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A Scheme of Evolution for Throwing Sticks

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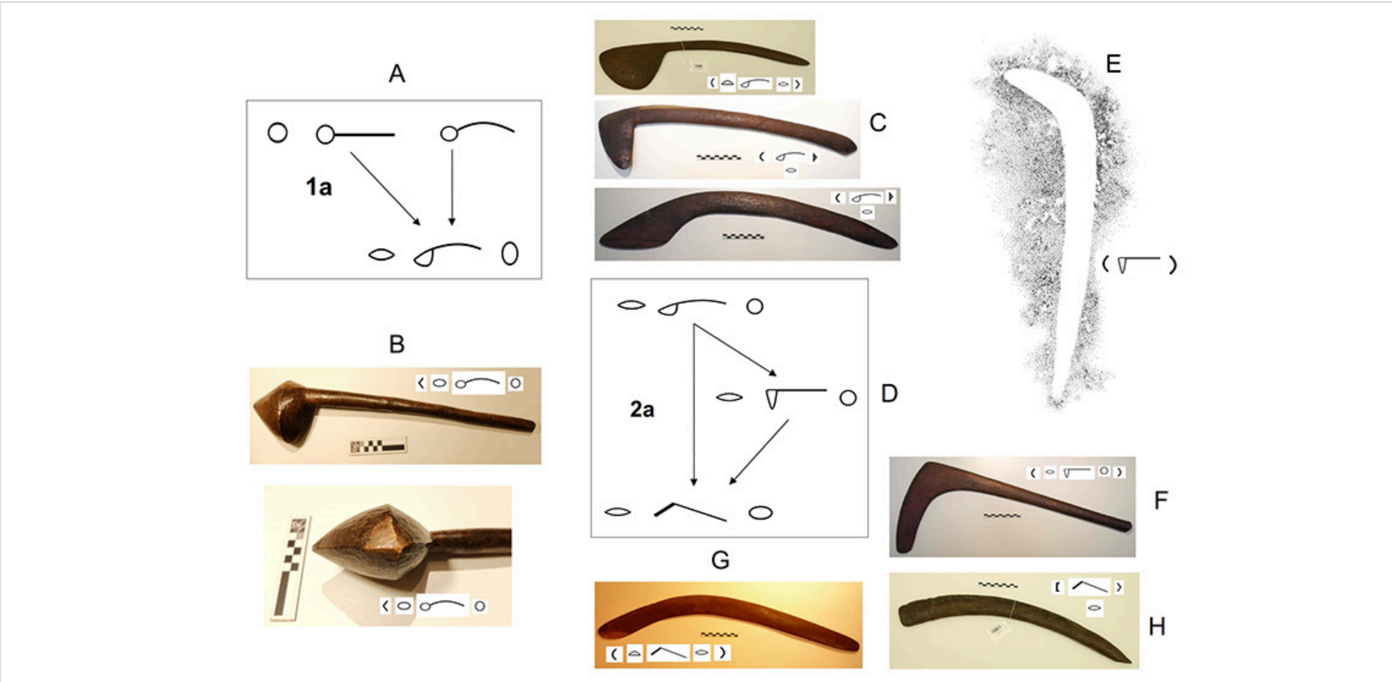

Prehistoric wooden projectiles likely have a complex evolutionary story in a similar way to stone tools, depending on their functions, and the cognitive and physical capabilities of hominins who used them. The technologies of some ancient projectiles (e.g., spears, arrows) can be studied more directly because they were equipped with stone points which survive archaeologically, but other implements made entirely of wood are extremely rare archaeological finds and need an indirect study of their ethnological diversity to try to shed light on their evolution. The evolution of throwing sticks is often restricted to the invention of boomerangs which, as returning objects, have fascinated Europeans, particularly since the early 19th century colonisation of Australia. However, the innovation of returning boomerangs is probably relatively recent, compared to their entire technological evolution. The resulting technological diversity of forms through time is reflected in the different morphological types of ethnological throwing sticks found on the Australian continent but is also present in other parts of the world. A scheme of evolution for throwing sticks is proposed here, according to the technology that can be observed on numerous ethnological objects studied in museum collections, and experience gained from throwing replicas, which allow us to distinguish different development phases for these projectiles.

> Surprisingly, Aboriginal people's myths can sometimes also shed light on the origins of Australian throwing sticks. Indeed, one of the most famous myths of the invention of boomerangs (Thomas, 1985) explains that it was an old man, forced to bend down at the creation of the world, because the sky and earth were too close, who planted his stick in the ground and pushed the sky away. His stick became bent after that, and he decided to keep it with him when he threw it away and saw how it could fly and return.

Introduction to throwing sticks

Throwing sticks can be considered as a large group of objects used as projectiles, but may also include many other functions (Jones, 1996; Bordes, 2014). Their use until the 19th and 20th centuries is well known ethnologically on different continents and regions, including Australia, Africa, India, Indonesia and America (Davidson, 1936; Hess, 1975; Jones, 1996; Bordes, 2014). The term throwing stick is general and designates a tool consisting of one or more pieces of wood or more rarely other natural materials forming between them an angle of 0 to 180 degrees. These parts are generally called blades, more or less cut, which are launched in rotation in the air, in a plane of rotation. We will use the term boomerang only for objects that have a curved trajectory approaching 180 ° back to the launcher. Several words in different Aboriginal languages of Southeast Australia (e.g., bargan, boomari), which later gave the word "boomerang", were clearly attached to this category of light throwing sticks (Butz, 2011). Later, the colonisers confused the different types of throwing sticks by placing under the same name, both these light throwing sticks and other heavier hunting sticks. This confusion continues today. As a specialized type of these implements, boomerangs, which can be considered as a subgroup of throwing sticks, have fascinated early Europeans in Australia with their returning property and have been the subject of many studies (Hess, 1975; Thomas, 1985; Bonin, 2001). However, boomerangs are just the tip of the iceberg, and their sheer popularity tends to divert attention away from the functional diversity of numerous other types of throwing sticks, which can be argued to shed light on their prehistoric evolution and origins.

Although their preservation is rare, due to the perishable nature of organic materials (mostly wood), many archaeological objects discovered from historical and prehistoric periods have been identified as throwing sticks and boomerangs (Hess, 1975; Bordes, 2014). Paradoxically, compared to the abundance of ethnological information, there are very few reported archaeological discoveries of throwing sticks in Australia. The oldest find is the famous set of throwing sticks discovered at Wyrie Swamp in South Australia which has been dated to about 10,000 BP (Luebbers, 1975). On this site, excavations recovered a few artefacts of returning boomerang type and throwing sticks having an open asymmetric shape, similar to those used by Aborigines of this region in the past few centuries. Other discoveries are more recent in age, and can be directly related to ethnography, such as the boomerang from Clarence River NSW (McBryde, 1977), the 600 year old wirlki (a peculiar "number 7" or "gooseneck" shaped throwing stick traditionally made in the area around Tennant Creek by the Warrunmungu people and distributed throughout the central desert area of Australia) throwing stick found at Riwi cave (Langley et al., 2016), or throwing sticks found in the Cooper river bed near Innamincka (Roberts et al., 2022), dated between the 17th and 19th centuries.

At Florisbad in South Africa, a wooden object could be a small throwing stick fragment dated to ~125,000 BP, but there are uncertainties in its identification (Marion et al., 2003). The other archaeological remains of throwing sticks attested in Africa, relate to the historical period of Egypt with known examples from the Old Kingdom (Hess, 1975). In ancient Egypt, the use of throwing sticks is well known, thanks to the objects from archaeological discoveries, as well as from depictions on wall paintings. The Egyptian archaeological objects have well-preserved wood because of stable, low-humidity conditions. The most famous examples are from the tomb of Tutankhamun, which have benefited from the detailed analysis of Jacques Thomas (Thomas, 1991).

The American continent is not empty of discoveries, with the oldest specimen located in Little Salt Spring, a site in Florida, dated from ~9,000 BP (Clausen, 1979). Other discoveries include Anazasi throwing sticks found in the Southwest of the continent. The Anazasi peoples, whose cultural period extends from 200 to 1300 AD, preceded the Pueblos cultures of Arizona and New Mexico, including the Zuni and Hopi people, who are best known for being throwing stick users (Heizer, 1942).

Surprisingly, while ethnological records of throwing sticks are almost lacking in Europe, it is the region where the highest number of archaeological specimens have been identified. The discovery of several double-pointed wooden sticks with a probable throwing stick/digging stick function in Schöningen, Germany, (Thieme, 1997, 1999; Milks et al., 2023; Leder et al., 2024) might confirm that these projectiles were in use well before spear-thrower technology, hundreds of thousands of years ago. Traces of impact have even been recognised on one of these artefacts on this same site (Conard et al., 2020). The great antiquity of throwing sticks in Europe is also marked by a late Palaeolithic throwing stick in mammoth ivory which has been identified from the Gravetian period (23 000 BP) at Oblazowa (Valde-Novak, 1987). Ivory could be seen nowadays as an uncommon material for a throwing stick, but this resource was probably relatively easy to access from mammoth carcasses. Ancient instances of this projectile are more numerous in Europe from the Neolithic period (Thomsen and Jessen, 1902; Stehrenberger, 1997; Ramseyer, 2000; Andersen, 2009; Leroy et al., 2023). For the protohistoric period, one can also cite the throwing stick found in Magdeburg in Germany, a boomerang type that is dated from ~800 BC (Evers, 1994); another returning type found in Velsen is dated from 300 BC (Hess, 1975); and more recently a Gallic light throwing stick was found in 2010, on the Urville Nacqueville site in Normandy (Bordes et al., 2015).

This sporadic chronology of discoveries is complemented by numerous rock art engravings and paintings depicting this type of object around the world and indicating that throwing sticks were in use by humans from the late Paleolithic. In Australia, these representations can be found in an engraving at Karolta and Paramitee Nord rock art sites in South Australia dated around 40 000 BP, (Flood, 1997), a painting in Arnhem land (Lewis, 1988) and in many other regions up to historical times. In Africa, Sudan and Western Sahara regions are also rich in prehistoric rock art representations of curved weapons, some of them being used in hunting scenes, which could be interpreted as throwing sticks (Leclant et al., 1980; Le Quellec, 2022). In Western Europe, Neolithic representations of throwing sticks appear as engravings on megaliths (Cassen, 2010, 2012) and as rock paintings, as in the Choppo Cave in Northeast Spain, showing an impressive full hunting scene (Picazo et al., 2001; Bordes, 2014).

The ethnology and experimentation to the rescue of archaeology of throwing sticks to get insight into their evolution

Confronted by the paucity of the archaeological record, a hypothesis on the evolution of throwing sticks cannot be based only on the rare preserved artefacts but also has to rely on more abundant ethnological and ethnohistorical data. Previous theories about the development of throwing stick technology focused exclusively on explaining the invention of boomerangs in Australia, so they focused on a particular type of specialized throwing stick. The famous antiquarian, Augustus Pitt Rivers, studied the evolution of these projectiles from prehistory to modern times and had a life-long interest in boomerang technology, studying ethnographic throwing sticks from Australia, India and Egypt. He experimented with many replicas, and defined four steps in the technological evolution of these objects thrown as projectiles to explain the appearance of the returning type (boomerang): a first phase of use of raw branches without modification, thrown in rotation; a second phase of discovering the stabilization by curvature, increasing range and accuracy; a third phase of cross-section improvement by splitting wood branches to create a plano-convex cross-section; a final fourth phase of improvement using throwing experience to control the returning flight (Pitt Rivers, 1883). Another study on the technological development of throwing sticks is the diagram of Bryan Cranstone, who was the curator of the Pitt Rivers Museum from 1976-1985.

His diagram is more a functional typology than a scheme of technological evolution, and he focused on the functional specialisation of striking and throwing sticks (including boomerangs) (See Figure 1).

Limits in the approach of throwing stick technology aiming to gain insight into their past evolution are linked to the lack of objective ethnological throwing stick and boomerang typologies based on aerodynamic characteristics of these projectiles. Indeed, they have been mainly based on morphology and stylistic aspects of decoration, which are linked to the cultural context of manufacture and use of these implements. Davidson (Davidson, 1936) established the main types of throwing sticks and boomerangs in Australia, where the highest diversity of ethnological objects is found. This work has been renewed by Jones (1996), who described different traditions and ethnological functions of throwing sticks on this. Then, a new perspective using a reference base to compare these ethnological implements with archaeological discoveries (which are often isolated and lacking in detailed cultural context) requiring more measurements of physical characteristics (e.g., weight, cross-section, thickness, blade tuning) was needed, if we are to move beyond descriptions of their shape and design. Measurements have been applied to several hundred throwing sticks and boomerangs from museum collections around the world (A corpus of 316 objects was studied: Quai Branly Museum (141), South Australian Museum (114), Pitt River Museum (41), Volkenkunde Museum (11), Toulouse Natural History Museum (9) and has the potential to build a more general classification, with the advantage of being more independent from cultural contexts and not largely pre-determined by the overall shape. This new classification includes aerodynamic parameters to better evaluate the ancient performance of these implements as projectiles and understand archaeological findings in terms of prehistoric technological evolution and functional specialization (Bordes, 2014). Additionally, this classification can be used to compare the technology of archaeological objects originating from different continents and cultures around the world, which is vital for a discussion of their general evolution as prehistoric weapons and tools.

Principles of throwing stick aerodynamics gained from experimentation

As we focus here on the projectile function of throwing sticks, we need to consider which aerodynamic evolution mechanisms contribute to their refinement and specialisation. Insight into these different principles of aerodynamics has been determined both by experiments and by examining artefact collections to document the main characteristics that influence their flight, from the archaic types (i.e., throwing clubs) to the most refined or specialized types (light throwing sticks launched at high range or with special capability (e.g., curved flight of boomerangs). The previously cited ethnological database has been used by the author to produce over two hundred experimental throwing sticks and boomerangs, exploring the different shapes, sections and tunings of these projectiles, including ethnological and archaeological replicas. Among them, a dozen of these experimental objects have been exclusively crafted with stone tools, getting the opportunity to evaluate different stone toolkits for their manufacture. All these implements have been tested by the author and their flight and range observed. These observations led to several articles focusing on different types of implements or technological aspects (Bordes, 2009a, 2009b, 2010, 2011, 2012). The experience gained through this long-term continuous experimentation allows a tentative evaluation of the role of their different physical characteristics during their evolution.

Besides this, we need to keep in mind that throwing sticks have been used not only as projectiles but for many other overlapping functions, including former functions such as digging or fighting which are older than their use as projectiles which could also have played a key role in their aerodynamic evolution (Jones, 1996; Bordes, 2014).

Blade streamlining of throwing sticks

Blade streamlining of throwing sticks increases from unmodified natural branches, archaic throwing sticks, clubs or straight sticks with circular sections, through more streamlined projectiles with biconvex sections, to specialized objects with almost plano-convex (This type of section shows a more accentuated biconvexity on the extrados (surface facing up) than the intrados (surface facing down) resulting in the increase of their overall aerodynamic lift) and plano-convex sections. This process is not only a matter of aerodynamic performance of the cross-section, but (most importantly) also leads to a decrease in their thickness, which increases the rotation of the projectile in flight. This rotation speed further increases the aerodynamic lift and, as a consequence, the gliding effect and the energy of impact (which is the sum of the translation plus the rotational energy), increasing throwing stick efficiency in striking targets at a greater range. One very important consequence of streamlining is the increase of the throwing stick's surface to keep the same resistance to breakage with a reduced thickness. In some cases, a compromise needs to be found between blade resistance (linked to wood section surface), mass and streamlining, depending on the wood hardness, and specific strategies to target preys (i.e., aerial or ground hunting), which can limit streamlining of throwing sticks. For example, the rectangular cross-section, found commonly on Pueblos Indian throwing stick blades, is probably an appropriate technical response to keep a good resistance with a high cross-section surface area, well-suited for hunting prey like rabbits on the ground, especially when only a medium density wood is available (such as oak) (Bordes, 2014). Another aspect of increasing blade streamlining is its relationship with woodworking technologies, and the innovative capacity of hominins to remove wood with more efficient stone tools, by improving their design and hafting techniques.

Weight and wingspan reduction

Weight reduction is a general tendency for prehistoric projectiles, such as arrows and throwing spears, which is also shared by throwing sticks. The manufacture of lighter and faster projectiles allows a greater number of them to be carried, which is a big advantage for people moving about on foot. Weight reduction can also be viewed as a consequence of streamlining or vice-versa which closely links both of these evolutionary mechanisms. Additionally, specialized advanced throwing sticks tend to be subject to wingspan reduction too, because rotating projectiles with a smaller diameter travel faster in flight, with a faster rotation, and are also easier to carry and throw. In human conflicts, they are more difficult to avoid and parry by an opponent. However, some throwing stick functions tend to limit weight and wingspan reduction. For example, some functions demand a firm grip, a long reach and striking efficiency, as in hand-to-hand combat; other functions may need more weight, as when digging or ground hunting at close range. This is a common limitation since asymmetric throwing sticks, most effective as striking weapons in close-quarter fighting. It is probably how *kylies* (A type of Australian throwing stick traditionally made in the Central Desert area) in central Australia evolved to stay as heavy multi-functional implements, which needed to respond to a range of tasks requiring weight and strong resistance.

Curvature as a response to streamlining for flight stabilisation

Continuous streamlining of a circular section along a straight throwing stick leads to unavoidable instability in flight, which can end with a sudden flip of the throwing stick in flight before impact, with almost complete loss of translation and rotation energy. This phenomenon is due to a rotation movement perpendicular to the rotation plane initiated during the launching. Weaker instability can also arise from slight oscillations perpendicular to the rotation plane which dramatically breaks the movement of the projectile.

The technical solution is to create a curve or bend the throwing stick to restore stability. One possibility is to accentuate the curvature during manufacture, as can be found in the crafting of rabbit sticks by Californian Indians (Campbell, 1999). However, as it's rather difficult to bend most throwing sticks made of hardwood, it is easier sometimes to craft another one with the same streamlining, after first selecting a piece of wood with a more accentuated natural curvature. This selection mechanism, by eliminating unstable throwing sticks, leads to the accentuation of their curvature with increasing streamlining. Once a certain curvature is reached (height: wingspan ratio >0.2 according to my experiments), streamlining can be increased to a biconvex cross-section or (even more advanced) to a plano-convex cross-section with no instability problem if fitted blade tuning is applied. A diagram representing the measurement of the height: wingspan ratio (expressing curvature) against the mass: surface ratio (expressing the carrying surface) of museum throwing sticks, shows that lighter objects need to have minimal curvature, and a technological limit relative to curvature is determined (See Figure 2) (Bordes, 2009a, 2011, 2014). Interestingly, another limit can be observed on figure 2, as throwing sticks need also to limit their curvature to maintain minimal resistance (see section **Blade streamlining of throwing sticks**). Indeed, projectiles with sharper angles are more fragile and tend to break more easily. Both limits define an "evolutionary corridor" of compromise or trade-off between stability and resistance needed for throwing sticks.

Compensation or accentuation of aerodynamic lift imbalance between blades

For throwing sticks, the two blades even being physically identical in the case of symmetric projectiles (i.e., same length, thickness and section) are not aerodynamically equivalent once in flight. Indeed, considering the projectile in rotation around its center of gravity, the one whose edge outside the curvature traverses the greatest angle in the wake of the other is called the attacking blade (Bordes, 2011). The other blade is, therefore, called the following blade. Travelling through one angle greater than the other, the attacking blade also acquires an intrinsic aerodynamic lift effect, always greater than the following blade. This effect increases with streamlining and weight reduction of the throwing sticks and leads to the tilting of the rotation plane of the object during flight by gyroscopic effect (same effect as on boomerangs, (Thomas, 1985)), which changes the straight flight of these projectiles to a "S" shaped flight. When this effect is minor, only the final part of the trajectory can be affected when the object has accumulated high rotational energy, but it nevertheless lowers the accuracy on a target, and needs to be somehow corrected. Two solutions are possible: either modifying the throwing stick blades or tuning them (see next section) to readjust this imbalance of lift or increasing the launching angle relative to the horizontal to delay this effect and keep a straight trajectory ending.

Blade tuning to prevent throwing stick flip and enhance range

Blade tuning incidence (The incidence is defined by the angle between the table plane and the medium axis passing through the middle of the throwing stick aerofoil section taken in the blade moving direction).and dihedral angle (A dihedral or dihedral angle is the angle formed by the plane on which the throwing stick is placed and the plane formed through its elbow, and the extremity of the measured blade). A positive incidence or dihedral will give slightly more aerodynamic lift than a negative incidence or dihedral. These tunings have little influence on a heavy throwing sick with circular or elliptical section, but advanced streamlining and weight reduction tends to dramatically increase their effect on lighter throwing sticks and are well known on boomerangs (Thomas, 1985; Bonin, 2001), which are subject to a superior aerodynamic effect. Blade tuning control the relative aerodynamic lift between attacking and following blades, hence playing a key role in compensation or accentuation of aerodynamic lift imbalance between blades for throwing sticks designed for aiming at a target in a straight trajectory (see previous section). They are also critical for stabilizing throwing sticks with a limited curvature (see section **Curvature as a response to streamlining for flight stabilisation**). However, blade tuning has also been used to increase the aerodynamic lift imbalance aiming to accentuate a curved trajectory, as is the case of the projectile precursors of boomerangs (being at the end of the weight reduction and streamlining evolution of throwing sticks), which induced a great loss of accuracy to hit a target, which then affected hunting strategy by restricting it to flying game (e.g., birds and bats), until ultimately losing all hunting function to be used only as a toy (i.e., toys boomerangs).

Other functions of throwing sticks

To fully understand their evolution as projectiles, throwing sticks also need to be considered in the context of "non projectile" functions. These implements originating from natural sticks are intrinsically multi-functional and have been used for many other activities. Indeed, prehistoric hominins, being frequently on the move and to avoid burdening themselves with too many tools, tend to utilise multi-purpose tools made of wood and stone. This multifunctional use is present among native people in Australia, increasing with the nomadism of the population (e.g., Central Desert).

Ethnological data suggest at least fourteen non-projectile functions: hand-to-hand combat, parade, digging stick, digging shovel, fire management, fire saw, livestock guidance, disarticulation of game, flintknapping hammer (Martellotta et al., 2022), plucking, music, dance, ceremony and exchange (Bordes, 2014). Some of these functions seem to have played a key role in the technological development of throwing sticks across continents (i.e., hand-to-hand combat, digging stick, fire saw, disarticulation of game, livestock guidance), but other incidental functions have influenced throwing stick features in a subtler and regional way (e.g., a digging shovel made by rounding off the extremities on *kylies* in Australia) (Jones, 1996). The former function of sticks, before they start to be used as projectiles, are then logically included in these side functions of throwing sticks. These are probably dependent on the general shape and symmetry.

Three defined archaic throwing sticks major groups according to their general shape and symmetry

Before being adapted for specialized use as a projectile, throwing sticks with different symmetry were adapted from a range of former functions involving different evolutionary trajectories. It should be noted that the notion of symmetry used here is not strictly mathematical, and that symmetry should be treated as relative shape and mass equilibrium tendency. No traditional or ancient throwing stick is strictly symmetric.

As underlined by Cranstone (See Figure 1), the functional range of archaic throwing sticks has probably been decisive in their technological evolution. One of the limitations of Cranstone's drawing is that it assumes the development of throwing sticks according to only one main former function. If the initial specific function of primitive throwing sticks (including use as a projectile) is important to determine a starting point for their technological evolution, the context of initial use or additional functions (and their disappearance) could have influenced their development in further phases. The initial functions of archaic throwing sticks appear to be intimately linked to their shape and symmetry. Three main groups of throwing sticks, having a different former function before being used as projectiles and then a different evolutionary pathway, will be considered in the following paragraphs. It should be noted that if these major groups are clearly separated from archaic throwing sticks, during their evolution, these projectiles could influence the innovation and shift to others groups.

Asymmetrical throwing sticks with a bulging distal end:

Asymmetric throwing clubs likely evolved from heavier fighting clubs used in close fighting or to finish animals. They can be considered as highly asymmetrical throwing sticks as they have a large bulging distal end with significantly increased thickness, width, and weight. Asymmetrical objects also clearly indicate how they were used-a distal part for striking and a proximal part which is held. Even if throwing clubs are straight they can be considered as throwing sticks, according to our throwing stick definition here, with the following in-flight projectile properties: a 180° aperture angle (or a zero value for height to wingspan ratio) with their proximal/handling blade defined as the attacking blade and the distal bulge as the following blade. These primitive throwing clubs could have been collected or extracted from a natural trunk and root junction or from abnormal branches with a bulge in forms requiring only slight modification. As with symmetrical throwing sticks, they probably encountered the same problem of stability when their section and thickness were refined, but as their handling or proximal blade (attacking blade) is generally less streamlined, longer, and heavier than the distal or following blade, they had the advantage of a natural compensation of the lift imbalance between blades (see section **Compensation or accentuation of aerodynamic lift imbalance between blades**). The asymmetrical weight between their blades also contributes to maintaining a superior rotation in flight.

Asymmetrical curved throwing sticks

Another large category of asymmetric throwing sticks is those without any bulge, and with more constant thickness and wideness from end to end. These implements could have been manufactured by collecting branches with a natural turn and elbow. Their initial function probably included use as a club or for plucking, but they were probably multifunctional tools, even more polyvalent than the previous group described.

The main advantage of naturally curved objects is that they are intrinsically stable when used as projectiles, but their disadvantage is that they are less resistant to breaking and less efficient when handled for use as a contact tool or weapon than the asymmetric throwing sticks with a bulging distal end. As they have also the same advantage as the previous group to counter lift imbalance between blades and in maintaining a superior rotation in flight, these throwing sticks are naturally prepared to be used as projectiles and, by consequence, would not have encountered many obstacles to their adaptation in this function, resulting in less morphological transformation through their evolution.

Symmetrical throwing sticks:

Archaic throwing sticks with symmetric tendencies were collected as a simple straight section of branches or trunks of young trees and started their human use-life story as one of the most multifunctional of all implements. Among these functions, one that can appear as essential for the day-to-day life of hominins already present a million years ago, as was the use of straight solid sticks for digging roots and yams to ensure a daily diet rich in starch; or for digging deep holes for water. Adaptation to these functions could have rapidly developed pointed extremities which are also beneficial for their efficiency as projectiles. It is this category of object which encounters the most difficulty transitioning to a projectile function. With their cross-section streamlined and refined, they are subject to instability and progressive imbalance of lift between blades. In consequence, they need additional technical solutions to be viable as efficient and accurate projectiles compared to the two previous groups. However, their ultimate failure led to the fascinating evolution of projectiles with turning trajectories, progressively addressed and modified for new functions.

How to reconstruct the development of throwing sticks?

Here we present a proposal of a new evolutionary scheme for the three previously defined major group of archaic throwing sticks according to their type of symmetry and former functions, aiming to refine the technological phases previously defined by Pitt Rivers. An evolutionary diagram showing key innovations is presented in this section (i.e., improvement of cross-section, accentuation of curvature, wingspan reduction) and adaptation responses of throwing stick major groups (i.e., asymmetric with head, asymmetric, symmetric) and discussed. This evolution scheme is divided in successive chronological-technical phases illustrated by archaeological discoveries, rock art and characteristics identified in ethnological studies. Additionally, the contribution of non-projectile functions in particular evolutionary stages is highlighted. Its scope is not to cover systematically regional histories, as ethnological and archaeological data for certain types of throwing sticks and developmental phases may be absent on some continents. For example, in Australia, the high diversity of throwing sticks attests that they probably went through phase I to V, but some innovations of phase VI are under-represented on this continent. In contrast, numerous throwing sticks present in India and Indonesia mainly belong to phase VI, but some specimens with archaic aerofoil cross-section attest to earlier phases. Africa is certainly a continent with a very old evolutionary story of throwing sticks. Ethnological objects appear in a dotted manner in each defined phase, except for phase IV. In America, ethnographic throwing sticks tend to reflect only phases II and III and recent diversification of phase VI. Nonetheless, bias of sampling of the ethnological collections of throwing sticks needs to be kept in mind, as the overrepresentation of Australian artefacts in Museums. Relative chronological phases are distinguished by the evolution of section streamlining, which is also proportional to the effective removal of wood, hence the development of woodworking tool efficiency. Some archaeological discoveries will be cited here to illustrate each defined evolutionary phase, along with ethnographic examples. Dating of archaeological artefacts will be used to propose a coarse chronology of these phases. The three major categories of throwing stick symmetry (described above) are considered in terms of some specific classes of shape (Bordes, 2014) that help to establish a relationship diagram (See Figure 3). Table 1 summarizes possible innovations in each defined phase and the invention of new types of throwing sticks. It should be noted that ethnological throwing sticks have all been crafted during a recent period, consequently, to illustrate some evolutionary steps, some examples presented to illustrate ancient shapes and sections have yet recent extremity type (e.g., truncated or bevelled). Finally, this scheme is designed to be further adapted for different cultural and natural environmental contexts (e.g., availability of dense wood) and according to the range of non-projectile functions of throwing sticks in each area.

Phase	Innovations	Invention of new types of throwing sticks	Proposed timeframe
I Archaic	Use of sticks as projectiles with raw extremities		Several Ma ago - 1 Ma
II Extremities adaptation	- Pointed extremities - Slight curving of straight symmetric projectiles	-Double pointed with slight curve (**1c**) (symmetric)	1 Ma - 100 ka
III Biconvex streamlining	- Rounded extremities - Streamlining to elliptical and biconvex section - Accentuated curving of symmetric projectiles - Blade tuning	- Asymmetric with flattened head (**1a**) - Asymmetric with widened short blade having mixed airfoil (**2a and 1b**) - Asymmetric with widened short blade losing mixed airfoil (**3a**) - Symmetric crescent (**3c**) or limitation of streamlining **(2c)** - Stabilization of symmetric to asymmetric **(4c)** - Diversification of symmetric shapes **(5c)** - Hooked asymmetric shapes with conic peg **(6c)** - Stabilization of archaic double pointed sticks by central bludge (**7c**)	100 ka - 60 ka
IV Splitting	- Splitting wood piece favoring almost plano-	- Archaic heavy boomerangs (throwing sticks with returning	60 ka - 20 ka

	convex section - Almost plano-convex section - Increased blade tuning	trajectories) **(8c)**	
V Refined streamlining	- Plano-convex section - Perfectionated blade tuning	- Boomerangs (throwing sticks with returning trajectories) **(9c)** - Beaked or "number seven" throwing sticks **(4a)** - Crescents with narrowed elbows (**10c**)	20 ka - 10 ka
VI Diversification, new shapes and airfoil sections, use of metal	- New aerofoil section (rectangular, rectangular convex, semi-convex, diamond) - Truncated and beveled extremities - Use of metal	- Throwing sticks mixing archaic, new aerofoil sections and recent type of extremities (beveled, truncated) **(2b, 6a, 11c, 12c)** - Appearance of crozier shaped throwing sticks linked to new functions **(5a)** - Development of "L" shaped throwing stick with widened short blade **(7a)** - Cross boomerangs **(13c)**	10 ka - present

TABLE 1. SUMMARY OF INNOVATIONS AND NEW TYPES OF THROWING STICKS FOR EACH DEFINED PHASE (FIG. 3)

Phase I: Archaic

In this phase, hominins start to use provisional straight or curved natural dry broken branches or green branches cut from a tree as projectiles which are mainly driven in flight by their mass. Section streamlining is absent and cross-sections remain close to the natural circular cross-section of the collected wood piece. Due to the limited resistance of degraded dry wood, green wood is progressively preferred, and modifications are probably limited to the removing of bark, cutting, or breaking of the natural branch to the desired length and coarse extremities, and cutting with crude unhafted tools (i.e., chopping tool biface, cleaver) (See Figure 4). These short-lived crude throwing sticks have a straight trajectory with very short efficient ranges (10-20 meters) in hunting. Asymmetrical curved throwing sticks can probably reach slightly higher ranges (20-30 meters), by stabilisation of the flight by their curvature, a phenomenon which was probably noticed by early hominids. At this stage, symmetrical and curved asymmetrical projectiles were of limited efficiency compared to asymmetrical throwing sticks with a bulge, which increased impact.

Launching techniques probably varied from horizontal throwing, advantageous to cover maximum wideness to increase the chance of hitting, to vertical throwing which has the advantage of increasing the rotation because blade weights maintain faster rotation during flight. It's possible that asymmetrical objects benefitted from horizontal throwing to increase chances of striking targets because of the role of the heavier blade in maintaining rotational energy, but symmetrical projectiles lacking this effect, could have benefitted from vertical throwing to compensate for their lack of rotation. It should be noted that the type of snake-shaped throwing stick equipped (or not) with a bulge head can date back to this period and is very stable in flight and among the older type used by Egyptians (See Figure 3) (Thomas, 1991).

This phase might date back millions of years, as early hominins took advantage of such simple projectiles to hunt small game and defend themselves against predators. Other great apes are also capable of throwing stones and sticks (Nakamichi, 1998; Lombardo and Deaner, 2018), but the absence of bipedality and partial standing prevented them from being efficient and accurate. It is a possibility that this throwing activity could have contributed to a progressive adoption of a stable standing position, favouring bipedality adopted by early hominins. The use of these archaic implements was probably in the range of hominins like Australopithecus with partial bipedality (Ward, 2002; Chevalier, 2006); so, this phase could have started several million years ago.

Early ancestors probably also noticed that throwing these projectiles in rotation leads to an increase in their speed and impact energy and learned how to choose the best-dried branches to do so. The absence of preservation of wood for this very early period of throwing stick use, combined with no evidence of major modification to branches to enhance the projectile function, explains the absence of archaeological finds. However, some crude ethnological African throwing sticks (See Figure 4) might shed light on the possible projectiles used in this very early phase.

Phase II: Extremities adaptation

The development of pointed extremities can be considered as a starting point from an unmodified branch to a wooden object with a modified section. The need for pointed extremities probably began with modification for digging stick use and was probably concomitant with the development of spears with which they could have shared some functions (i.e., fighting, digging) (Leder et al, 2024). Pointed extremities increase the piercing and striking (same amount of energy applied on smaller surface) efficiency of throwing sticks on impact. Innovation taking place in this phase of development of symmetrical projectiles produces double straight or slightly curved pointed sticks. Equivalent ethnographic examples of these latter objects are commonly used for hunting small animals by native people around the world, especially in the Southwest of northern America (Devereux, 1946), arid interior regions of Australia (Davidson, 1936; Jones, 1996, also see Figure 5C) and Tasmania (Noetling, 1911). In Africa, some ethnographic examples of a straight asymmetrical throwing stick can be found (See Figure 5D). One big advantage of having a multifunctional tool for both digging and throwing is that it can be used to dig out small animals from their burrow and also be thrown at them at short range if they manage to escape. Even when an extremity is not pointed, more time is spent to round edges and shape this part of throwing sticks. These pointed extremities could also have been modified for use in other tasks and activities (e.g., stone tool retouching) (Martellotta et al., 2022). Sticks are still only slightly modified natural branches with a minimum amount of wood removed, preserving a circular cross-section or modifying it in a slightly elliptic section. This simple woodworking requires only unhafted tools, as in the previous phase, selection of green wood, sawing to the desired length and hacking extremities to a point. The use of fire would have been a useful innovation to shape and harden worked extremities. As projectiles, these throwing sticks are mainly driven by their mass and wingspan in a similar way as to the previous phase. If the refinement of extremities can enhance the rotation of these projectiles at this stage, their circular or thick elliptic cross-section is still limits them to short range (10-30 m) in hunting according to ethnographic observations (Devereux, 1946). The discovery of double pointed sticks adapted to throwing function on the Schöningen site (Thieme, 1997, 1999; Conard et al., 2020; Milks et al., 2023; Leder et al., 2024) discovered with spears dated around 300 000 years ago (See Figure 5A-B), indicates a minimum antiquity for such modified throwing sticks, and possibly much older- the earliest hominin fires and thus their capacity to burn wood are dated to about one million years ago (Berna et al., 2012).

During phase II, low curvature was probably sufficient to stabilise heavy archaic double-pointed shaped sticks (See Figure 3, 1c), types of which are in ethnological records especially in arid regions of Australia (See Figure 5E). These solid objects also retain other contact functions, such as close fighting weapons and digging sticks.

Phase III: Biconvex streamlining

Resulting from the alternative removal of wood from opposed sides on a wood core, a natural circular or elliptical cross-section (which could also be natural and be produced by trunk or branch constrained growth) crafted to a biconvex section is the major innovation of this phase (see section **Blade streamlining of throwing sticks**). In fact, it can be observed experimentally that biconvex cross-sections are naturally produced by longitudinal wood removal. With stone tools, wood removal is harder to achieve at the centre (heartwood) of the stick than at the outer margin (sapwood) leading to a convex surface. When this process is repeated on the opposite side, a biconvex section is naturally obtained. As with the innovation of stone biface production, which proceeds with the same strategy of alternately removing matter on each side, the notion of symmetry could have been a new cognition key to organise this innovative way of removing wood during the manufacture of throwing sticks.

To explain the need for biconvex cross-section for non-projectile use, one possibility is that it could have been developed from the modifying of the extremities of pointed throwing sticks to increase surface area and to have a shovel function for digging in sandy ground or uprooting plants (See Figure 6E) (Jones, 1996; Clark, 2012). This use can be also illustrated by the digging sticks with a flattened extremity used to uproot agave by the indigenous people of California (Campbell, 1998); flat-ended digging sticks used by Peruvians (See Figure 6A-B); and among Neolithic digging sticks found on the site of La Draga in Spain (Palomo et al., 2013) (See Figure 6C). Additionally, regular use of these implements reduces edge sharpness and probably leads naturally toward rounded or slightly flattened extremities which have been recognized on Middle Palaeolithic digging sticks found at Poggetti Vecchi (Aranguren et al., 2018) (See Figure 6D).

If we consider these flattened extremities as a starting point for biconvex streamlining, this technical innovation probably originates in phase II as soon as bifaces spread in hominin tool kits, but its propagation of biconvex streamlining along the blade of throwing sticks could have been delayed until improved stone tool designs enabled more efficient removal of wood to produce such sections. In consequence, the beginning of this phase could be set sometime after the first evidence of double-pointed sticks at Schöningen, and perhaps during the Mousterian (Middle Palaeolithic) with abundant Levallois debitage (Binford, 1966), which afforded improved flake tool technologies for hafting (Rots, 2011; 2012; Bonilauri, 2015). From this period, numerous denticulate scrapers (Dibble, 1987, 1991), which are very useful for coarse wood removal and shaping throwing stick blades (according to my personal experience), could be a key indicator of stone tools with efficient woodworking capacity to create extended biconvex cross-sections. These new tools probably helped to achieve diversification of throwing stick extremities with regular shaped rounded forms. In this phase, the enhanced use of fire to char wood to speed its removal, recorded in Australia (see Bordes, 2012) could have also contributed to the manufacture of finer biconvex cross-sections.

This new flattened biconvex cross-section is a major innovation, marking a great improvement in the efficiency of archaic throwing sticks and extending their range, at least to 40-60 m (Callahan, 1975; Bordes, 2014). In this process, reducing thickness, but increasing the width and surface, thus keeping section area constant, is aiming to maintain resistance to shock. As a consequence, with this cross-section, lighter objects with increased surface area are produced, leading to the appearance of aerodynamic lift, and enhanced maximum range of these projectiles by hovering.

Additionally, a feature exclusively present on Australian throwing sticks (but could have disappeared on other continents) suggests a key role for a non-projectile function linked with the particularly high degree of streamlining of biconvex cross-sections on this continent (see also section **Blade streamlining of throwing sticks**). Indeed, Australian ethnological throwing stick blades have highly tapered edges in comparison with ethnological African and Indian throwing sticks (Bordes, 2014). Yet throwing sticks with highly tapered blade edges have no advantage in terms of range and accuracy, and could, conversely, be subject to aerodynamic instability because the leading-edge sections for subsonic wings are properly designed to be rounded to avoid this. On the other hand, in terms of impact efficiency, tapered edges are capable of more damage (same energy applied on a smaller hitting surface), but they could also be more fragile and susceptible to shock and impact damage if striking hard ground and rock. If we consider other non-projectile functions, one use of throwing sticks (notably, the *kylie*) in Australia is for butchering and disarticulating kangaroo carcasses (Jones, 1996). This particular cutting requirement of sharp wooden edges could have been the origin of such tapered edges and might have influenced the origin of highly streamlined biconvex cross-section. In Australia, the presence of fighting sticks equipped with sharp edges or heads and used as wooden swords and axes also testify to this "cutting" function for fighting (Basedow, 1925) which could have been transferred to throwing sticks. Indeed, they were used among the primary ranged weapons (i.e., hand spear, spearthrower) in human conflicts until colonization as bows have never been used there. At last, besides sharp stone edges, a variety of other materials were used for cutting in prehistory, including bone and antler (Bouzouggaret al., 2018).

In phase III, throwing sticks probably developed further by lowering the mass: surface area ratio (Bordes, 2014), encouraging a low to medium aerodynamic lift effect, which demanded more curvature to maintain stability. To take advantage of aerodynamic lift for a gliding flight, biconvex throwing sticks would be thrown horizontally. Aerodynamic lift and gyroscopic precession would have an increasing role in a curving trajectory, especially towards the end of the flight, when the projectile decreases in translation speed and accumulates more rotation energy. To overcome this problem, hominins adapted their throwing technique by increasing the launch angle relative to the horizontal. The use of fire in the manufacture process also initiated the possibility of heating blades to tune them, thus obtaining a better control of the flight (Bordes, 2011, 2012).

The diversity of ethnological type in Australia testifies that the biconvex streamlining has affected very differently the three major groups of throwing sticks defined in part 5, as the simultaneous reduction in thickness and increase in surface cannot be distributed in the same way:

Biconvex streamlining on asymmetric throwing sticks

Asymmetrical curved throwing sticks were refined from circular to elliptical cross-sections and even further towards a biconvex cross-section without major shape transformation, because the increase in surface happens evenly as an increase in width over the entire length of these projectiles (See Figure 3).

Asymmetrical projectiles with a distal bulge were more heavily modified in shape because the increase in surface affected the distal blade first, as the bulge head becomes flattened (See Figure 3, 1a), followed by a weaker streamlining of the proximal blade to keep the handling function. To minimize the accentuation of curvature on these objects (see section **Curvature**

as a response to streamlining for flight stabilisation), which could lead to a decrease in their resistance, a solution is found by shifting the flattened distal head toward the interior of curvature, obtaining the type of shape of Lil-lil which are archaic throwing sticks found in Southeast of Australia (Davidson, 1936; Jones, 1996). A trace of this modification can be found on some throwing clubs in this particular area with the head decreased in thickness and shifted from a centred position related to the handle (See Figure 7A-B), which can be considered as a mid-step toward Lil Lil type of throwing sticks with flattened heads (See Figure 7C). Lil-Lil flattened heads can take a variety of shapes (round, semi-round, rectangular, square, and pointed) (See Figure 7C). The pointed head shape, another typical "flag" shape present in Southeast Australia (i.e., *marpungy*) (See Figure 7D-F). This is also frequently depicted in rock art in Europe (Cassen, 2012). These flag-shaped throwing sticks with flattened heads tend to have the distal following blade perpendicular to the long proximal handling blade, thus linking them closely to an asymmetrical "L" curved shape (See Figure 3, 1b), which could have influenced their development.

During this phase, a further evolution might have taken place from these types of throwing sticks with a flattened head, to some types with a longer distal following blade (See Figure 3, 2a), which can be classified as asymmetrical throwing sticks with widened short blade (Bordes, 2014). This category of throwing sticks, having high performance in flight, is the most widespread ethnological type of throwing stick found around the world. A trace of this evolution might be found in rock art depictions of prehistoric asymmetrical throwing sticks with very short distal blades (Lewis, 1998), (See Figure 7E) which have since disappeared (probably because of lower stability) to be replaced by longer distal short blades (e.g., *kylies*) (See Figure 7G).

Indeed, because asymmetrical throwing sticks always stayed close to their initial contact function, the longer proximal blade is used for handling and does not have the same function as the short blade, which is the active part, and is useful to hit or reach an object to be manipulated. When these objects have been further improved as projectiles with biconvex cross-sections, they started to be used more frequently as projectiles, which is a shape symmetrizing factor, because morphological difference between proximal and distal blades is no longer critical in this function. The result is a tendency for the enlarged head to evolve towards a short following blade and get longer to increase blade symmetry.

Another feature is developed during biconvex cross-section development on asymmetrical throwing sticks: the appearance of a mixed aerofoil cross-section, always with a lower streamlining applied on the long attacking blade compared to the short following blade (See Figure 3, 1a, 2a). These features are frequently present on ethnographic Australian asymmetrical throwing sticks, especially those with a flattened enlarged head (i.e., Lil-Lil) or a widened short blade (i.e., *kylies*). This can be considered as a reflection of their ancestry from older asymmetrical objects with a prior non-projectile function, and later modified to improve the cross-section of the shorter distal blade to increase rotation speed when used as a projectile function but maintaining a rounded or a less streamlined cross-section for the long handling proximal blade. Even during the following evolutionary phases, this mixed aerofoil design continued to exist (See Figure 3, 4a), because it ensured an additional stability gain for a curved asymmetrical throwing stick, balancing the aerodynamic lift by decreasing it on the attacking blade (proximal blade) relative to the following blade (distal blade) (see section **Compensation or accentuation of aerodynamic lift imbalance between blades**), and thus avoiding a turning effect in flight, and improving accuracy. However, some types of this group lost the mixed blade and evolved into a new type of aerofoil and end. (See Figures 3, 3a and 7H).

Biconvex streamlining on symmetrical throwing sticks:

Symmetric throwing sticks belong to a category which has encountered the most problems of stability and trajectory deviation when the circular cross-section became streamlined into a biconvex cross-section in phase III (see section **Blade streamlining of throwing sticks**).

However, further reduction of thickness by streamlining of biconvex section rapidly leads to the need for more curvature (see section **Curvature as a response to streamlining for flight stabilisation**) restricting them to a projectile function as they would then be too fragile to be used for fighting or digging. If some types were limited and their cross-sections remained elliptical to retain stability and resistance (See Figure 3, 2c), hominins would have been forced to find a solution to allow further streamlining. To solve this problem, some of the symmetrical curved throwing sticks increased the width of their elbow (See Figure 3, 3c). This increased surface at the elbow has a drawback for throwing sticks, as it shifts the centre of gravity toward the exterior of the elbow, which leads to climbing trajectories (Turck, 1972; Thomas, 1985)-a feature exploited by specialised light throwing sticks for bird hunting and favoured by boomerang design in later phases.

This increased curvature also leads to the appearance of the unbalanced lift effect between blades (see section **Compensation or accentuation of aerodynamic lift imbalance between blades**), producing an "S" shaped trajectory deviation, due to the gyroscopic effect, which decreases accuracy for hunting compared to a straight trajectory.

A solution to this major problem probably leads to the further diversification and specialisation of projectile functions: some of these symmetrical objects stayed more heavy and less curved; others continue on the trajectory of weight reduction but become slightly asymmetrical to compensate for this flaw (See Figure 3, 4c). Other solutions are to apply blade tuning to correct it (see section **Blade tuning to prevent throwing stick flip and enhance range**), or to increase the launching angle from the horizontal and aiming to keep the trajectory straight and accurate for ground hunting. Other lighter throwing sticks used on groups of small animals and birds could accommodate trajectory deviation as they need less accuracy, and humans during this phase could have already taken the opportunity to use aberrant curved flight for playing games (See Figure 3, 5c).

Other different adaptations of throwing sticks to specific functions might have happened during this phase, such as the appearance of hooked throwing sticks with a conic peg which might have accommodated heavy archaic spear throwing (Bordes, 2020) (See Figure 3, 6c), or the further stabilization of archaic straight double pointed sticks by a central bulge (See Figures 3, 7c and 5F).

Phase IV: Splitting

This phase is strongly represented on the Australian continent, but a few African throwing sticks have blades with almost plano-convex cross-sections attesting to this phase, too. Crafting throwing sticks by halving a single wood piece is probably the origin of the new asymmetrical aerodynamic aerofoils with the intrados (see Note 6) flattened underneath, leading ultimately to the refined plano-convex cross-section in the next phase. Indeed, this new technique using wood or stone wedges, speeds the wood removal process four times, by producing two throwing sticks instead of one, with half the wood removal (See Figure 8E) (Bordes, 2010). If wood splitting technique on medium density soft wood (e.g., pine spruce) have been recognized recently from older Pleistocene period in Europe (Leder et al, 2024), it might probably have reached full development later in late Pleistocene, with the availability of more efficient tools to remove hard dense wood (e.g., acacia, eucalypt) on whole wide (>3 cm) biconvex throwing sticks. Indeed, aerofoil cross-section shaping is by hafted stone tools like hatchets or adzes in Australia. The introduction of hafted polished axes and wedges, which were present in parts of Australia at least from ~60,000 years ago (Clarkson et al., 2017), could have been crucial in the full development of this new crafting technique for throwing sticks. Another aspect about halving is the spiritual importance of the link that could exist between the two halved separated parts which were once part of the same piece. As an example, native people from the central desert Australian region were always keeping their *kylies*8 together when they are being used for non-projectile use, such as clapping them together as a pair to produce rhythmic music, and even keeping them as a pair when exchanging for trading (Jones, 1996). Apart from throwing sticks, this spiritual link could also have existed for many other "twin" objects crafted by halving a whole material in prehistory, even manufactured in other material than wood (i.e., bone, antler, ivory, stone). In Australia, a reflection of this halved technique might be represented in rock art by "twin throwing sticks" depicted as pairs (Jones, 1996; Bordes, 2010). Rock engraving at Karlota rock art site, South Australia (See Figure 8D)(Flood, 1997) dating back to 40 000 BP suggests a potential global start time for phase IV, during the Early Upper Palaeolithic. The famous *kylie* throwing sticks from the central desert region in Australia are still made traditionally using by this halving technique as it could be checked on the wood section of these implements by X-ray tomography (See Figure 8C) (Bordes, 2019). In Europe, a representative object of this phase

(Gravetian, ~23 000 BP) could be the ivory throwing stick discovered at Oblazowa, obtained by splitting a mammoth tusk (See Figure 8A-B) (Valde-Novak, 1987). Consequently, throwing sticks with decreased thickness and mass (see section **Weight and wingspan reduction**) with increased streamlining (see section **Curvature as a response to streamlining for flight stabilisation**) are produced, and the aerodynamic lift effect allows optimal long ranges (+80m) (Callahan, 1975; Bordes, 2014). Technological competition of throwing sticks with spear throwers might have explained the need for increased performance at this stage.

Solutions to maintain stability and resistance of almost plano-convex throwing sticks are the same as proposed for the previous phase but could have been even more refined during this period. Blade tuning (see section **Blade tuning to prevent throwing stick flip and enhance range**) starts to be more critical to maintain a good aiming trajectory on long range flights, and such developments during this phase explain its full maturity in the next one. Light symmetrical objects encounter flight instability when they have a low wingspan: height ratio (see section **Curvature as a response to streamlining for flight stabilisation**); and they encounter an accentuated gyroscopic precession effect, frequently leading to a curved trajectory with returning effect. For light throwing sticks, mastering advanced aerofoil design, and perfect blade tuning is the technological apex for achieving a very long straight range (+ 80 m) (Callahan, 1975; Bordes, 2014), But other failed designs shorten their range significantly with curved and returning trajectory, leading to new hunting technique adapted to birds. And finally, the first returning throwing sticks, known as archaic heavy boomerangs, are invented from such throwing sticks failure to maintain straight trajectories and then, exploited for new functions (See Figure 3, 8c).

Phase V: Refined streamlining

This phase is almost exclusively represented in Australia because the plano-convex section is most attested on this continent, even if some rare examples of African asymmetric throwing sticks with plano-convex flattened heads from Sudan exist (See Figure 3). It is a period of increasing wood removal on throwing sticks using commonly hafted stone tools like a hand axe or adze available at the end of the Upper Palaeolithic. Finer shaped aerofoils lead to an outstanding increase in aerodynamic lift with the appearance of true plano-convex aerofoil sections. Light throwing sticks and especially Australian boomerangs are improved in this phase (see section **Weight and wingspan reduction**) (See Figure 3, 9c). If the oldest returning throwing sticks (boomerang) found at Wyrie swamp are dated from 11 000 BP (Luebbers, 1975), the existence of such light returning type of projectile can be inferred earlier from the Bradshaw figures rock art in Kimberley (dated from 17 000 BP) which depict multiple short and very curved objects in the hands of dancers which have a high probability of being returning projectiles (Bordes, 2014). In consequence, a starting point for this phase can be proposed around 20 000 BP which is the antiquity proposed for boomerangs. During this period, a few other throwing sticks probably also found original solutions to solve the stability problem induced by streamlining to plano-convex sections. For example, low angled crescent-shaped objects with plano-convex sections from Kimberley narrowing their elbow to a lower gravity centre and so avoid flipping during flight (See Figures 3, 10c and 9A-C). But a large majority of others didn't change to the full plano-convex section in this phase because it could have endangered their stability and being too light, their efficiency and resistance. Instead, they more frequently adopted a mixed aerofoil as observed on *kylies* or hooked *wirlkies* from the central desert in Australia. Indeed, these types of throwing sticks are built with a plano-convex section on their short, wide following blade but keep a more ancient biconvex or almost plano-convex section on the attacking long blade used for grip.

Phase VI: Diversification, new shapes and aerofoils, and the use of metal

Diversification and specialisation of throwing sticks with a new type of geometric aerofoil section (rectangular, biconvex/rectangular, semi-biconvex, diamond) and truncated or bevelled ends happen in this last phase (See Figure 3). These new sections and type of extremities are probably the result of working with standardized hafted stone tools or metal tools and possibly a loss of the functions linked to rounded and pointed extremities (e.g., digging). An example of the final evolution of throwing sticks with widened short blade and mixed aerofoil is the Indonesian Parimpah using truncated ends, and a combination of diamond, rectangular and rounded sections (See Figures 3, 6a and 9D), some of these types, belonging to asymmetric angled shapes, using a combination of ancient sections (biconvex, rounded) (See Figures 3, 2b and 9E). Truncated ends have often been used on older types of throwing sticks in phase VI, testifying that these older types might have once existed in Indonesia. About Symmetric types, crescent shapes are also found with truncated ends in South Australian boomerangs, which, interestingly, maintain a very archaic biconvex section (See Figures 3, 11c and 9F), or crescent-shaped throwing sticks from Gujarat, India (See Figures 3, 11c and 9G). Other asymmetric crescents in Australia of recent manufacture are found with this same type of extremity (See Figures 3, 3b and 9H). Additionally, it should be noted the probable appearance in this last phase of cross-shaped boomerangs (See Figures 3, 13c) used for hunting birds and game originating from Sulawesi, Indonesia, and imported into Australia (Queensland) in this later period (Kaudern, 1925; Bordes, 2009b). The prehistoric origin of cross boomerangs is unknown, but might date back to phase IV as a splitting technique, and almost plano-convex section are required (See Figures 3, 13c and 9I-J). Asymmetric throwing sticks with mixed aerofoils are common at this period, and new shapes are made to answer to different specialized functions. Neolithization and herding of animals might have a relationship with the appearance of crozier and "L" shape shapes with a tendency to a widened short blade (See Figures 3, 5a, 7a, 2b and 10C-G). Neolithic people in Europe tend to favour highly stable and easy-to-tune asymmetric throwing sticks with a widened short blade and a small wingspan (See Figures 3, 7a and 10A) instead of using less archaic crescent shapes that are more difficult to master. These small wingspan "L" shaped projectiles are to be put in relation to a shift to bird and small game hunting as found on

Neolithic sites such as Egolzwil (Switzerland) or Bouchain lake (France) (Ramseyer, 2000; Leroy et al., 2023) or for ethnology around lake Tchad in Africa (See Figure 10B) (Bordes, 2014). These numerous Neolithic "L" and crozier shaped throwing sticks in Europe, along with the coexistence of other types which can be observed on the hunting scene painted in the Choppo cave, Spain, dating from 8000 BP (Picazo et al., 2001, Bordes, 2014) allow a proposed starting date from that final phase of around 10 000 years ago.

Indeed, in this phase, a change to a more sedentary way of living, throwing sticks lose their status as the primary ranged weapon to new weapons (i.e., bows). Their function shifts to a secondary weapon, possibly used by young people to keep birds out of crops as Parimpah are used in Indonesia to hunt birds over Rice fields (See Figure 9D-E) or for hunting game in conjunction with the bow (See Figure 10I). Nevertheless, as they are still revered for their antiquity and belong to a very old tradition, they also acquire a new symbolic status reflected by numerous throwing stick engraved shapes on megalith monuments (See Figure 10H) (Cassen 2000, 2012). Reflecting this tendency to pass to the symbolic sphere, the Gaulish bird hunting throwing stick found in Urville-Nacqueville (Bordes et al., 2015) has been recognised as functional after the first metal strip reinforcement, but probably non-functional as a throwing weapon, after the addition of four additional metal strips, which might have been the cause of its symbolic deposit (See Figure 11A).

At this stage, concomitant with the development of metallurgy, copper alloys and iron starts to be used as new materials for throwing sticks, which are also manufactured with metal tools, contributing to their diversification and innovation in new types of sections and extremities. Iron starts to be used to reinforce or repair throwing stick blades as with the Urville-Nacqueville Gaulish artefact cited above (See Figure 11A) or observed on South Indian *valari* (See Figure 11B-C)(Bordes, 2015, 2021). This progressive shift from wood to metal could be observed on the Indian *valari*, which started to be made from composite materials, mainly from wood, but sometimes with the addition of metal parts such as the blades at their extremities. In a last step, South Indian people produced *valari* throwing sticks entirely in metal, directly inspired by wooden projectiles such as Indian *katariya* (i.e., *valari*) (See Figure 11D)(Hornell, 1924). Throwing weapons entirely in metal based on throwing stick technology were probably invented to further enhance the striking efficiency of these projectiles on large and dangerous game (e.g., tiger hunts in India with kateriya) or when used at war. It's also possible to follow such final evolution of throwing sticks to metal weapons in Africa, as crozier shaped metal small throwing sticks of an old design can be found (See Figure 11E), but also with completely new multi-bladed designs such as metal knives in Africa (See Figure 11F) (McNaughton, 1970; Childs, 2016). However, this final evolution of throwing sticks removes them from the scope of study as wooden projectiles.

Conclusion

If the origin of throwing sticks is difficult to grasp with certainty, these projectiles have probably played a role in the early use of tools by hominids as they confer the "power" to act remotely, which is still sought nowadays.

The key discovery of an archaic double-pointed throwing stick in Schöningen set a very early starting point of the prehistory of these projectiles in Europe, hence we need to examine their technical evolution until Neolithic and historical times when they were still used. What about throwing sticks in Europe through the Ice Age when wood was less available? Does the discovery of the ivory throwing stick in Oblazowa mark an adaptation of available material? On another hand, the biconvex section of this object, probably started earlier, which also marks an important key step in throwing stick technology, which can be compared in importance to the discovery of the stone biface and its implication for all the resulting flaking technology. The later Neolithic period, with important settlement changes in human societies, seems to be reflected in some new types of throwing sticks used (e.g., crozier) probably in relation to the appearance of new functions (e.g., herding), and their slow shift to a symbolic status. In the gap between these periods, only ethnology and experimentation can help to gain insight into how this might have happened, waiting for future additional discoveries.

Paradoxically, in Australia, changes in throwing stick technology are not only seen through archaeological discoveries and rock art, but also through the large diversity of ethnological objects. Indeed, as observed about the use of stone tools, efficient archaic throwing sticks continue to be used alongside new types, leading to a diversification which is also a testimony to their antiquity and allows us to retrace their different former functions. This large panel of throwing sticks used in Australia by native people also helps to better understand how different types have evolved and refined as, for example, from throwing clubs through flattened head throwing sticks to asymmetric short wide blade types. These evolutions have been probably influenced by other side functions (e.g., cutting) which contributed to their efficiency as projectiles.

Surprisingly, Aboriginal people's myths can sometimes also shed light on the origins of Australian throwing sticks. Indeed, one of the most famous myths of the invention of boomerangs (Thomas, 1985) explains that it was an old man, forced to bend down at the creation of the world, because the sky and earth were too close, who planted his stick in the ground and pushed the sky away. His stick became bent after that, and he decided to keep it with him when he threw it away and saw how it could fly and return. From this story, one can think that it might be, before being a projectile flying through the air, symmetric pointed throwing sticks were perhaps linked to the earth as digging tools and that their functional and technological evolution has been like a hyphen between these two spheres. Besides aboriginal myths, the throwing sticks evolution scheme should be refined in different continents and subregions, according to their environment changes and weapons innovation, which could have influenced their functional adaptation.

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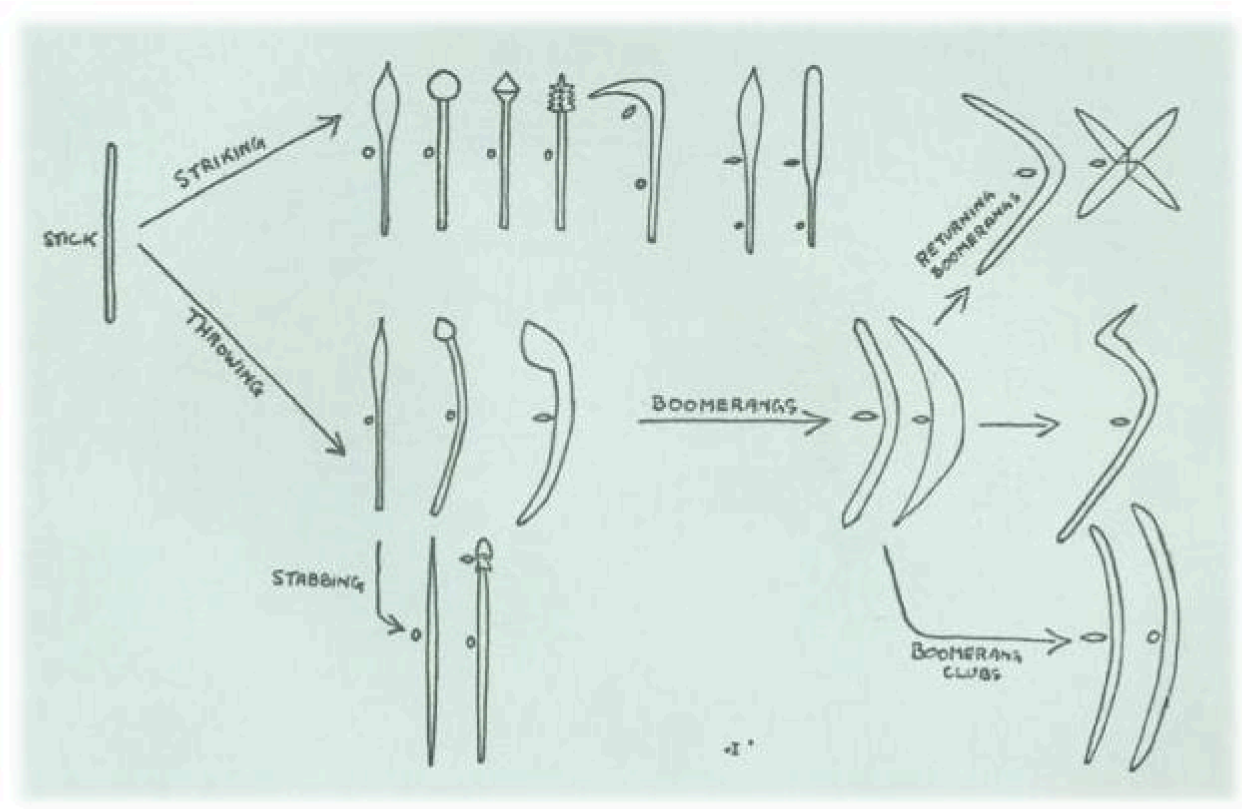

FIG 1. CRANSTONE LECTURE DRAWING OF THROWING STICK EVOLUTION IN FUNCTION OF THEIR USE AS PROJECTILE OR AS FIGHTING WEAPON (PITT RIVER MUSEUM,). HTTP://ENGLAND.PRM.OX.AC.UK/ ENGLISHNESS-PR-AND-BOOMERANG-TECHNOLOGY.HTML

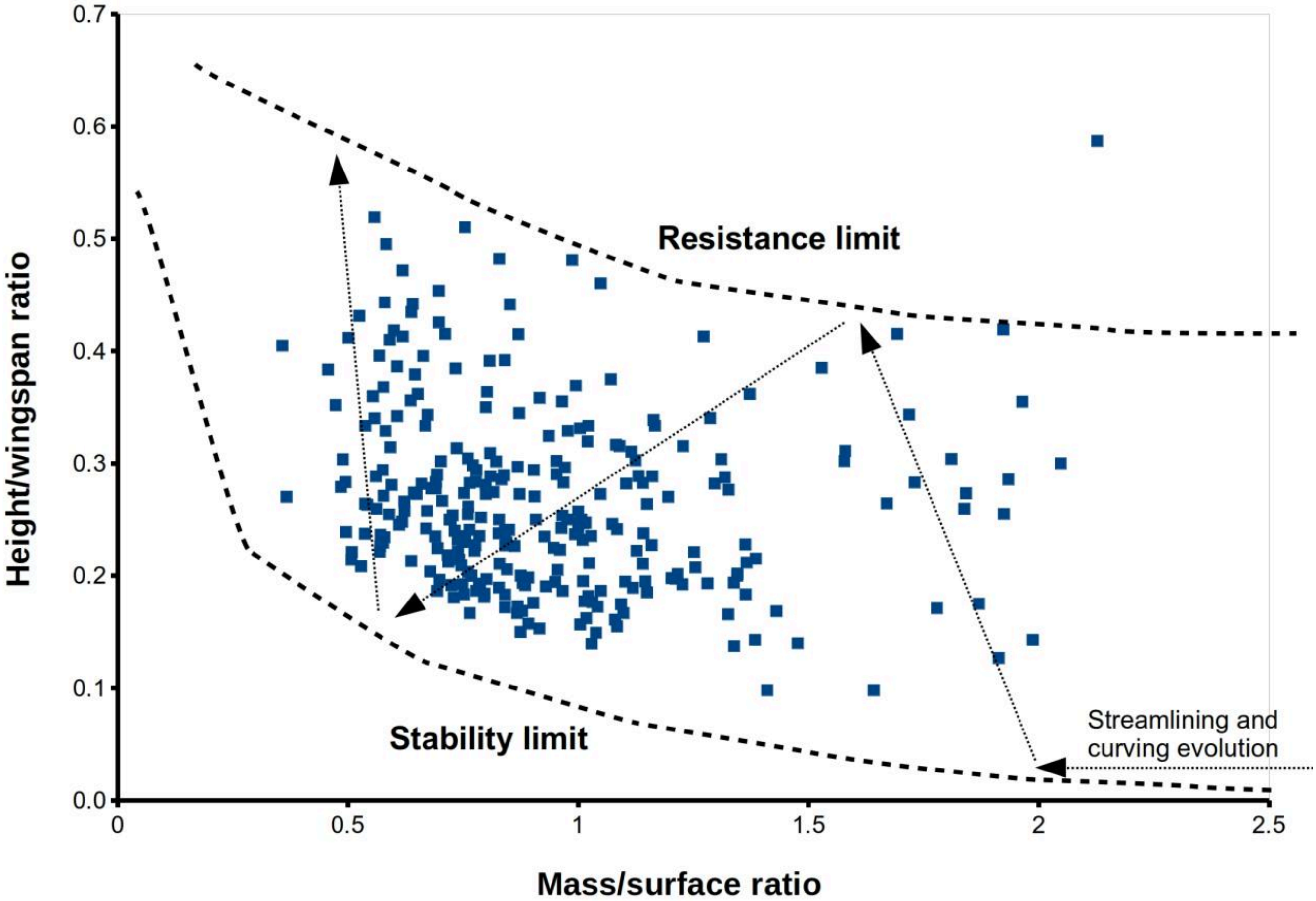

FIG 2. A DIAGRAM REPRESENTING THE MEASUREMENT OF THE HEIGHT TO WINGSPAN RATIO (EXPRESSING CURVATURE) AGAINST THE MASS TO SURFACE VALUE (EXPRESSING CARRYING SURFACE) OF 273 MEASURED THROWING STICKS IN DIFFERENT MUSEUMS7 SHOWING THAT LIGHTER OBJECTS NEED TO BE MINIMALLY CURVED AND THAT A TECHNOLOGICAL LIMIT RELATIVE TO CURVATURE IS VISIBLE ON THIS GRAPH (STABILITY LIMIT) WHEN INCREASING THE AEROFOIL SECTION STREAMLINING. ANOTHER LIMIT (RESISTANCE LIMIT) CAN BE OBSERVED ON THIS SAME GRAPH AS THROWING STICKS ALSO NEED TO LIMIT THEIR CURVATURE TO MAINTAIN MINIMAL RESISTANCE (BORDES, 2009).

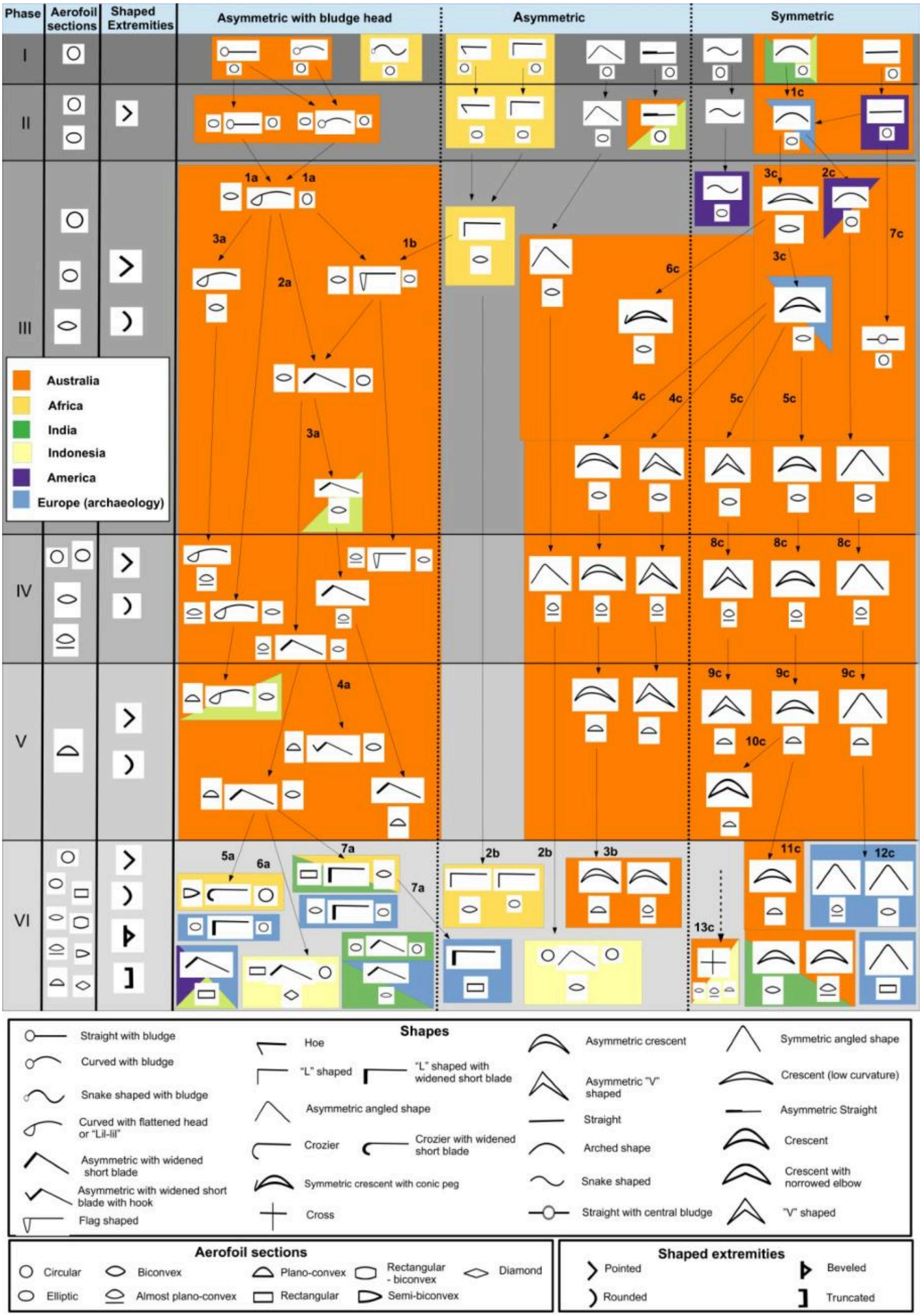

FIG 3. DIAGRAM OF EVOLUTION OF THROWING STICKS PER PHASE PROPOSING TYPE CHANGE ACCORDING TO THREE MAJOR CLASS OF SHAPE. INNOVATION CONCERNING AEROFOIL SECTION(S) AND EXTREMITIES ARE ALSO INDICATED PER PHASE. EACH THROWING STICK TYPE APPEAR EITHER WITH ONE TYPE OF SECTION (BELOW THE SHAPE), WITH TWO DIFFERENT SECTION FOR ATTACKING AND FOLLOWING BLADE (ON BOTH SIDE OF THE SHAPE), OR IN SOME CASES WITH THREE DIFFERENT MIXED SECTIONS (TWO FOR EACH BLADE AND A THIRD FOR THE ELBOW). PLAIN ARROWS ARE INDICATING A POSSIBLE EVOLUTION BETWEEN TWO TYPE OF THROWING STICKS,

DOTTED ARROWS INDICATING APPEARANCE OF A TYPE WITH AN UNKNOW ORIGIN. A COLOR CODE IS INDICATING ON WHICH CONTINENT ARE FOUND THE DIFFERENT TYPES OF ETHNOLOGICAL THROWING STICKS.

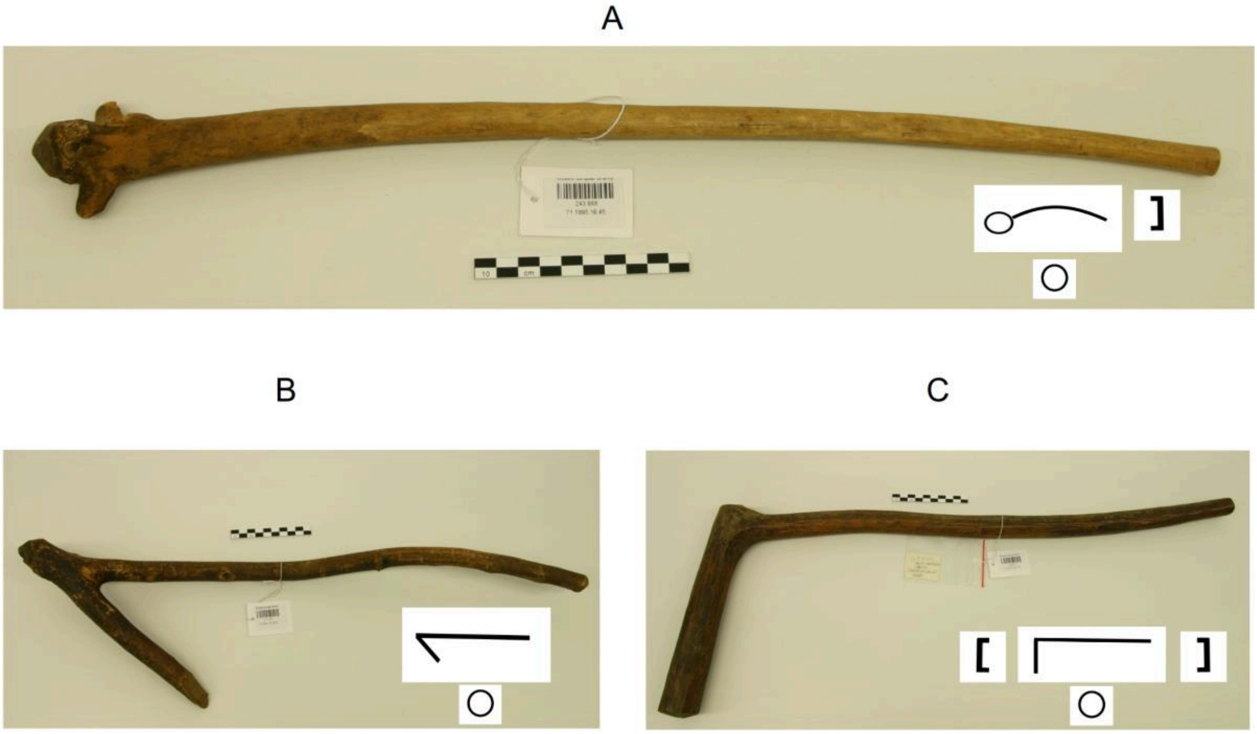

FIG 4. PRIMITIVE AFRICAN THROWING STICK WITH BULGE MADE OF A SLIGTHLY MODIFIED BRANCH, SOUDAN, DANKA PEOPLE (QUAI BRANLY MUSEUM, PARIS) (A), PRIMITIVE HOE SHAPED THROWING STICK FROM MALI, DOGON PEOPLE (QUAI BRANLY MUSEUM, PARIS) (B), “L” SHAPED PRIMITIVE THROWING STICK FROM MALI, SÉGOU, BOBO OULÉ PEOPLE (QUAI BRANLY MUSEUM, PARIS) (C). SYMBOLIC NOTATION SHOWING SHAPE, SECTION(S) AND SHAPED EXTREMITIES CLASSIFICATION (SEE LEGEND FIG. 3)) IS INDICATED ON EACH IMAGE. NOTE THAT THE ABSENCE OF SYMBOL FOR ONE OR BOTH EXTREMITIES MEANS ONLY A RAW CUTTED END, THEN THE ABSENCE OF ANY SHAPED EXTREMITY. ALL IMAGES AND GRAPHS ARE FROM THE AUTHOR UNLESS OTHERWISE CITED.

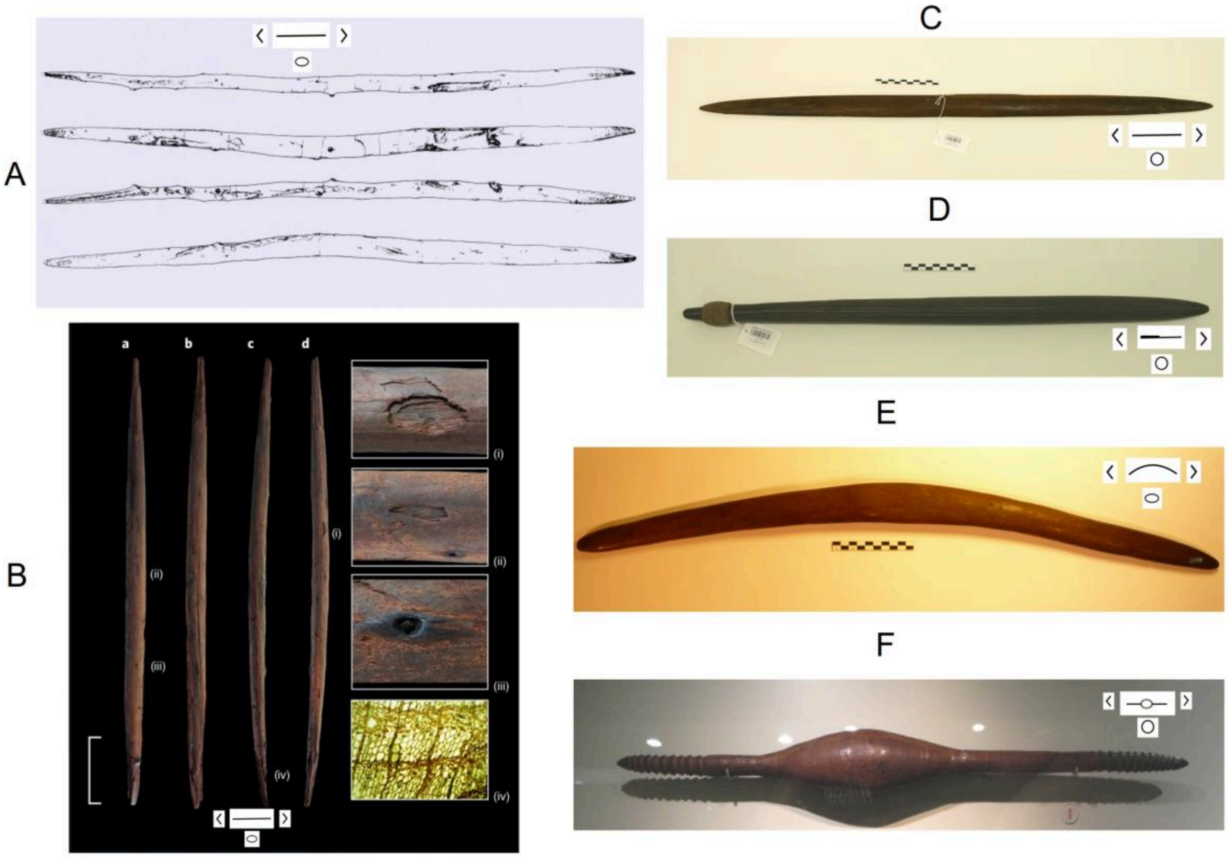

FIG 5. DOUBLE POINTED WOODEN STICK IN SPRUCE DISCOVERED ON SCHÖNINGEN SITE IN 1994 (WINGSPAN 78 CM) (THIEME, 1999, P471) (A), SECOND DOUBLE POINTED WOODEN STICK IN SPRUCE DISCOVERED ON SCHÖNINGEN SITE IN 2011 (CONARD ET AL. 2020, P2), (B), EXAMPLE OF ETHNOGRAPHIC ABORIGINAL SYMMETRIC DOUBLE POINTED STICK, ARID INTERIOR REGION OF AUSTRALIA (QUAI BRANLY MUSEUM, PARIS)(C), EXAMPLE OF AFRICAN (SOUDAN) ASYMMETRIC STRAIGHT THROWING STICK (QUAI BRANLY MUSEUM, PARIS) (D), DOUBLE POINTED THROWING STICK WITH LOW CURVATURE FROM WESTERN AUSTRALIA (PRIVATE COLLECTION, STEPHANE JACOB, PARIS) (E), RARE EXAMPLE OF DOUBLE POINTED THROWING STICK WITH CENTRAL BLUDGE (SOUTH AUSTRALIAN MUSEUM) (F). SYMBOLIC NOTATION SHOWING SHAPE, SECTION(S) AND EXTREMITIES CLASSIFICATION (SEE LEGEND FIG.3)) IS INDICATED ON EACH IMAGE.

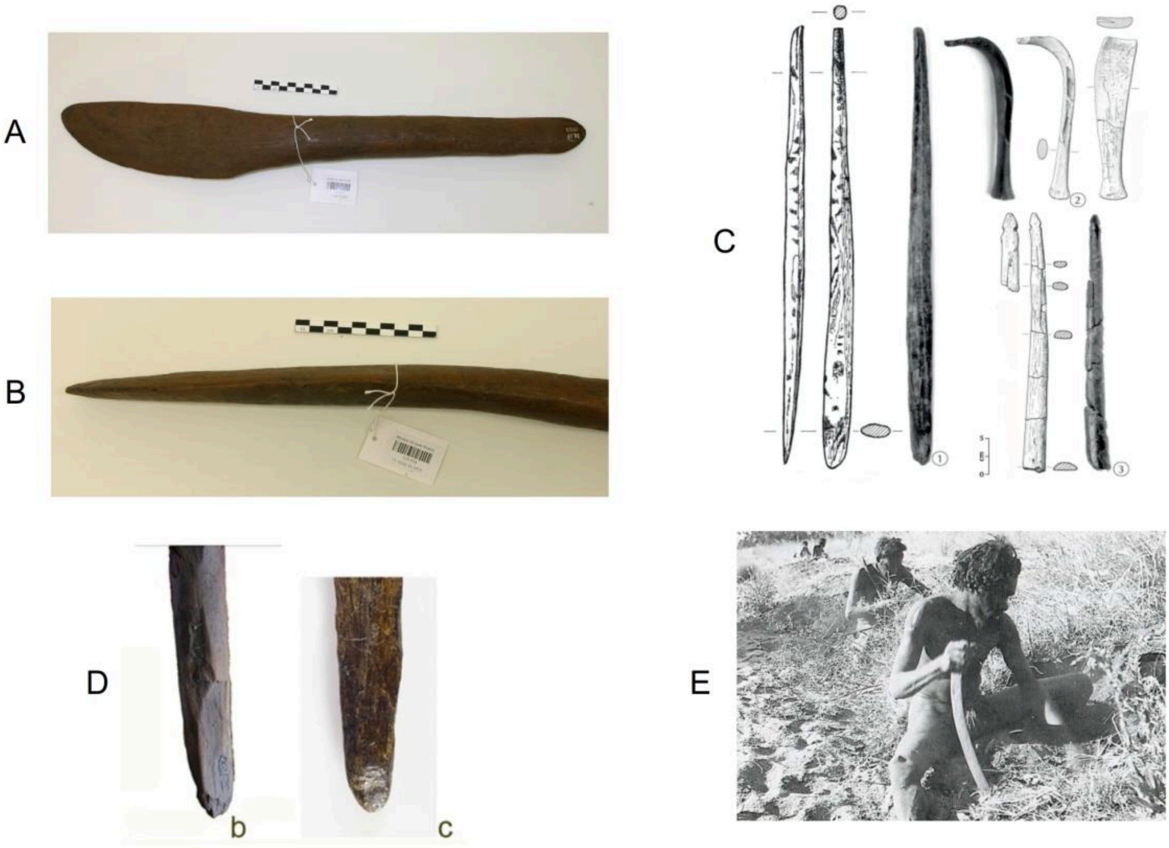

FIG 6. A FLAT ENDED DIGGING STICK FROM PERU (DATED FROM 1930) WITH VIEW FROM TOP SURFACE AND EDGE (QUAI BRANLY MUSEUM, PARIS) (A-B), A NEOLITHIC DIGGING STICK FOUND AT THE SITE OF LA DRAGA IN SPAIN, SHOWING A POINTED AND A FLATTENED EXTREMITIES (1) AMONG OTHER WOODEN DISCOVERED IMPLEMENTS (PALOMO ET AL., 2013, P392) (C), ONE OF THE DIGGING STICK FOUND AT NEANDERTHAL SITE OF POCHETTI VECCHI IN ITALY SHOWING A FLATTENED EXTREMITY, DUE TO A DAMAGE FROM USE (ARANGUREN ET AL., 2018, P2056) (D), ABORIGINAL MEN DIGGING WILD ONIONS WITH KYLIES IN AUSTRALIAN CENTRAL DESERT AREA (JONES, 1996, P34) (E).

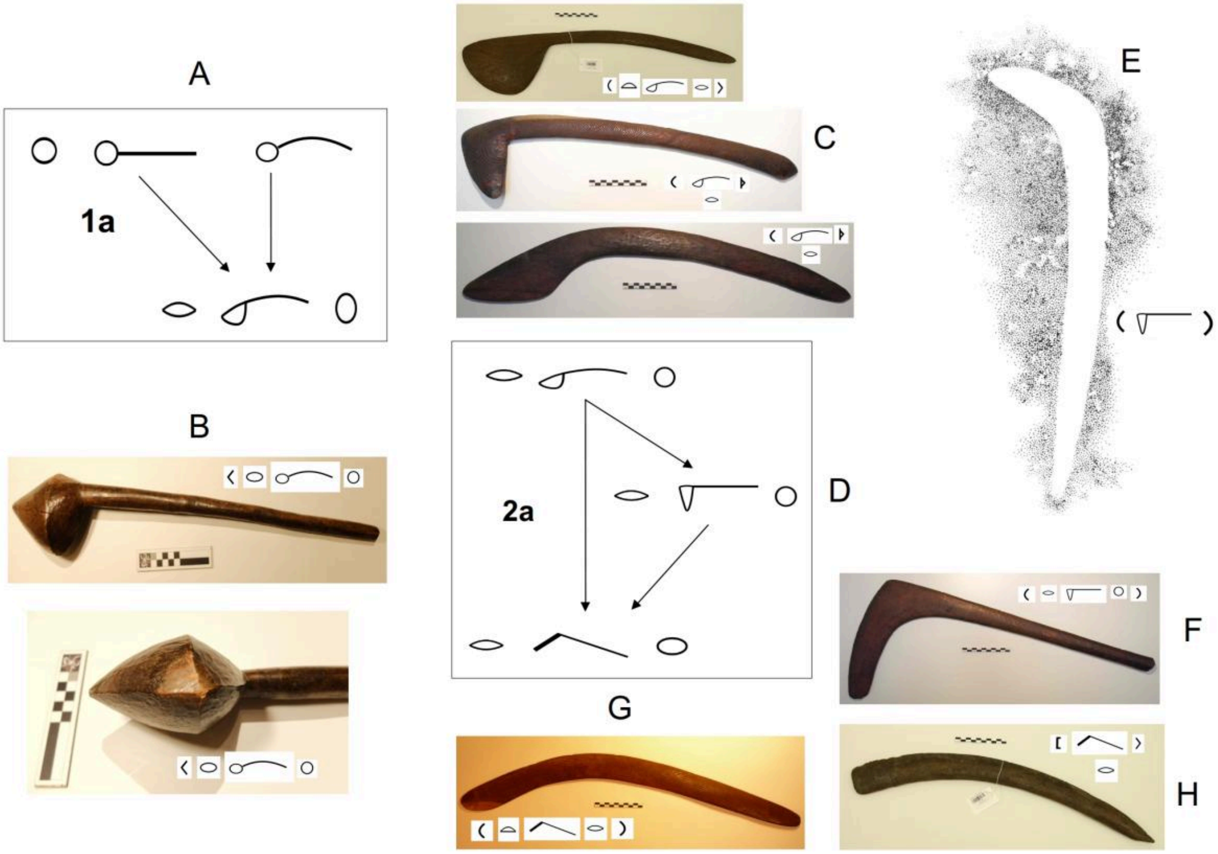

FIG 7. EVOLUTION FROM ASYMMETRIC SHAPE WITH BLUDGE HEAD IN AXIS TO SHIFTED FLATTENED HEAD (A), THROWING CLUB FROM SOUTHEAST OF AUSTRALIA WITH HEAD DECREASED IN THICKNESS AND SHIFTED FROM CENTRED POSITION RELATED TO THE HANDLE (PRIVATE COLLECTION, STEPHANE JACOB, PARIS) (B), AUSTRALIAN ASYMMETRIC THROWING STICKS WITH HEAD CALLED "LIL-LIL" (PITT RIVER MUSEUM, OXFORD), ROUNDED HEAD, TRIANGULAR HEAD, ELONGATED HEAD (C), EVOLUTION OF "LIL-LIL" SHAPED THROWING STICKS TO "FLAG" SHAPED AND ASYMMETRIC WIDENED DISTAL SHORT BLADE THROWING STICKS (D), STENCIL OF DISAPPEARED TYPE OF THROWING STICK WITH VERY SHORT POINTED DISTAL BLADE, UBIRR ROCK ART SITE (LEWIS, 1998, FIG45) (E), FLAG SHAPED MARPUNGY THROWING STICK (PITT RIVER MUSEUM, OXFORD) (F), TYPICAL KYLIE (PRIVATE COLLECTION, STEPHANE JACOB, PARIS) (G), BICONVEX THROWING STICK FROM TCHAD (LOGONE REGION) WITH RECENT TRUNCATED END AND AN ARCHAIC POINTED END (QUAI BRANLY MUSEUM, PARIS) (H).

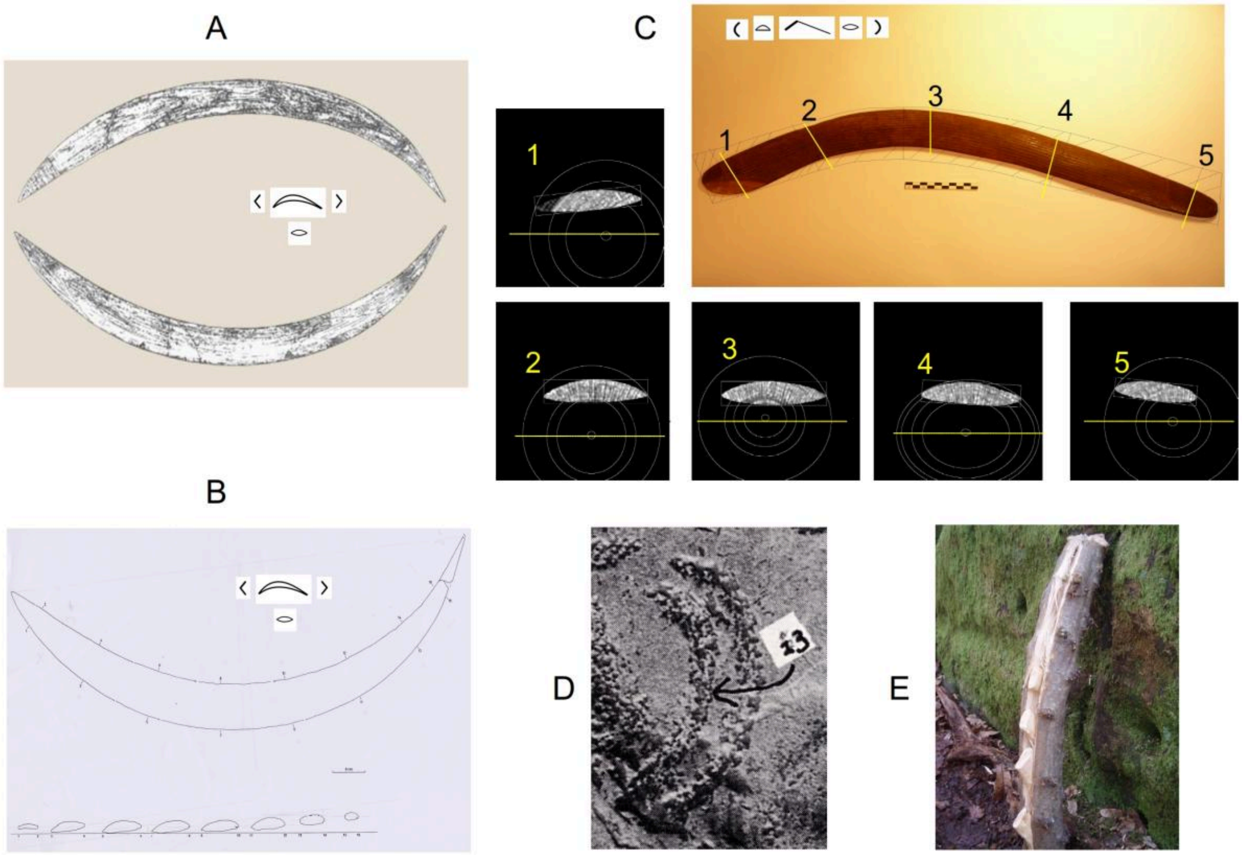

FIG 8. CRESCENT SHAPED ASYMMETRIC THROWING STICK MADE OF MAMMOTH IVORY DISCOVERED AT OBLAZOWA, POLAND (VALDE-NOWAK, 1987, P437) (A) , DRAWING OF THE OBLAZOWA THROWING STICK SHOWING VARIATION BETWEEN ELLIPTIC, BICONVEX AND ALMOST PLANO-CONVEX SECTION RESULTING FROM THE HALVING OF A MAMMOTH TUSK (VALDE-NOWAK, 1987, P437) (B), X-RAY TOMOGRAPHY ON A KYLIE FROM CENTRAL DESERT SHOWING THAT THE WOOD RINGS ARE ALWAYS LIMITED TO HALF OF THE WOOD PIECE, DEMONSTRATING THE TRADITIONNAL HALVING TECHNIQUE FOR THIS OBJECT (BORDES, 2019, HTTPS://EXARC.NET/ISSUE-2019-3/EA/X-RAY-TOMOGRAPHY-AND-INFRARED-SPECTROMETRY-ANALYSIS-THROWING-STICKS-BOOMERANGS) (C), ENGRAVING OF A PAIR OF THROWING STICKS AT KARLOTA ROCK ART SITE, SOUTH AUSTRALIA DATED AROUND 40 000 BP (FLOOD, 1997, P124) (D), EXPERIMENTATION TO HALVE A PIECE OF HORNBEAM WOOD IN A PAIR OF THROWING STICK WITH WOODEN WEDGE (BORDES, 2010, P79) (E). SYMBOLIC NOTATION SHOWING SHAPE, SECTION(S) AND EXTREMITIES CLASSIFICATION (SEE LEGEND FIG.3)) IS INDICATED ON EACH IMAGE.

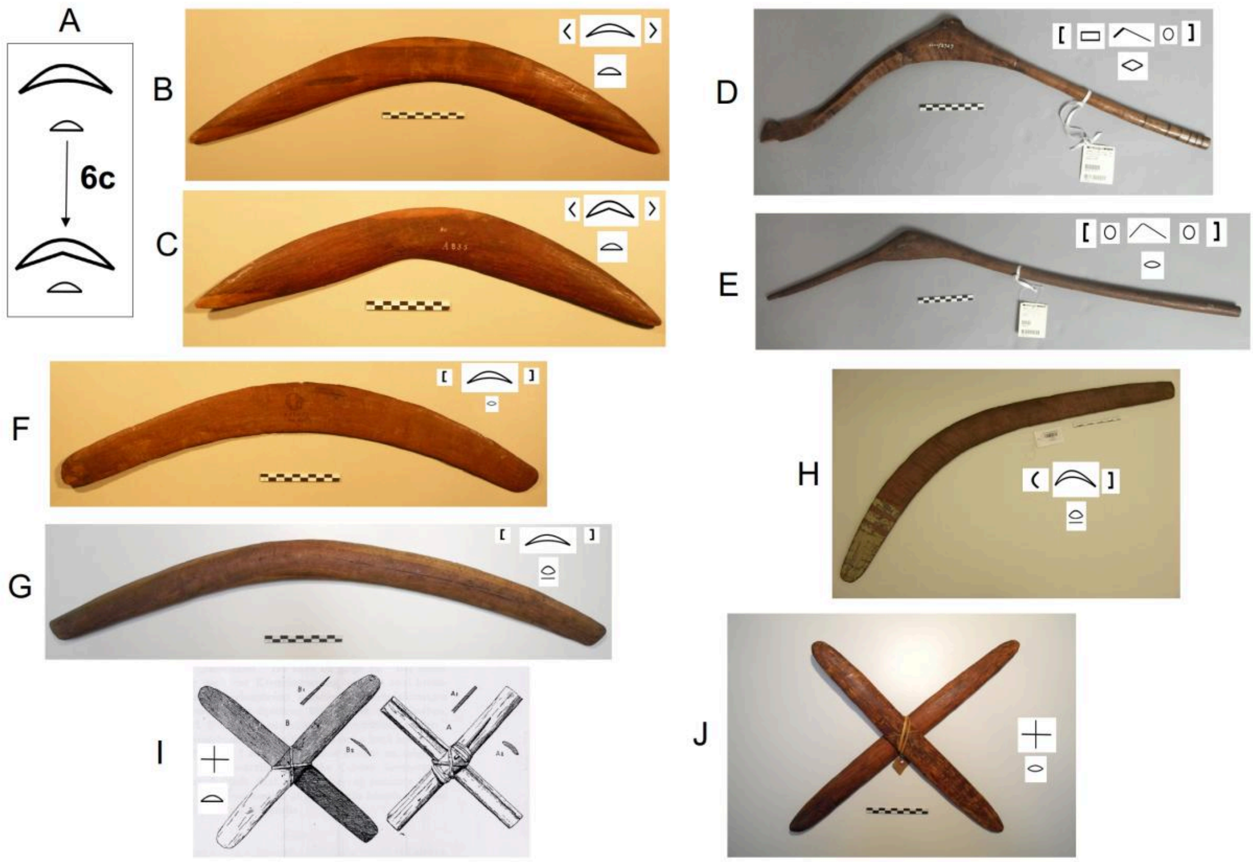

FIG 9. EVOLUTION STEP 6C EXTRACTED FROM FIGURE 3 (A), CRESCENT SHAPED THROWING STICK FROM NORTH WEST KIMBERLEY, KALUMBURU KALURI (SOUTH AUSTRALIAN MUSEUM) (B), CRESCENT SHAPED THROWING STICK WITH NARROWED ELBOW FROM, FITZROY RIVER (SOUTH AUSTRALIAN MUSEUM) (C), INDONESIAN THROWING STICKS FOR BIRD HUNTING (PARIMPAH), SULAWESI (VOLKENKUNDE MUSEUM, LEYDEN, NETHERLAND) (D-E), TRUNCATED CRESCENT SHAPED BICONVEX SOUTH AUSTRALIAN BOOMERANG (SOUTH AUSTRALIAN MUSEUM) (F), TRUNCATED CRESCENT SHAPED ALMOST PLANO-CONVEX INDIAN THROWING STICK FROM GUJARAT, INDIA (PITT RIVER MUSEUM, OXFORD) (G), TRUNCATED ASYMMETRIC CRESCENT SHAPED THROWING STICK FROM MORNINGTON ISLAND (AUSTRALIA) (QUAI BRANLY MUSEUM, PARIS) (H), COMPARISON BETWEEN AN AUSTRALIAN CROSS WOODEN BOOMERANG FROM AUSTRALIA AND A CROSS BOOMERANG IN BAMBOO FROM SULAWESI (KAUDERN, 1925) (I), CROSS WOODEN BOOMERANG FROM AUSTRALIA (QUEENSLAND) (PITT RIVER MUSEUM, OXFORD) (J).

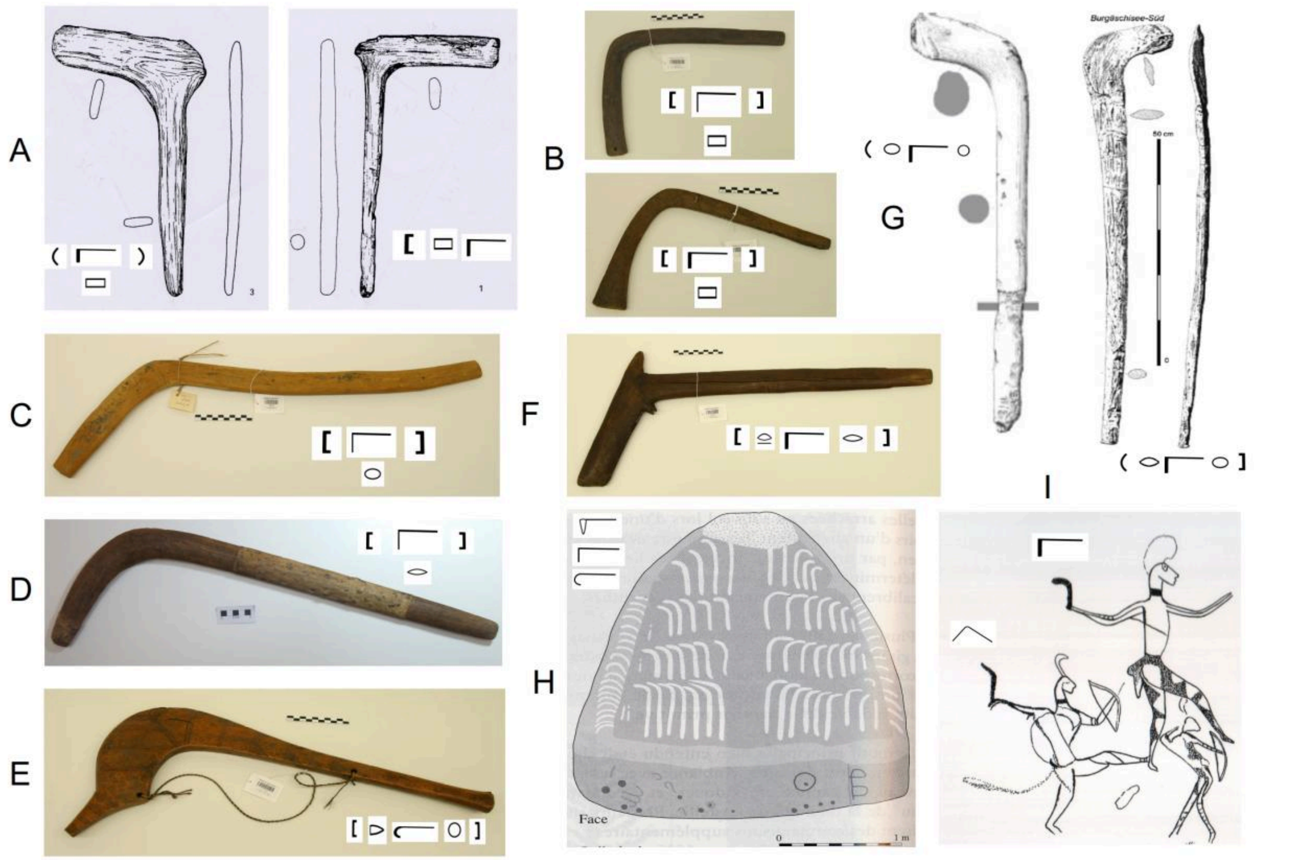

FIG 10. TWO “L” SHAPED THROWING STICKS FOUND AT ELGOZWIL, SWITZERLAND (A) (RAMSEYER, 2000, P139), TWO “L” SHAPED THROWING STICKS USED TO HUNT BIRDS OVER LAKE TCHAD (AFRICA) (QUAI BRANLY MUSEUM, PARIS) (B), “L” SHAPED ETHNOGRAPHIC TCHADIAN THROWING STICK USED TO HUNT SMALL ANIMALS AND HERDING (QUAI BRANLY MUSEUM, PARIS) (C), “L” SHAPED AFRICAN THROWING STICK WITH SKIN REINFORCEMENT (PITT RIVER MUSEUM, OXFORD) (D), CROZIER SHAPED HEAVY THROWING STICKS, MALI, SEGOU REGION, USED TO HUNT BUFFALO (QUAI BRANLY MUSEUM, PARIS) (E), SAFROUK, “L” SHAPED THROWING STICK FROM TCHAD (AFRICA) (QUAI BRANLY MUSEUM, PARIS) (F), TWO NEOLITHIC L SHAPED THROWING STICK FROM ROANES SKOV (DENMARK) (LEFT) (ANDERSEN, 2009), AND BURGASCHISEE SUD (SWITZERLAND) (RIGHT) (CASSEN, 2012, P190) (G), DRAWING OF THE MERCHANTS' TABLE IN LOCMARIAQUER (CASSEN, 2000, P678) (H), TWO HUNTERS HOLDING BOW AND THROWING STICK IN A HUNTING SCENE, IN-AGLIM ROCK ART SITE, IMMIDIR, TASSILI-N-AJJER, ALGÉRIA. AROUND 6500 BP (I) (GAUTHIER, 1996).

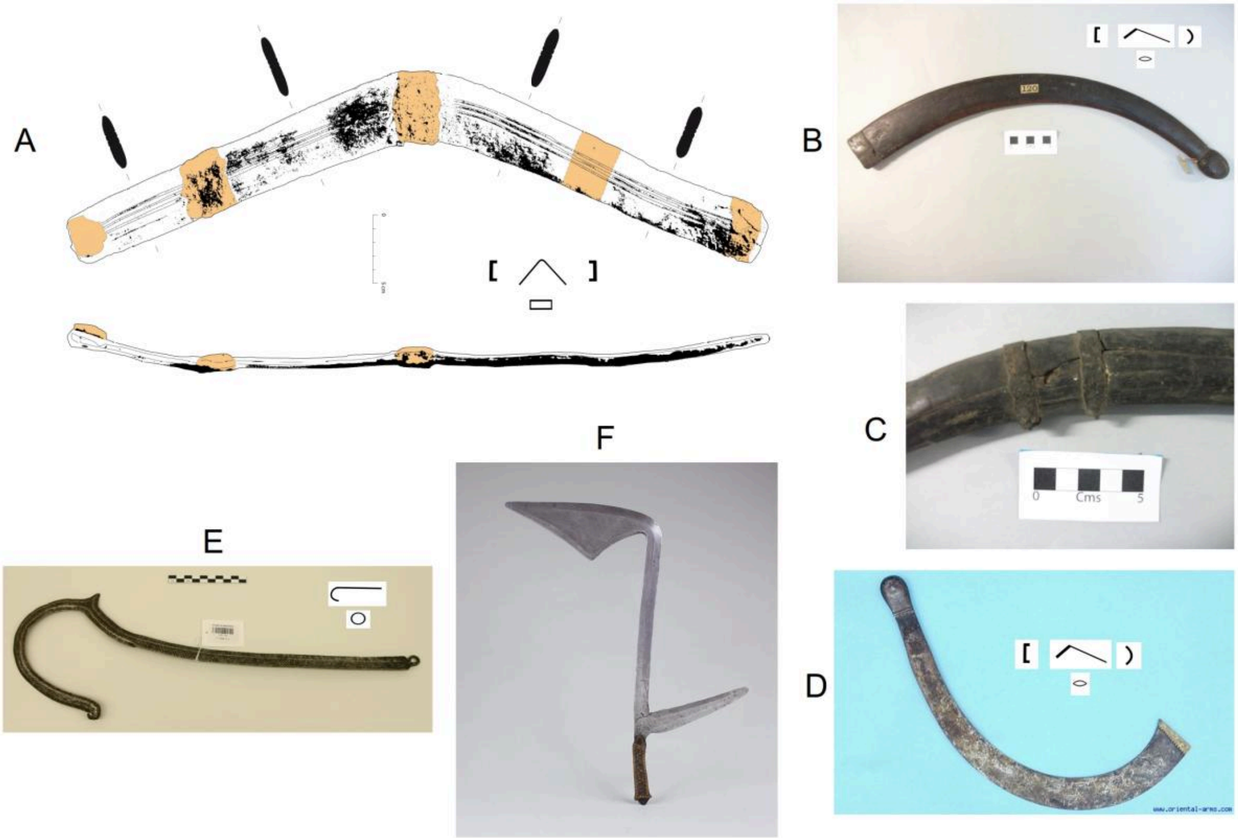

FIG 11. GAULISH THROWING STICK, WITH BICONVEX/RECTANGULAR SECTION, REPAIRED AND REINFORCED WITH METAL STRIP FOUND AT URVILLE-NACQUEVILLE DATED FROM 80 BC, NORMANDY, FRANCE (BORDES ET AL., 2015, HTTPS://EXARC.NET/ISSUE-2015-3/EA/GAULISH-THROWING-STICK-DISCOVERY-NORMANDY-STUDY-AND-THROWING-EXPERIMENTATIONS) (A), INDIAN VALARI, WITH TRUNCATED EXTREMITY ON DISTAL BLADE, REINFORCED BY A METAL STRIP AT THE EXTREMITY OF THE DISTAL (ATTACKING) BLADE (PITT RIVER MUSEUM, OXFORD) (B), DETAIL OF INDIAN OF TWO METAL STRIP ON VALARI ATTACHED BY A SMALL RING (PITT RIVER MUSEUM, OXFORD) (C), KATARIYA IN METAL WHICH DERIVE FROM WOODEN VALARI (D) (HTTP://WWW.ORIENTAL-ARMS.CO.IL/PHOTOS.PHP?ID=558), CROZIER SHAPED METAL SMALL THROWING STICK FROM TCHAD (LOGONE REGION), AFRICA (QUAI BRANLY MUSEUM, PARIS) (E), THROWING KNIFE, CENTRAL AFRICA REPUBLIC, BANDA TRIBE, (HTTPS://ORIENTAL-ARMS.COM/PRODUCT/RARE-BANDA-THROWING-KNIFE/) (F). SYMBOLIC NOTATION SHOWING SHAPE, SECTION(S) AND EXTREMITIES CLASSIFICATION (SEE LEGEND FIG.3)).