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THE ORE-DRESSING GRINDSTONE CALLED A 'QUIMBALETE': A MECHANICS-BASED APPROACH*

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The 'quimbalete' is a kind of grindstone used notably in Potosi (Bolivia) during the Spanish conquest of South America. It was used to grind pieces of ore gravel from centimetric sizes to the size of sand. Its physical functioning, as well as the reason why this strictly Andean tool occupied a central place in a mainly European production chain, have never been addressed. This study is aimed at answering these questions as a result of physics-based modelling. After introducing the historical context, we address geometrical and physical parameters relevant for understanding how this oscillating grindstone was used and what one can expect in terms of grinding. Then, a suitable approach for estimating the yield makes use of the modern industrial empirical estimator: the 'power index'. We offer our conclusions about the position of this tool, which appears as an ideal intermediate tool between the roughening process of the ore at the centimetre scale, and the suitable size for the material to be sorted by the subsequent methods in the chain (such as washing), which involve sandy-sized grains. The study also shows how classical physics can help in addressing questions concerning minerallurgy.

KEYWORDS: QUIMBALETE, GRINDSTONE, ORE DRESSING, MINERALLURGY, POTOSI

INTRODUCTION

'Minerallurgy' is a term that encompasses the processes from the preparation of minerals through to their smelting. It was coined in the 19th century, when Pernolet (1851–3) theorized the process. Linkenbach's treatise (1893) offers a complete view of the processes used prior to the introduction of chemical flotation in the 20th century, which allowed for the treatment of fine particles. These first treaties and theories were focused almost exclusively on the enrichment of minerals under water, and much less on questions of grinding and crushing natural ores. The Linkenbach treatise dealt principally with water washes. Of the 156 pages of the French-language work, only 20 focus on questions of grinding. Yet in 19th century mills, the ability to grind and triurate minerals was a critical element in the development of mining and metallurgical industries. It is fundamental for achieving the fine particulates (from 1.5 to 0.25 mm) required for the enrichment of minerals via water washes. When the triturating capacity was

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restricted to the interior of the workshop, the transformation of a mineral into a sand-like state for the wash was reserved for the poorest minerals. Actually, mechanization of the milling process appears very early on, whether operated by human, hydro or animal power. The stamp mill appeared between the end of the Middle Ages and the start of the Renaissance. It consisted of a series of iron pylons moved by a tree of hydraulic levers and it permitted a considerable increase in grinding capacity.

In general, questions related to mineral preparation have attracted much less attention from archaeologists than other aspects of mineral extraction or metallurgy, and this is also true in the Andes. Data related to this phase of the European production chain are particularly poorly developed, and even more so for production chains in the New World. However, simple observation of the vestiges of metallurgical workshops in the Andes permits us to identify at least one specifically indigenous tool, while the rest appear to be Old World systems. A reading of the treatise *El arte de los metales* tells us that '… he [Agrícola] teaches us to wash the metals before smelting them; something little done in these parts [the Viceroyalty of Peru] if not with tin…' ('… muy dilatadamente en seña el Agrícola a lavar los metales antes de fundirlos; poco se usa en estos reinos [Virreinato del Perú, Bolivia], si no es en metales de estaño …'; Barba 1640, 148). Although Barba's discourse could be read as denigrating indigenous knowledge, his definitive declaration of the non-existence of real metallurgical works carried out by the autochthonous population should not interpreted as colonialist, because his assessment of indigenous metallurgy valorized Andean techniques.

While exploiting the mineral resources of the Andes, the Spanish were very aware of the metallurgical processes current in Europe at the time. Yet they were face to face with a different system, one in which the quimbalete was the device used most recurrently. It was 'like a half moon, wider in the circular part below than in the flat part above, which is firmly tied to a stick of sufficient length so that the workers distributed on either end raise it and lower it without tiring, and using their weight and force, chop the metal …' (Barba 1640, 119). It was a heavy stone, semicircular in form, positioned over a flat rock. A rocking movement allowed it to grind the ore. In a form of technological syncretism, this indigenous tool, endemic to the Andes, was incorporated into the production chains of the new colonists, and remains present even now. Today, at celebrated sites such as Potosí, Bolivia, we can see systems of mineral flotation and grinding identical to those used by indigenous artisans before the arrival of the Spaniards. In the mills of the 17th and 18th centuries, the quimbalete took its place alongside the stamp mill and the hydraulic mill. Nonetheless, this technology did not cross the Atlantic and was not adopted in Europe, in contrast to the metallurgy of mercury.

How can we explain the place occupied by this strictly Andean tool in a mainly European production chain? Aware of the lack of information on these topics, in this paper we put forth an initial and tentative theorization of grinding capacity in order to assess the quimbalete's efficiency. Likewise, it is equally important to consider the social relations and demographics of the mining environment in which the quimbalete was integrated; that of Spanish businessmen who were assisted by indigenous labourers who evidently possessed their own capacities for invention and innovation.

Our study is based on material evidence observed at productive sites in the department of Potosi, which is the largest silver deposit in the world still in operation. 'Quimbatetes' are seen in use today in Potosi for craft activity and can be found in other districts such as Porco, a major silver mine that was under the control of the Incas until 1538, Tholapampa, a site involved in the production of copper and silver during the 18th century (where several buildings referred to as 'houses with quimbaletes' are found along the river) and San Antonio de Lipez. The latter is a ghost town today, and quimbaletes are found in colonial *ingenios* as well as in autonomous preparation sheds (for the locations of the sites, see Fig. 1).

The quimbalete, made of diorite or dacite (depending on the local resources) is used to grind gravel that is made of a mix of gangue and ore (of any kind). At Tholapampa, it was also employed to crush slag resulting from cupper metallurgy, which is composed of glass and embedded cupper beads.

The quimbalete is a minerallurgical device known throughout the Andes (and even in Mexico, but since when?). Here, we deal only with Bolivia, because it is the country in which we observed this kind of grindstone in ancient production units (17th–19th centuries).

MATERIALS AND METHOD

In the following, as well as in the Appendix, we develop the theory for a quimbalete grindstone found in Potosi. A photograph and the geometry and basic functioning of the quimbalete are depicted in Figure 2. It is a truncated circular cylinder (TCC) grindstone. In this study, we rely on two main hypotheses: (i) the base of the grindstone is cylindrical-circular with a radius R; and (ii) generally speaking, it rolls on a flat horizontal surface. In the framework of the present study (the Andean region and the Spanish period), these two hypotheses match the field artefacts.

The physical quantities relative to this quimbalete can be split into basic descriptive data ones (dimensions, density etc.) and computed ones (mass and period of oscillation) that result from the theory. The TCC is fully characterized by its thickness e, its radius R and a defining parameter such as θ or A. These geometrical parameters are used for calculating the mass, the moment of inertia (required to compute the free oscillation period) and the location of the centre of mass

Figure 1 *A map of Bolivia, with the location of the sites discussed in this work: Potosi, Porco Tholapampa and San Antonio de Lipez.*

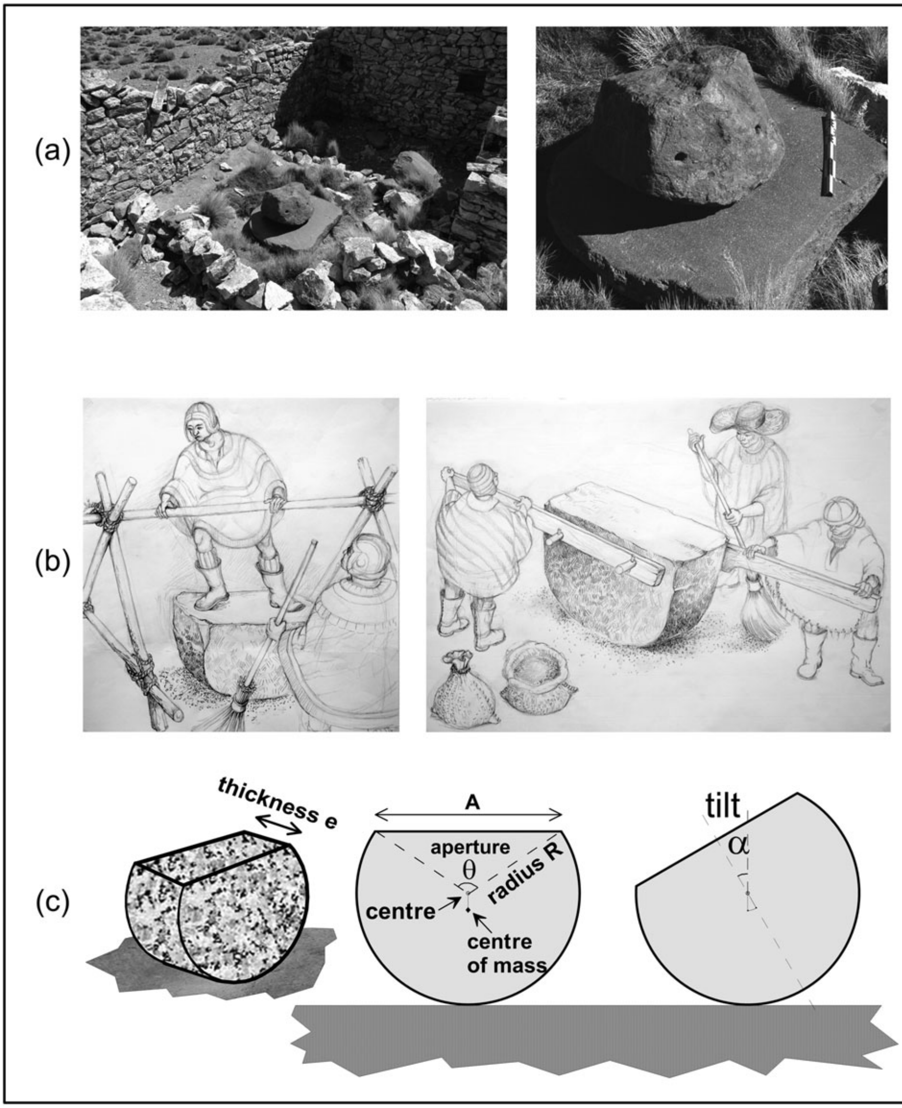

Figure 2 *(a) A 'quimbalete' artefact as found at Potosí, Bolivia. The diameter is close to 1.2 m. (b) Quimbaletes powered by men, making them oscillate to crush the ore: two possible configurations. (c) Quimbalete model geometry.*

of the grindstone. The moment of inertia J_C is relative to the axis crossing the quimbalete perpendicular to its lateral faces, and coincides with the cylinder centred axis, which is also the instantaneous proper axis of rotation.

The following input values (see Fig. 2) hold for the grindstone found in Potosi:
Radius, $R = 0.6$ m.
Truncated surface length, $A = 1$ m.
Thickness, $e = 0.5$ m.
Density, $\rho = 2900$ kg m^{-3}.
The gravity value g is set to 9.8 m s^{-2}.

Appendix A.1 provides the calculation of the output quantities. For the main quantities, we obtain the following:

Mass, M = 1366 kg (from equation (A.1.2)).
Distance from centre of circle to centre of mass, b = 8.8 cm (from equation (A.1.3)).
Moment of inertia, J_C = 226 kg m^2 (from equation (A.1.4)).

From the seminal paper by De Nigris (2012), the quimbalete is moved by applying a close vertical force on it, either by using a handle or by standing on it directly. The latter is expected to be much more efficient, because the operator can use his legs instead of his arms. Here, we consider only vertical forces provided by people on the upper surface of the grindstone and, hence, we follow the hypothesis and results from case number 14 of De Nigris (his fig. 31).

First, it is necessary to calculate the tilt angle, α_0, resulting when a vertical force F (possibly the operator's weight mg, where m is the mass of the operator) is applied, as shown in Figures 2 (b) and 3. The force is vertically applied at a point H at a distance d from the centre of the upper face Q (d may be greater than R if using spars). The formula in Appendix A.2 gives the tilt angle resulting from this force.

Assuming two workers of 70 kg each and applying their weight at ±30 cm from the centre of the grindstone top (i.e., assuming 60 cm between the two legs), the reachable angle is α_0 = 23.4° (=0.4086 rad) (from equation (A.2.1) or (A.2.2)).

The corresponding elevation of the centre of mass is h = 7.2 mm (from equation (A.2.3)).

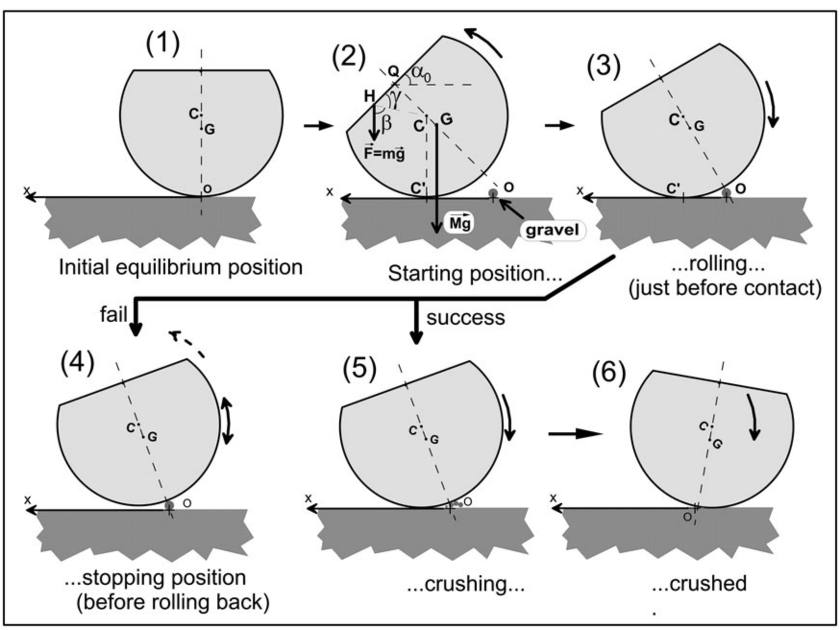

Figure 3 *The functioning of the quimbalete (the men powering it are not shown). (1) The initial position. (2) 'Arming': the angle has been exaggerated. (3) The release step: the angular velocity and inertia of the grindstone will facilitate the transfer of the quimbalete energy to crush the gravel. (4) An unlikely situation in which the gravel resists and the grindstone may go back to its initial position. (5) A likely situation in which crushing begins. (6) The crushing is done and the men powering the quimbalete provide some energy to reach the same initial tilt angle on the other side (the rearming stage): after a few oscillations, the ore is ground to powder, manually removed and new gravel is introduced under the grindstone.*

The functioning of the quimbalete

The steps of the grinding process We assume that once the grindstone has been tilted, a few pieces of gravel are placed in the area where the grindstone was initially in contact with the ground. Figure 3 shows the system with a single piece of gravel. The steps are as follows.

In the first step, the grindstone is horizontal and at rest.

In the second step ('arming the grindstone'), a vertical force exerted by the man (more or less his weight) tilts the stone until it reaches a new equilibrium, with a maximum angle of α_0. This elevates the centre of mass by the quantity h given just above.

During the third step, the grindstone is released. Then:

- If $d < h$, the gravel may or may not be (theoretically) crushed. In the first case, the energy accumulated in the grindstone by arming it is converted for 'destroying' (crushing) the gravel stone. Ideally speaking, if $h = d$, then the grindstone reaches the vertical position with a null angular velocity and the weight is fully applied on to the gravel, transforming it to dust. In such a situation, the accumulated kinetic energy is transformed into potential energy, the grindstone is stationary and the operator has to apply a force towards the opposite side just to 'rearm' the device. But, in the second case, gravel with $d < h$ could be very solid. Then, the energy is just transferred to the other side and the operator does not need to provide any significant energy input to swing the grindstone. The scenario just repeats itself on the other side.
- If $d > h$, two other possibilities may also arise. In case (i), if the gravel is brittle enough, the strength or impetus of the force of the grindstone may pulverize the gravel, even before the upper position is reached. That is, very little of the grindstone's stored energy will be spent, and the grindstone will swing over to the other side. On the contrary, in case (ii), if the gravel is resistant, then the grindstone will face against a wall of potential energy and will return to its initial position.

Finally, the fourth step is like step 2: the stone has passed (respectively, or not) over to the other side and a symmetrical (respectively, or reverse) scenario begins.

Let us come back to the third step and assume that the grindstone crushes the gravel. In the case of very brittle gravel, very little energy is required and then the grindstone will hold on to most of its stored energy. When the energy is dissipated in the gravel-destroying process, the grindstone loses the corresponding amount. It is with regard to this point that the quimbalete appears to be extremely smart and merits discussion. The trick of the rocking grindstone (with respect to other systems such as the stamp mill) is that it preserves part of its stored energy, which is not dissipated by the crushing itself. This is possible because the grindstone can tumble on to the other side, where the remaining energy will be fully employed in rearming. Let us compare this to the stamp mill. If the energy of stamp mill drop hammer is not fully used, the drop hammer possibly bounces several times but only a little and does not crush any more, but dissipates the energy as pure heat. This could explain why a quimbalete can be man-powered while a stronger energy-providing system is necessary to run the stamp mill.

Static equilibrium assuming a large ($d > h$) solid stone possibly blocking the process

In this static case, illustrated in Figure 4 (a) (sized to be easily readable), the grindstone is armed, tilted and a piece of gravel is placed underneath it. It is useful to calculate the force acting on the 'blocking' stone, to compare this strength with the weight of the grindstone. What, exactly, is the portion of the weight applied to the stone as a function of the ratio r/R (where r is the radius of

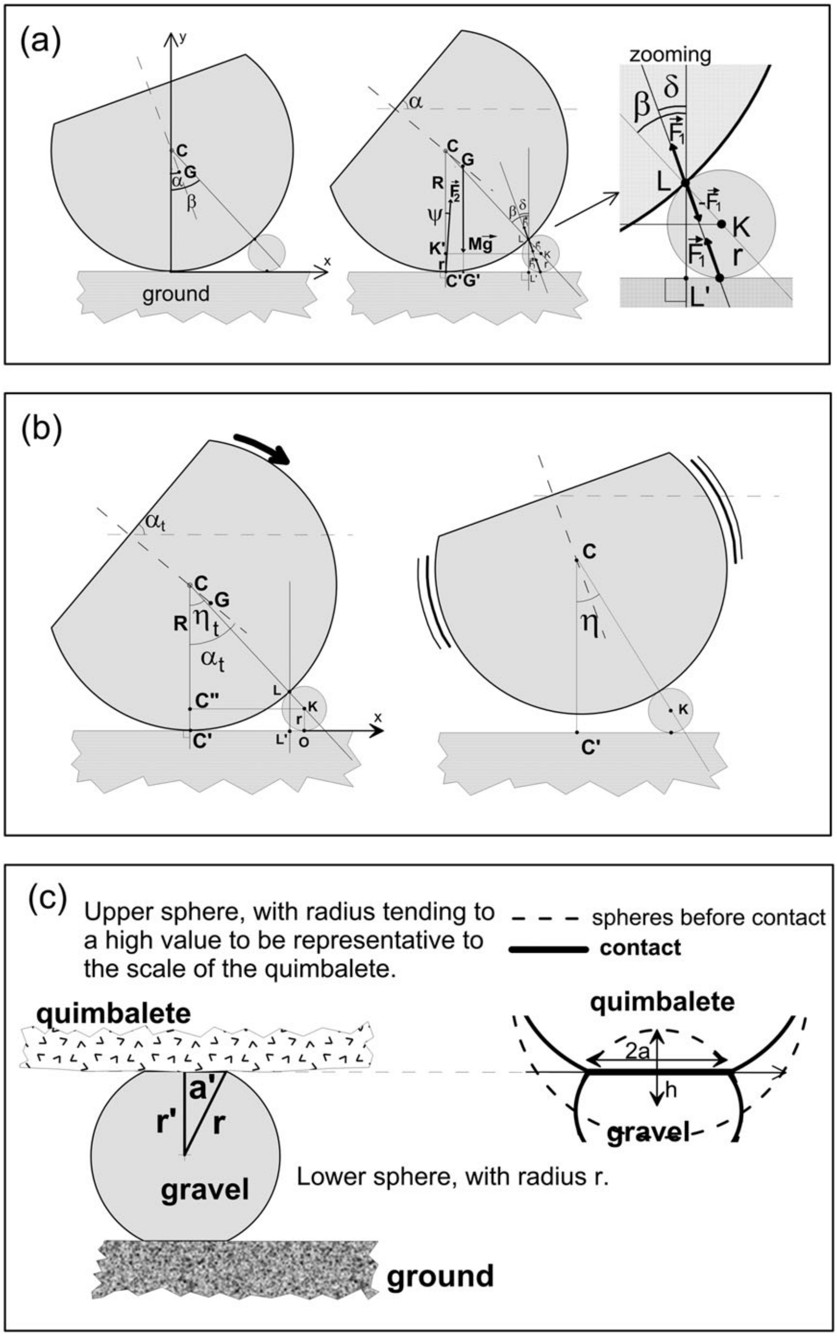

Figure 4 *(a) The geometrical quantities permitting the calculation of the force applied by the grindstone on gravel in a static case. (b) The parameterization of the quimbalete (with angle η) when it 'climbs over' the gravel and leaves the ground for a little while. (c) The geometry of the contact: right, how the two spheres are deformed in the Hertz theory; left, the top area (contact with the quimbalete) and the bottom area (contact with the ground), which are pulverized within a radius a′. If a′ > r, then the gravel is fully ground to powder.*

the stone and R is the radius of the quimbalete), in the case of static gravel? If we imagine a rather large stone, then we can no longer imagine that it will be crushed by the grindstone.

The aforementioned figure shows the various forces to be considered in solving this static equilibrium problem. The details of the reasoning and the final formula are given in Appendix A3.

The full dynamical case

However, the most relevant dynamical case occurs when considering gravel located close to the origin in the initial contact area of the grindstone with the ground, and when the grindstone as initially tilted rolls towards this position. In the case when $h > d$, we know that the grindstone will pass over the gravel. If $h < d$, then the grindstone will kick the gravel and bounce against it if it is not crushed. Then, when the grindstone arrives in contact with the gravel, its kinetic energy must transform into something else. If we assume that the gravel is not brittle, then we understand that the grindstone will begin to roll over the spherical gravel, 'climbing' it, and will lift a little bit from the ground. At this moment, the grindstone is no longer rolling on the ground, but on the gravel. Appendix A.4 provides the details of the physical approach in this case. The result gives a 'practical' limit diameter by taking into account only geometrical constraints. It corresponds to a geometry-based maximum grain diameter to be crushed, which is (from equation (A.4.3)) $d_{\mathrm{max}}^{\mathrm{in\ practice}} = 2.5$ cm.

Free oscillation period

The grindstone is definitely used in an oscillating manner. It is similar to a clock pendulum, for which the loss of energy at each beat is compensated by the incoming energy. For the operator's comfort, the less his contribution, the less tiring it is. The operator furnishes only what is required to maintain the oscillation. The period of oscillation is given in Appendix A.5 and for the Potosi grindstone it is found to be 4.37 s (from equation (A.5.1)).

Stress within the gravel and gravel failure

Here, we estimate the stress applied to the gravel and the chance that it will be crushed as a function of the diameter of the gravel. We first use a theory that involves rather smooth (but not slipping), more or less spherical gravel, and then provide a short discussion for rough gravel. Then we apply a failure criterion.

The main results of our calculations, detailed in Appendix A.6, are as follows:

(1) A piece of gravel of representative radius r will be crushed to powder as long as we have

$$r < a'_{\mathrm{max}} = \sqrt{\frac{F}{\pi \sigma_{\mathrm{MAX}}}}, \tag{1}$$

where F is the force acting on the gravel and σ_{MAX} is the maximum stress than can be supported by the gravel (this maximum is a failure threshold).

(2) More generally, n pieces of gravel of representative radius r will each be comminuted into N smaller pieces of gravel, as long as we have

$$nN \leq \left(\frac{a'_{\mathrm{max}}}{r}\right)^6. \tag{2}$$

Taking into account the inertia of the grindstone and the possibility that the full weight is acting on the gravel leads us to consider a force $F = Mg$ as realistic for practical applications. Actually, there is an additional force resulting from the inertia of the grindstone that is applied to the gravel, but the resulting 'impact effect' is negligible with respect to the weight applied by the grindstone, since the corresponding acceleration is small with respect to g.

About the threshold σ_{MAX}

Note that it would be tricky to determine the resistance limit for a given ore-body gravel. Such a stone may be very heterogeneous, and the excavation and relaxation from the lithostatic pressure when excavated may have provoked some interior micro-failures that would make it more brittle. Additionally, ore materials mix the exploited mineral with gangue and involve microcracks that weaken the rock at the gravel size. Here, we can only take a very arbitrary index suitable for our purpose. On the basis of Zhao (2007) and Ademeso and Adekunle (2011), we suggest $\sigma_{\mathrm{MAX}} = 50$ MPa as an indicative value.

How thinly will the gravel be ground?

It is possibly unrealistic to assume that the gravel is reduced to dust after only one pass. The quimbalete is constantly moving and the contact area between it and the ground is small. When the gravel is crushed, numerous resulting grains are pushed away from the contact area itself, and this reduces the efficiency of the grindstone. However, it is likely that only a few oscillations will be required to crush the ore to the desired size. It would be very difficult to predict the final grain size from the theory, and we must refer to further experiments in the field. Alternatively, another fruitful approach is given below, by using the so-called 'work index', and the corresponding idea is proposed hereafter.

Yield, energy, power and the 'work index'

From the ancient miners' point of view, the energy provided to grind the gravel is not the most explicit parameter. Power, energy per unit time, is much more important when the energy provided by a human is directly involved. A nominal realistic value of $W = 100$ W matches the capability of a man, considering sustainability at this altitude for several hours (in addition to the metabolic output, which is also more or less 100 W). This is the power to consider when studying the grindstone. The 'power index' W_i, a concept used in modern mining industry (in kWh kg^{-1} or J kg^{-1}), is a general index that is relevant for the economists: it describes the amount of ground matter for a given provided energy. Modern grinding machines are of different kinds (the 'jaw crusher' may be one of the most widespread), but there is a relatively uniform literature on grinding energy expenditure assessments (see, e.g., Hartman 1992). In the case where 0.05 mm $< d <$ 50 mm (our case), a popular formula is provided by Bond (1952, 1961), as follows:

$$W_{\mathrm{B}} = C_{\mathrm{B}}\left(\frac{1}{\sqrt{d_{\mathrm{E}}}} - \frac{1}{\sqrt{d_{\mathrm{A}}}}\right). \tag{3}$$

Here, C_{B} is a constant determined empirically, d_{A} is the grain size of the source material and d_{E} is the size of the ground material (more exactly, a size having 80% of the mass of the solid matter smaller than this size).

Bond's theory is semi-empirical and is based on a balance in which the energy required to break the particle—that is, the binding energy between molecules—is involved. It followed previous works: the one by Rittinger (1867), which was based on the surface energy, and the one by Kick (1885), involving a net specific energy. A synthesis of these various theories was proposed by Hukki, 1962. As recalled by Jankovic *et al.* (2010), in a paper devoted to magnetic ores, 'Bond (1952) proposed the "Third Law" of grinding. The Third Law states that the net energy required in comminution is proportional to the total length of the new cracks formed.'

One remarkable feature of this equation is that the term relative to the final small size d_E (i.e., the final product) is the most relevant parameter. Explicitly, we have the following approximation:

$$W_B = \frac{C_B}{\sqrt{d_E}}. \tag{4}$$

Stamboliadis *et al.* (2011) provide a recent study and numerous work indexes depending on the kind of ore. They also define an 'absolute' energy, where they apply the above formula by setting $d_A = +\infty$ and $d_E = 100\ \mu\text{m} = 0.1$ mm. They found a set of work indices lying between 7.7 kWh ton^{-1} for limestone and 25 kWh ton^{-1} for serpentine. For our purposes, let us keep to the following intermediate reference value:

$$W_{\text{ref}} = 10\text{kWh ton}^{-1} \Rightarrow C_B \simeq 3.17\left(\text{kWh mm}^{1/2}\right). \tag{5}$$

(We take this relatively low value because we assume that the mix between the precious mineral and the gangue is not very resistant—just a little more than a limestone). These results are definitely useful for our purposes. The 100 W yielded by the worker is equivalent to 0.10 kW, and then the energy released during 1 h is just 0.10 kWh. This immediately permits us to derive the mass of ground mineral provided during 1 h, which is 1/100 tons; that is, about 10 kg h^{-1} to reach 0.1 mm, or 22 kg h^{-1} to reach 0.5 mm. We will keep to this last amount and size.

FINAL RESULTS AND ADDITIONAL NUMERICAL APPLICATIONS

In this section, we apply the theory to estimate numerically several quantities related to the grinding done by using a grindstone.

Geometrical and dynamical quantities

Let us formulate the numerical application assuming the following values, which correspond to a 'quimbalete' found in Potosi.

To the basic input parameters already provided in the text (R = 0.6 m, A = 1 m, e = 0.5 m, ρ = 2900 kg m^{-3}), we add the elastic constants that we will use here:

Poisson coefficient, $\nu = \nu' = 0.3$.
Young's modulus, $E = E' = 50 \times 10^9$ MPa.

We have already given the mass (1366 kg) and other relevant parameters.

Now one important parameter to compute is the radius, a'_{max} (equation (A.6.7)), which determines whether a piece of gravel having a diameter greater than a given r can be destroyed under the total weight of the grindstone. We obtain:

$$a'_{\text{max}} = \sqrt{\frac{Mg}{\pi\sigma_{\text{MAX}}}} = \sqrt{\frac{1366\times9.8}{3.14\times50\times10^6}} = 9.2\ \text{mm} \simeq 1\ \text{cm} \Rightarrow \text{diameter} = 2\ \text{cm}.$$

This value is derived from the consideration on the stress and resistance. In parallel, equation (A.4.3) gives a 'practical' diameter by taking into account only geometrical constraint. This yields

$$d_{\max}^{\text{in practice}} = \frac{\alpha_0^2 R}{4} = 2.5 \text{ cm} \quad (\text{from equation (A.4.3)}).$$

These results, one derived from pure geometry and the other from material resistance, are very close. They demonstrate the coherent linking of quimbalete size with the proper resistance of the gravel, and provide good insight for the validity of the whole theory.

Probable yield

First, derivation of the quantity of ground materials does not require the whole theory, but just the working index.

If the mass of a 4 mm (diameter 8 mm) piece of gravel of density 2.5 g/cm^3 is close to 0.8 g, then the maximum capacity of the grindstone will be close to 10 kg/0.8g; that is, more or less 12 500 pieces of gravel an hour—or 208 pieces of gravel per minute, 200/60 × 4.3, which is about 14 pieces of gravel per period or seven pieces of gravel per single overpass.

DISCUSSION AND CONCLUSION

Modelling of the functioning of the quimbalete permits us to tackle several questions relating to this grindstone. The triturating capacity of the quimbalete permitted the processing of rocks with diameters of less than 20 mm. Thus, according to Linkenbach's nomenclature, it processed 'gravel' (1.5–30 mm) and could produce grains that qualified as 'sand' (0.25–1.5 mm). Its efficacy is evident in the few rocking motions needed to produce this sand. Typical values are as follows: 1.5 rocking motions to obtain sand with a grain size of 1.5 mm from 3 mm gravel, and 8.5 motions to go from gravel with a grain size of 13 mm to 0.25 mm sand.

Up to now, no other systems of preparation and enrichment of minerals have been found to have been developed with the use of the quimbalete in indigenous Andean culture. In this sense, we come close to echoing Barba's assessments, which stigmatized the absence of a real minerallurgy among indigenous Andeans. However, this trituration could not have been substituted by the manual selection of minerals, because the size of the grains impeded it. The quimbalete primarily crushed minerals that were suitable for smelting. But its job certainly was not, at the heart of a colonial mill, to crush mineral ready for smelting that would later be washed. Processing trituration for dispersed mineral was a European practice, not an Andean one. The proof of this lies in the existence of rotating mills next to the quimbaletes (such as the hydraulic installations visible in the majority of the mills), which allowed for the production of more homogenous sands. Thus, the quimbalete was an adaptation of a crushing tool that was recalibrated for triturating. Its integration into the European chain of production altered it from its original purpose. It became a tool facilitating the milling that would later occur in the hydraulic mill, prior to gravimetric selection under water.

Situated between the stamp mill and the rotating mill, or hydraulic mill, the quimbalete was inserted into the production chain without being a required device. Its principal advantage lay in the lack of investment that it required. In the majority of the cases we observed, the triturating table was a natural rock that workers used as they had found it. All hard rock could be transformed into a quimbalete, in contrast to a mill wheel that required the costly investment of carving. Thus, the quimbalete slightly modified the system of mineral preparation for the sorting and comminution steps. It was unnecessary to wait for minerals to be reduced to gravel under the pylons of the stamp mill. Its appearance in the metallurgical chain of non-ferrous minerals from the 16th century onwards testifies to the profound implications for the use of local workforces in these tasks. It also testifies to their ability to insert a device into the process that was unknown to the foreign businessman. The introduction of this indigenous implement highlights the difficulties of exploiting mining resources, as the excavations carried out on the island of Isabela also demonstrate (Thibodeau *et al.* 2007). If we add to this the disregard for the lesser arts (Halleux 2009), it is far from strange that European colonizers accepted the introduction of a new implement into the clearly established chain of production. The quimbalete's appearance is even more simple, due to the fact that it required no serious investment. It made it possible for new mining enterprises to obtain an efficient grinding device instead of a more costly system.

It is equally important to note that the quimbalete resembles the stones used to mill grains not just in the Andean region, but around the world. However, in no other place, to our knowledge, is such a large stone seen to be used. In different parts of Europe, and in the sphere of Arab influence, a rotating mill was preferred—and equally in the milling of flour. Only the Greeks developed systems of mills, though always on a reduced scale, seen in various ancient sites such as Laurion (Conophagos 1980, 221, 227–33).

In the Old World, the rotating movement permitted the efficient transition to the mill. In the New World, this apparatus is depicted as an archaic implement that the colonial power was unable to eradicate even if it had wanted to. With the innovation of mercury processing, from 1572 onwards in the Andes, the preparation chain for minerals did not change and the quimbalete remained a pertinent implement, as a profound trituration was needed to increase the surface area in contact with mercury, thereby accelerating the formation of the amalgam. Representing one of the first tools used in the preparation of minerals, the quimbalete kept its place because of two profound technical mutations: the arrival of the European metallurgical chains of production and the switch to amalgamation for silver. In this sense, it is something of a living fossil, despite the recent transition to the flotation system.

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APPENDIX

A.1. The main quantities: mass, centre of mass and moment of inertia

We note that $b = \left|\overline{CG}\right|$ and the moment of inertia is noted as J. Considering the TTC shape, the quantities θ and the flat part length, A, are linked by the following relations:

$$A = 2R\sin(\theta/2) \Leftrightarrow \theta = 2\arcsin(A/2R). \tag{A.1.1}$$

The axis crossing the quimbalete perpendicular to its faces through the centre of the circumscribed circle is the axis to which J must be expressed, since it is also the instantaneous axis of rotation with respect to the stone when rolling.

Given the density ρ, the mass is obtained by classical 3-D integration. We obtain

$$M = e\rho R^2\Lambda(\theta),\ \text{with}\ \Lambda(\theta) = \pi + \frac{\sin(\theta) - \theta}{2}. \tag{A.1.2}$$

The centre of mass is on the plane of symmetry of the body and located below the circumcircle-centred axis (the circle axis). The distance between these two centres is one relevant parameter of the problem, and is given by

$$b = R\cdot S(\theta),\ \text{with}\ S(\theta) = \frac{2}{3}\frac{\sin^3(\theta/2)}{\Lambda(\theta)}. \tag{A.1.3}$$

The moment of inertia with respect to the circle-centred axis is also obtained by analytical integration. We obtain

$$J_C = MR^2\cdot K(\theta),\ \text{with}\ K(\theta) = \frac{6\pi - 3\theta + (2+\cos\theta)\sin\theta}{12\Lambda(\theta)}. \tag{A.1.4}$$

The moment of inertia with respect to the axis perpendicular to the quimbalete faces and crossing the centre of mass G, which is required to compute the free oscillation period, is given by Huygens' theorem as $J_G = J_C - Mb^2$.

A.2. The initial tilt, α_0

After some calculation, we obtain

$$\alpha_0 = \tan^{-1}\left(\frac{d}{\frac{M}{m}b - q}\right), \quad \text{where } b = \overline{CG}, \ d = \overline{QH}, \ f = \overline{HC} \ \text{and}$$

$$g = \overline{QC} = R\cos(\theta/2). \tag{A.2.1}$$

If we take more generally a given force F instead of the operator's weight (which is $F = mg$), then we shall use

$$\alpha_0 = \tan^{-1}\left(\frac{d}{\frac{Mg}{F}b - q}\right). \tag{A.2.2}$$

The corresponding elevation of the centre of mass is given by the quantity:

$$h = b(1 - \cos\alpha_0). \tag{A.2.3}$$

A.3. The equilibrium of the quimbalete striking a piece of gravel: the static case

See Figure 3 (a). We do not explicitly include the forces applied to the ground, as they are not required. We neglect all the deformations in order to simplify the calculation, and we also neglect the mass of the small amount of gravel in the problem. We suppose that none of the contact is slipping. Hence, the reaction forces are not perpendicular to the surface. In the balance of the forces acting on the gravel, the two forces at the common contact are opposite. We call this force $\rightarrow F_1$ and it is also the one applied to the grindstone at the contact point L.

The calculation results in the following:

$$F_1 = \frac{e\,\rho g b \Lambda(\theta)\sin\alpha}{2} R\sqrt{1 + \frac{R}{r}}. \tag{A.3.1}$$

A4. The full dynamical case

The geometry of the problem is completely changed, as shown in Figure 4 (b). To make this geometry more readable, we exaggerate the gravel radius. Figure 4 (a) on the left shows the moment when the first contact occurs, while the right-hand part shows the grindstone lifted. We can parameterize the problem with the angle η between the vertical and the line connecting the two centres. Then η_t is this angle at the first contact, when $\alpha = \alpha_t$ (t for touch). We obtain the following relations:

$$\begin{cases} R\eta_t = |C'L| \\ |C'O| = R\alpha_t = |C''K| = (R + r)\sin\eta_t \end{cases} \Rightarrow \begin{cases} \alpha_t = \left(1 + \frac{r}{R}\right)\sin\eta_t = 2\sqrt{\frac{r}{R}} \Rightarrow |C'O| = R\alpha_t = 2\sqrt{rR} \\ \eta_t = \arccos\left(\frac{R - r}{R - r}\right) \end{cases}. \tag{A.4.1}$$

By the way, these results also lead to a first condition regarding the size of the gravel: what is the size of the gravel that can be put at the origin (i.e., the initial contact location of the grindstone with the ground) while the grindstone is armed? This question is only geometrical and is independent of dynamical considerations, but it is absolutely essential. This maximum radius $r_{\max}$ is obtained by solving (from equation (A.4.1))

$$R\alpha_0 = 2\sqrt{r_{\max}R} \Rightarrow r_{\max} = \frac{\alpha_0^2 R}{4} \Rightarrow d_{\max} = \frac{\alpha_0^2 R}{2}. \tag{A.4.2}$$

Note that when considering this case as exact, it means that the gravel is already in contact with the grindstone even before it is released and, thus, the results from the static case apply fully: this case is static again. If we want to benefit from the kinetic energy, it is realistic to assume that the maximum size for 'practical' gravel will be half of $r_{\max}$, and we can keep as indicative

$$d_{\max}^{\text{in practice}} = \frac{\alpha_0^2 R}{4} \Leftrightarrow r_{\max}^{\text{in practice}} = \frac{\alpha_0^2 R}{8}. \tag{A.4.3}$$

With this choice, the angle at which the contact occurs is $\alpha_{\text{contact}} = \alpha_0/\sqrt{2}$.

After release, the quimbalete reaches the first contact and, due to the kinetic energy close to its maximum in the central area, the grindstone really rolls on the gravel surface. It works like two cog-wheels, the small one welded on the ground.

A.5. The free oscillation period

The calculation is similar to those that apply to classic pendula. After these classical calculations, the free period is found:

$$T_0 \cong 2\pi\sqrt{\frac{MR^2\psi^2 + J_G}{Mgb}}. \tag{A.5.1}$$

A.6. Stress within the gravel and gravel failure

The weight Mg (or the force F_1 as calculated in A.3.1) of the quimbalete being known, an estimation of the mean main axis stress $\overline{\sigma}_1$ applied to the gravel can be computed, since the surface $s = \pi a^2$ of the contact is known. Basically, we just write

$$\overline{\sigma}_1 = \frac{Mg}{s} = \frac{Mg}{\pi a^2}\left(\text{or, more generally, } \overline{\sigma}_1 = \frac{F_1}{s} = \frac{F_1}{\pi a^2}\right). \tag{A.6.1}$$

The weight (Mg) only applies when the grindstone is really on the gravel. In that case, there is only the uniaxial stress σ_1 that is involved, and it is not necessary to take into account the other components of the stress—say, (σ_2,σ_3)—although at least one of them is not rigorously null when some transversal friction and shear stress occur. Since the main and dominant phenomenon is caused by the weight, and to keep the problem as simple as possible, here we do not manage the possible role of (σ_2,σ_3), and we just consider the uniaxial case involving a vertical force, even if it is not strictly vertical. In the above formula, one has to determine the surface of the contact—say, s. This problem of 'contact mechanics' was first solved by Hertz (1881). Hertz analysed the contact of two elastic bodies having ellipsoidal shapes in the area of contact.

We adapt the original results by first considering two spheres, and then by making the radius of one of them tend to infinity. This simulates our situation: a 'big stone' (the grindstone) against a 'small stone' (spherical).

A first involved quantity is as follows:

$$D = \frac{3}{4}\left[\frac{1-\nu^2}{E} + \frac{1-\nu'^2}{E'}\right] \triangleq \frac{3}{4}\frac{1}{E^*}, \tag{A.6.2}$$

where E (resp. E') and ν (resp. ν') are the Young's modulus and the Poisson coefficient of the gravel and the grindstone, respectively. In the Hertz solution, making the radius of the grindstone tend to infinity—that is, reaching the case of a flat surface—leads to the following results:

$$a = (FDr)^{1/3}, \tag{A.6.3}$$

where a is the radius of the surface contact and F is the applied force.

At the centre of the contact, the pressure reaches its maximum at 1.5 times the mean pressure:

$$\sigma_{\max} = \sigma_1(0) = \frac{3}{2}\frac{F}{\pi a^2} = \frac{3}{2}\overline{\sigma}_1. \tag{A.6.4}$$

However, generally speaking, the brittleness of the gravel is difficult to assess, because it depends on numerous factors, including: (i) its shape and ruggedness; (ii) the presence of crystal defaults in the minerals; (iii) the presence of weaknesses within the joints between mineral crystals; and (iv) the recent history of the gravel (lithostatic stress release followed by the mining extraction, pre-processing etc.).

Gravel failure

As stated above, it is not easy to establish whether or not a given size of gravel will be crushed under the grindstone. But it is obvious that the bigger the gravel, the lower will be the inner stress. One can reason further by considering the maximum stress in the case of the spherical gravel, $\sigma_{\max}$, given by equation (A.6.4). Substituting the radius (a) of the contact surface (s) provided by equation (A.6.3) leads to

$$\sigma_{\max} = \frac{3}{2\pi}(Dr)^{-2/3}F^{1/3}. \tag{A.6.5}$$

Will the gravel be crushed? To answer this, one must introduce a failure criterion. A sufficient and realistic expression for a failure criterion will involve a simple (a single) threshold stress σ_{MAX} and that we shall not have effective crushing as long as

$$\sigma_{\max} < \sigma_{\mathrm{MAX}}. \tag{A.6.6}$$

This type of criteria is often used for brittle materials, which is the case for gravel. It is not realistic for other types of rupture.

What do we mean by 'crushed'? All the stresses calculated above are given on the contact surface between the grindstone and the gravel. The Hertz theory establishes that for a given contact surface of radius a, the shear stress is at its maximum at a depth very close to $a/2$. For large gravel, in a first step, one expects that it is only a surface layer of the gravel—of, say, a thickness more or less equal to a—that will be destroyed. If we consider a more or less horizontal diameter of the grain of radius r, the stress on this diameter plane is approximately $F/\pi r^2$ and, more generally speaking, the stress is $F/\pi a'^2$ if we consider a surface of radius a' in the gravel, with $a' < r$.

What we can expect given a maximum resistance σ_{MAX} is the following: under the weight of the grindstone, the gravel will crumble, at least on its surface, in the part of the gravel volume where $\sigma_{\max} > \sigma_{\mathrm{MAX}}$. This increases the surface of the contact area, because the crystal coherence is destroyed. The increase stops when it reaches

$$a'_{\max} = \sqrt{\frac{F}{\pi\sigma_{\mathrm{MAX}}}}. \tag{A.6.7}$$

We are now able to calculate if and how a given mass of spherical gravel will be reduced by the grindstone. First, if $a'_{\max} > r$, this means that the gravel will be totally destroyed and reduced to sand (or smaller). If, on the contrary, the diameter reduction of the sphere involved both sides, we have (assuming vertical forces) a diameter reduction of $2r'$, as depicted in Figure 3 (c), with

$$r' = \sqrt{r^2 - a'^2_{\max}}. \tag{A.6.8}$$

However, this means that the force applied by the grindstone will not be sufficient to completely crush the gravel and, consequently, this equation is not really useful. Thus, for a given gravel of radius r, $a'_{\max}$ is the main parameter to determine whether or not the gravel is destroyed. We can call $a'_{\max}$ given by equation (A.6.7) the 'destroying radius'. In other words, if $r < a'_{\max}$ then the gravel is destroyed.

Three special additional discussions are needed to describe what occurs if several pieces of gravel are simultaneously stuck below the grindstone, as follows:

Case (1): we discuss what occurs in the presence of several initially similar pieces of gravel.

It is unlikely that all the grains will have exactly the same size, but once the comminution of the largest pieces of gravel begins, the quimbalete will press on several of them, say n, and the total weight on each will be divided by something like the same factor n. This factor is only indicative, because of the continuous rolling, which causes the contact points under the grindstone to change continuously. If the quimbalete was standing still, one could assume that it would rest first on only three pieces of gravel, those permitting a stable equilibrium of the grindstone. Actually, all the pieces of gravel are rolling all the time and if the largest pieces are supposed to be crushed, then they are reduced in size.

Let us assume that n pieces of gravel of approximately the same radius r are involved. The 'most conservative' case, the one that could limit the efficiency of the machine, would be the one in which the forces applied on them are all equal, because it corresponds to the best possible repartition of the grindstone weight on the pieces of gravel. Then, a fair estimation of the new crushing limit would be obtained by assuming that the force acting on each gravel was just F/n.

The new destroying radius, as derived from equation (A.6.7), now depends on n as follows:

$$a'_{\max}(n) = \sqrt{\frac{F}{n}\frac{1}{\pi\sigma_{\mathrm{MAX}}}} = \frac{a'_{\max}}{\sqrt{n}}. \tag{A.6.9}$$

Case (2): if we consider a single piece of gravel at the beginning, we can suppose that it 'reduces' into numerous smaller grains—say, N particles. The mean force acting on each particle is F/N. Here, we get N particles of approximate radius r_N resulting from a single piece of gravel of radius r (conservation of the whole volume), with

$$r_N = \frac{r_0}{N^{1/3}}. \tag{A.6.10}$$

By the way, the new destroying radius is

$$a'_N = \frac{a'_{\max}}{N^{1/2}}. \tag{A.6.11}$$

The resulting N ground particles will again be destroyed as long as we have

$$r_N \le a'_N \Leftrightarrow \frac{r_0}{N^{1/3}} \le \frac{a'_{\max}}{N^{1/2}} \Leftrightarrow N \le \left(\frac{a'_{\max}}{r_0}\right)^6. \tag{A.6.12}$$

For instance, if $r_0 = a'_{\max}/2$, only 64 particles will have been produced, each having a radius of $r_0/\sqrt[3]{64} = r_0/4$.

Note that this theory is far too idealized, because it relies on the hypothesis that the grindstone rests on all the N produced particles. This is not the case; not only may three particles sustain the grindstone, but the continuous movement changes the supporting particles all the time. However, the reasoning behind this shows that grinding is more difficult when the particle size decreases.

Case (3): we can now combine cases (1) and (2)—n pieces of gravel, each to be divided into N pieces of gravel. But this case is similar in all respects to case (2), with just N replaced by nN. That is, nN particles of radius r_0 will be crushed as long as we have

$$nN \le \left(\frac{a'_{\max}}{r_o}\right)^6. \tag{A.6.13}$$

The special case when a large piece of gravel is stuck under the tilted grindstone

This is the case shown in Figure 4 (a). Let us consider an armed (tilted) quimbalete with angle α_0, and a piece of gravel of diameter d (or radius $r = d/2$) under the stone. We again use equation (A.6.7) (and the reasoning that led to it) and substitute the strength given by equation (A.6.1). This leads to the following:

$$a'_0 = \sqrt{\left(\frac{Mgb\sin\alpha_0}{2R}\sqrt{1+\frac{R}{r}}\right)/\pi\sigma_{\mathrm{MAX}}}. \tag{A.6.14}$$

If $a'_0 > r$, the gravel is fully crushed. The index 0 here is to remind us that this applies when the quimbalete is fully titled with angle α_0.

SUPPORTING INFORMATION

Additional Supplementary material may be found in the online version of this paper on the publisher's website:

The ore dressing grindstone named "Quimbalete": a mechanics-based approach (long version)