This is a post-peer-review, pre-copyedit version of an article published in *Journal of Archeological Method and Theory*. The final authenticated version is available online at: http://dx.doi.org/10.1007/s10816-019-09425-x.

Material principles and economic relations underlying Neolithic axe circulation in Western Europe

To Vin Davis. In Memoriam

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Abstract

Neolithic societies produced and circulated axeheads made out of different rock types over substantial distances. These tools were indispensable to their economic reproduction, but they also demanded considerable manufacturing efforts. The material properties of the raw materials chosen to produce axeheads had a direct effect on the grinding and polishing processes, as well as on the use-life of these tools. However, surprisingly little is known about the criteria followed by these societies when it came to choosing adequate raw materials, or why certain rocks were exploited in greater volumes and circulated over larger distances than others. In order to determine the material parameters ruling axe production, circulation, and use, a range of different rock types were submitted to mechanical tests. For the first time, comparative values relating to the resistance to friction and to breakage are presented for some of the most important rock types used for the manufacture of axeheads by the Neolithic communities of Western Europe. These mechanical parameters allow us to approach hypothetical production and use values, which are then correlated with the distances travelled and the volumes of rock in circulation. This combination of petrographic, mechanical, and paleo-economic information leads to new understandings of the principles ruling Neolithic supply and distribution networks and the economic rationale behind them. It reveals how deeply the symbolic and social meanings of these outstanding Neolithic artefacts were rooted in their production and the use values.

1. Introduction

It is commonly accepted that stone axes, adzes, chisels, wedges, and similar edge-ground artefacts were essential to the technological revolution of the Neolithic, defined as the age of the "polished stones". In most regions, these tools would have been indispensable to clear whatever vegetation grew on the land required for cultivation. Apart from felling and uprooting of trees and bushes, axes and adzes were also used for woodworking in general, for the preparation of fibres, crushing of vegetables, quartering of animals, etc. (Dickson 1981; Godelier and Garanger 1973; McCarthy 1976; Mills 1993; Pétrequin and Pétrequin 1993; Steensberg 1980). Their use as combat weapons since the early Neolithic should not be underestimated, at least in certain areas and periods (Meller 2015; Schefzik 2015; Wahl and Trautmann 2012). However, apart from these profane uses, polished axeheads have also been interpreted as symbolic in social interactions and in ritual practices, as is suggested by their presence in graves and hoards, or by their depiction on rocks and stele. Ethnographic observations, which are particularly abundant for New Guinea, also show that the symbolic value of exceptionally curated axes can prevail over their value as a tool, being used to establish or perpetuate social relationships (Hampton 1999; Pétrequin and Pétrequin 1993).

The marked geological, productive and functional constraints of the life-cycle of stone axeheads has led archaeology from early on to perceive these artefacts and their raw material as a primary source of information concerning Neolithic economies (Clark 1965). While a substantial amount of information on quarries, production sites, petrographic characterisation and the spatial distribution of axeheads has been generated during the last years, the social practices behind their circulation are still a matter of debate. A simple, hand-to-hand transfer between communities or individuals does not offer a convincing explanation of the observed spatial and contextual patterns (see however, Zimmermann 1995). Certain rocks, regions, sites, such as causewayed enclosures, and collective or individual burials seem to have been more critical than others to the circulation and deposition of stone axes and other goods, at least during certain phases of the approximately three millennia over which the Neolithic period lasted in Western Europe. These spatial concentrations and material associations have led to the suggestion that certain communities and certain individuals, probably male, in view of some particularly rich burial assemblages, reached powerful positions through their control over the circulation of specific objects, which have been defined as gifts, prestige goods, fetishes, ceremonial goods, highly valued objects, means of social compensation, etc. (e.g., Bradley and Edmonds 1993, 157–199; Demoule 2018; Pétrequin et al. 2002; Pétrequin et al. 2015b; Risch 2011). Although nothing suggests that Neolithic economy was ruled by a "law of supply and demand" aiming at a maximisation of profits, as argued in the 1980s (e. g., Renfrew 1984; Torrence 1986, 38), at least in some situations, the spatial concentrations and material associations would seem to require some form of equivalent exchange value emerging between goods, such as stone axes, salt, variscite beads and high-quality flint (Risch and Martínez 2008; Weller 2015; Fíguls and Weller 2017). Recently, it has also been suggested that the Early Neolithic stone disc-rings could even represent a first form of *primitive currency* (Pétrequin et al. 2015a, 42; 2017a, 729 – 751). Other authors have proposed that the scale and the intensity of prehistoric exchange networks might simply have depended on population density (Kerig et al. 2015).

This diversity of economic and anthropological terms used to define elaborate artefacts, which circulated over long distances, reveals the theoretical and methodological shortcomings of archaeology when it comes to understanding the material as well as the social quality of an artefact and the modes of production and distribution bound to it. Central to this discussion is our approach to the social value of artefacts. A *marginalist* or formalist position will drive this discussion to the realm of the subjective desires and necessities of individuals interacting with others (Menger 1985; Simmel 1900). From a methodological perspective, if artefacts, such as Neolithic axeheads, are conceived in terms of their scarcity, rareness, desirability, accessibility, demand, or competition, the object is freed from its contingent materiality. This remittance to the subjective allows us to project the values dominant in modern society into the past, thereby universalising the present value system, which supposedly warrants free choice but in fact generates economic inequality at an unpreceded scale in history. Instead, any *materialist* approach, as prevalent in the economic thinking of political economy and ecological economy, will insist on the interplay between the natural and the social forces responsible for the manufacture, circulation and consumption of goods, conceived as natural resources as well as products. In particular, the heuristic importance of the notion of social value in Marx (Marx 1962, 49–98) emerges from the interplay between production and consumption, between objective material conditions and personal desires, between the power to impose certain economic constrains and the attempts to overcome them. The distinction between an *exchange value*, determined by the production costs and most of all the labour force, and a *use value*, expressing the subjective as well as objective perception of the qualitative properties of all goods, acknowledges the dynamic nature of value systems and hence their historical specificity (Lull 2007, 304ff.). However, in archaeology, Ricardo's and Marx' notion of *exchange value* is problematic, as it only applies to a market economy, where all products have become commodities. Instead, the understanding that all objects created and maintained by a community have a value resulting out of a production process that puts into action specific forces and materials can be conceived as their *production value* (Risch 2002, 28–31). It follows that any approach to the notion of value in archaeology needs to rest on an accurate definition of the material and productive dimensions of production, as well as consumption.

This dialectical approach to the concept of value has led to the articulation of a set of archaeological criteria to address the *production value* and the *use value* of stone axes (Risch 2011). Moreover, as prehistoric artefacts enter inter-community circulation networks, it can be expected that some form of *exchange value* emerged, which was not independent, but derived from the material and aesthetic qualities of the artefacts, as expressed in the production as well as the use value. One factor with a manifest impact on both its productive as well as its implemental dimension is the *material quality* of the rocks employed. The petrographic and, hence, the mechanical properties directly affect the work force and technical means expended in the manufacture of the axeheads, as well as their use and use-life. These dimensions can be expected to be highly relevant to the circulation of axes. Finally, the material properties of the rocks also need to be understood in order to clarify which part of the use value exceeds the technical utility and needs to be explained in symbolic or other non-material terms.

Surprisingly few studies have tried to establish the mechanical parameters of prehistoric stone tool production, circulation and use (Bradley et al. 1992; Delgado-Raack 2008; Delgado-Raack et al. 2009; Lewis et al. 2009, 2011). The aim of the present study is to apply this approach to some of the main raw materials used in stone axe manufacture in Neolithic Western Europe. Resistance to breakage, as well as to friction of these rocks, has been established through mechanical tests. This information, in combination with the main petrographic and paleo-economic variables, will allow us to understand which material properties were relevant to the prehistoric communities and how they might have affected manufacture times, circulation networks and the profane or symbolic use of axes. In sum, the aim of this study is to understand the social value of the circulating products by approaching the actions which create these values.

2. Axes as means of production

The mechanical properties of rocks have a direct effect on stone axe production, distribution and consumption. Regarding the manufacture of axeheads, few other prehistoric tools demanded more effort to produce. The production sequence starts with acquiring suitable rocks by exploiting a primary outcrop or by collecting appropriate cobbles in secondary deposits, such as moraines, river terraces or beaches (Risch and Martínez 2008). The blocks or cobbles must then be shaped through knapping or sawing into an adequate blank (Aimar et al. 1996, 279; Buret 1985; Pétrequin et al. 201b2; 2017c). These initial tasks are usually carried out in the rock-supplying areas themselves, while the next stages take place in settlements (Davis and Edmonds 2011). Roughouts can further be worked by pecking with hammerstones in order to reduce the crests of the knapping negatives. However, the most time-consuming task was grinding the surfaces to produce the finished form, at least of the bevel. The tool's resistance, once it was being used, is increased when surface irregularities are removed through abrasive processes (Harding 1983, 37–42). According to archaeological and ethnographic observations, grinding can be done on stone slabs, rocks and abraders, or on rough tree leaves, using sand abrasives and lubricants such as water (Harding 1983; Panyella and Sabater 1959; Pétrequin et al. 2011, 132, 149; Risch et al. 2011). Stone axe grinding times have been estimated to last between ten and several hundred hours, depending on three main factors: size of the blank, extension of ground surface and lithological features of the raw material (Harding 1983; Madsen 1984; Pétrequin and Pétrequin 1993). While the size of the blank and the degree to which surface grinding is extended beyond the cutting edge remains largely a social or individual decision within basic technical parameters, the petrology and hardness of the selected rocks is directly related to their resistance to friction. Some experimental tests have quantified the efforts required to grind different rocks in terms of grams reduced from the blanks per time unit. In the case of Alpine jadeitite and eclogite, only a mean of 1.8 g and a maximum of 3 g can be ground away per hour on sandstone platforms (Pétrequin et al. 2012a, 284). The massively exploited south Indian dolerite from Sanarachema (Deccan, India) is ground on granite slabs at a rate of 2.6-3.2 g/h (Risch et al. 2011). Instead, so called quartz-pelite from the quarry of Plancher-les-Mines, in the Vosges, seems to be much less resistant and can be reduced on sandstone slabs at a rate of 5-13 g/h (Pétrequin and Jeunesse

1995). Flint axes have provided similar coefficients, between 7.5-12 g/h (Pelegrin 2012, 99). This implies that, under equal technical conditions, some rocks would require a significantly more arduous manufacturing process than others.

A final, optional stage in axehead production is polishing. By reducing scratches, striations and rugosity a shiny and lustrous appearance is conferred to the surface. This process can either be achieved with soft materials, such as leaves or leather (Pétrequin and Pétrequin 1993), or by rubbing with the same material as the axeheads (Pétrequin et al. 2012a, 258-291).

Access to adequate raw materials had to be achieved either through direct access to outcrops and secondary deposits or through distribution networks. The specific mechanical requirements of the different types of axes and adzes considerably restricts the range of suitable rocks and, hence, the regions where they can be found. However, in western and southern Europe, with its marked geological diversity, Neolithic communities managed to find a variety of more or less tenacious igneous, metamorphic and sedimentary rocks, most of which were only worked and circulated at a local or regional scale (e.g., Clop 2004; Clough and Cummins 1988; Giligny and Bostyn 2016; Klimscha 2007; Le Roux 1999; Orozco Köhler 2000; Ricq-de Bouard 1996; Risch and Martínez 2008). Increasing information derived from the analysis of the distribution patterns of stone axes, but also of other raw materials such as obsidian suggests that, on average, Neolithic distribution networks were able to obtain a supply of the required raw materials or tools up to c. 200 km as the crow flies around the areas of extraction or the production workshops (Costa 2007; Darvill 1989; Pétrequin et al. 2017b; 2017c; Risch 2011). Above c. 250 km from their sources, most rock types rarely represent more than 20% of the locally used stone axes. Axeheads circulating beyond this distance could not be seen as a primarily economic resource to the Neolithic communities, but rather represented a socially or politically-valued resource. In regions lacking adequate raw materials and located beyond 200-300 km from raw material sources, a notable diversification of the rocks and provenances is usually detected, as a further expression of the limits of Neolithic bulk circulation (e.g., Risch 2011; Thirault 2005). Only Alpine rocks, mainly jadeitite/omphacitite and eclogite, and epidotized tuff from the Lake District in north-west England (British Group VI) circulated, during the apogee of their quarrying over larger distances and in greater volumes than any other European rock. Communities living up to 300-400 km from these sources could still obtain a substantial part of their tools from them, especially in regions where no alternative resources were available (Table 1).

In order to understand fully the dimension of Neolithic axe production we must also take into account the use-life of these tools. This is a complex issue, as direct values are difficult to obtain. Ethnographic information as well as archaeological approaches coincide in pointing out considerable variations in the use-life of woodworking tools, ranging between 1.5 and 17 years (Le Roux 1999, 207; Pétrequin and Pétrequin 1993; Ramminger 2007, 264; White and Modjeska 1978). Breakage depends on factors such as the local vegetation, the amount of land to be cleared, the size of the tools, and the duration of tasks carried out with them. Based on the extensively excavated Neolithic lake dwellings, it has been possible to estimate that each dwelling required about 4-8 axeheads during one generation of 25 years, if tools were provided form the outside, and between 6-14, if the community participated in their production (Schyle 2010, 96–99). However, under similar environmental and technical conditions, the quantity of axeheads required depends on the resistance to breakage and, hence, on the petrographic and mechanical properties of the rocks used for axehead manufacture.

3. Materials and methods

In order to determine the petrological differences between axeheads of different rock types and their mechanical properties, rock samples were collected, often in collaboration with colleagues working in the area (see acknowledgements), in the main known axe production centres in northern Italy (Mont Viso), France (Plancher-les-Mines), England (Cumbria, Cornwall), Ireland (Tievebulliagh), Shetland Islands, and the Iberian Peninsula (Arronches in Central Portugal, Alanchete ravine in Almería and Segre river, in Catalonia). These raw materials were exploited and circulated in western and southern Europe, with varying intensity, between the 6th and the 3rd millennium BCE. Rock samples were obtained either from Neolithic quarry sites or from the secondary fluvial deposits close to known axe manufacturing sites (Table 1).

As an independent geological reference is required, against which to compare and evaluate the petrographic and mechanical specificities of axe lithologies, a second series of rocks that had been used as mining tools during the Copper and Bronze Age was collected in the mining areas of Ulldemolins (Tarragona, Spain) and Cerro Minado, Huercal-Overa (Almería, Spain) (Fig. 1).

Rock type	Sample code	Provenance	Tools	Main and secondary supply areas (r)	Mean maximum circulation	Period of maximum exploitation

				50% - km	20% - km	- km	- cal BCE
Amphibolite	ANF1	Arronches, Alentejo, Ptr	Mainly axes	150(1)	250?	300?	3600-2400
Amphibolite	ANF2	Arronches, Alentejo, Ptr	Mainly axes	150(1)	250?	300?	3600-2400
Metagabbro	GAB1	Alanchete, Almería, Esp	Axes and hammerstones	150(2)	250(2)	375(2)	3600-2400
Metagabbro	GAB2	Alanchete, Almería, Esp	Axes and hammerstones	150(2)	250(2)	375(2)	3600-2400
Metagabbro	MBS	Huercal-Overa, Almería, Esp	Mining hammers and picks	local	local	local	2800-2200
Hornfels	HOR	Segre river, Alos, Lleida, Cat	Mainly axes	150(2)	200(2)	330(2)	3750-2850
Knotted schist	KNS	Ulldemolins, Prades mountains, Tarragona, Cat	Mining hammers and picks	local	local	local	2000-1500
Grano-diorite	GRA1	Ulldemolins, Prades mountains, Tarragona, Cat	Mining hammers and picks	local	local	local	2000-1500
Quartz-diorite	GRA2	Ulldemolins, Prades mountains, Tarragona, Cat	Mining hammers and picks	local	local	local	2000-1500
Omphacitite	JAD1	Paesana, Mont Viso, Piemonte, Ita	Mainly axes	200?(3)	300?(3)	1450(4)	4800-3700
Jadeitic omphacitite	JAD2	Porco-Oncino superior, Mont Viso, Piemonte, Ita	Mainly axes	200?(3)	300?(3)	1450(4)	4800-3700
Eclogite	ECL1	Paesana, Mont Viso, Piemonte, Ita	Mainly axes	300(3)	450(3)	1300(4)	4800-3700
Jadeitic omphacitite	JAD3	Porco-Oncino inferior, Mont Viso, Piemonte, Ita	Mainly axes	200?(3)	300?(3)	1450(4)	4800-3700
Omphacitite	JAD4	Paesana, Mont Viso, Piemonte, Ita	Mainly axes	200?(3)	300?(3)	1450(4)	4800-3700
Quartz-Pelite/ Metapsammite	MPS	Plancher-les-Mines, Vosges, Fra	Axes	150(5)	200(5)	270(5)	4100-3700
Epi-diorite	Group I	Mount's Bay area, Cornwall, Eng	Axes and perforated implements	180(6)	310(7)	570(6)	3300-2500
Epidotised tuff	Group VI	Great Langdale, Lake District, Eng	Axes	270(6)	400(7)	490(8)	3800-3300
Porcellanite	Group IX	Tievebulliagh, Co. Atrim, N Ire	Mainly axes	100?(9)	200?(10)	490(9)	3750-2500
Riebeckite	Group XXII	Shetland Islands, Sco	Axes and knives	Local(8)	local(8)	460(8)	3500-2800

Table 1. Rock types submitted to mechanical tests and petrographic analyses, and their economic relevance according to the *main* and *secondary supply areas*, in which a rock type represents, respectively, around 50% or 20% of all raw materials, and the *mean maximum circulation* distance, as the crow flies. For further information and references on the lithologies, see *supplementary information*. Distances have been calculated based on the following sources:(1) (Lillios 1997); (2) (Risch 2011); (3) (D'Amico and Starnini 2012; D'Amico 2011; Giligny and Bostyn 2016; Pétrequin et al. 2017c; Ricq-de Bouard 1996); (4) (Pétrequin et al. 2017b, Fig. 34); (5) Pétrequin et al. 2012b;

(6) (Clough and Cummins 1988; Pitts 1996); (7) (Clough and Cummins 1988; Dempsey 2013; Pitts 1996); (8) (Clough and Cummins 1988); (9) (Clough and Cummins 1988; Sheridan et al. 1992); (10)(Dempsey 2013; Driscoll 2013).

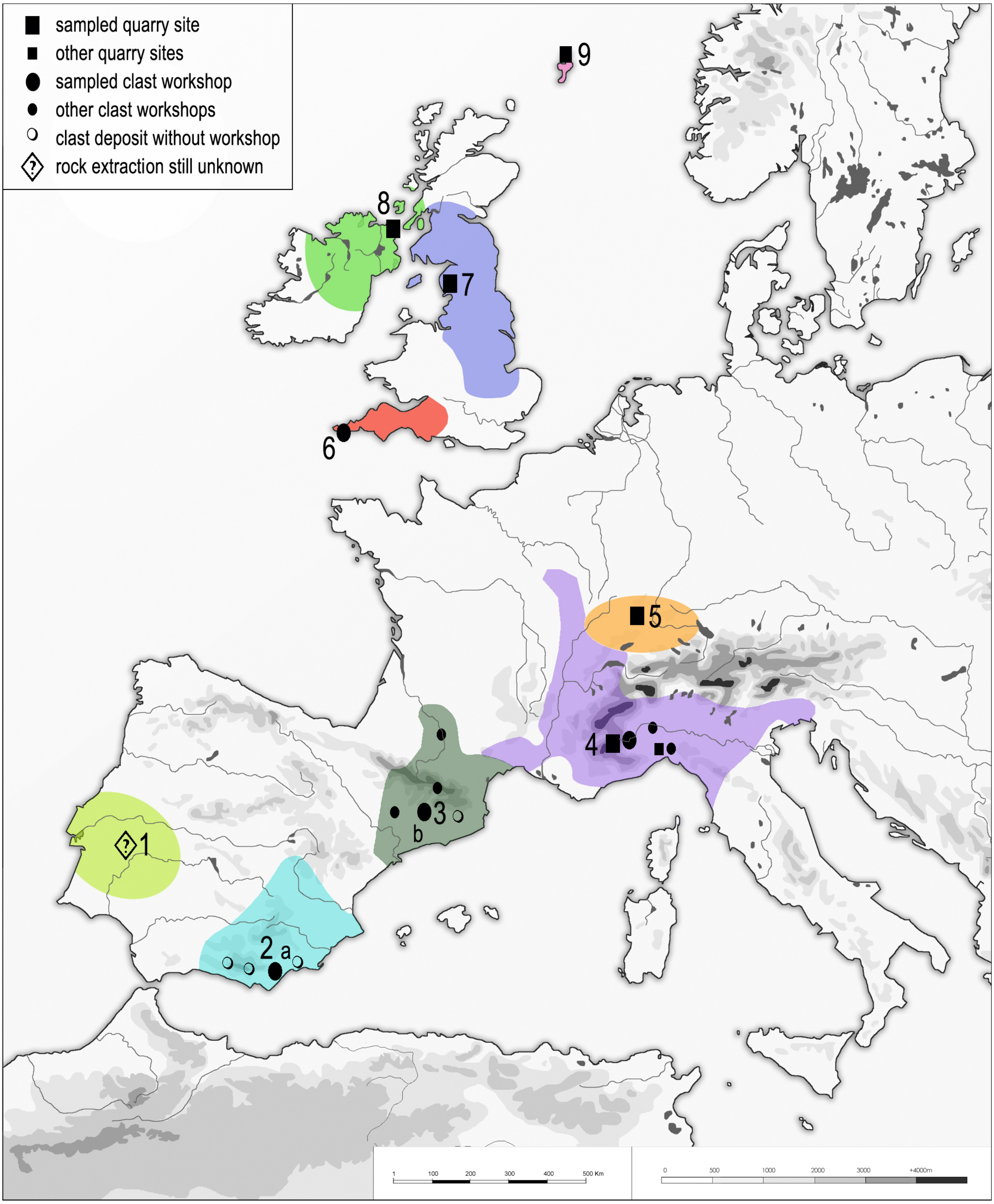

Fig. 1. Geological and geomorphological provenance and supply areas of the rock types analysed in this study. Sampling points of rocks used for axes: 1. Arronches, Alentejo; 2. Alanchete ravine, Almería; 3. Segre river, Alòs de Balaguer, Lleida; 4. Mont Viso, Piemonte; 5. Plancher-les-Mines, Vosges ; 6. Mount's Bay area, Cornwall; 7. Great Langdale, Lake District; 8.

Tievebulliagh, Co. Atrim; 9. Shetland Islands. Sampling points of rocks used for mining picks: a. Huercal-Overa, Almería; b. Ulldemolins, Prades mountains, Tarragona.

The petrographic descriptions of all sampled blocks and fluvial clasts have been obtained on the basis of petrological thin sectioning (see *supplementary information*). Particular attention has been paid to the main compositional, granulometric, and textural features, given their effect on the mechanical behaviour of rocks (Delgado-Raack 2008, 93–99; Delgado-Raack et al. 2009). In view of their petrographical complexity, the Alpine rocks have also been submitted to backscattered electron imaging and energy dispersed x-ray spectroscopy (see *supplementary information*)[1].

Two aspects of rock behaviour have been tested, allowing us to approach the mechanical reaction of rocks from the point of view of the manufacturing of the axeheads, as well as of their use. *Resistance to friction* was measured as a material parameter determining the grinding processes of edge-ground tools. The rock samples, each measuring 70x70 mm and 30 mm in thickness, are placed on the Böhme track (Matest C129), with a steel plate spinning at 28 revolutions per minute under the sample. The test was carried out according to the standards established in UNE-EN 13892-3:2006. Thereby, a load of 20 kg is put on the sample, while 31.25 g of corundum is added in order to increase friction (Fig. 2). After four spinning cycles, each of them composed of 28 rounds, the *volume loss* of the rock sample is measured in *cm*^{3}, based on the hydrostatic density of each rock type. The final value is the difference between the initial and the final sample volume, after four spinning cycles.

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[1] This study complements the spectroradiometric analyses undertaken by Errera et al. (2012: 440-533).

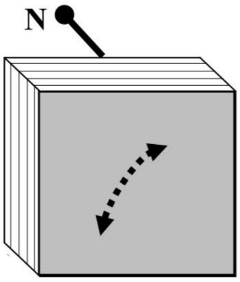
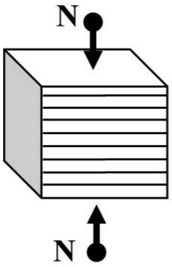
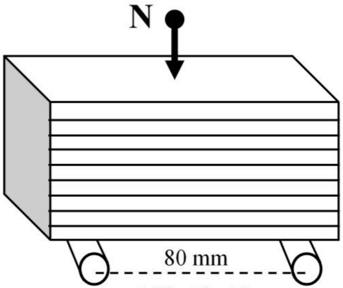
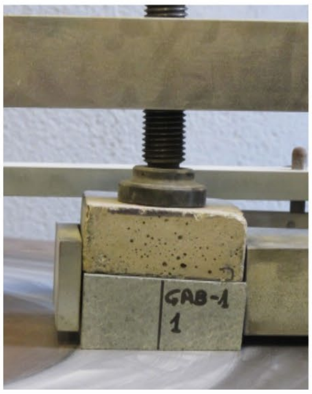
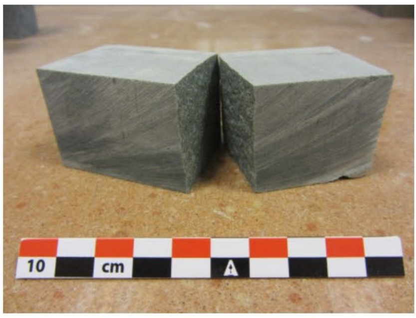
Type of test	**Abrasion**	**Compression**	**Flexion**
Emulated task	Manufacture (grinding)	Use	Use
Measured variable	Volume loss (g/cm^3)	Breakage load (kg/cm^2)	Breakage load (kg/cm^2)
Machines	 Böhme track	 Press	 Press
Wear mechanism and size of samples	 70x70x30 mm	 40x40x40 mm	 100x40x40 mm
Result			

Fig. 2. Test machines and samples. Sample drawings illustrate the fabric in the case of rocks with mineral orientation.

The second parameter, *resistance to breakage*, has been established in terms of compressive and flexural strength, which simulate two possible mechanisms that act on the artefacts when they cut into contact materials, mainly wood. The *compressive strength* of a material is characterized by the stress at which a solid body fails under compressive load (according to UNE-EN 1926:2007). In this case, the artefact is withstanding two opposite pressures, one acting from the butt to the edge (human and shaft strength) and the other acting in the opposite way (resistance of the contact body). The determination of compressive strength was tested in a uniaxial hydraulic press (Matest C006) equipped with top and bottom platforms, four columns and lead screws, where the top platform is pressed against the rock sample placed on the bottom plate. The machine constantly adds 160 kg/s to a sample measuring 70x70x70 mm until it fails (Fig. 2). Instead, the *flexural strength* of a material represents the highest stress experienced when it yields, using a three-point flexural test technique (according to UNE-EN 12372:2007). This kind of strength is expected to act on the artefact in a way a lever does, when it withstands back and forth movements once it has cut into the contact material. This technique was performed in a uniaxial flexure testing electro-mechanical press (Incotecnic MUTC200), made up of a 600x1000 mm table, two lower cylinders and one upper cylinder. The two lower cylinders are spaced at 80 mm, over which the 100x40x40 mm rock sample is placed. The third cylinder is put over the rock sample exactly at the same horizontal distance from both lower cylinders. The pressing device is capable to concentrate a load of several thousand kg in intervals ranging from 0.1 kg/s to 50 kg/s. In our case, a load of 0.15 kg/s was chosen until the sample broke, taking into account that rocks are hardly elastic materials. In both tests the measured variable is the *load/area*, that is to say, *kg/cm*^{2} at the point of breakage. It is important to stress that these tests are not supposed to reproduce actual work processes, as they took place in prehistory, but to provide a systematic and objective value of the physical reaction of rocks under controlled experimental conditions. Only in this way is it possible to achieve comparable values.

All tests were carried out at the inspection and certification company Applus, Barcelona. Rocks were previously cut in morphometrically standardized samples[2] (Fig. 2). Unfortunately, not enough material was available for all the rock types to carry out all three tests.

The economic importance of axeheds made of different rocks has been measured through three quantitative parameters. The *mean maximum circulation* refers to the mean distance, in different geographic directions, of the furthest findspots from the probable rock source, as the crow flies (Table 1). Another possibility to determine the economic push of a certain raw material is to consider the varying proportion of rock types identified in each region or settlement, as the distance from the proposed sources increases (Pitts 1996; Risch 2011). Although the number of petrographic studies of axeheads is still limited, the available published

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[2] Most of the rock samples were cut in the Department of Geology of the Autonomous University of Barcelona with the aid of a mechanical saw (Wendt Bart DV 27; Speed: 1480, 1950, 2400, 2900; Steel body: 400 mm diameter, 2.2 mm thickness, 3 kilowatts power, consumption of 1 litre/minute). The segment of the disc was made of agglomerate and resins provided with synthetic diamond. However, this saw was not able to cut all samples, and some had to be prepared with a special, 0.5 mm thick saw. This fact is worth noting, as it already illustrates the substantial mechanically differences between rocks.

information has been used to establish *main* and a *secondary supply area*s in terms of the distance from source, where a given lithology still represents, respectively, over 50%, or over 20% of all petrographically determined axeheads. The major caveat of this quantitative approach is the reliability of the geo-archaeological identification of the rock sources. Glacial, fluvial and marine transport has moved notable quantities of rocks away from their primary outcrops. Hence, in some areas at least secondary deposits probably provided the majority of raw materials used for workaday axeheads[3]. Primary outcrops were however the likely source for the manufacture of long blades (L>14 cm; Pétrequin et al. 2008: 309-334; Pétrequin et al. 2012d: 46-183). In order to establish the distances of the *main* and *secondary supply area*s (Table 1), we have located the source of a rock type at the primary outcrop, when archaeological evidence for quarrying exists, or at the most probable secondary deposit, where the working of clasts has been confirmed (for references, see Table 1).

4. Results

The petrographic analyses confirm that a considerable variety of rock was transformed into axeheads by the prehistoric communities of Western Europe (c. 5600-2200 cal BCE). All these rocks have in common a fine-grained matrix, though its mineral composition is highly variable. Na-rich clinopyroxene (jadeite and omphacite), different amphiboles, plagioclase (intensely albitised in many cases), epidote-clinozoisite, and quartz are the main minerals, which appear in different proportions and different rocks (Table 2 and *supplementary information*). Minor and accessory minerals are equally variable, but their effect on the mechanical properties of the rocks will be limited. Much more determining is the absence of porosity, the isotropic micro-texture of most rocks, and the small grain size of the dominant minerals (<100-1000 μ). Equigranularity is clearly avoided, and well-welded components of slightly different size seem to have a positive effect on the resistance to breakage of the rocks. Particularly important is retrogression or post-magmatic alteration of the rock selected for axeheads. Most of the samples show the development of secondary minerals, implying that these rocks underwent important mineral recrystallization processes overprinting their original igneous or metamorphic mineralogy. This secondary recrystallization increases the interpenetration of acicular or laminar crystals and can be compared to the effect of tempering on metals (Pitts 1996, 318; Risch and Martínez 2008, 52). This observation should be tested in the future by

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[3] Concerning the discussion on the importance of primary and secondary sources, see D'Amico (D'Amico 2011) for the West Alpine rocks, Briggs (Briggs 2011) for the British rock groups, and Risch and Martínez (Risch and Martínez 2008) for hornfels procurement in Northeast Iberia.

submitting non-retrograded rocks as opposed to those retrograded to mechanical analysis. For example, one should contrast the mechanical behaviour of non-retrograded gabbros composed of igneous-derived pyroxene plus plagioclase with an equivalent rock of the same formation and chemical composition, which had undergone a post-magmatic recrystallization with the development of secondary amphibole interweaved within the original pyroxene and plagioclase. How recrystallization was recognised by prehistoric stone workers remains unknown, but it must definitely be acknowledged as a notorious technical achievement of Neolithic communities, which has been also observed among present day stone axe manufacturers of Irian Jaya (Pétrequin and Pétrequin 1993, 226).

In comparison to axes, petrographic descriptions suggest that mining tools were made of more coarse-grained rocks, even where – in contemporary petrographic terms – the same lithology was used for both artefact categories (Table 2 and *supplementary information*). In general, coarse-grained rocks provide resistant percussion tools (although they more unpredictable in their ways of breakage) with rough surfaces, while more fine-grained rocks usually have a concoidal fracture, which allows the flaking of stone axe blanks, and an intense grain levelling, when submitted to grinding and polishing processes. Similar petrographic differences between stone- and woodworking tools have been observed at the large south Indian axe factory of Sanganakallu, Bellary (Risch et al. 2011).

Sample Code	**Lithology & Provenance**	**Fabric & Texture**	**Minerals**			**Retro-gression**
			Dominant min.	**Other min.**	**Grain size**	
ANF1	Amphibole-bearing orthogneiss Arronches, Prt	foliated	Qz & Pl (80%), acicular Amp (Hbl) (15%), K-Fd, Bi	Tnt, Op	10-100 µ inequigranula, seriated	-
ANF2	Amphibolite Arronches, Prt	foliated	Amp (Hbl) (60%), Pl (25-30%), Qz (10-15%)	Tnt, Ep	10-500 µ inequigranular	-
GAB1	Metagabbro, Cuevas, Esp	isotropic, decussate	sec. Amp (Px) (70%), sec. Ep-Cz (Pl) (20-30%), Qz (1-2%)	Bt, Pl	fine-grained intergrowth, inequigranular	++
GAB2	Metagabbro, Cuevas, Esp	isotropic, decussate granoblastic	sec. Amp (Px) 50%, sec. Ep-Cz (30%), Gr (10%), Op (10%)	–	<10-2500 µ inequigranular	++
MBS	Metagabbro, Huércal-Overa, Esp	isotropic, decussate	sec. Ms (Pl) (40%), sec. Ep (Cpx) (15%), matrix formed by Op+Amp+Ep (45%)	Chl	>10-500 µ inequigranular	++
HOR	Hornfels, Alós, Esp	isotropic, heteroblastic	Bi (50%), And (30%), Ms (20%)	Qz	<10-300 µ inequigranular	+

KNS	Knotted slate Ulldemolins, Esp	slightly foliated, granoblastic-porphidoblastic	Ms & sec. Bi (Crd) (80%), Qz (10%), Op (10%)	Tur	<10-1000 µ inequigranular	+
JAD1	Garnet-bearing omphacitite Paesana, Ita	locally anisotropic, decussate	Omp (90-95%), Gr (5%)	Ep, Zrn, Ru	<10-100 µ inequigranular	++
JAD2	Garnet-bearing jadeitic omphacitite Porco-Oncino sup., Ita	slightly foliated, decussate	Omp-Jd (90-95%), Gr (5%)	Ru, Ep, Zrn	≤100 µ inequigranular	++
ECL1	Eclogite Paesana, Ita	isotropic, granoblastic, decussate	Omp (45%), Ep-Cz (40%), Gr (5-10%), Ru+Tnt (3%), Op (3%)	Pl, Bi, Phg	<10-1000 µ inequigranular	++
JAD3 (ECL2)	Jadeitic omphacitite Porco-Oncino inf., Ita	isotropic, granoblastic, strongly decussate	Omp-Jd (90%), sec. Tnt+Ilm (Ru) (3%), Op (3%), Gr (1-3%), sec. Ep+Aln (1%)	Pl, Chl, Bi	<10-1000 µ inequigranular	++
JAD4 (ONF2)	Garnet-omphacitite	isotropic, strongly decussate	Omp (85%), Gr (10%), Ru (5%)	Ep, Bi, Zrn	<50-1000 µ inequigranular	+
PLM	Quartz metapelite Plancher les Mines, Fra	slightly anisotropic, granoblastic	Qz & Pl (90%), Chl+Ms (3-5%), Op (5%)	Chl (Bi), Ep, Ab	<50 µ equigranular	+
I	Cataclastic Epi-diorite Mount's bay, Cornwell, Eng	isotropic	Pl (65%), Chl (Bi) (7%), Op (7%), Fd veins (5%)	Amp, Ap, Qz, Ep, Cz	10-20000 µ inequigranular	++
VI	Epidotized tuff Great Langdale, Eng	isotropic, aphanitic	Pl (60%), Fd (20%), Ep (15%), Qz (1-3%)	–	<100 µ slightly inequigranular	+
IX	Porcellanite Tievebulliagh, N Ire	Isotropic, cryptocrystalline to afanitic	Op+Pl matrix (90%), sec. Ab (Pl) (5-7%)	–	<100 µ slightly inequigranular	+
XXII	Riebeckite felsite Shetland, Sco	slightly anisotropic, fluidal	Ab (60-70%)+Amp (10-15%), sec. Ep+Qz (20-30%)	–	100-15000 µ inequigranular	+
GRA1	Granodiorite Ulldemolins, Esp	isotropic, hypideomophic	Qz (45%), Pl-Ser-Ep (30%), Bi (5-10%), K-Fd (5%)	Ab	30-40000 µ inequigranular	+
GRA2	Quartz-diorite (pophidic micro-diorite) Ulldemolins, Esp	isotropic, allotriomorphic	Pl (60%), Qz (20%), Bi-Chl (20%)	–	10-30000 µ inequigranular	+

* Rocks used only as mining tools.

Table 2. Petrographic characteristics (intrinsic variables) of the analysed rocks. *Retrogression* refers to the degree of postmagmatic alteration of the rocks. In the case of secondary formed minerals, where the remains of the primary mineral survive,, these appear in brackets (Ab: albite; Aln: allanite; Amp: amphibole; And: andalusite; Bi: biotite; Chl: chlorite; Cpx: clinopyroxene; Crd: cordierite; Cz clinozoisite; Ep: epidote; Fd: feldspar; Gr: garnet; Hbl: hornblende; Ilm: ilmenite; Jd: jadeite; K-Fd: K-feldspar; Ms: muscovite; Omp: omphacite; Op:

opaque: Pl: plagioclase; Px: pyroxene; Qz: quartz; Rk: riebeckite; Ru: rutile; Ser: sericite; Tnt: titanite; Zrn: zircon).

Regarding the results gained in the mechanical tests, the Böhme track test confirms the existence of considerable differences regarding the *resistance to friction*. Taking into account those lithologies which were selected for axehead manufacture, these values range between 0.34 g/cm^3 and 1.89 g/cm^3 (Table 3). All rocks used as mining artefacts, included in this study as a reference material, have provided higher values, ranging from 1.93 g/cm^3 to 4.04 g/cm^3 of material loss. As both groups of rocks can be found at a close distance from each other in south-east and north-east Iberia, this difference strongly supports the idea that prehistoric communities were able to recognise the mechanical properties of rocks and that they selected them according to the different tasks to be performed.

The garnet-bearing jadeitic omphacitite (JAD2) from Porco-Oncino sup. (Piemonte, Italia) is clearly the most resistant raw material (0.34 g/cm^3), while the hornfels (HOR) from the Segre river terraces is the most friable raw material (1.89 g/cm^3). In practical terms, this difference implies that the Catalan hornfels would be about 5.5 times faster or easier to modify through grinding than the hardest Alpine rock.

Interesting differences can be observed among the high-pressure/temperature rocks of the Western Alps. Very fine grained omphacitites/jadeitites (JAD1, JAD2) are much more resistant than the other varieties. Eclogite and omphacitite axeheads (ECL1, JAD3), with a much lower proportion of omphacite minerals and/or larger average of grain size (see *supplementary material*), would be slightly more friable and, hence, faster to manufacture, as has also been noted experimentally (Pétrequin et al. 2012a). In terms of chemical and mineralogical composition, the amount of omphacite and jadeite seems to have a positive effect on the resistance against friction of the rocks, making them harder to grind.

The petrographic Groups VI (Great Langdale), IX (Tievebulliagh) and XXII (Shetland) of the British Isles appear to be very similar in terms of their *resistance to friction* (Table 3). The strength required to grind axeheads made out of these materials is similar to the softer varieties of Alpine eclogite and jadeitic omphacitite (ECL1, JAD3). The metagabbro from Almería (GAB1, GAB2) is slightly less prone to abrasion, while the Catalan hornfels and the quartz metapelite from the quarries of Plancher-les-Mines, Vosges, would represent the most easy to grind material of the whole series (Table 3). These results coincide with the initially mentioned differences between Alpine and Vosgian rocks, noted during experimental stone axe grinding. It might also be noted that all the rocks implemented as mining hammers and picks show a lower resistance to friction.

Mechanical tests also describe notorious differences between rocks in terms of their *compressive strength*. The resistance to breakage of certain rocks used as axeheads is ten times higher than that of others. Exceptionally resistant are some of the Alpine high-pressure omphacitites/jadeitites (JAD2, JAD4), which are able to resist a load of >5000 kg/cm^2 (Fig. 3). The rest of the Alpine rocks, as well as the metagabbro from Almería, are clearly more brittle and tend to fail under loads between 2300-4000 kg/cm^2. The compressive strength of the Catalan hornfels and the quartz metapelite from the Vosges is in the order of 2000 kg/cm^2. Surprisingly, all tested British rocks (Groups I, VI, IX and XXII) and the amphibolites from the Portuguese Ossa Morena region, resist less than 1000 kg/cm^2. Axeheads made out of these raw materials are more prone to fracture in situations of impact, than the other rocks used for axes and also than those selected for mining activities. Diorite, metagabbro and knotted schist (GRA1, GRA2, MBS, KNS), implemented as heavy-task picks and hammerstones, offer very similar values around 1200-1400 kg/cm^2 (Table 3). These results make it unlikely that, in the case of axeheads, *compressive strength* played a determinant role in Neolithic selection processes. First, most of the broken axeheads present transversal rather than longitudinal fracture, suggesting that *flexural strength* was probably more relevant. Second, all tested rocks withstand extremely high loads, which largely exceed every stress mechanisms a human being could submit the rock to. In fact, all analysed rocks tend to be much less resistant to flexion than to compression. In other words, despite both compressive as well as flexural aspects being present in the functioning of stone axes, the former aspect seems to have been more difficult to check in prehistory taking into account the human strength capacity.

Flexural tensions supported by axehead implements range between c. 340-950 kg/cm^2 (Table 3). The highest values are again provided by some of the Alpine omphacitites, although in a different order than the one resulting from the tests of compressive strength. Particularly striking is sample JAD1, which only withstood a limited load under compressive conditions, but proved to be a highly resistant rock in flexural terms (Table 3). Instead, the relatively hard jadeitic omphacitite JAD3, proved much less resistant to flexural tension. The variation of high-pressure/temperature Alpine rocks is notable, ranging between c. 560-950 kg/cm^2. Both the

Catalan hornfels and the Cumbrian tuff (Group VI) offer values around 600-700 kg/cm^2, and would support a similar flexural tension as the less resistant variants from the Alps (JAD3, JAD4). Moreover, Group VI proves that *compressive* and *flexural strengths* can work as somewhat unrelated mechanical parameters. This is also the case of metagabbro, but in a reverse sense: while proving more compact than some of the Alpine materials, these rocks resist lower flexural tensions. Their values are similar to the ones provided by the quartz metapelite of the Vosges and vary between c. 340-470 kg/cm^2. Among the rocks used as mining tools, knotted schist and the metagabbro of the Cerro Minado mine of Almería show a considerable resistance to flexile tensions, with values ranging between c. 490-700 kg/cm^2. Only granodiorites are significantly more brittle (Table 3).

Sample code	**Lithology**	**Hydrostatic density (g/cm^3)**	**Tests**			
			Friction		**Load**	
			Volume loss (cm^3)	**Stand. Dev. (during four cicles)**	**Compressive strength (kg/cm^2)**	**Flexural strength (kg/cm^2)**
ANF1	Amphibole-bearing orthogneiss	2.86	-	-	939.63	-
ANF2	Amphibolite	3.13	-	-	883.78	-
GAB1	Metagabbro	3.19	1.25	0.14	3351.45	461.20
GAB2	Metagabbro	3.44	1.31	0.02	3523.82	336.84
MBS*	Metagabbro	2.94	2.59	0.03	1371.87	492.12
HOR	Hornfels	2.89	1.89	0.02	1892.82	594.60
KNS*	Knotted slate	2.81	4.04	0.05	1228.74	699.43
JAD1	Garnet-bearing omphacitite	3.52	0.52	0.04	2340.63	885.53
JAD2	Garnet-bearing jadeitic omphacitite	3.49	0.34	0.01	5185.01	950.10
ECL1	Eclogite	3.57	0.92	0.02	2777.27	-
JAD3	Jadeitic omphacitite	3.47	0.83	0.03	3969.37	560.17
JAD4	Garnet-omphacitite	3.46	0.64	0.01	6099.39	723.00
MPS	Quartz metapelite	2.61	1.82	0.02	2249.38	474.98
I	Cataclastic epi-diorite	3.16	-	-	549.3	-
VI	Epidotized tuff	3,02	0.94	0.10	940	687.60
IX	Porcellanite	3,68	0.93	0.03	752.5	-
XXII	Riebeckite felsite	2,57	0.81	0.02	670.1	26.7[1]
GRA1*	Granodiorite	2,7	2.27	0.13	1185.63	203.51
GRA2*	Quartz-diorite	2.67	1.93	0.01	1394.23	251.15

* Rocks used exclusively as mining tools.

[1] Although no micro-fractures or veins were observed in the petrographic thin section, for un-known reasons this sample provided an extremely poor resistance to flexion and could definitely not have been used as an axe. This anomalous result has not been considered in the comparative analysis.

Table 3. Resistance to friction and breakage and hydrostatic density of the analysed rocks.

Fig. 3. Steel piece of compressive press showing the imprint left by omphacitite sample JAD4, before breakage under a load of 6099.39 kg/cm^2.

In order to assess how rock properties were relevant to the Neolithic communities it is necessary to understand how the three tested mechanical parameters are related to each other, as well as to the intrinsic properties of the rocks, such as density (Fig. 4). Correlation values confirm, in the first place, that the *compressive* and the *flexural strength* of rocks selected for axehead manufacture are independent parameters (Fig. 4A). *Compressive strength* also appears to be largely unrelated to *resistance against friction* (Fig. 4B). Instead, *flexural strength* is significantly bound to the *resistance against friction* of the rocks (Fig. 4C). It is also interesting to note that *hydrostatic density* shows a slight correlation with all three mechanical parameters (Fig. 4D-F). In very general terms, we could say that the higher the density of a rock, the more strenuous is its shaping through grinding and, probably, the higher its resistance to breakage. However, density alone will not allow us to decide which of the three parameters is more important in each lithology. In this sense, density appears to be a rough proxy of the quality of fine-grained rocks, when no mechanical tests can be carried out. No other mineral, textural or granulometric characteristic correlates with the resistance of the rocks towards breakage and friction.

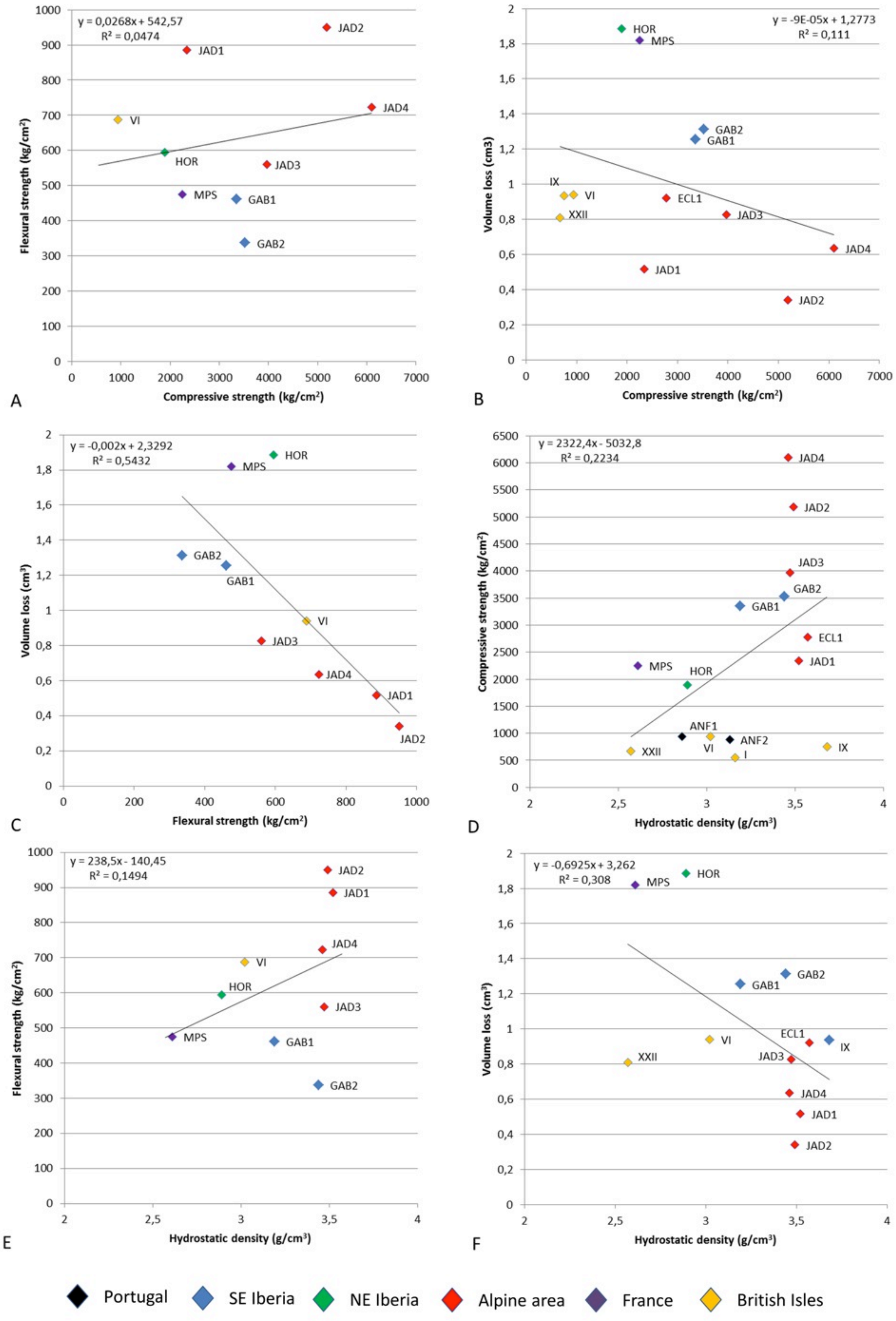
y = 0,0268x + 542,57
R² = 0,0474
Flexural strength (kg/cm²)
Compressive strength (kg/cm²)
JAD1
JAD2
JAD3
JAD4
VI
HOR
MPS
GAB1
GAB2
A
y = -9E-05x + 1,2773
R² = 0,111
Volume loss (cm3)
Compressive strength (kg/cm²)
HOR
MPS
GAB2
GAB1
IX
VI
XXII
ECL1
JAD3
JAD4
JAD1
JAD2
B
y = -0,002x + 2,3292
R² = 0,5432
Volume loss (cm³)
Flexural strength (kg/cm²)
HOR
MPS
GAB2
GAB1
VI
JAD3
JAD4
JAD1
JAD2
C
y = 2322,4x - 5032,8
R² = 0,2234
Compressive strength (kg/cm²)
Hydrostatic density (g/cm³)
JAD4
JAD2
JAD3
GAB2
GAB1
ECL1
JAD1
MPS
HOR
ANF1
ANF2
VI
XXII
I
IX
D
y = 238,5x - 140,45
R² = 0,1494
Flexural strength (kg/cm²)
Hydrostatic density (g/cm³)
JAD2
JAD1
JAD4
VI
HOR
JAD3
MPS
GAB1
GAB2
E
y = -0,6925x + 3,262
R² = 0,308
Volume loss (cm³)
Hydrostatic density (g/cm³)
HOR
MPS
GAB2
GAB1
ECL1
VI
IX
XXII
JAD3
JAD4
JAD1
JAD2
F
Portugal
SE Iberia
NE Iberia
Alpine area
France
British Isles

Fig. 4. Regression plots between the different mechanical parameters and density of rocks suitable for axehead manufacture. The flexural strength value for sample XXII (see Table 3) is omitted, as it is considered to be an outlier.

5. Discussion

The properties of the rocks, as defined by the mechanical tests, provide an estimate of the *production value* – or manufacture cost – and of the *use value* of the Neolithic axes. From a theoretical point of view, both economic parameters have an effect on the *exchange value* of the axeheads and, hence, on the volume and distances these rocks were circulating. Splitting the range of results provided by each mechanical parameter into four equal quartiles allows us to classify each rock into 16 possible categories, according to their resistance to breakage and friction (Table 4).

Following this classification most of the Alpine samples fall into the upper quartiles of compressive and/or flexural strength, parameters which would result in a longer use life and, consequently, in a higher use value. The British tuff (Group VI) and the Iberian metagabbro have similarly high values in at least one of the implied mechanical parameters. The rest of the rocks appear to be less resistant. As expected, their use value should have been lower. In practical terms, they required more frequent re-sharpening of their cutting edge and they were more prone to break during use.

Given their high resistance to friction, the Alpine materials could reach the highest production value, together with all the British rocks falling in the third quartile of this parameter (Table 4). The rest of the rocks were considerably easier to grind. Axeheads of quartz metapelite from the Vosges, the Catalan hornfels and probably also the amphibolites from the Ossa Morena would imply relatively low production values, but also low use values. The resulting low exchange value is confirmed by the less extensive circulation of these rocks, in geographical as well as in quantitative terms.

		Use value index LOW Compressive/***Flexural*** strength HIGH			
		1st Quartile	2nd Quartile	3rd Quartile	4th Quartile
HIGH	4th Quartile		JAD1	***JAD4***	JAD2-***JAD2*** JAD4 ***JAD1***
Production value index	3rd Quartile	Gr.XXII-***XXII?*** Gr.IX Gr.VI	***JAD3*** ECL1- ***ECL1?*** ***Gr.IX?***	JAD3 ***Gr.VI***	
Resistance to friction	2nd Quartile	***GAB1-2*** Gr.I	***Gr.I?***	GAB1-2	
LOW	1st Quartile	***MPS*** HOR ANF?	MPS ***HOR*** ***ANF?***		

Table 4. Classification of the rocks according to their mechanical values. Results from compressive strength (blue) and flexural strength (*green*) are split into quartiles. Where no direct behavioural values were available (derived from mechanical tests), these were indirectly estimated based on their petrographic properties and marked with "?". Flexural strength value for sample XXII (see Table 3) is omitted in the building of the quartiles, as considered to be an outlier.

Most of the British and Irish rocks differ from the aforementioned rocks in that these raw materials are as cost intensive in terms of their manufacture as many Alpine rocks, but their use value must have been low in view of their weak resistance to breakage, except in the case of the Cumbrian tuff (Group VI). The mostly local use of Riebeckite felsite (Group XXII) on the Shetland Islands suggests that this cost-ineffective combination of the production and use value was avoided, where alternative raw materials were available. The limited vegetation existing on the islands and the limited circulation of these axeheads supposes a socio-economic paradox, as it questions both their practical use as well as their supposed symbolic value. We expect the flexural strength of Group I and IX rocks to fall at least in the 2nd quartile, given the volume and geographic extension of their circulation. This, however, needs to be confirmed by future mechanical tests. In any case, it can be concluded that the axeheads from the British Isles required considerably more effort to be ground than their Continental equivalents, except the Alpine rocks.

Once the mechanical properties of the different rocks have been conceptualised in terms of classical economic thinking, it is possible to assess the relevance of these notions to the circulation of stone axes during the Neolithic. With regards to *main* and *secondary supply areas*, which we have established as the geographic area in which a specific type of rock supplied, respectively, over 50% and over 20% of all the axeheads, no significant relationships can be detected (Tables 1 and 3). All geological sources included in this study, except the Riebeckite felsite of Shetland, supplied an area of a few hundred kilometres around the sources. However, if the Alpine values are excluded, flexural strength seems to have had a positive effect on the extension of the *main* and *secondary supply area* of a given rock, up to a certain point. Main supply distances beyond 150-250 km were problematic, as is particularly well illustrated by the situations observed on islands. In the case of Shetland, the restricted access to axeheads made of English or Irish rocks seems to have obliged local communities to draw on Riebeckite felsite, which demanded considerable manufacture costs but only offered a limited resistance to breakage. The low use value of felsite axes is confirmed by their practical absence outside Shetland. The situation on the Orkney Islands appears to have been similar, as is suggested by the large variety of local rocks used for axeheads and the scarcity of imported materials (Clarke 2011, 312). The difficulty of the Neolithic distribution networks to supply overseas territories has also been noted in the Channel Islands (Patton 1991) and the Balearic archipelago (Risch 2011). The lack tenacious rocks on the latter, combined with the unreliability of these networks beyond c. 200 km distances from the Continent explains the exceptionally late colonisation of the Balearic Islands. Only during the second half of the 3rd millennium, when all other large Mediterranean islands had long been settled, could Bell Beaker communities establish themselves permanently on Mallorca and Menorca, thanks to their ability to exploit the local copper outcrops and manufacture copper artefacts.

However, the dominant Neolithic mode of distribution, organised according to regional supply networks, was surmounted in at least two cases. The epidotized tuff (British Group VI) form Great Langdale, Cumbria, circulated over larger distances, with a *secondary supply area* reaching up to 400 km from the source (Fig. 1; Table 1). The preponderance of this rock among British axeheads seems to have resulted from its higher use value, as compared to all other analysed British or Irish rocks (Fig. 4). However, the most extensive economic network is traced by the western Alpine materials, which circulated massively throughout the Po Plain, to the Fruili region, c. 400 km from the nearest secondary sources, as the crow flies (D'Amico 2011). In this large area, the use of omphacitites/jadeitites and, most of all, eclogites dominated over equally available rocks of the central and eastern Alps, such as serpentinite, which circulated at a much more restricted scale (e. g., Bernardini et al. 2018). The high to very high use value of the western Alpine rocks seems to have paid off their equally high production value (Fig. 4), derived from the exceptional efforts required to grind these rocks and the superior transport costs[4], as distance from primary or secondary sources increased. The gentle topography of the Po plain and its extended fluvial network might also explain the superior outreach of the Western Alpine eclogites and omphacitites/jadeitites.

If we now turn to the circulation of axeheads beyond the *main* and *secondary supply areas*, a significant correlation is detected between the *mean maximum circulation* distances and the *resistance to friction*, on the one hand, and *flexural strength*, on the other (Fig. 5). The long distance circulation of a limited number of Alpine stone axes seems to derive from both, their exceptionally high production value, as well as their high use value. In this, two markedly different distribution modes seem to have functioned during the Neolithic. While most European axeheads rarely circulated beyond 400-500 km away from their source, the Alpine rocks and, particularly, the jadeite-richer omphacitites and jadeitites, more than tripled these distances (Table 1).

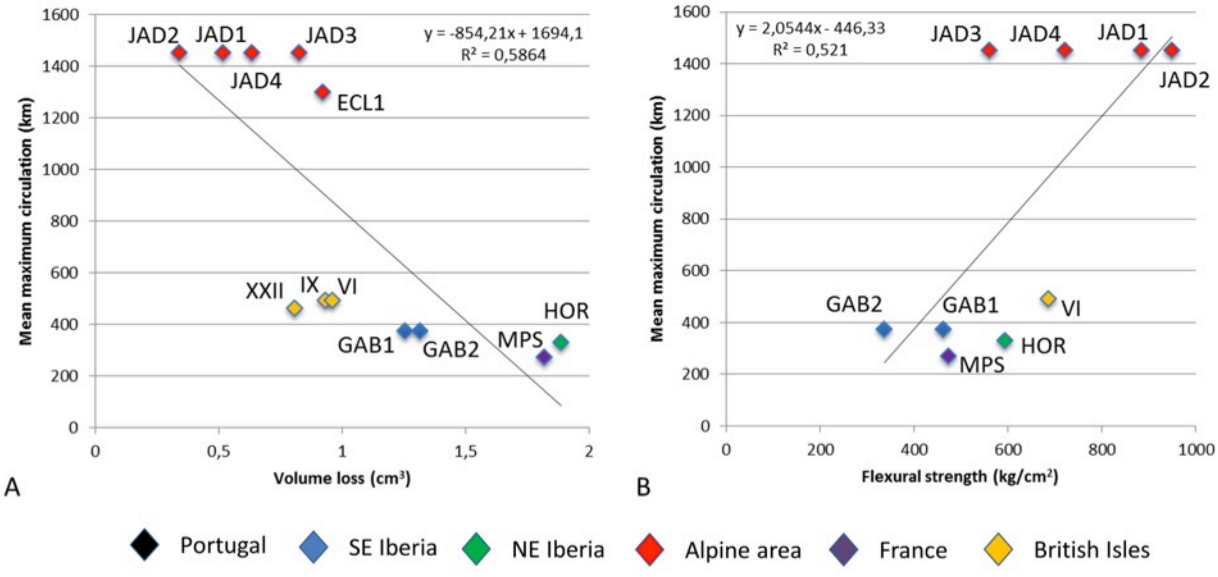

Fig. 5. Regression plot of the different rock types considering the maximum circulation distances in relation to the resistance to friction (volume loss) and flexural strength. The

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[4] We are aware of the relativism reducing the concept of "transport cost" to lineal distances, as goods did not necessarily circulate only away from their source, but in any direction. However, lineal distance seems to be the best common denominator for any analytical, comparative study.

flexural strength value for sample XXII (see Table 3) has been omitted, as considered to be an outlier.

Following these observations, we must expect a wholly different management of axes, depending whether they were circulating below or above the critical threshold of 400-500 km. Within this radius, most Alpine axes would have acted as workaday tools. In a context of regular use, their superior flexural strength would have favoured a prolonged use life of the artefacts and minimizing the need of maintenance of its cutting edge. Consequently, in this distribution mode the superior use value of axeheads made of omphacitite/jadeitite and eclogite would explain their larger *main* and *secondary supply regions*. However, in certain regions, beyond 200 km from the Alpine outcrops, jadeitite/omphacitite and eclogite axes were being replaced by alternative, less tenacious, but more closely accessible and equally functional rocks. This is the situation observed among the quartz metapelite from Plancher-les-Mines (Pétrequin et al. 2012c, 544–573), the glaucophanite in the lower Rhone valley, and the hornfels and calcic amphibolite in Roussillon (Ricq-de Bouard 1996).

Above the critical radius of 400-500 km, the distribution of Alpine axeheads seems to have become notably more complex. From that distance on, some specimens entered a wide distribution network, spreading throughout Europe, reaching peri- and even extracontinental areas. At this inflection point, most of the axes seem to have lost their productive nature, thereby changing from profane tools to means of exchange. In this second distribution mode, what distinguishes Alpine rocks from all the others in this far-ranging network is not so much their suitability as tree felling and wood working tools, but their potential to be modified without compromising their integrity, thanks to their exceptional resistance to friction. In fact, Alpine axeheads underwent complex re-shaping and grinding processes, beyond any functional requirement, at certain stages of their circulation throughout Europe, such as in the Bretagne, Paris Basin, the Carpathian Basin, the Balkans or Sicily (Pétrequin et al. 2017c). Extremely arduous grinding and special polishing processes have been identified beyond 500 km from the source (Pétrequin et al. 2011), a distance at which all other European rocks practically ceased to circulate. While all Neolithic communities must have been familiar with the exceptional resistance to friction of these tools, much more questionable is their awareness concerning the distant origin of the rocks among communities living hundreds of km away from the Alpine sources and decades or centuries after their original exploitation and working. Formulated in economic terms, the *exchange value* of these artefacts appears to have increased not only due to the higher transport costs, a factor which would have equally applied to any other rock type, but also because of the increasing amount of work force invested in them, as they were passing from community to community. Their higher material density and, in the case of the jadeitites and omphacitites, their colour, their ability to get translucent when ground sufficiently thinly, and brightness[5] (Pétrequin et al. 2017c, use the term *lumineuse*) were additional, aesthetically attractive aspects contributing to their circulation beyond 1000 km distances throughout Europe.

The intensity of exploitation and circulation of the different rocks varied in time, but this duality of distribution networks, appears to have been rather stable in Western Europe over the course of the 5th and the 4th millennium, even after the activity at the quarry sites in the Western Alps declined after 3700 BCE.

6. Conclusions

The insight gained from mechanical tests allows us to recognize important differences in the material properties of Neolithic axeheads. According to the *resistance to friction* test, the amount of labour required for axe production in regions such as the Iberian Peninsula, Central Europe or Cornwall was comparatively low. By contrast, the rocks worked in the West Alpine area and, to a lesser extent, in Cumbria, Northern Ireland and Shetland implied considerably higher manufacture costs. At the same time, the capacity to fell trees per axe was also variable among the studied areas. Regarding use, mainly the Alpine rocks, but also the ones coming from Cumbria and Southeast Iberia, offered the hardest and strongest mechanical properties. In general, it can be concluded that communities selected the most suitable raw materials among the resources regionally available to manufacture operative tools. The *flexural strength* of rocks seems to have been acknowledged by Neolithic communities, as it had a positive effect on the extension of the *supply areas* of the axeheads up to c. 250 km distance from the rock sources.

Axeheads rarely circulated over 400-500 km from the source of their raw material. Only the Western Alpine rocks overcame these territorial and economic limits, and participated in significantly larger distribution networks. The economic "success" of Alpine rocks derived at a

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[5] The quality of brightness seems to be a direct effect of the rock's resistance against friction. Most of the Alpine rocks offer a sufficient stable surface, on which mineral particles stay enough time exposed on the relief so that they can be shiny polished. In this way, the difficulty to grind turns into an advantage to polish.

first stage from utilitarian parameters, given their superior mechanical properties. However, the circulation of Alpine axeheads beyond 400-500 km does not seem to conform only to a functional and cost-effective logic, where each agent takes into account the manufacture and transport costs when choosing between different rocks, all of which can be transformed into fully operational tools. Given the availability of local resources in most regions, the profane use of Alpine axes became more and more marginal, as distance from the Alpine sources increased. Rather, the long-distance distribution networks point towards the emergence of a very different economic reasoning among the Neolithic societies. The distinctive factor underlying the exceptional *exchange value* of the axeheads made of Alpine rocks was arguably the increasing manufacture costs, resulting from the intensive reshaping and polishing of these highly friction-resistant rocks along their circulation. This complex economic practice reminds us of political economy thinking in 18th and 19th century Britain. According to the founder of this economic school, Adam Smith (1776) (Smith 1994), the *exchange value* of any good ultimately depends on the effort required by its production. Hence, the more elaborate and prolonged a production process becomes, the higher will be the *exchange value* of the resulting commodity. In the case of the Alpine axes, this increasing *exchange value* achieved through their repeated reshaping seems to have geared their passing on from community to community throughout most of Europe. No other Neolithic artefact category we know of was reworked and modified as intensely as the Alpine axeheads in successive stages and spaces. Such a spatially extended and temporally incremental work process would be superfluous or even detrimental, if these artefacts only represented symbols of power, ceremonial tokens or prestige goods. Such social products rather emphasise material endurance, perpetuity and often also uniqueness, as expressed by the most unequivocal artefacts and expressions of domination appearing in elite graves of the Copper and Bronze Age. Instead, the economic pattern of the Alpine products hints towards objects, which operated as fetishes of social and economic interaction among communities throughout Europe, with very different productive forces and socio-political orientations. Further archaeological aspects, particularly the find contexts of the axeheads in combination with their use wear traces (Masclans et al., 2017, 177 – 210), need to be analysed in more detail, in order to assess, if the long distance circulation of jadeitite/omphacitite and eclogite axes emerged as a first form of primitive currency among Europe's Neolithic communities, as has also been suggested for the Early Neolithic stone ring-discs, some of which were made out of the jadeitite/omphacitite and eclogite (Pétrequin et al. 2015a, 42; Pétrequin et al. 2017a, 729–751; Pétrequin et al. 2019, 305–333) .

Systematic morphometric and functional analysis are still needed to provide further support to the co-existence of two distribution modes, one prioritizing the profane use, the other the fetish character of axes. The Alpine rock data already shows that there was divergent production of workaday *vs* special axeheads, and that both of them left the utilitarian sphere at some point. The existence of regional types in Brettany, Central Europe (e. g. Chenoise and Altenstadt-Greenlaw types), the extremely long blades in Northern Europe (e. g. Puy type) and some perforated pieces in the British Isles and elsewhere in Europe (Bradley 1990, 299–304; Pétrequin et al. 2011, 55–82), offer some examples which seem to point into this direction, and even to the possibility that some particularly long artefacts entered directly into wide distribution networks, as products of a specific sawing technique, geared to long distance circulation.

Acknowledgments

Thin sections were prepared in the Geology Department, while SEM analyses were carried out at the Microscopy Sevice, both belonging to the Universitat Autònoma de Barcelona. We are grateful to Anne-Marie Pétrequin, Pierre Pétrequin, Vin Davis (†), and Kathina Lillios for providing samples from Italy, the British Isles, Ireland and Portugal. Anne-Marie and Pierre Pétrequin also guided us to the axe quarries of Plancher-les-Mines, where we spend a wonderful day taking samples. We extend our thanks to Juan Martínez Egea, from the inspection and certification company Applus (Barcelona), where mechanical tests were performed. Without his altruistic availability this study would simply not have been viable. Tim Darvill and Pierre Pétrequin are also acknowledged for their helpful remarks and suggestions. This research is made possible thanks to grants from the Spanish Ministry of Economy and Competitiveness (HAR2017-85962-P) and the AGAUR of the Generalitat de Catalunya (2017SGR1044).

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