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PAPER

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Iron Age stelae in the Flinn strain diagram

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Abstract

A recurrent, but often difficult issue when studying lithic monuments from the past is to determine both the origin and location of the corresponding source rocks. Addressing these questions necessarily requires an integrated archeological/geological approach that can be successfully applied when the megaliths under study display diagnostic physical attributes. This is the case for four Iron Age cigar-shaped stelae from SW Brittany (France) that typically show *L>S* and *L* tectonite fabrics similar to those of the Ordovician Nizon orthogneiss. Our integrated approach provides a better understanding of the criteria used by Iron Age people in selecting rock material, and the four Iron Age monoliths under study can be viewed in some ways as a pioneer application of the Flinn strain ellipsoid concept. Our work also emphasizes the prominent development of *L* tectonites in the eo-Variscan basement in SW Brittany, synchronous with sinistral ductile shearing and orogen-parallel elongation.

1 | INTRODUCTION

The high density of Iron Age stelae, erected *c.* 2.5 ka ago, makes the pre-Mesozoic basement massif in Brittany one of the most famous archaeological provinces in France (Le Brozec & Daire, 1998; Villard-Le Tiec, 2011). The preference of ancient people for using crystalline rocks for their religious and symbolic monuments is clearly evidenced in the Cornouaille region, at the western extremity of the South Armorican Domain (SAD in Figure 1a), where 350 documented Iron Age stelae are exclusively made of granitoid/gneissic material (Caroff, Grall, Moysan, Le Gall, & Cherel, 2016). Within this stele population, four stelae display a spectacular cigar-like 3D-shape, which appears at first sight to be developed in a high-strain crystalline felsic rock with a strong linear fabric. Such a specific structural fabric should therefore constitute a good search criterion for the corresponding *in situ* source rocks (Sullivan, 2013), if a regional origin for the monuments is assumed. Potential candidates could be either the tectonized leucogranites emplaced *c.* 318 Ma ago further north, along the South Armorican dextral shear zone (SASZ in Figure 1a) (Berthé, Choukroune, & Jegouzo, 1979), or the Nizon orthogneiss that constitutes the basement of most of the stelae (Figure 1b). Discriminating criteria have been found from the petrological, structural and strain analysis of the two crystalline rock units and the stele material. The results of our pluri-disciplinary approach have both geological and archaeological implications, by supplying new data about (a) the location of potential extraction sites for the Iron Age stelae under study, (b) the strategies used by ancient people for selecting and transporting heavy rock material, and (c) the structural significance of high-strain crystalline rocks in the SAD eo-Variscan framework.

2 | GEOLOGICAL CONTEXT

Most of the studied stelae (3 of the 4) are confined to a 5 × 10 km area comprising 100°-trending belts of gneisses and micaschists, west of the SAD. The fourth one rests on the neighbouring Pluguffan granitic complex (Figure 1b). The main metamorphic massif in the study area is the Nizon orthogneiss, which resulted from the deformation of a granodiorite that intruded sedimentary host rocks at 489 ± 5 Ma (Cocherie, 1999). The latter are currently represented by an elongate map-scale micaschist enclosure (Melgven series) within the gneiss. These rocks later underwent amphibolite-facies metamorphism during regional deformation that is chiefly expressed by a pervasive foliation, striking N100°, with varying dip attitudes (Figure 1b) (Béchennec, Guennoc, Guerrot, Lebret, & Thiéblemont,

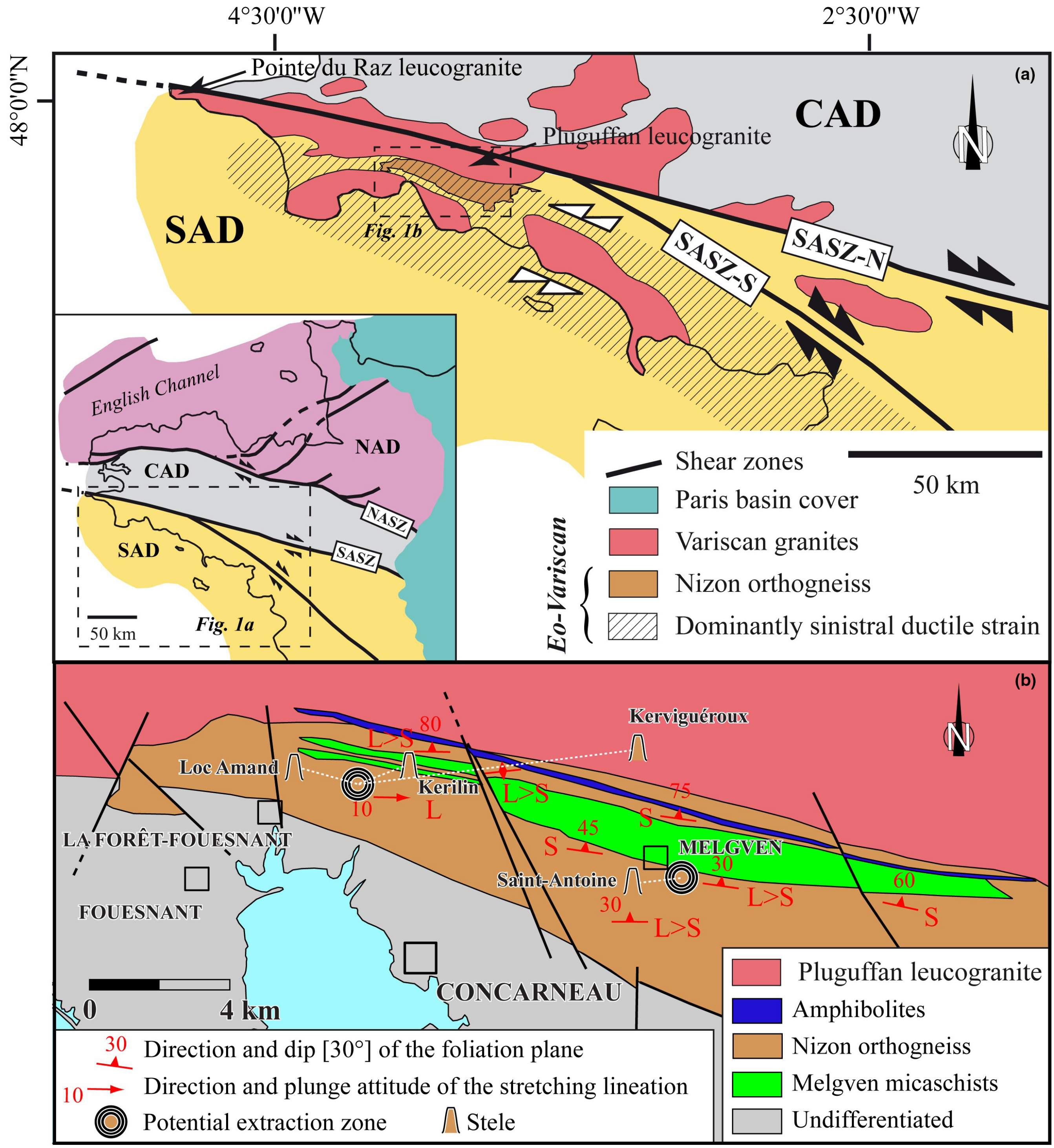

FIGURE 1 (a) Large-scale structural zonation of the South Armorican (eo-Variscan) domain with a dominantly sinistral ductile shear zone involving the Nizon orthogneiss to the north. (b) Map distribution of *S*, *L>S* and *L* tectonites in the Nizon orthogneiss, and location of (1) the four stelae under study and (2) two potential extraction sites of their source rocks (Moulin du Chef-du-Bois for the Loc-Amand, Kerilin and Kerviguéroux stelae, and Questel for the Saint-Antoine stele). Inset shows the major tectonic domains in the Variscan belt of Armorica, Western France [Colour figure can be viewed at wileyonlinelibrary.com]

1996; Béchennec, Hallegouet, & Thiéblemont, 2001). Most of these structures are consistent with sinistral shearing that operated at a regional scale along most of the SAD during the eo-Variscan collisional stage (Lower Carboniferous times), subsequent to subduction and oceanic closure at the southern margin of the Armorica microplate (Figure 1a) (see Ballèvre, Bosse, Ducassou, & Pitra, 2009; for a review). At a later stage, dextral ductile shearing occurred north of the SAD, along the SASZ (Berthé et al., 1979; Gapais & Le Corre,

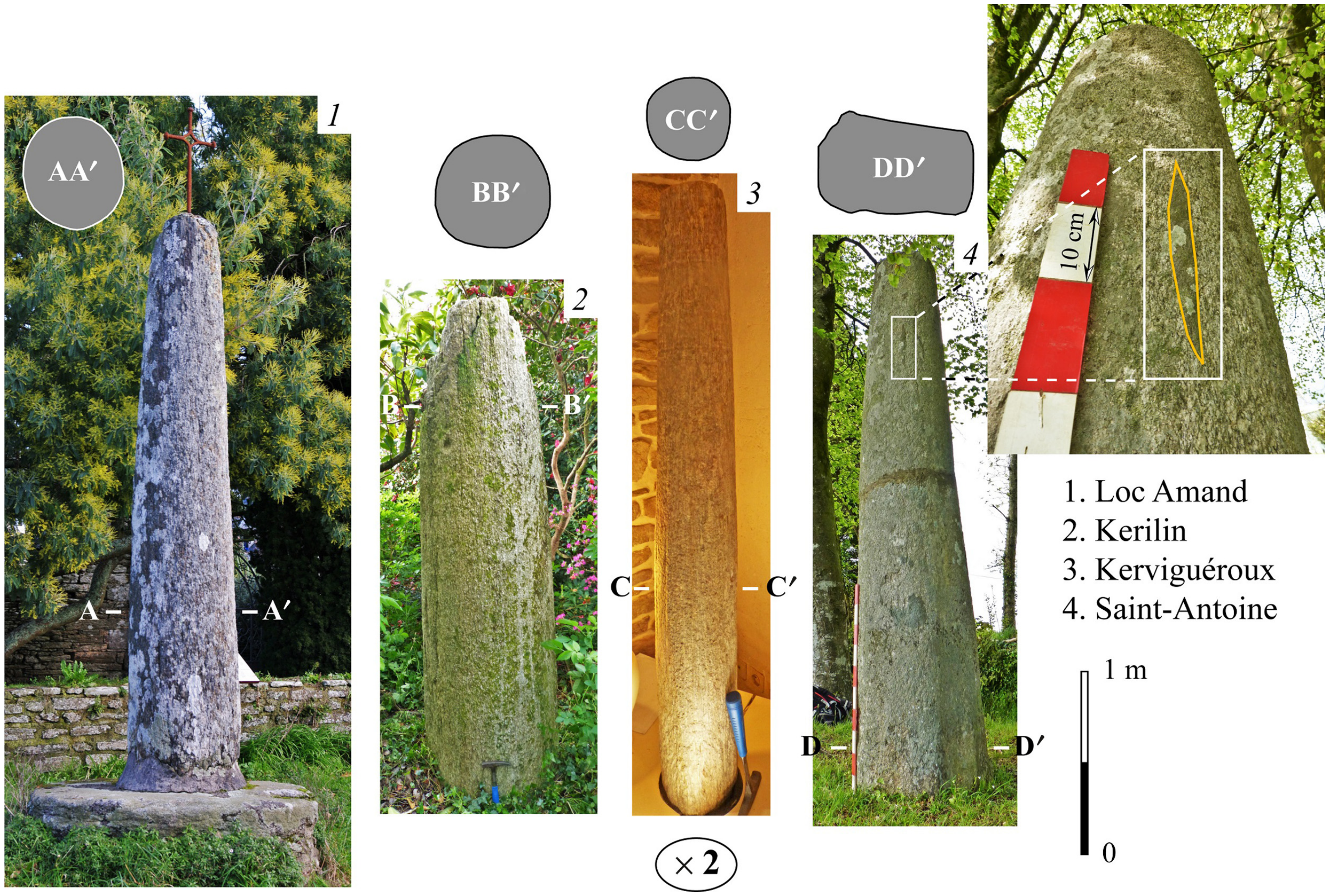

FIGURE 2 3D-cigar-shaped morphology of four Iron Age stelae in the South Armorican Domain. Normal-axis sections are drawn on top (XX′). Inset shows an elongated micaschist enclave parallel to the Saint Antoine stele axis [Colour figure can be viewed at wileyonlinelibrary.com]

1980), synchronous with 318 ± 4 Ma leucogranitic intrusions, represented in the study area by the Pluguffan massif (Figure 1a) (Béchennec, Hallegouet, & Thiéblemont, 1999).

3 | RESULTS

3.1 | Structure of the stelae

The four monolithic monuments under study display a similar 3D-morphology with height (H) and top diameter (D) dimensions in the range 1.75–3.15 m and 13–62 cm, respectively (Figure 2). The corresponding H/D ratios, typically >5, characterize the "high stelae network" of Giot (1965). The measured H/D values are minimum estimates for three erected stelae, the basal parts of which are not exposed. The only accurate H/D value (= 13.5) concerns the unburied Kerviguéroux stele (Daire & Villard, 1996). The stele material is a mesocratic, medium-grained, gneiss, showing alternations of light (quartz and K-feldspar assemblage) and black (biotite) layering. The granitic nature of its protolith is evidenced by the presence of quartz and K-feldspar porphyroclasts. These metamorphic fabrics are at odds with the tectonic structure (foliation and shear planes) of the SASZ leucogranites evoked above, hence leading us to exclude the latter as the potential source-material of the stelae, and instead to favour the Nizon orthogneiss. This assessment is further supported by the modal compositions of the three crystalline rock-types shown in Table 1. The most discriminating parameters are: (a) the plagioclase content, which is in the range 10%–20% for the stelae and the Nizon orthogneiss, and in the range 22%–30% for the leucogranites; (b) the biotite content, which is in the range 4%–10% for the stelae and the Nizon orthogneiss, and is <4% for the leucogranites, and (c) the muscovite content, which is <5% for the stelae and the Nizon orthogneiss, and in the range 4%–7% for the leucogranites.

The dominant structural attribute of the four stelae is a linear fabric, considered as the stretching lineation (L) and defined by various features including: aligned and elongated quartz and K-feldspar porphyroclasts; long axes of biotite laths; dynamically recrystallized mineral aggregates; and elongated micaschist hand-sized enclaves (Figure 2). The lack of any planar component in the fabric of the Loc Amand, Kerilin and Kerviguéroux stelae is morphologically expressed by their circular lineation-normal sections (Figure 2) that typically characterize *L* tectonites (Sullivan, 2013), located near the constrictional axis in the Flinn diagram, with strain axes X>>Y>Z (Figure 3; Flinn, 1965). By contrast, the stretching lineation in the Saint-

TABLE 1 Range of modal compositions (volume %) for the studied stelae, the Nizon orthogneiss and the Pluguffan and Pointe du Raz foliated leucogranites. Location of Nizon, Pluguffan and Pointe du Raz massifs in Figure 1a

	Quartz	K-feldspar	Plagioclase	Biotite	Muscovite
Stelae	40%–50%	30%–40%	10%–20%	4%–10%	1%–5%
Nizon	38%–40%	30%–32%	20%	8%–10%	0%–2%
Pluguffan	40%–45%	25%–30%	22%–30%	2%–4%	4%–7%
Pointe du Raz	40%–45%	30%–35%	25%–30%	<1%	5%–7%

Data for Nizon (melanocratic facies, western part of the orthognessic massif): Béchennec et al. (2001); data for Pluguffan: Béchennec et al. (1999, 2001); other data: this work.

Antoine stele, marked by the above-mentioned elongated features, is spatially associated with a rough foliation plane in a vertical position (equivalent to the schistosity *S*) (Figure 2). This planar anisotropy results in two parallel and rectilinear faces that contribute to the nearly rectangle-shaped section of the stele (50 × 87 cm in its basal part), normal to the lineation (Figure 2). When viewed in sections orthogonal to the foliation and parallel to the lineation, K-feldspar porphyroclasts display asymmetrical shapes that are consistent with rotation during simple shear strain. The 3D fabric of the Saint-Antoine stele, dominated by a strong lineation on a weakly developed foliation, is thus typical of a *L*>*S* tectonite (Sullivan, 2013). The corresponding strain ellipsoid still lies in the constrictional field in the Flinn diagram, but with respective strain axes X>Y>Z (Figure 3; Flinn, 1965). Given the almost total lack of any human reshaping (Caroff et al., 2016), the two morphostructural stele groups discriminated above are further qualitatively correlated with the strain ellipsoids of the orthogneissic material (Figure 3; Flinn, 1965).

3.2 | Structure of the Nizon orthogneiss

The Nizon orthogneiss country rocks have been extensively investigated because of their petrological affinities with the stele rock material. Their regional structure is dominated by a penetrative foliation defined by aligned biotite laths and quartz/K-feldspar grain-shape fabrics, striking consistently at N90–100°, with dip attitudes increasing northwards from 20° (N) to vertical. The relative densities of foliation and lineation in these rocks leads us to discriminate domains of *S*, *L*>*S* and *L* tectonites in the Nizon gneiss (Figure 1b). *L*>*S* and *L* fabrics share a common maximum elongation direction to the east (Figure 1b). Rock samples and thin sections observed in lineation-parallel faces (*L* and *L*>*S*), and orthogonal to the foliation (*S* and *L*>*S*), commonly show sigma-type K-feldspar porphyroclasts and asymmetrical, partly recrystallized, quartz crystals that systematically indicate a component of sinistral shearing, whatever the dip attitude of the foliation plane (where present). In addition, *L* tectonite samples observed on lineation-normal faces show no discernable mineral shape fabrics, but instead circular porphyroclasts, consistent with a true constrictional deformation (Fletcher & Bartley, 1994; Solar & Brown, 2001; Sullivan, 2013). At the regional scale, the transition between the *S*, *L*>*S* and *L* structural domains (not directly observed) appears to take place over a short horizontal distance (<1 km) (Figure 1b).

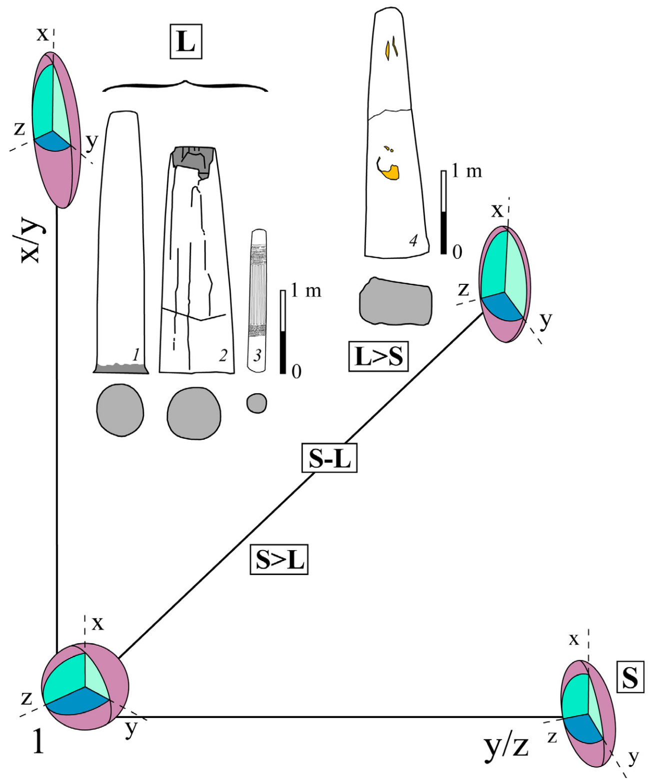

FIGURE 3 Structural interpretation of the highly strained gneissic material of the four stelae in terms of *L*>*S* and *L* tectonites, and their corresponding position in the Flinn strain diagram. Stele numbers as in Figure 2 [Colour figure can be viewed at wileyonlinelibrary.com]

3.3 | Potential extraction sites

Field investigations of extraction sites in the Nizon orthogneiss have been guided by specific lithological and structural criteria observed in the stele rock material. Among them, the presence of micaschist enclaves in the Saint-Antoine stele orthogneiss (Figure 2) points towards the primary contact between the initial Nizon granite and the Melgven metasediment map-scale enclosure (Figure 1b). Two potential extraction sites have been identified. They exhibit contrasting orthogneissic facies that are accurately correlated with the two discriminated stele material, as defined above. The Nizon orthogneiss exposed in the Questel area shows a weak but measurable foliation, dipping shallowly (30°) to the

FIGURE 4 3D structural fabrics of *L* tectonites involving the Nizon orthogneiss in the Moulin du Chef-du-Bois potential extraction site (see location in Figure 1b). (a) Cylinder-like bodies of gneiss attached to the rockmass. (b and c) Structural analogies between *L* tectonites exposed in the field (b), and viewed in a thin section from the Loc Amand stele (c). In both cases, the pervasive ductile lineation is expressed by elongated and commonly sigmoid-shaped K-feldspar phenocrysts. (d–f) Individual cigar-shaped gneissic bodies detached on the lower ground area of the site [Colour figure can be viewed at wileyonlinelibrary.com]

north (Figure 1b). However, its dominant structure is a pervasive linear fabric that plunges 20° to the NE, and results in a *L*>*S* fabric quite analogous to those of the Saint-Antoine stele. One additional criterion for regarding the Questel outcrop as a potential extraction site is its location, close (a) to the Saint-Antoine erection site (1.6 km) and (b) to the boundary of the Melgven micaschist enclosure. A second, more spectacular, potential extraction site is the Moulin du Chef-du-Bois area, <2 km away from the Kerilin and Loc Amand L-type stelae (Figure 1b). There, the extensively exposed Nizon orthogneiss exhibits a strong linear fabric, without any visible foliation, marked by elongated quartz and feldspar porphyroclasts plunging a few degrees to the east (Figure 4a, b). A number of natural orthogneiss cylinders, with 3D-morphostructal patterns and tectonic fabrics quite comparable to those of the three L-type stelae (Figures 2 and 4c), crop out still attached to the rock mass (Figure 4a). Others are observed as detached bodies and might result from either weathering/erosion or removing by ancient people, but without any clear evidence of human activity (Figure 4d–f).

4 | DISCUSSION–CONCLUSION

Thanks to a thorough structural analysis of orthogneissic stelae, further completed by a rough estimate of the corresponding finite strain ellipsoid, it is here concluded that the 3D-morphology of four cigar-shaped stelae in SW Brittany exploits the prominent linear fabric of *L*>*S* and *L* tectonites developed in the Nizon high-strained basement orthogneiss. Assuming that the latter is the likely source rock of the stele material has both archeological and geological implications. Our study first emphasizes the ability of ancient people to discriminate natural rocky shapes and to further exploit favourable tectonic fabrics for their symbolic monuments, with a view to shaping these latter with the least possible effort. The identification and use of *L* tectonites rocks for forming monoliths, as far back as 2.5 ka, were probably some of the pioneering applications of the strain ellipsoid concept in protohistoric times. On the other hand, the relatively short distance (<2 km) between the extraction (source rocks) and erection (stele) sites illustrates the strategies of ancient people to minimize energy for the transportation of heavy material. About the structural and kinematic patterns of the

Nizon orthogneissic substratum, emphasis is put here on its prominent linear fabric that expresses by spatially associated *L* and *L>S* tectonites, as commonly observed elsewhere (Holst & Fossen, 1987; Sullivan, 2006). The development of *L* fabrics in the high-strained Nizon orthogneiss is kinematically associated with sinistral ductile shearing, long known to have occurred at a wider scale over most of the SAD eo-Variscan orogenic belt (Jegouzo, Peucat, & Audren, 1986). The corresponding direction of extension (N100°), parallel to the regional lithotectonic boundaries (Figure 1a), is consistent with development of *L* tectonites in an orogen-parallel setting. The reversal of sense of ductile shearing along similarly trending (N100°) regional-scale structures from the eo-Variscan stage (distributed sinistral shear in the SAD) to the Variscan stage (localized dextral shear along the SASZ) necessarily required pronounced rotation of the shortening direction, in response to plate-scale mechanisms that remain to be elucidated.

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