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# Nomad Rover Field Experiment, Atacama Desert, Chile
# 2. Identification of paleolife evidence using a robotic vehicle: Lessons and recommendations for a Mars sample return mission

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**Abstract.** During the Nomad Rover Field Experiment in the Atacama Desert (Chile), a potential fossil was identified in a boulder by the science team remotely located at NASA Ames Research Center, California. The science team requested the collecting of the boulder that was returned for laboratory analysis. This analysis confirmed the evidence of paleolife. As the first fossil identified and sampled by a remotely located science team using a rover, we use the case of sample I-250697 to describe the process, both in the field and later in the laboratory during the rock analysis, which led to the identification, characterization, and confirmation of the evidence of paleolife evidence in I-250697. We point out the lessons that this case provides for future Mars sample return missions.

## 1. Introduction

The Nomad rover field experiment took place between June 23 and June 27, 1997. A remote science team based at NASA Ames Research Center was teleoperating the Nomad rover located in the Atacama Desert, Chile. The Atacama Desert includes a wide geological setting with volcanic, sedimentary, and intrusive rocks; regoliths of various block sizes; and playa lakes with "salars" (salt pans), as well as ponds, sands, and impact craters. Topography includes various types of slopes and terrain ranging from rough to smooth, which made the site an excellent analog for testing planetary surface mission scenarios. Ancient episodes of floods carved channels, now dry, that exposed outcrops of Mesozoic ages and left evaporitic deposits in basins [*Monti and Henriquez*, 1970; *Stoertz and Eriksen*, 1974; *Eriksen*, 1983; *Chong*, 1984, 1988; *Grosjean et al.*, 1995; *Berger and Cooke*, 1997]. The region shows folding, fault systems, and fractures in a geomorphology of tectonic blocks with a regional slope to the east. To the east the High Andes show an alignment of volcanoes, some of them active, forming the so-called Western Cordillera boundary of the desert with more wet regions to the east. The average elevation of the site is above 2400 m with flats, and knobby and hilly regions (Figure 1). The barrenness of the site also provided a good analog for the search for life on Mars. Few living organisms currently survive in the Atacama Desert environment. In the geological past, biologic history corresponded to marine and continental environments of Mesozoic age and late Paleozoic, hosting a diversified life later fossilized.

Four types of surface planetary exploration strategies were tested during the week of the science experiment. They included: (1) a simulated Mars mission; (2) a "science on the fly" mission (or reconnaissance mission); (3) visual and instrumental modes to remotely identify meteorites in extreme environments; and, finally (4) a test of the panospheric camera capability experiment associated with a time-delay simulation (see *Cabrol et al.*, [1998a; 1998b; 1998c; *Cabrol et al.*, this issue] for details concerning these different mission scenarios).

During the science on the fly experiment, the traverse designed by the remote science team led to the discovery of an exotic outcrop, and the return of a rock found at the foot of this outcrop, which was sampled upon request of the science team as a potential fossil. The rock was later confirmed to contain paleolife evidence by laboratory analysis fossil.

The following sections describe the process, both in the field and later in the laboratory during the rock analysis, which led to the identification, characterization, and confirmation of fossils evidence in rock sample I-250697. We also discuss the lessons (both promises and limitations) that the finding of this rock suggests for the future Mars Sample Return missions in terms of mission preparedness, exploration strategies, and instrumentation.

## 2. Sample I-250697 Discovery and Approach for the Search of Paleolife Evidence

The rock sample I-250697 was discovered and documented by the remote science team and sampled on the third day of the Nomad rover field test during the science on the fly experiment. During this particular day of the experiment the emphasis was put on the role of mobility in helping document a landing site area, and 75% of the operation time was

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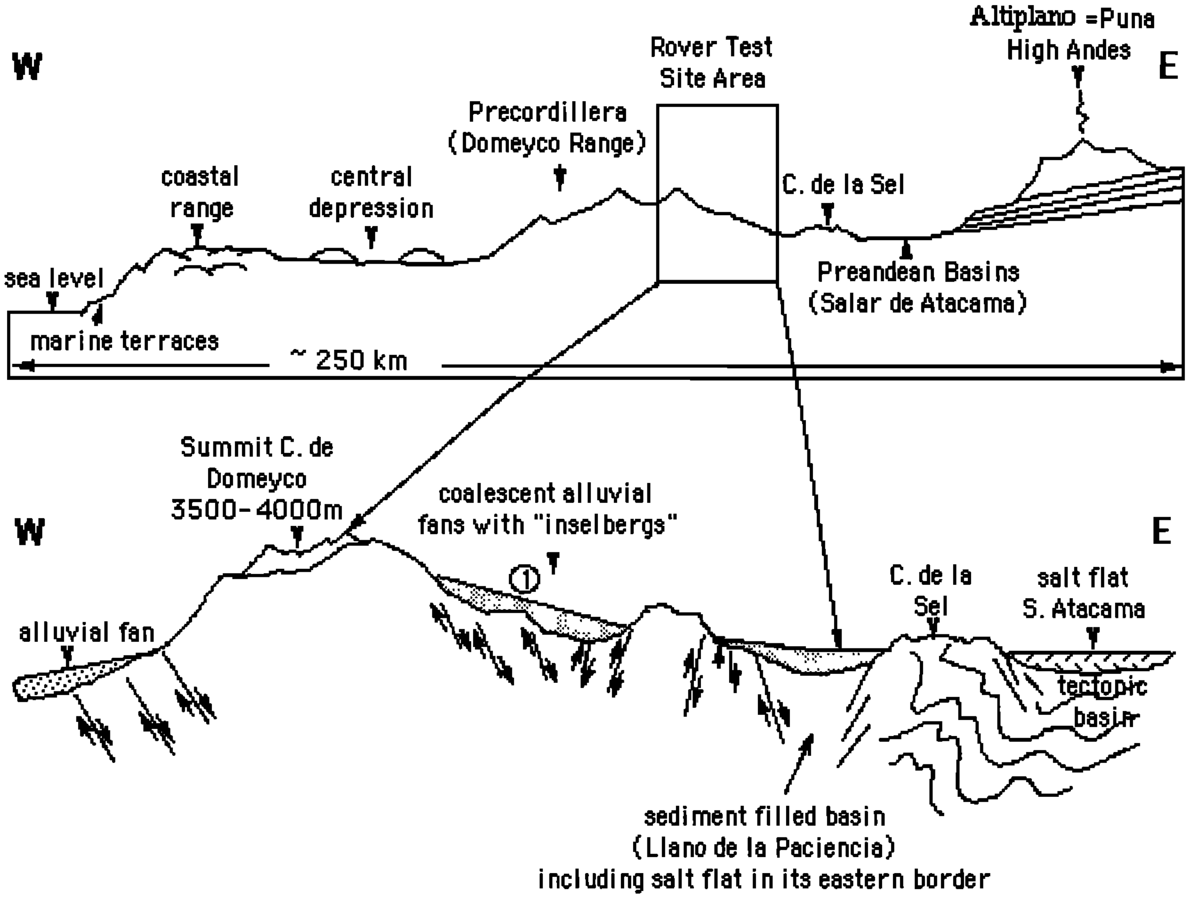


**Figure 1.** Geological setting of the test site area. The circled 1 indicates the position of the rover on LS1 the first day of the science experiment.

devoted to the traverse, while only 25% was used to actually document science targets during stops. During the previous two days of the "Mars mission" experiment the science team had investigated two areas east and southeast of the new starting point selected for the science on the fly experiment (Figure 2). Thus the science team members already had a set of observations and preliminary interpretations they could refer to in their selection of significant science targets (stops on traverse) they wanted to explore. Their objectives were to send the rover to these science targets and acquire as much information as possible about the local geology, biology and climate using the imaging systems on board Nomad.

### 2.1. Target Selection

The remote science team designed a traverse that included science targets potentially representative of the test site area. This selection was made using the aerial photographs (simulated orbital images) obtained at an altitude of 4000 m by an aircraft. These images had a Mars Orbiter Camera (MOC)-like high-resolution of 1 m/pixel. After the analysis of the aerial photographs, the objectives of the science team were to determine the origin of white outcrops, light colored units, and aligned promontories observed on aerial images (Figure 2) and to try to document if they were of sedimentary or volcanic origin. One of the concerns of the science team regarding these light colored high-albedo promontories was that they already encountered high-albedo material in channels and outcrops during the two previous days of the experiment. One of the interpretations for the high-albedo material was salt, possibly gypsum [see *Cabrol et al.*, this issue]. Since the ancient fluvio lacustrine environment of the test area had been identified earlier, the science team wanted to find outcrops where sedimentary material had been exposed in order to confirm their earlier hypotheses and possibly identify ancient environments that might have been favorable to life. Additional objectives of this traverse were to see if bedding and/or flow structures could be identified and, finally, whether or not the promontories were actually structurally controlled.

The presence of both sedimentary and volcanic material in the alluvium observed near the rover at the "landing" area

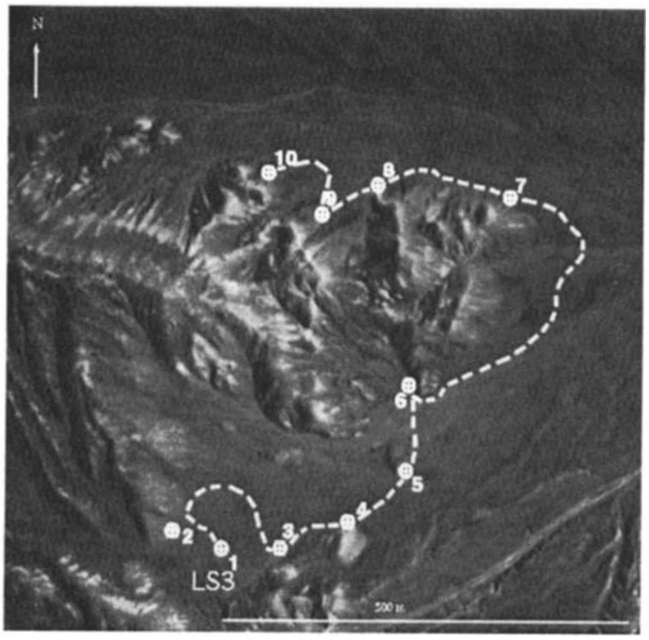


**Figure 2.** Aerial image of the test site area. These images were acquired at 4000 m of altitude by an airplane. They have a resolution of 1 m/pixel. They were provided to the science team as simulated orbital images. They show the landing site of day 3 and the traverse complete during the science on the fly experiment.

(starting point) was confirmed in the first two stops of the traverse. The remote science team also noted the colocation of these materials in an outcrop at site 3. The outcrop there corresponded to a sequence of well-stratified 15 to 20 m-thick red sandstone layers overlaid by friable conglomeratic sediments, and a wide range of lithologies that included fluidal tuffs, volcanic rocks, silicified acidic intrusion, tonalites, and rhyolites (G. Chong, unpublished post test field report, 1997). It was becoming clearer that the answer to the science team's main question regarding the promontories composition might not be "either sedimentary or volcanic," but possibly both. Although the remote science team did not have spectrometers to identify precisely the mineralogical composition of the rock materials in the outcrop, the close-ups and high-resolution images of bedding structures and rock textures of detached blocks and the diverse albedo signatures provided enough details for the science team to realize that both volcanic and sedimentary materials were present.These observations pointed to the complexity of the environment and the diversity of processes experienced by the area, diversity and complexity demonstrated later by the ground truth provided by the field science team.

### 2.2 Image Sequencing in Reconnaissance Mode (on the Fly)

At site 4 the outcrop was showing specific characteristics not observed in the previous stops. This specificity led the field science team to designate it as an exotic outcrop compared to the rest of the area. The rocks at site 4 were of a light gray color instead of the reddish or tan noted in the previously visited outcrops and composed of brecciated to conglomeratic material. The matrix was calcareous and partially siliceous. Clasts were mainly of volcanic origin, but abundant boulders of other origins (mainly sedimentary) were also included. Limestone possibly of lacustrine origin was also present. The conglomeratic nature of the rocks was related to the proximity of a paleo coastline by the field science team. The most significant difference compared to the previous stops was the presence of fossiliferous concretions and many boulders that contained reworked fossiliferous material of possible Jurassic-Cretaceous age (G. Chong, field report, unpublished, 1997). These concretions remained unnoticed by the science team. The field team in the post operation ground truth (Figure 3) also reported the presence of shells at site 4 (coquinae type) out of the field of view of the rover's camera.

Sample 1-250697 was identified using a reconnaissance mode, going from wide to narrow field of view and low to high resolution. An image of the outcrop stratigraphic section was first taken using the panospheric camera [*Whittaker et al.*, 1997, *Cabrol et al.*, this issue]. Several boulders and rocks were observed along the slope. Among them, one rock showed a dark feature on its upper side. The shape of the clast and its albedo difference compared to the surrounding rocks immediately caught the attention of the science team members (Figure 4), which requested the rover operator to close in on the rock while still taking snapshots. A total of seven navigation images at decreasing distance from the target were acquired as a result, the last one centered on the rock and the immediate surroundings. Once on target, the science team requested four mono black-and-white high-resolution single frames to identify the rock texture and possibly nature and

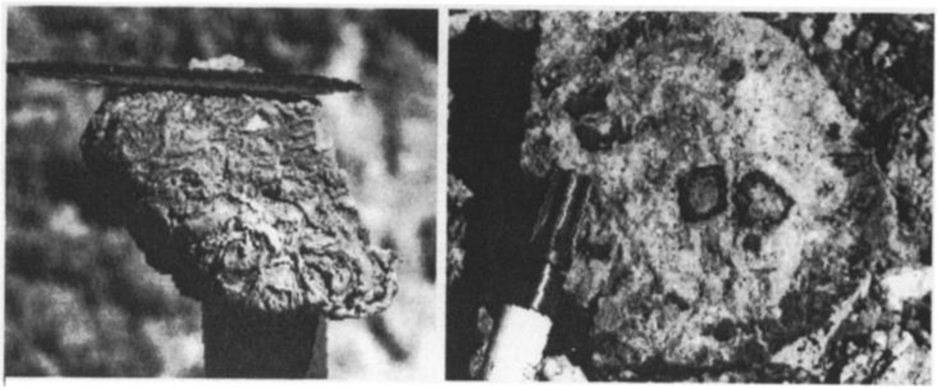


**Figure 3.** (Left) Concretion with fossils of shells; (right) organic relics in in concretion. Both were found at site 4 during the post experiment ground-truth investigation (pen for scale).

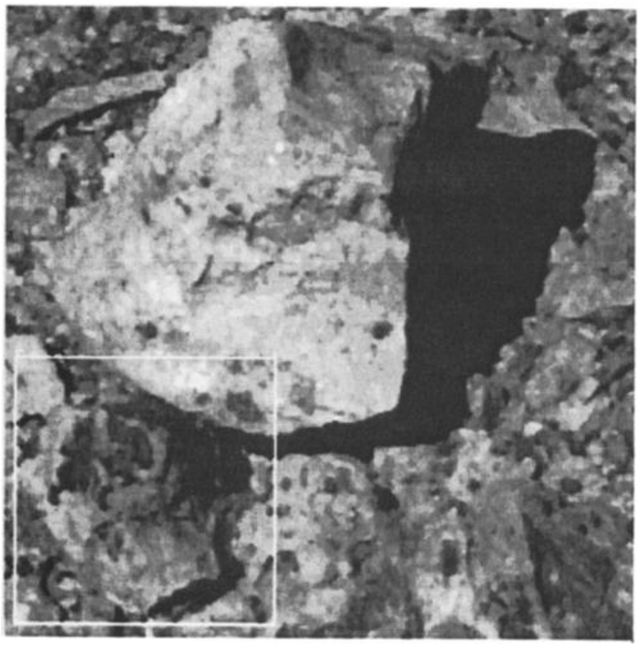


**Figure 4.** Rock sample I-250697 in situ at site 4 as it appeared in the field of view of the stereo-color high-resolution pancam system. The shape and dark albedo of the feature on the top side of the rock was the first detail that captured the attention of the remote science team at NASA Ames Research Center when the image appeared on the computer screens in the science operation room.

one stereo color high-resolution image on a close-up to try to assess the nature of the rock and the "anomalous" feature on its upper side. After the high-resolution stereo-color image was taken and compared to the surrounding rocks, the rock was noted to contain an "anomalous clast...possible fossil" by the unpublished remote science team operation daily log, (1997), which proposed three preliminary interpretations: (1) a fossil, (2) a chert nodule, and/or (3) an iron-rich conglomerate clast. The overall imaging sequence took 11 min (2% of the total operation time for the day). After the documentation of the science target the science team decided to cache the sample and requested that it be returned for analysis. Then, a command to continue the traverse was given, and the science team discontinued the investigation of site 4, thus missing more obvious fossils of coquinae and organic material at this site.

## 3. Sample Return, Laboratory Analysis, and Reconstruction of Paleoenvironments

After the test the sample acquired by the remote the science team was returned to NASA Ames Research Center. After several inconclusive hand examinations, the rock was sent to the Department of Geosciences at the University of Iowa for laboratory examination. It is important to point out that no information was provided about the origin of the rock, its age, or provenance to the researchers who undertook the analysis. The following sections describe the laboratory analysis of the thin sections and their interpretation as they appear in the report, before any information had been revealed.

### 3.1. Thin Section Analysis

The rock was shipped to the University of Iowa Department of Geosciences, where the specimen was examined with the naked eye and using a 10X hand lens. On the basis of these observations two thin section locations were selected.The regions thin sectioned consisted of (1) an area that contained small (2-4 cm), fractured chert (chalcedony) nodules suspended in the carbonate matrix of the rock and (2) an area that consisted primarily of carbonate matrix with small quartz-filled fractures. Polished thin sections were prepared using standard techniques. A third thin section, partially broken during the shipment, prepared for NASA Ames Research Center earlier in the study, was also provided.

The three thin sections of the rock sample were examined using a petrographic microscope (Olympus BH-2) at 25X and 100X magnification under plain, cross-polarized, and circular polarized light. The rock consists of a groundmass of cryptocrystalline to microcrystalline calcite (micrite) exhibiting equigranular xenotopic (mosaic-like and sutured) internal fabric (see *Bullock et al.* [1985] for a detailed explanation of micromorphological terminology used here). Very few detrital rock fragments (feldspar, quartz, vitrified in the micrite. Microcrystalline quartz fills irregular large to medium size irregular voids (vugs) with some evidence of calcite dissolution prior to or during quartz deposition. These quartz-filled voids are the chalcedony nodules observed in the hand specimen. A few smaller voids filled with euhedral quartz were also observed. An irregular network of straight planar voids (joint planes and fractures) filled with microcrystalline calcite consisting of similar-size euhedral crystals (equigranular idiotropic internal fabric) crosses the micrite and microcrystalline quartz. The calcite-filled joint planes, microcrystalline quartz, and micrite are further crossed by larger fractures (skew planes) filled with birefringent clay (craze plane illuviation cutans), iron oxides, other opaque compounds, and detrital fragments of microcrystalline quartz and calcite. The final fill in these fractures is microcrystalline calcite that occurs in the central part of the fractures. This calcite and the other fillings of the fractures have been slightly sheared and/or folded.

Within the micrite a few 100 to 200µm darker concentrations of ellipsoid and cone-shaped, very dense, very fine-grained calcite are present (Plate 1). These features occur in only a few concentrations, are somewhat fused, and have moderately distinct but intergrown boundaries with the adjacent micrite matrix. These features are interpreted as calcite-replaced fecal pellets similar in size and shape to those produced by modern Orabatid mites and millipedes (Julidae and Glomeridae).

### 3.2. Interpretation

Thin section analysis suggests the following history: Micrite was deposited in a subareal, evaporative environment with a high water table. Insects inhabited the site and deposited fecal pellets. This was probably a playa, tidal flat, or marginal lacustrine environment. The site was later submerged, and quartz-bearing fluids invaded the sediments and filled voids in the sediment matrix. An episode of microscale fracturing occurred (as a result of either uplift or emergence?) and the fractures were filled with euhedral calcite in a subaqueous environment. A final episode of fracturing, this time in a subareal environment occurred, and clay, iron oxides, and opaque compounds were transported into the fractures, along with pieces of the adjacent rock (lithified sediment).The movement of clay, iron oxides, and opaque compounds into the fractures (craze planes) occurred in a moist, terrestrial environment. At the end of this episode, conditions became drier, and microcrystalline calcite was deposited in the open fractures. Finally, the site was subjected to shearing forces that deformed the final fracture fill.

The thin section analysis revealed a complex evolution of the environment from a near-shore subareal to subaqueous, to moist subareal and, finally, to a drier subareal environment. Trace fossils were associated with the nearshore environment, and the presence of translocated clay associated with iron oxides and opaque minerals strongly suggests that the final subareal environment recorded in the specimen was also biotic.

### 3.3. Cross-Examination of the Evidence

Sample I-260597 was found at the foot of an outcrop of fossiliferous Jurassic-Cretaceous rocks (G. Chong, field report, unpublished, 1997). Since the rock was found detached from the outcrop, an in situ precise dating of the sample was not possible. However, the upper and lower boundaries are known, and correspond to the end of the Jurassic and the beginning of the Cretaceous. The hand specimen analysis gave indication that the rock was a calcrete, and some calcretes form in conditions quite similar to those present in the Atacama today. However, the laboratory analysis (thin section) of the rock showed that it experienced conditions that varied during its formation from nearshore subareal, to subaqueous, to moist subareal and, finally, to a drier subareal. This critical information allowed us to turn to the geologic history of the Atacama and try to match the nature of the rock with a specific geologic series and/or stage.

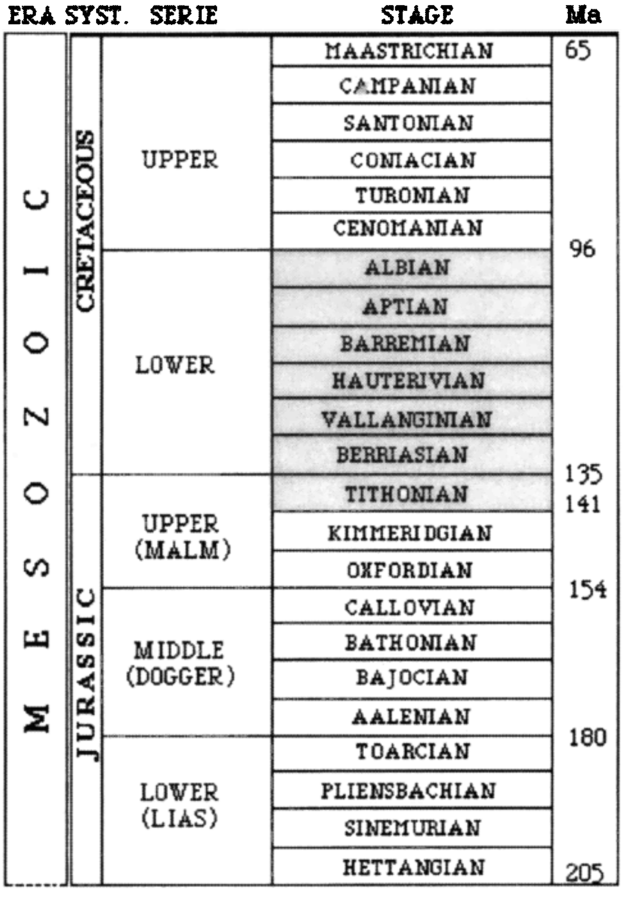
The remote science team assumed that the rock belonged originally to the outcrop at the foot of which it was found and therefore should belong to the Jurassic or Cretaceous age. Its chances to have been transported a great distance from where the remote science team discovered it were almost non existent, because: (1) the rock was similar to the in situ outcrop rocks and (2) this particular outcrop was defined as exotic by the field geologists and was isolated in the region. The field science team later confirmed the provenance of the rock.

The extreme desertic conditions currently experienced by the Atacama originated during the Pleistocene following a moist climatic episode during which many channels and deep canyons were formed. Pre-Pleistocene Cenozoic conditions included both moist and dry episodes. Desert conditions are recorded during the Oligocene and Lower Miocene *[Ramirez and Gardeweg,* 1982]. Still earlier during the Jurassic and Cretaceous, the Atacama experienced both moist and dry climatic episodes. During the Jurassic most of Chile was a volcanic island arc. Beginning the Tithonian Stage (end of Jurassic), and during part of the lower Cretaceous, a definitive moist continental domain was present, where dinosaurs lived in proximity of the regional swamps.

Other outcrops dating back from the same Tithonian-Neocomian times show fossil evidence of burrowing animals and plants with roots in the Atacama. This time span could therefore match both the climatic conditions needed to form the calcrete soil that makes sample I-260797 and the local fauna and flora that could correspond to the evidence observed in the thin section (fecal pellets from insects and evidence of translocated clay and iron oxides). From this more regional geology information we learned that the sample could be between 96 and141 Myr old and was formed during the early subareal history of the Atacama region (Figure 5).

## 4. The Role of the Imaging Systems

This science instrument package consisted of several imaging systems, as shown in Table 1. For a more detailed description of these instruments, their capabilities and results, see *Cabrol et al.,*[this issue]. The imaging systems were composed of four types of cameras: a human-eye high-resolution color stereoscopic camera pair identical to the one used in the 1999 Marsokhod Silver Lake Field Experiment [see *Stoker et al.,*this issue]; a monochromatic black-and-white stereo pair; a wide-angle monochromatic camera; and a panospheric camera. Overall, the remote science team could only count on a science payload limited to visible imaging at various resolutions to document the test site. With no instruments enabling mineralogical or microscopic investigations, Nomad science payload provided an interesting challenge to test the ability of achieving science objectives with limited instrumentation.The finding of the fossiliferous rock based on these instruments is therefore significant. It is also interesting to look back at the three hypotheses proposed by the remote science team when they were documenting the rock using the suite of imaging systems: (1) a fossil, (2) a chert nodule, and/or (3) a iron-rich conglomerate clast. Among all of the images the stereo-color high-resolution (0.3 mrad/pxl) image was the one containing the most information on texture, color, and shape of the rock. All three hypotheses were proposed after the survey of this



| ERA | SYST. | SERIE | STAGE | Ma |
|---|---|---|---|---|
| MESOZOIC | CRETACEOUS | UPPER | MAASTRICHIAN | 65 |
| | | | CAMPANIAN | |
| | | | SANTONIAN | |
| | | | CONIACIAN | |
| | | | TURONIAN | |
| | | | CENOMANIAN | 96 |
| | | LOWER | ALBIAN | |
| | | | APTIAN | |
| | | | BARREMIAN | |
| | | | HAUTERIVIAN | |
| | | | VALLANGINIAN | |
| | | | BERRIASIAN | 135 |
| | JURASSIC | UPPER (MALM) | TITHONIAN | 141 |
| | | | KIMMERIDGIAN | |
| | | | OXFORDIAN | |
| | | MIDDLE (DOGGER) | CALLOVIAN | 154 |
| | | | BATHONIAN | |
| | | | BAJOCIAN | |
| | | | AALENIAN | |
| | | LOWER (LIAS) | TOARCIAN | 180 |
| | | | PLIENSBACHIAN | |
| | | | SINEMURIAN | |
| | | | HETTANGIAN | 205 |

**Figure 5.** Geological scale representing the Jurassic and Cretaceous ages. The rows shadowed in gray represent all possible ages for I-250697 after in situ and laboratory analysis.

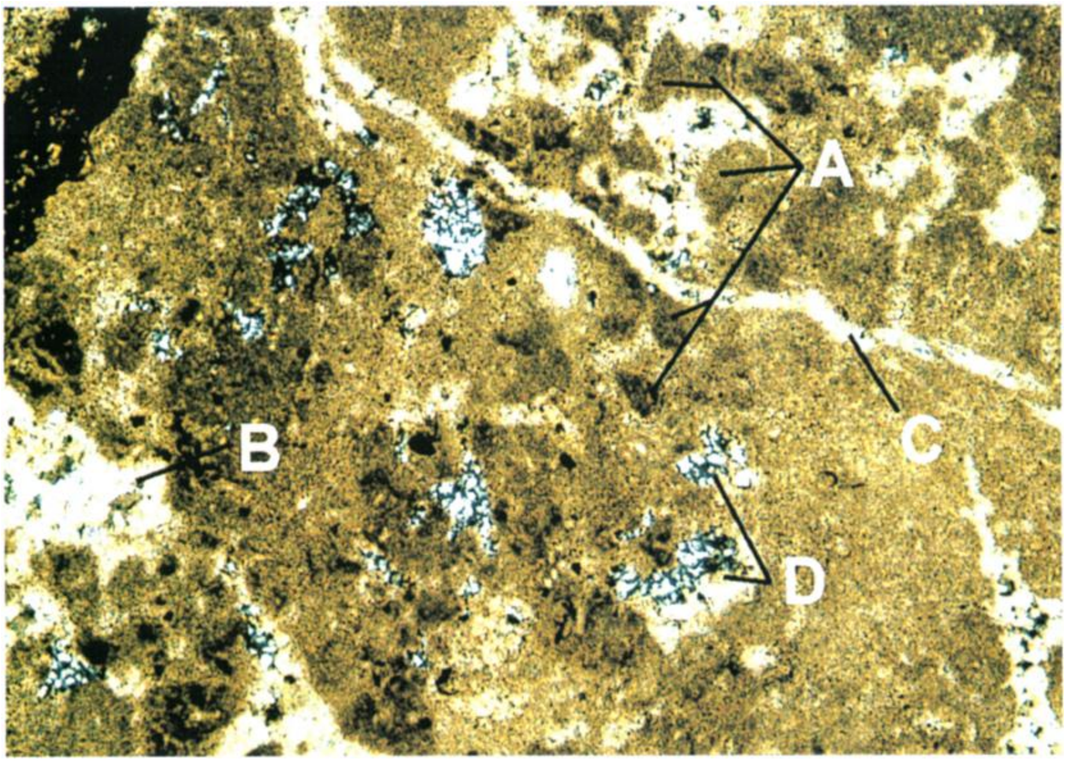


**Plate 1.** Photomicrograph of a portion of sample I-250697 showing several of the features decribed in the text: A, dense micrite area interpreted as calcite-replaced insect fecal pellets; B, calcite microspar-filled voids; C, calcite microspar-filled fractures; D, quartz-microspar filled voids in micrite matrix. The image is 3 mm long by 1.75 mm high. The light is cross-polarized.

**Table 1.** Nomad Navigation and Science Package

| | Description |
|---|---|
| *Navigation and Science Imaging Systems* | |
| Panospheric camera | 1 k x 1 k at 6 Hz |
| Rear camera | 1 k x 1 k grayscale, occasional |
| Compression | 100:1; DSP-based wavelet compression |
| High-resolution | 3 CCD color camera with a pan/tilt mechanism for remote geology |
| *Science Instruments* | |
| Weather sensors | temperature, wind velocity, humidity |
| Magnetometers | meteorite search |
| Metal detectors | meteorite search |

image, and the three of them were actually proved to be correct after the laboratory analysis of the sample.

Nomad's fossil argues then that a sophisticated imaging system can be an effective tool to identify life (extinct and/or extant) on Mars. Powerful rover-mounted cameras will be the tools that will likely identify fossiliferous units and any "suspicious" rocks within them. Since the next rover missions (Athena) will carry an imaging system with a comparable high-resolution imager [*Squyres et al.,* 1998], the finding of the first fossil by the Nomad rover is highly significant for the robotic exploration of Mars.

The ability of the high-resolution stereo pancam system to collect critical information to detect favorable environment for life, and life, has been confirmed during the Silver Lake Marsokhod Field Experiment [*Stoker et al.*, this issue]. Using the same stereo pancam system as during the Nomad Field Experiment, the Silver Lake experiment remote science team positively identified for the first time living chasmoendolithic biota on a rock from a high-resolution image. The preliminary interpretation of the remote science team was confirmed by spectral analysis.

In addition to the high-resolution stereo pancam system, other imaging systems would greatly increase the chance of robotic discovery of evidence for life on Mars. The finding of I-250697 stresses both the critical importance of having excellent orbital images to properly assess the nature of the regional environment where a rover is exploring and the role of an appropriate suite of imagers that can narrow down the right rock outcrops or rocks to sample. However, when the remote science team decided to sample I-250697, its fossiliferous nature was still a hypothesis. Considering the level of chertification of the rock, what science payload on Nomad would it have taken to be positive on its nature and leave site 4 with a certainty? Was that possible? For instance, if the science team had explored more thoroughly site 4, they would have discovered obvious shells and coquinae-type fossils that the resolution of the stereo color camera would have revealed. But what about more complex and evolved rocks for which the fossiliferous contents are not so obvious, like I-250697, and that are likely to represent better analogs for Mars than any terrestrial shell? Would the presence of spectrometers on board have provided the answer?

Spectrometers permit remote determination of mineralogy. If Nomad had carried spectrometers, we could have remotely determined that the specimen at site 4 had a carbonate composition. Carbonates have a high probability of having biotic influence in their formation and are likely to preserve evidence of paleolife as fossils, as trace fossils, or in their chemical (including isotopic) composition. However, some ambiguities can still remain (some carbonates are abiotic). We could face the same scenario on Mars as with I-250697 and return potentially fossiliferous rocks without having any certainty about their contents.

Identifying the fossils in situ would be very difficult on Mars. Microfossils or, as in the case of the Atacama rock, micropellets would require examination of a thin section for identification. Therefore it seems that we need to look for the environments and rocks bearing the most potential for life as we know it on Earth, that is, find and collect carbonates, and also find and collect samples with evidence of weathering. Weathering involves physical and chemical processes at the land surface that may be biologically mediated or influenced.

When returned to the laboratory, thin-section work will allow us to determine the history of the specimen and identify evidence of life in the form of fossils or trace fossils. If carbon is present, study of the isotopic composition of the carbonate could further help determine if biological processes were involved in deposition of the carbon. Lifeforms induce kinetic isotopic effects in sediment carbon. Biological processes strongly fractionate carbon isotopes and these effects are easily measured. So, as long as we are dealing with carbon-based lifeforms, analysis of carbon isotopic composition in samples would provide additional information on the presence or absence of biological activity.

## 5. The Critical Notion of Environment and the Role of Mobility

The shape of the anomalous clast, and the remotely interpreted environment in the vicinity of site 4, supported the fossil hypothesis. As a potential fossil, the rock was sampled and numbered by the field team upon request of the remote science team. After hand examination the preliminary interpretation of the field team in Chile about the rock's origin was a possible lacustrine limestone, conglomerate (in) proximity of an ancient coastline. The material corresponds to reworked fossiliferous material from the Jurassic Age (G. Chong, unpublished field report, 1997). Field hand inspection of the sample also confirmed the presence of advanced chertification process.

Site 4 showed that the imaging system was an important strategic and tactical tool, the utility of which cannot be denied in a reconnaissance of surface fossil records. In the context of Mars exploration with probably very similar environments (lake shorelines, channels, and possibly altered iron-rich carbonate units in outcrops), the primary tools for the rover reconnaissance and selection of potential study areas will remain the imaging system. Using only the imaging system, a correct area characterization of the basic geology and stratigraphy deduced from preliminary remote site exploration led the science team to site 4 and then to spot sample I-250697 on the fossiliferous unit.

This notion of becoming familiar with the explored environment is fundamental in the quest for life on Mars, and our ability to characterize it will be critical. Both in the case of sample I-250697 and later in the case of the meteorite search during day 4 of the Nomad science experiment [*Cabrol et al.*, this issue], the science team identified the correct rocks because they looked different from the surrounding environment with which the science team had become familiar. We might not be able to positively recognize life on Mars when we see it, or even when we perform spectrometry on rocks, but the identification of I-250697 and its sampling prove that we can certainly increase our chance for success by a proper approach and exploration strategy.

An interesting aspect of the discovery of I-250697 is that it did not happen during the two previous days of site investigation, when the science team was performing a thorough inspection of the test site on a limited area, a strategy which is comparable to the one used during the Pathfinder mission [*Golombek et al.*, 1999]. It occurred during the reconnaissance mode experiment, when the major part of the experiment time was devoted to traverse. Concerning the Nomad science team interpretations [see *Cabrol et al.*, this issue], the two previous days of thorough site investigation were critical because they helped the science team to build a mental map of the area and guide their decision for the traverse design of the third day. This traverse design contained site 4 as a potential candidate to look for sedimentary outcrops and material that could reveal environments for paleolife, but the critical decision was to leave the exploration site area of the two previous day and venture 1 km away from it to seek answers. In the discovery of I-250697, proper characterization of the environment and mobility were the keys to success. From the perspective of the exobiology exploration of Mars, it would have been difficult for the science team to properly interpret the environment if they had not reached the distant outcrop, simply because there was no clue for biologic activity at the rover site of the two previous days. However, the clues were not far, but on the current Mars exploration mode, they would have been missed. Mobility is a science instrument. There is little need to send rovers to Mars if these rovers are hardly moving or staying in the line of sight of landers. The exploration of Mars critically needs rovers that complete the task they have been designed for: to be mobile. If we are not using this capability to the full, we leave the discovery of signs of life (extant and/or extinct) on Mars to chance. If life appeared on Mars, the scientific and instrumental process that will lead to its discovery requires mobility and significant traverses not as an option, but as a requirement. In this respect, the 2003 Athena mission and its expected traverse capabilities shows promises that interesting outcrops and critical information can be reached. Following the results of the Nomad field experiment, our recommendation would be that mobility be used as needed already during the primary mission and not necessarily as the focus of the extended mission.

## 6. Finding a Fossil on Mars: Expectations and Limitations

From the Nomad experiment, and the recent Marsokhod rover field experiment in the Mojave Desert in 1999 [see *Stoker et al.*,this issue], we foresee that the current existing resolution of imaging systems has the potential to lead science teams to successfully interpret the geological setting of the Martian landscape. We also learned that MOC-like resolution of 1 m/pixel of the simulated orbital images used during the Nomad field experiment were critical to design the traverseand designate science targets which led to the discovery of the fossiliferous rock. Therefore it seems that the current and future planned mission science payloads and years of rover testing start to bring together the proper instrumentation for promising potential exobiology discoveries on Mars. Will it be sufficient? The case of I-250697 helps us to reflect on what to expect and the limitations we could face on Mars.

We now consider one of the most favorable cases by assuming that life appeared on Mars sometime at the beginning of its history [*Jakosky* 1997, 1998, 1999] and that environmental conditions were sufficient to allow fossilization processes [*Farmer et al.*, 1999]. If the rock sample I-250697 had been identified on Mars, cached, and returned, what would this sample have told us about Mars evolution, geologic history, climate and biology? In section 3 we showed how much information about a succession of paleo environments could be reconstructed from the petrographic analysis of a rock. The succession of moist and dry climatic episodes, the presence of tectonic forces, and episodes of volcanic activity were pointed out. The rock obviously had a long and complex evolution including biology. However, after the analysis we were able to replace I-250697 into the geological scale and a time span of 30 million years only because of one critical piece of information currently missing for Mars: the detailed knowledge of the regional and global geological, climatic, and biological evolution of the Earth. If we had found I-250697 in the same conditions on Mars, the rock would have taught us the same information about its evolution, but many questions would have remained unsolved. For how long did this evolution take place? What is the age of the sample and the age of the paleolife evidence it contains? Was the outcrop where the rock belonged related to a localized geological event or a major global geological, climatic, biologic episode?

Orbiters and rovers are critical in the first steps of the evaluation of the geologic, climatic and possibly biologic evolution of Mars. We have to admit, though, that we are just starting to unravel the superficial part of the history of Mars. We currently recognize three main chronostratigraphic divisions including various epochs at global scale [*Tanaka*, 1986; *Tanaka et al.*, 1992]. This knowledge has been acquired from orbit with Mariner 9, Viking I and II, and the ongoing Mars Global Surveyor Missions, after the observation of geological units visible at the surface. Detailed rock unit stratigraphy (origin of the units, thickness of the outcrop) at local scale is a painstaking task that was difficult at Viking resolution and only locally performed from orbital images. It took hundreds of years of field investigation including drilling, sounding methods, and recently, remote sensing, to acquire the local, regional, and global knowledge about the evolution of Earth. We are just starting to build this database on Mars.

Fossils on Mars could potentially be found in outcrops, in their vicinity, or anywhere directly at the surface if recent impact cratering has excavated ancient fossiliferous units and exposed fossils at the surface. This last case could be the more favorable to find fossils because it associates rapid burial and protection from destruction with recent exposure to the surface [*Farmer et al.*, 1999]. In this scenario we should be ready to identify rocks and fossils completely out of their original geological context. An impact crater might have ejected rocks kilometers away from their original unit. They are also likely to have excavated hundreds of meters deep into the Martian crust (and therefore in time), preventing us from knowing the age and the extent of the unit if it does not have any surface expression. How then to discriminate between a local geological occurrence (singularity) and the evidence of a dramatic geologic, climatic, and/or biologic change? What conclusions can we draw from a sample? Part of the answer resides in the number of samples and the places where we will sample on Mars. We need to have a number of samples that is statistically valid and representative of the geological setting of the explored area. We also need rovers that can cover kilometers in a relatively short amount of time to reach the boundary of unit exposures or, at least, surface expression of the geologic units to which the samples belong. It is critical to be capable of sending a rover to the site where the rock sample originates to facilitate the reconstruction of the geological context. That might be possible in the case of rocks and/or fossils recently exposed by young craters or rocks transported short distances from their outcrop by erosion and transportation agents. That might not be possible in outwash plains where the rocks are coming from hundreds of kilometers aways, have multiple origins and ages, and are mixed together. The more we sample all over the planet, the better the "big picture" of the Martian evolution will appear, and the better we will be able to replace the samples in their evolutionary context. In the mean time, our recommendation for the Mars sample return missions would be that the selected landing and survey sites include as a high-priority the possibility for the science teams to replace their samples in their geological and evolutionary context.That implies the presence of outcrops, exposures, and terraces. It also requires that the sampling of rocks and soil be done in places were we will be able to, at least roughly, identify in situ the stratigraphic sequence and extrapolate it at global scale.

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