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## Dokuchaev's soil paradigm and extraterrestrial "soils"

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### Abstract

The possibility of Dokuchaev's paradigm [ $S = f(cl, o, r, p)t$ ] application for studying of loose surface layers (regoliths) of terrestrial planets is examined. In a number of contemporary publications most loose substrates on the Moon and Mars are named as "soils". From the orthodox approach of Dokuchaev's paradigm these substrates are not soils *sensu stricto*, because none of these planets are known to have biota; there is no atmosphere or hydrosphere on the Moon as well. However, the Dokuchaev's factor paradigm could be broadened to accept all exogenic bodies, or simply **exons** (E), on terrestrial planets as the function of exogenic factors (ef) activity in time. In this case terrestrial formula of pedogenesis is transformed into general formula of planetary exogenesis  $E = f(ef_1, ef_2, ef_3 \dots)t$  and could be applied to any planet. All planetary exons could be divided into a) **exositons** - formed by on site transformation of planetary parent rocks by exogenic factors and processes and b) **exotransons** - laterally translocated and re-deposited along the surface. Pedology has highly developed methodology to study horizonated soil bodies, which could be applied to studying the extraterrestrial exositons as abiotic soil-like analogues of terrestrial soils. Extraterrestrial transons – the analogues of terrestrial sediments are already being studied with sedimentology and lithology approaches.

### Key Words

Extraterrestrial soils, regolith, exogenesis, soil-like bodies

### Extraterrestrial "soils" – a challenge to pedology

The term "soils" is used in scientific literature on Moon and Mars for denomination of their loose surface covers regardless of their genesis (Retallac 2001; Soderblom 2004). In the earth sciences the term and notion "soil" has more certain significance and the Earth soils are studied by pedology. This science is based on Dokuchaev's paradigm of soil as a function of interacting soil-forming factors. Now we meet with the luring challenge to pedology: can Dokuchaev's paradigm be applied extraterrestrially to study the regoliths of other planets?

### Orthodoxal response – accordance with Dokuchaev's paradigm

The soils are specific open bio-abiotic systems and bodies, which are forming and functioning in situ due to long-term ( $n \cdot 10^2 - 10^6$  years) interactions of climate and biota with parent rocks and topography of the upper layers of lithosphere:  $S = f(cl, o, r, p)t$ . The specific pedogenic and weathering processes are developing in functioning soil system and forming the vertically-anisotropic sequences of pedogenic horizons. It should be stressed that only those horizons which were formed *in situ* from parent material are recognized as pedogenic; sedimentary anisotropy – layers of regolith – are not accepted as soil horizons. The presence of biota was not still discovered in any terrestrial planets, the atmosphere is absent on the Moon, on the Mars only the atmosphere and paleoliquid hydrosphere were discovered. It means that the studied regoliths of these two planets could not be recognized as the Earth soils *sensu stricto* by the orthodoxal understanding of Dokuchaev's paradigm. They are formed without the influence of biota (on Mars) and even without biota, atmosphere and water (on Moon).

### Heterodoxal response – extension of Dokuchaev's paradigm

Nearly all loose covers of the Earth and terrestrial planets could be referred to the general class surface-planetary exogenic natural bodies formed by interaction of superficial parts of consolidated lithosphere with any kinds of exogenic factors, i.e. by planetary exogenesis. From this point of view, it is possible to extend Dokuchaev's paradigm and assume that all exogenic bodies, or in short – exons (E) are the functions of exogenic factors (ef) interaction in time and space. Then Dokuchaev's formula of the Earth pedogenesis should be turned into general formula of planetary exogenesis:  $E = f(ef_1, ef_2, ef_3 \dots)t$  and could be applied to any

planetary regoliths. On the basis of some empirical data we can conclude that the diversity, complexity and intensity of exogenic interactions are increasing from the Moon to Earth (Figure 1).

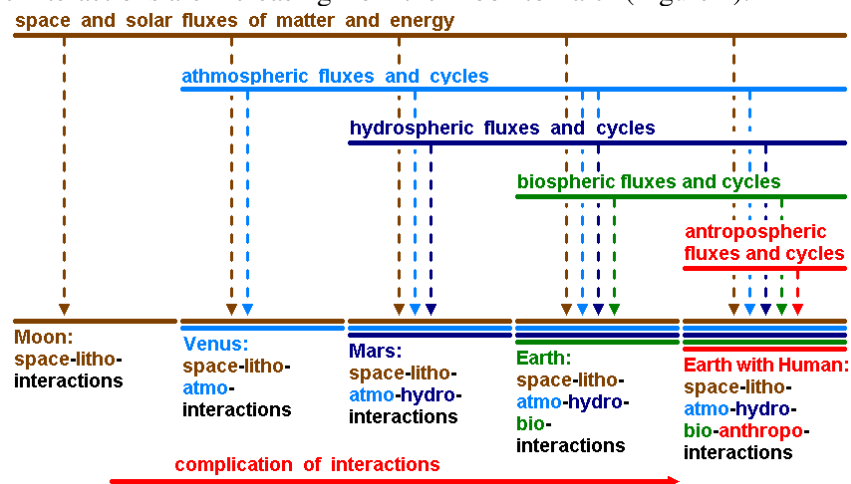


Figure 1. Exogenic interactions on the surfaces of terrestrial planets.

Next, the exons could be separated into two groups depending of their genesis but regardless of the acting exogenic factors and the composition of forming exons (Figure 2). The first group consists of exons formed from parent material due to its *in situ* transformation by exogenic factors, there are *sitons* or *exositons*. They record the character and duration of exogenic factors interactions in every point of planet surface. Exositons have vertical anisotropy (macro- or microhorization of profile) reflecting the decrease in diversity and intensity of exogenic factors as the level of their penetration into parent material becomes deeper. The second group consists of exons formed by any kind of lateral translocation of loose materials along the planet surface (by bombardment, gravity, by wind and water) and successive deposition. This group could be called transons or exotransons emphasizing its lateral transfer and absence of direct links with the underlying rocks. The typical exotransons of the Earth are all kinds of sediments, which are never called soils and studied by sedimentology and lithology, but not by pedology.

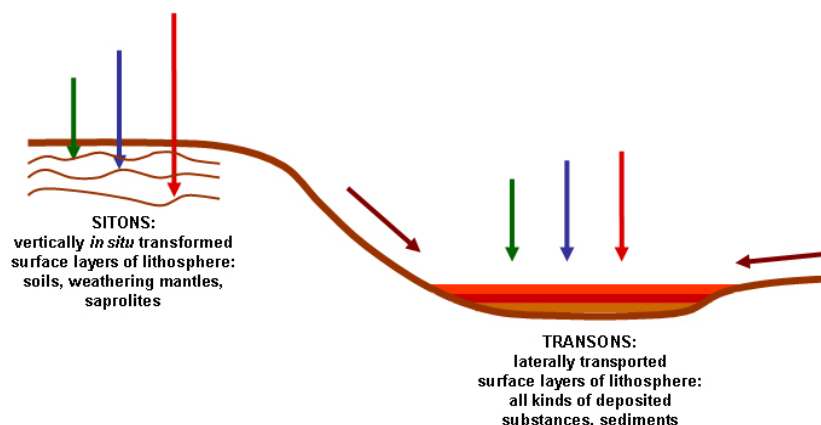


Figure 2. Two main types of exogenic unconsolidated earthy planetary covers – exons.

Only exositons of other planets could be recognized as extraterrestrial analogues of the Earth soils. If they were formed *in situ* and have on site horizonated macro- or microprofiles like the Earth soils, they can be realized as abiotic but soil-like bodies and studied by pedology methods. Among all earth sciences the pedology is the master of analysis of on site vertically horizonated natural bodies: soils, weathering mantles, saprolites. If we agree to extend Dokuchaev's paradigm, all extraterrestrial exositons will become one more non-traditional subject of pedology.

### Martian regolith

A number of the components, found in the Martian regolith could be interpreted as a result of interaction of the “exogenic” factors and the planet surface. The substantial compositions of the martian regolith indicate significant physical and chemical weathering processes. The following major components of regolith could be distinguished on the territory studied by Mars Exploration Rovers (Spirit & Opportunity) including Gusev crater, Meridiani Planum, Eagle crater and contiguous landscapes (Yen *et al.*, 2005; Haskin *et al.* 2005):

I) *basaltic rocks* and its *clasts* with olivine, pyroxene, feldspars as predominant minerals. Rocks are often coated in material enriched in sulphur, oxidized iron, chlorine and bromine, which can be explained by interaction of rocks with acidic water and subsequent evaporation. The coatings comprise light-toned and dark micro-layer sequences.

II) *loose substrates* including “soils”, dust and spherules:

- *dark soil* or *dark basaltic soil*, with particle size of 100-150µm, with olivine, pyroxene, nanophase iron oxide, and magnetite as dominating minerals (Yen *et al.*, 2005). Dark soil presumably is a re-deposited product of physical and weak chemical weathering of basaltic rock. S-, Cl-, Br-containing salts in the dark soil seem to have been separated according to solubility; the most deep filled cavities and veins of underlying rock’s interiors are enriched in bromine an element known to form highly soluble salts. In some samples smectite clays were detected.
- *bright dust* which cover basaltic rocks, its clasts and the dark soil. Found to be the mixture of the physical weathering products of basalts with particle size less than 1µm. Nanophase Fe(III)-oxides are the main component of bright dust closely associated with the occurrence of sulphur. Magnetic features are strongly pronounced and determined by the presence of magnetite. A nearly uniform elemental composition in all explored areas shows that the bright dust is distributed globally by winds.
- *spherules, granules, nodules* of 0.6- to 6-mm-diameter interpreted to be haematite concretions formed in the presence of water. Spherules cover sporadically basaltic rocks, dark soil and are often accumulated in depressions forming “blueberry bowls”.

Thus, at least two types of vertical profiles can be distinguished in Martian regolith:

a) the lithological heterogenic substrates determined by sedimentation processes, they are characterized by sequences of layers different in texture, mineralogy and genesis; their surface layers are unstable and exposed to various translocations by aeolian processes; b) relatively stable substrates transformed *in situ* by exogenic factors: consolidated basalts with coatings and loose basaltic depositions (“soils”). Their transformation occurred presumably in the presence of small amounts of acidic water and formed: the microprofiles or multi-layer coatings in surface layers of consolidated rocks and vertical salt profiles in dark soil differentiated according to solubility factor, brine’s freezing temperature and thermogradients.

### Possible paleoexogenesis

The question arises, if all these products could be attributed to the processes, controlled by actual environment or some of them are hereditary from the past environments. Type and distribution of most soluble Br salts – the most mobile alteration products – partly could be explained by the processes of water condensation in the subsurface cold traps, possible under climatic conditions similar to present day (Yen *et al.* 2005). However already distribution of S-rich soluble components requires more moisture, than is present in the atmosphere now (Haskin *et al.* 2005). Even more probable is the relict origin of iron oxides and smectites. Most researchers accept that these components are the products of chemical weathering of Martian basalts, although the overall weathering status of surface substrates is evaluated as low. Primary basaltic minerals, including olivine and glass are dominant whereas secondary components make up less than 5% in a typical Martian soils (Yen *et al.* 2005). It is supposed that this disperse haematitic component could be formed in the past humid period and than transported and mixed by eolian processes with the fresh physically weathered basaltic material (Goetz *et al.* 2005). The most conspicuous Fe oxide feature – the rounded concretions (spherules) which contain more than 50 % of haematite. They are present in the sediments together with the pores (vugs) left from the dissolution of the large salt crystals. These “*in situ* exogenic” soil-like relict properties are well correlated to the sedimentary features of the embedding materials which demonstrate crossed lamination of fluvial origin. Together these relict characteristics “clearly preserve a record of environmental conditions different from any on Mars today. Liquid water was once present intermittently at the martian surface at Meridiani, and at times it saturated the subsurface” (Haskin *et al.* 2005). The existing results demonstrate that the Martian regolith has components, features, layers and profiles which could be attributed to the surface exogenic processes developed under environmental conditions different from today. These elements make up the Martian analogues of “soil memory” and “soil records” and justify the possibility to apply the concepts and methodological instruments of paleopedology to these extraterrestrial objects. The application of paleopedological approach could be essential for the search of Martian paleoenvironments appropriate for life.

### Terrestrial models as a bridge from the extreme Earth environments to Martian soil-like bodies

The requisite conditions for life possibly have a place on Mars since ‘Mars-Odyssey’ and ‘Opportunity’ rovers had found water in the top meter of the high-latitude regolith. This makes the terrestrial models more or less realistic. It has been established that numerous (up to 10<sup>6</sup> cells/g of soil) of various viable microbial groups

survive under permafrost conditions since the time of its formation. They are the only known living organisms preserved over a geologically significant time. The permafrost up to 3 million years old and temperatures down to -28°C, inhabited by viable microorganisms, represents a range of possible extraterrestrial cryogenic ecosystems on the Earth-like planets without obvious surface ice such as Mars. In balanced permafrost environment on the Earth cells survive significantly longer than in other habitats. This is why if life existed during the early stages of Martian development, then remnants of primitive forms may be found within frozen material that protects them against unfavorable conditions.

The following models represent a probable bridge from the extreme Earth environments to Martian soil-like bodies with possible life forms: a) antarctic permafrost biodiversity with suggested age of permafrost somewhat closer to that of Mars; b) microbial population of overcooled (down to -11°C) lenses of water brines (cryopegs) within the permafrost as an only opportunity for free water formed when Mars became dry and cold; due to the geological events this saline water might sometime reach the surface; c) active volcanoes in permafrost areas, because one way to have liquid water on Mars could be volcano-ice interactions, and the thermophilic bacterial community in frozen ash and scoria deposited during the eruptions. In other words, the catastrophic geological events might transport the life from the depths to the surface.

Modern soil cover in polar and Alpine regions could be considered as a distant model of Martian “active layer”. Water ice within the top meters of the high-latitude Martian regolith, as well as visual similarities on the Earth’s and Martian surface - polygons formed by frost cracking - is the reason to consider the aborigines of frost-affected soils underlain by permafrost as an extraterrestrial model.

Metabolic activity of ancient microbial population was observed *in situ*, in the Arctic permafrost samples at temperatures between -5 and -35°C. It results in the formation of bacterial lipids, methane generation, CO<sub>2</sub> production and nutrient assimilation. The detected microbial activity documents the fact that subzero temperatures themselves do not exclude biochemical reactions.

Another case of microbial activity that occurs both at subzero temperatures and on geological time scales is the life of cryptoendolithic microbial community in the Antarctic desert. In contrast to permafrost, where the temperature is stable for up to thousand of years, the environment inside porous regoliths of the Antarctic desert is thermally highly unstable, and during the growth season (summer) the temperature oscillates across the freezing point. In this environment, during the approximately 10<sup>4</sup> year-long growth cycle, growth is continuous and ends abruptly when the carrying capacity of the porous rock substrate is reached, which results in exfoliation of the rock crust and loss (or death) of the organisms.

Among bacteria, the viable chemolithotrophic psychrotolerant anaerobic community (denitrifiers, methanogens, sulfate reducers) within terrestrial permafrost are more likely than aerobes to function as an extraterrestrial model for potential life forms. They have unique mechanisms to assimilate CO<sub>2</sub> and other compounds that may exist in frozen soil on Mars or other cryogenic planets without free oxygen, inaccessible organic matter, and a water phase near zero.

## Conclusions

The extension of Dokuchaev paradigm give us possibility to divide all extraterrestrial exogenic formations into two universal groups: sitons and transons. The goal of extraterrestrial pedology is the study of sitons of other planets, i.e. formed in situ vertically-horisonated exogenic profiles and coatings, with appropriate applying of all approaches and methods of terrestrial pedology. We guess that only the extraterrestrial sitons could be perceived as soil-like bodies, either abiotic or bio-abiotic (in case of life finding on Mars).

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# Soil physical measurements by the Thermal and Electrical Conductivity Probe aboard NASA's Mars Phoenix Scout Mission

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## Abstract

On May 25, 2008, NASA's Phoenix Scout Lander touched down on the Martian northern polar region. Part of Phoenix's payload was the Thermal and Electrical Conductivity Probe (TECP). During the 150 day mission, TECP probed the soil at the Phoenix landing site measuring multiple soil physical properties including dielectric permittivity, electrical conductivity, thermal diffusivity, volumetric heat capacity, and thermal conductivity. TECP thermal properties measurements ground-truthed satellite derived thermal inertia measurements and indicated dry, low bulk density soil at the landing zone. TECP detected no measurable electrical conductivity, again indicating dry soil. Dielectric permittivity of the soil increased significantly over the course of the mission alluding to vapour phase transport of water from the atmosphere to the soil as the soil cooled in the Martian Autumn.

## Key Words

Mars, Phoenix, thermal properties, dielectric permittivity, electrical conductivity, soil water content

## Introduction

As part of the 2007 Phoenix Scout Mission to Mars, TECP had the unique opportunity to make unprecedented *in situ* measurements of Martian soil physical parameters in the northern polar region. This region is characterized by a thin (~10 cm) soil layer on top of water ice. Phoenix's mission goals were to study the subsurface ice, search for evidence of past liquid water, and characterize present-day climatic processes. To that end, TECP was equipped with several measurement functions that are very sensitive to unfrozen water in the soil.

## Methods

Soil thermal diffusivity and volumetric heat capacity were measured with a modified dual needle heat pulse (DNHP) technique. Soil thermal conductivity was measured simultaneously using the DNHP technique and a modified single needle heat pulse technique. Both methods were developed specifically for this mission.

Dielectric permittivity was measured using a simple capacitance type sensor based on Decagon's ECH<sub>2</sub>O sensors at a measurement frequency of 6 MHz to stay below the relaxation frequency of tightly bound water films. Electrical conductivity was measured with a simple voltage divider at 1 kHz. Both electrical measurements were optimized for maximum sensitivity in the dry soil range with the goal of detecting trace amounts of unfrozen water in the soil.

All measurement functions (including several others outside the scope of this paper) were packaged in an aluminum enclosure that also served as the mechanical interface to the Phoenix Robotic Arm. Four metal needles served as the heated needles for the thermal properties measurements and also as electrodes for the electrical properties measurements (Figure 1). More details on the TECP design can be found in Zent *et al.* (2009a).



Figure 1. Picture of Thermal and Electrical Conductivity Probe.

## Results

TECP measured soil thermal conductivity of about  $0.085 \text{ W m}^{-1} \text{ K}^{-1}$ , which is far lower than even low density Earth soils. However, this result is consistent with dry soil at low (Martian) atmospheric pressure. TECP measured volumetric heat capacity of about  $1.05 \text{ MJ m}^{-3} \text{ K}^{-1}$ , which is lower than a typical mineral based soil on Earth. This indicates very low bulk density soil at the landing site. Measurements of thermal diffusivity yielded a diurnal damping depth of approximately 6 cm, which is consistent with the ice depth observed at the site. Combining thermal conductivity and volumetric heat capacity into thermal inertia (thermal admittance) yielded values of about  $250 \text{ J m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$  for the landing site. These results agree well with data obtained by the Thermal Emission Spectrometer aboard Mars Global Surveyor.

The electrical conductivity of the landing site never reached the lower measurement threshold of the TECP instrument, indicating an absence of continuous water films between the TECP electrodes. The magnitude of measured dielectric permittivity was consistent with dry Earth soil. Increases in dielectric permittivity late in the mission as the soil cooled during the Martian Autumn allude to robust scavenging of atmospheric water by the soil. However, the magnitude of the dielectric permittivity change is larger than would be expected from this type of scavenging, so additional data analysis and interpretation is ongoing. See Zent *et al.* (2009b) for more details on the initial results obtained by the TECP instrument.

## Conclusions

The TECP instrument aboard the Phoenix mission performed flawlessly over the course of the mission, and was able to successfully characterize the thermal and electrical properties of the soil near the Phoenix landing site over space and time. None of the TECP measurements indicated that liquid water is present at the Phoenix landing site.

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