The astrobiological aspects of Titan: A new vision from Cassini-Huygens

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Since the discovery of the presence of an active organic chemistry in its atmosphere, Titan is considered as a planetary body of prime astrobiological importance. The very first fly-bys of Titan by the Cassini spacecraft a few months ago, and the in situ exploration of its atmosphere and surface thanks to the Huygens probe, on January 14th 2005, are providing us new and spectacular data on Titan's environment.

Some of the astrobiological consequences of these new data will be presented and discussed.

Biologically enhanced energy and carbon cycling on Titan?

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With the Cassini-Huygens Mission in orbit around Saturn, the large moon Titan, with its reducing atmosphere, rich organic chemistry, and heterogeneous surface, moves into the astrobiological spotlight. Environmental conditions on Titan and Earth were similar in many respects 4 billion years ago, the approximate time when life originated on Earth. Life may have originated on Titan during its warmer early history and then developed adaptation strategies to cope with the increasingly cold conditions. If organisms originated and persisted, metabolic strategies could exist that would provide sufficient energy for life to persist, even today. Metabolic reactions might include the catalytic hydrogenation of photochemically produced acetylene, or involve the recombination of radicals created in the atmosphere by UV radiation. Metabolic activity may even contribute to the apparent youth, smoothness, and high activity of Titan's surface via biothermal energy.

Our calculations indicate that biothermal melting would be a possible explanation for the smooth surfaces observed by the Cassini-Huygens mission. Given the low temperatures, the biological effect on Titan, if it exists, should be larger than on Earth. In conditions where the ability to sustain liquid microenvironments is a key limitation on survival, then adaptive pressures could lead to a larger percentage of the free energy of exothermic metabolic reactions going towards heating the immediate environments of organisms living close to the freezing point. On the other hand, much energy has to be expended to reach the liquid state. If volcanic activity or other energy sources are present and significant, it would increase the chances for life on Titan by elevating temperatures and providing potentially habitable geothermal areas and gases that could be used for metabolism. Any liquid water-ammonia mixture is lighter than the surrounding ice and will float if produced at depth.

Given the current sample size of one biosphere upon which astrobiologists must base their theories and speculations, our ideas about life elsewhere must remain fluid and not too heavily based upon the specific metabolisms, strategies and structures of terrestrial organisms. The basic requirements of life, as they are understood today, are all present on Titan, including organic molecules, energy sources and liquid media.

Mars and Titan: Assessing the plausibility of life on two worlds with similar features and exotic differences

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Mars has long been considered conducive to the possibility of life because of its proximity to Earth, evidence for geophysical processes similar to those on Earth, and episodic temperatures above the melting point of water. The abundance of organic molecules on Titan has stimulated speculation about the possibility of life there as well. Recent data from robotic missions to Mars and Titan have opened the door to a reassessment of the plausibility of life (POL) on both. The abundance of subsurface water now evident on Mars has enabled the reconstruction of a planetary history highly conducive to the origin and possible persistence of at least microbial life (Schulze-Makuch, *et al.*, 2005), strengthening the case for a POL of II on Mars (Irwin & Schulze-Makuch, 2001). Images from the Huygens probe to Titan reveal a heterogeneous surface with superficial similarities to Martian topography, indicative at least of chemical and energy cycles capable of reshaping what appears to be a young surface. Coupled with the abundance of organic matter, some of the requirements for living systems appear to be met. The nature of solvent availability remains a question. Subterranian water liquefied by internal heating or gravitational flexing could support water-based cellular life beneath the surface as known on Earth. The much colder temperature and consequent liquid state of organic compounds near the surface, if they are the prevalent solvents, would require a very different cellular boundary (membrane) composition and metabolic systems substantially divergent from anything known on Earth. Titan thus presents the possibility of harboring either relatively familiar or totally exotic forms of life. Ongoing analysis of data from Huygens should eventually support one possibility over the other, and suggest whether the original POL rating of III for Titan (Irwin & Schulze-Makuch, 2001) deserves to be elevated to II (Schulze-Makuch & Irwin, 2004).

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Mars and Earth: Results of recent Mars missions

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Current news releases to the contrary, many geological investigators have known for thirty years that Mars had an early history with aqueous activity on its surface. However, new mission results are revealing the extensive sedimentary and geochemical evidence for that history. The new results strongly corroborate the long-standing geological and geomorphological inferences that early Mars had extensive lakes and probably transient seas ("oceans") that were associated with a climate capable of generating the precipitation and runoff to sculpt its landscape and transport materials to sedimentary basins.

High-resolution images from the Mars Orbiter Camera (MOC) of the Mars Global Surveyor (MGS) Mission reveal a diverse suite of exceptionally young, globally distributed landforms of aqueous origin, including glacial, periglacial, fluvial, lacustrine, mass moverment, and phreatovolcanic features. These landforms are uncratered or exceedingly lightly cratered, implying an age of less than a few million years. If observed on Earth, most of these landforms would be ascribed to processes requiring a relatively dense atmosphere and extensive movement of water through precipitation from that atmosphere. Because such conditions do not currently prevail on Mars, these observations imply ongoing climate change on Mars

Results from the Mars Odyssey Mission are consistent with an early phase of plate tectonics, which could have produced the Martian highland crust by continental accretion. By concentrating volatiles in a local region of the Martian mantle the early plate-tectonic phase of Mars would have led to a superplume at Tharsis. The resulting concentration of volcanism at Tharsis would iinfluence climate change by initiating immense megafloods. The observed persistence of this volcanism through later Martian history provides the mechanism for the episodic, short-duration aqueous phases.

Earth's early history of megaglaciations has some broad similarities to the newly understood history of Mars. Earth's late Proterozoic glaciation is particularly interesting since there is considerable geological evidence that Earth may have temporarily switched to Mars-like icehouse conditions by freezing of the surface of the global ocean. Both Mars and Earth may be subject to major endogenetically driven shifts in climatic states.

The past geochemical environment of Meridiani Planum, Mars, and its implications for astrobiology

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Motivation

The recent chemical and inferred mineralogical data returned from the Mars Exploration Rover Opportunity are unlike anything previously seen or anticipated on Mars. The data, combined with textural information and geologic context, suggest deposition in a shallow body of water and subsequent chemical weathering [1-2]. Aqueous geochemical modeling offers a way to explore the conditions required for emplacement and alteration of the mineral assemblages. This is crucial for assessing the potential habitability for life in the paleoenvironment. Our approach has been to use the known alteration products at the Opportunity site to evaluate potential geochemical pathways and range of environmental conditions that can produce the observed chemistry and mineralogy. From the likely chemical pathways we can calculate the energy yield available for chemosynthetic organisms and place constraints on duration of the fluid-rock interactions as well as assess habitability.

Example Results:

One typical simulation, run in *Eq3/6*, involves the reaction of "Martian" groundwater (pure water equilibrated with the current Mars atmosphere) with iron-bearing sediments in the form of pyrite (FeS_2). Pyrite is a common product from the hydrothermal alteration of basalt as seen from terrestrial examples.

As the fluid reacts with pyrite the pH drops rapidly through the production of sulfuric acid from oxidation of sulfide from pyrite, and dissolved Fe increases also. As a result, the fluid becomes saturated with hematite and jarosite and these minerals precipitate (the amount of jarosite precipitated is largely controlled by the assumed concentration of K^+ in the initial fluid). The model suggests it is feasible that known minerals at the Opportunity site (namely hematite and jarosite) could arise from interaction of pyrite-bearing sediments with an aqueous fluid in contact with a moderately oxidizing atmosphere like that currently on Mars. Using typical assumptions, a microbe could potentially obtain 10 kJ of energy from each gram of pyrite reacted under such conditions.

This is just one pathway we are exploring to understand the probable geochemical history of Meridiani Planum. Additional pathways will be presented as well as chemical energy yields and their implications for the suitability for the development of Martian life.

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Distribution of some elemental abundances on Mars: Results from the Mars 2001 Odyssey gamma ray spectrometer

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The 2001 Mars Odyssey Spacecraft has recently completed its first martian year in orbit. Data collection with full boom deployment began in June, 2002 and has continued to the present with only short interruptions due to Solar Particle Events, instrument annealings and related activities. Gamma rays produced by individual elements can be the result of any of three processes: inelastic scatter, capture of thermal neutrons, or radioactive decay, each of which requires a separate method of processing and normalization. Our data collection rate for individual gamma rays is measured in counts per thousand seconds. Nevertheless, sufficient data has now been gathered to begin to examine some elemental distributions for the mid-latitudes on Mars.

While we continue to analyze the data and determine the exact normalization procedures to use for each process leading to the observed gamma rays, we can now map out relative abundances for several elements. These elements include hydrogen (mapped as its water equivalent), chlorine, iron, silicon, potassium and thorium. The elements that we have been able to map to date show modest global differences in their distribution and these variations in elemental distribution are clearly associated with previously mapped geologic and morphologic regions on Mars.

Silicon has limited variability (less than a factor of 2) over the planet but shows a modest enrichment in the northern lowlands and a significant decrease over the Tharsis region. Iron varies by a factor of 2 globally and also shows enrichment over the northern lowlands. (It should be noted that all of the in situ measurements to date have come from landers in the northern lowlands.) Chlorine shows a larger variation, on the order of a factor of 3, and is particularly high in the Medusae Fossae formation west of Tharsis. The range in distribution of potassium and thorium is relatively modest, especially when compared to that of the Moon.

In addition to elements whch can be mapped in the mid latitudes, other elements can be averaged over large, geologically defined regions. Comparisons and correlations of these elements will be presented along with the maps.

Subsurface Sounding in "Mars Advanced Radar for Subsurface and Ionosphere Sounding" (MARSIS)

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According to the Mars Express mission, the MARSIS primary *scientific objectives* are to *map the distribution of water, both liquid and solid, in the upper portions of the crust of Mars*. Detection of such reservoirs of water will address key issues in the hydrologic, geologic, climatic and possible biologic evolution of Mars, including the current and past global inventory of water, mechanisms of transport and storage of water. According to the previous scientific objectives, this paper provides a description of the design approach and expected performances of the MARSIS, taking into account of Mars Orbital Laser Altimeter (MOLA) data. The principle of operation of MARSIS the following: the transmitted radar pulse will reach the top of the Mars surface producing a first reflection echo which propagates backward to the radar. However, due to the long wavelengths employed, a significant fraction of the e.m. energy impinging on the surface is transmitted into the crust and propagates downward. Additional reflections, due to subsurface dielectric discontinuities, will occur and the relevant echoes will propagate backward to the radar. As consequence time domain analysis of the strong surface return, eventually after multi-look non-coherent integration, will allow estimation of surface roughness, reflectivity and mean distance, just like in classical pulse limited surface radar altimeters. The presence of weaker signals after the first strong surface return will enable the detection of subsurface interfaces, while the estimation of their time delay from the first surface signal will allow the measurement of the depth of the detected interfaces.The detection of these subsurface echoes is limited by the surface echoes (especially if surfaces are rough), for this reason three different methods will be implemented in MARSIS: Doppler Beam Sharpening, Secondary Monopole Antenna, and Dual Frequency Processing. Finally, the Marsis frequency-agile design will allow to tune the sounding parameters in response to changes in sun illumination condition, latitude etc.. According to the previous scientific objectives and the operation planning, this paper provides a description of the approach referred to the data inversion and expected performances of the MARSIS

New results from the robotic exploration of Mars

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The Mars Exploration Rover *Spirit* landed successfully in Gusev Crater on January 4, 2004 (UTC), followed three weeks later with the successful landing in Meridiani Planum of its twin, *Opportunity*.

Guesev Crater: The landing site at Gusev Crater lies on a densely populated rock-strewn plan. Rocks identified around the lander range in a variety of sizes and angular shapes. Preliminary results of the rock textures show that a majority of the rocks consist of fine-grained volcanic and several (Adirondack) appear to contain some sort of surface coating.. Preliminary results are that the concentrations of presumably dust-borne elements like sulfur and chlorine decrease and you go deeper into the rock. A majority of the rock observations from the plains rocks being classified as an unweathered olivine, magnetite-bearing, low silica basalt. At the present time, three distinct rock types have been identified in the Columbia Hills. Since the initial landing, Spirit has traveled over 4 km and is presently heading up to the top of the Columbia Hills.

Meridiani Planum: The Opportunity landing site lies inside a 20 m diameter impact crater. The lander came to rest near an exposed layer (roughly 12 m long; 0.5 m high) of bedrock in the crater wall. Initial results from microscopic images (MI) data suggest this unit consist a fine-grained rock with a variety of sedimentary structures consisting of cross-bedded, thin layer of sediments. Alpha Particle X-ray Spectrometer (APXS) suggest a high concentration of sulfur. Embedded within the outcrop and weathering out are highly spherical granules. Opportunity spent 90 sols examining Endurance crater and is presently outside the crater examining its own heatshield which landing approximately 2 km from its initial landing spot.

The Tharsis and Elysium corridor: A marker for an internally active Mars?

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The paradigm of an ancient warm, wet, and dynamically active Mars, transitioning into a cold, dry, and internally dead planet has persisted up until recent in spite of published Viking-based geologic maps, which indicate geologic and hydrologic activity into the youngest part of the history of Mars, the Late Amazonian epoch. This paradigm is shifting to a water-enriched, still possibly internally active planet, based on a collection of geologic, hydrologic, topographic, and elemental evidences obtained by the Viking, Mars Global Surveyor (MGS), Odyssey, and Mars Express missions. A collection of diverse information unfolds this possibility, including: (1) stratigraphically young rock materials such as pristine lava flows with few, if any, superposed impact craters, (2) tectonic features that cut stratigraphically young materials, such as fractures, faults, graben, and pit crater chains, (3) features with possible aqueous origin such as structurally-controlled channels that dissect stratigraphically young materials and anastomosing-patterned slope streaks on hillslopes, (4) elevated elemental abundances, such as hydrogen and chlorine, and (5) methane, all of which occur in regions that reportedly record ancient, middle planet, and geologically recent magmatic, tectonic, and hydrologic activity. Specifically, parts of Tharsis, Elysium, and the region that straddles the two volcanic provinces, collectively referred to here as the Elysium/Tharsis corridor, unfolds a potentially internally active Mars.

Results from recent Mars missions and their implication to possible life

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The Mars Opportunity and Spirit rover missions, Mars Express, Mars Odyssey, and Mars Global Surveyor have revolutionaized our view of Mars. No scientist has faced these data with prior ideas well intact. While the orbiting missions have provided global and regional views of ice distribution in the shallow crust, topography,geology, and geochemistry, as well as aspects of local geology and geomorphology, the rover missions have provided critical ground truth that lend confidence to the global observations and add critical details not discernable from orbit. Most critically, the rovers have provided close-up chemical and petrologic data that elucidate important enviornmental conditions at two points in geologic time and space. It is evident from these orbital and rover data that Mars, like Earth, is a "water world," but it is one where most of the water has been locked as solid ice for most of Martian history. There were periods and places on the surface where liquid water was abundant for geologically significant periods of time. We see it in the landforms and in the chemistry and mineralogy. Limited rover-based ground truth points toward highly acidic, highly saline, and probably very cold brines as the depositional agent in Meridiani Planum and as a rock-altering agent in Gusev Crater. The rover data are consistent with a an interpretation that Mars is analogous to a global acid-mine waste site. Many aspects of Martian geology, geochemistry, and mineralogy--right down to the red color of Mars-- can be explained within the context of this aqueous acid model. Orbiter observations of very young water-related landforms indicate a surprising geologic recency of some aqueous activity. However, in retrospect, considerations of multicomponent solid-liquid-gas phase equilibria suggest that aqueous acid brines still are active at shallow levels and potentially even at the surface of Mars. Whether life ever could have originated or evolved there is an important unanswered question, but one which should bear very strongly on our exploration strategy. Recent Mars Express observations of methane are consistent with the past or present existence of methanogenic life; however, abiogenic formation of methane also is possible. In sum, we have answered long-standing questions about whether Mars was icy or wet; it was and still is both.

Sulfate minerals as targets for biomolecule detection on Mars

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A first step in the search for life on Mars must focus on the detection of specific organic molecules associated with biology as we know it. Amino acids are prime target molecules in this search strategy. Advanced fluorometric analytical techniques offer high detection sensitivities for amino acids, and amino acid chirality (handedness) can be used to distinguish biological from abiotic origins. One important consideration with respect to amino acids as target molecules is whether they are preserved over long periods of time at the cold temperatures characteristic of Mars. One way to address this issue is to investigate terrestrial mineral analogs to determine which types offer the best matrix for amino acid preservation.

Strong evidence for evaporitic sulfate minerals such as jarosite, gypsum, and anhydrite has recently been found on Mars by the Spirit and Opportunity rovers. As these minerals are deposited in terrestrial evaporitic environments, any organic molecules from extant or extinct microorganisms should be co-deposited. Thus, we have investigated concentrations of organic matter along with amino acids in natural terrestrial sulfate mineral samples. We have found that sulfate minerals contain between 0.03 to 0.69 % organic carbon as well as high ppb to low ppm abundances of amino acids and their degradation products in samples ranging from 30 million years old to contemporary.

From our data, it appears that amino acids and their amine decarboxylation products are well preserved over long geological time in the sulfate mineral matrices on Earth. This preliminary evidence indicates that sulfate minerals should be prime targets in the search for organic compounds, including those of biological origin, on Mars. Suitable *in situ* instrumentation is now available to detect amino acids at sub-ppb levels while also providing chiral resolution. We thus conclude that amino acids in sulfate mineral matrices are strong candidates in the search for organic molecules of possible biological origin on Mars.

Next-generation robotic planetary reconnaissance missions: A paradigm shift

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We introduce a fundamentally new scientific mission concept for remote planetary surface and subsurface reconnaissance that will soon replace the engineering and safety constrained mission designs of the past, allowing for optimal acquisition of geologic, paleohydrologic, paleoclimatic, and possible astrobiologic information of Mars and other extraterrestrial targets. Traditional missions have performed local ground-level reconnaissance through immobile landers and rovers, or global mapping performed by an orbiter. The former is safety and engineering constrained, affording limited detailed reconnaissance of a single site at the expense of a regional understanding, while the latter returns immense datasets, often overlooking detailed information of local and regional significance. A “tier-scalable” paradigm (Fig. 1) integrates multi-tier (orbit⇔atmosphere⇔ground) and multi-agent (orbiter⇔blimps⇔rovers) hierarchical mission architectures, not only introducing mission redundancy and safety, but enabling and optimizing intelligent, unconstrained, and distributed science-driven exploration of prime locations on Mars and elsewhere, allowing for increased science return, and paving the way towards fully autonomous robotic missions.

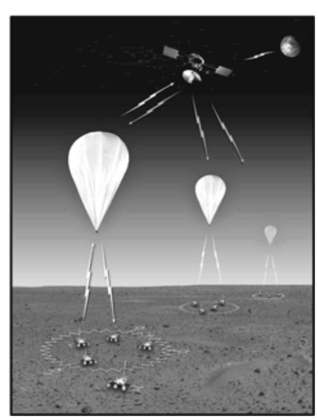

Fig. 1: Tier-scalable multi-tier and multi-agent hierarchical mission architecture

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Enigmatic linear patterns of hydrogen concentration on Mars

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Chemically or physically bound hydrogen within a meter of the Martian surface has been mapped using neutron spectroscopy [1]. The Neutron Spectrometer, part of the Gamma-Ray Spectrometer on board Mars Odyssey, is able to detect thermal, epithermal and fast neutron fluxes. Each of these have specific energy ranges with epithermal neutron energy ranging from 0.4 – 500 keV. This band is the most sensitive for hydrogen mapping purposes. Regions with high hydrogen concentrations have a low epithermal energy flux.

These concentrations are believed to indicate locations of subsurface water ice. As such the flux maps pinpoint locations where small quantities of liquid water may intermittently form today or where liquid water may have pooled in the past. The possibility of life existing on Mars – either in the distant past or at present – depends on the availability of liquid water.

Epithermal neutron flux maps of the equatorial region east of Schiaparelli Crater in Mars' eastern hemisphere indicate hydrogen ion concentrations in the shallow subsurface with a hydrogen water equivalent of just over 10 percent [1]. Published maps [2] reveal anomalous linear concentrations of hydrogen with a northeast to southwest trend. The width and trend of these linear anomalies match those of the graben between Scylla Scopulus and Charybdis Scopulus, west of Hellas Basin.

These linear ion concentrations suggest structural control of the hydrogen. Structural control of fluids can be attributed to fault activity or structural topography. Terrestrial faults are known to exert a strong control on groundwater flow immediately after earthquake events. Subsurface faults may also act as a barrier to fluid flow, creating a confined channel or aquifer within the width of the graben. Alternatively, the graben may have acted as a topographic control on surface water accumulation in the past. Any seepage of this water into the subsurface may have resulted in a hydrogen ion fingerprint in graben valleys, resulting in the linear patterns observed.

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Columbia Plateau Basalt as an analog to the basalt of the Martian Northern Plains

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The basalt of the northern plains on Mars is more andesitic and weathered than the basalt of the southern highlands. It appears to be well represented by the Bounce Rock at the Meridiani Site, which is dominated by pyroxene (clinopyroxene ~55%, orthpyroxene ~5%) and plagioclase (~20%), and is poor in olivine (~5%). Oxides are acounting for ~10%. The chemical composition of Bounce Rock is more evolved than the basalts in the Gusev crater. It has a high P_2O_5 content of 0.95wt%, a Fe/Mg ratio of 36, a low Mg number (molar MgO/ MgO+FeO) of 0.42 and a high Ca/Al ratio of 1.7, a lower FeO (15.6%), and a higher CaO (12.5%) content. The basalt in the northern plains is in general rich in sulfur and variably enriched in bromine relative to chlorine, indicating a past interaction with water.

The Columbia Plateau Basalt (CPB) is a typical continental flood basalt, composed of four basalt formations made up of more than 300 individual basalt flows. The wrinkle ridges and low viscosity of these basalt flows are typical features of CPB. On a normative cpx-ol-pl-qz projection, the Grande Ronde Formation (~ 87% of CPB), is very close to the 1 atmosphere pseudo-cotextic, indicating that the erupted melts underwent fractionation and mixing processes at a very shallow level. CPBs are dominated by relatively low Mg tholeiite and basaltic andesite, with SiO_2 at 52-58%, FeO 10.0-13.5%, CaO 8.6-10.4%, a Mg number of 0.55, and a higher P_2O_5 content of 0.68%.

Both, CPB and Mars basalt were formed at low pressure conditions with low-vicosity basaltic lava spreading over wide areas. Basaltic rocks in the northern part of Mars and the CPB were subject to sporadic interactions with water bodies, weathering, and glacial processes. The northern Martian basalts and CPB are similar geochemically and mineralogically being both evolved basalts with some signatures of andesite. Also, the higher P content of Bounce rock and the wrinkle ridges of Martian basalt are similar to that of CPB. Life based entirely on chemoautotrophic energy sources has been reported from a deep basalt aquifer of the CPB. Since Martian surface conditions are extremely hostile for life as we know it, the primary energy source for putative life on Mars is likely chemical energy rather than light energy. Thus, CPB and the chemotrophic organisms in the CPB serve as a suitable analog to Mars.

AGFA: (Airborne) Automated Geologic Field Analyzer

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This work reports on an integrated software system (AGFA) that automatically and unbiasedly characterizes rocks/soil in an imaged scene (in various wavelengths). This technology enables automated science analysis for robotic spacecraft, further expanding the possibilities for future intelligent and autonomous robotic exploration of remote planetary surfaces. This can be accomplished by merging the expertise of a field geologist with traditional exploration spacecraft to form a *science craft*. Its main benefit will be the ability to yield high science returns at a significant savings in cost and time. Although reconnaissance field geologists can become astronauts, the initial forays to Mars and other planetary bodies will be done by robotic craft. Numerous steps are necessary in order for a science craft to map, analyze, and characterize a geologic field site, and effectively formulate working hypotheses. We present and discuss a tool for automated science analysis of geologic field sites: the *Automated Geologic Field Analyzer (AGFA)*. AGFA, using various wavelengths, maps and characterizes rock/soil materials; this is done, both on the ground and from the air, by extracting features such as size, color, albedo, vesicularity, and angularity. Based on the extracted features, AGFA summarizes the field site numerically and flags targets of interest. It is our vision that this step will lead to autonomous robotic space exploration of remote planetary surfaces.

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Paleoenvironmental study of Doushantuo Formation: Insights of trace element and carbon isotope

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The upper phosphorite bed of Neoproterozoic Doushantuo Formation, Weng'an, South China, preserves a unique assemblage of what are propally the earliest metazoan fossils in the world that could contribute to a better understanding of early faunal evolution on Earth. However, no animal forms have been found in the lower phosphorite bed. Trace element geochemical characteristics show that the upper ore bed with clear negative Ce anomalies (Ce_{anom} ranging from -0.34 to -0.17) and lower redox element contents (Mn ranging from 125ppm to 452ppm, Mo ranging from 0.23ppm to 1.35ppm, U ranging from 3.79ppm to 7.05ppm and V ranging from 13.85ppm to 24.46ppm) compared to the lower ore bed with less negative Ce anomalies (Ce_{anom} ranging from -0.05 to -0.02) and higher redox element contents (Mn ranging from 897ppm to 1524ppm, Mo ranging from 1.52ppm to 13.95ppm, U ranging from 5.53ppm to 22.07ppm and V ranging from 9.70ppm to 52.68ppm), indicating the marine depositional environment changed from anoxic in the lower ore bed to oxic in the the upper ore bed. We might infer that increase of oxygen content in paleo-ocean probably caused the emergence of the earliest diverse eukaryote in the upper ore bed of Duoshantou Formation. $\delta^{13}C$ value trend generally increase from lower ore bed to upper ore bed although they are with several oscillations, indicating higher organic productivity and higher burial rate of organic carbon in the upper ore bed than in the lower upper ore bed.

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