# AN EXPERIMENTAL STUDY OF BIPOLAR AND FREEHAND KNAPPING OF NAIBOR SOIT QUARTZ FROM OLDUVAI GORGE (TANZANIA)

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*Recent excavations carried out in several Bed I and Bed II sites have shown that hominins at Olduvai Gorge used both bipolar and freehand knapping methods for quartz reduction. Due to the petrographic nature of quartz and to its heterogeneous response to fracture, the identification of bipolar knapping at any given site can be ambiguous and controversial. This work aims to overcome this problem by developing an experimental referential framework for the recognition of characteristic features of flakes produced through both bipolar and freehand reduction of Naibor Soit quartz cores. The final goal of this work is to use a set of variables related to the response of local Olduvai quartz to freehand and bipolar fracture, obtained through two independent controlled experiments, in order to statistically differentiate the diagnostic technological traits that best indicate bipolar reduction on this raw material type.*

*Las recientes excavaciones que hemos llevado a cabo en varios yacimientos localizados en los Lechos I y II han puesto de manifiesto que los homíninos de la Garganta de Olduvai se sirvieron de sendos métodos de talla bipolar y a mano alzada para llevar a cabo sus procesos de reducción del cuarzo. Dada la naturaleza petrográfica del cuarzo y su heterogénea respuesta a la fracturación, la identificación de la talla bipolar en un yacimiento dado puede ser ambigua y controvertida. El presente estudio pretende afrontar este problema con el desarrollo de un marco experimental de referencia para el reconocimiento de los rasgos diagnósticos de las lascas producidas a través de la talla, respectivamente, bipolar y a mano alzada de núcleos de cuarzo procedentes de Naibor Soit. El objetivo final de este trabajo es el de servirse de un conjunto de variables relacionadas con la respuesta del cuarzo local de Olduvai a la fractura producida por los modelos de reducción bipolar y a mano alzada, obtenidos a través de dos experimentos independientemente controlados, con el objeto de diferenciar estadísticamente los rasgos tecnológicos diagnósticos que pueden indicar de forma más acertada la presencia de la talla bipolar en este tipo de materia prima.*

Bipolar knapping is documented in the Early Stone Age (ESA) archaeological record between 2.3 and 1.3 Ma, in sites such as Senga (Democratic Republic of Congo), Omo Shungura (Ethiopia), Koobi Fora Formation (Kenya) and Olduvai Gorge (Tanzania) (de la Torre 2004; Leakey 1971; Ludwig and Harris 1998; Toth 1982). The use of a bipolar reduction strategy is closely linked to quartz. It is apparent that this technological choice constitutes an efficient adaptation to constraints posed by the raw material (Braun et al. 2009), particularly those constraints related to quartz morphology and quartz response to breakage (Breuil and Lantier 1951:71; Ludwig and Harris 1998:90; Toth 1982:126). In cases where available local raw materials are mainly fine-grained volcanic rocks, bipolar knapping is absent, such as at Gona (Rogers and Semaw 2009), or very marginal, such as at Koobi Fora (Ludwig and Harris 1998; Toth 1982). In other sites, such as Senga, the abundance of bipolar knapping constitutes a response to the local absence of lithic re-

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sources other than small quartz pebbles (Ludwig and Harris 1998:90).

In Olduvai Gorge, where a variety of rocks and textures were locally available for hominins (Hay 1976), the relationship between freehand and bipolar techniques reflects a more complex set of behaviors. There, Mary Leakey recognized the residual presence of bipolar reduction on quartz (following a typological nomenclature these items were referred to as *outils écaillés*; for an updated terminological discussion see Shott 1999: 218–219) in several Developed Oldowan sites, namely at BK (Leakey 1971:221). Jones (1994: Table 10.3) acknowledged that an important proportion of bipolar artifacts could be documented from Middle Bed II upwards. Later on, other authors have confirmed the presence of this reduction method in the same stratigraphic interval (Ludwig and Harris 1998). To our knowledge, Potts is the only author who, although in a rather subtle way, acknowledged the recurrent use of bipolar technique for quartz exploitation even during Bed I times (Potts 1988:245).

Taking into account these authors' views, it is perhaps surprising that other reevaluations of Leakey's collections have not reported any considerable signature of bipolar knapping, at least in Middle and Upper Bed II times (de la Torre and Mora 2005; Kimura 2002). Challenging de la Torre and Mora's (2005:215) interpretation of Leakey's collection, Diez-Martín, Sánchez, Dominguez-Rodrigo, Mabulla, and Barba (2009) and Diez-Martín et al. (2010) observed that the bipolar reduction method accounts for a relevant percentage of the new lithic collections excavated more recently in sites located in both Beds I and II, such as FLK North and BK. At both sites, while the reduction of volcanic rocks has been exclusively performed following a freehand method, quartz has undergone a more diversified treatment, which included freehand and bipolar reduction operational sequences. There are reasons to claim that a fraction of the lithic items considered by de la Torre and Mora as the by-products of percussion activities (a perspective that we have defined as the "anvil hypothesis") fit better within the bipolar knapping universe (Diez-Martín, Sánchez, Dominguez-Rodrigo, Mabulla, and Barba 2009; Diez-Martín et al. 2010).

The controversial interpretation of the Olduvai quartz materials is a good example of the present state of knowledge of bipolar technology in the ESA, dominated by the lack of experimental referential frameworks. Thus, analogies are needed, which could be used for the identification of the bipolar component in the lithic assemblages currently excavated in Olduvai Gorge. From an epistemic point of view, analogical frameworks have to be derived from experiments that aim to reproduce the premises and variables upon which the fossil record is constructed as faithfully as possible (Domínguez-Rodrigo 2008).

In this work we present a series of experiments focused on flake production through freehand and bipolar reduction methods. We have focused our attention on detached products for several reasons: (1) some authors have already pointed out that the identification of bipolar traits on cores is more reliable than on bipolar flakes (Diez-Martín, Sánchez, Dominguez-Rodrigo, Mabulla, and Barba 2009; Diez-Martín, Domínguez-Rodrigo, Sánchez, Mabulla, Tarriño, Barba, Prendergast, and Luque 2009; Jeske and Lurie 1993:140); (2) confusion is thus more common when defining bipolar traits in flakes; (3) the purported by-products of bipolar reduction (i.e., a high amount of shatter, blocky debris, flake fragments, chunks and exhausted cores), which can be linked to bipolar load application, tend to be more abundant than cores in the archaeological record (Bradbury and Carr 2004); and, (4) usable flakes are considered to be the main goal of lithic reduction. Comparing freehand and bipolar efficiency ([Eren et al. 2008; Jennings et al. 2010; Prasciunas 2007]: flake productivity, quality and potential of cutting-edges produced per flake in each technique) can shed light on the still-obscure issue of the functionality of bipolar knapping (Shott 1999). In sum, the final goal of this work is to use all the variables related to the response of local Naibor Soit quartz to freehand and bipolar fracture, recorded through two independent controlled experiments, in order to statistically determine the diagnostic technological traits that best identify bipolar reduction on this raw material type. This will provide the analogical basis upon which quartz exploitation documented at the Olduvai sites will be further interpreted in forthcoming site-specific analyses.

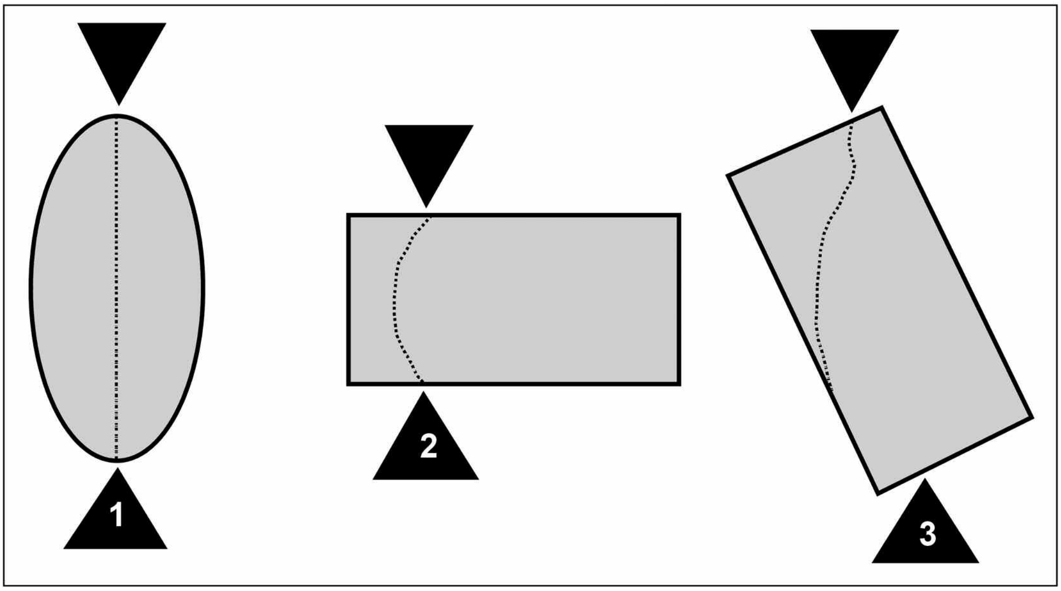


**Figure 1. Schematic representation of the various methods of bipolar reduction: 1. Vertical axial; 2. Horizontal axial; 3. Non-axial or oblique (Redrawn from Van der Drift 2001: figure 5).**

## Method of Analysis

*The Bipolar Experiment*

The positives (detached products) studied here were obtained through the bipolar reduction of nine quartz slabs quarried at their source in the Naibor Soit. The original mass of blanks used as cores is shown in Table 1. We define bipolar reduction technique as a method to obtain flakes by resting the core on an anvil and striking it from the top with a hammerstone (Figure 1). The core can be placed on the anvil vertically (the axial length of the core coincides with the striking plane and splitting is produced from center out) or horizontally (the axial length and the striking plane do not coincide and splitting is produced from outside in) (Toth 1982). In this experiment, we have tended to produce a horizontal bipolar technique, as it is best suited to the blocky morphology of the cores. Two possible and rather different bipolar flaking methods stem from the way in which impact is applied from the top with the hammerstone: (a) axial (Mourre 2004), straight (Van der Drift 2001) or simply bipolar technique (Callahan 1987), when the core tends to be struck straight downward from above, perpendicular to both core and anvil. In this case, the opposed compression forces produce two opposing points of impact and fracture directions, characteristic of the standard bipolar load application; (b) non-axial (Mourre 2004), oblique (Van der Drift 2001), or anvil (Callahan 1987) technique, produced when the core is struck obliquely or with the force directed away from the point of contact with the anvil (Callahan 1987:13). Without a distal contact point, flakes obtained by means of an oblique method do not differ substantially from freehand flakes. The main goal of our experiment was to obtain as many bipolar positives as possible from each core. To accomplish this objective in the most realistic possible way, the knapper was allowed free play for choosing the most suitable method among both axial and non-axial in the course of any reduction sequence.

A field sheet was used to record relevant information during the experiment: initial and final core measurements (length, breath, thickness, and weight), the sequential relationship between core rotation and flake detachment, the characteristics of the core striking area before each detachment episode (form and angle in platform, base, and striking surface), angle of the blow and miscellaneous observations (mostly relative to the results of each striking episode). A large black plastic sheet under the knapping area was used to keep

Table 1. Experimentally Knapped Bipolar Cores (BC) Indicating Reduction Model and Various Mass Parameters (measured in grams).

| Core No. | Reduction model | Original slab | Exhausted core | Waste/Shatter | Recorded positives |
|---|---|---|---|---|---|
| BC1 | C1 | 1659.3 | 334.2 | 676.2 | 648.9 |
| BC2 | | 2153.2 | - | 1321.2 | 308.3 |
| Bc2a | C2 | | 420.6 | | |
| Bc2b | C1 | | 103.1 | | |
| BC3 | | 1540.5 | | 540.1 | 500.2 |
| Bc3a | C3 | | 74.3 | | |
| Bc3b | C2 | | 217.0 | | |
| Bc3c | C1 | | 208.9 | | |
| BC4 | C3 | 2503.2 | 262.1 | 916.1 | 1325.0 |
| BC5 | | 2572.1 | | 516.6 | 1101.5 |
| Bc5a | C2 | | 488.9 | | |
| Bc5b | C1 | | 465.1 | | |
| BC6 | C1 | 261.9 | 83.5 | 57.1 | 121.3 |
| BC7 | C2 | 907.8 | 157.3 | 535 | 215.5 |
| BC8 | C1 | 1424.2 | 328.3 | 996 | 129.9 |
| BC9 | C3 | 770.0 | 243.9 | 131.6 | 394.5 |

*Note*: CR1= No core rotation; CR2= One core rotation; CR3= Two or more core rotations.

Table 2. Experimentally Knapped Freehand Cores (FC) Indicating Reduction Model and Various Mass Parameters (Measured In Grams).

| Core No. | Reduction model | Original slab | Exhausted core | Waste/Shatter | Recorded flakes |
|---|---|---|---|---|---|
| FC 1 | B.M.C | 1264.3 | 294.3 | 195.2 | 774.8 |
| FC 2 | U.U.S | 654.7 | 156.2 | 59.4 | 439.1 |
| FC 3 | U.U.S | 1215.4 | 391.3 | 152.6 | 671.5 |
| FC 4 | U.U.S | 411.3 | 103.0 | 54.8 | 253.5 |
| FC 5 | T | 1011.5 | 372.1 | 74.4 | 565.0 |
| FC 6 | B.U.O | 1210.5 | 326.9 | 650.5 | 233.1 |
| FC 7 | B.U.O | 900.2 | 371.0 | 320.6 | 208.6 |
| FC 8 | U.B.O | 1412.2 | 470.9 | 134.2 | 807.1 |
| FC 9 | U.B.O | 1454.2 | 249.3 | 554.0 | 650.9 |
| FC10 | B.B.O | 1510.1 | 273.7 | 468.2 | 768.2 |

*Note*: U.U.S = Unifacial Unipolar Semicircular; U.B.O= Unifacial Bipolar Opposed; B.U.O= Bifacial Unipolar Opposed; B.B.O= Bifacial Bipolar Opposed; B.M.C= Bifacial Multipolar Centripetal; T= Trifacial Multipolar.

shatter. Most of these by-products show a great morphological variability and constitute a large part of the abundant nondiagnostic component of the bipolar knapping. Shatter ($\leq$ 25 mm) was not studied in detail; only total shatter mass has been recorded. Tables 1 and 2 show the shatter weight produced in each experiment. The shatter mass (relative to the original block mass) has been compared in both bipolar and freehand techniques. A two-sample T test shows that bipolar reduction produces a much higher amount of shatter per slab mass than freehand reduction ($p = .03$). The difference is even sharper after the sample has been bootstrapped ($p = .000$) (see below for statistical details). Our study strongly confirms the consensus that bipolar knapping is a technique that wastes raw material (Shott 1989:2). Positives resulting from each knapping episode (usually fractured in several conjoinable pieces) constitute the diagnostic component of the bipolar knapping method. They received specific marks with a permanent marker pen to identify platform and base (a point for the platform and a cross for the base). Then, each positive was placed in a zip-lock bag, labeled with the same sequential code recorded in the field sheet, and stored in a large bag with the material resulting from the same reduction sequence for further analysis in the laboratory.

Cores were exploited according to two complementary variables (Binford and Quimby 1963; Diez-Martín, Sánchez, Dominguez-Rodrigo, Mabulla, and Barba 2009): core rotation and alternate use of platforms. Core rotation is an efficient response to both the intensity of exploitation and raw material morphology. The knapper compensated for the gradual loss of striking platform mass and base stability in the course of bipolar reduction by choosing a new platform/base equilibrium. Core rotation, thus, allowed the knapper to maintain a suitable striking platform and a stable base constant. It organized the volumetric progress of the exploited slab to obtain new knapping series. Core exploitation was systematized in three simplified groups: CR1 (Core Rotation 1) are specimens in which the relationship between platform (the striking surface) and base (the surface resting on the anvil and adding stability to the core) remain stable during the whole sequence of the block exploitation; CR2 are specimens in which one series of core rotation and therefore platform-base alternation was carried out. This rotation is usually orthogonal to the previous platform/base structure; CR3 are specimens in which a multiple series of core rotation and platform-base alternation (always more than 2) were undertaken. Table 1 shows the model in which bipolar cores have been exploited in each case.

*The Freehand Experiment*

The flakes studied here were obtained through the freehand reduction of ten quartz blocks quarried in Naibor Soit. The original mass of blocks used as cores is shown in Table 2. A two-sample T-test showed no statistical difference in original mass between blocks used for bipolar and freehand knapping ($p = .19$). A similar procedure for fieldwork analysis and recording to that previously explained for the bipolar experiment was used in this case. The response of Naibor Soit quartz to freehand knapping resulted in significantly fewer accidents related to core shattering. Unlike the bipolar experiment, no block broke up into different fragments and reduction sequences showed continuity from the original supports to the exhausted cores. The experiment aimed to produce as many flakes as possible through standard reduction models. The reduction strategies undertaken for the experiment have been defined according to three parameters: facial exploitation (the number of knapping surfaces exploited, i.e.: unifacial, bifacial, trifacial, multifacial), polarity (the number of striking platforms identified, i.e.: unipolar, bipolar, multipolar) and the relationship between different knapping series (linear, opposed, circular, orthogonal, centripetal). According to the combination of these three attributes, we have identified the following exploitation models in our lithic collection: unifacial unipolar semicircular; unifacial bipolar opposed; bifacial unipolar opposed; bifacial bipolar opposed; bifacial multipolar centripetal; and trifacial. Table 2 shows the model in which freehand cores have been exploited in each case.

*Selection of Variables*

*Metrical Variables.* Measurements include: axial length, proximal, mesial and distal width and thickness, and weight.

*Mechanical Variables.* Fracture mechanics related to lithic knapping have been treated in depth in a number of publications (Baker 2010; Bertouille 1989; Cotterell and Kamminga 1987, 1990; Dibble and Whittaker 1981; Lawn and Marshall 1979; Patten 2005; Speth 1972). Cotterell and Kamminga's (1987, 1990) work is a key reference regarding the mechanics of flake formation and the features defining both conchoidal and compression flakes. Other studies have focused more specifically on describing the traits that define the compression force related to bipolar knapping (Berman et al. 1999; Callahan 1987; Flenniken 1981; Jeske and Lurie 1993; Kobayashi 1975; Leaf 1979:30–40; Van der Drift 2001). We have selected those mechanical and technical parameters best suited to discriminate between freehand and bipolar fracture mechanics (Odell 2003). Regardless of fracture type, raw material plays an influential role in the process of fracture propagation. The coarse-grained Naibor Soit quartz is a fairly anisotropic rock that shows many cleavage planes. Quartz heterogeneity makes fracture propagation unpredictable and promotes a variety of flake accidents (Mourre 2004). By studying flake snapping, the way in which freehand and bipolar fracture mechanics respond to Naibor Soit petrographic traits can be addressed. Table 3 shows the traits that have been selected in our study.

Table 3. Mechanical Variables Selected for This Study.

| | |
|---|---|
| Initiation | 1. Hertzian; 2. Bending; 3. Wedging; 4. Wedging/Bending; 5. Wedging/Hertzian; 6. Bending/Hertzian; 7. Cleavage plane. |
| Termination | 1. Feather; 2. Step; 3. Hinge; 4. Overshot; 5. Axial or platform (positives bearing paired platforms). |
| Bulb of force | 0. Absent; 1. Diffuse; 2. Present. |
| Compression waves | 0. Absent; 1. One direction; 2. Two opposed directions. |
| Interior platform angle | 1. Obtuse (>90º); 2. Right (90º); 3. Abrupt (75-89º); 4. Semi-abrupt (55-75º); 5. Simple (35-55º). |
| Exterior platform angle | 1. Obtuse (>90º); 2. Right (90º); 3. Acute (<90º). |
| Crushing and splintering | 0. No crushing; 1. Crushing on one surface; 2. Crushing on two surfaces; 3. Crushing on three surfaces. |
| Flake fracture types (Figure 2) | 0. Complete flake; 1. Longitudinal Siret type fracture (flake breaks in two pieces along the axis of impact); 2. Siret type and platform fractures; 3. Siret type and base; 4. Siret, platform and base; 5. Siret and transversal; 6. Platform; 7. Base; 8. Platform and base; 9. Side longitudinal; 10. Transversal; 11. Double transversal.12. Lateral and transversal; 13. Basal flake. |

*Functional Variables.* We define functional variables as those traits that describe potentially usable cutting edges in flakes (Airvaux 1987:26). The three qualities describing functional and potential value in cutting edges are: (a) total amount of cutting edge per flake (measured with a caliper in total mm); (b) Number of cutting-edge segments, counting right-sided, left-sided and distal segments; (c) cutting-edge angle (measured with a goniometer). This angle measures the interaction between ventral and dorsal surfaces at the flake edge and records its potential acuteness and sharpness. We have recorded two potentially usable angle intervals: semi-abrupt (55–75º) and acute (15º–55º).

### *Statistical Analysis*

Several types of statistical analyses were carried out using R software (Crawley 2007). Standard T tests were performed to compare some metric variables (maximum length of flakes, width and thickness in proximal, middle and distal parts of flakes) in flakes produced by freehand and bipolar knapping. Previously, normality tests were conducted to test the adequacy of the sample. Shapiro-Wilk and Anderson-Darling normality tests were used both prior and after transformation of data. The kurtosis and skewness of data were measured using the "fBasics" library of R. The "nortest" library of R was used to perform normality tests. Those variables with a non-normal distribution were transformed using a Box-Cox method. For this purpose, the "geoR" and "car" libraries of R were used. Normal variables were standardized in order to minimize the wide range of continuous metric data in normal versus transformed variables. Metric values were logarithmically transformed prior to applying statistical analyses, so that relative values rather than absolute values were used, since the latter depend on the absolute dimensional properties of flakes, which can vary among experiments.

After comparing the significance of differences in metric properties of flakes between both knapping methods, a logistic regression analysis was carried out to test how and to what extent those selected metric variables could discriminate between each knapping method. For this purpose a general linear model (GLM) was applied following a binomial classification method. To compensate for the original (prior to data transformation for paired sample tests) lack of normality and linearity of the experimental sample used, a non-linear non-parametric approach was also used, based on general additive models (GAM) with binary data. In many cases when one or more continuous predictor variables do not follow a linear relationship or when no clear criteria exist as to whether the sample inter-relation is parametric or non-parametric, general additive models allow capturing the shape of the relationship without choosing any determined parametric form. GAM expand the range of application of GLM by introducing non-parametric smoothers in

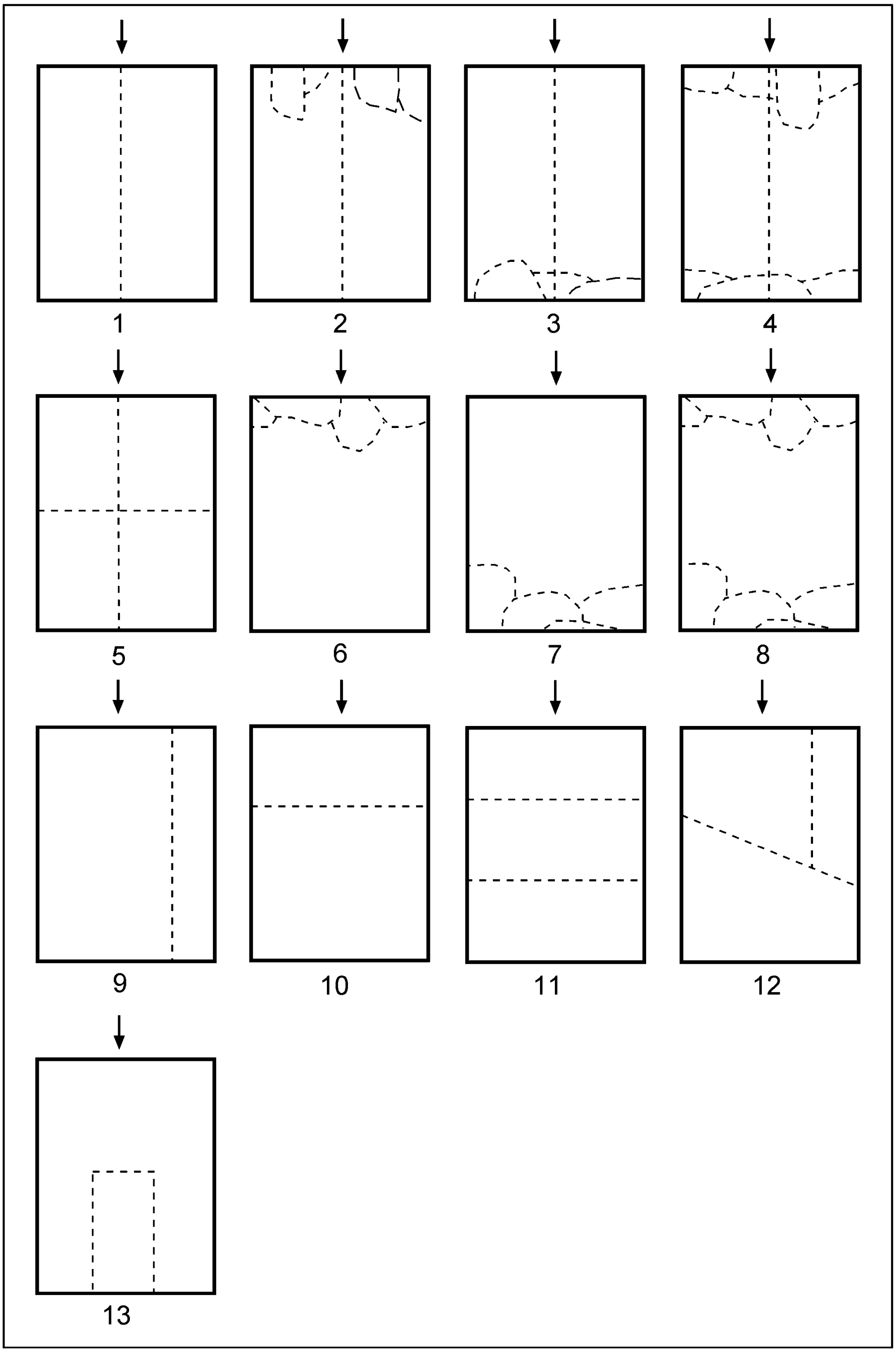


**Figure 2. Schematic representation of the fracture types recorded in our experiment. Arrows show the point of impact. 1. Longitudinal Siret type fracture (flake breaks in two pieces along the axis of impact); 2. Siret type and platform fractures; 3. Siret type and base; 4. Siret, platform and base; 5. Siret and transversal; 6. Platform; 7. Base; 8. Platform and base; 9. Side longitudinal; 10. Transversal; 11. Double transversal.12. Lateral and transversal; 13. Basal flake.**

addition to parametric algorithms in families of data errors representing binomial, gamma, Poisson, and normal distributions (Crawley 2007). The degree of smoothness of a model is estimated as part of fitting. For the present analysis, the library "mgcv" was used because this library uses a generalized cross-validation criterion in the selection of scale parameters, which correct oversmoothing. The "gam" and "gam.plot" functions were also used with this R library.

The set of categorical variables were statistically analyzed via a multiple correspondence analysis. Each variable showed a different type of contribution to the final dimensional solution of the model and each variable s factor subdivision also contributed differently to the discrimination of freehand and bipolar flakes. The analysis of edge types was carried out through a robust test of a two-way ANOVA procedure. For this purpose, a robust Welch test for a two-factor randomized pattern using trimmed estimators was applied. The "robust" library of R was used again in conjunction with the "t2way" function. The Welch test uses Snedecor s F instead of Fisher s F. Given that the original sample of angles for both freehand and bipolar flakes was smaller than 100, the samples were bootstrapped 1,000 times prior to the application of the robust test. When comparing the amount of edge available in the perimeter of each flake to its size, absolute values were log-transformed and analyzed through a robust correlation test. A population percentage bend correlation test available in R was used, in which Huber estimators determine the correlation. Then, a robust regression analysis was applied by using both a minimum square estimator and a B-robust M-estimator for a linear model approach. For this purpose the R "bmreg" function was used. To compare if freehand and bipolar flakes produce the same amount of potentially functional edge, a robust confidence interval test to compare trimmed mean values of two independent populations was applied by using the "yuen" function in R.

## Results

A total of 108 positives produced in the course of the bipolar reduction of nine quartz slabs (Experiment 1) have been analyzed. The freehand flake sample, produced after knapping ten cores (Experiment 2), includes 101 specimens. Our experimental collection therefore totals 209 detached objects (52 percent bipolar and 48 percent freehand). The results of our study are the following:

### *Metrical Features: Thick and Short Bipolar Positives*

Table 4 shows the mean size (mm) of products obtained through bipolar and freehand reduction strategies. T tests comparing dimensional variables yielded significant differences in axial length ($p = .000$), with freehand flakes being longer than bipolar flakes. Significant differences in width in the proximal ($p = .000$), mesial ($p = .000$), and distal ($p = .000$) areas exist, with freehand flakes being absolutely wider than bipolar flakes. In agreement with the mechanical particularities of Hertzian initiation and propagation (Bertouille 1989; Cotterell and Kamminga 1987), freehand reduction also produced thicker flakes in absolute values in the proximal area ($p = .000$), but definitely thinner in the mesial and distal parts of the flake ($p = .000$). These mass differences observed in mesial and distal areas strongly correlate with sharp differences in termination types observed between both methods (see below). Bipolar flakes are overall thicker also in relative terms, as documented in the thickness:width ratio, which shows a similar proportion for the proximal end of flakes in both methods, but a larger ratio for the mid section ($p = .000$) only. The ratio in the distal end is similar for flakes produced by both methods ($p = .062$). Despite being thinner, the overall larger size of freehand flakes accounts for the significant differences in weight ($p = .002$) compared to bipolar positives.

A logistic regression analysis following a stepwise method on the original variables selected four variables as more discriminant than the rest ($p = <.05$): width on the proximal and distal areas, and thickness on the middle and distal areas (Figure 3). However, the model is not completely valid because it classifies a small portion of the sample (38 percent) and also because it is based on a non-normal distribution of most variables, as can be seen by the occurrence of outliers in the "rugs" of plots in Figure 3. A transformed set of variables, using a Box Cox procedure of normal-

Table 4. Mean Size (mm) of Flakes Obtained in the Bipolar (B) and Freehand (F) Experiments.

| | Minimum | | Maximum | | Mean | | Std. deviation | |
|---|---|---|---|---|---|---|---|---|
| Variable | B | F | B | F | B | F | B | F |
| Axial length | 24 | 23 | 97 | 95 | 45.51 | 51.22 | 14.35 | 12.35 |
| Prox. Width | 1 | 2 | 73 | 71 | 21.72 | 30.29 | 14.12 | 12.13 |
| Mes. Width | 14 | 13 | 100 | 82 | 33.84 | 40.05 | 14.27 | 14.52 |
| Dist. Width | 4 | 7 | 84 | 90 | 32.26 | 37.16 | 16.48 | 18.11 |
| Prox. Thickness | 1 | 1 | 50 | 28 | 11.77 | 14.12 | 9.83 | 5.33 |
| Mes. Thickness | 5 | 7 | 43 | 34 | 18.1 | 16.35 | 8.34 | 5.91 |
| Dist. Thickness | 2 | 2 | 52 | 42 | 15.06 | 12.21 | 10.02 | 8 |

ization, complying with the requirements of normality as required by a standard logistic regression, failed to produce a model since all variables had alpha values higher than .05. This was due to the relationship among variables not being linear, which is also a requirement of logistic regression procedures, and also to the normalization having modified the outliers, making the ranges of variation of flakes for both knapping methods overlap more, despite their mean value differences (as shown by T tests; see above).

An alternative non-parametric analysis, based on a GAM (General Additive Model), yielded a different solution. The analysis selected four variables as the most influential (Figure 4): thickness of the middle section of flakes (.006), length (.009), thickness of the distal end (.021), and thickness of the proximal end (.037). That is, when a nonlinear distribution is contemplated, the model places special emphasis on flake thickness (proximal thickness was the next variable selected by the model when an alpha threshold of 90 percent instead of 95 percent was selected) and length as the most important discriminatory characteristics, with bipolar flakes being relatively and absolutely shorter and thicker in the middle section and on the distal end of flakes. Distal width was also discriminatory. Freehand knapping tends to produce flakes that have slightly wider ends than bipolar flakes, a feature more visible especially in large flakes. This model accounts for a large part of the sample variance and correctly classifies 59 percent of flakes. The GAM analysis shows that one variable (length) clearly has a linear relationship, whereas the other three are nonlinear (Figure 4).

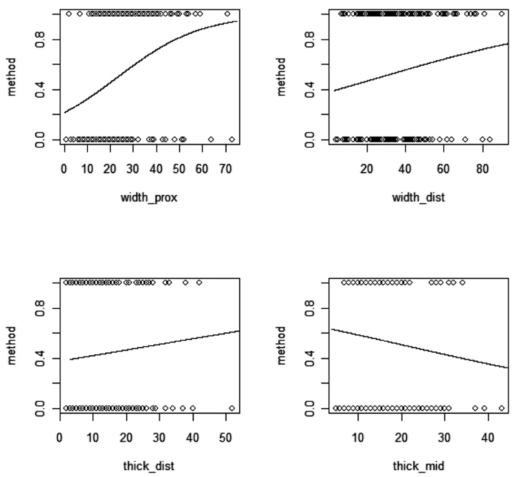


**Figure 3. Plots of the main variables selected in a logistic regression analysis using the non-transformed variables as raw data. Rugs below 0 represent the data for bipolar flakes and those above 0 represent freehand flakes.**

### *Mechanical Features: Crushing and Termination*

93 percent of bipolar flakes are included in one of the varieties of wedging initiation. In sharp contrast, while a considerable percentage of freehand specimens have been initiated in a wedging manner, 47 percent of them are characterized for a clear Hertzian initiation. Certainly Hertzian initiation shows a sharp contrast between each method, as almost no flake showing this pattern has been obtained through bipolar load application. Freehand flakes predominantly show a feather termination, followed at a great distance by other types. Feather, step, and hinge terminations explain 88 percent of the freehand sample. Conversely, bipolar positives preferentially have

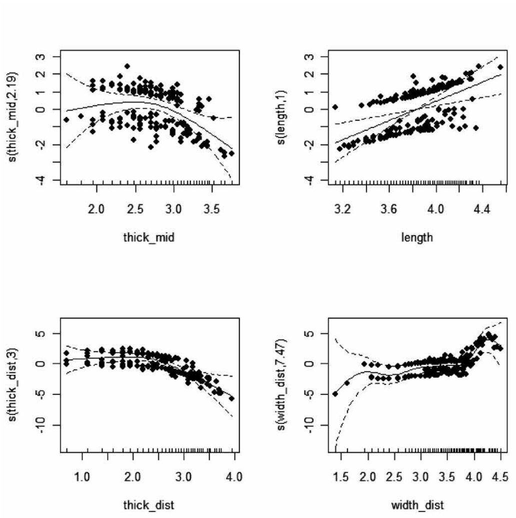


**Figure 4. A non-parametric GAM (General Additive Model) analysis, showing the distribution of objects in each of the four variables selected which explain most of the metric differences between freehand flakes (upper cluster in each graph) and bipolar flakes (lower cluster in each graph) and the type of relation that they exhibit (linear versus non-linear).**

an axial termination, and 82 percent of bipolar flakes that show a feather termination have been detached using a non-axial bipolar strategy. A logistic regression has been applied in order to determine the relationship between the ratio of width to thickness in proximal and distal areas in both techniques and to look for possible differences in that ratio that can be used as metrical discriminants between them. The result shows that differences are not significant when measuring this ratio ($p = .22$). However, mean distal areas are 70 percent thicker in bipolar positives than in freehand flakes. This means that, while Hertzian propagation tends to decrease in mass towards the distal area, wedging propagation differs substantially. The logistic regression shows a significant difference between each technique when measuring distal mass ($p = .000$).

Bulbs of force do not form easily in Naibor Soit quartz: 69 percent of freehand flakes do not show this feature. However, when bulbs do appear in this reduction method (31 percent), they are clear and unambiguous. In bipolar positives, 87 percent bear no sign of bulb of force in either platform or base. The remaining cases are positives with diffuse and ambiguous bulbs in platform (6 percent) or base (6 percent). Only one specimen (1 percent) shows a well-developed bulb of force that has been produced in the basal area. Confirming Crabtree's observations (1972:42), no opposed, double bulbs have been found in our experiment. Like the bulb of force, compression waves do not form easily in this quartz type. Only 47 percent of freehand flakes show clear and unambiguous signs of compression waves. Bipolar positives do not show signs of this feature (unidirectional or opposed). Crushing constitutes a characteristic feature of bipolar positives. While 59 percent out of the bipolar sample show this kind of stigma, only 4 percent of freehand flakes bear crushing. In bipolar positives, crushing has been recognized mostly in distal areas or bases (43 percent of the sample), but also in proximal platforms (22 percent) and dorsal areas (19 percent). In freehand flakes, crushing appears equally in dorsal and distal areas (2 percent in each). Complete flakes are more common among freehand (64 percent) than bipolar (46 percent) flakes. Freehand snaps tend to be mostly Siret and Siret/transversal types (28 percent). Snaps in bipolar positives are much more diversified than in freehand specimens. Thus, although pieces showing a combination of Siret (by far the most common type of snap in this raw material) and other types of fracture are common (22 percent), all the fracture types described in our work are represented in the bipolar sample (Figures 5 and 6).

A multiple correspondence analysis was carried out with all the mechanical variables described in the Methods section. This analysis yielded a two-dimensional model with an eigenvalue of .71 (out of ten variables), which explains a large part of the sample variance (Figure 7). The first dimension (eigenvalue = .47) was characterized by the following variables, which had a discrimination measure > .5: Crushing presence/absence (.82), crushing in the distal area (.65), termination (.60), and initiation (.53). The second dimension (eigenvalue = .24) was determined by crushing presence/absence (.632) and initiation (.44). These two variables, also participants of the first dimension, showed different values in each of the dimensions according to their factors. For instance, crushing in one area figured prominently in dimension 2, whereas no crushing or crushing in three areas scored high in dimension 1. Likewise, initiation in dimension 1 produced high

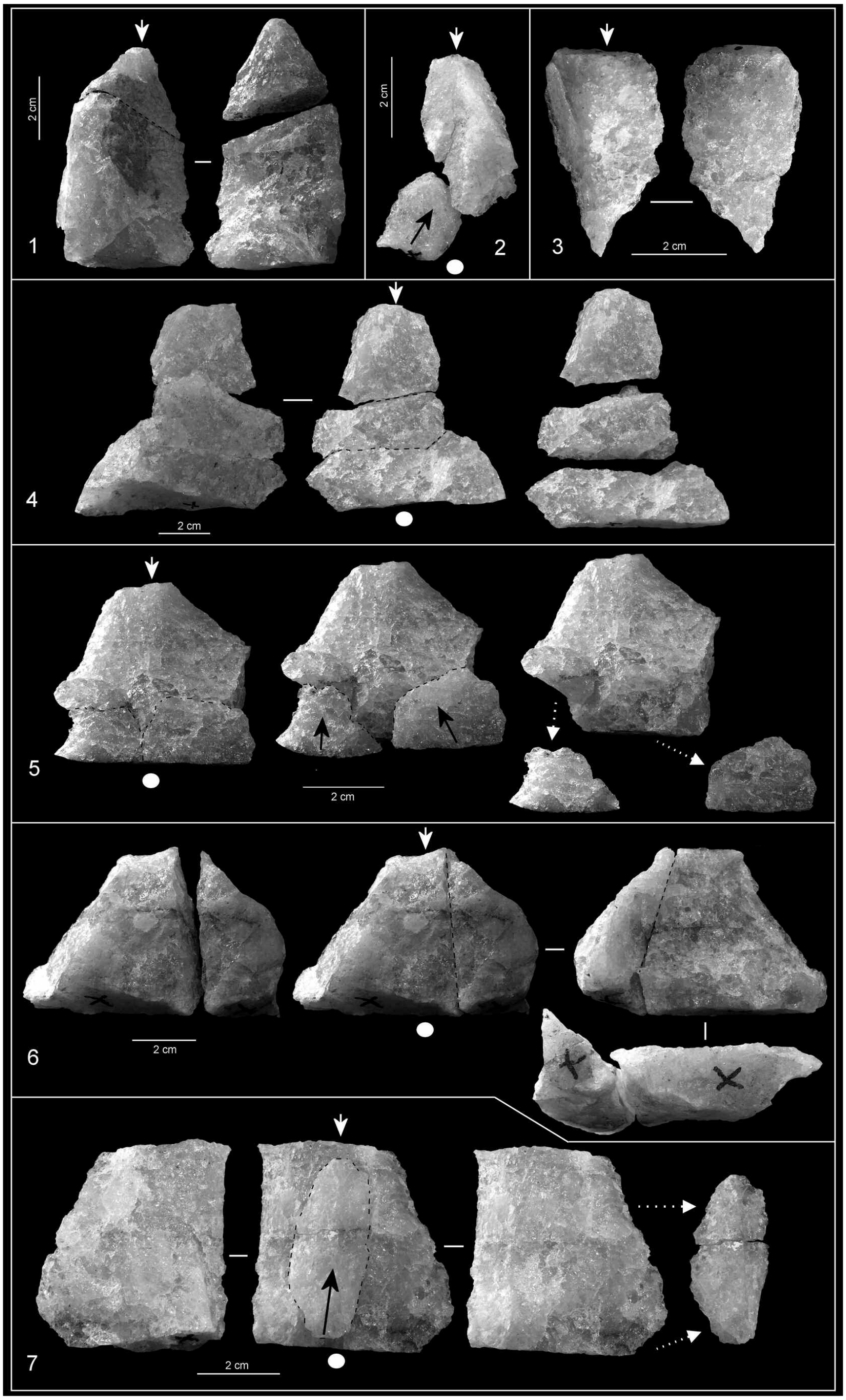


**Figure 5. Bipolar flakes (arrow shows platform and circle shows base): 1. Transversal fracture (10), dorsal and ventral views; 2. Basal fracture (7) produces a basal debris, crushing on dorsal area; 3. Non-axial bipolar flake with feather termination and freehand-like appearance; 4. Double transversal fracture (11), dorsal and ventral views; 5. Basal fracture (7) produces two basal debris, three ventral views; 6. Longitudinal Siret type fracture (1), dorsal, ventral and basal views; 7. Second basal flake (13) produced as the result of bipolar knapping, ventral and dorsal views.**

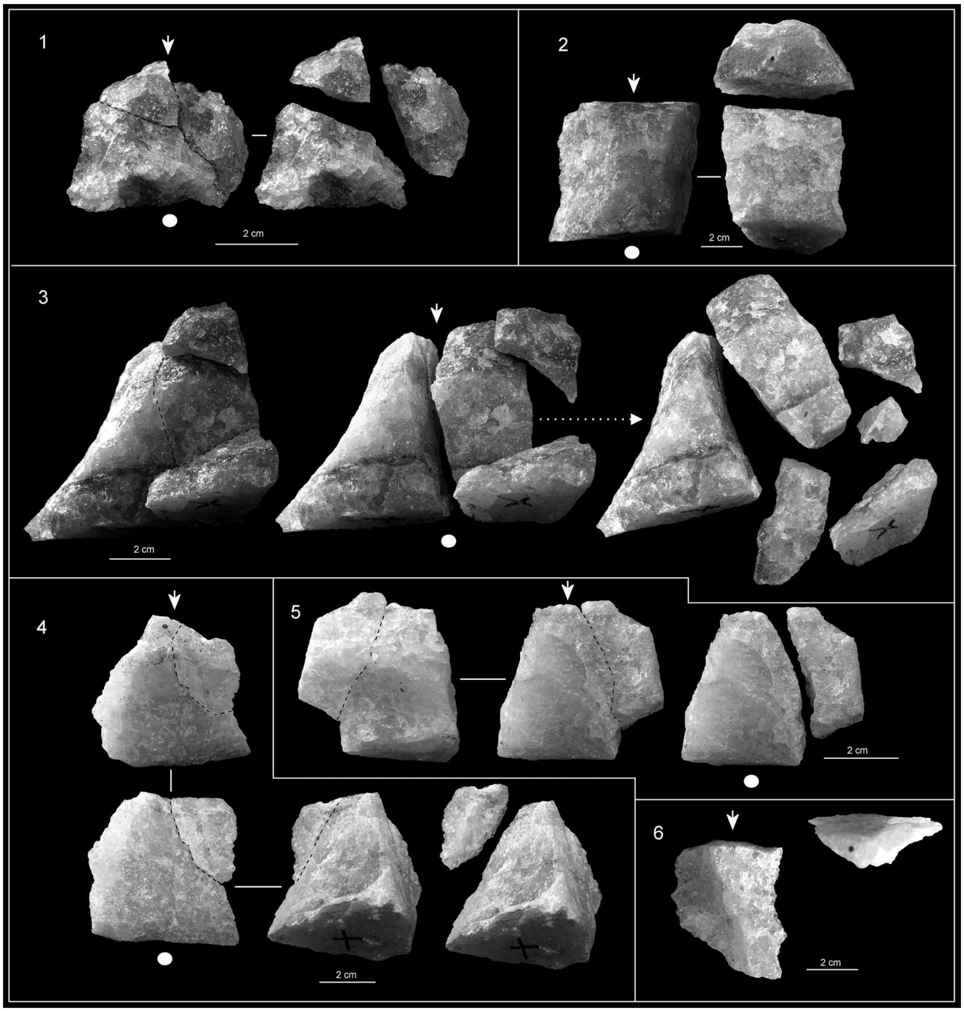


**Figure 6. Bipolar flakes: 1. Lateral and transversal fractures, dorsal view; 2. Typical features in bipolar flakes: wedging initiation and platform termination, dorsal, ventral and platform views; 3. Longitudinal, platform and base fractures, ventral views and blocky aspect of the fragments produced as a result of the same detachment; 4. Side longitudinal fracture, platform, ventral and dorsal views; 5. Side longitudinal fracture, dorsal and ventral views; 6. Non-axial bipolar flake with feather termination and freehand-like appearance.**

scores in Hertzian (positively) and Wedge/Hertzian (negatively) breakage patterns, whereas positive scores in Wedge/Hertzian, Bending/Hertzian, and cleavage plane breakage patterns characterized dimension 2.

In the resulting distribution of each variable factor, freehand and bipolar flakes could be differentiated by the attributes described as follows (Figure 7). Freehand flakes showed lower frequencies of distal stigma, longitudinal (Siret type), Siret and tranversal, transversal, and lateral and transversal fracture types, feather, step, and overshot terminations. Freehand flakes also showed less crushing on proximal areas, less crushing overall (when considering proximal, distal and dorsal altogether), more compression waves, bulbs of force, and an initiation that is predominantly Hetzian.

In contrast, the predominant initiation in bipolar knapping is wedging and wedging/bending and to a much lesser extent wedging/Hertzian and cleavage plane. Bipolar flakes also show crushing in two and three areas more frequently, as well as more stigmas on the distal and proxi-

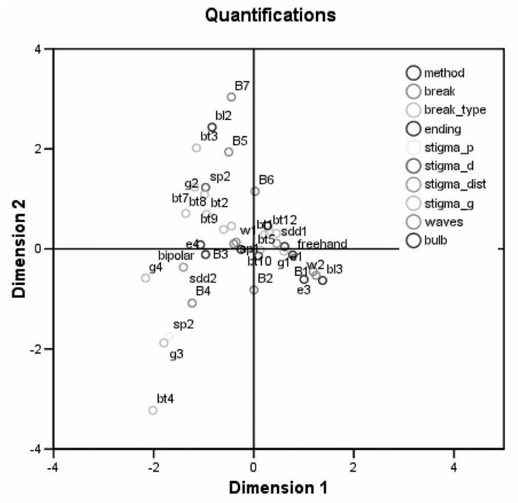


**Figure 7. Distribution of each class within ten categorical variables in a two-dimension model derived from a multiple correspondence analysis. Key: Initiation [B1, Hertzian; B2, flexion; B3, wedge; B4, wedge/flexion; B5, wedge/Hertzian; B6, flexion/Hertzian; B7, cleavage plain], flake snapping [bt1, longitudinal Siret fracture; bt2, Siret and platform; bt3, Siret and base; bt4, Siret, platform and base; bt5, Siret and transversal; bt6, platform; bt7, base; bt8, platform and base; bt9, side longitudinal; bt10, transversal; bt11, double transversal; bt12, lateral and transversal; bt13, basal flake], termination [e1, feather; e2, step; e3, hinge; e4, overshot, e5, axial], proximal crushing [sp1, absent; sp2, present], dorsal crushing [sd1, absent; sd2, present], distal crushing [sdd1, absent; sdd2, present], general crushing [g1, no stigma; g2, stigma in one surface; g3, stigma in two surfaces; g4, stigma in three surfaces], compression waves [w1, absent; w2, present], and bulb of force [bl1, absent; bl2, diffuse; bl3, present].**

mal areas. Their termination is predominantly axial or platform. This type of flake shows a much lower number of compression waves and bulbs of force. The most common snapping types are: Siret and base, base, platform and base, and side longitudinal. The application of these categorical variables would correctly classify 69 percent of flakes of the experimental sample.

### *Cutting Edge Potential Features: Different Cutting Edge Quality*

Table 5 shows, sorted by experiment, the total amount of cutting edge produced by experiment in each reduction method (mm), the total mass (g) of the supports produced, and the amount of cutting edge per mass (mm:g). After being bootstrapped, a two-sample t-test did not show statistical differences between methods ($p$ = .89) regarding mm:g ratio. When measuring the total amount of cutting edge per flake relative to flake size, after having log-transformed both variables, a robust correlation test (using a population percentage bend correlation) indicates that edge length is only moderately correlated with flake edge (.57), with a small fraction of the sample affecting this correlation ($R^2$ = .32). Figure 8 shows a regression analysis of these two variables, in which the standard minimum square regression line shows a more horizontal trajectory than the regression line derived from the use of a robust M-estimator, which minimizes the effect of the outliers. The presence of the outliers in the present case are important because of their number and their influence in determining that size alone does not explain the amount of edge generated. This opens the door to the possibility that the type of knapping technique could have a higher degree of influence in determining the total amount of edge, as shown when using the yuen robust comparative test. The amount of edge produced by freehand and bipolar knapping differ significantly ($p$ = .000), with freehand flakes exhibiting a higher amount of edge than bipolar flakes.

Bipolar technique produces a higher number of flakes with no usable edges (morpho-potential edge sharpness is absent, i.e., edge angle ≥70º). However, although differences in the frequencies of each number of edges exist ($p$ = .000), and these differences are related to the flake type factor (Snedecor s F > critical value), no statistically meaningful differences between freehand and bipolar techniques were identified ($p$ = .90), when considering the total number of edges simultaneously.

For the morpho-potential statistical analysis, we have taken into account two angle groups: semi-abrupt (55–75º) and acute (15–55º). A percentage distribution of edge angle reveals that semi-abrupt angles are more abundant in bipolar flakes (48 percent) than in freehand flakes (13 percent). Acute angles are slightly more abundant in freehand flakes (87 percent versus 66 percent). Despite the small sample size, a robust two-factor Welch test showed that differences in angle representation varied in the two sets of angle types ($p$ = .000) and that this variability was related to the interaction with the flake type factor (Snedecor s F >critical value), with significant differences between bipolar and freehand techniques ($p$ = .000).

Table 5. Cutting Edge Produced By Core, Total Flake Mass and Cutting Edge/Mass in Each Reduction Technique.

| | Total cutting edge (mm) | | Total support weight (gr) | | Cutting edge/weight | |
|---|---|---|---|---|---|---|
| Exp. No. | Bipolar | Freehand | Bipolar | Freehand | Bipolar | Freehand |
| 1 | 430 | 464 | 648 | 774 | .66 | .59 |
| 2 | 145 | 130 | 308 | 439 | .47 | .29 |
| 3 | 198 | 253 | 500 | 280 | .39 | .90 |
| 4 | 537 | 208 | 1325 | 124 | .40 | .67 |
| 5 | 342 | 286 | 1101 | 100 | .31 | 2.86 |
| 6 | 100 | 414 | 121 | 565 | .82 | .73 |
| 7 | 92 | 79 | 70 | 233 | 1.31 | .33 |
| 8 | 132 | 735 | 47 | 807 | 2.8 | .91 |
| 9 | 217 | 516 | 394 | 650 | .55 | .79 |
| 10 | - | 681 | - | 768 | - | .88 |

## Discussion

Archaeological research recently conducted at a number of Bed I and Bed II sites in Olduvai Gorge has shown that bipolar technique constituted a major strategy, commonly implemented by hominins in their exploitation of local Naibor Soit quartz (Diez-Martín, Sánchez, Dominguez-Rodrigo, Mabulla, and Barba 2009; Diez-Martín et al. 2010). The present work constructs an analogical framework aimed at understanding in greater depth the role played by the bipolar technique within the array of technological behaviors displayed by hominins in the Olduvai basin. This goal entailed two different but complementary parts. The first goal was to disentangle which are the most effective and statistically confident features that can guide lithic analysts when identifying signals of bipolar load application on flakes produced with the Naibor Soit type of quartz. Secondly, we aimed to gather more insights into the reasons that could have encouraged hominins to show two different technological solutions (bipolar and freehand) for their economic treatment of tabular quartz at Olduvai Gorge.

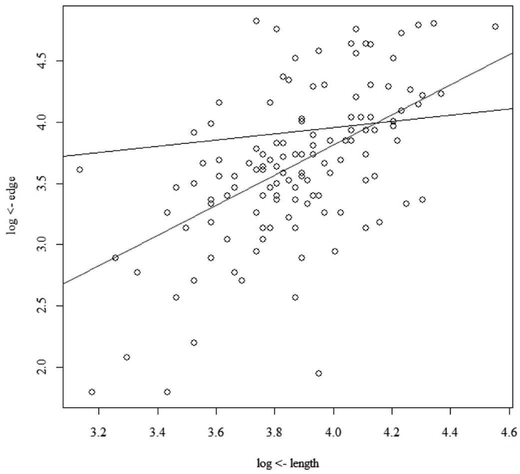


**Figure 8. A regression analysis of length and perimeter of edge (log-transformed) combining bipolar and freehand flakes. A minimum square estimator determines the standard regression line (black) and an optimal M-estimator regression line (red) shows the correlation if minimizing the impact of outliers. The widespread distribution of objects indicates a weak correlation.**

Macrocrystalline quartz constitutes a challenge for lithic analysts (Bisson 1990; Diez-Martín, Domínguez-Rodrigo, Sánchez, Mabulla, Tarriño, Barba, Prendergast, and Luque 2009; Kimura 2002:298). Most of the difficulties and uncertainties related to the anthropogenic interpretation of this mineral in archaeological contexts are due to its crystallographic and petrographic nature and its heterogeneous response to fracture. Particularly in those varieties with natural cleavages and crystalline flaws, breakage easily occurs in an unintentional manner, producing many unpredictable accidents and snaps during the knapping process and, thus, a high amount of shattered debris (Figures 5, 6). Other authors have already pointed out the high incidence of longitudinal Siret type fractures in quartz flakes (Mourre 1994:18). In agreement with Jones's report (1994:256), our work has confirmed the absolute importance of longitudinal splitting in flakes produced on Naibor Soit quartz and the high amount of mass loss during the process of quartz reduction (in bipolar knapping, a mean 41 percent of the original blank mass ends up being shatter, while this descends to 21 percent in freehand reduction). The rather anisotropic response of quartz to load propagation can mask conventional signatures of Hertzian fracture (Mourre 1994:24). In our experiment, while 31 percent of the handheld flakes show indisputable traits of Hertzian fracture (a combination of both clear bulbs of force and compression waves, 16 percent show signs of one of these two features, and 53 percent do not bear either of these features.

When quartz mechanical properties are combined with the poorly controlled bipolar knapping (Bertouille 1989:43–44; Shott 1989), difficulties in identification can be accentuated. Many of the nondiagnostic by-products of bipolar reduction (i.e. blocky debris, flake-like fragments, chunks, exhausted core fragments) can be of little help to confidently identify the presence of this reduction method at any given site (Figure 6.3). A meaningful context may only be proposed for these items if we can recognize the diagnostic component of bipolar knapping. Regarding Olduvai Gorge tabular quartz, this experiment has yielded a rather interesting outcome: presence or absence of crushing on any flake surface and termination constitute the most discriminating variables with statistical significance. Crushing is recurrently cited in literature on bipolar knapping (Bradbury and Carr 2004:75; Jeske 1992:472; Magne 1985:100), and our experiment has shown that it is a conspicuous trait in a high percentage of the bipolar positives produced, and that this feature is the most significant from a statistical perspective. On the other hand, and contrary to what has been suggested by other authors (see Shott 1989: 2), preservation of the basal platform is a major attribute in positives when tabular quartz is reduced axially (Figures 5.4, 5.6, 6.2, 6.4). Bipolar knapping may produce a low percentage of feather terminations but, as expected, they are mostly the consequence of oblique, non-axial load application (Figures 5.3, 6.6). In our experiment, we have observed that the knapper may intuitively select this strategy in order to reorganize core volumes or to prepare new knapping series, but due to the tabular and blocky nature of this raw material, axial reduction is the knapper's predominant choice. These experimental observations are in agreement with archaeological data. Both crushing and axial/platform terminations have been reported in our analysis of Bed I and Bed II Olduvai Gorge sites (Diez-Martín, Sánchez, Dominguez-Rodrigo, Mabulla, and Barba 2009: 281, 283) and, therefore, they are good indicators of bipolar knapping in contexts where, as it happens in many Olduvai Gorge sites, quartz reduction has produced a high number of nondiagnostic specimens.

The second outcome of our study is related to the functional meaning of bipolar reduction. While raw material constraints may be an explanation for the use of this knapping strategy in other ESA sites (Ludwig and Harris 1998), this is not the case at Olduvai Gorge. Here hominins had access to a great variety of rock types, with different textures and knapping qualities (Jones 1994; Kyara 1999). Hominins knew these properties and used these rocks in different, presumably complementary ways (Kimura 1999:809; Leakey 1971). The case of quartz, available during Bed I and Bed II times, is particularly interesting. Most authors acknowledge a rather expedient and locally based use of this raw material at most ESA sites (Blumenschine et al 2008; Potts 1988). Quartz nodules are engaged in both percussion activities and particularly flake production, although neither further curation nor retouching is observed in most flakes (de la Torre and Mora 2005; Kimura 2002:311). Although this rock type is characterized by a high degree of mass waste, knapping accidents, and unpredictable results, it seems that a strong balance between constraints and advantages must have encouraged hominins to keep focusing on the exploitation of this rock type over time (Leakey 1971, 1994). Among those advantages, immediate availability could have played an important role (Potts 1988). Although most studies tend to focus on Naibor Soit as the preferential source of quartz in the basin (Flébot-Augustins 1997; Hay 1976), it is possible that this material was also supplied by fluvial channels, as the rounded shape of a number of quartz items suggests (Diez-Martín, Sánchez, Dominguez-Rodrigo, Mabulla, and Barba 2009), or by another secondary source. However, cutting-edge strength (quartz scores 7 in Moh's scale) and durability seem to be one of the most plausible explanations for its preference by hominins (Jones 1994: 257; Tactikos 2005: 130). Despite the claims suggesting that blocky quartz would be better suited for bipolar reduction (Breuil 1954:11), our analysis of new lithic collections at FLK North (Bed I) and BK (Upper Bed II) have shown that hominins, when engaged in flake production strategies on Naibor Soit quartz, were implementing both freehand and bipolar techniques (Diez-Martín et al. 2009*, 2010). If hominins could overcome quartz constraints and successfully produce usable flakes through freehand knapping, why did they diversify their technological behavior by using an alternative strategy? The archaeological and ethnographic records are full of examples in which bipolar knapping is used as an alternative (rather than as a complement) to freehand knapping; these are cases in which handheld reduction is not possible due to raw material size or quality constrains (Breuil and Lantier 1951). At Olduvai, not only are both techniques recorded overlapping in the same spot but they are also subject to some sort of technical transfer (i.e., cores in which one or several bipolar reduction series have been produced also bear signs of new series of handheld percussion, Diez-Martín et al. 2010). The functionality of bipolar objects has been blurred by a myriad of possible explanations (see Shott 1999 for an in-depth discussion). Our study shows that neither statistically significant differences in the cutting edge per mass ratio nor in the number of edge segments per flake can be observed among flakes produced by each technique. However, confirming our archaeological observations (Diez-Martín, Sánchez, Dominguez-Rodrigo, Mabulla, and Barba 2009:284), this study shows that freehand knapping produces a higher amount of cutting edge length (a mean of 377 mm per core), while bipolar knapping produces a mean 35 percent less of usable cutting edges than freehand reduction (mean of 244 mm per core). Although we can ask why hominins implemented diversified strategies for quartz reduction if freehand knapping apparently was more successful in obtaining the desired cutting edges, we must bear in mind that the differences between each technique in terms of cutting edge production are not sharp. In a context in which quartz supplies seem to have been abundant and easily available for edge production (Potts 1988), both solutions might have been equally favored. Another possibility is that the selection of a particular knapping method was dictated by the shape of the original, unmodified core (e.g., presence/absence of suitable striking platforms in the natural quartz shapes). However, our analysis shows that the only possible advantage of bipolar reduction must be related to the quality of cutting edge. Certainly, we have observed that bipolar knapping produced semi-abrupt edges (55–75º). Edge angle could have been an important trait with functional meaning (as different edge angles could interact differently with potential tissues). Does this mean that bipolar reduction could have been favored in those cases in which a more abrupt edge was suitable for certain tasks? We are addressing this possibility though a number of experimental tests aimed at different tissue processing with both freehand and bipolar flakes. Further research on the anthropogenic treatment of quartz in the Olduvai lake basin should address a number of issues related to the freehand/bipolar dichotomy in order to expand our knowledge of this technological behavior in Oldowan and Acheulean contexts and to propose hypotheses for this pattern.

## Conclusions

The present study constitutes the first experimental replication aimed at discerning which are the most relevant technical and functional differences between freehand and bipolar reduction methods when they are applied to Naibor Soit quartz (a rock type widely used by hominins at Olduvai Gorge). Our experiment included the reduction of blocks quarried at the Naibor Soit slopes using both bipolar (in its two variants, axial and non-axial) and freehand techniques. The results of this study support the following conclusions:

—Naibor Soit quartz is a tabular, coarse-grained and heterogeneous rock type that shows a number of limitations for knapping: high incidence of accidental snapping (particularly longitudinal fractures along the striking axis), uncontrolled breakage patterns, and high incidence of nondiagnostic by-products (blocky debris, core fragments, shatter) that bear no traces of intentional knapping. Although longitudinal snaps are common to both techniques, bipolar load application tends to produce a more diversified variety of fractures. Many of these flake fragments plus the non-diagnostic materials cannot be studied from a conventional point of view.

—Freehand knapping produced flakes larger and wider than those produced through bipolar reduction. Although freehand reduction produced a considerable percentage of wedging initiation patterns, Hertzian initiation predominates. Unquestionable traits of Hertzian initiation (compression waves and/or bulbs of force) are observed in 47 percent of the freehand detached sample, while termination is particularly represented by the feather type, followed by step and hinge.

—Bipolar knapping produced shorter and thicker positives, particularly in their distal ends. Bipolar load application is characterized by wedging initiation, producing no clear Hertzian attributes (traces of compression rings have not been recorded and, when identified, bulbs are diffuse and disputable). Although feather terminations have been recorded, particularly in those cases when an oblique strike was required, bipolar flakes terminate in a rather characteristic axial way. That is, there is a tendency to preserve remaining areas of both platform and base on detached products. Presence of crushing on platform, base or dorsal areas (the latter as a consequence of core rotation) is quite common.

—Statistical analysis shows that, when differentiating bipolar and freehand products, the most representative features with statistical meaning are presence/absence of crushing areas and termination. A combination of these and other traits may be a confident indicator of the implementation of both techniques.

—Both freehand and bipolar flakes cannot be differentiated according to cutting edge per mass ratio nor the number of active cutting edges produced per flake. However, handheld flakes produced a larger amount of cutting edge (mm) per support and per core exploited. Regarding cutting edge, most representative differences between each technique are related to the quality of cutting edge. Bipolar flakes are better characterized by semi-abrupt (55–75º) interaction angles.

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