

Hydrothermal alteration at the Lonar Lake impact structure, India: Implications for impact cratering on Mars

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Abstract–The 50,000 year old, 1.8 km diameter Lonar crater is one of only two known terrestrial craters to be emplaced in basaltic target rock (the 65 million year old Deccan Traps). The composition of the Lonar basalts is similar to martian basaltic meteorites, which establishes Lonar as an excellent analogue for similarly sized craters on the surface of Mars. Samples from cores drilled into the Lonar crater floor show that there are basaltic impact breccias that have been altered by post-impact hydrothermal processes to produce an assemblage of secondary alteration minerals. Microprobe data and X-ray diffraction analyses show that the alteration mineral assemblage consists primarily of saponite, with minor celadonite, and carbonate. Thermodynamic modeling and terrestrial volcanic analogues were used to demonstrate that these clay minerals formed at temperatures between 130°C and 200°C. By comparing the Lonar alteration assemblage with alteration at other terrestrial craters, we conclude that the Lonar crater represents a lower size limit for impact-induced hydrothermal activity. Based on these results, we suggest that similarly sized craters on Mars have the potential to form hydrothermal systems, as long as liquid water was present on or near the martian surface. Furthermore, the Fe-rich alteration minerals produced by post-impact hydrothermal processes could contribute to the minor iron enrichment associated with the formation of the martian soil.

INTRODUCTION

The 50,000 year old, 1.8 km diameter Lonar Lake impact structure is located in the Buldhana district of Maharashtra, India (19°58'N, 76°31'E) (Nayak 1972; Fredriksson et al. 1973). This relatively small crater is one of only two known terrestrial craters to be emplaced in basaltic target rock, the other being the Logancha crater in Russia (Feldman et al. 1983). The floor of this crater currently lies 90 m below the pre-impact surface and the rim of the crater rises to a height of 30 m above the crater floor (Fudali et al. 1980). The target rocks are predominantly classified as quartz normative tholeiites that have a moderate degree of iron enrichment (Roy and Chatterjee 1998). These tholeiitic basalts have lower MgO, higher total iron, lower Al₂O₃, and higher CaO content than do other terrestrial tholeiitic provinces (Roy and Chatterjee 1998). The unusual compositional characteristics of the Lonar crater closely match the composition of martian basalts, which also have higher Fe and lower Al abundances than most terrestrial basalts (McSween 1994; McSween 2002) (Fig. 1). Therefore, the Lonar crater may be one of the best terrestrial analogues for studying geochemical processes on the basaltic surface of Mars. Previous studies that have attempted to use terrestrial craters as martian analogues involved craters that were emplaced into more felsic, and therefore, less representative target rock (e.g., Newsom et al. 1986; Morris et al. 1995; McCarville and Crossey 1996).

One of the more fascinating characteristics of the Lonar crater was documented in 1996 by Nayak, who suggested that the groundwater underlying the Lonar crater was heated by remnant impact energy, thus resulting in the establishment of post-impact hydrothermal activity. The validity of this hydrothermal hypothesis is supported by evidence of impactinduced hydrothermal systems in other terrestrial craters (e.g., Newsom et al. 1986; McCarville and Crossey 1996; Allen, Gooding, and Keil 1982) (Table 1). Previous investigations of the Lonar crater briefly mentioned "alteration products" (e.g., Kieffer et al. 1976; Fredriksson et al. 1973; Fudali et al. 1980; Nayak 1996), however, no detailed analyses were previously conducted. Therefore, a major goal of this study is to identify the major alteration phases in the available samples and to determine if the alteration was the result of impact-induced hydrothermal activity. These results are then used to make inferences for similar processes on the surface of Mars.



Fig. 1. Compositional comparison of Lonar target rocks and Hawaiian basalt to basaltic martian meteorites (McSween and Keil 2000) and results from the Mars Pathfinder mission (Brückner et al. 2001). The Lonar crater samples appear to be the closest in composition to martian rocks.

Table 1.	Compilation	of pertinent	characteristics	from selected	terrestrial craters.
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Crater	Reference	Diameter	Definitive hydrothermal activity	Occurrence of alteration	Alteration material
Praetoria Saltpan	Reimold et al. (1999)	1.2 km	No	None	None
Lonar	This study	1.8 km	Yes	Vugs/Vesicles	Saponite, Celadonite, Calcite
Rotter Kamm	Koeberl et al. (1989)	2.5 km	Yes	Not specified	Alteration clays, Calcite, Quartz
Brent crater	Allen et al. (1982)	3.8 km	Yes	Not specified	Chlorite, Smectite, Glauconite
Ilyinets	Gurov et al. (1998)	4 km	Yes	Vesicles & cracks	Chlorite, Montmorillonite, Calcite
Kärdla	Kirsimä et al. (2002)	4 km	Yes	Vugs&Vesicles	Chlorite, Quartz, Fe-oxides, Calcite
Lake Mien	Allen et al. (1982)	5 km	Yes	Vugs/Vesicles	Montmorillonite, Limonite, Zeolites
Saaksjarvi	Allen et al. (1982)	5 km	No	Vugs/Vesicles	Fe-Chlorites
Lake Wanapitei	Allen et al. (1982)	8.5 km	No	Vugs/Vesicles	Smectites
East Clearwater	Allen et al. (1982)	22 km	Yes	Not specified	General alteration clays
Ries	Newsom et al. (1986)	23 km	Yes	Vesicles & glasses	Smectite, Calcite, Illite, Chlorite,
Rochechouart	Allen et al. (1982)	23 km	No	Not specified	Mg-Chlorite
Lake St. Martin	Allen et al. (1982)	23 km	Yes	Vugs/Vesicles	Fe-Smectite, Montmorillonite
Haughton	Osinki et al. (2001)	24 km	Yes	Vugs/Vesicles	Sulfides, Sulfates, Carbonates
Mistastin	Grieve (1975)	28 km	Yes	Vugs/Vesicles	Fe-Montmorillonite, Calcite
West Clearwater	Allen et al. (1982)	32 km	Yes	Not specified	Saponite, Nontronite
Charlevoix	Allen et al. (1982)	46 km	No	Vugs/Vesicles	Fe-Chlorites, Calcite
Manicouagan	Allen et al. (1982)	70 km	Yes	Vugs/Vesicles	Saponite, Nontronite
Sudbury	Allen et al. (1982)	250 km	Yes	Vugs/Vesicles	Saponite, Nontronite

METHODS

Backscattered electron images were obtained using the Institute of Meteoritics JEOL 5800LV scanning electron microscope (SEM) with an attached Oxford Isis Series 300 energy dispersive microanalytical system and cathodoluminescence detector. The SEM was optimized for high resolution imaging, which requires a 20 kV acceleration voltage, a sample current of 20 nA, a spot size of 8–10 nm, and a working distance of 8–16 mm. A process known as "feature scan" was used on the SEM to determine the modal abundance of alteration phases in the Lonar samples. Backscattered electron imaging was combined with shortduration EDS analysis to classify phases on the basis of userdefined chemical criteria. An EDS spectrum was collected from each individual phase and a semiquantitative analysis was done on the spectrum from each phase. The phases were classified by sorting the elemental concentrations on the basis of standard minerals. The output of the program is an area percentage of all the defined phases plus any unclassified phases.

Major element abundances in the Lonar samples were obtained with the JEOL 733 electron microprobe using a 15 kV accelerating voltage, a 20 nA beam current, counting times of 20 s for major element peaks, and a 2-10 µm spot size. Trace elements in carbonates were measured using the Cameca ims 4f operated by the Institute of Meteoritics. Primary O⁻ ions were accelerated through a nominal potential of 10 kV. A primary beam current of 30 nA was focused on the sample over a spot diameter of 30 µm. Sputtered secondary ions were energy filtered using a sample-offset voltage of 75 V and an energy window of ±25 V. Absolute concentrations of each element were calculated using empirical relationships of trace element/44Ca intensity ratios, which in turn were normalized to known CaO content. Calibration curves were constructed using two carbonate standards, to account for matrix effects.

Powdered basalts from the Lonar crater were analyzed by X-ray diffraction (XRD) in the XRD Laboratory in the Department of Earth and Planetary Sciences at the University of New Mexico, using a Scintag Pad V diffractometer with DataScan 3.1 software (from MDI, Inc.) for system automation and data collection. Cu-K-alpha radiation (40 kV, 35 mA) was used with a Bicron Scintillation detector (with a curved graphite-crystal monochromator). Data were analyzed with Jade 5 Software (from MDI, Inc.) using the ICDD (International Center for Diffraction Data) PDF2 database (rev. 1999) for phase identification.

MINERALOGICAL AND TEXTURAL DESCRIPTION OF THE LONAR BASALTS

During the 1970s, the Smithsonian Institution worked in conjunction with the Geological Survey of India to obtain a representative suite of samples from the floor and rim of the Lonar crater (see Fredriksson et al. 1973, 1979) (Fig. 2). To characterize the type and degree of hydrothermal alteration at the Lonar crater, we have analyzed samples from each of the known textural varieties in the drill cores that were described by Fredriksson et al. (1973) (e.g., basalt, hard and soft trap rock, and shocked rock breccia). Because the nomenclature used by Fredriksson et al. (1973) is somewhat outdated, we refer to the proposed IUGS classification for impact rocks (Stoeffler, personal communication 2002).

Samples obtained from the Lonar site are generally vesicular, aphanitic basalts with sporadic occurrences of

plagioclase phenocrysts. Labradorite comprises 5–15% of the bulk basalt, and the labradorite grains themselves primarily occur as phenocrysts ranging in size from 1.5 mm to 1 cm in length (Kieffer et al. 1976). The pyroxenes, such as augite, comprise the majority of the primary mineral assemblage. These pyroxenes vary widely in shape, size, and extent, depending on the sample. The basaltic groundmass is composed of augite, relatively minor amounts of labradorite, and several textural varieties of ilmenite (Fredriksson et al. 1973, 1974, 1979; Kieffer et al. 1976). The ilmenite in the groundmass ranges from elongated rectangles to square-shaped cross sections. Additional information concerning the details of the petrology and mineralogy of these samples can be found in the detailed works by Fredriksson et al. (1973) and Kieffer et al. (1976).

Backscattered electron images (Figs. 3–9) of Lonar samples demonstrate textural evidence for post-impact hydrothermal alteration including replacement textures, ubiquitous pockets of alteration, alteration of impact glasses, and multiple generations of hydrothermal carbonate growth. We have used the alteration in these images to show that the degree of alteration at Lonar increases in abundance and severity from west to east across the crater (Fig. 2). The unique mode of alteration at Lonar is demonstrated through the descriptions of samples in each of the five drill cores, beginning with drill core LNR-1 (see Fig. 2 for location). It should be noted, however, that the drilling processes might have resulted in a biased sample, with the fresher material being over represented with respect to the altered material (Mittlefehldt, personal communcation 2002).

Drill Core LNR-1

Samples from this core contain an abundance of small, blocky, ilmenite crystals as well as several large labradorite phenocrysts. In particular, thin section NMNH 116569–5, can be classified as a parautochthonous target rock (IUGS terminology) with little to no evidence of shock. The primary minerals in this section, including augite, are sporadically altered to form Mg and Fe-rich layered silicates (Fig. 3). These layered silicates were further identified by the SEM point counting method "feature scan," which suggests that thin section NMNH 116569–5 contains 0.35 area percent saponite and 0.15 area percent celadonite.

Drill Core LNR-5

The majority of the material that was recovered from this core is in the form of lake sediment. One basaltic thin section from this core did, however, exhibit a fine-grained basaltic groundmass with several altered plagioclase grains that appear to be altered to celadonite (Table 2). This was the only thin section that contained celadonite as the major alteration phase (Table 2). This section also demonstrated a few vein



Fig. 2. Schematic cross section of the Lonar crater modified from Fredriksson et al. (1973). This diagram shows the location of the five drill cores obtained by the Fredriksson et al. group. The location of the three perennial springs is also shown.

Table 2. Results from microprobe analyses of alteration clays (cations based on 22 oxygens).

	Oxides in weight percent										
Label	SiO ₂	Al_2O_3	TiO ₂	MgO	FeO	MnO	CaO	Na ₂ O	K ₂ O	Total	H_2O
Saponite Reference	42.76	6.76	0.29	16.80	16.40	0.19	2.57	0.38	0.06	86.21	13.79
116569-42 Average	42.56	6.40	0.05	14.79	16.71	0.11	1.22	0.22	1.81	83.85	16.15
116569-13 Average	40.59	4.96	0.23	12.47	23.94	0.05	1.55	0.49	1.18	85.45	14.55
116569-26 Average	43.65	6.26	0.09	16.02	18.41	0.04	1.66	0.29	1.86	88.26	11.74
Celadonite Reference	53.12	0.36	0.05	2.49	29.69	0.03	1.51	3.04	0.30	87.55	12.45
116569-5 Average	52.02	0.68	0.10	4.37	25.03	0.07	0.67	3.75	0.50	87.18	12.82
	Formula Units										
	Formula	a Units									
Label	Formula Si	a Units Al	Ti	Mg	Fe	Mn	Са	Na	K	Total	
Label Saponite Average	Formula Si 6.72	Al 1.25	Ti 0.03	Mg 3.94	Fe 2.16	Mn 0.03	Ca 0.43	Na 0.11	K 0.01	Total 14.68	
Label Saponite Average 116569–42 Average	Formula Si 6.72 6.92	Al 1.25 1.23	Ti 0.03 0.01	Mg 3.94 3.58	Fe 2.16 2.27	Mn 0.03 0.02	Ca 0.43 0.21	Na 0.11 0.07	K 0.01 0.38	Total 14.68 14.68	
Label Saponite Average 116569–42 Average 116569–13 Average	Formula Si 6.72 6.92 6.77	Al 1.25 1.23 0.98	Ti 0.03 0.01 0.03	Mg 3.94 3.58 3.10	Fe 2.16 2.27 3.35	Mn 0.03 0.02 0.01	Ca 0.43 0.21 0.28	Na 0.11 0.07 0.16	K 0.01 0.38 0.25	Total 14.68 14.68 14.92	
Label Saponite Average 116569–42 Average 116569–13 Average 116569–26 Average	Formula Si 6.72 6.92 6.77 6.81	Al 1.25 1.23 0.98 1.15	Ti 0.03 0.01 0.03 0.01	Mg 3.94 3.58 3.10 3.72	Fe 2.16 2.27 3.35 2.40	Mn 0.03 0.02 0.01 0.00	Ca 0.43 0.21 0.28 0.28	Na 0.11 0.07 0.16 0.09	K 0.01 0.38 0.25 0.36	Total 14.68 14.68 14.92 14.83	
Label Saponite Average 116569–42 Average 116569–13 Average 116569–26 Average Celadonite Avgerage	Formula Si 6.72 6.92 6.77 6.81 8.33	Al 1.25 1.23 0.98 1.15 0.07	Ti 0.03 0.01 0.03 0.01 0.01	Mg 3.94 3.58 3.10 3.72 0.58	Fe 2.16 2.27 3.35 2.40 3.89	Mn 0.03 0.02 0.01 0.00 0.00	Ca 0.43 0.21 0.28 0.28 0.25	Na 0.11 0.07 0.16 0.09 0.92	K 0.01 0.38 0.25 0.36 0.06	Total 14.68 14.68 14.92 14.83 14.12	

structures (<10 μ m wide) running through the matrix that appeared to be lined with a very fine-grained material. However, a definitive microprobe analysis could not be conducted due to the small nature of these veins.

Drill Core LNR-2

This core from the center of the crater (Fig. 2) provides multiple lines of evidence for hydrothermal alteration. This core is represented by three distinctly different thin sections from three different levels in the drill core. Thin section NMNH 116569–13 is classified as a parautochthonous lithic impact breccia and was obtained from a depth of 110 m. This shocked lithic breccia contains large, fragmented pieces of plagioclase and several degraded ilmenite fragments. Overall, this thin section exhibits two major zones of alteration, including signs of primary mineral replacement (Fig. 4). This alteration texture is reminiscent of replacement textures seen in plagioclase and pyroxene phenocrysts that were hydrothermally altered by fissure fumaroles in the Valley of Ten Thousand Smokes (VTTS), Alaska (e.g. Spilde, Brearley, and Papike 1993).

Thin section NMNH 116569–13 also demonstrates the occurrence of pockets of alteration (Fig. 5). This type of alteration shows vesicles that have been filled in with clays and surrounded by hydrothermal carbonates (Fig. 5). This type of alteration is relatively common in the Lonar basalts and becomes increasingly abundant in drill cores on the eastern side of the crater. This mode of alteration is also demonstrated in thin section NMNH 116569–26 from LNR-2, a sample of parautochthonous target rock from a depth of 245 m. The feature scan results for this section found 6.0 area percent of saponite and 0.2 area percent of celadonite.

The deepest thin section from this core, NMNH 116569– 27, is a sample of parautochthonous lithic impact breccia from 310 m deep. This thin section has an extremely heterogeneous, brecciated, and altered groundmass, including several zones of alteration. Perhaps more important, however,



Fig. 3. Backscattered electron image of a "massive" clay from thin section NMNH 116569–5 (drill core LNR-1, scale bar 20 microns). This alteration material occurs sporadically throughout drill core LNR-1 and has been identified via microprobe analyses as celadonite.



Fig. 4. Comparison of dissolution textures (arrows) from the Lonar crater and from the Valley of Ten Thousand Smokes, Alaska. In each case, the primary mineral (plagioclase) is being replaced by an alteration clay: a) backscattered electron image of dissolution textures in sample NMNH 116569–13, scale bar 20 microns; b) backscattered electron image (scale bar 20 microns) of a hydrothermally altered plagioclase grain from VTTS (see Spilde, Brearley, and Papike 1993).

is the presence of multiple shocked plagioclase grains. These shocked grains are important because they provide evidence for the gradational conversion of plagioclase to maskelynite (Fig. 6). These grains also provide evidence for the preferential dissolution of maskelynite by hydrothermal fluids (Fig. 6). Both aspects of alteration in this thin section are similar to the alteration of shocked materials documented by French (1998) at the Ries crater in Nördlingen, Germany. Similar materials were studied in detail by Kieffer et al. (1976) who used the shock features to show that the impact event reached pressures of up to 100 GPa.

Drill Core LNR-3

The material from this core, which is the second closest core to the eastern edge of the crater (Fig. 2), has a relatively



Fig. 5. Backscattered electron image of "pocket alteration" in thin section NMNH 116569–13 (drill core LNR-2). Two vugs have been filled in with saponite and appear to be surrounded by hydrothermal carbonates. The image is approximately 500 mm wide.



Fig. 6. This backscattered electron image shows an example of dissolution textures from the Lonar crater (scale bar 100 microns). The arrows are pointing to the preferential dissolution of mechanically weak maskelynite.

coarse-grained matrix with large labradorite and augite phenocrysts. The samples also exhibit an abundance of bladed ilmenite crystals and several zones of alteration. The most dominant feature in this core, however, is the abundance of alteration pockets (Figs. 7 and 8), similar to that found in drill core LNR-2. Feature scan results for thin section NMNH 116569–42 suggest that there is 2.2 area percent of saponite and 0.5 area percent of celadonite in this thin section.

Drill Core LNR-4

Samples from the eastern most drill core LNR-4 (Fig. 2), demonstrate all of the hydrothermal textures that were

previously discussed and can be classified as parautochthonous cataclastic breccias. Thin section NMNH 116569–50 demonstrates a relatively large vesicle that has been intersected by multiple veins and is lined with secondary minerals including clays and carbonates (Fig. 9). Feature scan results for thin section NMNH 116569–50 suggest that there is 3.4 area percent of saponite and 0.02 (effectively zero) area percent of celadonite.

SAMPLE ANALYSIS

Detailed microprobe analyses were used to identify the Fe-rich clays in the available Lonar thin sections. This method of identification is similar to the procedures outlined by Smith and Norem (1986), Jepson and Rowse (1975), and Velde (1984). The average compositions of reference clays found in Velde (1985), Newman (1987), Deer, Howie, and Zussman (1996), and McKinley (1990) (Table 2) were plotted on a ternary diagram to provide a compositional reference for the unknown samples (Fig. 10). Microprobe analyses of the clay material in thin section NMNH 116569-42 (LNR 2), when compared to the above mentioned reference clays, show that the alteration material is best saponite approximated by the composition of $([Mg,Fe]_3[A1,Si]_4O_{10}[OH]_2^{-}[1/2Ca,Na]_{0.3} \cdot 4H_2O)$ (Fig. 10). Similar microprobe analyses of the clays in thin section NMNH 116569–13 (LNR 3) suggest that those clays are saponite as well (Fig. 10). It should be noted that saponite is a trioctahedral smectite that only forms as a result of the hydrothermal alteration of basalt (Deer, Howie, and Zussman 1996; Velde 1985). Fe-rich saponite typically forms in reducing environments (Güven 1988), as in our samples from below the crater floor, which contrasts with the oxidized



Fig. 7. Backscattered electron image of several pockets of alteration, which are dominant features in thin section NMNH 116569–42 (drill core LNR-3, scale bar 500 microns).



Fig. 8. Backscattered electron image of saponite in thin section NMNH 116569–42 (drill core LNR-3). This type of alteration becomes increasingly pervasive as one approaches the NE side of the crater.

impact melts formed in the rim materials. The Lonar saponite data can be compared with similar alteration products studied by Robert and Goffé (1993) in vesicles in basalts altered by fresh water during cooling in water-rich environments such as riverbeds. The Lonar saponite shows a close similarity in composition between the early formed "Fe-Mg saponite," as opposed to the later formed "Fe-saponite" in basal basalts from the Massif Central in France and the Cascade Range of Southern Washington.

Due to the limited mass and availability of the Lonar samples, it was difficult obtain abundant X-ray diffraction data. However, X-ray diffractometry of a fraction of sample NMNH 116569–40 revealed a strong indication of a phase expandable to 16.6 Å on glycolation. The pattern contained



Fig. 9. Backscattered electron image of a large vesicle from thin section NMNH 116569–50 (drill core LNR-4). This vesicle has been intersected by at least two veins, which has resulted in the deposition of clays and carbonates. Shown on the image are the 5 locations of microprobe analyses.

evidence of 5 peaks in the basal series and a marginal detection of the 060 spacing of 1.52 Å. This result closely matches an Fe-rich saponite, which was confirmed by microprobe data for this sample. A search by microprobe for minor alteration phases other than saponite was unsuccessful, with the exception of analyses from thin section NMNH 116569–5 (LNR-1), which show the presence of celadonite (KFe[Mg,Fe]Si₄O₁₀[OH]₂), a hydrothermal alteration product of basalt (Deer, Howie, and Zussman 1996; Newman 1987).

As was mentioned previously, thin section NMNH 116569–50 (LNR-4) contains a large vesicle lined with alteration products. Cathodoluminescence was used to show that the vesicle is lined by at least two generations of carbonate material (Fig. 11). Microprobe analyses of this carbonate material show that the carbonate is highly variable in nature and even appears to vary from location to location (Fig. 12), thus suggesting that there were multiple periods of deposition. This chemical complexity is exemplified by what appears to be strontium enrichment in location D relative to the other four locations (Fig. 12). SIMS analyses of each of the layers confirm that the Sr concentration in location D is approximately 10 times higher than in other locations (Fig. 13). The SIMS results also show that each layer has an HREE depleted pattern and a negative Eu anomaly (Fig. 13).

GEOCHEMICAL MODELING OF LONAR ALTERATION ASSEMBLAGES

An important issue for using the Lonar crater as a martian analogue is establishing that the hydrothermal alteration observed in the drill cores is due to the impact and not due to alteration during emplacement of the lavas or due to ambient alteration after the impact. The petrographic data clearly establishes that the clays and carbonates were deposited after the brecciation due to the impact, therefore the alteration could not have been associated with the initial cooling of the lavas. The next step is to establish that the alteration mineral assemblage is consistent with hydrothermal processes based on geological analogues and thermodynamic modeling.

Experimental investigations and recent studies of hydrothermally altered basalts provide information on the formation conditions for saponite. Velde (1985) suggests that saponite forms typically at temperatures of 130–170°C. Robert and Goffé (1993) and Robert (2001) studied hydrothermal alteration in basalts that flowed into rivers and alteration in basalts that formed due to thermal gradients driven by heat flow in the presence of water from regional aquifers during the final cooling of the lava sequence. Robert and Goffé (1993) estimated the formation of Fe-Mg saponite



Fig. 10. Ternary diagram depicting the composition of unknown clays in the Lonar basalts. Analyses from 116569–13 (LNR-3) and 116569–42 (LNR-2) plot near the reference point for saponites. Analyses from 116569–5 (LNR-1) plot near the reference point for celadonites. Reference data for vermiculite and chlorite plot outside the area of the figure.

in basalts from the Massif Central and Southern Washington to occur at temperatures of 100-140°C, based on modeling of basalt cooling and experimental results. Robert (2001) concluded that the saponite assemblages in Tertiary Irish basalts, for example, formed at conditions between 60–110°C. The observations and experimental data from Robert and Goffé (1993) also showed that smectites crystallize in higher temperature zones and zeolites crystallize at lower temperatures. A study by Fulignati, Malfitano, and Sbrana (1997) of hydrothermal alteration in a currently active geothermal system on Pantelleria showed that Fe-rich saponite occurs at depth in the system above a temperature of 200°C. Because the occurrence of saponite is also controlled by the composition of the mineral assemblages being altered, we have conducted numerical modeling experiments as a check on the formation conditions of the Lonar alteration.

The chemical equilibrium and mass transport code used for this modeling is PHREEQCI (Parkhurst 1995). The geochemical modeling assumes, as previous studies have, that the two main constraints on hydrothermal alteration are the temperature of alteration and the host rock composition (e.g., Griffith and Shock 1997). Thermodynamic data for several minerals were imported into PHREEQCI from a more expansive database such as that used by the geochemical modeling code EQ3/6 (Wolery and Daveler 1992). It should be noted that the following model is purely a qualitative exercise, meaning that the goal of this modeling effort is to show that the hydrothermal alteration at the Lonar crater is consistent with models that make extremely basic assumptions.



Fig. 11. Cathodoluminescence image of several generations of carbonate within a vug in thin section 116569–50 (LNR-4). The variation in brightness represents different compositions, in turn, possibly reflecting depositional conditions with time.

Hydrothermal Alteration of the Lonar Basalts

The mineral assemblage for the Lonar basalts consists of augite ([Ca,Na][Mg,Fe]Si₂O₆), labradorite (NaAlSi₃O₈ – CaAl₂Si₂O₈), ilmenite (FeTiO₃), and basaltic glasses. Microprobe analyses conducted in this study suggest that the secondary alteration assemblage contains calcite, saponite, and celadonite as relatively major constituents. The secondary mineral assemblage is surprisingly well represented by the PHREEQCI database. Even though thermodynamic data (e.g., ΔG , ΔH , and ΔS) for saponite were imported from an external database, several other alteration materials such as montmorillonite, kaolinite, chlorite, halloysite, nontronite, celadonite, illite, jarosite, beidellite, goethite, calcite, and pyrophyllite were already included within the PHREEQCI database.

Based on estimates of saponite formation temperatures described above, from 60°C to >200°C, we have assumed in our modeling an average maximum temperature of 170°C. It should be noted that the majority of the samples that were analyzed were obtained from a depth of >100 m. Therefore, the first phase of this model will assume that the hydrothermal reactions are occurring at depth, where there is little or no exposure to the atmosphere.

The basaltic sample described above was allowed to equilibrate with groundwater at depth and was progressively introduced to a hydrothermal temperature of 170°C by iteratively stepping up the temperature by 25°C until the final alteration temperature had been reached. An initial pH estimate of 9 is made, assuming that neutral water has reacted with the surrounding host rock but has not equilibrated with the terrestrial atmosphere. It is important to note that the pH is not a fixed value in this model and is allowed to change accordingly with temperature. PHREEQCI used simple



Fig. 12. Plot of microprobe data from the carbonate material in thin section NMNH 116569–50 (drill core LNR-4) (see Fig. 10). The compositional complexity of this material is exemplified by the Sr enrichment in location D relative to the other four locations. Each location is represented by the average of at least 5 microprobe analyses.

dissolution reactions to predict the formation of many alteration phases, several of which we have observed at the Lonar crater. The two main alteration phases that were predicted to precipitate under the described conditions are Fesaponite and celadonite, with Fe-saponite predicted to be 10 times more abundant than the celadonite. This is remarkably similar to the observed abundances. More importantly, both of these phases are predicted to be at least two orders of magnitude more abundant than all other alteration phases. PHREEQCI also predicted the minor occurrences of leonhardite, pyrophyllite, and dioctahedral montmorillonite, which we did not observe in our samples, and would not expect to, given their predicted abundance.

Ambient Alteration of the Lonar Basalts

For comparison with the high temperature results, we modeled alteration of the Lonar basalt assemblage under ambient terrestrial conditions (e.g., 25°C and atmospheric gases). We assumed that the interaction of atmospheric gases with neutral waters would produce water with a pH that is slightly acidic (a pH of ~5). The interaction of the Lonar basalts with ambient conditions is predicted to produce several alteration products, most of which are significantly different than those described in the hydrothermal step described above. For example, the ambient alteration model predicts that leonhardite, chlorite, laumontite, prehnite, beidellite, diaspore, gibbsite, illite, kaolinite, talc, and dioctahedral montmorillonite (listed in decreasing abundance) will be produced. These phases have not been observed in abundance in the Lonar cores. However, Kieffer et al. (1976) did find illite, chlorite, and kaolinite in some Deccan Trap basalts that had been exposed to ambient conditions away from the crater. These findings compare well with studies by Avasia and Gangopadhyaya (1984), who found that laumontite, chlorite, prehnite, and goethite were produced during the ambient alteration of the Deccan basalts in the Bombay-Baroda coastal tract. Clearly, the alteration products predicted from the modeling results correlate well with the observed ambient alteration products of Deccan Trap basalts and are quite distinct from those observed in shocked rocks from the crater floor.

IMPLICATIONS OF HYDROTHERMAL ALTERATION OF BASALTS IN THE LONAR CRATER

Impact events the size of the Lonar crater or larger appear to be capable of producing the heat necessary to generate hydrothermal systems that result in the formation of alteration minerals, as long as water is present in some form (Newsom 1980). Heat sources in impact craters include the impact melt deposits (Newsom 1980), heat that was deposited into the target rocks via shock waves, and heat due to the uplift of basement rocks (McCarville and Crossey 1996). In the case of the Lonar system, Nayak (1996) suggested that hydrothermal activity developed as the result of groundwater supplies interacting with the remnant impact energy (e.g., Newsom 1980; Newsom et al. 1996). More specifically, the lack of a central uplift and impact melt bearing rocks implies that heat was supplied by brecciated and shocked basement rock (Kirsimae et al. 2002). This hypothesis is supported by the



Fig. 13. Plot of rare earth element (REE) abundances in carbonate layers from sample NMNH 116569–50. For clarity, only the high, low and intermediate concentrations have been shown. Strontium (Sr) concentrations are also included to show the compositional variability in the layers.

observation that the formation of impact-induced hydrothermal systems at other larger terrestrial craters appears to be a relatively common process (Allen, Gooding, and Keil 1982; Newsom et al. 1986; McCarville and Crossey 1996).

Using SEM and petrographic analyses of the Lonar samples, we have demonstrated that all of the shocked basalts are heavily altered (e.g., they contain vugs and veins full of carbonate and clays). Therefore, the source of heat for this hydrothermal activity could not be the remnant eruptive energy of the Deccan Traps themselves because their activity ceased in the early Eocene epoch (55 Ma) (Roy and Chatterjee 1998). Furthermore, the alteration assemblage, primarily Fe-Mg saponite and celadonite, could not have formed under ambient conditions. Thus, the Lonar impact event is the only event that could have deposited enough energy into the host rocks to produce and sustain a hydrothermal system that, in turn, could have pervasively altered the Lonar basalts within the last 50,000 years.

The pervasive nature of hydrothermal alteration at the Lonar crater may be due to the fact that impact events can severely weaken the target rock by producing a variety of shock effects within the target materials, thus making the minerals highly susceptible to alteration (Boslough and Cygan 1988). Although the initial stages of cooling may involve locally high temperatures, rapid equilibration will lead to a long period of more uniform elevated temperatures during the main cooling and alteration stage. The thermodynamic data for these alteration products and comparisons with saponite occurrences in active geothermal systems allow us to place constraints on the potential temperatures achieved by the impact-induced hydrothermal system at the Lonar crater. This non-ambient temperature range is from 130 to 200°C (Robert and Goffé 1993; Deer, Howie, and Zussman 1996; Velde 1985).

We can also use the results described above to estimate the total amount of alteration at Lonar. Fredriksson et al. (1973, 1979) noted that the depth of alteration at Lonar extends to 400 m within the crater. Assuming that the average amount of alteration is 3%, based on the SEM feature scan results, the total volume of basalt that could be affected by hydrothermal activity is 0.03 km³. This is probably a minimum estimate, as Fudali et al. (1980) found that the Lonar ejecta blanket extends to 1400 m away from the crater and that there is evidence for extensive alteration in some samples from below the rim of the crater.

The presence of late stage calcite in the Lonar samples instead of extensive zeolitization provides more information about the conditions of alteration. During the late stages of cooling, alteration of basalts can produce either zeolites or calcite (as seen in the Lonar samples) depending on the partial pressure of CO₂ (Robert and Goffe 1993). Crossey, Frost, and Surdam (1984) show that the formation of extensive late stage zeolites requires a low partial pressure of CO₂. Robert and Goffe (1993) also suggest that the crystallization of calcite during basalt alteration may represent the final stages of alteration when the pore fluid comes in contact with the atmosphere, increasing the partial pressure of CO₂. The presence of calcite as the main late stage mineral in the Lonar samples (especially at elevated temperatures) is consistent with the brecciated nature of the rock and alteration by meteoric water, and also supports the use of Lonar as an analog for craters on Mars where a high partial pressure of CO₂ is more likely.

The relatively small size of the Lonar crater would suggest that the lifetime of its hydrothermal system would be much shorter than those associated with larger craters. There are factors, however, that will help to promote alteration during the short lifetime of this relatively small hydrothermal system. First of all, impact events, in general, create widespread fracturing of the host rock, increasing permeability, and thus increasing access of water to promote alteration (Berkley and Drake 1981).

A factor that will counteract the increase of permeability but can increase the thermal lifetime of even a small system is a geothermal feedback mechanism known as "self-sealing" (Cathles, Erendi, and Barrie 1997). This mechanism leads to conductive cooling through a near-surface layer of condensed liquid, which essentially changes the mechanism of cooling from convective to conductive. Studies of other terrestrial hydrothermal systems suggest that this is a common process even within basaltic host rock (Pitale 1996). Evidence for the self-sealing process at Lonar can be found in the form of layered clay and carbonate deposits within veins and vugs. The carbonate deposits are observed both in the available hand samples and in the thin section.

The presence of incipient hydrothermal alteration at the Lonar crater suggests that Lonar is near the lower heat limit for generating hydrothermal processes involving the formation of alteration clays (Table 1). A hydrothermal system has also been documented in the somewhat larger 4 km diameter Kärdla impact crater (Kirsimäe et al. 2002). However, no evidence of widespread hydrothermal activity has been found in the smaller 1.13 km diameter Pretoria Saltpan (Tswaing) crater (Reimold, Koeberl, and Brandt 1999) or in the 1.2 km diameter Meteor crater in Arizona (Hörz et al. 2002). The 1.8 km diameter Lonar crater, therefore, represents a lower size limit for impact-induced hydrothermal activity resulting in the formation of alteration clays. The possibility still exists that smaller craters may have some low temperature precipitation of calcite or other phases. This information implies that small martian craters greater than one or two kilometers in diameter may also have the potential to form hydrothermal systems leading to hydrothermal alteration, as long as water is present in some form.

GEOCHEMICAL MODELING OF MARTIAN BASALT ALTERATION ASSEMBLAGES

Given the good correspondence between the predicted and observed alteration minerals at Lonar, we have used similar modeling procedures to investigate the alteration of martian basalts. The primary mineral assemblage that was assumed for the basaltic martian meteorites (e.g., shergottites) includes: albite, anorthite, clinoenstatite, ferrosilite, hedenbergite, ilmenite, hematite, maghemite, magnetite, microcline, and silica glass (Stolper and McSween 1979). The nature of this martian mineral assemblage is reasonably well constrained by detailed petrographic studies of martian meteorites, however, the resulting alteration products have not been well constrained (Burns 1993). In this modeling, we assume the presence of shallow groundwater that could be available from a number of different sources as discussed below. In order to account for the martian environment, a decreased atmospheric pressure of 0.0069 atm was used (<1% of that of the Earth's), which includes CO₂ as the primary atmospheric constituent (e.g., Burns 1993). The decreased ambient temperatures (5-10°C) on the martian surface were also incorporated into the model. This model assumes that the majority of the hydrothermal alteration reactions on Mars occur at depth, where liquid water may be stable and where the hydrothermal temperatures predominate (e.g., temperatures of 170°C). As with the Lonar models, the pH is assumed to be more alkaline than neutral waters (i.e., a pH of \sim 9) and is allowed to change accordingly with temperature.

Hydrothermal Alteration of Martian Basalts

The model basaltic martian composition was allowed to equilibrate with a groundwater (e.g., pH = 9) at depth at a hydrothermal temperature of 170°C, until the final alteration temperature had been reached. Once again, a progressive temperature stepping of 25°C was used until the final temperature of interest was reached. PHREEQCI used simple dissolution reactions to predict that this hydrothermal interaction results in the precipitation of phases such as saponite, celadonite, boehmite, diaspore, gibbsite, and calcite. The celadonite and saponite are predicted to be two orders of magnitude more abundant than the other alteration products, with saponite being approximately 10 times more abundant than celadonite. These results are virtually identical to what has been observed at the Lonar crater, again pointing to the validity of using it as an analogue.

Ambient Alteration of Martian Basalts

The primary mineral assemblage of the basaltic martian sample was used once again for the ambient aspect of the martian model. As was the case with the ambient model of the Lonar system, this model will assume that the sample is only exposed to "ambient" conditions, which include a relatively thin martian atmosphere along with reduced ambient temperatures (i.e., 5–10°C). Although little is known about the chemistry of martian water, we will assume that, due to interaction with the early martian atmosphere, the pH was slightly more acidic than neutral (e.g., pH ~5). PHREEQCI predicts that the ambient alteration of the martian basalt will lead to the production of leonhardite, prehnite, tremolite, talc, annite, chrysotile, laumontite, aragonite, and calcite (listed by decreasing abundance), once again suggesting that there will be a significant difference between hydrothermal and ambient alteration even on Mars. Experimental studies of hydrothermal alteration by Baker, Agenbroad, and Wood (2000) also suggest that, even after a week of alteration, measurable quantities of carbonates can be precipitated on the surface of martian basalts at low temperatures. The short run times for their experiments, however, were not expected to produce clays.

IMPLICATIONS FOR MARS

Several workers have suggested that impact crater hydrothermal processes could be important on the surface of Mars (e.g., Newsom 1980; Allen, Gooding, and Keil 1982; Rathbun and Squyres 2002). Once impact-induced hydrothermal systems form, they will begin to alter the surrounding host rock, a process that can have a significant effect on the composition of the martian surface fines. Unfortunately, direct information about martian hydrothermal systems is limited, although the recent discoveries of hematite-rich deposits could be an indication of hydrothermal activity (Christensen et al. 2001). The availability of water is a necessary requirement for hydrothermal systems on Mars, but evidence continues to mount that near surface water has been available in the past and possibly during more recent episodic events (e.g., Carr 1996). Impact craters can also access shallow ground water, especially considering the deep penetration into the crust of even small impact craters (Newsom, Hagerty, and Thorsos 2001; Rathbun and Squyres 2002). Water may be supplied from a variety of sources including shallow aquifers and melting of subsurface supplies of ice. This possibility was strengthened by recent data from the Odyssey Gamma-Ray Spectrometer, which indicates the presence of near-surface deposits of ice at high latitudes (Boynton et al. 2002). Recent studies by Stewart, O'Keefe, and Ahrens (2000) have shown that an impact into the martian permafrost can produce a reservoir of water for a hydrothermal system. As the shockwave from the impact event propagates through the subsurface ice, the ice will be compressed and will be converted to water. This type of impact-induced production of water can melt large fractions of the ice in ejecta and below the crater (Stewart, O'Keefe and Ahrens 2000), which means that even small craters can supply water from deeply buried reserves of martian ground ice. Once water is made available, hydrothermal alteration will begin to occur in the impact melt deposits on the crater floor, in the central uplift, and in the shocked basement adjacent to the crater fill (e.g., Newsom et al. 1986; McCarville and Crossey 1996; Ames, Watkinson, and Parish 1998).

Several studies suggest that the chemical and mineralogical composition of the martian regolith could be consistent with the composition and chemical characteristics of basaltic hydrothermal alteration products (e.g., Allen, Gooding, and Keil 1982; Morris and Golden 1998; Bishop, Fröschl, and Mancinelli 1998). Spectral reflectance studies of the martian regolith have shown that Fe-rich smectites (e.g., saponites) are likely candidates for describing the chemical characteristics of the martian soil (Banin and Rishpon 1979; Banin, Margulies, and Chen 1985; Bishop et al. 1995; Formisano and Grassi 2000). Bishop et al. (1995) have also shown that the reflectance spectra of ferric-bearing montmorillonite (e.g., saponite) closely resemble martian bright region spectra. The existence of Fe-saponites on Mars is also suggested by petrographic observations and microprobe data for iddingsite in SNC meteorites (Burns 1993; Gooding 1992). Finally, the Pathfinder lander's dust magnetic properties experiments found evidence of clay-like aggregates stained or cemented with ferric oxides (Hviid et al. 1997), consistent with a hydrothermal origin for the clays (Newsom, Hagerty, and Goff 1999).

Chemical evidence for the presence of hydrous alteration products of basaltic rocks in the martian regolith includes Viking and Pathfinder analyses, which are consistent with as much as 1 wt% water (Banin, Clark, and Wänke 1992; Foley, Economou, and Clayton 2001). Baird et al. (1976, 1977), Toulmin et al. (1977), and Gooding (1992) found that the composition of the Viking soils could be matched with multicomponent models including hydrous alteration phases, such as smectites. Clark (1993) pointed out that the palagonite model is actually a variant of the smectite model but with poorer crystallinity. McSween and Keil (2000) concluded that palagonitization was consistent with the possible differences in major element concentrations between rocks represented by the basaltic martian meteorites and soils at the Viking and Pathfinder sites, which are somewhat enriched in iron oxide and depleted in mobile elements such as Na, K, and Ca. However, McSween and Keil (2000) suggested that hydrothermal processes would be incompatible with derivation of soils from either basalt or andesite, based on observations of mid-ocean ridge hydrothermal alteration that resulted in loss of iron oxide. Our results, in contrast, show that low water/rock ratio alteration of the Lonar basalts produces Fe-rich smectites (16.7 wt% FeO) which are even more enriched in FeO than the palagonites measured, for example, by Jercinovic et al. (1990) (12.9 wt% FeO). Therefore, the Lonar data and data from other craters, such as Mistastin (Nelson and Newsom 2003), suggest that preferential erosion and incorporation of a portion of Fe-rich saponite formed by incipient alteration of basalts into the Mars soil is consistent with the alteration trajectories allowed by the data shown by McSween and Keil (2000).

Impact cratering on Mars was more important as a global process during the first half billion years of martian history (Newsom, Hagerty, and Goff 1999), but small craters the size of Lonar still contribute to surface processes on Mars. Over the history of Mars, approximately one crater in the size range from one to eleven km in diameter was created in each 14 km² of the martian surface, based on cratering chronologies (Hartmann 1999). Assuming the availability of water in the form of ground ice or shallow aquifers (e.g., Malin and Edgett 2000) over much of the martian surface, these small craters would be capable of producing significant amounts of alteration of martian basalts under current martian conditions (Burns 1993). The formation of impact melt breccia deposits, which are commonly porous, would enhance the alteration process, even in the presence of low water/rock ratios (Newsom 1980; Berkley and Drake 1981). The effect of this alteration on the surface of Mars, such as the trapping of water, can be evaluated using the available data. For example, we can calculate the amount of water that could be trapped due to alteration of craters in the size range from 2 to 11 km in diameter. We have assumed an average depth of alteration of 400 m, an alteration extent of 3% based on the average of our SEM feature scan determinations and cratering rate data from Hartmann (1999). The resulting volume of altered material is equivalent to a global layer of 2.8 m that will be formed over martian history. Assuming a water content of 10 wt% (measured in the Lonar samples, and similar to the amount in Lafayette martian meteorite iddingsite alteration material [Treiman, Barrett, and Gooding 1993]), this amount of material could trap an amount of water equivalent to a global layer of water 0.7 m deep. This is a conservative calculation, because the larger craters will be altered to a much greater depth and probably to a greater extent, and this calculation does not take into account alteration of the ejecta outside of the crater. The one-meter value compares to estimates of the amount of water on Mars ranging up to a few hundred meters (Masson et al. 2001). In contrast, Griffith and Shock (1997) estimated that 8% alteration of 10% of the martian crust could trap 30 m global equivalent of water.

The alteration process can also release certain elements into the fluids via slow and complex hydrolysis reactions (Giggenbach 1981), which can then be transported to the surface (e.g., Newsom and Hagerty 1997; Newsom, Hagerty, and Goff 1999). These reactions preferentially release a variety of mobile cations into the solution (Drever 1997). If this process has been sustained for long periods of time, large volumes of mobile, volatile elements will have been introduced into the martian soil. Soil formation models proposed by Newsom, Hagerty, and Goff (1999) have suggested that the observed abundances of volatile elements in the martian soil can be at least partially explained by contributions from impact-induced hydrothermal systems.

CONCLUSIONS

This study has provided several lines of evidence showing that impact-related hydrothermal processes occurred at the Lonar Lake impact structure. In particular, backscattered electron images of shocked Lonar samples demonstrate textural evidence for post-impact hydrothermal alteration including replacement textures, ubiquitous pockets of alteration, alteration of impact glasses, and multiple generations of hydrothermal carbonate growth. They suggest that alteration could have only taken place after the impact event had occurred. Electron microprobe and X-ray diffraction results suggest that the majority of the clays in the Lonar samples are saponite with minor occurrences of celadonite. Geochemical modeling and data from terrestrial geothermal systems indicate that saponite and minor celadonite are produced during the hydrothermal alteration of basalt, typically at temperatures of 130-200°C, while a different assemblage will form under ambient conditions. The presence of hydrothermal alteration clays at the Lonar crater compared with data for other small terrestrial impact craters shows that the lower size limit for impact craters that can produce and sustain a significant hydrothermal system resulting in the formation of alteration clays is probably somewhat less than 1.8 km in diameter. A similar limit should apply to Mars, although similar impacts on Mars produce slightly larger craters due to the reduced gravity.

The comparable compositions of Lonar basalts and martian basalts suggest that similar alteration products should have been produced on Mars due to impact-induced hydrothermal activity. Because impact craters, especially small ones similar to Lonar, are largely surficial in nature, they have the potential to contribute to the physical and chemical evolution of the near surface environment on Mars, including the uppermost crust and the martian soil. These processes include the possibility of transporting mobile elements to the surface and trapping water in hydrated minerals. Over the course of martian history, hydrothermal alteration in small craters in the 2-11 km diameter range on Mars could conservatively trap as much as 0.7 m of water in alteration minerals near the surface. Some of these alteration phases could also contribute material to the martian soil. In fact, preferential erosion of the Fe-rich martian alteration products observed in this study could provide a component of the martian soil that would help explain the Fe-enrichments observed by McSween and Keil (2000) in martian soils compared to basaltic martian meteorites. Our results suggest that the Lonar crater has great potential as a laboratory to further study geochemical and hydrothermal processes that may be important on the surface of Mars.

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REFERENCES

- Allen C. C., Gooding J. L., and Keil K. 1982. Hydrothermally altered impact melt rock and breccia: Contributions to the soil of Mars. *Journal of Geophysical Research* 87:10083–10101.
- Ames D. E., Watkinson D. H., and Parish R. R. 1998. Dating of regional hydrothermal system induced by the 1850 Ma Sudbury impact event. *Geology* 26:447–450.
- Avasia R. K. and Gangopadhyaya M. 1984. Distribution of secondary minerals in the western Deccan Traps of Bombay, Baroda coastal tract, India. *Indian Mineralogist* 52:215–230.
- Baird A. K., Castro A. J., Clark B. C., Toulmin P., III, Rose H., Jr., Keil K., and Gooding J. L. 1976. The Viking X-ray fluorescence experiment: Sampling strategies and laboratory simulations. *Journal of Geophysical Research* 82:4595–4624.
- Baird A. K., Toulmin P., III, Clark B. C., Rose H., Jr., Keil K., Christian R. P., and Gooding J. L. 1977. Mineralogic and petrologic implications of the Viking geochemical results from Mars: Interim report. *Science* 194:1288–1293.
- Baker L. L., Agenbroad D., and Wood S. 2000. Experimental hydrothermal alteration of a Mars analog basalt: Implications for Martian meteorites. *Meteoritics & Planetary Science* 35:31–38.
- Banin A. and Rishpon J. 1979. Smectite clays in Mars soil: Evidence for their presence and role in Viking biology experimental results. *Journal of Molecular Evolution* 14:133–152.
- Banin A., Margulies L., and Chen Y. 1985. Iron-montmorillonite: A spectral analog of Martian soil. Proceedings, 15th Lunar and Planetary Science Conference. *Journal of Geophysical Research* 90:C771–C774.
- Banin A., Clark B. C., and Wänke H. 1992. Surface chemistry and mineralogy. In *Mars*, edited by Kieffer H. H., Jakosky B. M., Snyder C. W., and Matthews M. S. Tucson: University of Arizona Press. pp. 594–625.
- Banin A., Han F. X. Kan I., and Cicelsky A. 1997. Acidic volatiles and the Mars soil. *Journal of Geophysical Research* 102:13341– 13356.
- Berkley J. L. and Drake M. J. 1981. Weathering on Mars: Antarctic analog studies. *Icarus* 45:231–249.
- Bishop J. L., Pieters C. M., Burns R. G., Edwards J. O., Mancinelli R. L., and Fröschl H. 1995. Reflectance spectroscopy of ferric sulfate-bearing montmorillonites as Mars soil analog materials. *Icarus* 117:101–119.
- Bishop J. L., Fröschl H., and Mancinelli R. L. 1998. Alteration processes in volcanic soils and identification of exobiologically important weathering products on Mars using remote sensing.

Journal of Geophysical Research 103:31457–31476.

- Boslough M. B. and Cygan R. T. 1988. Shock-enhanced dissolution of silicate minerals and chemical weathering on planetary surfaces. Proceedings, 18th Lunar and Planetary Science Conference. pp. 443–453.
- Boynton W. V., Feldman W. C., Squyres, S. W., Prettyman T. H., Brückner J., Evans L. G., Reedy R. C., Starr R., Arnold J. R., Drake D. M., Englert P. A. J., Metzger A. E., Mitrofanov I., Trombka J. I., d'Uston C., Wänke H., Gasnault O., Hamara D. K., Janes D. M., Marcialis R. L., Maurice S., Mikheeva I., Taylor G. J., Tokar R., and Shinohara C. 2002. Distribution of hydrogen in the near surface of Mars: Evidence for subsurface ice deposits. *Science* 297:81–85.
- Brückner J., Dreibus G., Rieder R., and Wänke H. 2001. Revised data of the Mars Pathfinder alpha proton X-ray spectrometer: Geochemical behavior of major and minor elements (abstract #1293). 32nd Lunar and Planetary Science Conference. CD-ROM.
- Burns R. G. 1993. Rates and mechanisms of chemical weathering of ferromagnesian silicate minerals on Mars. *Geochimica et Cosmochimica Acta* 57:4555–4574.
- Carr M. H. 1996. *Water on Mars*. New York: Oxford University Press. 229 p.
- Cathles L. M., Erendi A. H. J., and Barrie T. 1997. How long can a hydrothermal system be sustained by a single intrusive event? *Economic Geology* 92:766–771.
- Christensen P. R., Morris R. V., Lane M. D., Bandfield J. L., and Malin M. C. 2001. Global mapping of Martian hematite mineral deposits: Remnants of water-driven processes on early Mars. *Journal of Geophysical Research—Planets* 106:23873–23885.
- Clark B. C. 1993. Geochemical components in Martian soil. Geochimica et Cosmochimica Acta 57:4575–4581.
- Crossey L. J., Frost B. R., and Surdam R. C. 1984. Secondary porosity in laumontite-bearing sandstones. In *Clastic diagenesis*, American Association of Petroleum Geologists Memoir 37:225–237.
- Deer W. A., Howie R. A., and Zussman J. 1996. *Rock forming minerals*. New York: John Wiley and Sons, Inc. 720 p.
- Drever J. I. 1997. *The Geochemistry of natural waters*. New Jersey: Prentice Hall. 436 p.
- Feldman V. I., Sazonova L. V., Mironov Y. V., and Kapustkina I. G. 1983. Circular structure Logancha as possible meteorite crater in basalts of the Tunguska syncline. Proceedings, 14th Lunar and Planetary Science Conference. pp. 191–192.
- Foley C. N., Economou T. E., and Clatyon R. N. 2001. Chemistry of Mars Pathfinder samples determined by the APXS (abstract #1979). 32nd Lunar and Planetary Science Conference. CD-ROM.
- Formisano V. and Grassi D. 2000. Identification of clays, quartz, and sulfates on the surface of Mars from IRIS Mariner 9 spectra. *Bulletin of the American Astronomical Society* 32:1113.
- Fredriksson K., Dube A., Milton D. J., and Balasundaram M. S. 1973. Lonar Lake, India: An Impact crater in basalt. *Science* 180:862– 864.
- Fredriksson K., Brenner P., Nelen J., Noonan A., Dube A., and Reid A. 1974. Comparative studies of impact glasses and breccias. *Lunar Science* V:245–247.
- Fredriksson K., Brenner P., Dube A., Milton D., Mooring C., and Nelen J. A. 1979. Petrology, mineralogy, and distribution of Lonar (India) and lunar impact breccias and glasses. *Smithsonian Contributions to the Earth Sciences* 22:1–12.
- French B. M. 1998. Traces of catastrophe. *LPI Contribution 954*. Houston: Lunar Planetary Institute. 120 p.
- Fudali R. F., Milton D. J., Fredriksson K., and Dube A. 1980. Morphology of Lonar crater, India: Comparisons and implications. *Moon and Planets* 23:493–515.

- Fulignati P., Malfitano G., and Sbrana A. 1997. The Pantelleria Caldera geothermal system: Data from the hydrothermal minerals. *Journal of Volcanology and Geothermal Research* 75: 251–270.
- Giggenbach W. F. 1981. Geothermal mineral equilibria. *Geochimica* et Cosmochimica Acta 45:393–410.
- Gooding J. L. 1992. Soil mineralogy and chemistry on Mars: Possible clues from salts and clays in SNC meteorites. *Icarus* 99:28–41.
- Grieve R. A. F. 1975. Petrology and chemistry of the impact melt at Mistastin Lake crater, Labrador. *Geological Society of America Bulletin* 86:1617–1629.
- Griffith L. L. and Shock E. L. 1997. Hydrothermal alteration of Martian crust: Illustrations via geochemical model calculations. *Journal of Geophysical Research* 102:9135–9143.
- Gurov E. P., Koeberl C., and Reimold W. U. 1998. Petrography and geochemistry of target rock and impactites from the Ilyinets crater, Ukraine. *Meteoritics & Planetary Science* 33:1317–1333.
- Güven N. 1988. Smectites. In *Hydrous phyllosilicates*, edited by Bailey S. W. Washington DC: Mineralogical Society of America. pp. 497–559.
- Hartmann W. K. 1999. Martian cratering VI: Crater count isochrones and evidence for recent volcanism from Mars Global Surveyor. *Meteoritics & Planetary Science* 34:167–177.
- Hörz F., Mittlefehldt D. W., See T. H., and Galindo C. 2002. Petrographic studies of the impact melts from Meteor crater, Arizona, USA. *Meteoritics & Planetary Science* 37:501–531.
- Hviid S. F., Madsen M. B., Gunnlaugsson H. P., Goetz W., Knudsen J. M., Hargraves R. B., Smith P., Britt D., Dinesen A. R., Mogensen C. T., Olsen M., Pedersen C. T., and Vistisen L. 1997. Magnetic properties experiments on the Mars Pathfinder Lander: Preliminary results. *Science* 278:1768–1770.
- Jepson W. B. and Rowse J. B. 1975. The composition of kaolinite: An electron microscope microprobe study. *Clays and Clay Minerals* 23:310–317.
- Jercinovic M. J., Keil K., Smith M. R., and Schmitt R. A. 1990. Alteration of basaltic glasses from north-central British Columbia, Canada. *Geochimica et Cosmochimica Acta* 54:2679– 2696.
- Kieffer S. W., Schaal R. B., Gibbons R., Hörz F., Milton D. J., and Dube A. 1976. Shocked basalt from Lonar impact crater, India, and experimental analogues. Proceedings, 7th Lunar and Planetary Science Conference. pp. 1391–1412.
- Kirsimae K., Suuroja S., Kirs J., Kärki A., Polikarpus M., Pura V., and Suuroja K. 2002. Hornblende alteration and fluid inclusions in Kardla impact crater, Estonia: Evidence for impact-induced hydrothermal activity. *Meteoritics & Planetary Science* 37:449– 457.
- Koeberl C., Fredriksson K., Goetzinger M., and Reimold W. U. 1989. Anomalous quartz from the Roter Kamm impact crater, Namibia: Evidence for post-impact hydrothermal activity? *Geochimica et Cosmochimica Acta* 53:2113–2118.
- Masson P., Carr M. H., Costard F., Greeley R., Hauber E., and Jaumann R. 2001. Geomorphologic evidence for liquid water. *Space Science Reviews* 96:333–364.
- Malin M. C. and Edgett K. S. 2000. Evidence for recent groundwater seepage and surface runoff on Mars. *Science* 288:2330–2335.
- McCarville P. J. and Crossey L. J. 1996. Post-impact hydrothermal alteration of the Manson impact structure, Manson, Iowa. In *The Manson impact structure*. Geological Society of America Special Paper 302. pp. 347–369.
- McKinley J. P. 1990. Alteration of Columbia river basalts and the chemical evolution of Columbia Plateau groundwaters. Ph.D. thesis, University of New Mexico, Albuquerque, New Mexico, USA. 277 p.

McSween H. Y., Jr. 1994. What have we learned about Mars from

SNC meteorites? *Meteoritics* 29:757–779.

- McSween H. Y., Jr. 2002. The rocks from Mars, from far and near. Meteoritics & Planetary Science 37:7–25.
- McSween H. Y., Jr. and Keil K. 2000. Mixing relationships in the Martian regolith and the composition of globally homogeneous dust. *Geochimica et Cosmochimica Acta* 64:2155–2166.
- McSween H. Y., Jr., Murchie S. L., Crisp J. A., Bridges N. T., Anderson R. C., Bell J. F., III, Britt D. T., Brückner J., Dreibus G., Economou T., Ghosh A., Golombek M. P., Greenwood J. P., Johnson J. R., and Moore H. J. 1999. Chemical, multispectral, and textural constraints on the composition and origin of rocks at the Mars Pathfinder landing site. *Journal of Geophysical Research* 104:8679–8715.
- Morris R. V. and Golden D. C. 1998. Goldenrod pigments and the occurrence of hematite and possibly goethite in the Olympus-Amazonis region of Mars. *Icarus* 134:1–10.
- Morris R. V., Golden D. C., Bell J. F. III., and Lauer H. V., Jr. 1995. Hematite, pyroxene, and phyllosilicates on Mars: Implications from oxidized impact melt rocks from Manicouagan crater, Quebec, Canada. *Journal of Geophysical Research* 100:319– 5328.
- Nayak V. K. 1972. Glassy objects (impactite glasses?)—A possible new evidence for meteoritic origin of the Lonar crater, Maharashtra State, India. *Earth and Planetary Science Letters* 14:1–6.
- Nayak V. K. 1996. A hypothesis for the salinity of lake water and economic potential of the Lonar impact crater, India. *Proceedings of the NIPR Symposium on Antarctic Meteorites* 21: 136–137.
- Nelson M. J. and Newsom H. E. 2003. Can low water/rock hydrothermal alteration of impact materials explain the rock component of the martian soil? (abstract #1780). 34th Lunar and Planetary Science Conference. CD-ROM.
- Newman A. C. D. 1987. Chemistry of clays and clay minerals. *Mineralogical Society Monograph* 6:480.
- Newsom H. E. 1980. Hydrothermal alteration of impact melt sheets with implications for Mars. *Icarus* 44:207–216.
- Newsom H. E. and Hagerty J. J. 1997. Chemical components of the Martian soil: Melt degassing, hydrothermal alteration, and chondritic debris. *Journal of Geophysical Research* 102:19345– 19355.
- Newsom H. E., Hagerty J. J., and Goff F. 1999. Hydrothermal fluids and the origin of the Martian soil. *Journal of Geophysical Research-Planets* 104:8717–8728.
- Newsom H. E., Hagerty J. J., and Thorsos I. E. 2001. Location and sampling of aqueous and hydrothermal deposits in Martian impact craters. *Astrobiology* 1:71–88.
- Newsom H. E., Graup G., Sewards T., and Keil K. 1986. Fluidization and hydrothermal alteration of the suevite deposit at the Ries crater, West Germany, and implications for Mars. Proceedings, 17th Lunar and Planetary Science Conference. *Journal of Geophysical Research* 91:E239–E251.
- Newsom H. E., Brittelle G. E., Crossey L. J., and Kudo A. M. 1996. Impact cratering and the formation of crater lakes on Mars. *Journal of Geophysical Research* 101:14951–14955.
- Osinski G. R., Spray J. G., and Lee P. 2001. Impact-induced hydrothermal activity in the Haughton impact structure, Canada: Generation of a transient, warm, wet oasis. *Meteoritics & Planetary Science* 36:731–745.
- Parkhurst D. L. 1995. User's guide to PHREEQ—A computer program for speciation, reaction-path, advective transport, and inverse geochemical calculations. U.S. Geological Survey Water-Resources Investigations Reports 95–4227. 143 p.
- Pitale U. L. 1996. Hydrothermal alteration mineralogy—A clue to thermal history of west coast geothermal system, Maharashtra,

India. Geothermal Energy India 45:41-60.

- Rathbun J. A. and Squyres S. W. 2002. Hydrothermal systems associated with Martian impact craters. *Icarus* 157:362–372.
- Reimold W. U., Koeberl C., and Brandt D. 1999. The origin of the Pretoria Saltpan crater. *Geological Survey of South Africa* 85:35– 54.
- Rieder R., Economou T., Wänke H., Turkevich A., Crisp J., Brückner J., Dreibus G., and McSween H. Y., Jr. 1997. The chemical composition of Martian soil and rocks returned by the mobile alpha proton X-ray spectrometer: Preliminary results from the Xray mode. *Science* 278:1771–1774.
- Robert C. H. 2001. Hydrothermal alteration processes of the Tertiary lavas of Northern Ireland. *Mineralogical Magazine* 65:543–554.
- Robert C. H. and Goffe B. 1993. Zeolitization of basalts in subaqueous freshwater settings: Field observations and experimental study. *Geochimica et Cosmochimica Acta* 57:597–612.
- Roy A. and Chatterjee A. K. 1998. Deccan basalts and its mineralogical alterations in the central and western peninsular India. *Clay Research* 17:72–89.
- Smith D. G. W. and Norem D. 1986. The electron-microprobe analysis of palygorskite. *Canadian Mineralogist* 24:499–511.
- Spilde M. N., Brearley A. J., and Papike J. J. 1993. Alteration of plagioclase and pyroxene in a fissure fumarole, Valley of Ten Thousand Smokes, Alaska. *American Mineralogist* 78:1066–

1081.

- Stewart S. T., O'Keefe J. D., and Ahrens T. J. 2000. The role of subsurface ice in rampart crater formation. *Bulletin of the American Astronomical Society* 32:1112.
- Stolper E. M. and McSween H. Y., Jr. 1979. Petrology and origin of the shergottite meteorites. *Geochimica et Cosmochimica Acta* 43: 589–602.
- Toulmin P., III, Baird A. K., Clark B. C., Keil K., Rose H., Jr., Christian R. P., Evans P. H., and Kelliher W. C. 1977. Geochemical and mineralogical interpretations of the Viking inorganic chemical results. *Journal of Geophysical Research* 82: 4625–4634.
- Treiman A. H., Barrett R. A., and Gooding J. L. 1993. Preterrestrial aqueous alteration of the Lafayette (SNC) meteorite. *Meteoritics* 28:86–97.
- Velde B. 1984. Electron microprobe analysis of clay minerals. Clay Minerals 19:243–247.
- Velde B. 1985 Clay Minerals: A physiochemical explanation of their occurrence. New York: Elsevier. 427 p.
- Wolery T. J. and Daveler S. A. 1992. EQ6: A computer program for reaction path modeling of aqueous geochemical systems. Theoretical manual, user's guide, and related documentation (version 7). Report UCRL-MA-110662 PT IV. Livermore: Lawrence Livermore National Laboratory.