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Loess and dust on Earth and Mars: particle generation by impact mechanisms

Research Article

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Abstract: Impact between windblown quartz grains as a source of desert dust is consistent with laboratory abrasion experiments and has received some field confirmation in the Negev. The suggestion is that an important process on Mars now gains support from laboratory studies; even though their geochemical interpretation is controversial, they show that dust generation by impact is tenable even for quartz.

A simple mechanism for small dust production from sand seas is proposed; internal stresses can be mobilized by impact energy. A speculative mechanism (the andesite scenario) is proposed for fine particle production by particle impact on Mars. The internal stress range in terrestrial sand grains may vary, depending on the nature of the source rock, and this may influence particle production by impact processes.

Keywords: Loess • dust • particle impact • stresses in sand particles • andesite weathering • Mars

Dust in the air suspended
Marks the place...
T.S.Eliot

1. Introduction

Despite decades of investigation in the field and in the laboratory the origin of the material for dust and silt deposits on Earth remains unclear. Much of the literature deals with the redeposition of existing fine particles (large and small dust) on land and at sea, with the emphasis on the climatic conditions at the source or at the site of deposition, but the generation of the particles themselves is generally left unstated.

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Where an origin is specified two options are favoured: the breakdown of crystalline rocks which include crystals of suitable dimensions, and the weathering of larger fragments. In the context of loess studies, however, doubtless because particle size is an integral part of the subject matter, a number of studies have focussed on particle generation. Loess emanating from glaciated areas, whether through latitude or altitude, has been widely seen as the product of glacial grinding, although this simple view is now being modified [1]; where the source is thought to be a hot desert opinions are still divided between those who favour weathering, especially by salt and frost, those who promote abrasion by running water or wind, and those who believe that the fine particles were brought into the desert regions from zones of particle formation [2]. The abrasion group includes proponents of fracture of suitable grains by interparticle impact; a mechanism proposed by Smalley & Vita-Finzi [3] but developed by Whalley et al. [4].

Some support for the impact mechanism has recently come from field studies on Earth and laboratory experiments designed to illuminate the colour of the Martian regolith. In an analysis in what they termed primary loess in the Negev desert, Couvi et al. [5] showed that the only proximal source was desert sand in Sinai and the Negev which was composed of coarse quartz grains, and concluded that large dust had been generated by aeolian abrasion. At about the same time laboratory experiments appeared to show that the reddening of the Martian regolith was due to prolonged abrasion [6]. This discussion paper reassesses the impact model in the light of the new data and shows how it might be extended to Mars by broadening the range of suitable source grains to include feldspars derived from basalt, and perhaps andesite.

Crouvi et al. [5] have shown that loess in the Negev, Israel is derived in part from nearby sand deposits. They found an interesting bi-modality in the Negev loess; particle modes at around 50 µm and 3-5 µm, a classic occurrence of ‘large’ dust and ‘small’ dust. They proposed that the larger particles came from the proximal sand deposits, perhaps furnished by a chipping mechanism like that proposed by Smalley and Vita-Finzi [3], and the smaller particles from distant Saharan sources. They bring back into discussion the idea of fine particles for dust clouds and dust deposits being made by impact processes, by wind-borne, relatively small impactors transferring enough energy to produce new particles. This paper continues this discussion and considers some possible production mechanisms for loess and dust particles on Earth and Mars (discussed in outline by Smalley & Krinsley [7]).

Stuut et al. [8] produced a very simple, but sensible, classification of aeolian fine particulates which are carried in suspension. They divided dust into large dust and small dust. In a terrestrial situation the large dust consists mostly of quartz particles in the 10-50 µm size range, which may go on to form loess deposits. This material travels in suspension, but for relatively short distances (<100 km). For a large loess deposit to form a very efficient production source for this large dust material is required. Terrestrial small dust is largely produced from (a) dry lake beds (e.g. the Bodele depression in North Africa) and tends to consist of clay mineral aggregate particles with sizes around 3-5 µm. or (b) from sand seas, accumulations of desert sand, which can deliver fine quartz dust via impact processes. This small dust can travel enormous distances in high suspension; this is the dust which fell on Charles Darwin and the Beagle and is believed to make an important contribution to the soils of the great rain forests in northern South America. There is a very well marked bi-modality in terrestrial mineral dusts and this led Stuut et al. [8] to propose their simple classification. The classification does need to be developed slightly; satellite observations have shown clearly that although dry lake basins are major contributors to African dust there is an important dust output from sand seas. It seems likely that sand seas deliver quartz chips while lake basins deliver clay mineral aggregates (CMA). There is some understanding of the nature of mineral dust on Earth; this is largely lacking for Mars.

The formation of small CMA mineral dust in North Africa has been considered by Evans et al. [9] and they have shown, by a simple Monte Carlo simulation, how the bottom structure of fine particle lake sediments develops and how this has a critical influence on the size of the eventual small dust particle. This may account for much of the desert dust but there will be a proportion which can be formed by sand grain impact, yielding a small-size fracture product, and it is this impact production of small particles which is considered in this paper. If it can be shown that this is a realistic way of producing an appreciable amount of fine particulate material on Earth, it is reasonable to extend the argument to the production of Martian dust.

2. Lithological controls on terrestrial dust

It could be that there is a very simple lithological control on terrestrial dust. The major continental crustal rock is granite; the ideal granite consists of primary feldspar crystals and a eutectic-type structure of fine quartz and fine feldspar. On weathering the feldspars are turned into clay minerals and the high feldspar contents of granites is reflected in the abundance of mudstones in the sedimentary record. Some of the clay mineral particles wash into lakes and some of them become CMA dust particles. The quartz part of the eutectic becomes sand; the eutectic system controls the size of quartz sand and the passing of the quartz in the granite through the high-low displacive transformation produces high stresses and crystalline defects in the quartz particles. These control quartz silt production; some of the quartz silt produced goes on to form loess deposits. Aeolian systems on Earth are very dependent on crustal lithology.

The quartz sand in sand dunes is full of crystalline defects and it is possible that in certain high energy situations sand grain collisions will produce chipping and particle formation. Smalley & Vita-Finzi [3] outlined a chipping process, and this has been reproduced by Stuut et al. [8], and Crouvi et al. [5] have produced satisfying field evidence of the production of loess sized impact products from local sand systems. It is the high-low displacive crystal structure transformation in quartz which introduced the trapped stresses which aid in particle formation; it may be that certain sands are more highly stressed than others. For example sand derived from a heavily metamorphosed parent rock may contain more stress than sand produced from a simpler granite. There is no doubt that the region around the Sahara is not well endowed with loess (large dust) deposits, but the sand in the Negev regions yields loess material.

3. Lithological controls on Martian dust

There are on-going studies of Martian dust, promoted by the presence of exploration vehicles both on the surface and in orbit around the planet [10–14] but mineralogical and material studies are still difficult to conduct; more data is certainly needed on the nature of the major crustal rocks- possible sources of dust particles.

The dominance of granite in the terrestrial continental crust has a major influence on the nature of terrestrial mineral dusts. The quartz for sand, and the feldspar for clays, control the nature of the terrestrial particulates. What similar/related controls might exist on Mars? A series of questions still needs to be considered:

- What is the size distribution of Martian dust?
- What is the mineralogy of the Martian dust?
- What is the dominant mineralogy of the Martian crust?
- If quartz is largely lacking, and unable to provide cooling stresses, how is the Martian crust stressed in such a manner as to produce particulates?
- What size of particulates might be favoured?
- If impact breakage occurs on Mars, what is the nature of the impactors and how were they formed?
- How does Martian gravity and meteorology affect the movement of the impactors, and any subsequent debris?
- How long have Martian processes been in action? Most current terrestrial particulates are Quaternary items and tend to be produced by Quaternary processes within a Quaternary timescale. Some of these are powerful processes; could relatively ineffective processes operating for a long time on Mars produce significant particulate products?
- Or, if it turned out that there had been ancient seas on Mars a CMA type of mechanism becomes possible. The great terrestrial dust sources are dried-up lake beds; is it possible that much of Mars is covered by a dried-up sea bed? Surely an ideal source of small dust.

4. Impact mechanisms

There has been considerable discussion about the possibility of producing particles by aeolian impact [4, 15–17]. There are certain alternatives that need to be defined, and discussed. Much of the discussion has concerned the production of loess sized particles (say around 30 μm) of quartz, from impactors which were sand sized quartz particles (say around 500 μm). Whalley et al. [4] produced some elegant ideas which would allow the enormous loess deposits of North China to be produced by impact shattering of particles in the northern deserts.

The result of a high energy impact may be a shattering of a particle into relatively large fragments, or the chipping off of a small fragment, the removal of a small projection, the formation of a small particle by stress combination, or there may be no product at all, simply a rebound. The energy requirements for shattering or chipping are very different. The energy required for comminution is proportional to the amount of new surface produced. So a simple shattering action on a 500 μm particle could produce about 500 000 μm^2 of new surface if a simple splitting into two new particles occurred. Consider the same particle which has only suffered the loss of a chip; a 5um chip being detached will only produce about 50 μm^2 of new area. This factor of 10 000 between shattering and chipping suggests why chipping might be observed but shattering is unlikely. Another major factor is the speed of the wind. This provides the kinetic energy for the particles which is transformed into fracture energy on impact. It is the square of the wind velocity which is a key variable; a wind of 100 km hr^{-1} delivers 25 times the impact energy of a wind of 20 km hr^{-1}. So very high wind speeds will favour vastly enhanced particle production. It may be that very high wind speeds on Mars can generate high energy impacts. They could also move larger impactors, and although the mass factor is not so effective as the wind velocity factor the larger particles will deliver more impact energy.

5. Abrasion experiments

Kuenen [18] did some interesting experiments on particle impacts in wind streams. He produced a totally negative result: i.e. sand grain impactors did not produce significant numbers of silt sized debris particles, and thus sand grain impact could not contribute to loess deposit formation. His experimental error was to use perfect quartz particles as his impactors; these tended to lack internal defects and be very resistant to breakage (see discussion [19]). When Whalley et al. [4] repeated the experiments with more realistic material, i.e. quartz from granite containing internal stresses, silt sized quartz particles were produced.

Wright [16] has developed the experimental approach to particle production and has produced interesting suites of particle product. She introduced the Bromhead ring shear machine to model glacial grinding and made some comparisons between model glacial grinding and model wind impact particle production. She found that impact mechanisms compared well, in terms of efficiency, with glacial grinding processes.

6. Sand seas making dust

The sand in sand seas is distinctive [20] and relatively easily lifted by the wind to perform the role of small-particle-producing impactor. There have been careful studies of the nature and rate of dust production from natural dune sands [21], and we hope to progress slightly along this route. The actual production of small dust from a sand sea could include a contribution from impact chipping. Stuut et al. [8] identified sand seas as sources of dust but no actual dust producing mechanism was specified. The actual particle production mechanism is probably an extension of the original Smalley & Vita-Finzi [3] chipping mechanism. The SVF chipping mechanism was originally devised as a possible way of producing loess sized (e.g. ~30 μm) particles in sandy deserts, and it was presented as an unlikely scenario (although Crouvi et al. [5] seem to find it acceptable); Smalley & Vita-Finzi were suggesting that sandy deserts were not effective generating regions for loess sized particles. With modification their basic chipping mechanism could deliver quartz fragments which are an order of magnitude smaller (e.g. ~3 μm). They only considered the removal of protuberances but it is possible to see how direct impact might generate small dust particles (Figure 1).

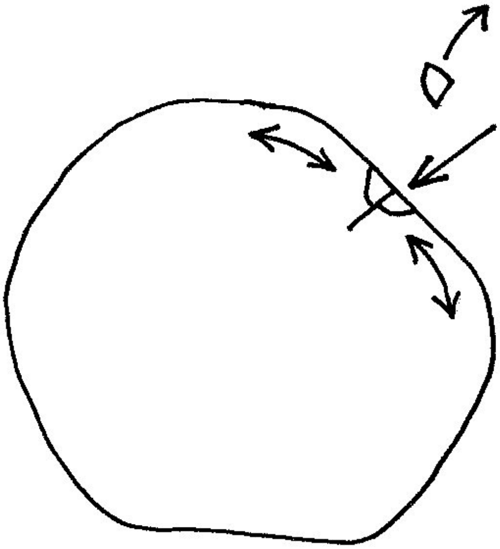

Figure 1. A simple scheme for the production of very small impact particles from quartz sand particles in a sand sea. The combination of internal stresses (a legacy of the high-low quartz crystal transition) and a wind driven impact stress causes the formation of a small particle, a very small amount of new surface is produced. The combinatorial positioning of the stresses is just right to produce a small chip product.

A sand sea is made up ideally of vast amounts of quartz sand which consists traditionally of well-rounded particles. Current observations from space show that sand seas are producing contemporary small dust. The sand particles have long been rounded semi-perfect particles, but they continue to produce small dust. It could be that a combination of impact stresses and internal stresses can produce very small chips. The internal stress in sand sea particles is produced by the eutectic quartz forming mechanisms in the original granite [22]; these stresses are retained in the sand particles. There is an effective subsurface tensile stress; this is released by the impact opportunity and a small chip is produced. Only a relatively small amount of energy is available (impact + stored) and therefore only a small amount of new surface is produced; the chip is small.

7. An andesitic scenario

It has been suggested that the Martian crust might be andesitic, or contain a substantial proportion of andesite, possibly in the form of lava flows, deposits resulting from trap-type volcanism. It is possible to propose a tentative mechanism for fine particle production from andesitic ground in a Martian environment.

To produce dust particles could require a sequence of weathering actions which involve a whole range of rock particles; it might initially be divided into three stages:

On Earth a wide range of weathering forces is available [23, 24]; the range of weathering forces available on Mars is much smaller. No biogenic forces are available and it seems likely that water has been lacking for a long time. There are external forces due to wind action and to variations in environmental temperature, and there are internal forces generated by formation mechanisms and possible structural mineralogical changes. If the andesitic terrain is formed from a lava flow then there will be well developed internal cooling stresses. These are the stresses which cause columnar jointing in terrestrial lava flows and must develop in any solidifying and cooling lava flow. In the flow situation a range of random stress centres develops and tensile stresses develop throughout the entire system. A random crack pattern develops in which the geometrical constraints lead to the observed columnar jointing [25]. If, however, the stress level does not exceed the tensile strength of the system a highly stressed lava flow develops with relatively high tensile stresses locked in place. These will promote eventual weathering, and tend to generate fairly large weathered fragments.

In addition to the locked-in cooling stresses there could be crystal transformation stresses. These are the stresses which are so effective in producing weathering in terrestrial granites. Granites are quartz rich and the quartz is usually found as part of a feldspar-quartz eutectic. This controls sand formation [22] and is the source of much internal stress in the granite system. The quartz undergoes a high-low displacive crystallographic transformation on cooling and since low quartz has a higher density than high quartz tensile stresses develop. Any cooling rock which contains quartz probably has such stresses. If the Martian andesites are silica-rich andesites they might contain quartz crystals. There is unlikely to be a high quartz content but there could be enough to promote some weathering.

So the combination of cooling stresses due to thermal contraction and transformation stresses may cause weathering to occur in the Martian andesites. Martian time is available for a relatively inefficient process to generate some weathering product, which should exist in the form of relatively large fragments.

Initial weathering produces fairly large fragments. There is however a size range in these fragments and it is proposed that the smaller of these fragments might be moved by the Martian winds. If movement can be initiated then the chip forming process can begin. The low Martian gravity aids the movement but the low atmospheric pressure may hinder aeolian travel; but the high wind speed acts as a travel promoter. With moderate sized aeolian impactors in motion chip formation will occur at collision sites. It seems likely that the impact energy could be relatively low and chipping might be achieved, but larger scale fracture is unlikely. Some widespread modalities will begin to develop (similar to the terrestrial modalities proposed by Smalley & Vita-Finzi in 1968 [3].

Small chips are carried up into the atmosphere and a dust cloud forms. There is no discernable sand forming on Mars (nothing similar to that on Earth); it is possible that there are no particles intermediate between the dust and the dust causing impactors. But the nature of Martian dust may differ from terrestrial dust. Dust is defined as material in suspension in the atmosphere. With the lower Martian gravity larger particles may be kept aloft by atmospheric forces; but the atmosphere is thin and may not provide much support. However the wind speeds are high and this may counteract the thinness of the atmosphere.

There are some transient indications that the Martian dust may have a larger particle size than small dust on Earth. It may have, occasionally, to fulfil the role of sand and form dunes; dunes are observed on Mars. But it seems not to form substantial stable deposits, it appears to have relatively low cohesion. Cohesion depends very much on particle size [26] and in the dry atmosphere of Mars any moisture related cohesive effects will not occur. On Mars it would appear that very simple cohesive conditions apply, exactly as imagined in the Smalley [26] equations, which indicate that cohesion increases very rapidly as particle size is reduced. When the exploration machines were covered in 'dust' it was imagined that their function would be impaired, but the dust appeared to have low cohesion and quickly disappeared from the solar panels. The dust clouds observed to occasionally cover the planet dissipate quickly, which suggests inefficient suspension and larger particles. The particles though are probably formed by chipping, and given the long period of formation it is interesting that there is relatively little 'dust' on Mars. There is a lack of dust because of a lack of dust forming mechanisms.

Actually the 'andesitic' scenario could just as well be a 'basaltic' scenario in terms of cooling and contraction stresses. The basalt may lose some potential particle forming stresses because of a lack of free quartz.

8. Commentary

A large sand sea should produce small quartz dust. The material is right, sand sized granitic quartz, and the desert winds produce abundant chipping activity. The terrestrial energy requirements suggest that it is unlikely that sand seas produce significant amounts of large dust; different levels of energy are required for large dust and loess deposit formation- although Crouvi et al. [5] have detected loess sized material emanating from the Negev desert. Large dust does emerge from large sandy deserts but (as Smalley & Krinsley [2] noted long ago) this is usually transient material, it goes into the sandy desert as large dust and emerges as large dust; the desert acts as a holding area; recently careful science has shown that the Chinese loess is not made in the northern deserts, but may be stored there for a while [27, 28]. The loess dust is made in the mountains, in 'High Asia' and transits through the deserts on its way to the great deposits.

On Earth small dust mostly is made in dry lake beds, and consists of clay mineral aggregates CMAs, or in sand seas where the product is fine quartz produced by impact chipping, as shown in Figure 1. This novel mechanism probably accounts for most of the quartz dust. It can be complemented by already known mechanisms [3, 9]; observations from satellites suggests strongly that these are the two main sources.

On Mars however, there are no straightforward small dust production scenarios. There has been a vast amount of research on Martian dust from the various investigating machines which have reached Mars, but there is little actual data on the particle size analysis or mineralogy of the observed dust clouds. Approaching the problem of dust nature from the point of view of particle production presents many difficulties. No sand seas appear to be available, and there is a lack of dried up lake beds (although there may be some) so the mechanisms which link crust to particle are difficult to discern. The 'andesite scenario' offers a possible route, there is nothing too exotic in the various requirements, but it must contain a high content of speculation. This is an intriguing problem because it has many layers; it is difficult to design a mechanism for the production of the intermediate particles, it is difficult to envisage the initial weathering of the crustal rock, it is hard to sustain a picture of the attenuated Martian atmosphere moving impacting rock fragments and producing substantial dust.

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