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CHEMIE der ERDE GEOCHEMISTRY

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INVITED REVIEW

The Moon 35 years after Apollo: What's left to learn?

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Received 11 December 2007; accepted 29 July 2008

Abstract

With the cancellation of the Apollo program after Apollo 17 returned from the Moon in 1972, the focus of NASA switched to other areas of the Solar System. Study of the Moon did continue through analysis of the returned samples and remotely sensed data sets (both orbital and surface), as well as through Earth-based telescopic studies. In the 1990s, new orbital data were obtained from several missions (fly-by and orbital), the first being Galileo that allowed the lunar farside to be mapped, followed by global mapping by the Clementine and Lunar Prospector missions.

Interest in the Moon started to increase at the beginning of the 21st century as other nations focused their space exploration programs on the Moon. The speech by President Bush in January 2004 put the Moon back into the critical exploration path for NASA, paving the way for humans to return to the lunar surface by 2020. This return will be critical for developing technologies and protocols for the eventual human exploration of other parts of the solar system. At the time of writing (June 2008), the SELENE/Kaguya mission (Japan and Chang'e-1 (China) are orbiting the Moon, with Chandrayaan-1 (India) and Lunar Reconnaissance Orbiter (USA) being scheduled to launch later in 2008.

The past (and present) exploration of the Moon begs the question "what's left to be done?" With the renewed focus on the Moon, now that it is on the pathway for the exploration of Mars (and beyond) a similar question has been raised – what should the astronauts do on the Moon? The publication of the *New Views of the Moon* book [Jolliff et al., 2006. New Views of the Moon, Reviews in Mineralogy, vol. 60. American Mineralogical Society, 721pp] highlighted a number of important scientific questions that remain unanswered as well as posing many more on the basis of the currently available data. These questions resonated in three Lunar Exploration Analysis Group (LEAG) reports pertinent to this discussion, which were also published (on line) during 2006 (http://www.lpi.usra.edu/leag), and in the National Research Council of the National Academies [2007. The Scientific Context for Exploration of the Moon. National Academies Press, Washington, DC, 112pp] report entitled "The Scientific Context for Exploration of the Moon". This paper synthesizes these recent studies, along with those from the 1980s and 1990s, to emphasize the lunar science questions that remain unanswered. In addition, it summarizes the missions already flown to the Moon along with those that are planned in order to give the reader an idea of exactly what lunar science has been and will be conducted in the hope that it will inspire proposals for missions to address the outstanding science questions.

Keywords: Lunar; Exploration; Moon; Mission; In situ resource utilization; Science; Remote sensing; Sample return; Impact; Lunar magma ocean

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0009-2819/$ - see front matter © 2008 Elsevier GmbH. All rights reserved.
doi:10.1016/j.chemer.2008.07.002

Please cite this article as: Neal, C.R., The Moon 35 years after Apollo: What's left to learn? Chemie Erde-Geochemistry (2008), doi:10.1016/j.chemer.2008.07.002

1. Introduction

The study of the Moon has produced amazing insights not only about Earth's only natural satellite, but also into planetary and solar system evolution. The *New Views of the Moon* (Jolliff et al., 2006) synthesized the data collected and models produced from it, covering the period up to and including Lunar Prospector in 1998. The combination of orbital remote sensing data with geophysics measurements (both from orbit and the lunar surface) and sample return data has demonstrated clearly that an integrated approach to exploration yields the most information regarding origin and evolution of any solid planetary body. The geophysics experiments deployed at the Apollo sites gave a first glimpse into the lunar interior and allowed mantle models inferred from mare basalt compositions to be tested, albeit at a rudimentary level. Lunar exploration has clearly shown that planetary evolution via a magma ocean is a tenable hypothesis (e.g., Smith et al., 1970; Wood et al., 1970; Warren, 1985) and that the unique nature of the Earth's Moon, relative to the moons of other planets in the solar system, is consistent with an unusual origin, such as the Earth colliding with a Mars-sized planetesimal and the Moon forming from the debris thus created (Benz et al., 1989; Cameron and Benz, 1991; Cameron, 1997, 2000; Canup and Asphaug, 2001; Canup et al., 2001, 2002). In addition, the combination of returned samples and remote observations has allowed the cratering rate through time to be explored and has put absolute ages on some of the larger impact events on the Moon and gives a few fixed points to which the cratering rate can be used to date the surfaces of the planets in the inner solar system. This has allowed identification of much younger lunar basalts (~0.9–1.2 Ga) around the Aristarchus Plateau and Marius Hills (Schultz and Spudis, 1983; Hiesinger et al., 2003) than are represented in the existing sample collection (~3.1–4.25 Ga; Dasch et al., 1987; Nyquist and Shih, 1992). The recognition of lunar meteorites (Bogard and Johnson, 1983) has increased the diversity of samples from the Moon, including the identification of the youngest mare basalt in the sample collection (Borg et al., 2004).

The data sets that have been used in the studies outlined above, as well as many others, were collected by a variety of missions to the Moon over several decades, and have benefitted from continued analysis of returned and meteoritic samples. Integrating these diverse data sets has been a challenge, but it has produced a fundamental leap forward in our knowledge of the Moon. So what is left to be done? In order to address this question, we need to understand how we got to this point in our understanding of the Moon.

This paper gives a broad outline of what we have learned from past exploration of the Moon and from this, a non-exhaustive list is developed of science questions that still remain. In addition, a description of the objectives and instrumentation on lunar missions that are currently at the Moon or those that are scheduled for launch in the near future is given, and finally a description of missions that are currently being planned (pre-phase A) is also given.

2. Previous investigations of the Moon: a timeline

2.1. Missions to the Moon

The exploration of the Earth's Moon actually began in earnest with the invention of the telescope in the early 17th century to dispel some of the myths initiated by the philosophy of Aristotle (384–322 BCE) that postulated that the Moon belonged to the "realm of corruption". Englishman Thomas Harriott is credited with the first telescopic observations in August of 1609 (Shirley, 1974). This preceded Galileo's lunar study by several months (Galileo, 1610, translated and annotated by van Helden, 1989). Many hypotheses put forth regarding the Moon (it harbored life, contained oceans, bright areas were rhyolitic in composition) were still being debated at the turn of the 20th century and some up to the Apollo program. It was only by visiting the Moon, making observations on the lunar surface, and returning samples for detailed (and still ongoing) analyses, that our understanding of Earth's celestial neighbor took a giant leap forward.

Unmanned missions to the Moon began in 1959 with the Soviet Luna-1 fly-by mission that arrived at the Moon on 3 January 1959 (Table 1). Luna 1 passed within 5995 km of the lunar surface and discovered that the Moon had no global magnetic field. This was followed closely by the American Pioneer 4 fly-by mission that arrived at the Moon on 4 March 1959 (Table 1). The capsule contained a lunar radiation experiment but was too high above the lunar surface (~60,000 km) for the experiment to register any radiation from the Moon. Between the time of Pioneer 4 and the beginning of Apollo (Apollo 8, launched on 21 December 1968), a total of 37 missions were launched to the Moon: 16 from the Soviet Union (Luna 2–14; Zond 3, 5, and 6) and 21 from the USA (Ranger 1–9; Surveyor 1–7; Lunar Orbiter 1–5; see Table 1).

Six Apollo spacecraft + astronauts landed on the Moon between 1969 and 1972, each returning lunar samples to Earth (Apollo 11, 12, 14, 15, 16, 17; Tables 1 and 2; Fig. 1). Between 1970 and 1976, three robotic Luna spacecraft landed and also returned lunar samples (Luna 16, 20, 24; Tables 1 and 2; Fig. 1). In addition to these returned samples, meteorites from the Moon have

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Table 1. History of Moon missions

Year	Launch date	Name	Mission	Nationality
1959	2 January	Luna 1	Flyby	USSR
1959	3 March	Pioneer 4	Flyby	USA
1959	12 September	Luna 2	Designed impact	USSR
1959	4 October	Luna 3	Photographed farside	USSR
1961	23 August	Ranger 1	Attempted test flight	USA
	18 November	Ranger 2	Attempted test flight	USA
1962	26 January	Ranger 3	Attempted impact	USA
	23 April	Ranger 4	Designed impact	USA
	18 October	Ranger 5	Attempted impact	USA
1963	2 April	Luna 4	Fell back to Earth	USSR
1964	30 January	Ranger 6	Designed impact (Mare Tranquilitatis)	USA
	28 July	Ranger 7	Designed impact (Mare Nubium)	USA
1965	17 February	Ranger 8	Designed impact (Mare Tranquilitatis)	USA
	21 March	Ranger 9	Designed impact (Crater Alphonsus)	USA
	9 May	Luna 5	Soft lander-crashed	USSR
	8 June	Luna 6	Soft lander-missed moon	USSR
	18 July	Zond 3	Flyby	USSR
	4 October	Luna 7	Soft lander-crashed	USSR
	3 December	Luna 8	Soft lander-crashed	USSR
1966	31 January	Luna 9	Soft lander (Oceanus Procellarum)	USSR
	31 March	Luna 10	Orbiter	USSR
	30 May	Surveyor 1	Soft lander (Oceanus Procellarum)	USA
	10 August	Lunar Orbiter 1	Orbiter	USA
	24 August	Luna 11	Orbiter	USSR
	20 September	Surveyor 2	Soft lander-crashed	USA
	22 October	Luna 12	Orbiter	USSR
	6 November	Luna Orbiter 2	Orbiter	USA
	21 December	Luna 13	Soft lander (Oceanus Procellarum)	USSR
1967	4 February	Luna Orbiter 3	Orbiter	USA
	17 April	Surveyor 3	Soft lander (Oceanus Procellarum)	USA
	8 May	Lunar Orbiter 4	Orbiter	USA
	14 July	Surveyor 4	Soft lander-crashed	USA
	1 August	Lunar Orbiter 5	Orbiter	USA
	8 September	Surveyor 5	Soft lander (Mare Tranquilitatis)	USA
	7 November	Surveyor 6	Soft lander (Sinus Medii)	USA
1968	7 January	Surveyor 7	Soft lander (N. rim of Tycho)	USA
	7 April	Luna 14	Orbiter	USSR
	15 September	Zond 5	Return probe (biology experiments)	USSR
	10 November	Zond 6	Return probe (crashed)	USSR
	21 December	Apollo 8	Crewed orbiter	USA
1969	18 May	Apollo 10	Crewed orbiter	USA
	13 July	Luna 15	Sample return probe (crashed)	USSR
	16 July	Apollo 11	Crewed landing[a]	USA
	7 August	Zond 7	Return probe	USSR
	14 November	Apollo 12	Crewed landing[a]	USA
1970	11 April	Apollo 13	Aborted crewed landing	USA
	12 September	Luna 16	Sample return probe[a]	USSR
	20 October	Zond 8	Return probe	USSR
	10 November	Luna 17	Landed rover (Mare Imbrium)	USSR

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Table 1. (*continued*)

Year	Launch date	Name	Mission	Nationality
1971	31 January	Apollo 14	Crewed landing[a]	USA
	26 July	Apollo 15	Crewed landing[a]	USA
	2 September	Luna 18	Sample return probe (Crashed)	USSR
	28 September	Luna 19	Orbiter	USSR
1972	14 February	Luna 20	Sample return probe[a]	USSR
	16 April	Apollo 16	Crewed landing[a]	USA
	7 December	Apollo 17	Crewed landing[a]	USA
1973	8 January	Luna 21	Landed rover (Mare Serenitatis)	USSR
1974	2 June	Luna 22	Orbiter	USSR
	28 October	Luna 23	Sample return probe (failed)	USSR
1976	14 August	Luna 24	Sample return probe[a] (Mare Crisium)	USSR
1989	18 October	Galileo	Flyby (1990, 1992)	USA
1990	24 January	Hiten	Flyby and orbiter	Japan
1994	25 January	Clementine	Orbiter	USA
1997	24 December	AsiaSat/HGS-1	Flyby	China/USA
1998	7 January	Lunar Prospector	Orbiter	USA
2003	9 May	Hayabusa/MUSES-C	Flyby	Japan
2003	27 September	SMART-1	Orbiter	ESA
2007	14 September	SELENE	Orbiter	Japan
	24 October	Chang'e 1	Orbiter	China
2008	22 October	Chandrayaan-1	Orbiter	India
2009	April	Lunar Reconnaissance Orbiter	Orbiter	USA

Adapted from http://nssdc.gsfc.nasa.gov/planetary/lunar/lunartimeline.html.

[a] Indicates lunar samples were returned to Earth.

Table 2. Sample masses returned from the Moon

Mission name	Location	Mass returned (kg)	Date returned
Apollo 11	Mare Tranquilitatis	21.6	24 July 1969
Apollo 12	Oceanus Procellarum	34.3	24 November 1969
Luna 16	Mare Fecunditatis	0.10	24 September 1970
Apollo 14	Fra Mauro (Mare Imbrium)	42.3	9 February 1971
Apollo 15	Hadley Rille/Appenine Mts	77.3	7 August 1971
Luna 20	Apollonius Highlands	0.03	25 February 1972
Apollo 16	Descartes Highlands	95.7	27 April 1972
Apollo 17	Taurus-Littrow/Mare Serenitatis	110.5	19 December 1972
Luna 24	Mare Crisium	0.17	22 August 1976

been recognized on the basis of mineralogic, isotopic, and chemical compositions compared with returned samples. While the originating locations of these meteorites on the Moon cannot be pin-pointed precisely, these samples extend the measured diversity of lunar samples. As of the summer of 2008, 59 meteorites have been recognized as being from the Moon (see http://meteorites.wustl.edu/lunar/moon_meteorites.htm or http://curator.jsc.nasa.gov/antmet/lmc/index.cfm). The lunar meteorites have added important milestones to our understanding of the Moon. For example, Borg et al. (2004) reported the age of KREEP-rich mare

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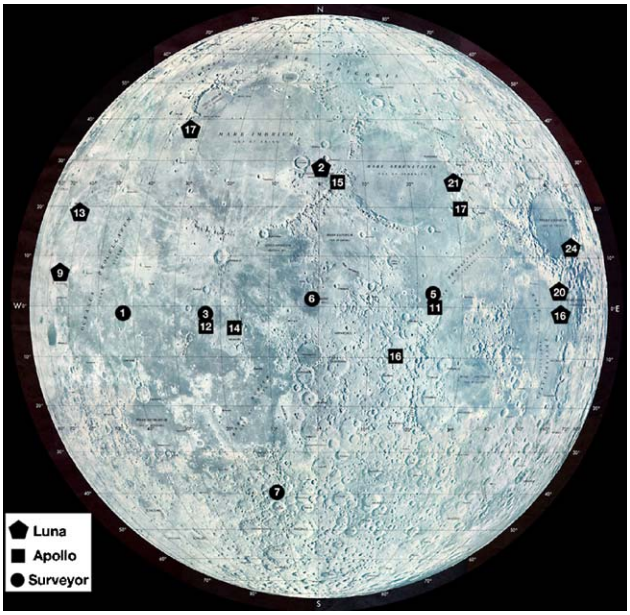

Fig. 1. Map of the lunar nearside showing the locations of the landed elements during the Soviet and USA space race of the 1960s and 1970s. See Table 1 for more details.

basalt NWA-773 as being 2.865±0.031 Ga, which represented the youngest age of any basalt thus far dated from the Moon. In addition, the Mg-Suite is poorly represented in fragmental feldspathic (highlands) meteorites, suggesting that the Apollo missions sampled an apparently anomalous (unrepresentative) portion of the lunar highlands and the broader lunar highlands is KREEP-poor and ferroan in composition (e.g., Korotev, 2005).

The USSR landed two robotic Lunokhod rovers (Luna 17 and 21 – Table 1). Lunokhod-1 (Luna 17 – Mare Imbrium) was a solar-powered rover that operated for 11 Earth days (but did not survive the lunar night), traveled 10,540 m, transmitted >20,000 TV pictures and >200 panoramas, and conducted >500 soil tests. Lunokhod-2 (Luna 21 – Mare Serenitatis) was also solar-powered, but with a polonium-210 radioisotope heater to help it survive the lunar night. The mission objectives were to collect images of the lunar surface (including ambient light levels to assist astronomical observations from Earth), measure local magnetic fields, observe solar X-rays, perform laser ranging experiments, and study mechanical properties of the lunar surface material. Lunokhod-2 operated for 4 months, traveling over 37 km, sending back >80,000 TV pictures and 68 panoramas (for comparison, the Mars Exploration Rovers, Spirit and Opportunity, have been operating for 4 years and have traveled a little over 7.5 km and almost 12 km, respectively). The primary objectives of the mission were similar to Lunokhod-1, namely to collect images of the lunar surface, examine ambient light levels to determine the feasibility of astronomical observations from the Moon, perform laser ranging experiments from Earth (the retroreflector is still in use), observe solar X-rays, measure local magnetic fields, and study mechanical properties of the lunar surface material.

Since 1976, there have been missions that have flown by, orbited, or impacted the Moon: Galileo, Hiten, Clementine, AsiaSat/HGS-1, Lunar Prospector, Hayabusa-MUSES-C, and SMART-1 (Table 3). Clementine and Lunar Prospector produced the most comprehensive lunar data sets highlights of which include:

- The first data to support the presence of H deposits at the lunar poles (Nozette et al., 1996; Feldman et al., 1998).
- Refinement of the lunar gravity field based on the pre-existing model of Bills and Ferrari (1977) from Lunar Orbiter and Apollo 15 and 16 subsatellites (Zuber et al., 1994; Lemoine et al., 1997) and evidence for three new large "mascons" (mass concentrations) on the nearside of the Moon as well as partially resolving four mascons on the farside (Konopliv et al., 1998, 2001).
- The most comprehensive lunar surface compositional maps to date (e.g., Lucey et al., 1995, 1998, 2000; Elphic et al., 1998, 2002; Lawrence et al., 1998; Gillis et al., 2003, 2004; Feldman et al., 2004; Prettyman et al., 2006).
- The first lunar topographic map (e.g., Spudis et al., 1994).
- Compositional data on the central peaks of impact craters and possible exposed upper mantle at South Pole-Aitken basin (e.g., Pieters et al., 1997; Pieters and Tompkins, 1999; Tompkins and Pieters, 1999).
- Identification of a thorium-rich "hotspot" on the lunar nearside centered on Mare Imbrium (Lawrence et al., 1998, 2003, 2004, 2005; Haskin 1998; Haskin et al., 2000), which was hinted at by the Apollo gamma-ray spectrometer data (e.g., Metzger et al., 1977; Haines et al., 1978; Hawke et al., 1981).
- Evidence for induced crustal magnetism at the antipodes of major impact basins (Lin et al., 1998; Halekas et al., 2003) as well as compositional evidence for antipodal ejecta deposits (e.g., Haskin et al., 2000).
- The presence of a small iron-rich core with a radius of 340±90 km (Hood et al., 1999).
- The data from the Clementine and Lunar Prospector missions also led to the definition of different terranes on the lunar surface by Jolliff et al. (2000), which included the Procellarum-KREEP Terrane, the Feldspathic Highlands Terrane, and the South Pole-Aitken Terrane.

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Table 3. Lunar missions since Apollo and Luna

Name	Launch date	Primary objective	Secondary objective	Instrumentation	References
Galileo – NASA	18 October 1989	Jupiter and its satellites.	Earth's Moon (esp. the polar regions and farside).	Multispectral imaging using a Solid State Imaging (SSI) camera; field of view of 0.46°; three broad-band filters: violet (404 nm), green (559 nm), and red (671 nm); four near-infrared filters: 727, 756, 889, and 986 nm; and one clear filter (611 nm) with a very broad (440 nm) passband.	Belton et al. (1992, 1994), Greeley et al. (1991, 1993), Head et al. (1991, 1993), McEwan et al. (1993), Pieters et al. (1993).
Hiten (Muses-A) – JAXA	24 January 1990	Technology demonstration. Conduct optical navigation experiments on a spin-stabilized spacecraft; test trajectory control utilizing gravity assist double lunar swingbys; test fault tolerances of onboard computer and packet telemetry; conduct cis-lunar aero-braking experiments; hard landing on the lunar surface.	Subsatellite "Hagaromo" for orbital insertion; detect and measure mass and velocity of micrometeorite particles; examine excursions to the L4 and L5 Lagrangian points of the Earth–Moon system.		Uesugi et al. (1988, 1989, 1991), Uesugi, (1993, 1996)
Clemetine – NASA/Strategic Defense Initiative	25 January 1994	Test lightweight miniature sensors and advanced spacecraft components by exposing them to the harsh space environment. Make observations of NEO 1620 Geographos.	Produce compositional maps of the Moon.	UV/Visible camera (415, 750, 900, 950, and 1000 nm). Near-IR Camera (1100, 1250, 1500, 2000, 2600, and 2780 nm). Long-Wavelength IR Camera (8000–9500 nm). Hi-Res. Camera (415, 560, 650, and 750 nm). Star Tracker Camera. Laser Altimeter (LIDAR). Bistatic Radar Experiment. Gravity Experiment. Charged Particle Telescope.	Nozette et al. (1994, 1996), Spudis et al. (1994), Lucey et al. (1995, 1998, 2000), Zuber et al. (1994), Lemoine et al. (1997).

AsiaSat-3/HGS-1 – Peoples Republic of China	24 December 1997	Television distribution and telecommunications services throughout Asia, the Middle East, and Australia.	Accidental – first successful lunar flyby of a commercial satellite.		No lunar data sets produced.
Lunar Prospector – NASA	7 January 1998	Map surface composition and possible polar hydrogen deposits, measure magnetic and gravity fields, study lunar outgassing events		Gamma-ray spectrometer Neutron spectrometer Magnetometer Electron reflectometer Alpha particle spectrometer Doppler gravity experiment.	Binder (1998), Lawrence et al. (1998, 2003, 2004, 2005), Feldman et al. (1998, 2004), Haskin (1998), Hood et al. (1999), Haskin et al. (2000), Lin et al. (1998), Halekas et al. (2003), Konopliv et al. (1998, 2001), Elphic et al. (1998, 2002), Gillis et al. (2003, 2004), Prettyman et al. (2006).
Hayabusa (MUSES-C) – JAXA	9 May 2003	Asteroid sample return mission.	Lunar farside observations to test instruments.	Multiband imaging camera Laser Altimeter (LIDAR) Near-IR spectrometer X-ray spectrometer	Fujiwara et al. (2000), Mukai et al. (2002, 2006), Okada et al. (2000, 2002a, 2005), Yano et al. (2003).
SMART-1 – ESA	27 September 2003	Technology demonstration: solar powered ion drive.	Image the lunar surface.	Advanced Moon micro-imager experiment (AMIE) Demonstration of a compact imaging X-ray spectrometer (D-CIXS) X-ray solar monitor (XSM) IR Spectrometer Electric propulsion diagnostic package (EPDP) Spacecraft potential, electron and dust experiment (SPEDE) Experimental telecommunication and tracking system, the Kα/X-band TTC (Telemetry and Telecommand) experiment (KaTE) On-Board Autonomous Navigation (OBAN) system.	Foing et al. (1999, 2003, 2005, 2006, 2007a, b, 2008), Marini et al. (2002), Racca et al. (2002), Muinonen et al. (2002), Josset et al. (2006, 2007), Kellet et al. (2006), Grande et al. (2002, 2007), Huovelin et al. (2002), Tajmar et al. (2002), Rathsman et al. (2005), DiCara and Estublier (2005), Ehrenfreund et al. (2007), Veillet and Foing (2007), Volvach et al. (2007), Grieger et al. (2008).

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2.2. Telescopic observations

Remote sensing data of the Moon have also been collected from Earth using a variety of telescopes (e.g., Hawke and Bell, 1981; Hawke et al., 2003; Campbell et al., 2005, 2006, 2007; Thompson and Campbell, 2005; Thompson et al., 2006). These new data have been highly important in helping to define "cryptomare" on the Moon, especially when coupled with orbital data. Cryptomare are areas of ancient mare deposits that have been buried by highlands ejecta and are now revealed by impact craters that have penetrated the covering ejecta blanket – these craters typically have dark haloes associated with them (e.g., Schultz and Spudis, 1979, 1983; Hawke and Spudis, 1980). Several examples of these cryptomare deposits were also revealed in the Galileo multispectral images of the Moon (e.g., Head et al., 1991, 1993; Greeley et al., 1991, 1993). Head and Wilson (1992) suggested that the number of candidate cryptomaria is such that the total area covered by mare deposits may now exceed 20% of the lunar surface area.

In addition to Earth-based telescopes, the Hubble Space Telescope was used in 2005 to examine the Moon for potential resources (Robinson et al., 2007). This was done because there has been little progress made in the accurate determination of surface TiO_2 abundances (associated with ilmenite distribution – a mineral important for in situ resource utilization, discussed below) in the visible through near-infrared wavelengths. Hubble was used to look at the ultraviolet to visible reflectances and noted a strong correlation at Apollo landing sites between Hubble-determined TiO_2 abundances and those defined by returned samples. Robinson et al. (2007) concluded that "accurate identification and quantification of TiO_2-rich deposits serves to guide future human exploration of the Moon". I will show in this paper, there is plenty of science left to do on the Moon, both in terms of basic and applied (exploration) science.

3. The importance of Apollo scientific results to future lunar exploration science

The six Apollo spacecraft that landed with astronauts on the Moon between 1969 and 1972, each returned to Earth lunar samples from known locations (Fig. 1; Tables 1 and 2). While two of the crew descended to the lunar surface the orbiting return vehicle made photographic, geophysical, and spectral observations and measurements of the Moon (see http://www.lpi.usra.edu/lunar/www.lpi.usra.edu/lunar/ for details, and Metzger et al., 1977; Haines et al., 1978; Andre et al., 1979; Andre and El-Baz, 1981; Hawke et al., 1981; Taylor, 1982). One of the most significant discoveries made through these observations and measurements was the detection that the lunar crust is thicker on the farside relative to the nearside (e.g., Bills and Ferrari, 1977; Haines and Metzger, 1980). Initial crustal thicknesses were estimated based on iron concentrations in the crust (directly related to density) and concluded that the farside crust was 86 ± 2 km and the nearside average crustal thickness was 64 ± 2 km. The nearside crustal thickness was confirmed by initial interpretations of the Apollo seismic data (e.g., Toksöz et al., 1972). Refinements of the Apollo seismic data have modified the initial thicknesses of the highlands crust. For example, estimates of crustal thickness around the Apollo 12 and 14 landing sites has been estimated as >55 km (Toksöz et al., 1974), 58 ± 8 km (Nakamura et al., 1982), 45 ± 5 km (Khan et al., 2000), 38 ± 3 km (Khan and Mosegaard, 2002), and 30 ± 2.5 km (Lognonne et al., 2003). Chenet et al. (2006) used a Markov chain Monte-Carlo algorithm, along with estimated travel times of seismic waves originating from multiple meteoroid impact locations, to invert for lateral variations of crustal thickness. The average nearside crustal thickness estimated was 34.25 km and the average farside thickness was 56.5 km. Wieczorek et al. (2006) presented single-layer and double-layer crustal thickness models. They concluded the nearside crustal thickness around the Apollo 12 and 14 landing sites was 45 km for the single-layer model and 26.9 km for the upper crust in the dual-layer model. The farside crust was estimated to be 16.7 and 23.2 km thicker, respectively, for each model. Basically, no matter how crustal thicknesses are calculated, the farside crust is always thicker than that of the nearside.

Another significant discovery using the Apollo orbital data was that the Moon's center of mass was offset from the center of figure by ~2.5 km (Kaula et al., 1972, 1974; Haines and Metzger, 1980). Wieczorek et al. (2006) revisited this using the global data sets available from post-Apollo missions and refined the offset to ~1.9 km. The offset has been explained as a result of crustal thickness variations (e.g., Kaula et al., 1972, 1974) or crustal density variations (nearside crust has a higher FeO content by about 4 wt%; Wieczorek and Phillips, 1997), although the exact causes are still under debate.

The samples returned by the Apollo and Luna missions (Table 2) heralded the beginning of a golden age of lunar research that continues to this day. The samples from the lunar nearside provide vital ground truth because they allow orbital compositional data to be calibrated thus making remotely sensed data sets much more valuable. However, the samples have been invaluable in their own right because they have been instrumental in making fundamental discoveries about the Moon: (A) establishing that the lunar surface is ancient (e.g., Nyquist and Shih, 1992); (B) the Moon,

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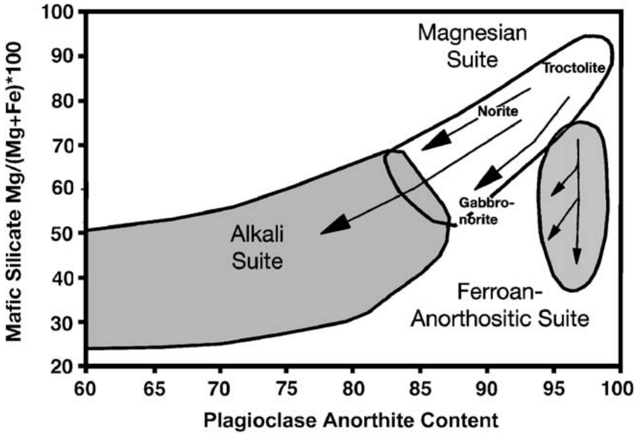

Fig. 2. Plot of mafic silicate magnesium number (molar Mg/(Mg/Fe) × 100) vs. anorthite content of coexisting plagioclase (molar Ca/(Ca + Na + K) × 100). Adapted from Wieczorek et al. (2006), this diagram shows the field of the three suites of highlands rocks determined from returned lunar samples. Mafic silicates include olivine, low-Ca pyroxene and high-Ca pyroxene. Arrows represent typical crystallization trends and hint at a possible relationship between the magnesian- and alkali-suite rocks. The ferroan anorthosite and magnesian suites are difficult to relate through magmatic processes. The groups depicted in the magnesian suite field (norites and gabbronorites) appear to have evolved via different petrogenetic processes and are represented by different fractional crystallization arrows (James and Flohr, 1983). Magnesian suite troctolites are the most primitive rock types.

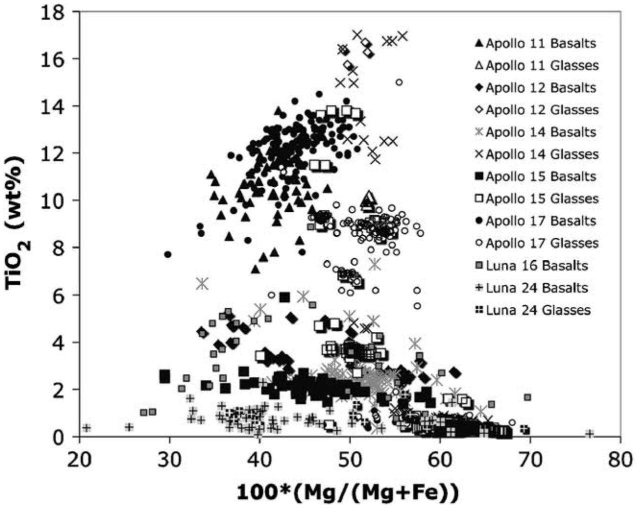

Fig. 3. Mare basalt and volcanic glass compositions defined by magnesium number (molar Mg/(Mg + Fe) × 100) demonstrating the range of Ti contents. While the majority of low-Ti basalt and glass suites (i.e., <6 wt% TiO_2 – Neal and Taylor, 1992) appear to plot on olivine control lines, the high-Ti basalts and glasses do not. Data are from numerous source and the plot was created from the "mare basalt database" that is part of the electronic appendix to Jolliff et al. (2006) and available at www.minsocam.org/MSA/Rim/.

and possibly other planetary bodies, differentiated quickly via a magma ocean (e.g., Smith et al., 1970; Wood et al., 1970; Shearer and Newsom, 2000; Rankenburg et al., 2006); (C) how space weathering can affect the orbital remote sensing data (e.g., Keller and McKay, 1997; Pieters et al., 2000; Taylor et al., 2001a, b); (D) demonstrating that the highlands to be composed of three types of feldspathic material – ferroan, magnesian, and alkali-rich, which are defined on the basis of their mineral compositions (Fig. 2); (E) establishing geochemical evidence for a magma ocean, with the last dregs being enriched in incompatible elements and named "KREEP" (because of enrichment in potassium (K), rare-earth elements (REE), and phosphorus (P), although it is also enriched in other incompatible elements); (F) the high-Ti mare basalts and volcanic glasses have no terrestrial equivalent with both glasses and basalts having variable Ti contents extending up to 17 wt% TiO_2 (Fig. 3); (G) the volcanic glasses and crystalline basalts have unique liquid lines of descent. With the possible exception of Apollo 17 very low titanium (VLT) glasses, none of the glasses are parental to the mare basalts at the specific landing sites (e.g., Delano and Livi, 1981; Delano, 1986, 1990; Longhi, 1987, 1990, 1992; Shearer et al., 1991). Although many attempts have been made to link the crystalline basalts with the volcanic glasses (e.g., Vaniman and Papike, 1977; Taylor et al., 1978), no connection has been unequivocally established and petrogenetic relationships between mare basalts and volcanic glasses remain grossly defined only in terms of similar igneous processes; (H) recent analyses of picritic volcanic glasses (Saal et al., 2007, 2008a, b) have demonstrated that they contain significant volatile contents (i.e., H_2O, F, S) that are difficult to reconcile with the "giant impact" hypothesis for the origin of the Moon; (I) experimental studies on the volcanic glasses indicate derivation from depths of 18–25 kbar (360–520 km), the deepest extremes of which may be below the depth of the lunar magma ocean (e.g., Shirley and Wasson, 1981; Warren, 1985; Delano, 1986; Longhi, 1992, 1993); (J) mare basalt compositions indicate that the source regions contained mixtures of early and late stage magma ocean cumulates, indicating the cumulate pile experienced an overturn event shortly after formation (e.g., Spera, 1992). Longhi (1992) reported the pressures of multiple saturation for primitive mare basalts to be between 5 and 12.5 kbar (100–250 km). Even though multiple saturation pressures and temperatures of the basalts may have been conducted on evolved (i.e., non-primary) compositions, thus yielding a minimum depth, volatile contents and isotope ratios demonstrate the derivation of the mare basalts and volcanic glasses from compositionally distinct and separate sources (e.g., Tatsumoto et al.,

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1973, 1987); (I) the Moon is predominantly mafic, although evolved lithologies (e.g., granite, quartz monzodiorite) are also present in minor quantities (e.g., Ryder, 1976; Blanchard and Budhan, 1979; Warren et al., 1983; Jolliff, 1991; Jolliff et al., 1991; Ryder and Martinez, 1991; Marvin et al., 1991); (J) establishing the early impact history of the Earth–-Moon system (e.g., Ryder, 2002; Cohen et al., 2005; Hartmann et al., 2007).

Integrating sample analyses with orbital data to provide ground truth made the remote sensing data sets of the Clementine and Lunar Prospector missions much more important. They extended the Apollo data sets and allowed global maps of FeO, TiO_2, Th, and H abundances to be created (Lucey et al., 1995, 1998, 2000; Lawrence et al., 1998, 2000; Feldman et al., 1998, 2000; Elphic et al., 1998, 2002). This showed a number of fascinating features: (A) the Apollo and Luna mare basalt samples were not representative of the compositional diversity on the lunar surface as determined by remote sensing data. The sample collection suggests that there is a bimodal distribution of low-Ti and high-Ti basalts, whereas the Clementine data indicate that the low-Ti basalts are much more common and continuously decrease in abundance towards high-Ti basalts (Giguere et al., 2000). The dichotomy has implications for the thermal evolution of the Moon as well as the distribution of high-Ti source regions; (B) there is a Th concentration or "hotspot" on the lunar nearside centered on Mare Imbrium (Lawrence et al., 1998, 2000), which was interpreted as a concentration of KREEP-rich material that was uncovered by the Imbrium impact. While this was hinted at by the Apollo orbital data (e.g., Haines and Metzger, 1980), these data sets were not global in their coverage. Interestingly, the Lunar Prospector data showed the deeper South Pole-Aitken basin only exhibits a minor Th anomaly, indicating that KREEP is heterogeneously distributed around the Moon; (C) the polar regions appear to contain increased abundances of H (Feldman et al., 1998, 2000, 2004) and these are at least partly correlated with permanently shadowed regions; (D) combining the global data sets from Clementine and Lunar Prospector, Jolliff et al. (2000) defined three different terranes within the lunar crust: the Procellarum-KREEP Terrane, the Feldspathic Highlands Terrane, the South Pole-Aitken Terrane; (E) recognition of evolved lithologies in the sample collection and recognition of high-Th areas on the Moon (e.g., Metzger et al., 1977; Lawrence et al., 1998) has allowed Lawrence et al. (2005, 2007) to define locations of potential outcrops of these rock types (e.g., Hansteen Alpha) by reinterpreting the Th abundances derived from Lunar Prospector gamma-ray spectrometer data. These evolved lithologies are poorly represented in the sample collection and establishing how abundant these are on the Moon is a question that will aid in understanding the growth and evolution of the lunar crust.

4. Why go back to the Moon?

With all the scientific advances made regarding our understanding of the Moon, especially since Apollo, what is left to be done? Since the last Apollo Moon landing there have been a number of publications and reports that have stated the reasons why the Moon is still important both scientifically and for exploration purposes (e.g., Mendell, 1986; Spudis et al., 1986; LExSWG, 1992, 1995; Taylor and Spudis, 1990; Spudis, 2003). The reasons stated in the various publications are somewhat overlapping, but it was President Bush in his speech "A Renewed Spirit of Discovery" (Bush, 2004) put the Moon back on the critical path for solar system exploration: "*Returning to the Moon is an important step for our space program. Establishing an extended human presence on the Moon could vastly reduce the cost of further space exploration, making possible ever more ambitious missions. Also the Moon is home to abundant resources. Its soil contains raw materials that might be harvested and processed into rocket fuel or breathable air. We can use our time on the Moon to develop and test new approaches and technologies and systems that will allow us to function in other, more challenging, environments. The Moon is a logical step toward further progress and achievement. With the experience and knowledge gained on the Moon, we will then be ready to take the next steps of space exploration: human missions to Mars and to worlds beyond.*"

Table 4 gives details of the scientific, exploration, and economic rationale for going back to the Moon. This table also includes important feed-forward reasons for returning to the Moon in order to enhance mission success in going to Mars and beyond.

5. Remaining lunar science questions – we have barely scratched the surface

The current architecture of lunar return indicates that the astronauts will have ample time to conduct scientific exploration (Yoder, 2007). So what should they do? The publication by Jolliff et al. (2006) was timely given the renewed exploration focus on the Moon. The synthesis of 45+ years of data of various forms presented therein brought sharp focus on those areas we know little about and presented many unanswered science questions. The ensuing National Research Council (NRC) of the National Academies (2007) also highlighted many unanswered science questions that could be addressed

Table 4. The scientific, exploration, and economic rationale behind President Bush's speech (Bush, 2004)

Reason to return	Rationale
The Moon is a cornerstone for planetary science.	The Moon provides a rich record of planetary differentiation and early evolution that is not preserved on the larger terrestrial planets. For example the Moon has preserved its primordial crust.
The Moon is a natural laboratory for planetary processes.	The Moon allows the study of fundamental planetary processes (i.e., volcanism and meteoroid impact) in a different gravitational environment and essentially in a vacuum. For example, the Moon has retained a record of post-accretional impact history, not seen on Earth.
Origin of the Earth–Moon system.	The origin of the Moon is intricately linked to that of the Earth. For example, if a terminal cataclysm of meteoroid impacts around 3.9 Ga is confirmed on the Moon, this age could signal the time after which life was able to develop on Earth.
Location, location, location.	The Moon is the keystone to understanding the processes that shaped the terrestrial planets and is the closest planetary body to Earth; it is only 2 or 3 days away and is almost always within a launch window.
The Apollo and Luna legacy.	As the Moon is the only planetary body of which we have samples taken from known locations, remotely sensed data can be calibrated and absolute ages determined. Therefore, we are now in a position to ask increasingly detailed and sophisticated questions about the Moon that can be answered by targeted missions and measurements.
The Solar wind record.	As the Moon has essentially no atmosphere, the regolith has been exposed to solar wind and solar flare activity over time. Sampling of ancient regoliths (i.e., regolith developed between two datable lava flows) will contain a record of the Sun's evolution for that particular time interval.
The Moon will be a testbed for new technologies and human adaptation to the space environment.	For the human exploration of Mars and beyond, it is vital that we take advantage of the functional testbed close to Earth for the development laboratory for technical capabilities that will be required for enabling a sustained presence on the Moon. Essentially, the Moon will serve as a nearby asset for learning to live off planet (Spudis, 2003). Its proximity will allow results to be known quickly, allowing for rapid development of new technologies. The short light travel-time allows direct control of experimental robotic systems, such as rovers, will lead to more rapid development of autonomous systems and surface infrastructures.
The moon as a refueling station.	Part of President Bush's (2004) speech stated that "*Spacecraft assembled and provisioned on the Moon could escape its far-lower gravity using far less energy and thus far less cos*t." Much of the mass of spacecraft leaving Earth is in fuel required to escape the gravity field. This leaves less room for payload and could limit human exploration missions beyond the Moon. In situ resource utilization (ISRU – see below) on the Moon can be used to refuel (e.g., Bienhoff, 2007), as well as provide vital life support elements (e.g., Allen et al., 1994a, 1996). The lunar surface contains the ingredients for fuels and life support (e.g., Arnold, 1979; Lingner et al., 1996; McCullogh and Hall, 2001; Taylor and Martel, 2003). Such ISRU will reduce launch costs (less mass to get out of Earth's gravitational well; fuel for return will not be required), enable risk reduction, and enhance mission objectives (e.g., more Earth-bound return cargo mass). For details see Sanders and Duke (2005).
International cooperation.	Establishing a lunar habitat will be expensive and will require the cooperation of different countries. Therefore, the Moon is an excellent venue for establishing and strengthening international space cooperation (e.g., Abdul-Kalam, 2005). NASA and 13 other national space agencies have begun this process with the Global Exploration Strategy (2007).
Educational opportunities.	The short round trip communications time between the Earth and Moon provides a unique environment for exciting our youth and enhancing science and engineering educational opportunities. It is possible to create complex interactive exploration activities in conjunction with either human or robotic exploration missions. Inspiring students of all ages through the use of teleoperations/telepresence systems will demonstrate the positive benefits of advanced technology.
Science from the Moon.	The lunar surface is a good place for making astronomical observations because of its relatively low seismicity, lack of atmosphere, lower gravity (bigger telescopes can be built – e.g., Mumma and Smith, 1990). The lunar farside is an ideal location for a radio telescope because it is shadowed from the Earth (Maccone, 2001). However, as the same side of the Moon is always facing Earth, the lunar nearside is an ideal location for making long-term Earth observations (see Jolliff, 2007 for details).
Commercial opportunities.	A major feature of the President's speech in 2004 was that the human and robotic exploration of the Moon, Mars and beyond should be sustainable. This will require shifting the expense of maintaining the lunar outpost from government to the private sector (e.g., Schmitt, 2003) or creating public–governmental–private sector partnerships (e.g., Sadeh et al., 2005). The success of such endeavors depends on how government reduces risk (risk = technological, legal, political, financial, and market) for the private sector. Singh (2004) concluded that the United States could lead the way by establishing markets for "lunar" products, as well as infrastructure that could be used by the

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Table 4. (*continued*)

Reason to return	Rationale
	private sector. One area that could generate "lunar" products both for use on the Moon and at least some potentially being used on Earth, is in situ resource utilization (e.g., Duke et al., 2003; Schmitt, 2003, 2006). While this is discussed in more detail below, it is becoming increasingly evident that establishing ISRU production on the lunar surface and private sector involvement will be intimately linked (e.g., Sanders and Duke, 2005).

Table 5. Scientific goals for the Moon developed and ranked by LEAG and evaluated by MEPAG for relevance for feed-forward to Mars

Theme	Objective ID	Name
Investigate the geologic evolution of the Moon and other terrestrial bodies.	GEO-01	Determine the internal structure and dynamics of the Moon to constrain the origin, composition, and structure of the Moon and other planetary bodies (10/High).
	GEO-02	Determine the composition and evolution of the lunar crust and mantle to constrain the origin and evolution of the Moon and other planetary bodies (10/Medium).
	GEO-03	Characterize the lunar geophysical state variables to constrain the origin, composition, and structure of the Moon and other planetary bodies (9/Medium).
	GEO-05	Characterize the crustal geology of the Moon via the regolith to identify the range of geological materials present (9/Low).
Quantification of impact processes and histories of the solar system.	GEO-06	Characterize the impact process on the Moon and other planetary bodies to understand this complex process (9/Low).
	GEO-07	Characterize impact cratering over the Moon's geologic history, to understand early solar system history (10/High).
	GEO-08	Study meteorite impacts on the Moon to understand the early Earth history and origin of life (7/Low).
Characterization of regolith and mechanisms of regolith formation and evolution.	GEO-09	Study the lunar regolith to understand the nature and history of solar emissions, galactic cosmic rays, and the local interstellar medium (9/High).
	GEO-10	Determine lunar regolith properties to understand the surface geology of the Moon and other planetary bodies (7/Low).
	GEO-11	Characterize the lunar regolith to understand the space weathering process (6/Low).
	GEO-14	Characterize potential resources to understand their potential for lunar resource utilization (7/Low).
Study of endogenous and exogenous volatiles on the Moon and other planetary bodies.	GEO-04	Determine the origin and distribution of endogenous lunar volatiles as one input to understanding the origin, composition, and structure of the Moon and other planetary bodies (7/Low).
	GEO-12	Characterize lunar volatiles and their source to reveal the nature of impactors on the Moon (8/Medium).
	GEO-13	Characterize transport of lunar volatiles to understand the processes of polar volatile deposit genesis and evolution (7/Low).
Development and implementation of sample return technologies and protocols.	GEO-15	Provide curatorial facilities and technologies to ensure contamination control for lunar samples (10/Low).
	GEO-16	Provide sample analysis instruments on the Moon to analyze lunar samples before returning them to Earth (9/Medium).

LEAG rankings are on a scale of 1–10 with 10 being the highest rank. MEPAG evaluations are low, medium, and high.

by an integrated exploration program of orbital and lander missions (robotic and/or human).

These questions also resonated in three LEAG analysis reports, which were published (on line) during 2006, produced by Specific Action Teams (SATs; see http://www.lpi.usra.edu/leag for details). These reports, which were not restricted to purely lunar science (they also included astronomy, heliophysics, and Earth science that could be conducted from the Moon), fed into the initial Lunar Architecture Team deliberations

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Table 6. Science themes and research objectives for the Moon defined by the NRC (2007)

Theme	Research objective
1. Bombardment history of the inner solar system is uniquely revealed on the Moon.	• Test the cataclysm hypothesis by determining the spacing in time of the creation of the lunar basins; • Anchor the early Earth–Moon impact flux curve by determining the age of the oldest lunar basin – the South Pole-Aitken Basin; • Establish a precise absolute chronology; • Assess the recent impact flux; • Study the role of secondary impact craters on crater count ages.
2. Structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated planetary body.	• Determine the thickness of the lunar crust (upper and lower) and characterize its lateral variability on regional and global scales; • Characterize the chemical/physical stratification in the mantle, particularly the nature of the putative 500-km discontinuity and the composition of the lower mantle; • Determine the size, composition, and state (solid/liquid) of the core of the Moon; • Characterize the thermal state of the interior and elucidate the workings of the planetary heat engine.
3. Key planetary processes are manifested in the diversity of lunar crustal rocks.	• Determine the extent and composition of the primary Feldspathic crust, KREEP layer, and the other products of planetary differentiation; • Inventory the variety, age, distribution, and origin of lunar rock types; • Determine the composition of the lower crust and bulk Moon; • Quantify the local and regional complexity of the current lunar crust; • Determine the vertical extent and structure of the megaregolith.
4. The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history.	• Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and depth) of the volatile component in lunar polar regions; • Determine the source(s) for lunar polar volatiles; • Understand the transport, retention, alteration, and loss processes that operate on volatile materials at permanently shaded lunar regions; • Understand the physical properties of the extremely cold (and possibly volatile rich) polar regolith; • Determine what the cold polar regolith reveals about the ancient solar environment.
5. Lunar volcanism provides a window into the thermal and compositional evolution of the Moon.	• Determine the origin and variability of lunar basalts; • Determine the age of the youngest and oldest mare basalts; • Determine the compositional range and extent of lunar pyroclastic deposits; • Determine the flux of lunar volcanism and its evolution through space and time.
6. The Moon is an accessible laboratory for studying the impact process on planetary scales.	• Characterize the existence and extent of melt sheet differentiation; • Determine the structure of multiring impact basins; • Quantify the effects of planetary characteristics (composition, density, impact velocities) on crater formation and morphology; • Measure the extent of lateral and vertical mixing of local and ejecta material.
7. The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies.	• Search for and characterize ancient regolith; • Determine the physical properties of the regolith at diverse locations of expected human activity; • Understand regolith modification processes (including space weathering), particularly deposition of volatile materials; • Separate and study rare materials in the lunar regolith.
8. Processes involved with the atmosphere and dust environment of the Moon are accessible for scientific study while the environment remains in a pristine state.	• Determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity; • Determine the size, charge, and spatial distribution of electrostatically transported dust grains and assess their likely effects on lunar exploration and lunar-based astronomy; • Use the time-variable release rate of atmospheric species, such as ^{40}Ar and radon, to learn more about the inner workings of the lunar interior; • Learn how water vapor and other volatiles are released from the lunar surface and migrate to the poles where they are adsorbed in polar cold traps.

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Table 7. Unanswered science questions grouped under themes designed by the Lunar Exploration Analysis Group (LEAG) and the National Research Council of the National Academies

Theme	Science questions
Investigate the geologic evolution of the Moon and other terrestrial bodies.	• What were the initial thermal state and the early thermal evolution of the Moon? • What role did early (i.e., >4 Ga) volcanism play? • What is the composition and depth of origin of the farside and young (i.e., <3 Ga) nearside basalts? • What is the nature of the Moon's global-scale crustal asymmetry, what caused it, and what are the implications for the Moon's internal evolution and present-day distribution of materials? • What is the cause of the center-of-mass/center-of-figure offset? • Is it related to convection and density inversion dynamics, early giant impacts, asymmetric crystallization of the magma ocean, or earth–moon tidal effects? • What is the vertical and lateral structure of the lunar crust and how did it develop? • What is the provenance of the Magnesian Suite rocks? • What is the composition and origin of the lower crust? • What are the characteristics of the lunar core (size, composition), and did the Moon ever support a dynamo-driven magnetic field? What are the origins of lunar paleomagnetism? • Was there a significant late veneer of accretion (post-core formation/early differentiation)? • Are the Apollo geophysical (seismic, heat flow) measurements representative of the whole Moon or are they only valid for the small regions encompassed by the Apollo landing sites? • What is the origin and lateral extent of the 500-km seismic discontinuity? • What is the origin of Shallow Moonquakes (i.e., high-frequency teleseismic events)? • Is there an undifferentiated lower mantle (limited or no involvement in magma ocean melting)? If so, what was its role in lunar magmatism? • Did at least some of the volcanic glasses come from a deep, garnet-bearing region beneath the cumulate mantle? • What was the extent of lunar magma ocean differentiation? • Is the surface distribution of KREEP representative of the underlying crust? • What were the sources and magnitude of heating to drive secondary magmatism? • How was heat transferred from Th, U, K-rich crustal reservoirs to the mantle? What was their role in large-scale crustal insulation? • How are the different suites of plutonic rocks related to specific or localized geologic terranes and to the global geochemical asymmetry? • How is the surface expression of lunar materials related to the Moon's internal structure and evolution (or where exactly do the different rock types come from)?
Quantification of impact processes and histories of the solar system.	• What were the timing and effects of the major basin-forming impacts on lunar crustal stratigraphy? What is the nature and composition of the South Pole-Aitken Basin, did it penetrate the lunar mantle, and how did it affect early lunar crustal evolution? • What was the impactor flux in the inner Solar System and how has this varied over time? Was there a terminal cataclysm at $\sim$3.9 Ga? • What are the absolute ages of the large rayed craters that are assumed to be Eratosthenian and Copernican in age (e.g., Autolychus, Copernicus, Tycho)? • What are the unequivocal ages of the large multiring basins (i.e., Nectaris, Imbrium, and Orientale)? • Why are there no impact melts older that $\sim$4.2 Ga in the sample collection? Is this a sampling problem or is it because they simply do not exist?
Characterization of regolith and mechanisms of regolith formation and evolution.	• What is(are) the origin(s) of lunar swirls, the light and dark colored "swirl-like" markings up to 100 km across (e.g., Reiner Gamma in Oceanus Procellarum)? • How do the physical/geotechnical properties of the lunar regolith differ between measurement on Earth and in its natural environment on the lunar surface? • How does the process of space weathering occur? • How has the solar wind flux changed over time?
Development and implementation of sample return technologies and protocols.	• What technology development is needed to be able to collect, transport, and curate samples from permanently shadowed regions of the Moon (i.e., samples containing H deposits)? • What technology is currently (commercially) available to aid in (a) robotic and (b) astronaut sampling of lunar lithologies, including contextural information for each sample?

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Table 7. (*continued*)

Theme	Science questions
Study of endogenous and exogenous volatiles on the Moon and other planetary bodies.	• What volatiles are (were) present in the deep lunar interior and what was their role in magmatic processes and eruptive styles? • What happens to elemental species volatilized during impact? • What and where are the most concentrated, extensive, and readily extractable deposits of H and ^{3}He? • What are the origin and mineralogical or physical form, thickness, and concentration of H or H_2O ice deposits in permanently shadowed craters at the poles?
Processes involved with the atmosphere and dust environment of the Moon are accessible for scientific study while the environment remains in a pristine state.	• What elemental and molecular species make up the lunar exosphere and how has it changed with time? • Are there seasonal fluctuations in the lunar exosphere? • How quickly does the lunar exosphere recover from (a) a meteoroid impact and (b) landing of a spacecraft?

and were followed by the NASA Advisory Council (NAC) sponsoring a workshop in Tempe, AZ (Jolliff, 2007 – see http://www.hq.nasa.gov/office/oer/nac/). As the focus of this paper is on lunar science, the results of the NAC Planetary Science Subcommittee sessions at the Tempe workshop are most relevant as they ranked the 16 LEAG GEO-SAT objectives (see Table 5). Basically, the 16 GEO-SAT objectives can be grouped under five themes: (1) investigate the geologic evolution of the Moon and other terrestrial bodies (GEO-1, -2, -3, -5); (2) quantification of impact processes and histories of the solar system (GEO-6, -7, -8); (3) characterization of regolith and mechanisms of regolith formation and evolution (GEO-9, -10, -11, -14); (4) study of endogenous and exogenous volatiles on the Moon and other planetary bodies (GEO-4, -12, -13); (5) development and implementation of sample return technologies and protocols (GEO-15, -16) (Table 5).

The NRC report in 2007 focused the unanswered lunar science questions into eight themes under which there were 35 research objectives (Table 6). As can be seen, there is considerable overlap between the LEAG and NRC themes and research objectives. These can be used to focus the science questions that have been crafted and presented in a wide variety of reports and papers from the early 1970s until the present day (the pertinent references have been cited above). The relevant science questions are grouped under the applicable themes and presented in Table 7. The questions grouped under the "geologic evolution of the Moon" theme reflect the following: (1) while the Moon records early solar system processes, the pre-4 Ga history has been partially masked by later meteorite impacts; (2) Apollo sampled a very limited area of the Moon, which has been shown not to be representative of the lunar highlands (from lunar meteorites: Korotev, 2005) or of mare basalts (from remote sensing: Giguere et al., 2000); (3) Apollo and subsequent orbital missions have told us very little about the deep lunar interior or heterogeneity within the lunar crust and mantle.

Those questions grouped under the remaining themes in Table 7 basically demonstrate the limited lunar sampling and exploration that has been undertaken. This is reflected in the limited number of impact craters that have been sampled (and accurately dated), which leaves questions regarding a possible late (~3.9 Ga) heavy bombardment. The questions also reflect the lack of knowledge regarding the exogenous vs. endogenous volatile budget of the Moon. Such questions have important implications for ISRU (e.g., H deposits) and also for the giant impact hypothesis, which requires that the Moon be depleted in volatile elements (but see Saal et al., 2007, 2008a, b). Our understanding of regolith formation, evolution, and geotechnical properties is also limited (Table 7). Other issues involve sample return technologies and protocols, because developments are required in order to sample and curate materials from permanently shadowed regions, perfecting robotic sample return, as well as remote high grading of sample suites for eventual return to Earth. Finally, long-term networks are required in order to monitor tectonic activity as well as solar wind and lunar atmosphere fluctuations.

It is evident, therefore, that there is an abundance of science that still needs to be conducted on the Moon, which requires robotic and human exploration. Robotic exploration includes both orbital and surface systems, as well as networked monitoring stations for geophysics (seismic stations, heat flow, magnetism), solar wind, and the lunar exosphere studies. This should be conducted prior to or during the next human exploration of the Moon (so the natural lunar exosphere can be studied, seismic and radiation hazards evaluated, etc. Joosten and Guerra, 1993). Once humans have returned to the

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Moon, exploration could continue robotically or by human–robotic partnerships (e.g., telepresence operations; Cooper et al., 2005).

6. In situ resource utilization (ISRU)

The subject of ISRU on the Moon is where the realms of exploration, science, and commerce are intricately interwoven (see GEO-14 in Table 5). ISRU requires products to be manufactured from lunar raw materials and, provided a market for these products is available, it provides an ideal on ramp for the private sector to become involved in lunar exploration. Involvement of ISRU can reduce the risk and cost of operating and maintaining the lunar outpost, so understanding the distribution of potential resources is an important consideration for locating the outpost. Products of ISRU could produce life support (O_2, H_2O), propellant (e.g., H_2, O_2), construction materials, metals, and energy (e.g., Cameron, 1987, 1991: Allen et al., 1992, 1994a, b, 1996; McCullogh and Hall, 2001; Schmitt, 2006). Some processes use solar wind implanted species (H, C, etc.) to reduce element oxides (specifically FeO) in lunar materials. As can be seen from Fig. 4(a–d) there is a positive correlation between regolith maturity (defined by I_S/FeO) and the amount of solar wind derived species. If the regolith remains exposed at the lunar surface it is continually modified through micrometeoroid impacts and interaction with high-energy cosmic and solar particles and spallation products. Newly created regolith is made of rock that is relatively fresh or "immature". Increasing soil maturity involves the mechanical breakdown of the regolith particles to smaller and smaller sizes (McKay et al., 1974; Fig. 5a). It also involves the formation of agglutinates–aggregates of smaller particles (minerals, glasses, older agglutinates) bonded together by impact-induced, sometimes flow-banded glass. This impact-induced melting also facilitates the reduction of FeO to nanophase metallic Fe, such that more mature regolith undergoes "spectral reddening" (Adams and McCord, 1973; Noble et al., 2003). Spectral reddening means the regolith has significantly reduced mineral absorption bands and exhibits a spectral continuum that increases with wavelength into the near infrared, relative to fresh lunar rock (Pieters et al., 2000). The nanophase metallic iron is produced on grain surfaces by a combination of vapor deposition and irradiation effects associated with space weathering (Keller and McKay, 1993, 1997; Pieters et al., 2000). There is a broad positive correlation between I_S/FeO and the percentage of agglutinates in the regolith (Fig. 5b). Vapor fractionation can also occur as more volatile elements may be lost to space

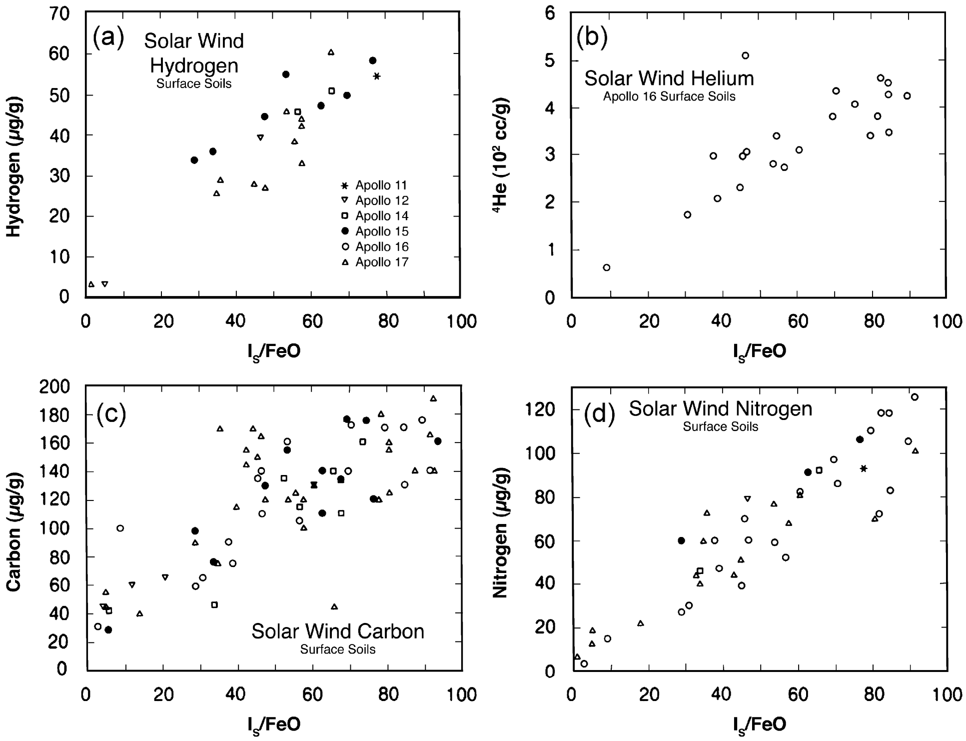

Fig. 4. Correlations between Apollo 16 regolith maturity index (I_S/FeO, where I_S is the relative concentration of fine-grained metal as measured by ferromagnetic resonance (FMR) and FeO is the total concentration of iron; e.g., Morris, 1976, 1978a, b) and solar wind implanted species. Adapted from Heiken et al. (1991) with data from Morris and Gose (1976) and Blanford et al. (1979).

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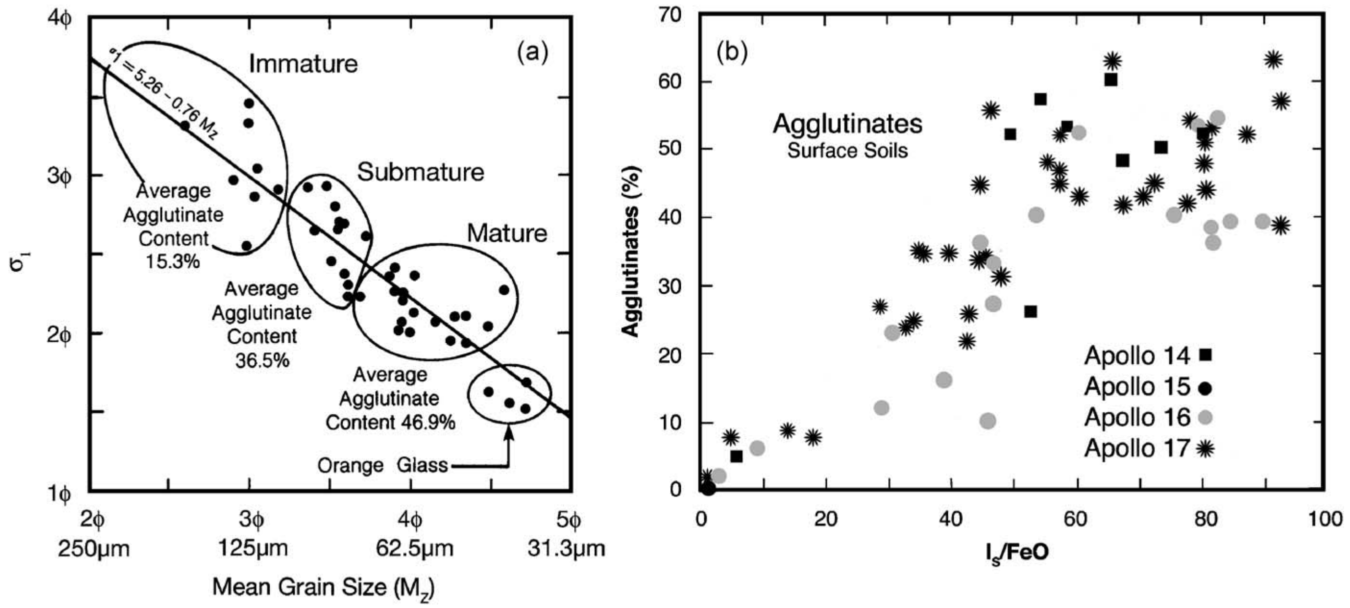

Fig. 5. (a) Plot of I_S/FeO vs. particle size showing the relationship between grain size, sorting, and agglutinate content for 42 Apollo 17 regolith samples (McKay et al., 1974). The graphic Mean Grain Size (MZ) is plotted vs. the inclusive graphic standard deviation ($\sigma 1$); subcentimeter data only. Increased agglutinate content correlates with increased soil maturity. Adapted from McKay et al. (1974) and Heiken et al. (1991). (b) Plot of I_S/FeO vs. agglutinates showing the positive correlation between these two lunar soil maturity parameters. Adapted from Heiken et al. (1991) with data from Morris and Gose (1976) and Blanford et al. (1979).

during energetic meteoroid impacts, although it is likely they recondense at other places on the Moon (e.g., cold traps).

6.1. Ilmenite

It has been recognized that ilmenite is particularly good at adsorbing solar wind and cosmic particles, such as H, N, C, and He (e.g., Eberhardt et al., 1972; Cameron, 1987, 1991; Taylor, 1994). These elements are critical for sustaining a permanent lunar outpost as well as for sustainable commercial development of the Moon. The effect of ilmenite can be seen in Fig. 6 where the bulk 12001 soil shows increasing inert gas content with decreasing grain size (i.e., increasing maturity). Comparing the left panel with that of the ilmenite size fractions in the right panel of Fig. 6 shows a marked increase in the overall abundances of the gases at each grain size (although the smaller grain sizes still exhibit increasing gas content) compared to the same grain size in the bulk sample. Therefore, solar wind resources in the regolith are related to its composition *and* maturity.

Regolith composition is important for determining resources critical for sustaining a long-term lunar habitat (e.g., Lingner et al., 1996). For example, regolith rich in Ti contains relatively large abundances of the mineral ilmenite. Ilmenite has been highlighted as a potential feedstock for the production of oxygen through the simple reduction reaction (e.g., Gibson and Knudsen, 1985; Williams, 1985; Cutler and Krag, 1985):

$$FeTiO_3 \xrightarrow{\text{Vacuum Heating}} Fe + TiO_2 + 0.5O_2$$

As noted by Heiken et al. (1991 and references therein), there are broad positive correlations between C and other light volatile elements H, He, and N. The solar wind origin of these elements is seen in the positive correlation of their abundances with maturity (Fig. 4). The influence of ilmenite on the retention of solar wind implanted elements was described by Stoenner et al. (1974), where the H/He ratios of the Apollo 17 drill cores were similar to that of solar wind and the H and He abundances correlated positively. However, the H/He ratios of the Apollo 16 drill cores showed more variability (Stoenner et al., 1974), which was attributed to a lack of ilmenite that can retain He more efficiently than plagioclase. Indeed, the abundance of He in the regolith exhibits a broad positive correlation with bulk TiO_2 content (Fig. 7).

If ilmenite is extracted from a relatively mature soil, it will contain higher abundances of solar wind implanted species, including hydrogen. Therefore, the above reaction can be modified:

$$FeTiO_3 + 2H \xrightarrow{\text{Vacuum Heating}} Fe + TiO_2 + H_2O$$

The resulting water could be used for habitat support or split by electrolysis with H being recycled, and O going for habitat support.

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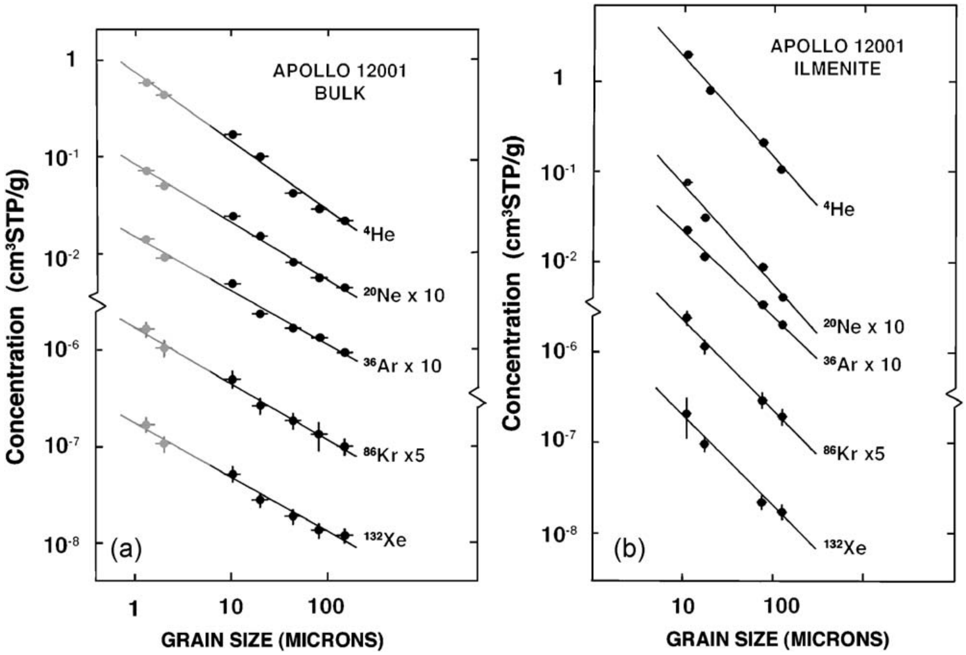

Fig. 6. Influence of grain size and ilmenite on retaining solar wind and cosmic particles (adapted from Eberhardt et al., 1972). (a) Grain size dependency of the trapped solar wind implanted ^{4}He, ^{20}Ne, ^{36}Ar, ^{86}Kr, and ^{132}Xe abundances in Apollo 12 regolith sample 12001. (b) Grain size dependency of the trapped solar wind implanted ^{4}He, ^{20}Ne, ^{36}Ar, ^{86}Kr, and ^{132}Xe abundances in ilmenite separated from Apollo 12 regolith sample 12001. The grain size scale in (a) is de-emphasized beneath 10 μm to make it consistent with the scale on panel (b).

While the abundances of implanted particles will depend on the maturity of the regolith, they also depend on the amount of gardening that the regolith has experienced from subsequent impacts. Energy from such impacts will release at least some of the previously implanted volatile species. This increases the importance of ilmenite in the regolith and shows that ilmenite is particularly good at holding on to implanted gaseous species during the gardening process. This is because of its close-packed hexagonal crystal structure (e.g., Papike et al., 1991), and the fact that it is relatively refractory (melting point is ~1800 °C) so it is only melted by the most energetic impacts (Figs. 8 and 9).

6.2. Polar hydrogen deposits

Arnold (1979) suggested the possibility of water ice being present at the lunar poles and the Clementine bistatic radar test gave a tantalizing suggestion that it could be present, at least at the lunar South Pole (Nozette et al., 1996). Lunar Prospector confirmed increased levels of H (up to ~1700 ppm) at the North and South Poles (e.g., Feldman et al., 1998, 2000). As noted earlier, the exact nature of the polar H deposits is not known. For example, Nozette et al. (2001) suggested the polar H signature represented water ice, but on the basis of theoretical modeling Hodges (2002) concluded this was unlikely. Campbell et al. (2006) using Earth-based radar telescopes concluded that there was no water ice at the lunar South pole. Crider and Vondrak (2002) presented a model that showed solar wind H (as OH) could be transported to the permanently shadowed craters (and be preserved as H_2O) of the lunar poles through a series of ballistic "hops", with the process taking ~7 Myr. Exogenous (cometary) and endogenous (fire-fountain eruptions) H sources have been proposed. Polar regions are now considered potential outpost sites not only because of the ISRU potential of the polar H deposits, but also because certain areas may be in permanent sunlight making available continuous solar power (Bussey et al., 1999, 2003, 2005; Burke, 2005).

There have been many papers extolling the virtues of using lunar materials to produce different products (Mendell, 1986; Allen et al., 1992, 1994a, b, 1996; Ruiz and Duke, 2004) that could sustain a lunar outpost. Many of these require application of known processes to the lunar situation. However, to date there has not been a technical demonstration of ISRU on the lunar surface and hence ISRU is not in the critical path of the current Lunar Architecture. The LEAG 2007 meeting in Houston, TX (see http://www.lpi.usra.edu/meetings/leag2007) concluded that ISRU will be an *enabling* technology for the sustainability of any lunar outpost and that it is vital for a technology demonstration of ISRU potential to be placed on the lunar surface prior to outpost build up in order to reduce the risk of such capabilities. Returning to the Moon, establishing the

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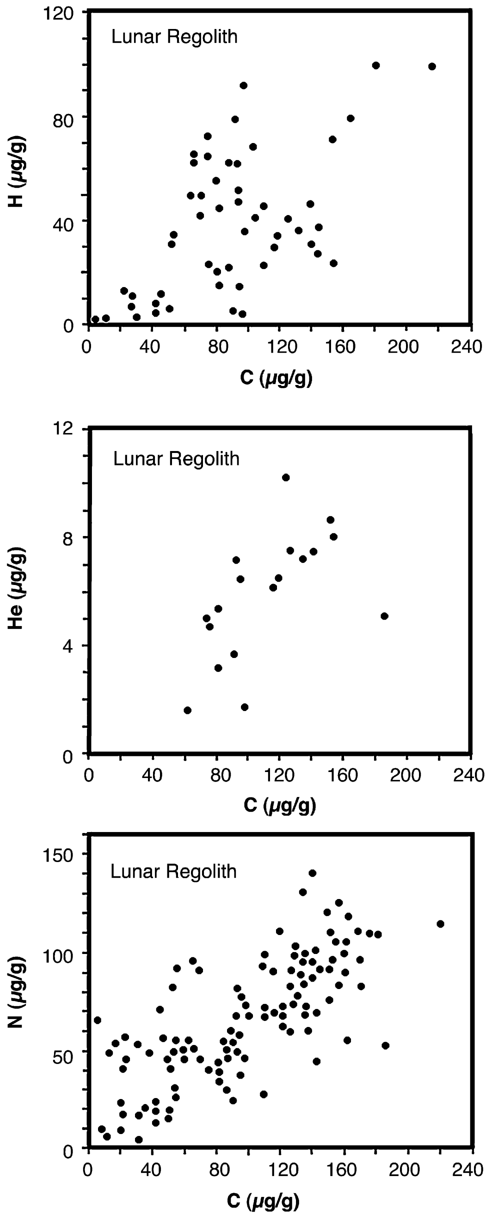

Fig. 7. Correlation between solar wind implanted species in lunar regolith samples. Adapted from Heiken et al. (1991) and references therein.

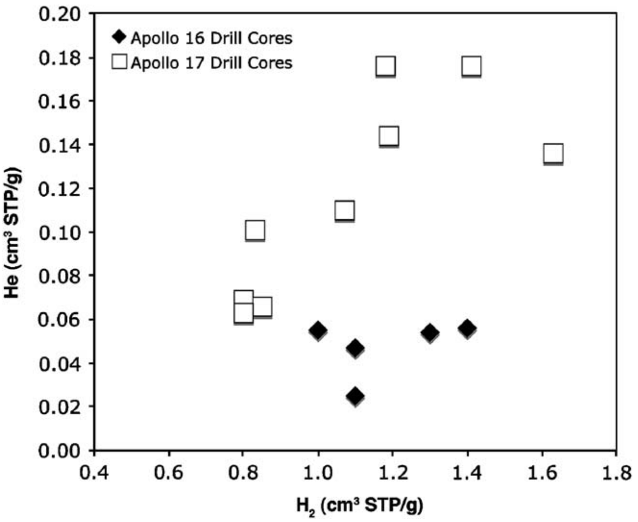

Fig. 8. Hydrogen and helium contents of the Apollo 16 and Apollo 17 drill cores. The positive correlation between these solar wind implanted species in the Apollo 17 samples and the lack of correlation from Apollo 16 has been attributed to the presence of ilmenite in the former. Data are from Stoenner et al. (1974).

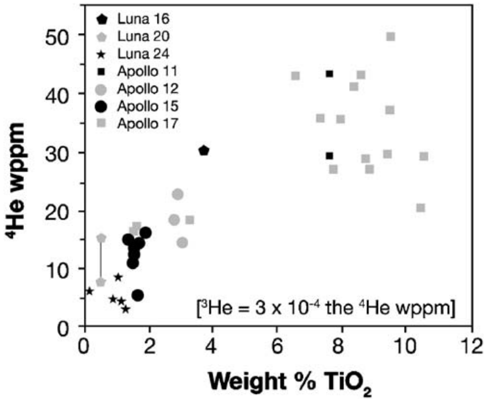

Fig. 9. Relationship between TiO_2 (Ilmenite) and helium contents in lunar regolith samples.

outpost, and learning to live off the land through ISRU has dramatic implications for the human exploration of the solar system. Using lunar raw materials to enhance our ability to live off planet will reduce the cost and risk of sending humans to Mars (see below).

6.3. Helium-3

The Moon also beckons to us because it contains in its regolith high abundances (relative to Earth) of the isotope helium-3, and it has been proposed that this will be the only economically viable export from the Moon back to Earth (Schmitt, 2006 and references therein). Helium-3 is present in the lunar regolith as one of several important trapped solar wind species (Fig. 4). As with other solar wind implanted species, helium abundances are greatest in mature Ti-rich regolith (i.e., rich in ilmenite – Taylor, 1993, 1994) (Fig. 7). Cameron (1993) estimated that the Ti-rich regolith in Mare Tranquilitatis contains at least 10,000 metric tons of ^{3}He. Theoretically, ^{3}He can be fused with deuterium to produce ^{4}He (an alpha particle), a proton, and energy, or ^{3}He can be fused with itself to produce ^{4}He and two hydrogen atoms (e.g., Wittenberg et al., 1986). As all products are stable there is no hazardous waste to dispose of. Calculations suggest that 40 metric tons of ^{3}He could fuel the United States for 1 year (Kulcinski

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and Schmitt, 1992). Using an average lunar regolith concentration of 25 μg/g ^{3}He, Duke et al. (2006) estimated that in order to produce 1 metric ton of ^{3}He from low-Ti regolith, 11 km^2 of regolith would need to be mined to a depth of 3 m. This amount would be less in areas of mature, Ti-rich regolith, where ^{3}He contents can reach 35–45 mg/g (Cameron, 1992). While progress in this area is being made, the technology to realize such power generation is not yet developed. A detailed discussion of the Moon's potential for supplying nuclear fusion fuel can be found in Schmitt (2006).

6.4. Solar power

Criswell and Waldron (1990) proposed the collection of solar energy by photovoltaic cells on the lunar surface, conducting the electricity to a microwave transmitter than beams the energy, as microwaves, back to Earth. This concept has been refined by Criswell (2002, 2005) who concluded that as the lunar surface intercepts ~1000 times more solar power than the commercial output of all the terrestrial power stations combined, solar power could be an exportable commodity. Setting up solar arrays in the areas of permanent (or near permanent) sunlight (see Bussey et al., 1999, 2003, 2005) would allow a relatively constant supply of energy to be gathered and transmitted via microwaves to distribution centers on Earth. DuBose (1985) noted that all the raw materials needed to construct solar energy collection arrays, as well as conversion and power-beaming facilities in space or on the Moon are available from lunar materials. Criswell and Thompson (1996) and Criswell (1996) conducted an analysis of space- and lunar-based power systems that would beam power back to Earth and noted that the cost of power production on the Moon could be up to a factor of 10 lower than the cost of power beamed to Earth from orbit. However, establishing the initial infrastructure would require considerable investment. See Duke et al. (2006) for a full discussion of this issue.

At least three major questions remain for ISRU: (1) Will regolith processing methods and ISRU designs developed on Earth work on the lunar surface given different atmospheric pressure and gravitational conditions? If such processes do work on the Moon, ISRU will be pivotal in reducing cost and risk of establishing a lunar outpost (Sanders and Duke, 2005); (2) How extensive are deposits that can be efficiently used for ISRU? Maturity and composition of the immediate global surface regolith are known from orbital data (e.g., Lucey et al., 1995, 1998, 2000; Morris, 1976; Morris et al., 1998). For the polar deposits, resolution of the Lunar Prospector data is 1.5° × 1.5° (~45 km × 45 km) per pixel (Feldman et al., 1998), although some improvements have been made (Feldman et al., 2000). Therefore, understanding the geochemistry and maturity of the regolith with depth is a critical need for adequately assessing the extent of any in situ resource; (3) What is the exact nature of the H deposits at the lunar poles? The reader is directed to Sanders and Duke (2005) where the ISRU capability roadmap for lunar exploration is defined. This document contains many more details regarding ISRU implementation and capabilities than can be included here.

7. Lunar exploration in the 21st century

Questions that can guide lunar exploration during the 21st century have been posed above and encompass both basic and applied science. At the time of writing this paper, it will be 2018–2020 before humans set foot on the lunar surface again. This leaves 10–12 years for robotic exploration opportunities to address at least some of the questions raised above and pave the way for a sustained human presence on the Moon. Since the turn of the 21st century, interest in the Moon has increased dramatically and there are missions from various nations already at the Moon, scheduled for launch, or under concept study.

7.1. Current and scheduled missions to the Moon

Currently, three orbital missions have been successfully launched and are in orbit around the Moon – the Japanese SELENE/Kaguya, the Chinese Chang'e 1, and the Indian Chandrayaan-1 missions. In addition, the United States (Lunar Reconnaissance Orbiter) has a lunar mission scheduled for launch in 2009 (Table 1). If all these are successful, some of the remaining lunar questions posed above could be answered. There follows a summary of these missions, their payloads, and the science questions/goals they are trying to address/achieve.

SELENE/Kaguya (http://www.isas.ac.jp/e/enterp/missions/kaguya/index.shtml): The SELenological and Engineering Explorer is an orbital mission from the Japanese Space Agency (JAXA) to study the origin and evolution of the Moon, the lunar environment, and observe the solar-terrestrial plasma environment (Sasaki et al., 2003; Hisahiro et al., 2005; Kato and Minamino, 2005; Kato et al., 2006, 2007, 2008). It was launched on 14 September 2007 and is designed to maintain a circular polar orbit 100 km above the lunar surface for 1 year of science operations, with a 2nd year being considered at a lower (40–70 km) orbit. With its instrument suite (Table 8) SELENE will generate global data sets of elemental abundance, mineralogical composition, topography, geology, and surface structure, lunar gravity field. In addition, SELENE will also explore the lunar and solar-terrestrial plasma

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Table 8. Current and planned Lunar missions

Name	Country	Launch date	Instruments	References
SELENE/Kaguya	Japan	16 August 2007	X-ray and gamma-ray spectrometers (XRS and GRS): 20 km spatial resolution.	Okada et al. (1999, 2002b, 2008), Ogawa et al. (2006), Kobayashi et al. (2008).
			Spectral profiler: 0.5–2.6 μm; UV–VIS–IR spectrometer. Spectral bands: 415, 750, 900, 1000, 1050, 1250, 1550 nm. 20 m resolution for VIS; 62 m for IR/Near-IR for a 100 km orbit.	Asada et al. (2007), Ohtake et al. (2006, 2007, 2008), Matsunaga et al. (2008), Ogawa et al. (2008).
			High-resolution Terrain Camera (10 m/pixel); Radar Sounder; Laser Altimeter (5 m vertical resolution).	Araki et al. (1999, 2008), Haruyama et al. (2006, 2008), Honda et al. (2007), Demura et al. (2008).
			Lunar gravity field: measurements using relay satellite (RSAT); Very Long Baseline Interferometry (VLBI) Radio (VRAD) satellite.	Heki et al. (1999), Matsumoto et al. (1999, 2008), Namiki et al. (1999, 2008), Iwata et al. (2007), Liu et al. (2007), Kikuchi et al. (2008), Imamura et al. (2008).
			Magnetometer: Flux-gate variety; upper atmosphere and plasma imager; charged particle spectrometer.	Nishimura et al. (2006).
			Lunar radar sounder.	Ono et al. (2008).
			Plasma energy angle and composition experiment – PACE.	Oyama et al. (2002), Nabatov et al. (2003), Saito et al. (2008).
			High Definition TV Camera.	Honda et al. (2008).
Chang'e 1	China	24 October 2007	Optical Imaging System: • CCD Stereo Camera (120 m spatial resolution, 60 km swath width); • Interferometer; Spectrometer Imager 0.48–0.96 μm (∼200 m resolution; 25.6 km swath width); Laser Altimeter (1 m resolution); Gamma/X-ray spectrometers; Microwave radar system (at frequencies of 3, 8, 20 and 37 GHz penetrating the regolith to 30, 20, 10, and 1 m, resp.). Space environment monitor system: • High-energy solar particle detector; • Low-energy ion detector.	Sun and Dai (2005), Huixian et al. (2005), Zhi-Jian et al. (2005).
Chandrayaan-1	India	22 October 2008	High Energy X-ray spectrometer (HEX: volatile ^{210}Pb measurement). Spatial resolution = 20 km.	Goswami et al. (2005), Sreekumar et al. (2007).
			Hyper-Spectral Imaging spectrometer (HySI: determines mineral composition using the spectral range 400–920 nm; spatial resolution = 80 m.	Kumar and Chowdhury (2005a), RoyChowdhury et al. (2007).

Table 8. (*continued*)

Name	Country	Launch date	Instruments	References
			Terrain Mapping Camera (TMC): will provide a three-dimensional map of the lunar surface with an elevation resolution of ~5 m (spatial resolution = 10 m).	Kumar and Chowdhury (2005b).
			Moon Impact Probe containing Radar Altimeter, Video Imaging system, Mass Spectrometer.	
			Laser altimeter (LLRI: combined with the TMC data, an elevation map with an accuracy of 10 m will be produced.	Kamalakar et al. (2005).
			Miniature Imaging Radar Instrument (mini-SAR or mini-RF: to map polar dark areas and look for polar ice). Spatial resolution = 75 m/pixel.	Spudis et al. (2005), Bussey et al. (2006, 2007).
			Sub Atomic Reflecting Analyzer (SARA), which consists of three subsystems: a low-energy neutral atom or LENA detector; a Solar Wind Monitor or SWIM; a digital processing unit. Spatial resolution = 100 m.	Bhardwaj et al. (2005).
			The Moon Mineral Mapper (M^3). 430–3000 nm spectral range. Spatial resolution = 30 m.	Pieters et al. (2006, 2007), Green et al. (2007, 2008).
			Radiation Dose Monitor (RADOM).	
			Chandrayaan-1 X-ray Spectrometer (C1XS) for measuring Mg, Al, Si, Ca, Fe, Ti. (25 km spatial resolution)	Grande et al. (2008), Narendranath et al. (2008), Joy et al. (2008).
			Near Infra Red spectrometer (SIR-2: 0.93–2.4 μm; spectral resolution = 6 nm). Spatial resolution = 100 m.	
Lunar Reconnaissance Orbiter (LRO)	USA	April 2009	Lunar Orbiter Laser Altimeter – LOLA, to: determine global geodetic lunar topography (to 0.1 m vertical resolution, 5 m lateral resolution at poles, >100 m at equator); characterize polar region illumination over 1 year and map permanently shadowed regions; determine the distribution of meter-scale features (e.g., boulders); identify (if present) polar surface ice.	
			Lunar Reconnaissance Orbiter Camera – LROC; contains a narrow-angle and a wide-angle camera, with the latter having multispectral capabilities. Resolution: 50 cm/pixel images in Narrow Angle Camera; 100 m/pixel in 5 wavelengths in the Wide Angle Camera.	
			Lunar Exploration Neutron Detector – LEND. Neutron flux measurements from the lunar subsurface to search for significant accumulations of H (variations of 100 parts per million) with a 5 km spatial resolution at the poles and produce global H maps at a resolution of 5–20 km.	Sanin et al. (2006, 2007).
			Lyman-Alpha Mapping Project – LAMP will: map the lunar surface in the far UV; provide images and maps	

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			(100 m resolution) of the permanently shadowed regions using sky glow; assay the lunar exosphere and its variability; search for ice/frost in the polar regions.	
			Diviner Lunar Radiometer Experiment – DLRE is a nine channel infrared mapping radiometer. It will: chart the lunar day/night surface temperature at ~500 m resolution to identify cold traps; characterize thermal environments for habitability; determine global rock and mineral variations. Spatial resolution: 500 m scale maps of surface temperature, albedo, rock abundance, and ice stability.	Greenhagen and Paige (2006).
			Cosmic Ray Telescope for the Effects of Radiation – CRaTER will use tissue-equivalent plastics to investigate the effects of galactic cosmic rays on humans.	
			Mini-Radio-frequency technology demonstration – mini-RF baseline includes S-band (13 cm) and X-band (4 cm), two resolutions (baseline = 150 m/75 m pixels; zoom – 15 m/7.5 m pixels), and dual polarization capabilities.	
			Lunar crater observation and sensing satellite – LCROSS will use the Earth departure upper stage of the Atlas 5 as a 2000 kg impactor into a permanently shadowed region of the Moon. The 700 kg LCROSS satellite will actually pass through the impact plume and impact several kilometers from the initial impact to study heterogeneity of the lunar regolith (e.g., H distribution).	Heldmann et al. (2007), Chin et al. (2007a, b), Colaprete et al. (2008a, b), Ennico et al., (2008).
Gravity Recovery And Interior Laboratory (GRAIL)	USA	September 2011	2 twin spacecraft in a low-altitude (50 km), near-circular, polar lunar orbit to perform high precision range-rate measurements between them using a Kα-band payload. A high-resolution (30 × 30 km) high accuracy (<10 mGal) global gravity field map will be produced.	Zuber et al. (2008).

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environments, development critical technologies for future lunar exploration (e.g., lunar polar orbit injection, three-axis attitude stabilization, and thermal control; Takano et al., 2005), and the lunar surface using a high-definition TV camera for public outreach.

Chang'e 1 (http://www.cnsa.gov.cn/n615709/n772514/n772543/index.html): Chang'e 1 is the first in a series of lunar missions planned by the China National Space Administration and was launched in on 24 October 2007. It has four science objectives (Yue et al., 2007):

(1) obtain 3-D imagery of the lunar surface (excluding the poles) at a spatial resolution of 120 m and a swath width of 60 km;
(2) detect the contents and distribution of a number of chemical elements on the lunar surface (e.g., K, Th, U, O, Si, Mg, Al, Ca, Te, Ti, Na, Mn, Cr, La, etc.);
(3) preliminarily probe the depth of lunar soil (or regolith), and assessing its importance as a helium-3 resource; and
(4) explore the cis-lunar space environment.

These four goals will be realized through an array of instruments that are summarized in Table 8.

Chandrayaan-1 (http://www.isro.org/chandrayaan/htmls/home.htm): This represents India's first mission to the Moon and is designed to orbit the Moon for a 2-year period and was launched on 22 October 2008. The primary objectives of the Chandrayaan-1 mission are simultaneous chemical, mineralogical, and topographic mapping of the lunar surface at high spatial resolution (see Bhandari, 2005). Chandrayaan-1 will carry five domestic instruments (High Energy Gamma-ray spectrometer – HEX; Hyper-Spectral Imaging spectrometer – HySI; Moon Imapct Probe – MIP; Terrain Mapping Camera – TMC; Laser altimeter – LLRI) and six contributed instruments from international partners (Miniature Imaging Radar Instrument – mini-SAR or mini-RF, from the USA; Near-infrared spectrometer – SIR-2, from Germany; Sub Atomic Reflecting Analyzer – SARA from ESA (Sweden); Radiation Dose Monitor – RADOM, from ESA; Moon Mineral Mapper – M^3, from the USA); the Chandrayaan-1 X-ray Spectrometer (C1XS) from the UK. See Table 8 for a summary of these instruments.

Lunar Reconnaissance Orbiter (LRO) (http://lunar.gsfc.nasa.gov/): The LRO represents NASA's first mission returning to the Moon since the launch of Lunar Prospector in 1998. The LRO mission is scheduled to launch during April, 2009, and will have a minimum duration of 12 months including a 2-month commissioning phase (Chin et al., 2007a), with the possibility of extending the mission for up to 5 years. The LRO will be in a polar orbit at 40–50 km above the lunar surface and will contain seven instruments that will return data to define terrain roughness, usable resources, and the radiation environment (Chin et al., 2006, 2007a, b). Such data will aid in choosing landing sites for future human exploration of the Moon. The instruments are: Lunar Orbiter Laser Altimeter (LOLA); Lunar Reconnaissance Orbiter Camera (LROC); Lunar Exploration Neutron Detector (LEND – contributed by Roscosmos, Russia); Diviner Lunar Radiometer Experiment (DLRE); Lyman-Alpha Mapping Project (LAMP); Cosmic Ray Telescope for the Effects of Radiation (CRaTER); Radio-Frequency Technology Demonstration (mini-RF); Lunar Crater Observation and Sensing Satellite (LCROSS). See Table 8 for more details. The LROC data will be used for landing site identification (with unambiguous identification of meter-scale hazards, such as boulder fields), mapping areas of permanent shadow and permanent sunlight, meter-scale mapping of polar regions, global mineral mapping (e.g., ilmenite), characterization regolith properties, creation of global base maps, and will undertake repeat observations to enable the derivation of meter-scale topography as well as determine the recent flux of small impactors. The mini-SAR will be carried as a technology demonstration as its synthetic aperture radar (SAR) imaging modes are relevant to the goals of LRO, namely the search for water ice at the poles. The data generated will complement those from other LRO instruments, especially LEND. The LCROSS companion satellite will be launched in the same Atlas 5 launch vehicle as LRO. The LCROSS satellite, along with Earth- and space-based (e.g., LRO, Chandrayaan-1, etc.) observations will characterize the ejecta from a permanently shadowed crater created by the LCROSS impactor using visible through mid-IR and UV through radio spectrometers and cameras.

Gravity Recovery And Interior Laboratory (*GRAIL*) (http://moon.mit.edu/): The recently selected Discovery-class mission GRAIL has two primary objectives: (1) determine the structure of the lunar interior (crust to core); (2) advance understanding of the thermal evolution of the Moon (Zuber et al., 2008). This will be achieved by using a lunar analog of the terrestrial GRACE (gravity recovery) mission (Tapley et al., 2004). GRAIL will place two identical spacecraft in a 50 km circular polar orbit to perform high precision range-rate measurements between them (Zuber et al., 2008; Table 8). It is predicted that a high-resolution (30 km × 30 km) high accuracy (<10 mGal) global gravity field will be produced.

7.2. Future missions to the Moon: concept studies

The renewed focus on the Moon has inspired several nations to undertake mission concept studies and as such, there are a number of lunar missions being considered by various national space agencies. At the time of writing, no firm launch dates have been set. A

Table 9. A summary of lunar concept missions (as of June 2008)

Country	Mission name	Mission type	Objectives	Instrumentation	Nominal launch date	References
China	Chang'e 2	Lander		Rover.	2012	Yan et al. (2006).
China	Chang'e 3	Lander		Robotic sample return.	2017	Yan et al. (2006).
European Space Agency	MoonNext	Lander	Autonomous soft precision landing (200 m); Hazard avoidance; Lunar internal structure (ILN node); in situ geochemistry of the lunar South pole area; study lunar South pole environment, including the ULF/VLF background radiation of the universe.	TBD: Could include a rover. **Core** Instruments from: Site imaging, camera, Seismometer, Langmuir probe, Magnetometer, Laser retroreflector, man made ecosystem, Reversible solid oxide fuel cell. **Other** from: XRD, Gas analysis package, Sample prep and dist system, Lunar radio env., IR Spectrometer, Lunar meteoroid env., remote Raman-LIBS.	2016–2020	Crawford and Geelen (2007), Carpenter et al. (2008), Houdou et al. (2008), Koschny et al. (2008).
Germany	Lunar Exploration Orbiter (LEO)	Low Altitude Orbiter	Improve understanding of the lunar surface structure and composition, surface ages, mineralogy, physical properties, interior, thermal history, gravity field, regolith structure, and magnetic field. Mission length = 4 years.	Spectrometer: 0.2–14 μm, <1 m in stereo, <10 m spectrally. Hi-Res. Synthetic Aperture Radar (25 cm wavelength) and microwave instrument (regolith structure to 2 m); two subsatellites with magnetometers.	2012	Jaumann et al. (2008).
India	Chandrayaan-2	Lander	Chemical analyses of rocks and regolith at the poles.	Rover with possible RTG power system.	2010–2011	www.chandrayaan-1.com/chandrayaan2/index2.html
Italy	Missione Altimetrica Gravimetrica geochimica Italiana lunAre (MAGIA)	Orbiter and subsatellite	Fundamental physics: measurement of the gravitational red shift; measurement of the selenocenter.	Atomic clock, laser retroreflector array.	2014	Dell'Angelo et al. (2008)
Japan	SELENE-B (SELENE-2)	Lander	Examine either the central peak of a large impact crater or inside one of the permanently shadowed craters at the poles. Technology demonstration – survive the lunar night.	Rover: multiband stereo imager, a gamma-ray spectrometer, and a sampling tool, magnetometer. Lander: a multispectral telescopic imager, a sampling system, and a sample analysis package with an X-ray spectrometer/diffractometer, a multiband microscope as well as a sample cleaning and grinding device.	2010–2011	Sasaki et al. (2002), Shirai et al. (2003), Kubota et al. (2005), Matsumoto (2005a, b), Matsumoto et al. (2006), Okada et al. (2006), Tanaka et al. (2008).
Japan	SELENE-C (SELENE-3)	Lander	Exploring the polar regions of the Moon and for testing technology for long-term survival of the lunar night, sample return, and in situ resource utilization.	Rover: TBD.	2013–2015	Matsumoto et al. (2006).

Table 9. (*continued*)

Country	Mission name	Mission type	Objectives	Instrumentation	Nominal launch date	References
Russia	Lunar Glob	Orbiter with penetrators	Explore the internal structure of the Moon and also polar volatiles.	3 broad-band seismometers deployed using penetrator-landers (a semi-hard landing of 80 ± 20 m/s). 2 deployed near the A11 and A12 sites, 1 at S pole (Shackleton Crater?). Ten high-speed (2.5 km/s) penetrators deploy a dense seismic network in Mare Fecunditatis. Orbiter: gamma-ray, neutron, Vis-IR spectrometers; space environment studies (plasma, particles and magnetic field).	2012	Galimov (2005), Covault (2006).
Ukraine	Ukrselena	Orbiter	Study the global distribution of surface roughness in mm-cm scales (including the permanently shadowed regions). Investigate physical properties of the lunar surface (e.g., determination of average particle size of the regolith; examination of the arrangement of the regolith in mm-scales).	Synthetic aperture imaging radar working in mm-range. An imaging optical spectropolarimeter.		Shkuratov et al. (2003, 2007).
United Kingdom	Moon Lightweight Interior and Telecom Experiment (MoonLITE)	Orbiter with penetrators	Investigate: the origin, differentiation, internal structure and early geological evolution of the Moon; the origin and flux of volatiles in the Earth–Moon system; 'ground truth' geochemical data to complement orbital remote-sensing observations.	4 penetrators containing seismometer, heat flow sensors, X-ray spectrometer, and mutual impedance probe/calorimetric analyzer/pressure sensor/optical spectrometer/miniature ion trap mass spectrometer. Operational life of 1 year. The orbiter will also carry technology demonstration experiments for navigation and telecommunication technologies that will support future missions.	2011–2013	Phipps and Gao (2006), Gao et al. (2007, 2008), Ball (2007), Davies (2007), Crawford et al. (2008), Smith et al. (2008).
USA and Others	ILN (International Lunar Network)	Landers	Understand the internal structure of the Moon, along with its thermal evolution.	Two landers containing the first nodes of the network. Seismometer, heat flow sensors, magnetometer, laser retroreflector.	2012–2014	Cohen et al. (2008), Stern et al. (2008), http://nasascience.nasa.gov/missions/iln.
USA	Lunar Atmosphere and Dust Environment Explorer (LADEE)	Orbiter	Determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity; determine if the Apollo astronaut sightings of diffuse emission at 10 s of km above the surface were Na glow or dust; document the dust impactor environment (size-frequency) to help guide design engineering for the outpost and also future robotic missions.	Dust detector; neutral mass spectrometer.	September 2011	Leshin et al. (2008), http://nasascience.nasa.gov/missions/ladee.

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summary of these mission concepts, including scientific objectives and instrumentation, is presented in Table 9 along with the relevant references.

8. Technological developments

The next era of lunar exploration has highlighted several areas that require significant technological developments in order to enhance or, in some cases, facilitate scientific investigations. The NASA Advisory Council Tempe workshop (Jolliff, 2007) made recommendations concerning technological investments needed to achieve several of the highest-ranked scientific objectives. These include (but are not limited to) the following:

- Imaging, ranging, position determination and other aids to field exploration and sample documentation.
- Interfacing of human and robotic field exploration capabilities.
- Long-lived (6-year lifetime minimum) power supplies, especially in the 1–15 W range – vital for network science.
- Hard vs. soft landing options (capabilities) for deploying instrument packages from orbit to establish network stations.
- Development of robotically deployable heat-flow probes.
- Analytical capabilities in the field – efficient sample documentation and analysis by astronauts on EVAs and by robotic field assistants (e.g., hand-held laser Raman spectrometer, X-ray fluorescence spectrometer, etc.).
- Field exploration equipment development and systems integration for lunar fieldwork.
- Automated instrumentation/equipment deployment capabilities.
- Automated (robotic) sample return.
- Technologies to sample, document samples, and make measurements in extreme (e.g., permanently shadowed) environments.
- Integration of scientific equipment and systems with surface mobility systems, including rovers, flyers, and space suits.

It is critical for the success of the next stage of lunar exploration that such technology developments are to be encouraged. As noted in NAC Recommendation S-07-PSS-4 (Technology Development Needs), such technologies need not be lunar-specific, but can feed forward to Mars (and beyond).

9. Getting ready for Mars

While the above discussion concentrates on the science aspects of returning to the Moon, there are many other considerations. These are highlighted by concentrating upon the aspect of the exploration strategy that puts the Moon in the critical path to go to Mars and beyond. Although Mars is distinct from the Moon because it has an atmosphere and liquid water was present on the surface at some point in its history, many of the science questions regarding the Moon may also be asked of Mars. This is especially true of the planetary interior questions, regolith development, and volatile budgets, as well as thermal and bombardment histories. For example, the Moon can be used to develop, test, and establish network science instrumentation off planet. This could then be fed forward to Mars. Networks could be established for geophysical, atmospheric, and radiation monitoring – the data would be equally useful for the Moon and Mars.

9.1. ISRU

One of the four ‘‘Goals and Objectives’’ of President Bush’s (2004) speech was to ‘‘Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations’’. In order to do this, ISRU will be critical for any human Mars mission. Therefore, involvement of ISRU in any lunar outpost scenario will mitigate risk for Mars by, at the very least, demonstrating the capability of manipulating regolith in a non-terrestrial environment. A robotic pilot plant that can generate fuel and life support constituents from regolith could be demonstrated on the Moon. Such a demonstration would greatly help reduce risk if it can be shown to be applicable to Mars and could be sent ahead of human arrival.

9.2. Planetary protection

Planetary protection protocols are not required for the Moon, although recently it was designated a ‘‘category II body’’, meaning documentation of mission operations and an inventory of organic materials carried by visiting spacecraft must be made (Conley, 2008). The Moon can, however, provide an excellent testbed for developing technologies that will enable human exploration of planetary bodies that are protected, such as Mars. Such technologies would include those that limit human-associated contamination, as well as limiting organic contamination from equipment required for exploration. At the Tempe Workshop (Jolliff, 2007), the Planetary Protection Subcommittee of the NAC submitted six recommendations that have distinct feed-forward implications for Mars. These were given different priorities and are summarized in Table 10.

9.3. Mission development

Drake (2007) succinctly presented what needed to be learned at the Moon in order to support subsequent

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Table 10. Planetary protection priorities for the Moon as defined by the Planetary Protection Subcommittee of the NASA Advisory Council

Priority	Level
Perform in situ investigations of a variety of locations on the Moon by highly sensitive instruments designed to search for biologically derived organic compounds to assess the contamination of the Moon by lunar spacecraft and astronauts. Understand possible contamination of lunar ices with non-organically-clean spacecraft. Evaluate and develop technologies to reduce possible contamination of lunar ices to address both mission science and resource contamination concerns. Use the Moon and lunar transit/orbits as a testbed for planetary protection procedures and technologies involved with implementing human Mars mission requirements prior to planning human Mars missions.	High
Perform chemical and microbiological studies on the effects of terrestrial contamination and microbial survival, both during lunar robotic and human missions (dedicated experiments and "natural" experiments in a variety of lunar environments/depths, etc.) and during the Apollo missions (study Apollo sites). Develop technologies for effective containment of samples collected by humans to feed forward into designs that will help prevent forward and backward contamination during Mars missions.	Medium
Use the lunar surface as a Mars analog site, to test proposed life detection systems in a sterile environment that are designed to go to Mars.	Low

human exploration of Mars. These suggestions were based upon a 900-day Mars mission scenario with 500 days on the Martian surface and included:

(1) Development and testing of long-term life support systems through long-duration Moon missions:
  - closed-loop systems (e.g., water, O_2);
  - integrated testing of multiple systems (O_2 generation; CO_2 removal; reliability of crop production);
  - validation and demonstration of radiation protection systems, medical equipment, food systems (including storage);
  - protocols for plant growth (nutrition and psychological health);
  - validation of the effectiveness and performance of countermeasure equipment over the long term (years);
  - development of dust mitigation strategies.

(2) The Moon can serve as a vital planetary venue for demonstration of:
  - developing efficient human–machine interactions;
  - surface EVA in greater numbers and durations for system validation;
  - validate EVA traverse mapping and route planning techniques;
  - system performance and reliability;
  - integration of technology for efficient sampling, documentation, and mapping in the field;
  - high grading of samples at the outpost for return to Earth;
  - planetary protection (forward and backward) protocols.

9.4. Science goals

Some of the science objectives for the Moon developed by the LEAG GEO-SAT have direct relevance for the feed forward to Mars, as evaluated by MEPAG. Generally, the highest priority science goals in terms of feed forward to Mars are the high priority objectives for the Moon (Table 5) and these are: (A) determine the internal structure and dynamics of the Moon to constrain the origin, composition, and structure of the Moon and other planetary bodies; (B) characterize impact cratering over the Moon's geologic history, to understand early solar system history; and (C) study the lunar regolith to understand the nature and history of solar emissions, galactic cosmic rays, and the local interstellar medium.

10. Summary

The next two decades will see a flotilla of spacecraft heading to the Moon to conduct scientific exploration in order to answer at least some of the questions that remain for the Moon and pave the way for much more detailed human exploration that was conducted during Apollo. The major difference between this "renewed spirit" of lunar exploration and the Apollo era is that it is broader in scope: it is a multinational effort and will build up a lunar outpost for human occupation lasting several months. Coordination between different space agencies is critical for ensuring the safety of multiple craft orbiting the Moon at any one time and integration of data sets from the various missions. It is unclear how this will be achieved at present, but will require

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international cooperation heretofore unseen in the history of space exploration (e.g., Abdul-Kalam, 2005). The Global Exploration Strategy (2007) is a good first step towards this enhanced international cooperation, as is the proposed Internal Lunar Network (see Table 9).

It is also vital that the big picture be kept in focus while developing a long-term exploration program. In the case of human return to the lunar surface it is linked to developing knowledge, protocols and instrumentation to allow humans to travel beyond the Moon. NASA will need a transition strategy in order for it to go beyond the Moon. The infrastructure established on the Moon should not be abandoned, but be given over/leased to commercial enterprises to use and maintain. Therefore, it is vital that on ramps for commercial participation be built in to the lunar architecture as early as possible (e.g., Sadeh et al., 2005). The inclusion of ISRU in the sustainability of the lunar outpost is one way to achieve this (e.g., Duke et al., 2003).

This broad framework will allow important scientific exploration to be conducted and technological discoveries to be made. It will stimulate the youth to become involved in science and engineering as well as open up an exciting new area of commercial opportunities. After nearly a decade in the exploration wilderness, the Moon is back in a brighter spotlight that clearly shows how much we still have and need to learn from our closest neighbor in the Solar System.

Acknowledgments

This paper greatly benefitted from thoughtful and detailed reviews by Chip Shearer, Paul Spudis, and Klaus Keil, whose time and efforts are greatly appreciated. This research was partially supported by NASA Cosmochemistry Grant NNG06GF11G-S1.

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Please cite this article as: Neal, C.R., The Moon 35 years after Apollo: What's left to learn? Chemie Erde-Geochemistry (2008), doi:10.1016/j.chemer.2008.07.002

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Please cite this article as: Neal, C.R., The Moon 35 years after Apollo: What's left to learn? Chemie Erde-Geochemistry (2008), doi:10.1016/j.chemer.2008.07.002

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Please cite this article as: Neal, C.R., The Moon 35 years after Apollo: What's left to learn? Chemie Erde-Geochemistry (2008), doi:10.1016/j.chemer.2008.07.002

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Please cite this article as: Neal, C.R., The Moon 35 years after Apollo: What's left to learn? Chemie Erde-Geochemistry (2008), doi:10.1016/j.chemer.2008.07.002

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Please cite this article as: Neal, C.R., The Moon 35 years after Apollo: What's left to learn? Chemie Erde-Geochemistry (2008), doi:10.1016/j.chemer.2008.07.002

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