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Age of the Fontainebleau sandstones: a tectonic point of view

Yves Missenard*, Oriane Parizot and Jocelyn Barbarand

GEOPS, Univ. Paris-Sud, CNRS, Université Paris-Saclay, Rue du Belvédère, Bât. 504, 91405 Orsay, France

Abstract – The age of the cementation of the Fontainebleau sandstones, located in the upper part of the Rupelian Fontainebleau Sand Formation and largely outcropping in the south of the center of the Paris Basin, remains a matter of debate: did the silicification occurred at early times during Miocene, following sedimentation, or did it occurred during Quaternary cold climate episodes? In this work, we determined an orthogonal fracture network (main directions N115° ±5° and N025° ±5°) over an area of ~6000 km^2. The fractures are oblique to the adjacent valley orientation and to the quarry working face orientation, discarding a gravitational origin. This tectonic fracturing is superimposed on regional scale antiforms and synforms that may be at least partly controlled by inherited basement faults reactivation during Alpine episodes. The whole Fontainebleau Sand Formation seems to be folded, including the Fontainebleau sandstones. We establish a relative chronology of the various phenomena and propose that silicification at the origin of the Fontainebleau quartzite occurred during early or middle Miocene. Alpine stresses then induced Fontainebleau sand and quartzite folding and fracturing during late Miocene and Pliocene. Finally, the fracture network facilitated fluid circulations and secondary carbonate sandstones or quartzite precipitation probably during Quaternary cold climate episodes.

Keywords: Fontainebleau Sand Formation / Fontainebleau sandstones / tectonic joints / intraplate deformation / Paris Basin / Alpine deformation

Résumé – L'âge des grès de Fontainebleau : apport de l'analyse tectonique. L'âge de la cimentation des grès de Fontainebleau, affleurant dans la partie supérieure des sables de Fontainebleau d'âge rupélien et largement répandus dans le sud de l'Ile de France, reste encore sujet à débats. Plusieurs modèles ont été développés depuis une cimentation précoce après la sédimentation, au cours du Miocène, jusqu'à une cimentation de nappe en lien avec les épisodes froids du Quaternaire. Dans ce travail, une analyse de la fracturation des grès a permis de mettre en évidence l'existence d'un réseau de fractures orthogonales (N115° ±5° et N025° ±5°) à l'échelle de l'ensemble du Sud de l'Ile de France (~6000 km^2). L'obliquité de ce réseau de fractures par rapport à l'orientation des vallées adjacentes et des fronts d'exploitation des carrières permet de conclure à une origine tectonique et non gravitaire de cette fracturation. Nous montrons également que cette fracturation se superpose à une structuration régionale en antiformes et synformes probablement en partie liée à la réactivation de failles de socle lors de la déformation alpine. Cette déformation plicative semble affecter l'ensemble de la série des sables de Fontainebleau, y compris les parties grésifiées. Nous établissons ainsi une chronologie relative des différents évènements mis en évidence et proposons que la cimentation des sables ait eu lieu au cours du Miocène inférieur ou moyen. Les contraintes se propageant en avant de la chaîne alpine du Miocène supérieur au Pliocène auraient ensuite réactivé les failles héritées de socle, contribuant à plisser les sables et grès de Fontainebleau, et développant le réseau de diaclases observé dans les grès de Fontainebleau. Des précipitations secondaires gréseuses ou carbonatées associées à une circulation tardive de fluides ont enfin probablement lieu lors des épisodes glaciaires du Quaternaire.

Mots clés : sable de Fontainebleau / grès de Fontainebleau / joints tectoniques / déformation intraplaque / Bassin parisien / déformation alpine

* Corresponding author: yves.missenard@u-psud.fr

1 Introduction

Although widely used for petrophysical, geophysical and sedimentological studies (*e.g.*, Bosch *et al.*, 2016; French and Worden, 2013; Haddad *et al.*, 2006; Nasseri *et al.*, 2014), for the pavement of Paris roads during the 19th century, or even as well-known climbing walls of the Fontainebleau massif, the origin, *i.e.*, the age of silicification of the Fontainebleau sandstones remains a strong matter of debate.

These hard consolidated sandstones, sometimes corresponding to quartzites, are mostly located in the upper part of a sandy unit, the Rupelian Fontainebleau Sand Formation (lower Oligocene), and widely crop out south of the Seine River southward from the centre of the Paris Basin (Fig. 1).

They were first described in the mid-18th century by Buffon (1749). Many other naturalists wondered about the origin and age of these rocks. The first modern model of silicification was proposed by Alimen (1936). In this model, the silicification occurs on crest of dune at the end of Rupelian. However, this model is now considered as outdated, and more recent models argue for a cementation induced by groundwater. Debate is existing on the age of this silicification. Plaziat (1995) proposes that it occurred during Miocene times, after burial of the sands below younger lacustrine limestones. Thiry *et al.* (1988) and Thiry and Maréchal (2001) suggest that silicification occurred in surface condition during Late Pleistocene or Quaternary times, while the present-day hydrographic network was developing. Recent work by these last authors suggests that silicification might have taken place during the last 300 ky during cold periods (Thiry *et al.*, 2015). Thus far, no consensus has been reached.

The presence of numerous fractures in the sandstones is known for a long time. Daubrée (1880) measured the orientations of these joints in quarries near Paris city and showed that these joints locally form two main orthogonal sets. More recently, Obert (1984) also measured fracture orientation in the Fontainebleau area in order to discuss the origin of silicification and to establish a potential link with geomorphology. However, these works are restricted to small areas and this fracturing network has never been studied at a regional scale. More recently, Thiry *et al.* (2013) proposed that all the joints affecting the Fontainebleau sandstones were related to withdrawing of the underlying sands (*i.e.*, gravitational fracturing). These authors conclude that “all observations indicate that the fractures are not related to tectonic stresses”.

In this study, we measured joint directions in Fontainebleau sandstones disused quarries in an area over 6000 km^2 south of Paris (Fig. 1). We compared the results to the adjacent

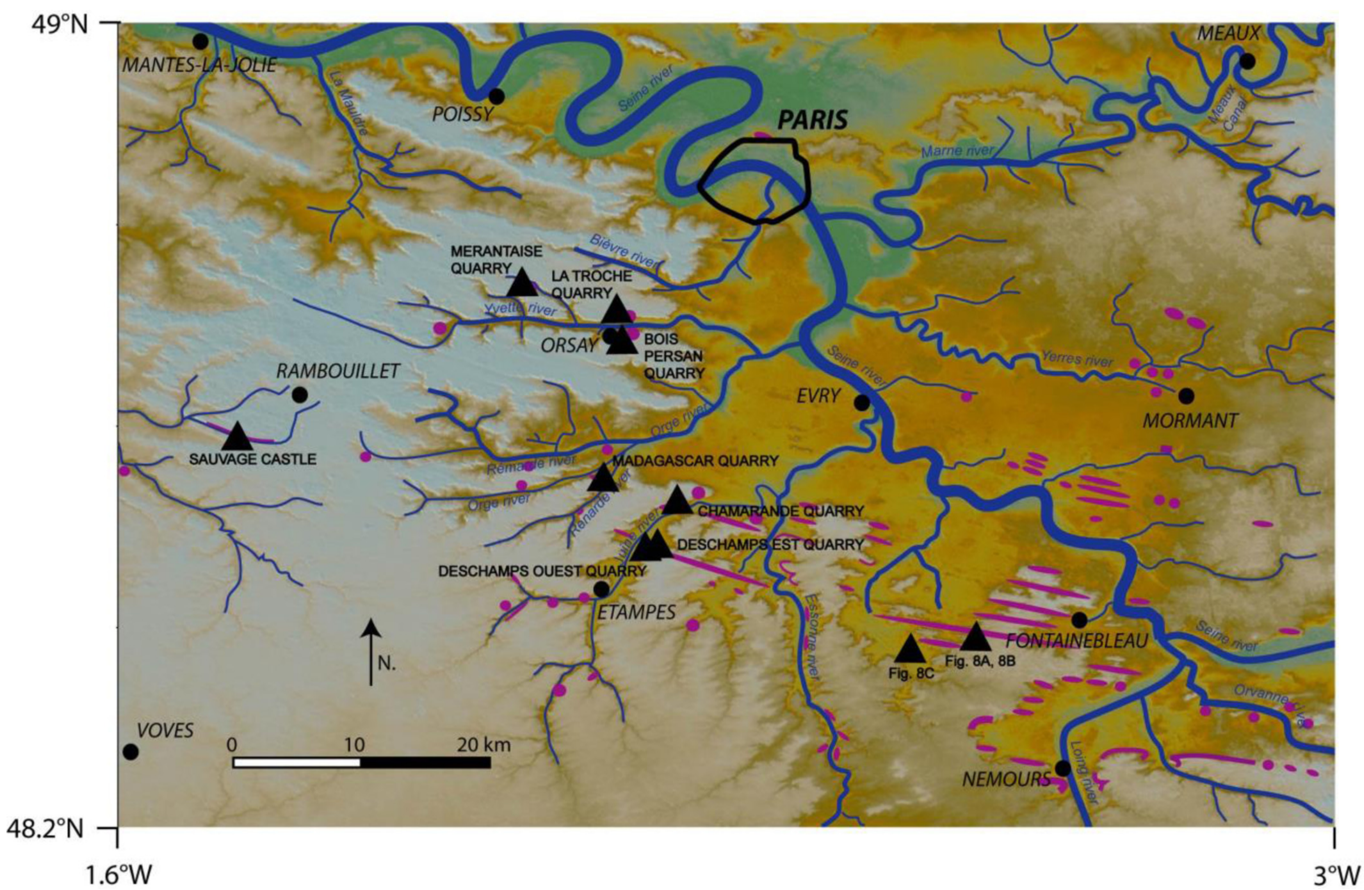

Fig. 1. Topographic map of the center of the Paris Basin. Purple outlines and dots: main Fontainebleau quartzite outcrops. Black triangles: studied sites.

valleys and working face orientations to discuss the gravitational *versus* tectonic origin of the joints. We show that the joints form a regular network at regional scale, and that this network is related to a tectonic event. We finally discuss the consequences of our results on the age of the silicification.

2 Geological context and previous models

Quarztite lenses are observed in the upper part of the Fontainebleau Sand Formation. These sands are generally azoic, uniform and of Rupelian age (deposition between 31.5 My to 28.5 My, [Delhaye-Prat *et al.*, 2005]). The former stratigraphic term Stampian is often used to characterize this period in the Paris Basin (Lozouet, 2012). Active exploitation of the sands and the sandstones during the last three centuries has led to acquire a large knowledge on these rocks. There is now a consensus on the sedimentological characteristics of this formation. The paleoenvironnements as well as the sequential stratigraphy are relatively well established. General informations are taken mostly from the synthesis published in (Lozouet, 2012) and from (Delhaye-Prat *et al.*, 2005). More specific aspects can be found in the reference lists of these publications.

Fontainebleau sands deposited in a context of very low subsidence (< 10 m/My) in the centre of the Paris Basin (France), an intracontinental basin formed since Triassic times (Guillocheau *et al.*, 2000). Their mean thickness is of 50 to 60 m. A maximum depth of burial has been estimated at 100 m and was limited in many areas to a few tens of meters during Miocene (Thiry and Maréchal, 2001; Thiry *et al.*, 1988). They lie unconformably on a Cretaceous to lower Eocene sedimentary succession (Fig. 2). These sands are formed of 99% of quartz, the remaining 1% being heavy minerals or clays. Locally peculiar facies have been described including shell-rich or gravel-rich levels (so called “Faluns d’Ormoy”, “Sables à galets de Saclas”...). Most of the sands accumulated in an upper shoreface environment, as shown by various fossils or bioturbations and sedimentary figures. Several palaeosoils in the upper part of the sands testify of a global evolution from marine to continental environment. The last 10 to 20 meters are made of aeolian dunes elongated in a NNW-SSE direction. Landscape reconstruction envisages marine sands originated

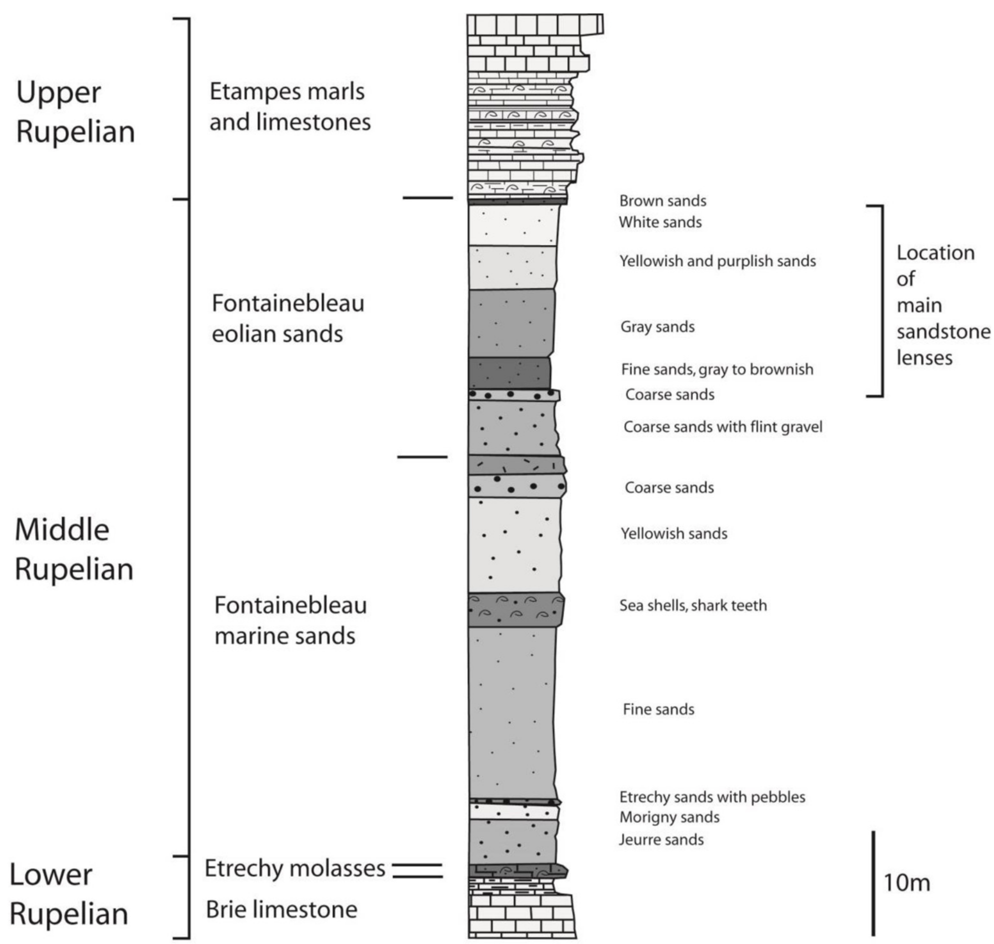

Fig. 2. Detailed stratigraphic column of the Rupelian formations two kilometres west of Etampes. The contact between the sands and older units is unconformable, and lateral facies variations in the sands occur at the scale of the basin. Modified after Lozouet *et al.*, 2012.

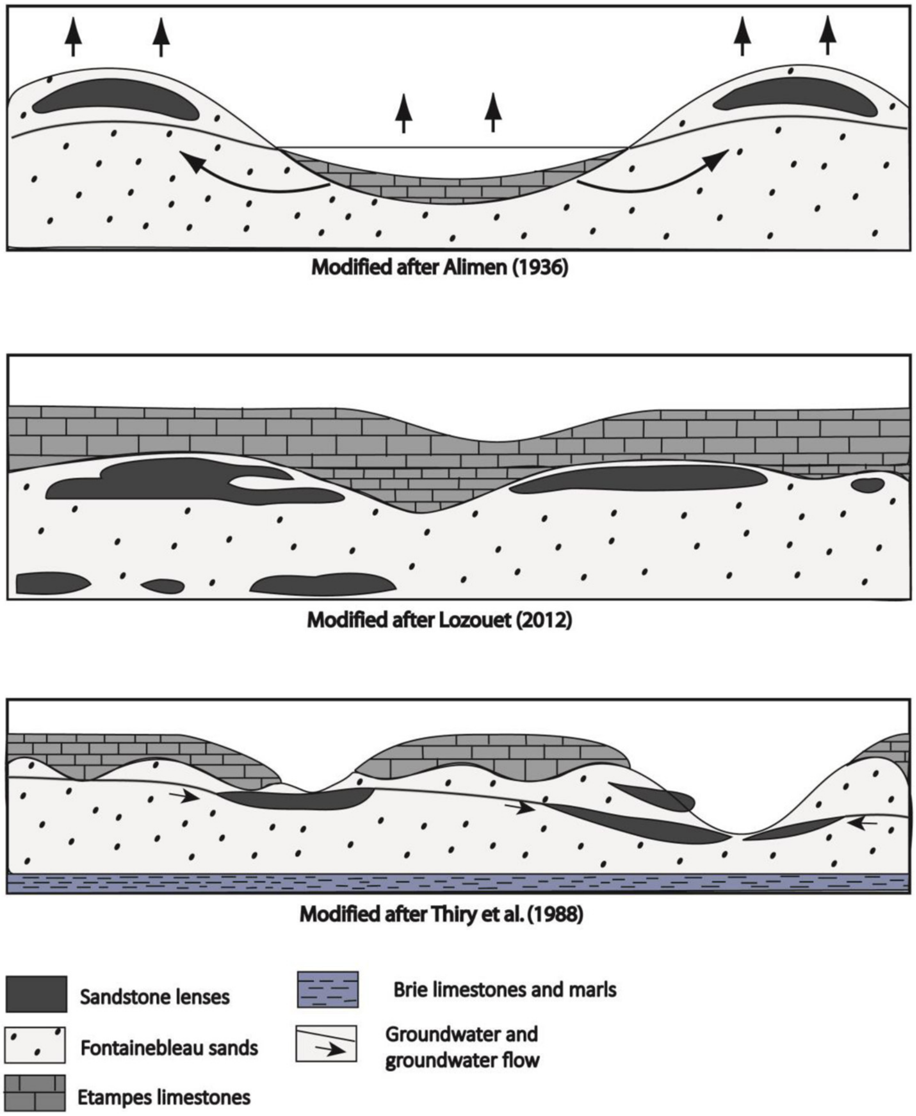

Fig. 3. Main published models of Fontainebleau sand silicification (after Alimen, 1936; Lozouet, 2012; Thiry *et al.*, 1988). See text for discussion.

from the Atlantic Ocean transported northward by the wind and forming dunes. The silicification leading to the formation of the Fontainebleau sandstones mostly took place in this aeolian upper part, although some silicifications are also reported in the marine bottom part.

The sandstones form very elongated lenses with largest axes running parallel to the dune crest lines (Fig. 1). The lenses are several kilometers long, tens to hundreds meters large, and 1 to 10 meter thick. Contacts with the sands at the top and the bottom of the lenses are generally very sharp. Cementation was sometimes irregular, and sand pockets may be preserved in the lenses.

Until the 1980s, Alimen's model (1936) prevailed. Her model (Fig. 3) suggests that the silicification occurred during late Rupelian, while the waters of the Beauce Lake was progressively submerging the aeolian dunes. During the elevation of the phreatic table, the silicification would have been triggered by pedological evaporation under an arid climate. The preservation of root traces in the sandstones was one of the arguments supporting this scenario. However, even if morphological observations strengthen this model (Obert, 1988), it came up against physical facts: the permeability of sands in dunes is too high to allow capilar ascent of underground waters. Silicification in the top of current dunes has actually never been observed.

In the 1980's, several models were released, emphasizing the major role of groundwater flows on silicification and two of them are still frequently cited. Thiry *et al.* (1988) and Thiry and Maréchal (2001) propose that silicification occurred during Plio-Quaternary when the underground water table in the sands flew across the surface during valley incision (Fig. 3). Recently, Thiry *et al.* (2013) dated several calcite crystals (so-called "Belle-Croix Sand calcite", well-known from mineralogists) cementing the Fontainebleau Sand Formation.

Ages range between 300 ky and less than 20 ky, *i.e.*, Quaternary, and correspond to various glacial stages. For two of the dated samples, crystal rhomb shapes are moulded by the quartzite. These results strengthen the idea of a recent (< 300 ky) silicification of the sandstones.

On the other hand, Dewolf *et al.* (1988, 1994) used morphological arguments and heavy mineral datings to demonstrate that silicification occurred before Quaternary valley incisions. Plaziat (1995) and Lozouet (2012) support the idea of a middle to late Miocene silicification (Fig. 3). The process of silicification is here again thought to originate from the flow of a water table, but in this case under a sedimentary cover.

Although these two models are the most satisfactory, many other ones were issued by numerous authors during the last 130 years in relation with large amount of outcrops due to quarry exploitation or urban planning. Among them, the Obert's model (1974, 1984) deserves to be addressed as it stresses the major role of tectonics in the silicification process, and therefore constitutes an alternative to the classical hydrological model of silicification. Obert (1974, 1984) postulates that cementation occurred parallel to the maximum principal stress acting during the Rupelian. While Obert's model is debatable as the link between stresses, fracture network and quartzite lenses is not straightforward, it is worth noting that the Thiry *et al.* (1988), Plaziat (1995) and Lozouet (2012) models do not include either way the fracturing of the sandstones.

3 Results

Observations and measurements were performed in eight disused quarries and one natural outcrop (Sauvage Castel, site 2 – Fig. 1). Sandstones are mainly observed close to the valleys as they represent erosion site where quarries have been implanted. Sites were selected:

- to represent a large area;
- for the quality of the outcrop;
- for the orientation of the working face in the quarries and the orientation of the adjacent valleys, in order to discuss the role of gravitational fracturing (see below).

We did not perform measurements in the Fontainebleau area (Fig. 1) as data are already available and complementary (Obert, 1984).

Fracturing has been observed in all studied sites. The fractures in the Fontainebleau sandstones can be defined as joints (mode I fractures) in the sense of Mandl (2005), as they correspond to fractures without visible shear displacement. These joints are generally sinuous, both in direction and in dip (Fig. 4). When necessary, *i.e.*, when joints were too sinuous, we measured the mean direction of the joints. All dips are stated sub-vertical. Fracture plane length is highly variable, from decimeter to decameter. They frequently form regular dihedrons, only visible when the working face is oblique to joint directions (Fig. 4).

Some of the joints show typical plumose structures with prominent hackle structures (Fig. 5). This observation is of importance as it indicates that joints formed in a competent material, *i.e.*, after silicification.

Results of joint direction measurements are presented in Figure 6. For sites 1, 2, 5 and 6, two principal directions are evidenced, one family being NNE/SSW, the other one being ESE/WNW. It is not possible to distinguish between systematic or nonsystematic sets, as each set sometimes crosses the other one, sometimes ends on the other (Fig. 4G). The ESE/WNW family dominates for sites 3, 4, 7. Dispersion is much more important for site 8 than for the other sites, preventing identification of a main direction. The origin of dispersion in this site remains unknown.

When considered all together (Fig. 6), two joint families are clearly evidenced. The mean directions are N115° and N025°, defining a perpendicular set of joints at the scale of the studied area. The N115° and N025° joints are equally represented. Slight dispersion around these mean directions is probably related to the irregular shape of the fractures.

4 Discussion

4.1 Comparison with previous studies

Daubrée (1880) measured fractures (236 measurements) located mostly in the Lutetian limestones, but some data are corresponding to the overlying late Eocene gypsum and marls and to the Fontainebleau sandstones. Figure 7 shows a representation of his results. Two main directions are also evidenced, N110° and N025°. These directions are particularly clear in the Fontainebleau quartzites and in the Lutetian limestones.

More recently, Obert (1984) measured the orientation of more than 700 fractures in the Fontainebleau area (Fig. 1), all located in the Fontainebleau sandstones. He evidenced two main directions, N115° and N025° (Obert, 1984). Figure 8C shows his data in the "Trois Pignons" massif. A similar result has been reported by Gely *et al.* (1986) in Paris underground quarries where the Lutetian limestones are affected by the same fracture network.

All the data including our new results converge to similar values: N115° ±5° and N025° ±5°. This indicates that the fracture network we evidenced in this study affected the Fontainebleau sandstones and older units as a whole over ~6000 km^2. As far as we know, fracturing in younger units has never been studied.

4.2 Origin of the N115°/N25° fracture network

4.2.1 Gravitational collapse or tectonic fracturing?

Due to their strong resistance to erosion, the Fontainebleau sandstones generally crop out in the upper part of the valley flanks. Vertical fractures in this formation have thus generally been associated to gravitational collapse after removal of the underlying sands on the flank of the valley (see for instance Thiry *et al.*, 2013). If such a mechanism had occurred, a relationship should exist between the fracture orientations and either the orientation of the valleys, the orientation of the working faces in the quarries, or the orientation of the sandstone lenses that form elongated hills in the Fontainebleau area (Fig. 1).

Our study demonstrates that such relationships do not exist (Tab. 1). For instance, the Yvette valley close to sites 4 and 5 is oriented N090°, the Mérantaise valley close to site 3 is oriented

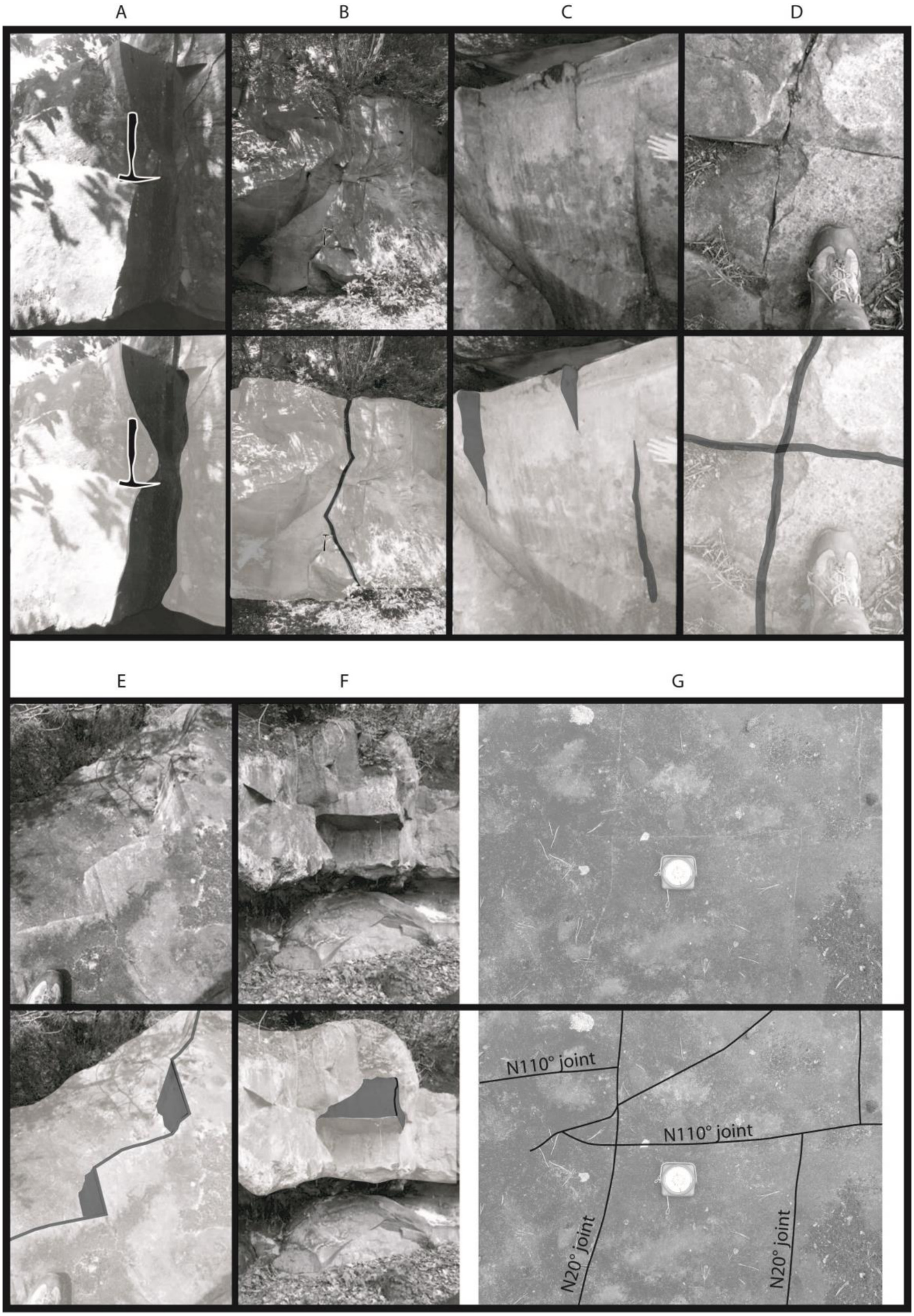

Fig. 4. Field pictures of fractures in the Fontainebleau quartzite. Upper line: raw pictures. Lower line: highlight of the fractures (dark grey) in the quartzite (light grey). A, B, C: typical geometry of the joints at metric scale. D, E, F: orthogonal joint network forming regular dihedrons seen from above (D) or along the working face (E,F). G: geometrical relationship between both joint sets (top view). It has not been possible to characterize systematic or non-systematic joints. A, B, D: Chamarande quarry, site 6. C, E, G: Madagascar quarry, site 1. F: Bois Persan quarry, site 5. Location Figure 1, Table 1.

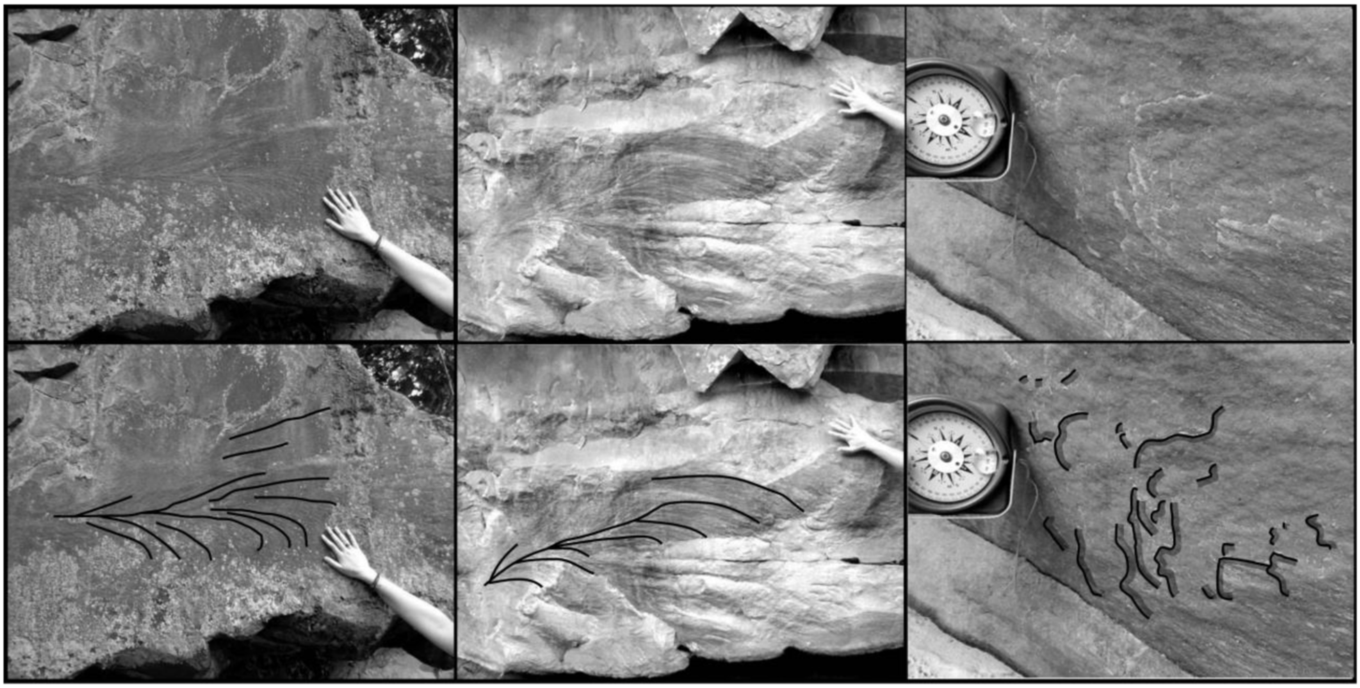

Fig. 5. Field pictures of plumose or hackle plumes on fracture planes in the Fontainebleau quartzite. Upper line: raw pictures. Lower line: highlight of the plume structures. Left: Bois Persan quarry, site 5; centre and right: Madagascar quarry, site 1. Location Fig. 1, Table 1.

Table 1. Details on the studied sites, including adjacent valley direction, quarry face direction and mean fracture directions. Although both valleys and quarry face directions vary, the same orthogonal network of joints is measured for all studied sites.

Setting	Proximal town	Site name	Coordinates	Adjacent valley direction	Quarry face direction	Mean orientations of fractures	Altitude of sandstones (m)
1	Souzy-la-Briche	Madagascar quarry	48°32’15”N 2°09’02”E	N40°	N105° and N30°	N115°–N022°	140
2	Émancé	Sauvage Castle	48°35’13”N 1°44’34”E	N70°	N65°	N109°–N021°	140
3	Saint-Rémy-lès-Chevreuses	Mérantaise quarry	48°42’58”N 2°06’30”E	N140°	N030° and N165°	N111°–N027°	150
4	Orsay	La Troche quarry	48°41’33”N 2°11’44”E	N90°	Changing from N020° to N095°	N116°–N025°	150
5	Orsay	Bois Persan quarry	48°41’30”N 2°11’55”E	N90°	Changing from N070° to N115°	N108°–N026°	145
6	Lardy	Chamarande quarry	48°31’08”N 2°14’16”E	N70°	Changing from N020° to N100°	N106°–N019°	140
7	Auvers-Saint-Georges	Deschamps Est quarry	48°28’40”N 2°12’47”E	N25°	N060°	N106°	135
8	Auvers-Saint-Georges	Deschamps Ouest quarry	48°28’35”N 2°12’21”E	N25°	Changing from N005° to N115°	N117°–N008°	130

N140°, and the Essonne valley near site 6 is oriented N070°. For all of these sites, the main fracture direction is N110° to N120°. The working faces orientations in the various quarries is variable, being for instance N105° and N030° for site 1, N065° for site 2, or N165° and N030° for site 3. The aerial photographs in the Fontainebleau area also show that the fracture network is oblique to the direction of the lens largest axis (Fig. 8), an observation already made by Obert (1984).

The fracture network regularity across the whole area (Fig. 6), its independence relative to the valley, quarry and lens

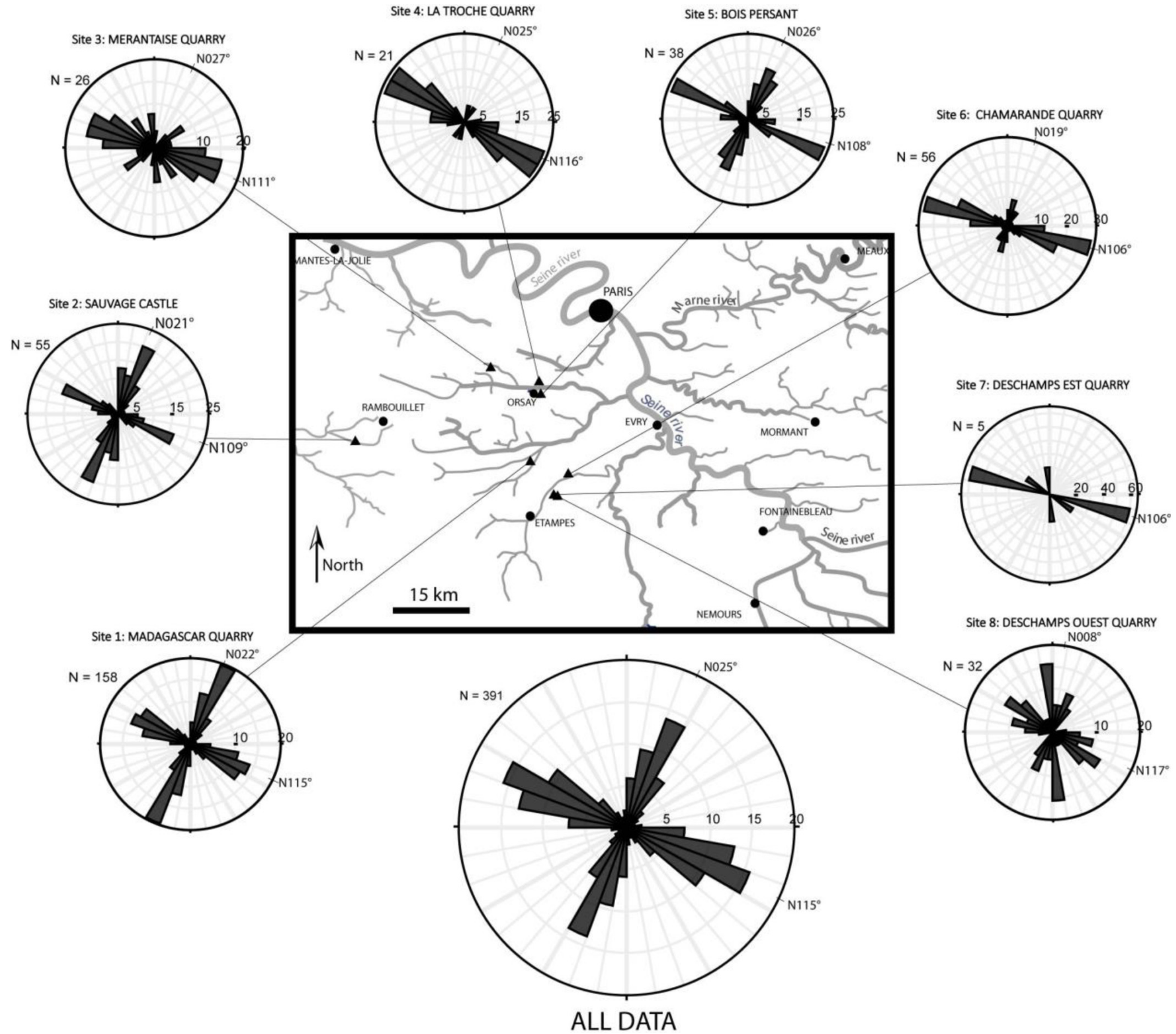

Fig. 6. Results of joint direction measurements shown as rose diagram for each site. N is the number of data and rose diagram axis is graduated in percent of the number of the data. The mean directions of the fracture sets are indicated on the edges of the diagrams. The larger rose diagram at the bottom includes all data together, evidencing two main directions, N025° and N115°.

main axis orientations indicate a conspicuous tectonic origin. In the next section, we investigated the relationships between this tectonic feature and the regional scale deformation.

4.2.2 Fracture pattern and regional scale tectonic structures

Meso-Cenozoic tectonic deformation of the centre of the Paris Basin has yet been poorly investigated at a regional scale. For the whole Paris Basin, the building of the isohypse map of the base of the Tertiary shows folds (Guillocheau *et al.*, 2000), but these structures are at least partly related to Eocene Pyrenean stress field and cannot be directly correlated to Neogene tectonic events. Following (Bourgeois *et al.*, 2007; Briais, 2015, Briais *et al.*, 2016; Guillocheau *et al.*, 2000), post-Rupelian deformation is mostly expressed by lithospheric flexure at the scale of the Paris Basin.

Nevertheless, very gentle structures are reported on the 1/50 000 geological maps, but a tectonic map of Oligocene formations for the studied area has never been published. To fill this gap, we digitized the altitude of the base of the Rupelian unit from the geological maps (red points, Fig. 9) and from boreholes (black crosses, Fig. 9). We then extrapolated the values to reconstruct the geometry of the surface using minimum curvature gridding method in Golden Software Surfer software. The obtained surface was filtered to remove high frequency anomalies due to the relative lack of precise data. The final map (Fig. 9) shows that the basal surface of

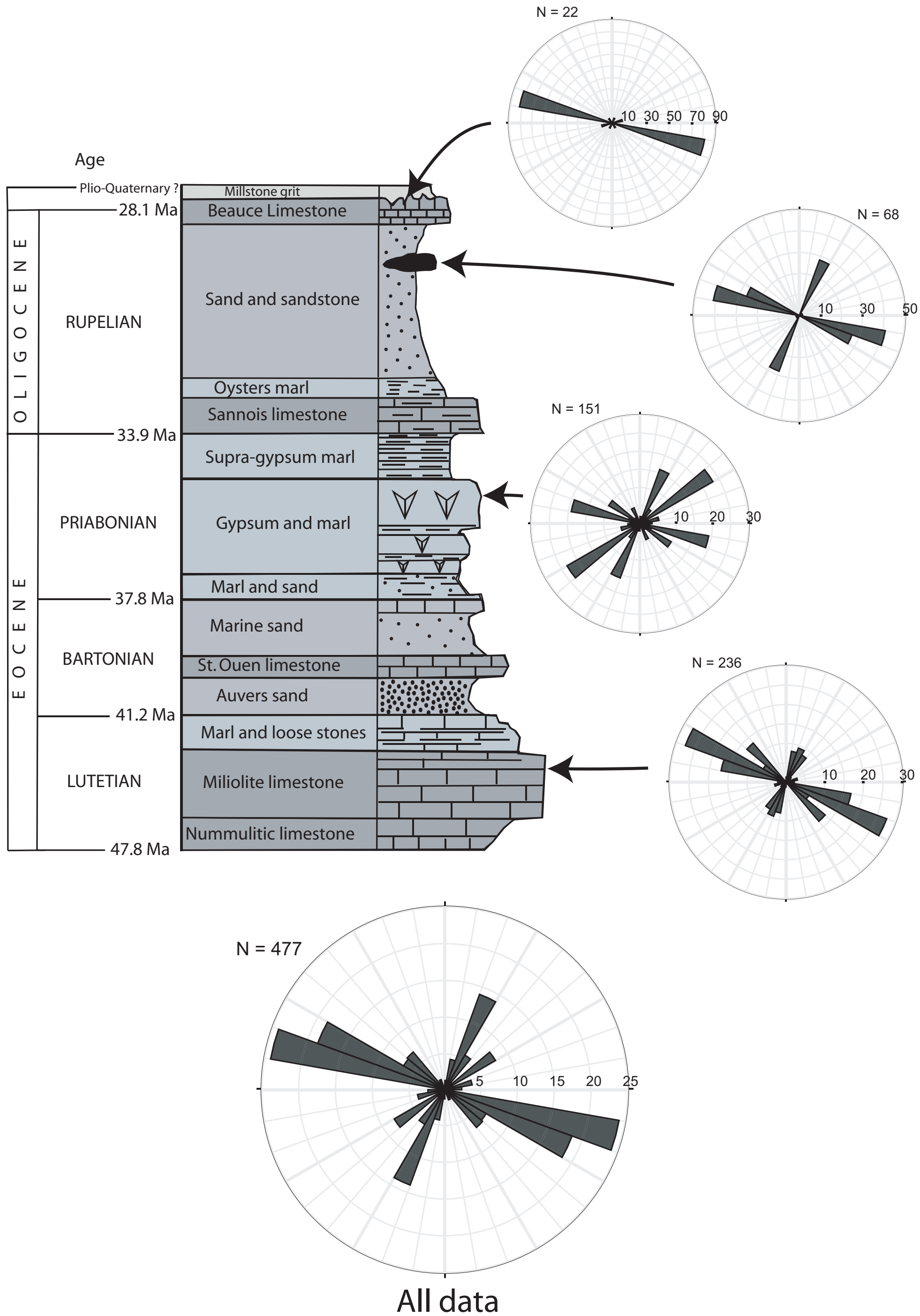

Fig. 7. Daubrée (Daubrée, 1880) data of fracture orientations in various formations in and close to Paris city in disused quarries. Location of the various measurement sites is given in the original paper available at http://jubilotheque.upmc.fr Magnetic field variations since the initial measurements were corrected. Although slightly dispersed, the full set of data (bottom rose diagram) indicates results similar to our new data with two main joint directions. The joint network we evidence in this study is thus not restricted to the Fontainebleau quartzite but also affect older formations of the centre of the Paris Basin. Time scale after Cohen *et al.* (2016).

the Fontainebleau sands is undulating, with altitudes ranging between 60 to 170 m. Three main domains can be recognized.

To the west, a succession of synforms and antiforms trends in a N120° direction, and dips of the extrapolated surface never exceed one degree.

The centre part of the map (Fig. 9) corresponds to a low elevation domain: the base of the Fontainebleau sands stands at elevations lower than 100 meters in the so-called Saint-Denis trough, Longjumeau trough and in the Etampes area. The boundary with the eastern domain is rather sharp and

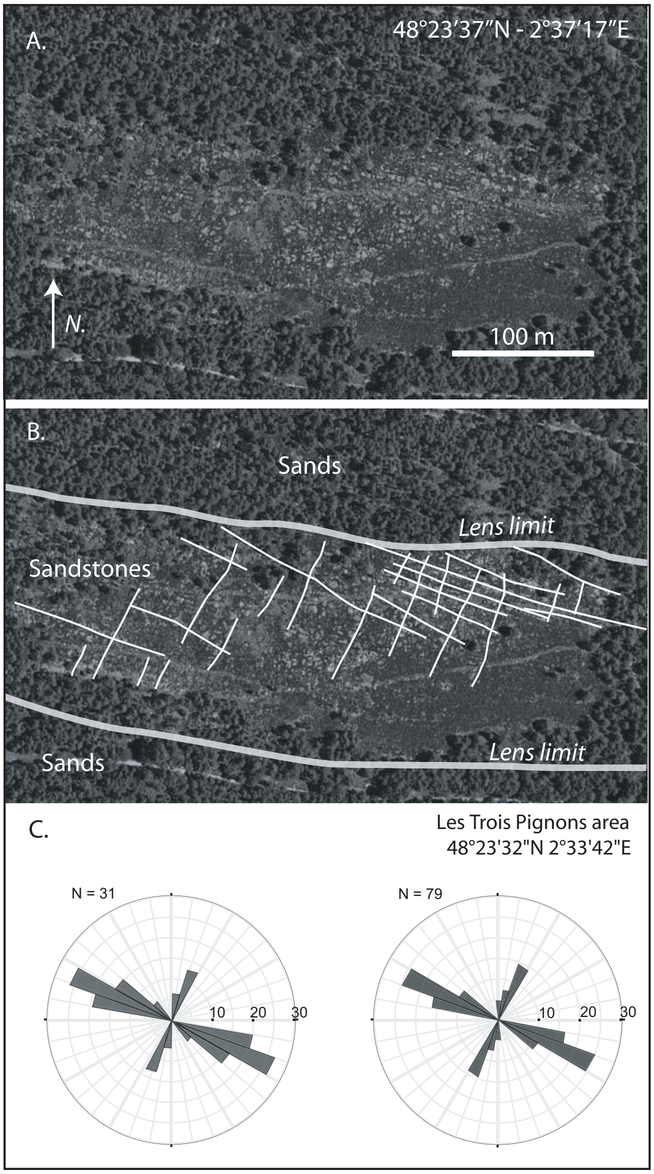

Fig. 8. Aerial picture (Google Earth©) of a sandstone lens in the Fontainebleau area (Location Fig. 1). The sandstone lens forms a plateau (also called "platière") surrounded by valleys in the sands. A. Raw picture and coordinates. B. Highlight of the lens limit and fracture pattern (white lines). The main joints direction is N120°, oblique to the N100° lens limit, discarding gravitational origin of the fractures. The secondary N25° joint set is also highlighted. C. Two rose diagrams of fracture orientations in the Fontainebleau area published by Obert (1984) – N: number of data.

the N120° synforms and antiforms disappear abruptly along a N040° discontinuity (dotted lines, Fig. 9).

Finally, the eastern domain shows again a succession of antiforms and synforms with N060° axes. As in the western domain, dips never exceed one degree. These antiforms and synforms seem to plunge toward the central troughs and progressively disappear.

The interpretation of the map in terms of post Rupelian deformation is not straightforward, as the base of the Rupelian unit corresponds to a transgressive surface: the undulations evidenced here may correspond to a pre-Rupelian paleotopography.

However, all the undulations correspond to the known tectonic structures described on some of the 1/50 000 geological maps: to the west, one can recognize from north to south the Vigny Anticline, Seine Syncline, Beynes Anticline, Eure Syncline, La Rémarde Anticline, Ablis Syncline. To the east, the antiforms and synforms of the base of the Rupelian unit are located at the emplacement of the Coulommiers Anticline, Melun Syncline, Valence-en-Brie Anticline and Nemours Syncline. Although some of these structures, growing during the Pyrenean event, did result into a paleotopography (for example, La Rémarde Anticline corresponds probably to a paleo-high at the beginning of the Rupelian [Bricon and Ménillet, 1969]), it is unlikely that the pre-Rupelian topography mimics all these structures. Thus, the undulations evidenced here probably formed after the Fontainebleau Sand formation deposition and are related to latter tectonic events.

Such post-Rupelian deformation is also recorded by tilting of the Miocene deposits. These formations, mostly made of lacustrine limestones, lay conformably on the Oligocene units. Although they are not preserved in most of the studied area, they are well-known on its southern limit (northern part of the Beauce trough). The Malesherbes geological map indicates that the Aquitanian unit ("Molasse du Gâtinais" Formation) is tilted to the southwest. Similar deformations are reported on the Méréville geological map (Gigot, 1980). The Aquitanian "calcaire de Beauce" is also folded southward, in the Orgères-en-Beauce area (Gigot, 1975). These observations strengthen the idea that the N120° and N60° antiforms and synforms of the base of the Rupelian unit are mostly due to Neogene deformations. The origin of the N40° discontinuity (dotted lines, Fig. 9) remains to be determined: it may correspond to flexure controlled by deeper faults or to a shoal on which the sands have been deposited.

Strikingly, the fracture network evidenced in this study is not always correlated with these regional folds. In the western domain, the N115° fracture set is roughly parallel to the fold axis but in the eastern domain this N115° direction (see Fig. 6) is clearly oblique to the Melun and Fontainebleau folds. In a similar manner, the N115° and N025° fracture orientations evidenced in the Longjumeau trough (sites 4 and 5, Fig. 6) cannot be associated to the trough shape nor to its N040° limit. The fracture network recorded in the Fontainebleau sandstones seems then to be independent from the regional scale tectonic structuring.

We suggest that the regional structuring is controlled by reactivation of inherited deeper faults of various directions, whereas micro-fracturing in non-previously weakened rocks is most representative of the regional stress field and might have occurred before or during folding. This hypothesis is strengthened by the maps of Triassic faults of Delhaye-Prat *et al.* (2005), Gely and Hanot (2014), or by the work of Lacombe and Obert (2000) that shows that these inherited faults are roughly parallel to the folds evidenced here. This indicates a strong decoupling between kilometer scale folding and mesoscale fracturing.

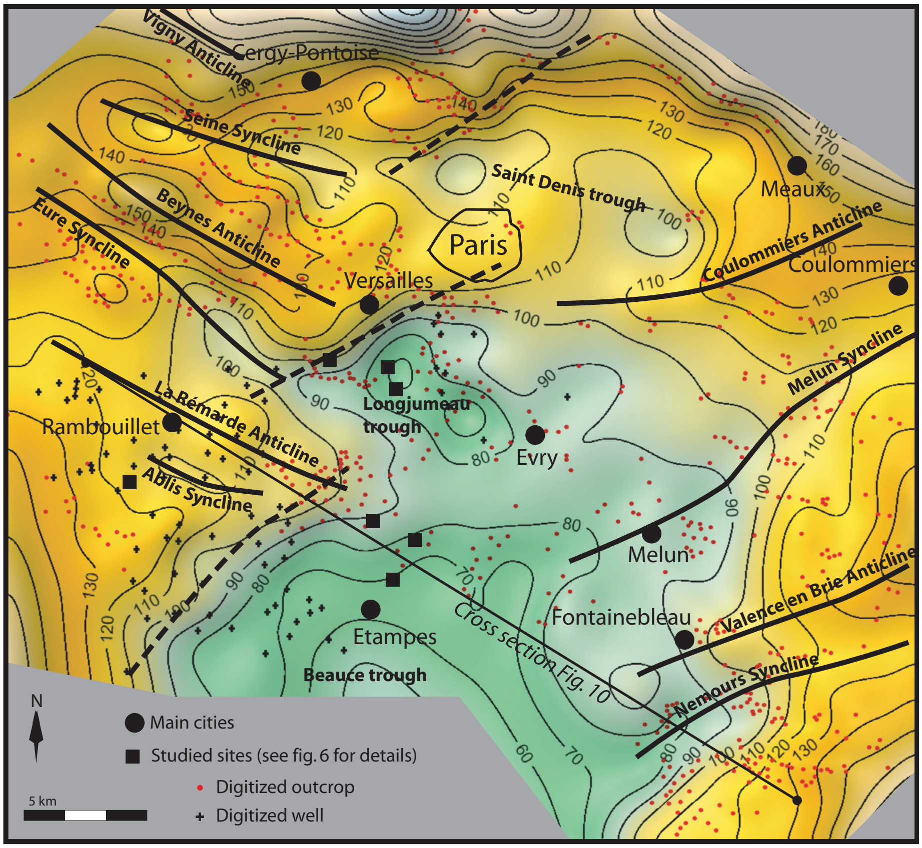

Fig. 9. Structural map of the base of the Fontainebleau Sand Formation. The map was constructed by digitizing outcrops (red points) or using well data (black crosses). Altitudes of the base of the formation were then extrapolated to reconstruct the whole surface. Altitude of the surface is given in meters above mean sea level. Black lines highlight axes of main undulations. See text for discussion.

4.3 Chronological aspects: how old are the Fontainebleau sandstones?

4.3.1 Silicification vs. folding

In order to establish the relative chronology between folding and cementation, we digitized the altitude of the base of the Fontainebleau sandstone lenses along a NW-SE cross section (Fig. 10, location Fig. 9) and made the comparison with the altitude of the base of the Fontainebleau Sand Formation (deduced from Fig. 9). The sand thickness below the sandstones is rather constant (~50 to 60 m) in the western part of the profile and progressively decreases to the east until the formation becomes only few meters thick. In the western part of the cross-section, the quartzite base is undulating and its geometry mimics the one of the Rupelian unit base, even if we consider an uncertainty of ±10 m (grey area, Fig. 10) related to a relative precision of geological mapping. The parallelism between both curves seems to indicate that the base of the sands and the sandstones are folded together, and hence that silicification occurred before regional tectonic deformation. Considering an age of 300 ka for the silicification – one of the oldest values proposed by Thiry *et al.* (2013) and given a fold amplitude of 60 m between la Rémarde Anticline crest and Beauce trough bottom (Figs. 9 and 10), deformation rate would be around 200 m/Ma. Such a rate is clearly too high for the intracontinental setting of the Paris Basin centre, and folding certainly occurred for a much longer time. Consequently, cementation must be older than Quaternary.

4.3.2 Silicification vs. fracturing

The age of the joint network discussed here, that postdates silicification, cannot be precisely defined. Indeed, the interpretation of orthogonal set of joints is not straightforward: they are commonly related either to stress field perturbation associated to folding or a rotation of regional principal stresses by 90° resulting in the formation of early systematic joints and late non-systematic joints. As discussed previously, the joint network cannot be linked to the regional folds, discarding the first hypothesis. Concerning the second hypothesis, in the case of the centre of the Paris Basin, regional stress rotation is unlikely: the stress field during late Cenozoic is controlled by the Alpine collision and remains stable through times during middle Miocene to Pliocene. Furthermore, field observation did not reveal distinct systematic and non-systematic joint sets.

Following Rocher *et al.* (2005), during the late Miocene to Pliocene Alpine events, the stress regime corresponds to strike-slip with $\sigma 1$ ~WNW south-east of Paris city and extension to the north of Paris with $\sigma 3$ ~ENE. Although the limit between both tectonic regime is vague due to a lack of

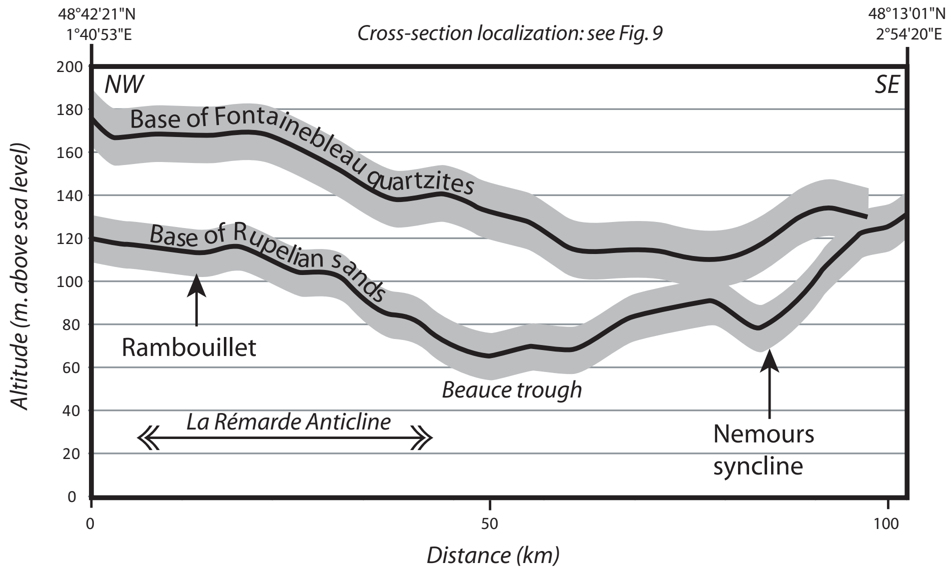

Fig. 10. NNW-SSE cross-section through the Rémarde Anticline and the Beauce trough (location Fig. 9) showing the geometry of the base of Fontainebleau Sand Formation and the base of the Fontainebleau quartzite. The main altitude variations related to the La Rémarde Anticline and Beauce trough are similar for both curves – even if considering an uncertainty of ±10 m (grey area) – indicating that both surfaces are folded together. Curves merge in the eastern part as the thickness of the Fontainebleau sands decrease until complete disappearance of the formation (Rupelian basin border).

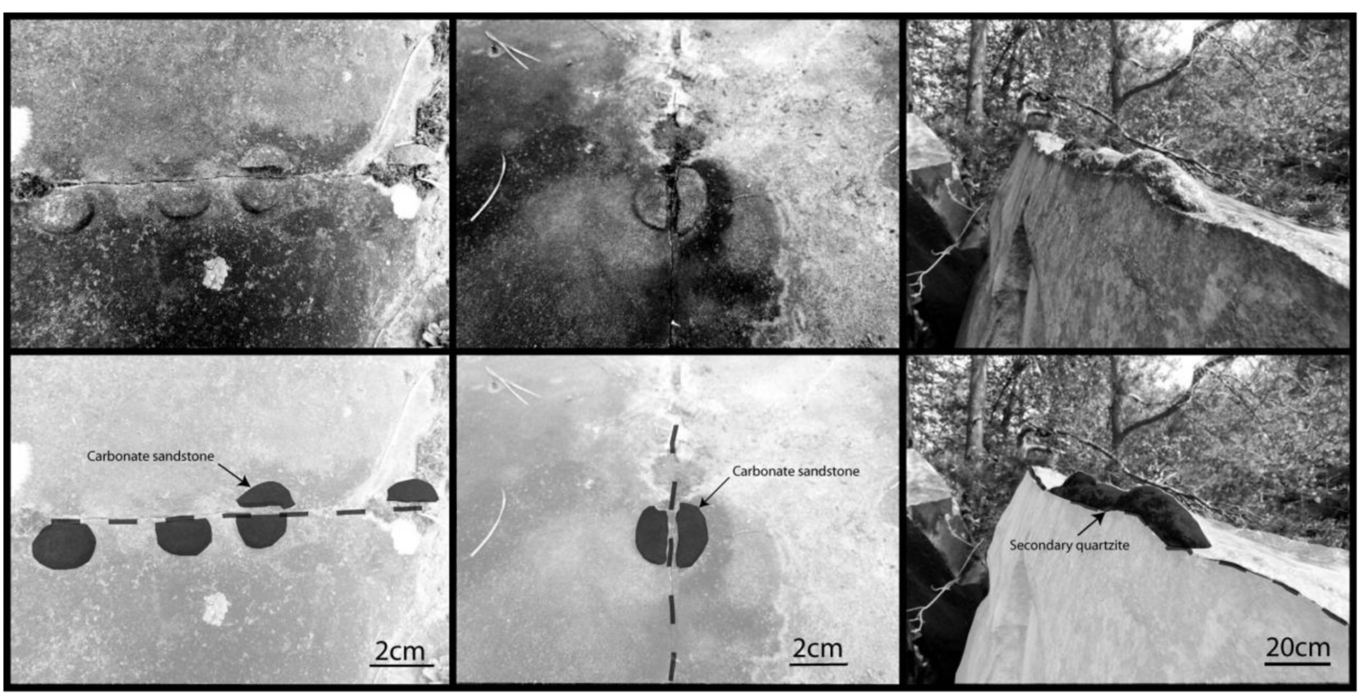

Fig. 11. Field pictures of secondary carbonate sandstones or quartzites along tectonic joints in the main Fontainebleau quartzite (Madagascar quarry, location Fig. 1). These late precipitations are clearly linked to the fracture network, indicating that it allowed fluid circulation(s) posterior to the main silicification event.

data, both regimes allow formation of the N125° fracture set, either parallel to σ1 (cleavage joints) or perpendicular to σ3 (tension joint). The formation of the N025° joints family is more puzzling due to the lack of regional stress field rotation. It can be explained by Bai *et al.* (2002) model of local stress rotation that allows the development of both families within the same stress field, requiring that both horizontal principal stresses are tensile. This is in agreement with the position of the studied area at the southern border of the extensional domain defined by Rocher *et al.* (2005).

We thus propose that both the orthogonal joint network and the regional folds formed during stress propagation from the Alpine domain toward its northern foreland, along with the formation of the Jura fold-and-thrust belt. As this chain formed from Serravallian to early Pliocene (Becker, 2000; Laubscher, 1992), silicification could have occurred during early to middle Miocene.

4.3.3 Silicification vs. calcite crystallizations

From recent calcite datings (14C and U-Th methods) in various formations (Rupelian, Bartonian, Ypresian, Thanetian) in the centre part of the Paris Basin including crystal rhomb forms moulded by the Fontainebleau quartzite, Thiry *et al.* (2013) suggest a Quaternary age for the cementation of the sands. These authors propose that the calcites formed during cold stages and correspond to cryocalcite. Our work demonstrates that most of the Fontainebleau sandstones cannot be as young as Quaternary. As a consequence, the quartzite that moulded the dated crystals must have been cemented after the main event of silicification. Such secondary, late cementations have been observed on the field (Fig. 11): centimetric bumps formed by yellow to grey sandstones are aligned along some of the tectonic joints, on the top of the main sandstone mass. These crystals may then correspond to a late event of silicification, not associated with the main event of quartzite formation.

5 Conclusion

Despite hundreds of years of naturalistic and scientific works regarding the Fontainebleau sandstones, the question of their age still remains puzzling. Results from this study, which is the first to focus on the post-Rupelian deformation in the centre of the Paris basin at a regional scale, shade on new light on this question. The joint network evidenced here (N115° and N025° joints), with homogenous directions at the scale of the studied area, indicates that the Fontainebleau sandstones underwent brittle tectonic deformation, together with large scale folding of the whole sedimentary pile.

We thus propose the following chronology:

– deposition of Fontainebleau sands during Rupelian, in marine environment and afterwards eolian environment;
– main silicification event during early or middle Miocene;
– fracturing of the Fontainebleau quartzites and folding of the whole sedimentary pile during late Miocene and Pliocene in response to the Alpine event. Folding occurs in various directions in response to slight reactivation of deeper inherited faults;
– valley incision during Quaternary, calcite precipitation during cold episodes (<300 ka) and finally secondary silicification.

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