EXECUTIVE SUMMARY

Assessment of a Luminescence Dating (LD) Technique in Martian Surface exploration

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Chronology is the key to understanding climatically and tectonically driven changes on Mars. The objective of the present proposal was to assess the potential of ***in-situ*** Martian sediment dating using luminescence techniques. The work was divided into two parts.

a) Work package 1 : Review and optimisation of appropriate techniques and instrumentation, and

b) Work package 2 : Laboratory measurements and proposals for instrumentation.

WP1 aimed to accomplish a broad literature survey on both geological and luminescence dating aspects, and identify key experiments that could be partly accomplished during WP2 to comment on the viability of in-situ luminescence dating and the relevant instrumentation on Mars. A brief summary of results is given here.

I. Work package I

Datable materials

Over the last three decades a succession of spacecraft missions have revealed the complexity of Martian environments in increasing detail. Episodes of water (fluvial, lacustrine, shallow marine) and ice related activity (rock glaciers) punctuate the geological history of Mars. Aeolian activity is probably the most prevalent, non hydrous, geomorphic agent, and has generated a wide spread of dunes, sandsheets and drifts. In addition to water, ice and wind related processes, volcanogenic deposits can be present locally.

The common minerals available for luminescence dating are pyroxines, olivines, plagioclase with minor amounts of Fe-oxides and phylolosilicates. Sulphates can be locally very important. Although basalt is the common rock type, local concentrations of quartz on Mars may be expected.

Resetting of the luminescence clock

The main difference between the solar spectrum at the martian and terrestrial surface is the presence on Mars of UVC and UVB (between 300 and 200 nm). UV radiation reaches the Martian surface directly or with a diffused flux because of scatter and absorption by dust. The proportion of the diffuse to direct flux is a function of the optical depth of the dust; this varies significantly in the two hemispheres in different seasons. In contrast to UV, the photon fluence in the visible light spectra on Mars is slightly less than about 50% of that on Earth, simply because Mars in further from the Sun (distance ratio earth/mars ~ 0.66). Therefore, visible light bleaching will be less rapid on Mars compared to on Earth.

Luminescence characteristics of minerals in Martian regolith

Luminescence properties of the JSC Martian-1 soil stimulant, a Hawaiian tephra, have been investigated by others. Tephra ejection is, however, not common on Mars, and from a luminescence point of view the JSC Mars-1 sample is probably less sensitive (more glassy) than the majority of material on Mars.

The potential dating range on Mars will be limited by the saturation dose. Studies on the saturation dose characteristics of volcanic feldspars or volcanic materials are almost non-existent. In case of plutonic feldspars, some studies show that the saturation dose may be in the range of 2-4 kGy for alkali feldspars.

Not much is known about fading in minerals other than feldspars. In terrestrial feldspars, anomalous fading rate is found to vary between 1 – 35% per decade. Volcanic feldspars are generally known to show high anomalous fading rates. Possible solutions to the fading problem include :

Dose rate – charged particle irradiation

The surface dose rate on Mars is derived mainly from charged particles from a) galactic cosmic rays (GCR) and b) solar energetic particle events (SEPE). The GCR consists of ~85% protons, 12% helium, 1% heavy ions (Z>2) and about 2% electrons and positrons; these charged particles have energies up to 10^{12} MeV; the spectrum peaks at about 1000 MeV. The luminescence efficiency of these charged particles depends on their Linear Energy Transfer (LET); this varies by several orders of magnitude for individual species. Most of the primary particle flux occurs with LET values smaller than 10 keV/µm.

In order to calculate effective dose rates on Mars it important to know a) luminescence efficiency against LET for the different charged particle species in the materials of interest, b) particle flux on the Martian surface, c) particle transport through the atmosphere and regolith. Since GCR particles have very high energies, nuclear interactions and production of secondary particles will be important. The luminescence efficiency of some charged particle species (a function of the LET of the incident radiation) has been measured using OSL and TL dosimeters such as Al_2O_3:C.

At present, there are estimates of dose rate available which do not account for luminescence efficiency variations with LET. The MARIE instrument onboard the 2001 Mars Odyssey spacecraft obtained a surface dose rate of about 73 mGy/a for solar minimum conditions ; this dose rate is in good agreement with the HZERTN (high charge and energy transport) model prediction. Based on these calculations the average annual surface dose rate is about 50mGy/a (taking into account the reduction of GCR during SEPE) and it gradually reduces by about 50% over the first 2 m depth.

One potentially important issue related to charged particle interaction is the effect of radiation damage at high energies.

Effect of temperature

Martian temperatures are much lower than those on earth. The minimum temperature on Mars is about -60ºC and the maximum temperature may be close to 0ºC. This implies that traps with shallow thermal depths are likely to be stable for longer periods and hence may be used for dosimetry. Also the presence of these traps may result in changes in trap competition during irradiation. Similar effect may occur during OSL readouts. On Earth these traps usually remain empty and therefore always compete for charge. Investigations are required to study these possible effects.

2. Work package II

The main issues to be addressed in the WP2 were:

a) examination of mineral groups,

b) laboratory measurements with key hardware elements,

c) first pass conceptual design,

However the findings from WP1 suggest that significant improvement in understanding of luminescence properties of Martian minerals and dose rates is required before one can reasonably assess points #b) to #c). Therefore in WP2 we mainly concentrated on the following aspects :

1. Understanding the mechanism of UV bleaching in feldspars, which is one of the important mineral groups on Mars.
2. Investigations into the sensitivity and dose response characteristics of different Martian analogue materials.
3. Some assessment of fading in the Martian analogue materials.
4. Dose rate investigations: a) Luminescence efficiency vs. LET for proton irradiation. b) radiation induced damage c) discussion on the dose-depth profile.

Luminescence characteristics of minerals in Martian regolith

We present below luminescence characteristics of representative Martian analogue materials (ortho-pyroxine, clino-pyroxine, olivine, gypsum, anhydrite, obsidian, trachy Andesite, basalt).

Sensitivity and OSL decay characteristics

The overall conclusion from the OSL measurements from the analogue samples are:

a) There is a five orders of magnitude variation in the sensitivity. Anhydrite and pyroxines are found to be the most sensitive.

b) The CW-OSL curves of different materials show different decay rates. This property can perhaps be used advantageously for separating luminescence from different minerals.

c) The recombination processes of the different analogue materials appear to be the same as that for feldspars. A similar fading behaviour as feldspars may be expected.

Saturation dose

The saturation dose in different samples using the experimental conditions described above was investigated using SAR protocol. These meteorite samples showed severe reduction in growth rate at around 20 to 30 kGy, suggesting that it may be possible to measure precise ages up to 0.6 my with an average dose rate of 50 Gy/ka. The other analogue materials showed saturation between 2-16 kGy. Saturation doses were also measured on two alkali feldspar samples using a red – TL approach. Although there is signal growth to up to 50 kGy, the rate of increase is severely reduced at about few 15 of kGy. Therefore, the uncertainties on dose measurement will be large above 15 kGy.

Anomalous fading

We measured the analogue samples for anomalous fading by holding the samples at room temperature for various times between irradiation and luminescence measurement. All the samples examined here show fading; the fading rate is greatest for trachy andesite followed by basalt. Orthopyroxine, olivine and obsidian show the lowest fading rate.

Luminescence zeroing by UV light in feldspars

As shows in WP1 the major difference between the Martian and the terrestrial solar spectra is the occurrence of an additional component in the range 200-300 nm (4.3-6.4 eV). Since feldspars are one of the important and widely present mineral groups on Mars, and since their luminescence properties are better understood than the other Martian simulant minerals, investigations were carried out using synchrotron radiation to assess the effect of near UV excitation on the two feldspar end members. We identified a trap having an energy depth of 4.3 eV in both Na and K feldspars. Under terrestrial conditions such deep traps will not be emptied during sediment transport. However, the special UV bleaching conditions on Mars offer the possibility of using such deep trap(s) for dating.

Dose rate : Investigations of Efficiency against LET in different dosimeters

We measured the response of Al_2O_3:C to protons with different LET values. A 175 MeV proton beam was used to irradiate a fibre-coupled Al_2O_3:C crystal at different positions in a water tank (absorber). At low values (up to 1keV/µm) there is a good correlation between the known dose, i.e. the dose recorded by diode (solid line), and the apparent dose measured using Al_2O_3:C dosimeter (filled circles) suggesting that the luminescence efficiency compared to the reference beta source is one. However, as the LET value begins to increase rapidly at about 180 cm depth there is a sharp drop in the apparent dose measured by Al_2O_3:C; the luminescence efficiency is decreasing.

The efficiency variation with LET has also been measured using a different approach at PSI, Switzerland, where we have directly exposed samples of quartz, Na-Feldspar and aluminium oxide to proton beams of different energies 250-60MeV. This work is in progress and the energies will be extended to 8 MeV in the next phase.

Dose rate : Radiation damage

We have begun to use samples from the natural laboratory, space, to examine the effect of radiation damage. Two meteorite fall samples with very similar composition, (H5 ordinary chondrites), but different Cosmic Ray Exposure (CRE) ages of 5.1 Ma (Allegan; 1899, Michigan USA) and 59 Ma (Hessle; 1869, Uppsala, Sweden) were used. Our preliminary results suggest that effect of radiation damage during a typical datable burial period (up to 1 Ma) is not important. This work will continue with a range of samples with different CRE ages.

Dose rate - depth variation

The variations in the dose rate in the Martian regolith can be estimated from those in the Earth's atmosphere at high latitudes. At high latitudes the effect of magnetic field is very small therefore GCR flux will be similar to that on the Mars. The published studies of ionisation in the Earths atmosphere due to cosmic rays show that the attenuation of the dose rate is very rapid and there is a maximum (Pfotzer's maximum) at the depth around 50 or 150g.cm-^{2}. In the published modelled dose rate for the Martian regolith these features are not seen. Because of these discrepancies in the modelled and the observed results we consider that dose rate modelling requires a revisit.

Conclusions

Based on the above review of published work relevant to Martian dating and our new experimental results, the following conclusions can be drawn :

1. Feldspar is a common mineral on Mars. Other silicate minerals such as pyroxenes and olivines, and sulphate and chloride minerals can also be volumetrically important. These minerals are likely to be present in a variety of sediment sizes and mineralogical differentiation may occur in different geomorphological environments.

2. Sub-aerial bleaching is likely to be very efficient on Mars, while sub-aqueous bleaching is likely to be relatively slow compared to that on Earth. Deep trap dating may be possible because of efficient UV bleaching. We have identified a deep trap at 4.3 eV in alkali feldspars which can be used for dating using photo-transfer procedure. Because of their likely greater saturation limit, these deep traps may contribute to increasing the age range.

3. Anomalous fading is observed in all the Martian analogue samples. It is at a minimum for Na-feldspar, intermediate for obsidian, olivine, orthopyroxine and basalt, and greatest for the trachy andesite sample. Pulsed-stimulation was tested on two samples for comparison; unfortunately, there was no significant difference in fading rate between the measurements made using the CW-OSL and pulsed-OSL mode. Fading rates using red luminescence have not been measured.

4. Saturation dose levels in Martian analogue minerals and rocks using OSL have been generally found to be from 2 to >12 kGy. The only exception to this is the two meteorite samples which show onset of dose saturation at about 20-30 kGy using OSL. Saturation dose using red thermoluminescence (TL) in alkali feldspars is about 50 kGy; however the uncertainty above 15 kGy is likely to be very high.

5. Dose rate modelling for Mars requires a revisit. One important input in the dose rate models will be luminescence efficiency functions for different charged particles. We have some preliminary results relevant to this based on proton irradiation of quartz, Na-feldspar, and Al_2O_3. These experiments require completion with a range of proton energies (50-8 MeV), and also need to be repeated for other particles, such as helium ions.

6. The effect of radiation damage on luminescence properties is poorly known. Our premilinary measurements using meteorite samples suggest that it may not be significant, in the luminescence dating range (last 1 my or so); however it can severely limit the overall sensitivity of the materials present.

7. The combination of saturation dose (2-30 kGy) and maximum dose rate (50 Gy/ka) on the surface of Mars suggest that the range of luminescence dating on Mars may be between 40 – 600 ka. More data are required to improve our estimates of this range. Also experiments are required to

establish robust protocols for dose determination (including fading corrections) from Martian analogue materials. Known age analogue materials will be especially useful in such research.

8. The success of Martian luminescence dating will depend upon our understanding of the luminescence properties of silicates such as olivine, pyroxenes and plagioclases, and precipitates such as sulphates and chlorides. Our preliminary conclusion is that luminescence dating on Mars is viable. Major sources of uncertainty in luminescence age estimates on Mars are likely to be a) anomalous fading, b) characteristics of luminescence from likely mineral mixtures, and c) extent of pre-depositional zeroing.

Publications arising from the project

M. Jain, L. Bøtter-Jensen, A.S. Murray, C.E. Andersen, H. Haack, J.C. Bridges, M.T. Rosing (submitted). Luminescence dating on Mars: further investigations into luminescence characteristics of analogue materials and GCR dosimetry. ***Radiation Measurements***.