Luminescence dating to quantify eolian depositional process on Earth and Mars on decadal to million year-timescales

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Biography

Steve Forman has advanced luminescence dating for (Earth) Quaternary eolian systems for the past 30 years. Research has focused on climate sensitivity of eolian systems in the Americas, Asia, Africa and Europe. This research highlights the sensitivity of palaeodune systems in semi-arid environments to re-activation with 21st century warming and anthropogenic activity. He received a Geology B.Sc. from Univ. of Illinois-Urbana, had an NSF-sponsored Ph.D. fellowship to study thermoluminescence dating at Cambridge University, and a Ph.D. in Geological Sciences, Univ. of Colorado-Boulder. He directs the Geoluminescence Dating Research laboratory which undertakes fundamental research on method development for challenging sedimentary environments.

Advances in luminescence dating on Earth over the past 20 years has propelled a revolution of knowledge on quantifying rates and processes for eolian systems, spanning the past 150 ka (e.g. Forman et al., 2009; 2014; Guo et. al. 2018). This dating technique, based on environmental dosimetry is poised to provide ages on eolian deposits, particularly with planned sample return from Mars. Luminescence metrics can quantify rates of dune movement, vertical accretion, extension of eolian landscapes and periods of eolian quiescence; and provide possible insights on changing cosmic dose. Luminescence or optically-stimulated luminescence (OSL) dating provides a measure of time since sediment grains were deposited and shielded from further light or heat exposure, which often effectively resets the luminescence signal. Accurate ages spanning the past ca. 150 ka are possible with the advent of single aliquot and grain analysis and associated protocols with blue LED excitation that can effectively compensated for laboratory induced sensitivity changes (e.g. Aitken, 1998; Wintle and Murray, 2006; Duller, 2012). Most recently, the development of protocols for inducing the thermal-transfer of deeply trapped electrons and UV-excitation technology has extended luminescence dating to the 10^6-year timescale, particularly for well solar-reset quartz and potassium feldspar grains from eolian and littoral environments (e.g. Brown and Forman, 2012).

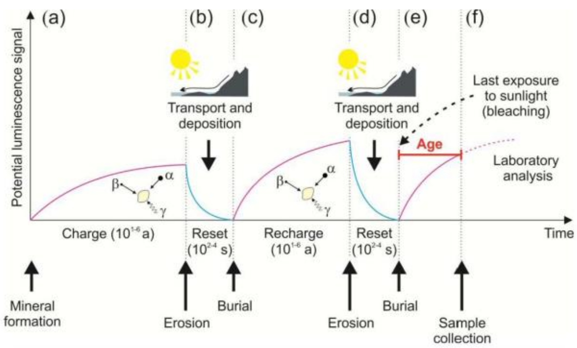

Figure 1: Processes associated with OSL dating. (a) Luminescence is acquired in mineral grains with exposure to ionizing radiation & trapping electrons. (b) The luminescence is zeroed by light exposure with erosion & transport. (c) Electron-storage within crystal lattice with burial & exposure to ionizing radiation (d) Further light exposure of grains with erosion and transport zeros the luminescence. (e) The grains are buried again, and luminescence is acquired with exposure to ionizing radiation. (f) Sediment sampling sans light exposure for laboratory dating (Forman, 2015).

On Earth common silicate minerals like quartz and potassium feldspar contain lattice-charge defects formed during crystallization and from subsequent exposure to ionizing radiation. These charge defects are potential sites of electron capture with a variety of trap-depth energies. A subpopulation of stored electrons with trap depths of ~1.3 to 3 meV is a subsequent source for time-diagnostic luminescence emissions. Free electrons are generated within the mineral matrix by exposure to ionizing radiation from the radioactive decay of daughter isotopes in the ^{235}U, ^{238}U and ^{232}Th decay series, ^{40}K, with lesser contributions from ^{85}Rb and on Earth cosmic sources. Thus, the population of stored electrons in lattice-charge defects increases with prolonged exposure to ionizing radiation and the resolved luminescence emission increases with time. Exposure of mineral grains to light or heat (at least 300˚C) reduces the luminescence to a low and definable residual level. Often this luminescence "cycle" occurs repeatedly in many depositional environments; with signal acquisition of mineral grains by exposure to ionizing radiation during the burial period, and signal resetting ("zeroing") with light exposure, concurrent to sediment erosion and transportation (Fig. 1). Often mineral grains that are fresh from a bedrock sources have significantly lower luminescence emissions per radiation dose in comparison to grains that have cycled repeatedly. OSL dating provides an estimate of the time elapsed with latest period of burial and thus, yields a depositional age (Fig. 1).

Principles of Luminescence Dating

The exposure of mineral grains, like quartz and feldspar grains, common in Earth eolian systems, to sunlight for >60 seconds effectively diminishes the time-stored OSL signal to a low definable level. This residual level is the point from which the geological OSL signal accumulates post burial (Fig. 1). Many types of sediment receive prolonged (> 1 hr.) light exposure with transport and deposition, particularly in eolian, littoral and sublittoral sedimentary environments. In addition, the inherent residual level is influenced by the susceptibility of the luminescence signal of a specific mineral to solar resetting. The OSL signal of potassium feldspar is usually more resistant to solar resetting than most quartz. However, there is significant variability in the luminescence properties of quartz and potassium feldspar grains related to crystalline structure, minor and rare-earth impurities, solid-solution relations, number of luminescence cycles and radiation history (Fig. 1). Thus, because of this inherent variability in dose sensitivity of quartz and feldspar, analytical procedures for dating often need to be tailored for a specific geologic provenance or site. The advent of single aliquot regenerative (SAR) dose procedures for quartz (e.g. Wintle and Murray, 2006) has provided the needed analytical flexibility to compensate for variable luminescence properties of quartz and feldspar grains and laboratory-induced sensitivity changes, particularly associated with preheat treatments and with laboratory beta irradiation.

OSL dating is predicated on the dating a specific mineral and particle size, usually quartz or potassium feldspar on Earth. Mineral separations are performed by standard techniques using heavy liquids and hydrofluoric acid (HF) to digest non-quartz minerals and etch the outer 10 to 20 µm of quartz grains which is affected by alpha radiation. The purity of the mineral extract is primal for effective dating because a small amount contamination (1%) by potassium feldspar and other minerals can dominate the luminescence emissions. Purity of the separate is accessed through microscopic inspection and by Raman Spectrometry. Spectral purity of quartz is often determined by excitation by infrared light from a diode array with subsequent light emissions associated presumably with feldspar contaminants, which can occur as grains or inclusions.

Sediment grains act as long-term radiation dosimeters when shield from further light exposure with the luminescence signal a measure of radiation exposure during the burial period. The radiation dose that is equivalent to the natural luminescence emission of isolated quartz and feldspar grains is referred to as the equivalent dose (D_e: measured in grays: 100 rads = 1 gray) and is one half of the OSL age equation (Eq. 1). In most dating applications on Earth quartz is often the favored mineral because of its abundance in sediments, ease of physical separation and known stability of luminescence emissions. In contrast, feldspar minerals are often less abundant, and have a troubling signal instability (called "anomalous fading"), though yield considerably brighter OSL emissions. The recent development of charge transfer techniques for potassium feldspar (e.g. post IR290) that use elevated preheats (~290˚C) to transfer electrons from stable deeper to shallower traps for ease of measurement has extended dating possibilities to 10^6 timescales for well solar reset grains (e.g. Duller and Wintle, 2012). Similar protocols have been also developed for quartz that has been particularly useful for dating Pleistocene loess deposits (e.g. Brown and Forman, 2012).

$$\text{OSL age (yr)} = \frac{\text{Equivalent dose } (D_e\text{; grays})}{\text{Dose rate } (Dr\text{; grays/yr}) \; (aD_\alpha w + D_\beta w + D_\gamma w + D_c)} \quad \text{Eq. 1}$$

a = Alpha efficiency (0.03-0.15) for grains >50 µm = 0

D_α = Alpha dose D_β = Beta dose

D_γ = Gamma dose D_c = Cosmic dose

w= Attenuation by water

Perspectives on luminescence dating of eolian systems on Mars

A significant difference in the application of OSL dating on eolian systems on Mars is a distinctly different mineralogy of grains compared to Earth. Recently, the *Curiosity* rover landed in Gale Crater and traversed through an active basaltic eolian deposit, informally named the Bagnold Dune Field (Achilles et al., 2017). At the Gobabeb site, with minimal dust contribution, the mineralogy of sand grains is dominated by plagioclase (36.5 wt. %), olivine (25.8 wt. %), pyroxene (32.6 wt. %) with minor amounts of quartz (1.3 wt. %), at or near detection limits. Two potential pyroxene monoclinic phases were identified an augite, high-Ca and the other a pigeonite, low-Ca. Further analysis of grains <150 um, an amenable size for OSL dating, indicated a dominant mineralogy of plagioclase (36.16 wt. %), Hypersthene (29.21 wt. %), diopside (13.14 wt. %), olivine (7.75 wt. %), and orthoclase (2.90 wt. %). The most common grain mineralogy for eolian deposits in Gale Crater are plagioclase, olivine, and pyroxene, but there is limited knowledge of dosimetric properties of these minerals for dating (e.g. Takada et al., 2006; Tsukamoto et al., 2011). Suitable Mars-simulant eolian environments are coastal and inland dune systems on Iceland and Hawaii, dominated by volcanic deposits (pers. comm. Ryan Ewing). However, volcanic minerals formed at lower temperatures are well-known to exhibit anomalous fading, an instability in the laboratory induced signal, which needs to be tested and obviated for Mars sand grains, prior to dating. Rigorous preheat treatments and empirically-derived algorithms to correct for underestimates in equivalent dose can obviated most anomalous fading challenges (e.g. Jain et al., 2006).

There are substantial differences in the cosmic and galactic radiation environment on Earth and Mars, which effects the dose rate calculation for luminescence dating. Mars lacks a planetary magnetic field, which yields a more uniform radiation flux than on Earth. The Martian atmosphere is about 100-times thinner than that of Earth resulting in substantially less shielding. Surface radiation on Mars is derived mostly from secondary particles produced with interactions of galactic radiation with the atmosphere, albedo particles from Mars' surface and the uncommon solar particle events (Hassler et al., 2014). Direct environmental dose rate measurements were taken for about 300 days in 2015 and 2016 on the surface of Mars by the Radiation Assessment Detector on the *Curiosity* rover. The dose rate on the surface of Mars and while the rover was in transit were respectively ~76 mGray/earth-year and ~175 mGray/ earth-year (Hassler et al. 2014). In comparison, the dose rate in Austin, TX at the ground surface is 0.20 mGray/earth-year. The cosmic and galactic dose is 300-400 times greater on Mar's surface than Earth and dominates the dose rate environment. At a 3-m depth the galactic and cosmic dose rate decreases by orders to ~1.8 mGray/earth-year and may account for 30-70% of the total environmental dose rate in basaltic dunes. Thus, repeated changes in thickness of sediment coverage during the burial period can alter the dose rate by magnitudes and could lead to large dating uncertainties and potentially inaccuracies.

The solar resetting environment for Mars is distinctly different from Earth. The solar spectral reaching the surface of Mars includes ionizing and non-ionizing UV radiation, reflecting the low-density atmosphere, composed mostly of CO_2 with a thin Ozone layer. Models and measurements of solar irradiances indicate the near, middle and some far UV (122–200 nm), visible light and IR radiation fluxes to Mar's surface. Laboratory experiments with a simulated Mars radiation environment with enhanced UV components shows that the luminescence of K-feldspar (orthoclase), Ca-feldspars (anorthite), anhydrite and sulfates are reset within 10 to 100 minutes with no signal ingrowth from UV components. In contrast, Na-feldspar (albite) acquires luminescence with low-wavelength UV light (< 300 nm) exposure and may be less suitable for dating (Detschel and Lepper, 2009). There is no information on UV light exposure effect on single crystal of olivine and pyroxene, common mineral grains on Mars.

The time is ripe to investigate further the theory and practice of OSL dating eolian systems on Mars, with widespread deposits and identifiable single grains of inferred mineralogy (cf. McKeever et. al. 2006; Blair et al., 2007). Recent surveys by the *Curiosity* rover of the Bagnold Dunes indicate the dominance of plagioclase, olivine of pyroxene grains; mineral phases in which OSL dating systematics are not fully defined and certainly not for Mars volcanic systems (Takada et.al. 2006; Tsukamoto et al., 2011). Though, laboratory IR stimulation of some olivine crystals yield robust, stable emissions and sensitivity to additive dose; an encouraging sign for dating (e.g. Takada et al., 2006). Luminescence reading technology for a Mars rover needs to be designed and built understanding the specific methodical requirements for meaningful luminescence measurements for eolian landscapes (Dewitt and McKeever, 2011). The return of light-tight, sealed cores sampled from Mars eolian deposits would propel our knowledge for luminescence dating these systems and the technological requirements for in situ measurement.

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