C. R. Palevol 12 (2013) 69–79

Contents lists available at SciVerse ScienceDirect

Comptes Rendus Palevol

www.sciencedirect.com

General Palaeontology, Systematics, Evolution (Palaeobotany)

Discovery of an Autunian macroflora and lithostratigraphic re-investigation on the western border of the Lodève Permian basin (Mont Sénégra, Hérault, France). Paleoenvironmental implications

Découverte d'une flore autunienne et réinvestigation lithostratigraphique dans la bordure occidentale du bassin permien de Lodève (mont Sénégra, Hérault, France). Conséquences paléoenvironnementales

Georges Gand[a], Jean Galtier[b,*], Jacques Garric[c], Pierre-Alexandre Teboul[a], Pierre Pellenard[a]

[a] *UMR CNRS/uB 6282, laboratoire biogéosciences, université de Bourgogne, 6, boulevard Gabriel, 21000 Dijon, France*
[b] *CNRS, UMR AMAP, CIRAD, TA-A51/PS2, université Montpellier-2, boulevard de la Lironde, 34398 Montpellier cedex 05, France*
[c] *16, rue des Azalées, La Chamberte, 34070 Montpellier, France*

ARTICLE INFO

Article history:
Received 22 November 2012
Accepted after revision 15 January 2013
Available online 13 March 2013

Presented by Philippe Taquet

Keywords:
Sedimentary unconformity
Stephanian
Basal Autunian
Asselian
Coniferophytes
Peltasperms

Mots clés :
Discordance sédimentaire
Stéphanien
Autunien basal
Assélien
Coniférophytes
Peltaspermes

ABSTRACT

Re-investigation of the western edge of the Lodève basin allows reassignment of one sandstone-conglomerate formation previously identified as "terminal Stephanian" to Early Autunian. The existence of two unconformable (Stephanian and Autunian) megasequences, separated by a sedimentary gap, which had been rejected, is thus re-affirmed. The authors also found, less than 20 m above the basal Autunian conglomerate, a macroflora with taxa characteristic of the famous Tuilières flora from a site, located in the eastern part of the basin near Lodève, in the Grey Autunian group. This confirms that the new Mont Sénégra fossiliferous beds belong to the Lower Autunian. Moreover, the taxonomic differences between these plants and those from the underlying coal-bearing Stephanian beds indicate an important change in the vegetation between the Stephanian and the Autunian. The first Autunian sequences were initially deposited within a distal alluvial fan environment, which developed vertically into a floodplain, within an active volcanic context.
© 2013 Académie des sciences. Published by Elsevier Masson SAS. All rights reserved.

RÉSUMÉ

La ré-investigation de la bordure occidentale du bassin de Lodève a permis d'identifier une formation gréso-conglomératique de la base de l'Autunien à la place du « Stéphanien terminal », précédemment décrit. L'existence de deux mégaséquences, stéphanienne puis autunienne, discordantes et séparées par une lacune sédimentaire, est donc réaffirmée. Les auteurs ont aussi découvert, à environ 20 m au-dessus du conglomérat basal de cette formation gréso-conglomératique, une macroflore identique à celle du site des Tuilières, localisée à la base de l'Autunien gris, dans la partie orientale du bassin permien de Lodève. Outre le fait que cette macroflore confirme, au mont Sénégra, l'appartenance de cette nouvelle formation fossilifère à l'Autunien, ses différents taxa indiquent un changement important

* Corresponding author.
E-mail address: jean.galtier@cirad.fr (J. Galtier).

1631-0683/$ – see front matter © 2013 Académie des sciences. Published by Elsevier Masson SAS. All rights reserved.
doi:10.1016/j.crpv.2013.01.003

de la végétation par rapport à celle du Stéphanien productif sous-jacent. Les premières séquences autuniennes se sont d'abord déposées dans un environnement de cône alluvionnaire distal, passant verticalement à celui d'une plaine d'inondation évoluant dans un contexte volcanique actif.

© 2013 Académie des sciences. Publié par Elsevier Masson SAS. Tous droits réservés.

1. Introduction

Research in the Lodève Permian basin has been made possible by many natural outcrops and opencast uranium mines of *Compagnie générale des matières nucléaires* (COGEMA). This resulted in the establishment of a continuous stratigraphic framework for the Lodève basin (Laversanne, 1976; Odin, 1986) and has allowed significant discoveries in many fields, such as paleobotany (Galtier and Broutin, 1995, 2008), paleoichnology (Gand, 1987; Gand et al., 2000, 2008), paleoentomology (Béthoux, 2003), invertebrates (Gand et al., 1997a, b, 2008; Garric, 2000), vertebrates (Falconnet, 2006, 2010; Werneburg et al., 2007) and volcanism (Nmila, 1995). As a result, the Lodève basin was recently selected as a reference for studies of climate development of the continental Permian (e.g., Pochat and Van den Driessche, 2011; Schneider et al., 2006). However, the western area of the Lodève basin remains unstudied, with the exception of the work of Garric (2004, 2007, 2008).

On the western side of Mont Sénégra, at the limit of the Graissessac Carboniferous and Lodève Permian basins (Fig. 1A, B), nine coal seams, referred to as the "Orb group", are exposed. However, only coal seams numbered 3 to 7 were worked by the coal-mine company (HBCM: *Houillères des Bassins du Centre-Midi*) in a very large opencast mine (Fig. 1D and 4A–C). These coal seams alternate with sandstone and siltstone layers, which contain abundant and well-preserved floras (Martin-Closas and Galtier, 2005). They belong to a Stephanian unit, dipping towards the SSE, dated as Upper Pennsylvanian (= Gzhelian) on the basis of its paleofloral content. Towards the south of Mont Sénégra, these coal-bearing strata are uncomformably overlain by a grey conglomeratic-sandstone formation, about 50 m thick, which belongs to the Autunian (Figs. 1D and 2B) (Anonymous, 1988; Debriette and Gand, 1990; Garric, 2004). This geological formation was also identified more formerly towards the southwest, from Lunas to Le Bouché (Fig. 2B) by the geologists making the "Bédarieux" map (Bogdanoff et al., 1984) and in several drillings by the *Commissariat à l'énergie atomique* (CEA) then by COGEMA (Jousseaume, 1969; Saint-Martin, 1993).

However, in the Mont Sénégra area, the stratigraphic attribution to the Autunian of the formation above the unconformity was changed to Stephanian by Becq-Giraudon and Van den Driessche (1993), who mentioned the presence, under the Autunian formation, of "une série gréso-silteuse du Stéphanien terminal" overlain in conformity by the "Grès de la base de l'Autunien à ciment carbonaté et à clastes de dolomies cambriennes". Recent study of the Mont Sénégra outcrops by the authors (Garric, 2004, and present work) did not allow us to distinguish this "Stéphanien terminal". Instead, we observed aggradational detrital formation of which the lower part consists of plurimetric conglomerates, such as mass- and debris-flows, alternating with sandstones and siltstones. It is near the top, within fine grained siltstones, that we found a new macroflora. In the present paper, we provide the stratigraphical context of these fossiliferous levels, the description of the flora, and a discussion of the stratigraphical and paleoenvironnemental implications of these other findings.

2. Description and stratigraphic location of the levels F1-F3 with macroflora

2.1. Description

A first level of grey to greenish siltstones forming a wavy surface with centimeter-scale symmetrical ripple-marks, rich in carbon and plant debris, was first discovered near the 572-m altitude location (F1, Fig. 1C). A few meters from this place, a new search conducted in the overlying 50 cm thick sandstone, allowed us to find other plants on the surface of some sandstone-siltstone beds with a thickness ranging from 1 to 8 cm (F2, Figs. 1C and 2G). Examination of thin sections shows that these layers consist of millimeter- to centimeter-thick sequences, each starting with a bed of quartz often very angular, immediately topped by a clay-siltstone drape containing fusinized plant remains (Figs. 2I, J and 3A); the cement is more or less dolomitic; this last mineral forms thin layers in some sequences. During the excavation, the rather high whiteness of some siltstone levels suggested the presence of volcanic ash. However, a search for indicators (bubbles, glass) from three samples was negative (Teboul, 2010). Recently, another level with plants (F3, Fig. 1C and 2H) has been observed from grey and dolomitic siltstones located about 10 m from the F2 site.

2.2. Stratigraphic location of plant levels F1–F3 in the formation overlying the Stephanian (coal-bearing "Orb group")

A section of the lower part of this formation was studied from its contact with the Stephanian deposits, which is visible on the slope of the former coal mining trail (A7, Fig. 1C, D). Although heavily fragmented up to point B (Fig. 1C), we have distinguished five positive sequences, from the base to the top.

The first sequence (1, Fig. 2D) is 5- to 6 m thick and begins with several meters of coarsely deposited conglomerate-sandstones. One of them is surmounted by a thin (less than 10 cm thick) lenticular bed of sand/siltstones. In the conglomeratic portion, the breccias contain abundant pebbles. These consist mostly of angular quartz mixed with pebbles of blavierite, migmatites and grey–black sandstones, the latter originating from the

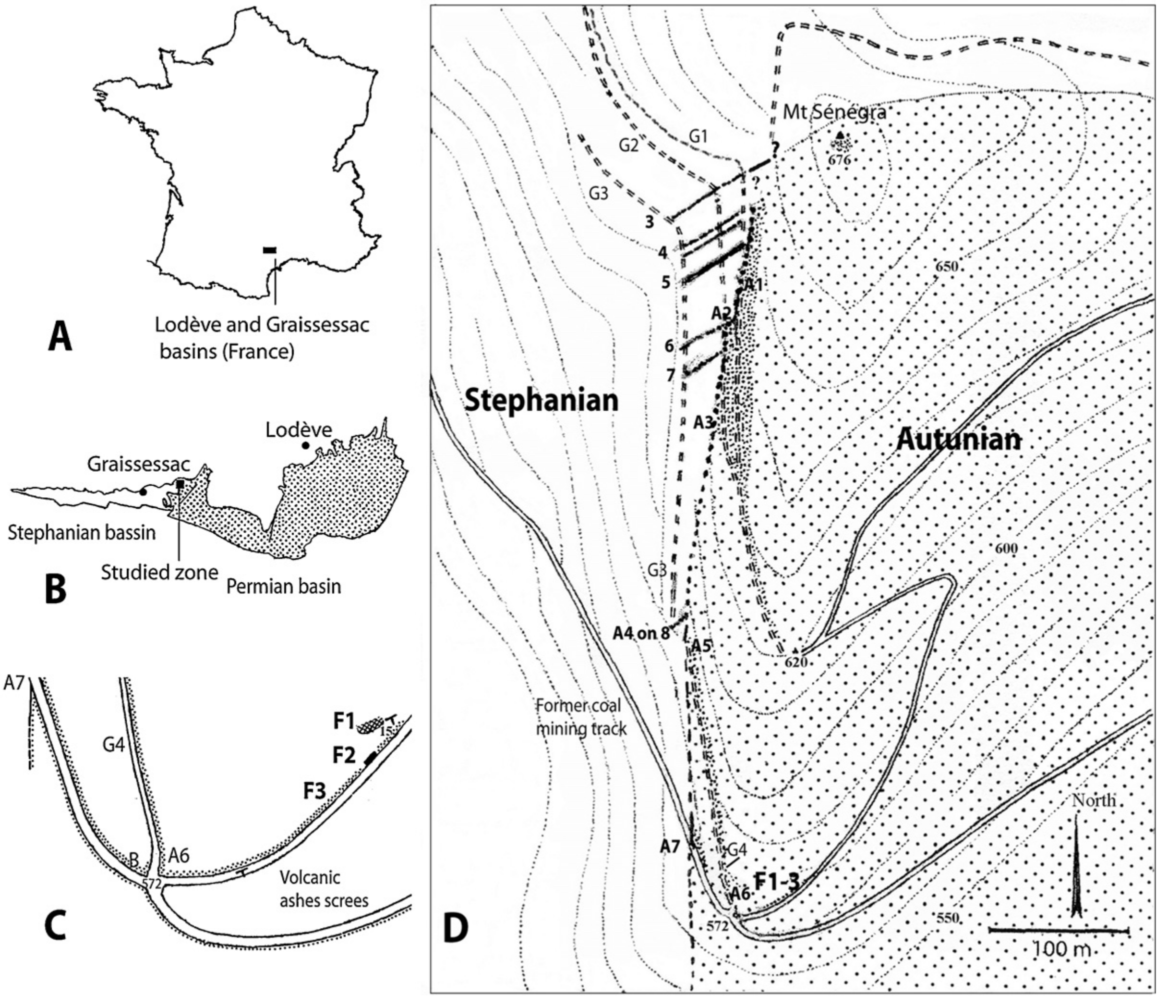

Fig. 1. **A**, **B**. Graissessac Carboniferous and Lodève Permian basins. **C**. Location of F1–F3 levels with Autunian macroflora; A7-B-A6: location of the log section drawn in Fig. 2D. **D**. Detail of the zone of contact between Stephanian and Autunian (stippled) in the Mont-Sénégra area; G1–G4: trails used in open pit during the coal working; 3–8: coal seams of the Orb Group; A1, A2, A4, A7: Stephanian–Autunian contacts still visible; A5–A6: Autunian outcrops; dense stippling: sandstones and mass/debris-flow, of Early Autunian clearly visible.

Fig. 1. **A**, **B**. Les bassins carbonifère de Graissessac et permien de Lodève. **C**. Localisation des niveaux F1–F3 à macroflore autunienne ; A7-B-A6 : situation du log D de la Fig. 2. **D**. Zone de contact entre le Stéphanien et l'Autunien dans le secteur du mont Sénégra ; G1-G4 : gradins/banquettes d'exploitation de la houille ; 3–7 : couches de charbon du faisceau de l'Orb ; A1, A2, A4, A7 : contacts Stéphanien-Autunien visibles ; A5–A6 : affleurements d'Autunien ; pointillés serrés : grès et mass/débris-flow de l'Autunien inférieur.

Stephanian. Angular cavities also mark the location of dissolved dolomitic breccias that were inherited from the local Cambrian basement. This basal conglomeratic part, characteristic of detrital material (mass debris-flows) transported over a short distance, was also mentioned by Garric (2004), northwards in the slope of trails G1 and G2 (Fig. 1D), overlying with unconformity the coal-productive Stephanian. Along trail G1, these conglomerates are also found between A1 and A2 (Fig. 4C), and continuously contact (Fig. 4D) the Stephanian basement with an unconformity of 40° (Fig. 4E, F). The contact boundary between this coarse formation and the underlying Stephanian is very irregular. Along the former coal mining track, from A7 to B (Fig. 1C), this detrital sequence No. 1 ends with an ochre siltstone layer, 1 m thick, very fractured and in which the sequential organization is difficult to interpret. This sequence No. 1 is also observable in the trail G2 at point A3 (Fig. 1D), where it has the same thickness but is much better preserved, and where it was also described by Garric (2004). In this place, at the base of the "siltite grise à rubans ocre" a volcanic-ash ("cinerite") level was identified by Teboul (2010, sample 28).

Sequences No. 2 and 3 (Fig. 2D) can be followed up to point B (Fig. 1C). Sequence 2 begins with a conglomeratic bed showing cavernous brecciated parts (B, Fig. 2D) without apparent layering, and with polygenic, rounded to angular pebbles of the same type as those in the lower sequence, but with more dolomitic blocks up to 10 cm in diameter. All these clasts are distributed within a sandstone-dolomitic matrix. This conglomerate is topped by a thick sand-siltstone-dolomitic bed including

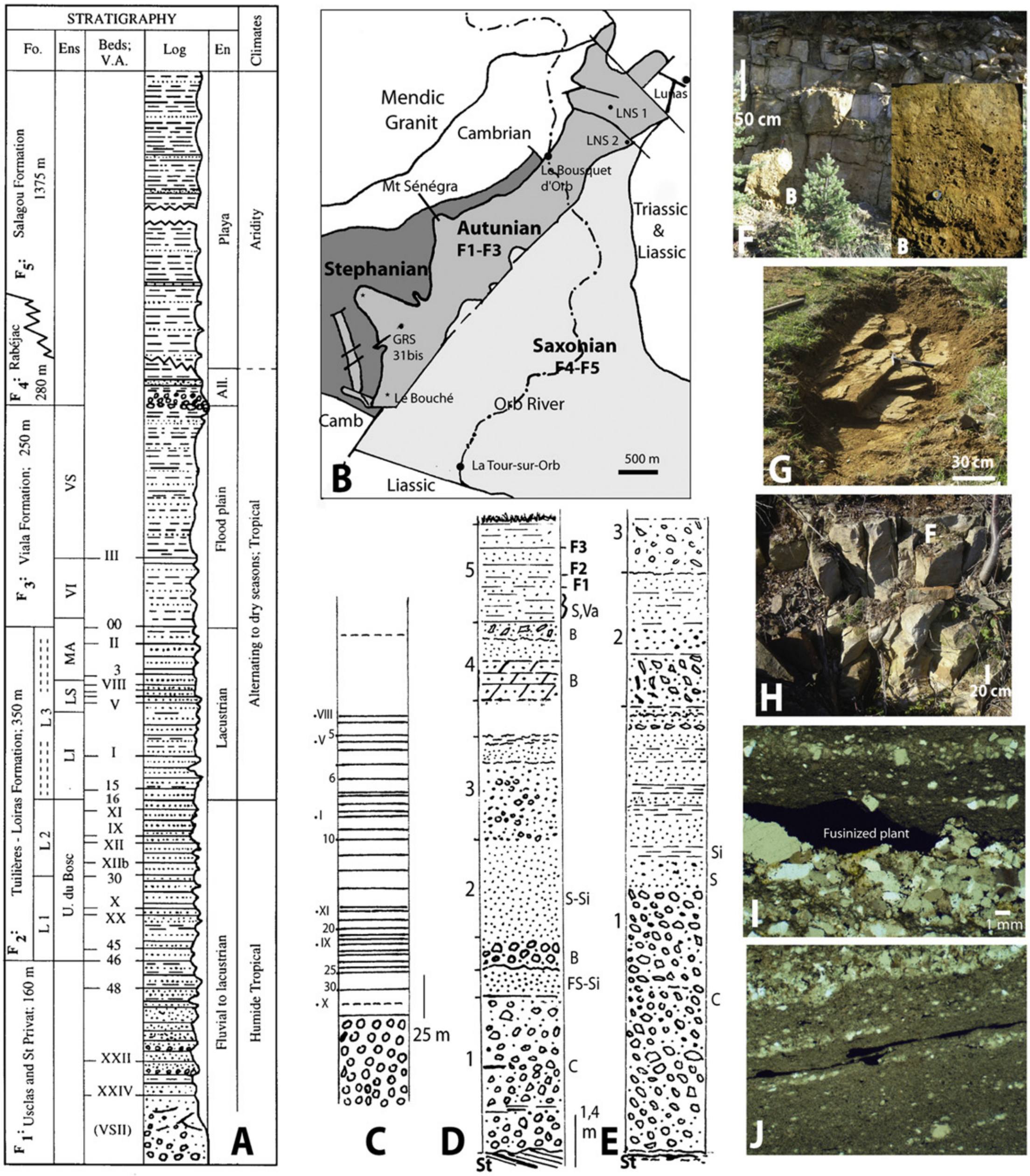

Fig. 2. A. Permian synthetic 1og of the Lodève basin eastern part (Fo: Formations; Ens: Ensembles; V.A.: volcanic-ashes; En: palaeoenvironments). **B.** Geological map of the Lodève basin western part (after Garric, 2012), F1–F3: Autunian formations; F4–F5: Saxonian formations. **C.** Log of the LNS2 boring, volcanic-ashes are in roman figures, "bituminous shales" are in Arabic figures. **D.** Section of the Early Autunian between A7 and A6, detailed in Fig. 1C (1–5: macroscopic sequences; St: Stephanian; C: conglomerates, debris/mass-flows, FS–Si: fine-grained sandstones/siltstones; B: Breccias with dolomitic elements; S/Si: sand/siltstones; Va: volcanic-ash Ldci18; F1–F3 siltstones levels with Autunian macroflora). **E.** Sketch of the Early Autunian formation from the GRS31bis boring; 1–3: sequences numbering. **F.** A6 outcrop showing the sequences Nos. 4 and 5 of Fig. 2D; B enlarged on the right side: dolomitic breccias of sequence No. 4. **G.** Layers with plants of the site F2. **H.** Fossiliferous site F3. **I, J.** Microscopic thin sections of fossiliferous sequences from site F2; detailed description in text.

Fig. 2. A. Log synthétique de la série permienne de la partie orientale du bassin de Lodève (Fo : formations ; Ens : Ensembles ; V.A : cinérites ; En : environnements). **B.** Carte géologique de la partie occidentale du bassin de Lodève (d'après Garric, 2012), F1–F3 : formations de l'Autunien ; F4–F5 : formations du Saxonien. **C.** Log du sondage LNS2, cinérites en chiffres romains, couches bitumineuses en chiffes arabes. **D.** Log de l'Autunien basal entre les points A7 et A6 de la Fig. 1C (1–5 : séquences macroscopiques ; St : Stéphanien ; C : conglomérats, débris/mass-flows, FS–Si : grès fins/siltites ; B : brèches à éléments dolomitiques ; S/Si : grès/siltites ; Va : cinérite Ldci18 ; F1–F3 : niveaux de siltites à macroflore autunienne). **E.** Base de la formation autunienne dans le sondage GRS31bis ; 1–3 : séquences. **F.** Affleurement A6 (séquences 4 et 5 de la Fig. 2D) ; encart, à droite **:** agrandissement de la zone conglomératique et bréchique dolomitique B (séquence 4). **G.** Niveaux à macroflore du site F2. **H.** Niveaux fossilifères F3. **I, J.** Lames minces de séquences du site F2 ; lits de quartz anguleux alternant avec des siltites à ciment dolomitique ; abondance de débris végétaux charbonneux en noir ; fusain probable.

centimetric microconglomeratic layers with dolomite and quartz intraclasts. Sequence No. 3 has the same characters as No. 2.

After a small gap, sequences No. 4 and 5 are visible in the slope of the trail G4 (A6, Figs. 1C, D and 2F). They are petrographically similar to the previous ones; nevertheless, in the lower part of No. 4, dolomitic breccia zones seem to be more frequent (Fig. 2D). The sandstone matrix shows abundant dolomite, quartz pebbles and volcanic-ash rock debris.

Discontinuous and fractured outcrops between the A6 exposure and those beds containing the Autunian macroflora (F1–F3, Figs. 1C, D and 2D) did not allow us to locate fossiliferous beds quite precisely in sequence No. 5, which is approximately 3.5 m thick. Considering the dip of the beds, we suggest that the succession of plant-bearing layers – from F1 to F3 – is about 2 m in thickness up to near the top of sequence No. 5. Actually, the top of this is not fully visible due to vegetation cover and is partially covered by colluvial deposits. The volcanic-ash Ldci 18 (Fig. 2D, Va), identified by Garric (2004) below layer F1, was confirmed by Teboul (2010). It contains desiccation cracks, traces of roots and dolomitized seeds.

3. The macroflora of the sites F1–F3

The fossil plants are very fragmentary, none exceeding a few centimeters in length. In some levels, they even occur as accumulations of millimetric-sized pieces (Fig. 3A). It is noteworthy that, in this case, many fragments are of a bright black color, suggesting that they are burnt fragments of plants or fusain. This is supported by the fact that thin sections of these plants seen under reflected light are opaque (Fig. 2I, J). However, we did not succeed in isolating these fragments using acid maceration. Despite the unpromising facies, several attempts to extract palynomorphs have been carried out in different laboratories, but all have been unsuccessful. Fossil plants mainly occur in layers of ochreous color. Slightly larger plant fragments are found at the boundary of apparently grey beds of angular quartz. But the largest fragments have been found in relatively soft grey siltites; it is only in these softer rocks (Fig. 3B) where it was possible to use the "dégagement" technique to expose the plant fragments.

The identified plant assemblage consists of a small number of taxa, all belonging to seed plants:

- firstly we recognized leafy twigs of coniferophytes in the form of dispersed ultimate branches; due to their small size, they are attributed with some reservations to *Culmitzschia frondosa* (Fig. 3B), *Hermitia schlotheimii* (Fig. 3B, C) and *Walchia piniformis* (Fig. 3D). In addition, dwarf shoot scales similar to those of *W. piniformis* cones (Fig. 3J) and numerous dispersed ovules have been found, including *Cordaicarpus* sp. (Fig. 3I);
- less common are representatives of peltaspermous pteridosperms with characteristic frond fragments (Fig. 3A, G, F) and fertile parts attributed to *Peltaspermum* sp. (Fig. 3H). The specimen illustrated in Fig. 3 F is an ultimate pinna with a distinct rachis (more than 1 mm broad) bearing dissected sphenopteroid pinnules (5 mm long) as well as small round intercalary lobes between the pinnules (white arrow, Fig. 3F). This specimen is similar to *Gracilopteris bergeronii*; however, if intercalary pinnules are present on the penultimate rachis, such intercalary lobes borne on the ultimate rachis have not been mentioned in this species (Doubinger, 1956; Kerp and Haubold, 1988). Alternatively, this specimen could be attributed to *Arnhardtia mouretii*, which possesses longer, but similar, pinnules and intercalary lobes on the ultimate pinna rachis (Zeiller, 1898). The pinna illustrated at the same magnification in Fig. 3G is either a large pinnately compound pinnule or, more probably, an ultimate pinna with a narrow rachis bearing small three-lobed pinnules; it is tentatively attributed to *Rhachiphyllum diabolica* or to *R. lyratifolia.* The same taxonomic identity is proposed for the poorly preserved pinna with lobed pinnules illustrated in Fig. 3A (arrow);
- at last, one leaf fragment of the possible cycad *Taeniopteris* is shown in Fig. 3E.

4. Stratigraphic and paleoenvironmental results

4.1. Stratigraphic attribution of F1–F3 levels with macroflora to Autunian

4.1.1. Paleontological data

The list of the macroflora results from a preliminary investigation. Though quantitatively small, it is nonetheless significant that the flora contains no element recognized in the underlying Stephanian coal-bearing levels (Martin-Closas and Galtier, 2005). Actually, all identified taxa of the new flora have been described historically (Doubinger, 1956; Florin, 1938–1944; Grand'Eury, 1877; Zeiller, 1898) from the Tuilières fossiliferous site near Lodève, which contains the most diverse flora known in Europe for the Early Autunian. This site is located in the eastern part of the Lodève basin and corresponds to the stratigraphic interval between "beds 45 and 48" of the Lodève basin stratigraphic column (Fig. 2A), i.e. to the basal Usclas–Saint-Privat Formation.

Among the taxa identified in the new flora of Mont Sénégra, only two (*W. piniformis* and *Taeniopteris* sp.) have a relatively broad stratigraphic distribution, from the Late Stephanian–Gzhelian (of many Euramerican basins) to the Autunian/Lower Rotliegend (e.g. Lodève, Autun, Thuringia, Saar-Nahe basins) correlated with Asselian to Sakmarian times (Schneider et al., 2006). In contrast, the other taxa (*C. frondosa*, *R. lyratifolia*, *G. bergeronii*) are restricted to the Lodève, Autun, and Saar-Nahe basins (Broutin et al., 1999; Kerp and Fichter, 1985). Moreover, some taxa (*A. mouretii*, *H. schlotheimii)* are only known from the Tuilières locality. This supports the idea that on the western border of the Lodève basin, in the area of Mont Sénégra, the base of the sandstone conglomeratic formation containing the new flora must be correlated with the basal Usclas–Saint-Privat Formation of the Lodève basin and considered as Early Autunian. This stratigraphic attribution confirms the one previously based on paleoichnofauna by Debriette and Gand (1990) for similar levels located near Mont Sénégra.

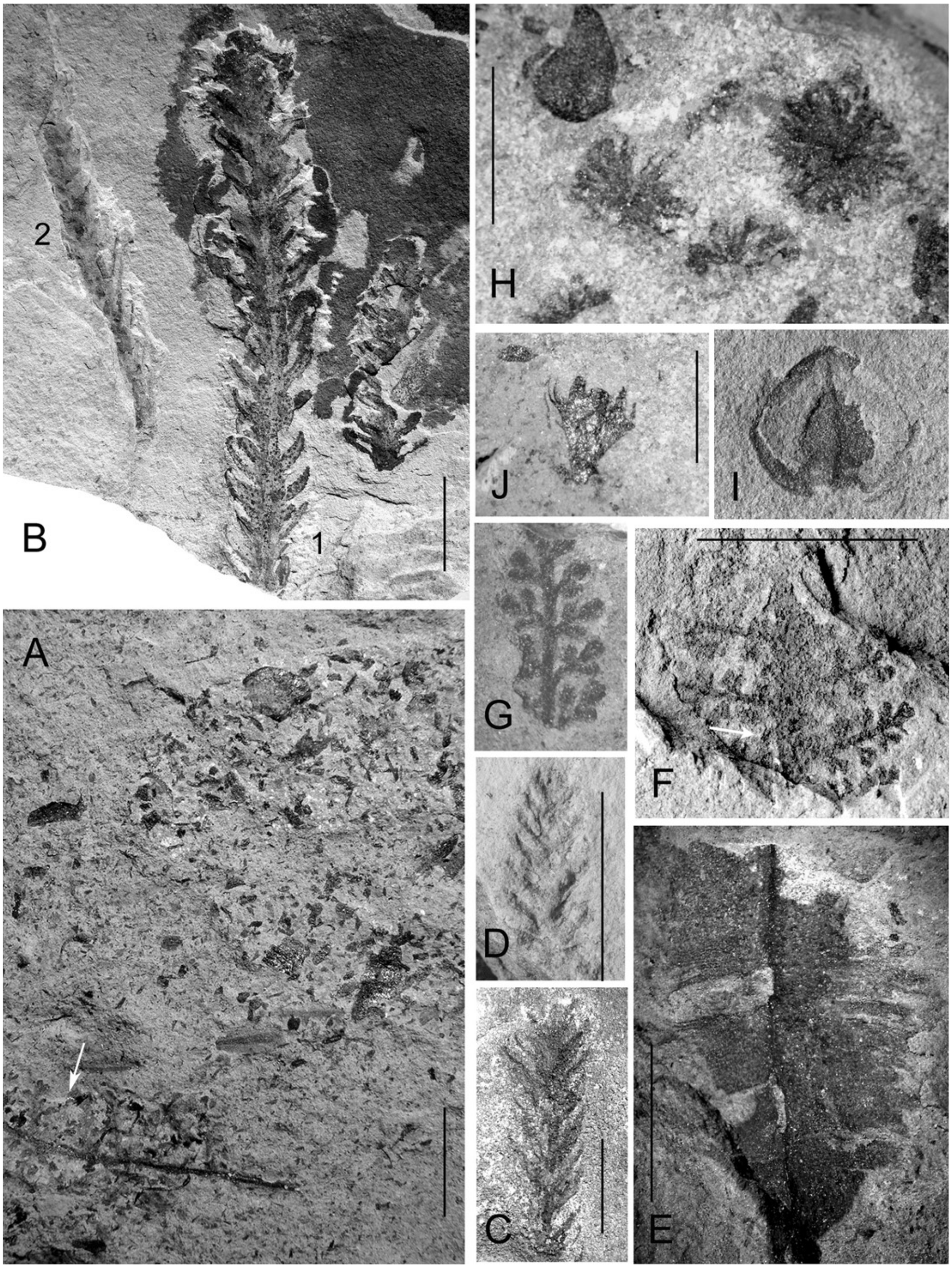

Fig. 3. **A**. Siltstone surface showing abundant very small plant fragments including fusainized material (bright black) and *Rhachiphyllum lyratifolia* pinna (arrow), SEN19. **B**. Leafy twigs of *Culmitzschia frondosa* (1) and *Hermitia schlotheimii* (2) SEN14. **C**. *Hermitia schlotheimii*, SEN20. **D**. *Walchia piniformis*, SEN09. **E**. *Taeniopteris sp.*, leaf fragment, SEN15. **F**. *Gracilopteris bergeronii* or *Arnhardtia mouretii* pinna, SEN 01. **G**. *Rhachiphyllum diabolica* or *R. lyratifolia* ultimate pinna, SEN15 (same magnification as F). **H**. *Peltaspermum* sp., SEN12. **I**. *Cordaicarpus* sp. dispersed ovule, SEN 02. **J**. Dispersed dwarf shoot of *W. piniformis* cone, SEN12. Palaeobotanical collections, Montpellier-2 University. Scale = 1 cm, except **I** and **J**, same scale = 5 mm.

Fig. 3. **A**. Surface d'une siltite montrant de nombreux petits fragments de plantes dont certains (noir brillant) transformés en fusain et penne de *Rhachiphyllum lyratifolia* (flèche), SEN19. **B**. Rameaux feuillés de *Culmitzschia frondosa* (1) et *Hermitia schlotheimii* (2) SEN14. **C**. *Hermitia schlotheimii*, SEN20. **D**. *Walchia piniformis*, SEN09. **E**. *Taeniopteris sp.*, fragment de feuille, SEN15. **F**. Penne de *Gracilopteris bergeronii* ou d'*Arnhardtia mouretii*, SEN 01. **G**. *Rhachiphyllum diabolica* ou *R. lyratifolia*, penne ultime, SEN15. **H**. *Peltaspermum* sp., SEN12. **I**. *Cordaicarpus* sp., ovule dispersé, SEN 02. **J**. Écaille ovulifère dispersée du cône de *W. piniformis*, SEN12. Collections paléobotaniques de l'université Montpellier-2. Barre d'échelle = 1 cm, excepté pour **I** et **J**, dont l'échelle = 5 mm.

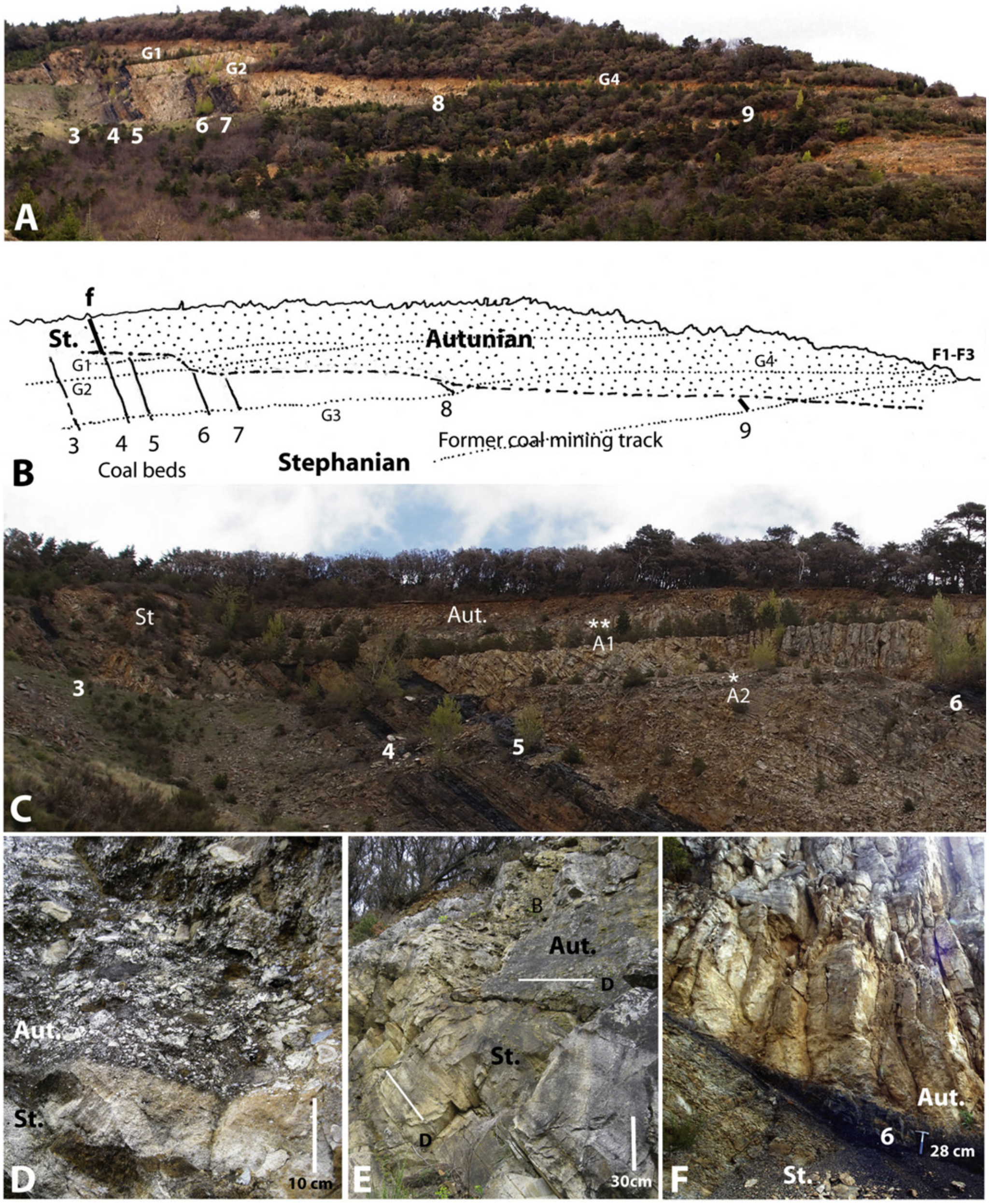

Fig. 4. **A**. Present view of the Stephanian and Autunian formations on the west slope of Mont Sénégra. **B**. Geological interpretation of Fig. A; Autunian: stippled, and dash line: contact; f: possible fault; G1–G4: former mine trails; 1–9: coal seams numbers (see also Fig. 1D). **C**. Enlargement of fig. A between coal seams No. 3 to No. 6; St: Stephanian; Aut.: Early Autunian: mass/debris-flows, sand/siltstones formation overlying in unconformity the Stephanian; A1, A2: places showing clearly the Stephanian/Autunian contact. **D–F**. Detail of Stephanian–Autunian contact zones observed between A1 and A2. **D**, **E**. Normal but discordant contact between the Stephanian sandstones (St.) and the Autunian (Aut.), the latter consists of mass/debris-flows (DF) made of angular/weathered blocks/pebbles of dolomite, quartz, quartzite, blavierite, Stephanian sand/siltstones spread into sandstone-dolomitic matrix (A1 location ** in Fig. 4C). **D**. Enlargement of the contact zone. **E**. General view of the same with dolomitic breccia zones (B) in mass/debris-flows; D white bars: deepening. **F**. Autunian/Stephanian contact on a lystric fault in A2 (*location in Fig. 4C); the Autunian conglomeratic formation slid on coal-seam 6.

Fig. 4. **A**. Vue actuelle du Stéphanien et de l'Autunien sur la pente ouest du mont Sénégra. **B**. Interprétation géologique de A, l'Autunien est figuré en pointillés ; mêmes abréviations que pour la Fig. 1D ; f : contact masqué, possible faille. **C**. Agrandissement de la zone A1-A2 ; faisceau stéphanien (St) de l'Orb (couches 3 à 6), recouvert par l'Autunien (Aut.). **D–F**. Détails des zones du contact Stéphanien-Autunien, observées entre A1 et A2. **D**, **E**. Contact normal mais discordant entre le Stéphanien gréseux (St.) et l'Autunien constitué de brèches (B) et de débris-flows (DF) à galets/blocs anguleux/usés, de dolomie, quartz, quartzite, blaviérite, grès/siltites stéphaniens, matrice gréso-dolomitique, vus entre A1 et A2 (** sur la Fig. 4C). **D**. Agrandissement d'une zone de contact. **E**. Vue plus large de la même zone avec les brèches (B) ; barre blanche D : litage. **F**. Contact Stéphanien/Autunien sur une faille lystrique en A2 (* sur Fig. 4C) ; la formation conglomératique autunienne a glissé sur la couche de charbon n°6.

4.1.2. Corings and field geological data

The base of the Autunian megasequence consists of conglomeratic layers in sharp unconformity above the Stephanian. This was regularly observed in drill cores carried out in the Autunian of the western part of the Lodève basin for the research of uranium as summarized by Saint-Martin (1993).

One of these corings (GRS 31bis), located to the southwest of Mont Sénégra (Fig. 2B), went through 691 m of rocks from the surface, across the Autunian, and into the Stephanian. In order to facilitate the comparison with our outcropping section of Mont Sénégra (between A7 and A6: Fig. 1D and illustration in Fig. 2D), we have reproduced at the same scale in Fig. 2E the first 20 m of the Autunian Formation as exposed in the drill core. Lying with an unconformity of 10° on the Stephanian coal siltstones, the basal Autunian is represented by 8 m of mass/debris-flows. They consist of a reddish sandstone and carbonate matrix including altered angular and rounded granite pebbles up to 20 cm in diameter, as well as Stephanian debris, up to 5 cm long, as well as quartz. These data (Anonymous, COGEMA 1988–1989) were supplemented by Saint-Martin (1993), who produced a detailed study, including petrographic, sedimentological, and tectonic information.

Above the basal conglomeratic beds, sequence No. 1 (Fig. 2, E1) consists of alternating coarse sandstones and siltstones. It is overlain by sequences No. 2 and 3 of the same type, but that are less conglomeratic and coarse (Fig. 2E2–3). Such a vertical change was also noted in the A7–A6 section of Mont Sénégra (Fig. 2D).

From the top of the conglomeratic part of sequence No. 1 (level 117 m of the GRS 31bis core), Saint-Martin (1993) attributes the overlying beds (ranging from level 117 to 36 m) to the "Grey Autunian Formation". In the synthetic log of the Permian established by COGEMA for the eastern part of the Lodève basin (Fig. 2A; Gand, 1994; Gand et al., 1997b), this "Grey Formation" represents the section extending between the basal conglomerate and bed No. 16.

Saint-Martin (1993) attributed the uppermost part of the cored section to the "Grey and Red Autunian" ending at "mark 00" in the lithostratigraphic log in Fig. 2A. Based on the nomenclature of Odin (1986), the "Usclas–Saint-Privat (F1)" and "Tuilières-Loiras (F2)" Formations were included in the GRS 31bis core. This interpretation implies that the sequential organization of the Autunian series in the western part of the Lodève basin is similar to that of the eastern part. Similar sequential organization was also found in cores LNS1 and LNS2 (Fig. 2B) made in the Lunas area. The Jousseaume report (1969) indicates that the LNS1 coring reached the basal Cambrian after coming through a large part of the Grey and Red Autunian and then the whole Grey Autunian, beginning with its basal conglomerate. The volcanic-ashes/cinerites IX and X were for the first time discovered here, in the eastern part of the basin. The LNS2 core (Fig. 2B, C) is more complete; it probably came through the beds No. 5 to 30 and cinerites V to X. In the Lunas area, some of these volcanic markers were also observed in outcrops by Garric (2008). In addition, based on the general eastward dip of the Autunian series and on the geographic location of cinerites V and X (about 1 km west of the Mont Sénégra), one can suggest that the Autunian levels, with the macroflora described here, are underlying cinerite X. Therefore, they should be contemporary with those of the "Tuilières" site, which have provided a very diverse Autunian macroflora. As stated above, the levels containing the flora also overlie fanglomerates with volcanic-ash layers that are currently impossible to correlate with those in the eastern part of the Lodève basin. But, on this western border, Garric (2007) also identified similar volcanic rocks in the base of the Lower Autunian, along the D23 road, 250 m west of Le Bouché (Fig. 2B). Considering their metric thickness, this author believes that they are comparable to the cinerite markers XXIV to XII (Fig. 2A).

4.2. Age of the Stephanian and overlying Autunian formation with macrofloras near Mont Sénégra

The flora found in the Stephanian of Mont Sénégra, between coal layers No. 3 to 7, has the same characteristics as the flora of the Upper Stephanian (Stephanian B + C = "Forézien") described in the Saint-Étienne coal basin and proposed as a reference in France by Doubinger et al. (1995). In Mont Sénégra, this Stephanian flora has been dated as Upper Pennsylvanian (Martin-Closas and Galtier, 2005) and can be more precisely attributed to a Gzhelian age, as suggested by Doubinger et al. (1995: 305) for the French Late Stephanian. The same age would be extended to the Latest Carboniferous deposits found at Mont Sénégra above the coal layers 3 to 7 (Fig. 4A, B) towards the South of the Graissessac Carboniferous basin.

Importantly, in this same place, Brugier et al. (2003) have dated as 295.5 ± 5.1 Ma (using the zircon $^{206}Pb/^{238}U$ method) several samples of a bentonite located between coal seams 4a and 4b. This gives these coal seams an Asselian age (i.e. Early Permian), date based on the recent International Chronostratigraphic Chart of IUGS (Cohen et al., 2012), which provides a numerical age of 298,9 ± 0.2 Ma for the Gzhelian/Asselian limit (or Carboniferous/Permian boundary) and of 295.5 ± 0.4 Ma for the top of the Asselian.

Schneider et al. (2006: 172) attributed the whole coal-bearing sequence of Graissessac to the Stephanian C; however, taking into account geochronological results of Brugier et al. (2003), they dated the major coal seams at 299 Ma (i.e. on the Carboniferous/Permian limit on their chart) and consider the top of the sequence (and accordingly the top of Stephanian C) as Early Asselian. This is in disagreement with the usage of Carboniferous chronostratigraphy (Heckel and Clayton, 2006), which includes the whole Stephanian within the Carboniferous and the top of the Stephanian as equivalent to the Gzhelian.

In the Sénégra opencast mine, above coal seam 7, there is a thick sequence of detrital deposits in which coal beds are rare, thin and not worked (e.g., 8 and 9, Fig. 4A, B). From 5 m above coal seam 7, plant remains become rare and several conglomeratic lenses with small quartz pebbles are visible. This would correspond to the top of the Stephanian C *sensu* Schneider et al. (2006) and perhaps, partly, to what was interpreted as "Terminal Stephanian" by Becq-Giraudon and Van den Driessche (1993). These authors studying the exposures of the Mont Sénégra opencast mine suggested a continuity of the sedimentation between the

Stephanian and the Permian. They described, as Terminal Stephanian (2 in their Fig. 2b), a sand-siltstone series extending northwards, within a very clear unconformity, on the coal seams No. 4–7 (see Fig. 4F for coal-seam 6). However they have drawn it overlain in conformity by the basal Autunian sandstones (3 in their Fig. 2b) with carbonate cement and Cambrian dolomite clasts. Actually neither Garric (2004) nor the authors of this paper recognized this sandstone-siltstone terminal horizon of the Stephanian. In its place, and particularly well exposed between A1 and A2 (Figs. 1D and 4A–C), this horizon corresponds to a conglomerate of mass/debris-flows with a carbonate matrix and breccias showing dolomitic angular elements, which are often dissolved (Fig. 4(?) D, E). These are characters that are precisely those of the Autunian conglomerate defined *in* Becq-Giraudon and Van den Driessche (1993: 942).

To summarize, as Saint-Martin (1993) and Garric (2007) have successively pointed out from petrographic, sedimentological and tectonic data, confirmed by the GRS 31bis coring and observed to the south, in the Aire Raymond and Le Bouché areas, the two sedimentary megacycles Stephanian and Autunian are truly separated by a significant discordance that corresponds to a major tectonic phase. The rubefaction of the Uppermost Stephanian layers, the presence within basal Autunian conglomerates of pebbles of Stephanian origin and of others with dolomite, quartz, quartzite, blavierite and granite from the regional basement, all indicate the emersion and erosion of the Stephanian basin and its borders. The second Autunian cycle then took place eastwards within a new extensive basin (Saint-Martin, 1992, 1993). Based on paleontological correlations between various European Permian basins, Schneider et al. (2006, Fig. 9) proposed the beginning of this Autunian cycle in Lodève at the very end of the Asselian, after a long gap (about 6 Ma). However, the Asselian duration being reduced to 3.4 Ma (Cohen et al., 2012), it seems likely that the sedimentary gap has been shorter in time.

5. Paleoenvironments and climate

5.1. During the mass/debris-flow deposits of Mont Sénégra

The first Autunian conglomeratic layers of Mont Sénégra are mass/debris-flows of alluvial fanglomerates. As the result of weathering, these were deposited at the foot of elevated areas along a fault scarp in a subsiding basin of tectonic origin. Such a mechanism still underway in semi-arid regions (Friedman and Sanders, 1978) was illustrated for the western part of the Lodève basin by Garric (2007). As for the Stephanian deposits, the active area was always located on the southern border of the basin. However, the presence of pebbles of Stephanian sandstones, granite, blavierite and dolomite suggest that detrital sediments also come from the western and northern borders, especially of the Mendic area. The size of pebbles, not more than 10 cm long, suggests that the deposits were carried out in the distal part of an alluvial fan at the edge of the flood plain.

5.2. Conditions during deposition of plant-bearing siltstones

Overall, these fossiliferous rocks are constituted of regular, thin sequences with horizontal bedding. This organization, as well as the millimeter-sized plant fragments observed in the inter-beds, but also in the clay-siltstone and the dolomitic matrix, suggests that sediment and plant debris were deposited in a rather low-energy flood plain environment. Centimeter-scale wave lengths of symmetric ripple-marks, as well as rare oblique lamination also demonstrate its shallowness and a moderate hydrodynamism, the latter being shown by the fossil plants, which are not deformed. Desiccation cracks observed in some volcanic-ash layers with traces of roots suggest plant colonization of periodically exposed surfaces, close or within the sedimentary areas. The Autunian plants, mainly conifers and peltasperms, are considered to be mesophytic to xerophytic. They constitute evidence of a clear change in environment and climate compared to earlier Stephanian vegetation, which was dominated by a quite different flora composed of mesophytic to hygrophytic sigillarians, calamiteans, ferns and pteridosperms (Martin-Closas and Galtier, 2005).

5.3. Floral change and climate

Similar floristic changes occur in other areas in the world, subject to well-known trends towards "drying" at the Pennsylvanian/Permian boundary. Representatives of conifers and peltasperms appear sporadically, during the Late Pennsylvanian, in tropical basinal lowlands where they become dominant during the Permian. This has been documented in detail, both in Europe and North America (e.g., Broutin et al., 1990; DiMichele and Aronson, 1992; Kerp and Fichter, 1985). Inversely, taxa from Carboniferous-type wetland biome, such as calamiteans, re-appear later (= "recurrence" of Broutin et al., 1990) in landscapes dominated by conifers and they are interpreted as stream and lake-side elements (DiMichele et al., 2006). Such occurrence of calamiteans in a plant assemblage dominated by conifers and peltasperms has been actually reported from younger Early Permian deposits of the same Lodève basin (Galtier and Broutin, 1995). Recently, DiMichele et al. (2008) proposed that the Pennsylvanian/Asselian vegetational change is not an evolutionary one, but reflects tracking of climate change, with the conifer–peltasperm flora tolerant to seasonal drought replacing a flora with low drought tolerance. Therefore floral change reflects climate, but climate is highly geographically heterogeneous and can confound terrestrial plant biostratigraphy. We agree with this interpretation, but we consider that the newly described flora from Mont Sénégra is the first appearance, in the Lodève basin area, of such a conifer–peltasperm flora. In the present example, we have no evidence that a similar "dry flora" was already somewhere in the landscape during the well paleobotanically documented (Martin-Closas and Galtier, 2005) Pennsylvanian time for this area.

6. Conclusions

The authors have discovered, in the Mont Sénégra area, beds rich in fossil plants located about 20 m above the Stephanian/Autunian contact. From its taxonomic content, this plant assemblage is identical to the famous flora of the Tuilières site, near Lodève, which comes from the lower part (Grey Autunian) of the Permian series and is considered to be Asselian in age. We suggest that a similar age should be attributed to the here newly defined, Autunian conglomeratic-sandstone formation of Mont Sénégra. This formation unconformably overlies the Stephanian coal-bearing Orb Group. Between the Stephanian and Autunian deposits, we have not found the sandstone-siltstone series of the Terminal Stephanian, as interpreted by Becq-Giraudon and Van den Driessche (1993), and we consider the continuity of sedimentation between Stephanian and Autunian as unproven. As a result, we confirm the existence of two unconformable sedimentary megasequences, one for the Stephanian and one for the Autunian, separated by a time gap (? a few Ma) during a part of the Asselian. It is expected that the real duration of this gap will be demonstrated, in the future, by dating of cinerites occurring locally in the basal Autunian.

The discovery of plants in the Autunian near Mont Sénégra including conifers and peltasperms, which are interpreted as xerophilous to mesophilous plants, is important because it reflects a sharp change of vegetation compared to the underlying Stephanian coal group that is dominated by sigillarians, calamiteans, ferns and pteridosperms, mostly hygrophilous and mesophilous. In the Mont Sénégra area, as early as Early Permian, vegetation tolerant of periodic soil moisture deficits had colonized alluvial fanglomerates and flood plains, on the borders of a new sedimentary basin. This basin would develop during the Permian period into an increasingly larger area, moving progressively eastward relative to the former Carboniferous basin of Graissessac.

Acknowledgements

We thank J. Broutin, W.A. DiMichele and an anonymous reviewer for positive critical comments on this manuscript.

References

Anonymous., 1988. Étude de stabilité de la découverte d'Alzou (H.B.C.M.-U.E. Hérault), Rapport CERCHAR 88(1)88-71-1632 sept 1988, 32 p.

Anonymous., 1988–1989 Coupe du sondage GRS31bis. Doc. inédit, COGEMA, Archives Centrales Mines, Razès, Limousin, 13 p.

Becq-Giraudon, J.F., Van den Driessche, J., 1993. Continuité de la sédimentation entre le Stéphanien et l'Autunien dans le bassin de Graissessac-Lodève (Sud du Massif Central) implications tectoniques. C. R. Acad. Sci. Paris, Ser. II 317, 939–945.

Béthoux, O., 2003. Évolution des Archaeorthoptera (Insecta : Neoptera) du Paléozoïque supérieur au Mésozoïque inférieur. Diversité taxonomique, disparité morphologique, paléoécologie. Thèse Paléontologie, Muséum d'histoire naturelle de Paris, 2 tomes, 213 p. + 300 p.

Bogdanoff, S., Donnot, M., Ellenberger, F., 1984. Note explicative de la feuille de Bédarieux à 1/5000. BRGM, Orléans, 105 p.

Broutin, J., Doubinger, J., Farjanel, G., Freytet, P., Kerp, H., Langiaux, J., Lebreton, M.L., Sebban, S., Satta, S., 1990. Le renouvellement des flores au passage Carbonifère-Permien : approches stratigraphique, biologique, sédimentologique. C.R. Acad. Sci. Paris, Ser. II 311, 1563–1569.

Broutin, J., Chateauneuf, J.J., Galtier, J., Ronchi, A., 1999. L'Autunien d'Autun reste-t-il une référence pour les dépôts continentaux du Permien inférieur d'Europe ? Apport des données paléobotaniques. Geol. Fr. 2, 17–31.

Brugier, O., Becq-Giraudon, J.F., Champenois, M., Deloule, E., Ludden, J., Mangin, D., 2003. Application of in situ zircon geochronology and accessory phase chemistry to constraining basin development during post-collisionnal extension: a case study from the French Massif Central. Chem. Geol. 201, 319–336.

Cohen, K.M., Finney, S., Gibbard, P.L., 2012. International chronostratigraphic chart. IUGS-ICS. www.stratigraphy.org

Debriette, P., Gand, G., 1990. Conséquences stratigraphiques et paléoenvironnementales de nouvelles observations paléontologiques dans le Permien de la partie occidentale du bassin de Lodève, Sud du Massif Central. Geol. Fr. 1, 19–32.

DiMichele, W.A., Aronson, R.B., 1992. The Pennsylvanian–Permian vegetational transition: a terrestrial analogue to the onshore-offshore hypothesis. Evolution 46 (3), 807–824.

DiMichele, W.A., Tabor, N.J., Chaney, D.S., Nelson, W.J., 2006. From wetlands to wet spots: environmental tracking and the fate of Carboniferous elements in Early Permian tropical floras. In: Greb, S.F., DiMichele, W.A. (Eds.), Wetlands through time, 399. Geol. Soc. Am. Spec. Pap., pp. 223–248.

DiMichele, W.A., Kerp, H., Tabor, N.J., Looy, C.V., 2008. The so-called "Paleophytic-Mesophytic" transition in equatorial Pangea–Multiple biomes and vegetational tracking of climate change through geological time. Palaeogeogr., Palaeoclimatol., Palaeoecol. 268, 152–163.

Doubinger, J., 1956. Contribution à l'étude des flores autuno-stéphaniennes. Mem. Soc. geol. France N.S. 35, 1–180.

Doubinger, J., Vetter, P., Langiaux, J., Galtier, J., Broutin, J., 1995. La flore fossile du bassin houiller de Saint-Étienne, 64. Mémoires du Muséum national d'histoire naturelle, Paris, pp. 1–355.

Falconnet, J., 2006. Redescription d'*Aphelosaurus lutevensis* Gervais 1859 (Diapsida, Araeoscelidia) du Permien de Lodève. Implications phylogénétiques et morpho-fonctionnelles. Mémoire de Master 2, UMR 5143 CNRS, Département Histoire de la Terre, Muséum national d'histoire naturelle, inédit, 43 p.

Falconnet, J., 2010. Diversification initiale des Amniotes : l'apport des Amniotes français. Thèse, Muséum national d'histoire naturelle, Paris, 340 p.

Florin, R., 1938–1944. Die Koniferen des Oberkarbons und des Unteren Perms. Palaeontographica B 85 (1-7), 1–654.

Friedman, G.M., Sanders, J.E., 1978. Nonmarine Environments I, II. Principles of Sedimentology. John Wiley & Sons, New York/Chichester, pp. 199–269.

Galtier, J., Broutin, J., 1995. La flore de la zone de transition de l'Autunien supérieur de Lodève. Sci. Geol. 48, 83–93.

Galtier, J., Broutin, J., 2008. Floras from red beds of the Permian basin of Lodève (Southern France). J. Iberian Geol. 34, 57–72.

Gand, G., 1987. Les traces de Vertébrés tétrapodes du Permien français Paléontologie, Stratigraphie, Paléoenvironnements. Thèse d'État, université de Bourgogne. Edit. Centre des Sciences de la Terre, 341 p.

Gand, G., 1994. Ichnocoenoses à *Isopodichnus furcosus* nov. ichnosp. dans le Permien du bassin de Lodève, Massif central, France. Geobios 27, 74–86.

Gand, G., Garric, J., Demathieu, G., Ellenberger, P., 2000. La palichnofaune de vertébrés tétrapodes du Permien supérieur du bassin de Lodève (Languedoc, France). Palaeovertebrata 29, 1–82.

Gand, G., Garric, J., Lapeyrie, J., 1997a. Biocénoses à Triopsidés (Crustacea, Branchiopoda) du Permien du bassin de Lodève (France). Geobios 30, 673–700.

Gand, G., Lapeyrie, J., Garric, J., Nel, A., Schneider, J., Walter, H., 1997b. Découverte d'Arthropodes et de Bivalves inédits dans le Permien continental (Lodèvois, France). C. R. Acad. Sci. Paris, Ser. IIa 325, 891–898.

Gand, G., Garric, J., Schneider, J., Walter, H., Lapeyrie, J., Martin, J., Thiery, A., 2008. Notostraca trackways in Permian playa environments of the Lodève basin (France). J. Iberian Geol. 34, 73–108.

Garric, J., 2000. Les rigoles fossilifères du Saxonien du bassin de Lodève (Languedoc, France). Bull. Soc. Hist. Nat. Autun 174, 7–48.

Garric, J., 2004. Le passage du Stéphanien à l'Autunien dans la découverte des houillères (HBCM) du mont Sénégra, à la limite du bassin carbonifère de Graissessac et du bassin permien de Lodève (Hérault). Bull. Soc. Hist. Nat. Autun 192, 29–40.

Garric, J., 2007. Le passage du Stéphanien à l'Autunien au nord-ouest de La Tour-Sur-Orb, à la limite du bassin de Graissessac et du bassin permien de Lodève (Hérault-France). Bull. Soc. Hist. Nat. Autun 194, 29–51.

Garric, J., 2008. Étude stratigraphique et tectonique de la partie nord de la bordure occidentale du bassin permien de Lodève, secteur de Lunas (Hérault-France). Bull. Soc. Hist. Nat. Autun 197, 31–44.
Garric, G., 2012. Données géologiques nouvelles sur la partie occidentale du Bassin Permien de Lodève (Hérault France) - première partie. Bull. Soc. Hist. Nat. Autun. 203, 25–40.
Grand'Eury, C., 1877. Flore carbonifère du département de la Loire. Mem. Acad. Sci. Paris 24, 1–624.
Heckel, P.H., Clayton, G., 2006. The Carboniferous system. Use of the new official names for the subsystems, series and stages. Geologica Acta 4 (3), 403–407.
Jousseaume, J., 1969. Campagne de sondages géologiques de Lunas. HER No. E 10 bis joint aux rapports 69.2 et 69. 3. Doc. du CEA inédits, Archives de la COGEMA, Razès, Limousin.
Kerp, J.H.F., Fichter, J., 1985. Die Makrofloren des saarpfälzischen Rotliegenden (?Ober-Karbon-Unter-Perm; SW-Deutschland). Mainzer Geowiss. Mitt. 14, 159–286.
Kerp, J.H.F., Haubold, H., 1988. Aspects of Permian palaeobotany and palynology. VIII. On the reclassification of the west- and central European species of the form-genus *Callipteris* Brongniart 1849. Rev. Palaeobot. Palynol. 54, 135–150.
Laversanne, J., 1976. Sédimentation et minéralisation du Permien de Lodève Hérault. Thèse 3^{e} cycle, université de Paris Sud-Orsay, 300 p.
Martin-Closas, C., Galtier, J., 2005. Plant Taphonomy and Paleoecology of Late Pennsylvanian Intramontane Wetlands in the Graissessac–Lodève Basin (Languedoc, France). Palaios 20, 249–265.
Nmila, A., 1995. L'empreinte du volcanisme dans le remplissage permien du bassin de Lodève. Étude pétrographique et géochimique. Implication métallogénique. Thèse d'État, université Pierre-et-Marie-Curie, Paris-6, 202 p.
Odin, B., 1986. Les formations permiennes, Autunien supérieur à Thuringien, du « bassin » de Lodève, Hérault, France : stratigraphie, minéralogie, paléoenvironnement, corrélations. Thèse d'État, université Aix-Marseille, 375p.
Pochat, S., Van den Driessche, J., 2011. Filling sequence in Late Paleozoic continental basins: a chimera of climate change? A new light given by the Graissessac-Lodève Basin (SE France). Palaeogeogr., Palaeoclimatol., Palaeoecol. 302, 170–186.
Saint-Martin, M., 1992. Genèse et évolution structurale du bassin permien de Lodève. Cuadernos de Geologica Iberica 16, 81–106.
Saint-Martin, M., 1993. Évolution du bassin stéphanien de Graissessac en relation avec les tectoniques hercyniennes et tardi-hercyniennes de la Montagne Noire (Sud du Massif Central français). Thèse, université Montpellier-2, 235 p.
Schneider, J., Körner, F., Roscher, M., Kroner, U., 2006. Permian climate development peri-Tethys area. The Lodeve basin, French Massif Central, compared in a European and global context. Palaeogeogr., Palaeoclimatol., Palaeoecol. 240, 161–183.
Teboul, P.A., 2010. Caractérisation pétrographique et minéralogique de cinérites permiennes du bassin de Lodève (Hérault–France). Rapport de stage, inédit, UMR 6282, laboratoire de biogéosciences, université de Bourgogne, 24 p.
Werneburg, R., Steyer, J.S., Sommer, G., Gand, G., Schneider, W., Vianey-Liaud, M., 2007. The Earliest Tupilakosaurid amphibian with diplospondylous vertebrae from the Late Permian of southern France. J. Vertebr. Paleontol. 27 (1), 26–30.
Zeiller, R., 1898. Contribution à l'étude de la flore ptéridologique des schistes permiens de Lodève. Bull. Mus. Hist. Nat. Marseille 1, 6–69.