consists of a box of excellent glossy prints of telescopic photos from the 1.55-m NASA-LPL (Catalina) and Naval Observatory (Flagstaff) telescopes. Data on the Orbiter photography, without photographs, is also given by LOPO member Tom Hansen (1970). See also L. A. Schimerman, *Lunar cartographic dossier* (prepared by Defense Mapping Agency for NASA, 1975) (also rare). Langley produced the best prints of Orbiter frames. Those printed by AMS have too much contrast for most qualitative uses but are good for detecting small blocks and craters. Prints made by JPL during and shortly after the missions are intermediate in quality. Subsections of the frames are numbered differently by the three agencies.

43. Lowman 1969; Kosofsky and El-Baz 1970; Mutch 1970; Schultz 1976; Wilhelms 1987.

44. Carr 1965.

45. Dietz 1946; Shoemaker 1962a, 302; Shoemaker and Hackman 1962; Baldwin 1963, 378; Schmitt, Trask, and Shoemaker 1967. Kuiper got the maar idea from J. Harlan Bretz (1882–1981), best known in planetology for his once-scorned interpretation that the Channeled Scablands of Washington State were carved by a stupendous flood.

46. Fielder 1961, 222.

47. V. R. Oberbeck and R. H. Morrison, "On the formation of the lunar herringbone pattern," *PLSC* 4 (1973):107–23; Oberbeck and Morrison, "Laboratory simulation of the herringbone pattern associated with lunar secondary crater chains," *The Moon* 9 (1974):415–55.

48. McCauley 1967b, 1968.

49. Milton 1968b.

50. McCauley 1968.

51. Maps of the Moon at the 1:5,000,000 scale were constructed by Wilhelms and McCauley 1971; Wilhelms and El-Baz 1977; Scott, McCauley, and West 1977; Lucchitta 1978; Stuart-Alexander 1978; Wilhelms, Howard, and Wilshire 1979.

52. J. A. O'Keefe, P. D. Lowman, and W. S. Cameron, "Lunar ring dikes from Lunar Orbiter I," *Science* 155 (1977):77–79.

53. Lunar Orbiter Data Screening Group 1967b, 125–27, figs. C-1–C-6; Lunar Orbiter Data Screening Group 1968, 158–64 (another gray literature burial).

54. S. R. Titley, "Seismic energy as an agent of morphologic modification on the Moon," in "ASAPR July 1965–July 1966" (December 1966), pt. A, 87–103; D. J. Milton, "Slopes on the Moon," *Science* 156 (1967):1135.

55. Muller and Sjogren 1968.

56. The interpretations described here and some others were published together in the 20 December 1968 issue of *Science* (162:1402–10).

57. J. J. Gilvarry, "Mensuration and isostasy of lunar mascons and maria," *Nature* 223 (1969):255–58.

58. R. B. Baldwin, "Lunar mascons: Another interpretation," *Science* 162 (1968): 1407–8.

59. W. M. Kaula, "The gravitational field of the Moon," *Science* 166 (1969):1581–88; D. U. Wise and M. T. Yates, "Mascons as structural relief on a lunar 'Moho,'" *JGR* 75 (1970):261–68; C. Bowin, B. Simon, and W. R. Wollenhaupt, "Mascons: A two-body solution," *JGR* 80 (1975):4947–55; W. L. Sjogren and J. C. Smith, "Quantitative mass distribution models for Mare Orientale," *PLSC* 7 (1976):2639–48; Solomon and Head 1979, 1980.

CHAPTER 10. APOLLO LIFTS OFF (1967 – 1969)

1. See chapter 4, Volcanophilia Lives On. Fielder (1965, 125–29) welcomes convection as the cause of the lunar grid.

2. Compton 1989, esp. 344–48.

3. NASA 1967; Compton 1989, 97–101.

4. James was chief geologist between 1965 and 1971, succeeding William Pecora (1964–1965) and succeeded by Vincent McKelvey (1971–1972). James was the father-in-law of lunar petrologist Odette Bricmont James.

5. For example, Mösting C to Copernicus by way of Gambart, Herschel to the Apennines by way of Archimedes, Tycho to Straight Wall by way of Deslandres.

6. The Fecunditatis site was originally called A-1, then 1P-1 after the Orbiter 1 mission, then 3P-1 for Orbiter 3, and V-8 for Orbiter 5. It received 13 Orbiter 5 frames, including 3 west-looking obliques. It contains mesas, faults, and diverse mare units that seemed interesting at the time (special features) but today are considered normal phenomena resulting from mild activity at a typical mare margin.

7. Members who were at Falmouth: Don Beattie (secretary), Ed Goddard, Harry Hess, Hoover Mackin, Jack Schmitt, Gene Shoemaker, Aaron Waters, and Bob Speed (JPL). New members: John Adams, Al Chidester, Dave Dahlem, John Dietrich, Ted Foss, Tim Hait, Noel Hinners, Dick Jahns, Martin Kane, Thor Karlstrom (USGS), William Lambe (MIT), Hal Masursky, James Mitchell (Univ. Calif.), Bill Muehlberger, Lee Silver, Gordon Swann, Jim Thompson (Harvard Univ.), Ken Watson (USGS), Dick Wilmarth (formerly USGS, now chief of lunar and planetary programs, OSSA), and Don Wise.

8. "ASAPR July 1963–July 1964" (November 1964), 102–34.

9. Levine 1982, 209, 293. The formal announcement of the termination did not come until February 1970 (see chapter 13, The Ax).

10. Koppes 1982, 187–92; Levine 1982, 85, 147–48, 173, 194. The name Voyager was later used for outer-planets missions. After watering down, the Mars Voyager became Viking. The actual Voyager and Viking missions were brilliant successes.

11. Brooks, Grimwood, and Swenson 1979, 188, 362; Newell 1980, 396–97; Levine 1982, 248–49, 253–59; Compton 1989, 101–3.

12. G. E. Ulrich, with a section by R. S. Saunders, "Advanced systems traverse research project report," *Interagency Report Astrogeology* 7 (July 1968).

13. The original GLEP membership, made up largely of Santa Cruz group chairmen: Wilmot Hess, GLEP chairman; Elbert King, GLEP secretary; Gene Shoemaker; Dick Jahns; geochemistry group cochairmen Paul Gast and Jim Arnold; geophysics group chairman Frank Press; astronomy group cochairwoman Nancy Roman; geodesy-cartography group chairman Charles Lundquist (Smithsonian Astrophysical Observatory); bioscience group chairman Melvin Calvin (Univ. Calif., Berkeley); lunar atmospheres group chairman Francis Johnson (Southwest Center for Advanced Studies); particles and fields group chairman Donald Williams (Goddard SFC); NASA engineers or managers Richard Allenby, Philip Culbertson (OMSF), Maxime Faget, Harold Gartrell (MSC-AAP), and William Stoney; and Jack Schmitt (NASA 1967, 3–4; Compton 1989, 100).

14. Compton 1989, 102–3.

15. A popular description of plans for scientific lunar exploration as of about 1968 is given by Wilmot Hess, Robert Kovach, Paul Gast, and Gene Simmons, "The exploration of the Moon," *Scientific American* 221, 4 (October 1969):54–72, including the hopeful plans for elaborate missions à la Santa Cruz. They single out Censorinus, Mösting C, Copernicus, Tycho, Marius, and Hadley-Apennines as leading candidates for landings,

as indeed they were. They also refer to the Orientale basin and the popular volatiles-at-the-poles idea.

16. Technically, Saturn 5s were not launched from "the Cape" (called Cape Canaveral originally and now, and Cape Kennedy between 1963 and 1973) but from the Kennedy Space Center just to the north. Nevertheless, almost everybody calls the whole launching area "the Cape."

17. Brooks, Grimwood, and Swenson 1979, esp. 231–34. The Saturn 5 and other Apollo hardware are also described in numerous other books including Lewis 1969; Wilford 1969; Farmer and Hamblin 1970; Cortright 1975; Gatland 1981; Baker 1982; T. A. Heppenheimer, "Requiem for a heavyweight," *Air and Space* 4, 2 (June–July 1989): 50–61.

18. Brooks, Grimwood, and Swenson 1979, 234–35, 364.

19. Pellegrino and Stoff 1985; Aldrin and McConnell 1989, 177–78.

20. Woods 1981.

21. Baker 1982, 312; Hart 1987, 158–59.

22. Aldrin and McConnell 1989, 180–83; Burrows 1990, 160–61.

23. *Apollo 6 photomaps of the west-east corridor from the Pacific Ocean to northern Louisiana,* USGS Map (4 sheets).

24. Baker 1982, 311–12; Hart 1987, 88.

25. This is the evaluation of Frank Borman (1988), whose list of giants also includes Robert Gilruth, Chris Kraft, and Wernher von Braun, all of whom he contrasts with the lesser folk who now run NASA.

26. C. Murray and Cox 1989, 322–23.

27. Trento 1987, 78–80.

28. Levine 1982, 257–58.

29. Collins 1974, 267–68.

30. The present crew titles were devised in July 1967. Previously, the commander was called the commander pilot, the CMP was the navigator copilot, and the LMP was the engineer-scientist (Brooks, Grimwood, and Swenson 1979, 261).

31. Ibid., 256–60, 273–74. This is an excellent account of the decision to send Apollo 8 to the Moon; the mission is described on pp. 274–84.

32. Borman 1988, 189.

33. Good summaries of the Soviet program during this time, taken partly from the other works referenced here, are by Aldrin and McConnell (1989) and Burrows (1990).

34. Oberg 1981, 112–27.

35. NASA Manned Spacecraft Center 1969.

36. D. E. Wilhelms, D. E. Stuart-Alexander, and K. A. Howard, "Preliminary interpretations of lunar geology," in NASA Manned Spacecraft Center 1969, 17–18. This is the South Pole–Aitken basin. See chapter 13, The Russians Fill the Gap.

37. *Time,* 3 January 1969; *Newsweek,* 6 January 1969; *Life* (special issue), "The Incredible Year '68," 10 January 1969.

38. Aldrin, Armstrong, Collins, Conrad, Irwin, Mitchell, Stafford, and Young were all born in 1930. *Apollo astronauts* as used here means those who actually flew a lunar Apollo

mission, not the third group selected, as the term has been used earlier in the book. Four Apollo astronauts were born before 1930 and 12 after.

39. Brooks, Grimwood, and Swenson 1979, 261; Baker 1982, 306; Compton 1989, 135. Swigert, Evans, and Pogue had constituted the first support crew, for Apollo 7.

40. The 6 December 1968 issue of *Time* (90) reported that Tass confirmed at the time that the Zonds were preparations for a manned flight, and James Oberg (1981), a Houston engineer who closely follows the Soviet space program, also did not doubt it.

41. The Soviets gave difficulty in perfecting the launch rocket as the reason the lander was not used. Oberg (1981) cited Korolev's death and the Soviets' recognition that Apollo 8 signaled their defeat in the Moon race.

42. The LM's call sign was *Spider* and the command module was *Gumdrop*. Gemini missions and Apollos 7 and 8 needed no special call signs because they flew only one spacecraft.

43. Veterans of Lunar Orbiter called ALS 1 by its Orbiter designation, 2P-2. Other aliases include Ellipse East Two and the Maskelyne DA region of the Moon.

44. M. H. Carr, *Geologic map of the Maskelyne DA region of the Moon*, USGS Map I-616 (1970); D. E. Wilhelms, *Geologic map of Apollo landing site 1*, USGS Map I-617 (1970).

45. Quaide and Oberbeck 1969—a good pre-landing summary of the geology of the potential landing sites. Their method is described in chapter 9, Three out of Three.

46. ALS 2 lies within Surveyor candidate site 9-100, Lunar Orbiter Mission A candidate site A-3, Lunar Orbiter 2 site 2P-6, and the Sabine D region of the Moon; Orbiter veterans always called it 2P-6. In November 1963 MSC had called a nearby spot Area IV.

47. Trask's study was published as a pamphlet to accompany all the USGS early Apollo maps (USGS Maps I-616–I-627); see also Trask 1971 and Wilhelms 1987, 131–35.

48. Grolier 1970a (scale 1:100,000); 1970b (scale 1:25,000). These "I maps" were published after the mission but included only very preliminary mission results.

49. T. B. McCord and T. V. Johnson, "Relative spectral reflectivity 0.4–0.1 microns of selected areas of the lunar surface," *JGR* 74 (1969):4395–4401.

50. H. H. Schmitt, telephone conversation, April 1990.

51. Brooks, Grimwood, and Swenson 1979, 301.

52. Ibid., 310.

53. This quote was kindly supplied to me by Andrew Chaikin, who is listening to all the Apollo voice tapes in preparation for writing his own book.

54. NASA Manned Spacecraft Center 1971. Note the report's late date. Like the Apollo 8 report, this one contains reproductions of all the orbital Hasselblad photographs.

55. Both rovers and sample returners are consistent with later missions conducted by the Soviets. Other apparent lunar attempts in this period were given only the all-embracing name Kosmos.

56. A student of the secret American space reconnaissance and surveillance program gives a date of early June for the explosion (Burrows 1986, 232); 4 July is given by Aldrin and McConnell (1989, 223–24) and P. S. Clark, "The other side of the race," *Air and Space* (June–July 1989):36–37.

57. Brooks, Grimwood, and Swenson 1979, 319–22; Compton 1989, 95–96.

58. Compton 1989, 115–18.

59. J. C. McLane, Jr., E. A. King, Jr., D. A. Flory, K. A. Richardson, J. P. Dawson, W. W. Kemmerer, and B. C. Wooley, "Lunar Receiving Laboratory," *Science* 155 (1967):525–29; Compton 1989, esp. 103–9, 119–26; King 1989.

60. Compton 1989, 265.

61. The original LSPET: Wilmot Hess, Ed Chao, Elbert King, Hoover Mackin, Klaus Biemann (MIT), Almo Burlingame (Univ. Calif., Berkeley), Clifford Frondel, Davis O'Kelley (Oak Ridge National Lab.), Oliver Schaeffer (SUNY Stony Brook), and Gene Simmons (Compton 1989, 105). Mackin died in August 1968 in Houston.

62. The original LSAPT: Wilmot Hess, Elbert King, Edward Anders (Univ. Chicago), Jim Arnold, P. R. Bell, Clifford Frondel, Paul Gast, Harry Hess, Hoover Mackin, Gene Shoemaker, Gene Simmons, Brian Skinner (Yale Univ.), Wolf Vishniac (Univ. Rochester), and Gerald Wasserburg (Compton 1989, 105). Harry Hess died in August 1969 at Woods Hole.

63. Newell 1980, 240–42; Compton 1989, 110.

64. King (1989, 70–71) gives the date of Johnson's visit as 1 April 1968, but the records of LSI (now LPI, the Lunar and Planetary Institute) give 1 March. On 31 March 1968 Johnson announced his withdrawal from candidacy for reelection. LSI/LPI, now in new quarters, is operated by a consortium of universities, the Universities Space Research Association.

65. Mutch 1970 (a second edition appeared in 1972, after the first Apollo results were in).

66. Wilhelms and McCauley 1971.

67. Wilhelms and Davis 1971.

68. I thought we understated the importance of basin secondaries, but I recently found a letter from Canadian crater expert Mike Dence dated 16 December 1970 criticizing us for overemphasizing them.

69. Mutch 1970, 197.

70. Ibid., 240–47; T. A. Mutch and R. S. Saunders, *Geologic map of the Hommel quadrangle of the Moon,* USGS Map I-702 (1972).

CHAPTER 11. TRANQUILLITY BASE (1969)

1. Woods 1981. Both ideas are consistent with later missions conducted by the Soviets.

2. Farouk El-Baz and Don Beattie once spent many days trying to track down a specific written record of the choice of the site but failed to find one. Minutes of the last prelaunch meetings of the ASSB, on 3 June and 10 July 1969, list only the sequence ALS 2, ALS 3, ALS 5, and so imply merely that the easternmost site available in a given month would be the prime target. As discussed in chapter 10, the need for a backup site was the ultimate reason for concentrating on the easternmost site that met all other requirements (ALS 1 was marginal). Jack Schmitt's suggestion that ALS 2 be the sham target for Apollo 10 was accepted, and when the site looked reasonably good to Stafford and Young and

appeared to fit flight operation needs, there was no reason to go elsewhere. Members of the ASSB in June and July 1969: Sam Phillips, chairman; Lee Scherer, secretary; John Disher, Oran Nicks, John Stevenson, and Don Wise, also from NASA Headquarters; Wilmot Hess, John Hodge, and Owen Maynard from MSC; Roderick Middleton from KSC; Ernst Stuhlinger from Marshall.

3. This account of the conduct of the mission is taken mainly from the well-researched book by Baker (1982, 342–59), from the good book by someone who was there (Aldrin and McConnell 1989, 225–46), and from one of my favorite books about Apollo: C. Murray and Cox 1989. See also the early postmission books: Lewis 1969; Wilford 1969; Farmer and Hamblin 1970; Mailer 1970; Thomas 1970. The accounts in these references differ in details, and I have melded them. For example, Baker but not Aldrin mentions Slayton's impatience with Duke.

4. FIDO = flight dynamics officer; G&C = guidance and control officer.

5. Gordon Swann furnished the following details of the identification of the landing spot. The field geology team had narrowed it down to either of two locations based on the astronauts' descriptions of a "doublet." In a debriefing during the transearth coast, Armstrong commented on the crater he "strolled to" that it was "70 or 80 feet in diameter and 15 or 20 feet deep . . . [with] rocks in the bottom of pretty good size." The geology team could then pin down which doublet the astronauts had seen. The photographs taken by the 16-mm sequence camera during LM descent confirmed this location after the return to Earth. So the location ultimately depended on photographs and not calculations.

6. All quotes are from N. G. Bailey and G. E. Ulrich, "Apollo 11 voice transcript pertaining to the geology of the landing site," USGS informal publication (1974); available as report no. USGS-GD-74-026 from National Technical Information Service, Springfield, Va. 22151. The USGS had a contract to prepare such transcripts of all landing missions, keying the conversations to the returned rocks and photos and omitting matters not relevant to science. As seen from the date, the effort took some time, partly because word processors were primitive in those days. However, one was indeed used; it was called WYLBUR and resided in the National Institute of Health's computer.

7. My German hosts mentioned but did not dwell on the comparison with the V-2s. I was able to praise the achievements of the von Braun team and ignore the malicious purpose of the V-2s because 20 July was also the anniversary of the most serious attempt by German officers to kill Hitler (1944).

8. I even saw one of my own maps as the cover illustration for the generally accurate and geologically informative 12 July 1969 issue of *Paris Match,* marred only by the erroneous caption "the map that the astronauts will have on board" (la carte lunaire que les cosmonauts auront à bord). This was the 1965 compilation of the equatorial belt by me, Newell Trask, and Jim Keith mentioned in chapter 6.

9. I am told that back home, Chet Huntley did it right by saying something like, "I am going to be quiet. Let your imagination soar."

10. Aldrin 1973.

11. Compton 1989, 118.

12. According to Wilson (1987, 59), Luna 15 struck the Moon at a velocity of 480 km per hour at 1551 GMT on 21 July 1969 at 17° N, 60° W. Other sources give somewhat different coordinates and are less sure that the reason for the final loss of signal was a crash. In any case Luna 15 ended up in the general region of the later successful Luna 16, 20, and 24 sample-return landings, suggesting that this was also its purpose.

In August 1969 Zond 7 repeated the feat of Zond 6 by bringing film, including color film, back to Earth — a little late to beat the Americans if that was Zond's original purpose.

13. H. S. F. Cooper 1970. Cooper, a descendant of novelist James Fenimore Cooper, enhances his ironic, detached tone by carefully designating each person by his correct title: Mr. Gold, Mr. Masursky, Lt. Col. Collins, Dr. Urey, Dr. Shoemaker. This entertaining and accurate book is a superb record of the feeling and atmosphere at MSC and in the halls of science at the time of Apollo 11.

14. Ibid., 27–28. Pumice is a porous, lightweight volcanic rock with many vesicles.

15. Lewis 1974, 80–81; T. Gold, "Apollo 11 observations of a remarkable glazing phenomenon on the lunar surface," *Science* 165 (1969):1349.

16. H. S. F. Cooper 1970, 55.

17. J. Green, "Origin of glass deposits in lunar craters," *Science* 168 (1970):608–9.

18. G. G. Schaber, D. R. Scott, and J. B. Irwin, "Glass in the bottom of small lunar craters: An observation from Apollo 15," *Bulletin of the Geological Society of America* 83 (1972):1573–77.

19. The quote is from an informal transcript of the debriefing prepared by MSC, which contains many errors. This quote is attributed to Aldrin, but to me it sounds more like Armstrong, and one wonders if *books* was the word used.

20. Brooks, Grimwood, and Swenson 1979, 329.

21. Lunar Sample Preliminary Examination Team 1969; NASA 1969. Preliminary results were also discussed at a meeting at the Smithsonian Institution in September 1969.

22. J. J. Gilvarry, "Internal temperature of the Moon," *Nature* 224 (1969):968–70.

23. Officially called the Apollo 11 Lunar Science Conference; Robin Brett organized it. The following year the name of the annual meeting was changed to Lunar Science Conference, and in 1978 to Lunar and Planetary Science Conference.The 30 January 1970 issue of *Science* remains a valuable record of the Apollo 11 results, as well as a little from Apollo 12. See also Mason and Melson 1970; Frondel 1975.

24. *Proceedings of the Apollo 11 Lunar Science Conference, Geochimica et Cosmochimica Acta,* supp. 1 (New York: Pergamon, 1970) (*PLSC* 1). Jack Schmitt, Gary Lofgren, Gordon Swann, and Gene Simmons summarized the sampling results on pp. 1–54. The results cited here are taken mostly from these volumes and the 30 January 1970 *Science.* Volumes of the conference proceedings are still being published annually (at least through the twentieth conference as this is written) though with changes in title, publisher, and number of volumes over the years.

25. S. E. Haggerty, "The chemistry and genesis of opaque minerals in kimberlite," *Physics and Chemistry of the Earth* 9 (1975):295–307; A. El Goresy and E. C. T. Chao, "Identification and significance of armalcolite in the Ries glass," *Earth and Planetary Science Letters* 30 (1976):200–208.

26. A. L. Turkevich, E. J. Franzgrote, and J. H. Patterson, "Chemical composition of the lunar surface in Mare Tranquillitatis," *Science* 165(1969):277–79.

27. D. F. Weil, R. A. Grieve, I. S. McCallum, and Y. Bottinga, "Mineralogy-petrology of lunar samples . . . ," *PLSC* 2 (1971):413–30. These petrologists' work discounts earlier explanations that large amounts of iron and titanium cause the low viscosity.

28. Now, four or five flows ranging from 3.57 to 3.84 aeons old have been identified. Standard radiometric decay constants were changed in 1977, so ages stated before and after 1977 may differ by several tens of millions of years.

29. Gault 1970. The data suggested a much higher present rate of meteor entry into Earth's atmosphere than had been thought, meaning that the accumulation of a given crater density on Earth or Moon took less time than had been thought. The data came as a by-product of an effort by the Atomic Energy Commission to monitor atmospheric shock waves caused by foreign nuclear blasts.

30. R. B. Baldwin, "Lunar crater counts," *Astronomical Journal* 69 (1964):377–92; Baldwin, "Absolute ages of the lunar maria and large craters," *Icarus* 11 (1969):320–31. In 1970 Baldwin reconciled the basis for his age estimates, the rate of isostatic adjustment of craters, with the actual ages of the Apollo 11 samples; see "Absolute ages of the lunar maria and large craters. II. The viscosity of the Moon's outer layers," *Icarus* 13 (1970):215–25.

31. W. K. Hartmann, "Terrestrial and lunar flux of large meteorites in the last two billion years," *Icarus* 4 (1965):157–65.

32. The rock ages were based on measurements made on several minerals in the same rock (*internal isochrons*), whereas the soil ages were based on analyses of a bulk sample and the assumption that its original ratio of strontium isotopes was the same as that in the oldest known meteorites (*model ages*).

33. Marvin 1973b.

34. French 1977, 202.

CHAPTER 12. A WESTERN MARE? (1969)

1. Brooks, Grimwood, and Swenson 1979, 365.

2. The G and H missions were usually referred to as "walking" missions, and J missions as "roving," "riding," or "driving" missions. A J-type walking mission was conceivable; the lunar rover was part of the J missions but its inclusion on J-1 was not certain when the site for that mission was selected.

3. See also Compton 1989, 160–67.

4. "Relocated" meant that a new approach trajectory was required. "Redesignate(d)" meant that the astronauts could adjust their approach from the existing trajectory.

5. The original designation of the Surveyor 1 Flamsteed site was simply ALS 6. In June 1969 MSC recommended that it be called 6R to show that it was one of the point-landing sites that had recently been added to the list.

6. Lunar Orbiter Photo Data Screening Group 1967b, 69. Surveyor 3 landed two months after Orbiter 3 took the pictures.

7. Surveyor Program 1967a, 12–16.

8. The exact location of the Apollo 12 site has been stated differently in different publications. *Apollo 12 preliminary science report* (NASA Manned Spacecraft Center 1970) gives 3.2° S, but in ACIC coordinates it is 2.99° S, 23.34° W. The difference of 0.2° in latitude corresponds to 6 km.

9. Fellow astronaut Walt Cunningham (1977) ranks both Conrad and Bean in the very top among the astronauts. However, I have the impression that for Conrad, at least, the next notch on his aviator's belt could just as well have been in some new machine back at Earth as the Apollo 12 LM.

10. Brooks, Grimwood, and Swenson 1979, 148–49. All astronauts specialized in one aspect of the flight systems or operations and worked closely with the engineers who were developing them.

11. Gibson was in the group selected with Jack Schmitt in June 1965 and was the first scientist-astronaut assigned to a crew. Carr and Weitz were among the group of 19 pilot-astronauts (fifth group overall) selected in April 1966.

12. C. Murray and Cox 1989, 382–86. The solution was to track the LM's position precisely by the Doppler effect and not worry about the mascons.

13. Adjusting to the sudden decision, Howie Pohn polished up one of the 1:100,000-scale hand-colored maps that the USGS had prepared for planning (Pohn 1971). As usual, maps at the 1:25,000 scale were also prepared, but they were not updated for publication because the hour was getting late. The first such 1:25,000-scale map was prepared in 1967 by Steve Saunders and Tim Mutch (*Preliminary geologic map of ellipse III-9-5 and vicinity*), and the second by P. Jan Cannon in 1969 (*Geologic map of Apollo landing site 7*).

14. In August 1969 Harry Hess had died and Curt Michael had resigned to return to Rice University. The resigning scientists all expressed various degrees of dissatisfaction with NASA's scientific attitude (Compton 1989, 168–71, 193). Don Wise is now at the University of Massachusetts.

15. C. Murray and Cox 1989, 371–79. Although most interested parties who were around in 1969 remember that lightning almost aborted the Apollo 12 mission, in March 1987 NASA repeated the mistake of launching in threatening weather. The result was the destruction of one of its last expendable launch vehicles and a valuable satellite. This easily avoidable fiasco wasted $161 million of the taxpayers' money, but NASA's initial statement was that the loss was not really critical.

16. Baker 1982, 364–72.

17. NASA Manned Spacecraft Center 1970, 2–6, 39–102.

18. In 1989, after the *Challenger* explosion, some environmentalists were upset when a similar generator was included on the Galileo mission to Jupiter.

19. H. S. F. Cooper 1969. Although Cooper's book and the *New Yorker* articles from which it was derived were written before the Apollo 11 landing, they remain probably the best and certainly the liveliest description of the evolution of the ALSEP for the general reader.

20. My favorite story concerning NASA's love of reinventing simple things in complex ways came some years later. To measure the volume of a human body, somebody built a

chamber in which sound waves, I believe, were reflected off the subject. They had forgotten Archimedes and his bathtub.

21. NASA 1972; 11 papers in *PLSC* 2 (1971):2683–2795. The uneven tan color resulted from both radiation and the dust cover. Small pits were attributed to impact of particles dislodged from the lunar surface. A bacterium also seems to have survived the Earth-Moon round trip.

22. L. C. Wade, "Photographic summary of the Apollo 12 mission," in NASA Manned Spacecraft Center 1970, 7–27.

23. NASA Manned Spacecraft Center 1970, 29–38.

24. R. L. Sutton and G. G. Schaber, "Lunar locations and orientations of rock samples from Apollo missions 11 and 12," *PLSC* 2 (1971):17–26. An updated summary is J. M. Rhodes, D. P. Blanchard, M. A. Dungan, J. C. Brannon, and K. V. Rodgers, "Chemistry of Apollo 12 mare basalts: Magma types and fractionation processes," *PLSC* 8 (1977):1305–38. This paper contains a good stratigraphic analysis as well as the subjects implied by the title.

25. Lunar Sample Preliminary Examination Team 1970; and in NASA Manned Spacecraft Center 1970, 189–216. About 50 professionals are named as contributors to these articles. There are four main types of basalt at the Apollo 12 site; they have been given a variety of names but are commonly referred to as olivine, pigeonite, ilmenite, and feldspathic basalt.

26. NASA Manned Spacecraft Center 1970, 113–88, by the geology team plus the three astronauts.

27. T. Gold, "Evolution of mare surface," *PLSC* 2 (1971):2675–80.

28. L. A. Soderblom, "A model for small-impact erosion applied to the lunar surface," *JGR* 75 (1970):2655–61. Larry officially entered on duty in August 1970.

29. L. A. Soderblom and L. A. Lebofsky, "Technique for rapid determination of relative ages of lunar areas from orbital photography," *JGR* 77 (1972):279–96.

30. All the basalts, despite their compositional diversity (four types, three flows), were emplaced at very nearly the same time. This and similar findings from other missions indicate that the mare basalts were produced by partial melting of small pockets of compositionally heterogeneous mantle rock (Taylor 1982, 301, 320–21).

31. Based on the U-Th-Pb system (by Lee Silver) and two ways of measuring ages from isotopes of argon (Turner 1977). References and a discussion are given by Wilhelms 1987, 269–70.

CHAPTER 13. THE BEST-LAID PLANS (1970)

1. Because of the early interest in the Censorinus site, a geologic map was prepared of it, though the map was not published until after a landing was no longer being considered (West 1973).

2. R. E. Eggleton, "Geologic map of the Fra Mauro region of the Moon—Apollo 13" (1970) (scale 1:250,000); T. W. Offield, "Geologic map of part of the Fra Mauro region of the Moon—Apollo 13" (1970) (scale 1:50,000); these are USGS maps, printed

in color but not formally published. Offield joined Astrogeology from the Foreign Geology Branch and Eggleton returned to Flagstaff from his university studies in Tucson in the same month, February 1966.

3. John Glenn resigned in January 1964, Scott Carpenter in August 1967, Wally Schirra in July 1969, and Gordon Cooper in July 1970.

4. MacKinnon and Baldanza 1989, 4.

5. Cunningham 1977, 225–27; the other book-length astronaut memoirs cited in the present book (Aldrin, Borman, Collins, Irwin, Schirra) also discuss crew selection but none in such frank detail as Cunningham's; see Compton 1989, 281.

6. The name changed slightly to Apollo Lunar Geology Investigation Team for Apollo 15 and Apollo Field Geology Investigation Team for Apollos 16 and 17.

7. Hoyt 1987, 105.

8. Shoemaker's statements made many newspapers. I quote from the *Washington Post*, 9 October 1969.

9. Newell 1980, 292–93.

10. Interview with Muehlberger in Denver, November 1988.

11. Levine 1982, 110–15.

12. Low had replaced Joseph Shea in this position at MSC, taking a demotion to do so, while Shea went to NASA Headquarters (C. Murray and Cox 1989, esp. 268–70). The ASPO manager was essentially local deputy to the Apollo program director at NASA Headquarters (Rocco Petrone after Sam Phillips left in September 1969).

13. Baker 1982, 373, 390–92.

14. Vice President Spiro Agnew chaired the Space Task Group, filling a function of the vice president that began with Lyndon Johnson and is continuing today with J. Danforth Quayle. Other members were NASA Administrator Paine; Robert Seamans, NASA associate or deputy administrator between September 1960 and January 1968 and then secretary of the Air Force until May 1973; and Lee DuBridge, Nixon's science adviser and president of Caltech from 1946 to 1969. Observers were U. Alexis Johnson, undersecretary of state for political affairs; Glenn Seaborg, chairman of the Atomic Energy Commission; and Robert Mayo, director of the Bureau of the Budget. Their first report to the president (prepared by NASA) appeared in September 1969, but Nixon did not act on it until March 1970. Nixon dissolved the group in January 1973.

15. Between 1959 and 1969 NASA consumed $35 billion, of which $19 billion was for Apollo. NASA's funding represented 2.5% of the $1.4 trillion federal spending in that period.

16. Press Conference, Key Biscayne, Florida, 7 March 1970, Office of the White House Press Secretary. Trento 1987, 94.

17. Compton 1989, 196. At the same time, Mercury and Mars missions were deferred and 50,000 of the 190,000 NASA employees, contractors, and university scientists were laid off. Funding and staffing of the USGS's Branches of Astrogeologic Studies and Surface Planetary Exploration for lunar studies also peaked in fiscal year 1970 at about $4.5 million and 200 people, of whom 146 were permanent full-time employees. Planetary

work kept the levels up for a few years, but they plummeted in the mid-1970s.

18. Baker 1982, 374–90; Bond 1987, 226–42.

19. The saga of Apollo 13 is brought beautifully to life by Pellegrino and Stoff 1985; C. Murray and Cox 1989; and Cooper 1973. The lifeboat use of the LM was possible because the potential need for it had occurred in 1961 to Grumman engineer Al Munier, who got extra margins of fuel, oxygen, water, and electric power built into the LM (Pellegrino and Stoff 1985, 190).

20. A number of papers were published by the experimenters and their associates, who included Gary Latham (principal investigator), James Dorman, Frederick Duennebier, Maurice Ewing, Robert Kovach, David Lammlein, Yosi Nakamura, Frank Press, George Sutton, and Nafi Toksöz. For example, see G. V. Latham et al., "Seismic data from man-made impacts on the Moon," *Science* 170 (1970):620–26; and Latham et al., "Moonquakes," *Science* 174 (1971):687–92; Toksöz 1974.

21. Zdeněk Kopal, *Physics and astronomy of the Moon,* 2d ed. (New York: Academic, 1971), 219.

22. Lewis 1974, 172. Urey's and other protests are in Compton 1989, 201–3.

23. Trento 1987.

24. Ordway and Sharpe 1979; Baker 1982, 389–90.

25. See chapters 10 and 11. Kosmos 300, launched in September 1969, Kosmos 305, launched in October, and another unnumbered Luna, launched in February 1970, apparently were further attempts to deploy rovers or return samples.

26. This zone was chosen to allow a free-fall straight to Earth after lunar lift-off without need for a mid-course correction (Gatland 1981, 137).

27. *Earth and Planetary Science Letters* 13, 2 (January 1972), special issue; Basaltic Volcanism Study Project 1981, 236–67.

28. J. F. McCauley and D. H. Scott, "The geologic setting of the Luna 16 landing site," *Earth and Planetary Science Letters* 13 (1972):225–32.

29. J. A. Wood, J. B. Reid, Jr., G. J. Taylor, and U. B. Marvin, "Petrological character of the Luna 16 sample from Mare Fecunditatis," *Meteoritics* 6 (1971):181–94. See also papers cited in the special Luna 16 issue (n. 27).

30. Klaus Keil, Gero Kurat, Martin Prinz, and J. A. Green, "Lithic fragments, glasses and chondrules from Luna 16 fines," *Earth and Planetary Science Letters* 13 (1972):243–56, esp. 244–45. I thank Ursula Marvin for alerting me to this reference. Minerals that define the rock names are *plagioclase* for anorthosite, *orthopyroxene* and *plagioclase* for norite, and *olivine* and *plagioclase* for troctolite. Rock names are not really appropriate for the small and highly modified Luna grains.

31. Hartmann and Kuiper 1962, 60.

32. Stuart-Alexander 1978 (gives references to Russian papers on Zonds 6 and 8); Wilhelms, Howard, and Wilshire 1979. Massifs of the basin were photographed by Apollo 8 before their origin was realized. The Galileo (Jupiter mission) flyby of the Moon in December 1990 confirmed the basin's existence.

33. A. P. Vinogradov, "Preliminary data on lunar ground brought back to Earth by

automatic probe 'Luna-16,'" *PLSC* 2 (1971):1–16. An exhaustive report appears in A. P. Vinogradov, ed. *Lunnii Grunt iz Morya Izobiliya* (*Lunar Soil from the Sea of Fertility*) (Moscow: Nauka, 1974) (in Russian).

34. The acronym first appeared formally in N. J. Hubbard, C. Meyer, Jr., P. W. Gast, and H. Wiesmann, "The composition and derivation of Apollo 12 soils," *Earth and Planetary Science Letters* 10 (1971):343. Hundreds of papers have been subsequently written about KREEP; 142 appear in the index for the first nine Lunar (or Lunar and Planetary) Science Conferences alone (Masterson 1979). See reviews by Taylor 1975, 1982; Charles Meyer, Jr., "Petrology, mineralogy, and chemistry of KREEP basalt," *Physics and Chemistry of the Earth* 10 (1977):239–60; P. H. Warren and J. T. Wasson, "The origin of KREEP," *Reviews of Geophysics and Space Physics* 17 (1979):73–88.

35. The distinctive KREEP trace elements do not easily enter into rock-forming minerals. Therefore they are either squeezed out quickly when a rock mass begins to melt or they linger in a melt until the last minute before joining more compatible elements in a crystal.

36. Hubbard et al., "Apollo 12 soils"; N. H. Hubbard and P. W. Gast, "Chemical composition and origin of nonmare lunar basalts," *PLSC* 2 (1971):999–1020.

CHAPTER 14. PROMISING FRA MAURO (1971)

1. The sites on the August 1969 list are listed, in a slightly different order, in one of the few records of site selection and planning formally published during this fast-paced period: John E. Naugle, "Excerpts from NASA description of Apollo 12 through 20," *Icarus* 12 (1970):134–39. Naugle had replaced Homer Newell as associate NASA Administrator for OSSA in September 1967 as Newell moved higher up the NASA hierarchy.

2. Urey and others had criticized NASA for not consulting them and other appropriate specialists, so the October 1969 GLEP meeting was postponed a week to allow Gold, Press, Shoemaker, Urey, the ALSEP principal investigators, and other major figures to attend. As an annoyed Gene Simmons wrote in a memo dated 21 October 1969, Shoemaker stopped by for 15 minutes because he was in town anyway, Urey arrived after the meeting had ended, and none of the others showed up at all. So GLEP and the Rump GLEP continued to carry the ball on site selection.

3. Jahns died of long-standing heart problems on the last day of 1983, as he was preparing for a New Year's Eve party.

4. The artificial crater fields and NTS were visited in November 1970. One of the few formal publications that reported the astronaut training was H. J. Moore, "Nevada Test Site craters used for astronaut training," *Journal of Research USGS* 5 (1977):719–33. However, this paper concentrates on dull geologic details about the craters, and not on the training. The 300-m nuclear crater Schooner was a good analogue for Cone crater. After the Apollo missions ended, Dale Jackson obtained some money to write a professional paper about the training program but could not generate enough enthusiasm among most of his colleagues to finish the ambitious project. His files are in a warehouse in Flagstaff.

5. The 400-m Sedan crater at the Nevada Test Site, which was filmed during its formation by a 100-kiloton bomb in early 1963 and studied geologically afterward, served as a particularly valuable replica of lunar craters because it was formed by a shallowly buried bomb. Wayne A. Roberts ("Shock—a process in extraterrestrial sedimentology," *Icarus* 5 [1966]:459–77) mapped and described Sedan before its fine-scale features could become eroded.

6. Eggleton and Offield 1970 (2 sheets, scales 1:250,000 and 1:25,000).

7. Details of the mission are given by Baker 1982, 400–408. Launch was at 1603 EST (2103 GMT). Numerous problems plagued prelaunch preparations, the countdown, extraction of the LM en route to the Moon (almost leading to cancellation of the landing), and the LM's descent.

8. Farouk El-Baz and S. A. Roosa, "Significant results from Apollo 14 lunar orbital photography," *PLSC* 3 (1972):63–83.

9. MacKinnon and Baldanza 1989, 87–89 (interview with Mitchell).

10. Conversation with Lee Silver at Caltech, September 1989.

11. The Apollo 14 sample collection included 33 rocks weighing more than 50 g each, two short (12.5 and 16.5 cm) core samples, one doubly long (39.5 cm) core sample collected by fastening two short drive tubes end to end, a bulk sample, and two comprehensive samples. The quarantine was retained for fear the deep core samples might contain organisms that could not survive nearer the surface.

12. NASA Manned Spacecraft Center 1971; Lunar Sample Preliminary Examination Team 1971; Swann et al. 1971.

13. Cited as *PLSC* 3, for *Proceedings of the Third Lunar Science Conference.* The three-volume proceedings were published by MIT Press, Cambridge, Mass., and constitute supplement 3 of the journal *Geochimica et Cosmochimica Acta.*

14. M. Cooper, Kovach, and Watkins 1974.

15. E. C. T. Chao, "Geologic implications of the Apollo 14 Fra Mauro breccias and comparison with ejecta from the Ries crater, Germany," *Journal of Research USGS* 1, 1 (1973):1–18. We see that Chao had the honor of inaugurating this USGS publication, which was introduced to expedite the publication of short papers for a wider audience than would see them in the professional papers called *Geological Survey Research,* where they had been buried since 1960. In 1978 Director William Menard canceled the series because he thought it contained trivial results—and then established a separate newsletter to present his own views.

16. People who doubt the impact origin of lunar basins or who wish to remain objective often use "Imbrium event" instead of "Imbrium impact." Although I strongly favor objectivity in lunar and planetary work, I consider "event" too fussy.

17. D. A. Papanastassiou and G. J. Wasserburg, "Rb-Sr ages of igneous rocks from the Apollo 14 mission and the age of the Fra Mauro Formation," *Earth and Planetary Science Letters* 12 (1971):36–48. The ages cited in this paper and all others published before 1977 differ from the values accepted today; for example, they state 3.85 aeons as 3.88 aeons. The ages given here and in the rest of this book were calculated with the radioactive decay constants in use since 1977; see Basaltic Volcanism Study Project 1981.

18. Preliminary reports by the geology team are cited in note 12, and a last word is in Swann et al. 1977.

19. J. L. Warner, *PLSC* 3 (1972):623–43. The distinction between regolith breccias, which had been found by Apollo 11 and 12, and bedrock breccias, obtained by Apollos 14–17, was not yet clear to many analysts. They were included under the same heading in the tables of contents of the conference proceedings for several more years. Warner included both regolith breccias and Fra Mauro breccias in his study, suggesting that most of them originated in the Fra Mauro blanket.

20. Additional references and discussion of the Fra Mauro's petrology and origin are given in Wilhelms 1987.

21. Ages of young lunar craters have been determined by measuring how long samples of their ejecta have been exposed to cosmic rays. See summary by Arvidson et al. 1975.

22. Ryder and Spudis 1980.

23. Norman Hubbard, Paul Gast, and their MSC colleagues suggested that KREEP-poor aluminous rock might also be highland basalt, though they admitted that this was "more of a concept than a rock type" (N. J. Hubbard, P. W. Gast, J. M. Rhodes, B. M. Bansal, and H. Wiesmann, "Nonmare basalts. Part II," *PLSC* 3 [1972]:1161–79). Small fragments of regolith *glass*—not crystalline rock—were also called highland basalt by analysts participating in an Apollo Soil Survey.

24. One often sees the term *KREEP basalt.* But *KREEP-y basalt* is better because *KREEP* is a geochemical term that refers to a collection of relatively rare chemical elements that are *in* certain rocks or glasses. KREEP-y basalts and other materials are now usually called Fra Mauro basalt even if not volcanic or from the Fra Mauro Formation. The abbreviations LKFM, MKFM, and HKFM, for low-K, medium-K, and high-K Fra Mauro basalt, are universally understood in the Moon rock community to refer to relative amounts of potassium and other elements typical of KREEP in lunar rocks. KREEP basalt in the volcanic sense probably does exist, but was sampled, at most, at only the Apollo 15 site.

25. Masterson 1979. A non-conference USGS contribution (favoring impact-melt origin) is O. B. James, *Crystallization history of lunar feldspathic breccia 14013*, USGS Professional Paper 841 (1973). It is still not entirely certain that the *Imbrium* impact created sample 14310.

26. Post-Apollo reviews of breccias include James 1977; Stöffler, Knöll, and Maerz 1979; Stöffler et al. 1980.

CHAPTER 15. GOLDEN APENNINE-HADLEY (1971)

1. Compton 1989, 201–3, 329–30; Baker 1982, 360. Baker, but not Compton, gives President Nixon credit for restoring the J-mission funds while cutting NASA's overall budget.

2. Brooks, Grimwood, and Swenson 1979, 362–63; Newell 1980, 286–90; Baker 1982, 360–63, 372–73, 410–13; Levine 1982, 252–61.

3. Brooks, Grimwood, and Swenson 1979, 81, 365.

4. Compton 1989, 159. As explained in chapter 13 and this chapter, the mission that became Apollo 15 was still called Apollo 16 in 1969.

5. Baker 1982, 410.

6. Metric frames are square in format and easy to view stereoscopically. Panoramic frames, which resolve objects as small as a meter across under ideal conditions, cover bow-tie-shaped strips because the camera scanned from side to side. In my opinion, neither kind of photograph has much geologic value when taken at Sun angles higher than 45°. See Masursky, Colton, and El-Baz 1978 (an especially fine volume of Apollo photographs).

7. The analyzed and photographed strips were not exactly the same because photography and X-ray fluorescence can work only in sunlit areas; see Adler and Trombka 1977.

8. The organizational hierarchy of geoscience at MSC was Science and Applications Directorate (Calio), Lunar and Earth Science Division (Gast), Geology and Geochemistry Branch (Ted Foss). Ted was Dale Jackson's old nemesis, but he now viewed the USGS more favorably. Larry Haskin replaced Gast after Gast's death in 1973.

9. Even Silver and Bill Muehlberger, though university professors, were USGS employees in a sense. They had the status called WAE (when actually employed), commonly used by the USGS as a device for paying outsiders for part-time work. A large percentage of the professional geologists in the United States are or have been WAE.

10. Conversation with George Ulrich, June 1987. The Flagstaff exercise was led by diatreme expert Tom McGetchin. The cancellation of the two Apollos is discussed in chapter 13, The Americans Take a Break.

11. R. E. Lingenfelter, S. J. Peale, and G. Schubert, "Lunar rivers," *Science* 161 (1968):266–69; S. A. Schumm and D. B. Simons, and reply by Lingenfelter et al., "Lunar rivers or coalesced chain craters?" *Science* 165 (1969):201–2; Schumm and Simons thought, erroneously, that sinuous rilles were formed by coalesced gas emissions along fissures. In their reply, Lingenfelter et al. reiterate that the riverlike form of rilles *requires* them to have been eroded by surface water maintained as a liquid by an ice capping.

12. Copernicus was also seriously considered for Apollo 15 but, unlike Palus Putredinis, offered no smooth landing site close enough to its central peaks to be reached by walking in case the LRV was not ready for a flight in mid-1971 or failed on the Moon. Also, Copernicus was considered the only good backup to Descartes for the Apollo 16 "highlands" mission that was shaping up. The geophysicists did not like Marius for the next mission after Apollo 14 because it was on a line rather than on a triangle leg with the earlier landing sites, and some geochemists were skeptical of its petrologic significance. Apparently it was Scott who tipped the balance away from Marius and toward Apennine-Hadley (Compton 1989, 218; conversation with Andrew Chaikin, 1988).

13. Carr, Howard, and El-Baz 1971 (scale 1:250,000 by Carr and El-Baz, and 1:50,000, by Howard).

14. Bond 1987, 300–304.

15. Robin Brett was preparing Shepard and Pete Conrad for the interview and remembered Shepard uttering this revealing quote.

16. Irwin 1973, 60–62.

17. This was said on the way between Spur crater and Dune crater during the second EVA. In the transcript I am using (N. G. Bailey and G. E. Ulrich, "Apollo 15 voice transcript pertaining to the geology of the landing site," USGS informal report, available as USGS-GD-74-029, National Technical Information Service, 1975), Irwin is quoted as saying, "That's really beautiful. Talk about organization!" followed by the quote I attribute in the text to Scott. I have been told that it was Scott who said it about Mount Hadley.

18. E. W. Wolfe and N. G. Bailey, "Lineaments of the Apennine Front—Apollo 15 landing site," *PLSC* 3 (1972):15–25.

19. Irwin 1973, 71–72.

20. Ibid., 73–74, 245–51. I know of no lasting heart problem for Scott.

21. Gordon A. Swann and the field geology team, in NASA Manned Spacecraft Center 1972a, sec. 5 (in the unfortunate absence of a USGS professional paper, this remains the most complete report of the mission by the geology team); Apollo Lunar Geology Investigation Team 1972.

22. The story of the drilling is told by Irwin (1973) and Lewis (1974, 221–22).

23. K. A. Howard, J. W. Head, and G. A. Swann, "Geology of Hadley Rille," *PLSC* 3 (1972):1–14.

24. Yes, I know that the story of Galileo dropping the two objects from the Leaning Tower has been debunked.

25. Compton 1989, 240.

26. Crozaz 1977.

27. Original sources for most facts and interpretations in A Profile of the Moon are referenced in Basaltic Volcanism Study Project (1981) and Wilhelms (1984, 1987).

28. P. D. Spudis, G. A. Swann, and R. Greeley, "The formation of Hadley Rille and implications for the geology of the Apollo 15 region," *PLPSC* 18 (1988):243–54.

29. The concept of the magma ocean arose in 1970. The term, coined by John Wood, first appeared in print in J. A. Wood, "Fragments of terra rock in the Apollo 12 soil samples and a structural model of the Moon," *Icarus* 16 (1972):494. I thank Ursula Marvin for tracking down this origin of the term.

30. M. N. Toksöz, F. Press, A. Dainty, K. Anderson, G. Latham, M. Ewing, J. Dorman, D. Lammlein, G. Sutton, and F. Duennebier, "Structure, composition, and properties of lunar crust," *PLSC* 3 (1972):2527–44.

CHAPTER 16. MYSTERIOUS DESCARTES (1972)

1. N. W. Hinners, in NASA Manned Spacecraft Center 1972b, sec. 1.

2. See chapter 3, sections on basins and special features, and chapter 4, Volcanophilia Lives On.

3. "ASAPR July 1963–July 1964" (November 1964), pt. A, 17–27; Milton 1968b.

4. Wilhelms and Trask 1965.

5. We never got around to defining the Descartes Formation formally, but the name is simpler than the long-winded "Material" one.

6. D. J. Milton, "ASAPR July 1963–July 1964" (November 1964), pt. A, 17–27; Milton 1968b; D. E. Wilhelms, "ASAPR July 1964–July 1965" (November 1965), pt. A, 13–28; USGS Map I-548 (LAC 59) (1968); Wilhelms 1970; Morris and Wilhelms 1967; K. A. Howard and H. Masursky, USGS Map I-566 (LAC 77) (1968); Wilhelms and McCauley 1971. These papers and maps interpreted the light plains either as marelike basalt brightened by longer exposure to cratering or as volcanic tuffs or lavas that were born bright because they are more silicic than basalt.

7. David Cummings, USGS Map I-706 (LAC 126) (1972).

8. I suppose the Fra Mauro site was called a mare because it lies on a low-lying peninsula surrounded by maria. Or possibly people thought the Imbrium "mare-basin" ejecta qualified it (and the Apennine Mountains) as mare. These mistakes are sometimes still made today. The confusion explains why I prefer the term *terra* to *highlands* or *uplands*. However, *highlands* and *Descartes Highlands* were the terms in common use during the Apollo era, and I use them here where appropriate.

9. Davy is probably a secondary-impact chain and not the surface expression of a deep-seated structure (V. R. Oberbeck and R. H. Morrison, "On the formation of the lunar herringbone pattern," *PLSC* 4 [1973]:107–23). It would therefore have been an ordinary site not worthy of a J mission.

10. Jack Green, "Copernicus as a lunar caldera," *JGR* 76 (1971):5719–31; Green, "Review of 'Planetary geology,' by N. M. Short," *Sky and Telescope* 51 (1976):417–20.

11. Farouk El-Baz, telephone conversation, May 1989. Petrone went to the Nevada Test Site with the Apollo 16 crew and took an active interest in all aspects of Apollo. I have never heard a bad word said about him.

12. I thank Bill Phinney of the Johnson Space Center for sending me copies of his training documents. Petrologist Phinney was hired by Gast in summer 1970, was in Gast's back room in the LRL for Apollo 14 and in Gast's back room in the science building (Building 31) for Apollos 15–17, and was deeply involved in the field training.

13. Robert Dietz is credited as the first to suggest the impact origin of Sudbury, in 1962 [R. S. Dietz, "Sudbury structure as an astrobleme," *Journal of Geology* 72 (1964): 412–34]. See B. M. French, in French and Short 1968, 383–412.

14. J. W. Head and A. F. Goetz, "Descartes region: Evidence for Copernican-age volcanism," *JGR* 77 (1972):1368–74.

15. Farouk El-Baz and S. A. Roosa, "Significant results from Apollo 14 lunar orbital photography," *PLSC* 3 (1972):63–83.

16. This opinion was repeated shortly before the mission by D. P. Elston, E. L. Boudette, J. P. Schaefer, W. R. Muehlberger, and J. R. Sevier, "Apollo 16 field trips," *Geotimes* 17, 3 (1972):27–30.

17. N. J. Trask and J. F. McCauley, "Differentiation and volcanism in the lunar highlands: Photogeologic evidence and Apollo 16 implications," *Earth and Planetary Science Letters* 14 (1972):201–6. Trask was serving as staff geologist for Astrogeology in Washington at this time, having replaced Arnold Brokaw in mid-1971. He held the position (though not Brokaw's high civil service rating) until 1973.

18. Noted during McCauley's review of this chapter and in conversations in San Francisco, December 1990.

19. See chapter 13, The Russians Fill the Gap. The entire April 1973 issue of *Geochimica et Cosmochimica Acta* (vol. 37, no. 4) was devoted to the Luna 20 samples. For ANT terminology see Martin Prinz, Eric Dowty, Klaus Keil, and T. E. Bunch (981–82); and G. J. Taylor, M. J. Drake, J. A. Wood, and U. B. Marvin (1088–89); and the later review by Prinz and Keil (1977).

20. Baker 1982, 430–36.

21. Technical information about site geology and samples is from Ulrich, Hodges, and Muehlberger 1981. This USGS professional paper is divided into sections by individual authors, as discussed later in the text. For example, the section about the central area including Stations 1, 2, and 10 is by Gerald G. Schaber (21–44).

22. The observations were made with the MIT Haystack Observatory radio telescope. In the absence of high-resolution photographs of North and South Ray craters, their depolarized 3.8-cm radar echoes were compared with those from a very blocky 512-m mare crater covered by a Lunar Orbiter 3 H frame. Theoretical massaging of the radar data suggested that South Ray was only marginally less blocky. See S. H. Zisk and H. J. Moore, "Calibration of radar data from Apollo 16 results," in NASA Manned Spacecraft Center 1972b, sec. 29X. Gordon Swann told me that the radar also failed to predict the nature of the Apollo 17 bright mantle correctly.

23. All Apollo sample numbers have five digits, followed by a comma and more numbers if the sample has been split. Earlier sample numbers begin with the mission number, except that 10 represents Apollo 11, and the subsequent three digits were chosen almost arbitrarily. Muehlberger's system begins the numbers with 6 for Apollo 16 or 7 for Apollo 17, followed by the station number.

24. A silver lining of the narrow track is increased measurement accuracy achieved by repeatedly overflying the same spot.

25. Apollo 16 photographed craters made by the crashed S-4B stage, Rangers 7 and 9, and the Apollo 14 S-4B and LM ascent stages. Ewen Whitaker and Henry Moore reported the identifications in NASA Manned Spacecraft Center 1972b, secs. 29I and 29J. *Orion* was not crashed into the Moon for a seismic experiment and continued to orbit the Moon.

26. NASA Manned Spacecraft Center 1972b, sec. 7; Apollo 16 Preliminary Examination Team 1973.

27. T. K. Mattingly, Farouk El-Baz, and R. A. Laidley, "Observations and impressions from lunar orbit," in NASA Manned Spacecraft Center 1972b, sec. 28.

28. Arthur Koestler, (1959). *The sleepwalkers.* New York: Macmillan. Koestler's subject is astronomy, and he includes histories of how such greats as Kepler, Tycho, Galileo, and Newton groped their way by error to great truths.

29. Mitroff 1974, 88.

30. Po-zen Wong, "The statistical physics of sedimentary rock," *Physics Today* 41, 12 (1988):24. The different approaches to science by different kinds of scientists are also discussed by Chapman 1982, 1–12.

31. Oberbeck 1975; V. R. Oberbeck and R. H. Morrison, "Candidate areas for *in situ* ancient lunar materials," *PLSC* 7 (1976):2983–3005; D. E. Wilhelms, "Secondary impact craters of lunar basins," *PLSC* 7 (1976):2883–2901; D. E. Wilhelms, V. R. Oberbeck, and H. R. Aggarwal, "Size-frequency distributions of primary and secondary lunar impact craters," *PLPSC* 9 (1978):3735–62; R. E. Eggleton, "Map of the impact geology of the Imbrium basin of the Moon," in Ulrich, Hodges, and Muehlberger 1981, pl. 12; Wilhelms 1984, 1987.

32. Moore, Hodges, and Scott 1974; C. A. Hodges, "Apollo 16 regional geologic setting," in Ulrich, Hodges, and Muehlberger 1981, 6–9; C. A. Hodges and W. R. Muehlberger, "A summary and critique of geologic hypotheses," in ibid., 215–30.

33. See chapter 14, Lunar Stratigraphy Divided.

34. O. B. James and F. Hörz, eds., *Workshop on Apollo 16*, Lunar and Planetary Institute Technical Report 81-01 (1981).

35. J. W. Head, "Stratigraphy of the Descartes region (Apollo 16): Implications for the origin of samples," *The Moon* 11 (1974):77–99. Details of my refutation are given in James and Hörz, *Workshop on Apollo 16*, and Wilhelms 1987, 219–22. In previous papers about the region I ignored "unnamed A" and "B" in the hope they would go away unassisted.

36. Paul Spudis told me that petrologists attacked the Apollo 16 rocks in detail after they had seen the Apollo 17 rocks. A model of impact melts had led them to think each melt was homogenized, so each composition had to be created by a different impact. However, unnamed A and B do not explain the melts because the different compositions cannot be made of the local substrate.

37. O. B. James, "Petrologic and age relations of the Apollo 16 rocks: Implications for subsurface geology and the age of the Nectaris Basin," *PLPSC* 12B (1981):209–33; P. D. Spudis, "Apollo 16 site geology and impact melts: Implications for the geologic history of the lunar highlands," *PLPSC* 15/*JGR* 89 (1984):C95–107 (*PLPSC* 13–17 were published as volumes of the *Journal of Geophysical Research*).

38. Stuart-Alexander and Wilhelms 1975; Wilhelms 1987.

39. Arvidson et al. 1975.

40. For example, Norman and Ryder 1979; Warren and Wasson 1980.

41. N. H. Hubbard, J. M. Rhodes, H. Wiesmann, C.-Y. Shih, and B. M. Bansal, "The chemical definition and interpretation of rock types returned from non-mare regions of the Moon," *PLSC* 5 (1974):1227–46.

42. Y. Nakamura, D. Lammlein, G. Latham, M. Ewing, J. Dorman, F. Press, and N. Toksöz, "New seismic data on the state of the deep lunar interior," *Science* 181 (1973): 49–51. The meteorite hit at 30° N, 147° E, near Mare Moscoviense.

43. Basaltic Volcanism Study Project 1981, 671.

44. Howard, Wilhelms, and Scott 1974; Wilhelms 1984, 1987.

CHAPTER 17. BEAUTIFUL TAURUS-LITTROW (1972)

1. Compton 1989, 95–96.
2. Newell 1980, 210; Compton 1989, 219–21, 242–44.

3. Compton 1989, 219–21, 242–44.

4. Telephone conversation with Jack Schmitt, April 1990.

5. N. W. Hinners, "Apollo 17 site selection," in NASA Johnson Space Center 1973, sec. 1; Compton 1989, 247–49.

6. For Apollo 17, Silver served on the Science Working Panel, the Traverse Planning Team, both the EVA and planning subteams of the geology team during the mission, and the Lunar Sample Analysis Planning Team.

7. See chapter 16. Marius Hills might satisfy the young-mare objective but it would not yield any terra material. Also, Marius was barely accessible by the winter launch planned for Apollo 17 (it would have been marginally accessible to Apollo 16). Apollo 16 photographs would not be available in time to plan a mission to Davy. Tycho was too rough and too far south. Copernicus was already tentatively dated and in an already sampled region.

8. Telephone conversation with Jack Schmitt, April 1990.

9. NASA Manned Spacecraft Center 1972a, secs. 25H–25K. The attraction of Proclus was that it was fresh and therefore would furnish relatively fresh rock samples from a point whose horizontal (not vertical) position was clear.

10. NASA Manned Spacecraft Center 1972a, secs. 25A, 25I; Farouk El-Baz, A. M. Worden, and V. D. Brand, "Astronaut observations from lunar orbit and their geologic significance," *PLSC* 3 (1972):85–104; T. R. McGetchin and J. W. Head, "Lunar cinder cones," *Science* 180 (1973):68–71.

11. See appendix 2; G. Simmons, *On the Moon with Apollo* 17, NASA EP-101 (1972). The latter completes this excellent series of authoritative premission guidebooks.

12. Except where otherwise noted, information in this chapter on geophysical experiments is from NASA Johnson Space Center 1973.

13. Not to be confused with astronaut Dave Scott; see chapter 7, Meanwhile, Back at the Office. Scott, Carr, and Lucchitta 1972 (2 sheets); D. H. Scott and H. A. Pohn, USGS Map I-799 (LAC 43) (1972).

14. "ASAPR July 1965–July 1966" (November 1966), pt. A, 11–16; Carr 1966.

15. Ronald Greeley and D. E. Gault, "Crater frequency age determinations for the proposed Apollo 17 landing site at Taurus-Littrow," *Earth and Planetary Science Letters* 18 (1973):102–8.

16. Cappellari 1972.

17. Levine 1982, 133–37.

18. Baker 1982. Skylab 1 was an unmanned orbital emplacement of the lab itself by the last launch of a Saturn 5 on 14 May 1973, followed in May, July, and November 1973 by launches of three-man crews by Saturn 1Bs. The USA-USSR joint Apollo-Soyuz mission was finally agreed to in May 1972 and flew in July 1975. Its purpose was to foster cooperation between the two superpowers and, from the U.S. side, to maintain the manned-mission support teams between flights of Skylab in 1973 and the shuttle (planned for 1978). It used a modified CSM that had been built, but was "not needed," for Apollo.

19. The STG report is discussed in chapter 13.

20. Newell 1980, 286–90, 389–92; J. M. Logsdon, "The Space Shuttle program: A policy failure?" *Science* 232 (1986):1099–1105; Trento 1987; Burrows 1990, 230–254.

21. Mariner 9 was launched on 30 May 1971, began returning images blurred by a dust storm in November, and obtained clear images of almost all of Mars between January and October 1972. Pioneer 10, bearing a plaque with a message for somebody or something out there, was launched 2 March 1972 and reached the orbit of Mars on 25 May 1972 on its way to reconnoiter Jupiter, Saturn, and interstellar space.

22. See chapter 8, The Bigger Picture. Lopoliths are discussed in chapter 3, Maria.

23. Scott and Trask 1971.

24. Compton 1989, 191–93.

25. Cappellari 1972, 1031–34; Compton 1989, 249.

26. Apollo 17 landed at 1955 GMT on 11 December 1972, four days, 14 hours, and 22 minutes after launch.

27. See chapter 3, The Surficial Material.

28. Nicholas Steno (Nils Steensen; 1631–1687). His laws held that each new deposit (1) was deposited on older deposits and remains above them unless subsequently disturbed (law of superposition), (2) was deposited approximately horizontally and parallel to the underlying surface (law of original horizontality), and (3) spread out laterally until it pinched out or was blocked (law of original continuity). See James Gilluly, A. C. Waters, and A. O. Woodford, *Principles of geology* (San Francisco: Freeman, 1951). Hal Masursky was among those who worked in the field with Gilluly, a USGS stalwart for decades. Aaron Waters was an early member of the Apollo field geology team. Woodford, who celebrated his 100th birthday in February 1990 and died in June 1990, was one of my geology professors at Pomona College.

29. Burnett and Woolum 1975; R. J. Drozd, C. M. Hohenberg, C. J. Morgan, F. A. Podosek, and M. L. Wroge, "Cosmic-ray exposure at Taurus-Littrow," *PLPSC* 8 (1977):3027–43.

30. Silver and Schultz 1982; Chapman and Morrison 1989.

31. See chapter 9 for Baldwin's and other early references. In NASA Johnson Space Center 1973, sec. 31C, Howard and Muehlberger champion the thrusting idea. By means of laboratory modeling, Baerbel Lucchitta added the counterintuitive interpretation that vertical downdrop caused the surface thrusting (*PLSC* 7 [1976]:2761–82). Her model makes sense to me (Wilhelms 1987, 112).

32. Richard Brautigan's book is *Trout Fishing in America,* and the character's full name is Trout Fishing in America Shorty.

33. *San Francisco Chronicle,* 14 December 1972.

34. Heiken 1975.

35. Lucchitta, in Scott, Lucchitta, and Carr 1972. Shorty is described but not named on the maps.

36. E. D. Jackson, R. L. Sutton, and H. G. Wilshire, "Structure and petrology of a

cumulus norite boulder sampled by Apollo 17 in Taurus-Littrow Valley," *Bulletin of the Geological Society of America* 86 (1975):433–42.

37. Ages of pristine and Serenitatis melt rocks in the rest of this chapter are as compiled by Wilhelms (1987, 156, 177) from other sources.

38. For example, James 1980; Warren and Wasson 1980. Hard-core lunar petrologists no longer use the acronym ANT (anorthosite-norite-troctolite) because it is an amalgam of two suites, (ferroan) anorthosite and magnesian.

39. My source for Cernan's actual words is Cunningham 1977, 241.

40. M. Cooper, Kovach, and Watkins 1974.

41. Postmission sample summaries: Apollo 17 Preliminary Examination Team 1973b; NASA Johnson Space Center 1973, sec. 7; A. E. Bence, ed., "Apollo 17 results," *Eos* 54 (1973):580–622.

42. Apollo Field Geology Investigation Team 1973b; NASA Johnson Space Center 1973; H. H. Schmitt, "Apollo 17 report on the valley of Taurus-Littrow," *Science* 182 (1973):681–90.

43. E. W. Wolfe et al. 1981. Shorter and earlier reports are: W. R. Muehlberger and E. W. Wolfe, "The challenge of Apollo 17," *American Scientist* 61 (1973):660–69; E. W. Wolfe, B. K. Lucchitta, V. S. Reed, G. E. Ulrich, and A. G. Sanchez, "Geology of the Taurus-Littrow valley floor," *PLSC* 6 (1975):2463–82.

44. C. H. Simonds, "Thermal regimes in impact melts and the petrology of the Apollo 17 Station 6 boulder," *PLSC* 6 (1975):641–72; J. A. Wood, "The nature and origin of boulder 1, station 2, Apollo 17," *The Moon* 14 (1975):505–17.

45. Fouad Tera, D. A. Papanastassiou, and G. J. Wasserburg, "Isotopic evidence for a terminal lunar cataclysm," *Earth and Planetary Science Letters* 22 (1974):1–21.

46. Graham Ryder, "Lunar samples, lunar accretion and the early bombardment of the Moon," *Eos* (6 March 1990):313. In his review of this chapter Clark Chapman reported that a discussion he led in Perth, Australia, in summer 1990 failed to resolve the matter of the impact melts and the cataclysm. Participants included Chapman, Hartmann, Ryder, Shoemaker, and Wetherill.

47. Geochronologic matters about mare basalts and the dark mantle are summarized in Basaltic Volcanism Study Project 1981. Earlier reviews of geochronology are in Wetherill 1971; Nyquist 1977; and Turner 1977.

48. K. A. Howard, M. H. Carr, and W. R. Muehlberger, "Basalt stratigraphy of southern Mare Serenitatis," in NASA Johnson Space Center 1973, sec. 29A. A group at AFCRL (see chapter 4, Maria and Dark Mantles), had seen the large marginal craters and interpreted the age relations correctly.

49. A group of former Caltech students, including John Adams, Tom McCord, Torrence Johnson, and their student, Carlé McGetchin Pieters, have continued to explore the relation between compositions of the samples returned from the Moon against the spectra they obtain telescopically in as many wavelengths as can get through Earth's atmosphere. Summaries include Head et al. 1978; Pieters 1978; Moore 1980; Basaltic Volcanism Study Project 1981, 447–56.

CHAPTER 18. DEBRIEFING (1973 – 1984)

1. Mailer 1970.

2. The reference to the dumpster is not a figure of speech. After Apollo 17, Fran Waranius, librarian of the Lunar and Planetary Institute (then LSI), happened to see JSC's large collection of Lunar Orbiter and Apollo photographs, maps, and mission documents being thrown out. She and visiting scientist Ron Greeley literally pulled them out of the dumpster, and they became the nucleus of the institute's collection in the data center known as McGetchin Hall.

3. Cunningham 1977, 62–63; Schirra 1988, 180. The two books word the quote slightly differently and the version given here is eclectic.

4. Masursky's letter was dated 10 September 1970, eight days after the cutoff. Miller's reply was dated 21 September. See Compton 1989, 203.

5. Lunar and Planetary Institute 1978. The Luna 24 samples are lower in titanium than those from other maria, are highly feldspathic, and are 3.3 aeons old.

6. Unless otherwise noted, references for the scientific facts stated in this chapter are given in earlier chapters or in my earlier lengthy syntheses of the Moon's geology (Wilhelms 1984, 1987). Hinners (1971), Marvin (1973b), El-Baz (1975), and J. A. Wood (1975) summarized Apollo science before and soon after the program ended. Book-length reviews have been written by Bevan French (1977), Ross Taylor (1975, 1982), Peter Cadogan (1981; lacks references), and John Guest and Ronald Greeley (1977). The Moon is included in more general books by Bill Hartmann (1972), Elbert King (1976), John Wood (1979), Billy Glass (1982), Nicholas Short (1975), and Bruce Murray, Mike Malin, and Ron Greeley (1981). The Moon chapter in *The New Solar System* was written by Bevan French for the first two editions and by Paul Spudis for the third (Beatty and Chaikin 1990). See also Jones (1984), part of the admirable British Open University effort in public education. A splendid recent addition to the lunar literature — too recent for incorporation into this book — has been compiled by Grant Heiken, David Vaniman, and Bevan French (1991).

7. The thin crust and greater heat inside basins lower the viscosity of the craters' substrate, allowing it to reach isostasy with its surroundings more quickly than can other craters (Solomon and Head 1980).

8. Pike 1976, 1980; the latter summarizes Dick's years-long work on crater morphometry, including criteria for the impact-volcanic distinction.

9. Howard and Wilshire 1975.

10. G. V. Latham, H. J. Dorman, P. Horvath, A. K. Ibrahim, J. Koyama, and Y. Nakamura, "Passive seismic experiment: A summary of current status," *PLPSC* 9 (1978):3609–13; Goins, Toksöz, and Dainty 1979; Basaltic Volcanism Study Project 1981.

11. Ryder and Spudis 1980.

12. Pieters 1978.

13. For example, L. L. Hood and C. R. Williams, "The lunar swirls: Distribution and possible origins," *PLPSC* 19 (1989):99–113. Hood authored many earlier papers on the

subject, including some with me as coauthor. The antipodal effects have been ascribed alternatively to a focusing of seismic waves and a concentration of secondary impacts. Reviews of lunar magnetism are in Dyal, Parkin, and Daily 1974 (orbital); Fuller 1974 (surface); Ness 1979; and Russell 1980.

14. Roddy, Pepin, and Merrill 1977. This book contains everything one could possibly want to know about cratering mechanics except a few recent concepts; a paper therein by H. F. Cooper, Jr., summarizes the subject as relevant to the planets (11–44). Other reviews include: Shoemaker 1962a; Baldwin 1963; D. E. Gault, W. L. Quaide, and V. R. Oberbeck, "Impact cratering mechanics and structure," in French and Short 1968, 87–99; D. E. Gault, "Impact craters," in Greeley and Schultz 1974, 137–75; Melosh 1980, 1989. I have also tried to summarize the subject from the Blue Bible and other sources (Wilhelms 1987).

15. R. B. Baldwin, "On the origin of the mare basins," *PLSC* 5 (1974):1–10; J. B. Murray, "Oscillating peak model of basin and crater formation," *The Moon and the Planets* 22 (1980):269–91.

16. French 1977, 267.

17. The Congressional Research Service of the Library of Congress estimates the cost of the Vietnam War as $570 billion in 1990 dollars. Any one of the later years of that war cost more than all of Apollo; see Andrew Chaikin, "Why haven't we gone back?" *Air and Space* (June–July 1989):90–97.

18. Bates, Lauderdale, and Kernaghan 1979.

19. Silver and Schultz 1982; Alvarez 1987, 251–67; Chapman and Morrison 1989.

20. Among other honors, Shoemaker received the GSA's Day Medal in 1982 (presented by Gordon Swann) and its first G. K. Gilbert Award in 1983 (presented by Lee Silver). He also presented Gilbert Awards to George Wetherill in 1984, Walter Alvarez in 1985, and me in 1988. Swann's characteristically humorous Day Medal citation and Shoemaker's reply are in *Bulletin of the Geological Society of America* 94 (1983):424–27. The Gilbert citations and replies also appear in the *Bulletin* in the year after they were given. In June 1992 President Bush personally presented Shoemaker with the National Medal of Science.

21. Royal Society of London 1977, 555–59; T. Gold, "Moon: The debate about the nature of the Moon's surface," in H. Messel, ed., *Highlights in Science* (Pergamon, 1987).

22. Jastrow (1981) heard both the original claim of deep dust and Gold's latter-day disavowal. I also heard about the disavowal from a Cornell University professor. A recent example of Gold's expensive nonconformity is described in R. A. Kerr, "When a radical experiment goes bust," *Science* 247 (1990):1177–79.

23. J. W. Hartung, "Was the formation of a 20-km-diameter impact crater on the Moon observed on June 18, 1178?" *Meteoritics* 11 (1976):187–94; H. H. Nininger and G. I. Huss, "Was the formation of lunar crater Giordano Bruno witnessed in 1178? Look again," *Meteoritics* 12 (1977):21–23.

24. By 1967 ACIC had completed the 44 LACs that cover the central near side where scientific attention was concentrated and lunar spaceflights would be targeted. AMS and ACIC merged as the Defense Mapping Agency (DMA) in 1972. Colonel Arthur Strickland

of AMS wanted DMA to take over the lunar and planetary mapping, but ACIC would not agree to make the Viking Mars mission their first priority (Hal Masursky, conversation in Flagstaff, 1987). Therefore, after much dickering, the mapping went to Ray Batson's USGS cartographic group in Flagstaff.

25. R. M. Batson, "Cartography," in Greeley and Batson 1990, 80–95.

26. O'Keefe 1976. King (1976) strongly rebuts the lunar origin of tektites.

27. Letter from Jack Green, September 1990. He underlined the word *major* in the letter because he agrees (as he always has) that many small lunar craters were created by impacts.

28. Wilhelms 1987. McCauley's two long sections were originally written for a professional paper on basins that he, Dave Roddy, Dave Scott, and I planned to write but gave up on. Trask's section originally appeared in Trask 1971 and was so well written and so current in its concepts that almost no editing was required to adapt it to my 1987 book.

29. See MacKinnon and Baldanza 1989; and Andrew Chaikin, *The men in the Moon* (forthcoming from Viking Press), for the present whereabouts of other astronauts. C. Murray and Cox (1989) do the same for NASA managers and engineers.

30. This or a similar quote is commonly attributed to Urey, and it matches his style, but I am not sure it originated with him. It became popular in various wordings among everyone contemplating the Moon's origin.

31. Brush (1982) and most of the books cited in note 6 except mine discuss pre-Kona meditations about lunar origin. I believe that Bevan French (1977) originated the daughter-sister-spouse analogy, though with "girlfriend" instead of "spouse."

32. Hartmann, Phillips, and Taylor 1986; A. P. Boss, "The origin of the Moon," *Science* 231 (1986):341–45; S. R. Taylor, "The origin of the Moon," *American Scientist* (September–October 1984):469–77; S. G. Brush, "A history of modern selenogony: Theoretical origins of the Moon, from capture to crash 1955–1984," *Space Science Reviews* 47 (1988):211–73; H. E. Newsom and S. R. Taylor, "Geochemical implications of the formation of the Moon by a single giant impact," *Nature* 338 (1989):29–34.

33. W. K. Hartmann and D. R. Davis, "Satellite-sized planetesimals and lunar origin," *Icarus* 24 (1975):504–15; A. G. W. Cameron and W. Ward, "On the origin of the Moon," *Lunar Science VII* (abstracts of Seventh Lunar Science Conference, 1976), 120–22 (Houston: Lunar and Planetary Institute, 1976).

34. Daly 1946. See chapter 1, Interlude; Ralph B. Baldwin and Don E. Wilhelms, "Historical review of a long-overlooked paper by R.A. Daly concerning the origin and early history of the Moon," *JGR* 97 (1992):3837–43. Differing from current concepts are Daly's suggestions that the planetoid was not completely disrupted and that the lunar craters were created by the impact of Earth fragments remaining from the collision.

35. H. H. Schmitt, "Evolution of the Moon: The 1974 model," in Pomeroy and Hubbard 1977, pt. 1, 63–80. The conference was held in Moscow in June 1974.

36. Papike et al. 1982.

37. Mendell 1985; Wilhelms 1987, 280–81; Graham Ryder, P. D. Spudis, and G. J. Taylor, "The case for planetary sample return missions," *Eos* 70 (1989):1495–1509.

38. More than 13% of the returned samples have been released from the curator's custody since they arrived in Houston. This includes the 7% (by weight) that have gone out for analysis and returned, 2.6% allocated for museums or other educational displays, almost 2% consumed in destructive tests or sample preparation, and the approximately 2% now being studied in laboratories around the world. I thank John Dietrich for correcting and updating this paragraph.