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The Permian-Triassic boundary and Early Triassic sedimentation in Western European basins: an overview

El límite Pérmico-Triásico y la sedimentación durante el Triásico inferior en las cuencas de Europa occidental: una visión general

S. Bourquin[1], M. Durand[2], J. B. Diez[3], J. Broutin[4], F. Fluteau[5]

[1]*Géosciences Rennes, UMR 6118, Univ. Rennes 1, 35042 Rennes cedex, France, sylvie.bourquin@univ-rennes1.fr*
[2] *47 rue de Lavaux, 54520 Laxou, France, mada.durand@wanadoo.fr*
[3]*Departamento Geociencias Marinas y Ordenación del Territorio, Universidad de Vigo, Campus Lagoas-Marcosende, 36200 Vigo, Pontevedra, Spain, jbdiez@uvigo.es*
[4]*Classification Evolution et Biosystématique: Laboratoire de Paléobotanique et Paléoécologie. Université Pierre et Marie Curie Paris VI, 12 rue Cuvier, 75005 Paris, France, jbroutin@snv.jussieu.fr*
[5]*Laboratoire de Paléomagnétisme, IPGP, Université Paris VII, 4 place Jussieu, 75252 Paris cedex 05, France, fluteau@ipgp.jussieu.fr*

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Abstract

At the scale of the peri-Tethyan basins of western Europe, the "Buntsandstein" continental lithostratigraphic units are frequently attributed to the "Permian-Triassic" because, in most cases, the lack of any "Scythian" (i.e. Early Triassic) biochronological evidence makes it very difficult to attribute the basal beds of the cycle to the Permian or to the Triassic. A careful recognition of unconformities and sedimentary indications of clearly arid climate provide powerful tools for correlation within non-marine successions that are devoid of any biostratigraphic markers, at least on the scale of the West European Plate.

From a review of the "Buntsandstein" series of several basins we can characterize the Permian-Triassic boundary and the beginning of Triassic sedimentation at the scale of Western Europe. We clearly show that, except for the Central Germanic Basin, an unconformity can be observed between the Permian and the Triassic. Apart from the Germanic Basin, there is a total lack of typically "Scythian" fossils in the rest of West European basins, and the oldest biochronological markers yielded by these units are palynomorphs allowing to assign an Anisian age generally to the upper part of the "Buntsandstein", but also its lowermost in a few cases. In the peri-Tethyan basins of western Europe, the Permian-Triassic boundary corresponds to an unconformity overlain by conglomerates containing ventifacts (followed by fluvial sandstones, sometimes rich in paleosols and sometimes totally devoid), which are attributed mainly to the lower Olenekian, i.e. Smithian. Alternatively, the succession passes up directly into fluvial sandstones containing the first paleosols, and then plant debris and palynomorphs attributed to the Anisian. In this way, the lack of typically Early Triassic fossils in most of the peri-Tethyan basins, at the scale of the west European Plate, can be explained by a true stratigraphic hiatus in the earliest Triassic (i.e. Induan) and by arid conditions unfavourable for the development of flora and fauna and their preservation during the Olenekian.

Keywords: Permian-Triassic boundary, Early-Middle Triassic, Western Europe basins, Scythian, Anisian.

Resumen

En las cuencas peritéthicas de Europa occidental, la unidad litoestratigráfica continental “Buntsandstein” es frecuentemente atribuida al “Pérmico-Triásico”, porque, en la mayoría de los casos, la falta de elementos biocronológicos “scythienses” complica la atribución de los niveles basales al Pérmico o al Triásico. Un cuidadoso examen de las discordancias, y el uso de indicadores sedimentarios de climas claramente áridos constituyen herramientas fundamentales para la correlación de estas unidades no marinas, desprovistas de cualquier marcador bioestratigráfico, al menos en el Oeste de la Placa Europea.

La revisión de las series “Buntsandstein” de varias cuencas nos ha permitido caracterizar el límite Pérmico-Triásico y el comienzo de la sedimentación durante el Triásico inferior en el oeste de Europa, demostrando claramente que, excepto en la Cuenca Germánica Central, se puede observar una discordancia entre las series pérmicas y triásicas. Excepto en esta Cuenca Germánica, existe una falta total de fósiles típicamente “scythienses”, y los elementos bioestratigráficos más antiguos encontrados son conjuntos de palinomorfos que permiten asignar a los niveles superiores de las series “Buntsandstein” una edad Anisiense, en algunos cortes los niveles inferiores. En las cuencas peritéthicas de Europa occidental, el límite Pérmico-Triásico se corresponde con una discordancia que se recubre por conglomerados con ventifactos (seguidos por areniscas fluviales, a veces ricas en paleosuelos y a veces totalmente desprovistas de ellos), atribuidos principalmente al Olenekiense inferior (Smithiense), o directamente areniscas fluviales donde aparecen los primeros paleosuelos, así como restos de plantas y palinomorfos, atribuidos al Anisiense. De esta forma en el Oeste de la Placa Europea, la falta de fósiles característicos del Triásico Inferior, en la mayoría de las cuencas perithéticas, puede explicarse por un importante hiato estratigráfico durante el Triásico Inferior (Induense) y por unas condiciones áridas, desfavorables para la vida y la preservación de fósiles durante el Olenekiense.

Palabras clave: Límite Pérmico-Triásico, Triásico Inferior-Medio, cuencas de Europa occidental, Scythiense, Anisiense

1. Introduction

At the scale of the western Europe peri-Tethyan basins, the lowermost part of the Mesozoic sedimentary cycle is composed of continental deposits generally described as “Buntsandstein”. A “Permian-Triassic” age has often been proposed for this lithostratigraphic unit because, in most cases, the lack of any “Scythian” (*i.e.* Early Triassic) biochronological evidence makes it very difficult to attribute its basal beds to either the Permian or the Triassic. The oldest Triassic fossils, generally yielded by the upper part of the “Buntsandstein” but also its lowermost in a few cases, are attributed there to the Anisian. Nevertheless, the lack of typically Early Triassic fossil remains can be explained either by environmental conditions (*i.e.* “desert” environments) unfavourable for the development and preservation of a fauna/flora, or by a true stratigraphic gap.

Throughout the northern hemisphere, where continuity can be demonstrated between the Permian and Triassic, there is no evidence for a sudden collapse of the terrestrial ecosystems. The climate seems to have evolved towards rather more humid conditions during the Griesbachian Stage (e.g. Fuglewicz 1980; Kozur 2003); the macroflora continues to exhibit a predominantly Permian character, while the palynoflora is transitional (Shu and Norris, 1999; Lozovsky *et al*., 2001). This explains why we should expect a more or less significant hiatus when outcrops display an abrupt change in depositional style or palaeoclimatic conditions at the Permian-Triassic boundary (Durand, 2006). Consequently, a careful recognition of unconformities, and the use of sedimentary indicators of a clearly arid climate can provide powerful tools for correlations. This applies at least on the scale of the West European Plate, within the non-marine successions devoid of any biostratigraphic markers that straddle the Permian-Triassic boundary.

The aim of this paper is to characterize the Permian-Triassic boundary and the onset of early Triassic sedimentation at the scale of Western Europe, based on a review of the “Buntsandstein” series of several European basins (Fig. 1).

2. The Permian-Triassic boundary in Western European basins

During the Late Permian, exceptional falls of global sea level (Ross and Ross, 1987; Hallam and Wignall, 1999; Seidler, 2000; Heydari *et al.,* 2001) led to more or less deep erosion in most western European basins. Moreover, paleontologists recognize the end-Permian as representing the major Phanerozoic mass extinction episode. During the earliest Triassic, these areas under erosion were bypassed by sediments, and the time gap corresponding to the sub-Triassic unconformity increased progressively towards the edges of the basin (Durand, 2006). Indeed, the only localities on the West European Plate where continuity of sedimentation can be proven correspond to the deepest part of the endoreic central European basin, *i.e.* the Germanic Basin (Nawrocki, 2004).

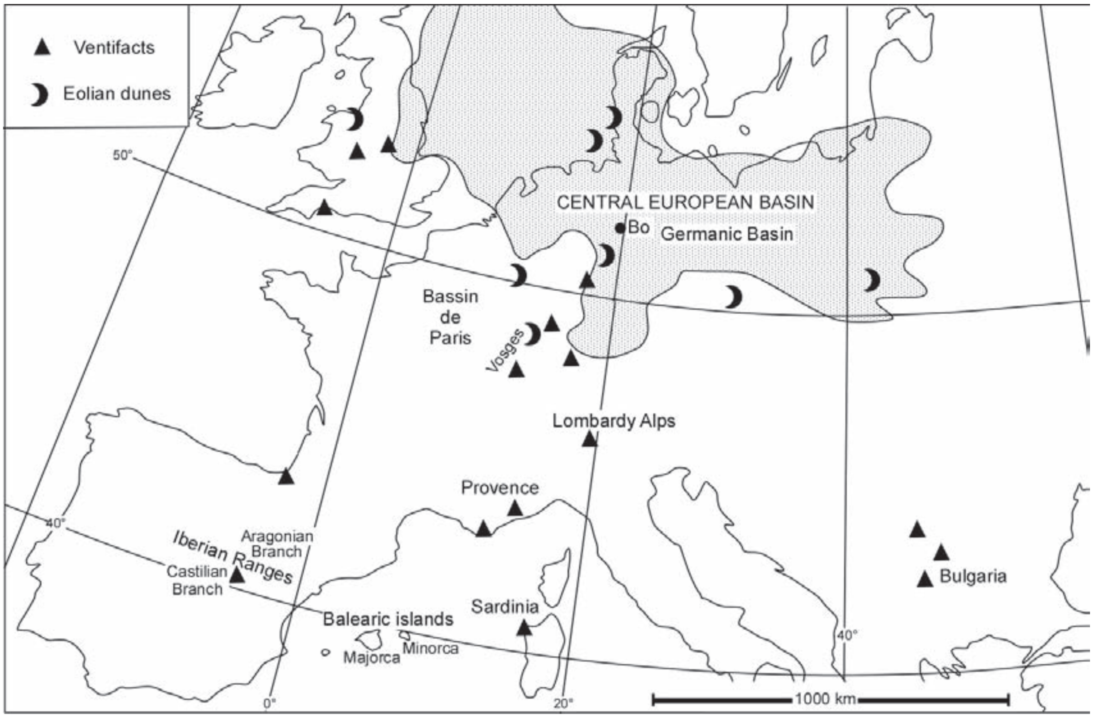

Fig. 1.- Location of the "Buntsandstein" (Permian-Triassic) units studied in the peri-Tethys basins of Western Europe and geographical distribution of the sedimentary features ascribed to the Dienerian - Smithian arid period in SW Europe. Since the maximum extension of coeval deposits is yet known with inadequate precision, only that of the uppermost Permian "Zechstein", indicating roughly the central part of the Lower Triassic basin, is represented here (dotted area). Bo: Bockenem. (Modified after Durand, 2006).

Fig. 1.- Localización del "Buntsandstein" estudiado (series Pérmico-Triásicas) en las cuencas peritéthicas de Europa Occidental y la distribución geográfica de caracteres sedimentarios atribuidos al período árido Dieneriense-Smithiense en el SO de Europa. La extensión máxima de los depósitos de esta edad no se conoce con precisión, sólo que el Pérmico más alto "Zechstein", indica aproximadamente la parte central de la cuenca durante el Triásico Inferior, representada en la figura (área punteada). Bo: Bockenem. (Modificado de Durand, 2006).

2.1. Germanic Basin

In the central part of the Germanic basin, the transition form Permian to Triassic seems to be gradual between Zechstein to Lower Buntsandstein sequences (Szurlies *et al.*, 2003). However, a sub-Triassic unconformity is clearly observed on its western edge associated with a progressive onlap of the Triassic succession (Bourquin *et al.*, 2006, Fig. 2). During the Early Triassic, the Paris and Bresse-Jura basins formed the western extremity of the Germanic Basin. The Paris Basin only existed as an independent basin from the middle Carnian onwards (Bourquin and Guillocheau, 1993, 1996). In the Vosges (Fig. 1), the "Buntsandstein inférieur" formations (Senones Sandstones and Anweiller Sandstones) can be attributed to the uppermost Permian, *i.e.* equivalents of the Zechstein (Durand *et al.*, 1994). Whereas the "Buntsandstein Group" in the major part of the Germanic basin is separated from the Rotliegende by the typical-Zechstein carbonate-evaporite facies (uppermost Permian), the latter are completely lacking in France where they are partly replaced by fluvial facies (Table 1).

2.2. Southeast France

The major criterion used to define the "Buntsandstein" in France is the clear change from local drainage systems in several distinct basins, a characteristic feature of the Permian palaeogeography, to a single widespread system that is typical of the Triassic. In the Provence Trough, which borders the Variscan Maures Massif, the main paleocurrents directions of the "Buntsandstein" are locally even opposite to those observed in the Permian (Durand *et al.*, 1989; Durand, 1993). In this area, the sub-"Buntsandstein" surface can be likened to the Permian-Triassic boundary (PTB) (Table 1) by comparison with the very similar statigraphical relationships observed in some marginal parts (south of the Vosges massif) of the Germanic Basin (Durand, 2006). The uppermost unit below the PTB (La Motte pelitic Formation of the Bas-Argens basin, called Fabregas Fm. in the Toulon area) made up of playa deposits, yields vertebrate tracks of Guadalupian age (Gand and Durand, 2006). The PTB exhibits three types of contact according to the location, ranging from the central axis to the margins of the depositional area:

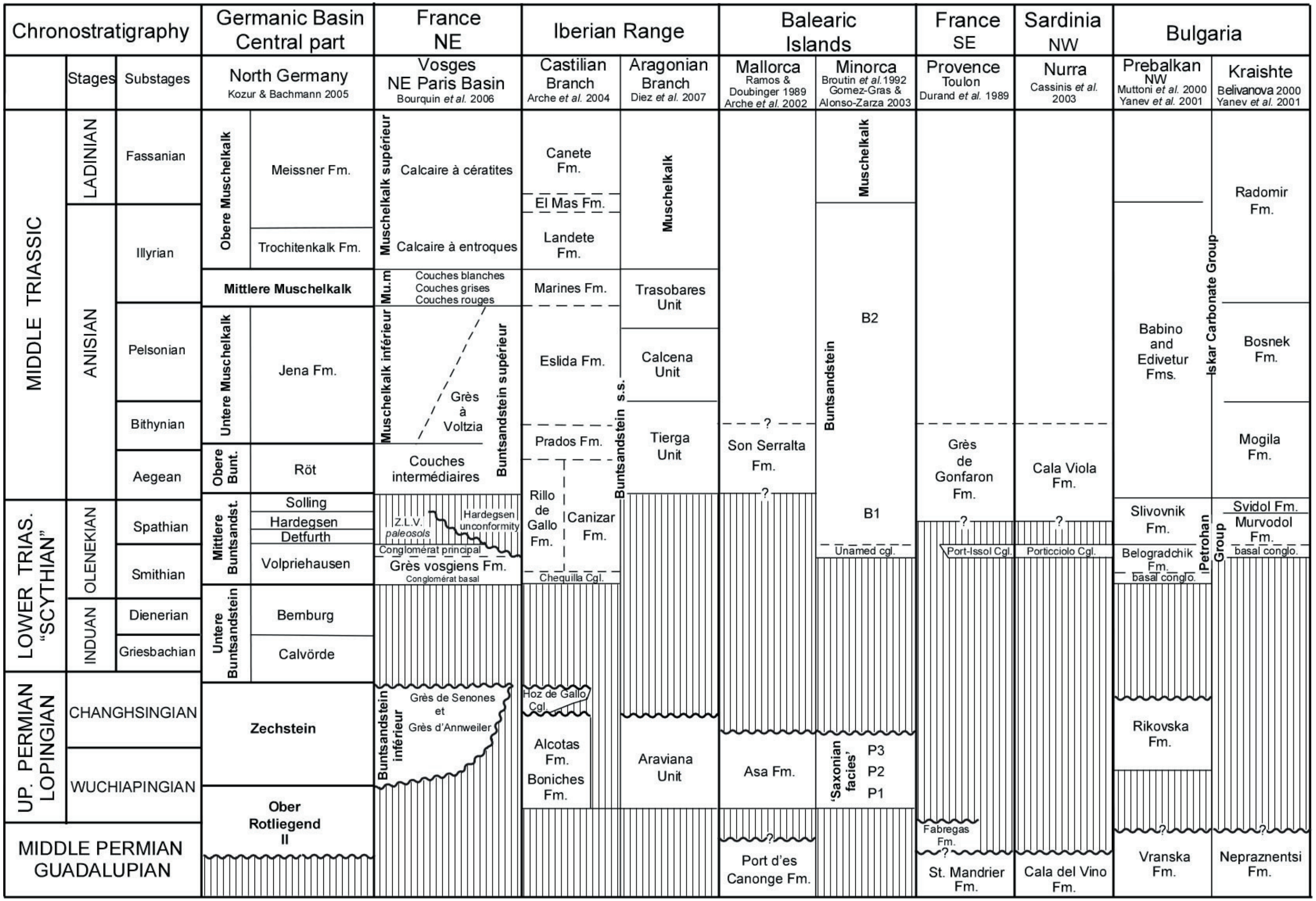

Table 1.- Stratigraphic comparison between different Permian-Triassic formations of Western Europe. Without scale.
Tabla 1.- Comparación estratigráfica entre diferentes formaciones del Pérmico-Triásico del Oeste de Europa. Sin escala.

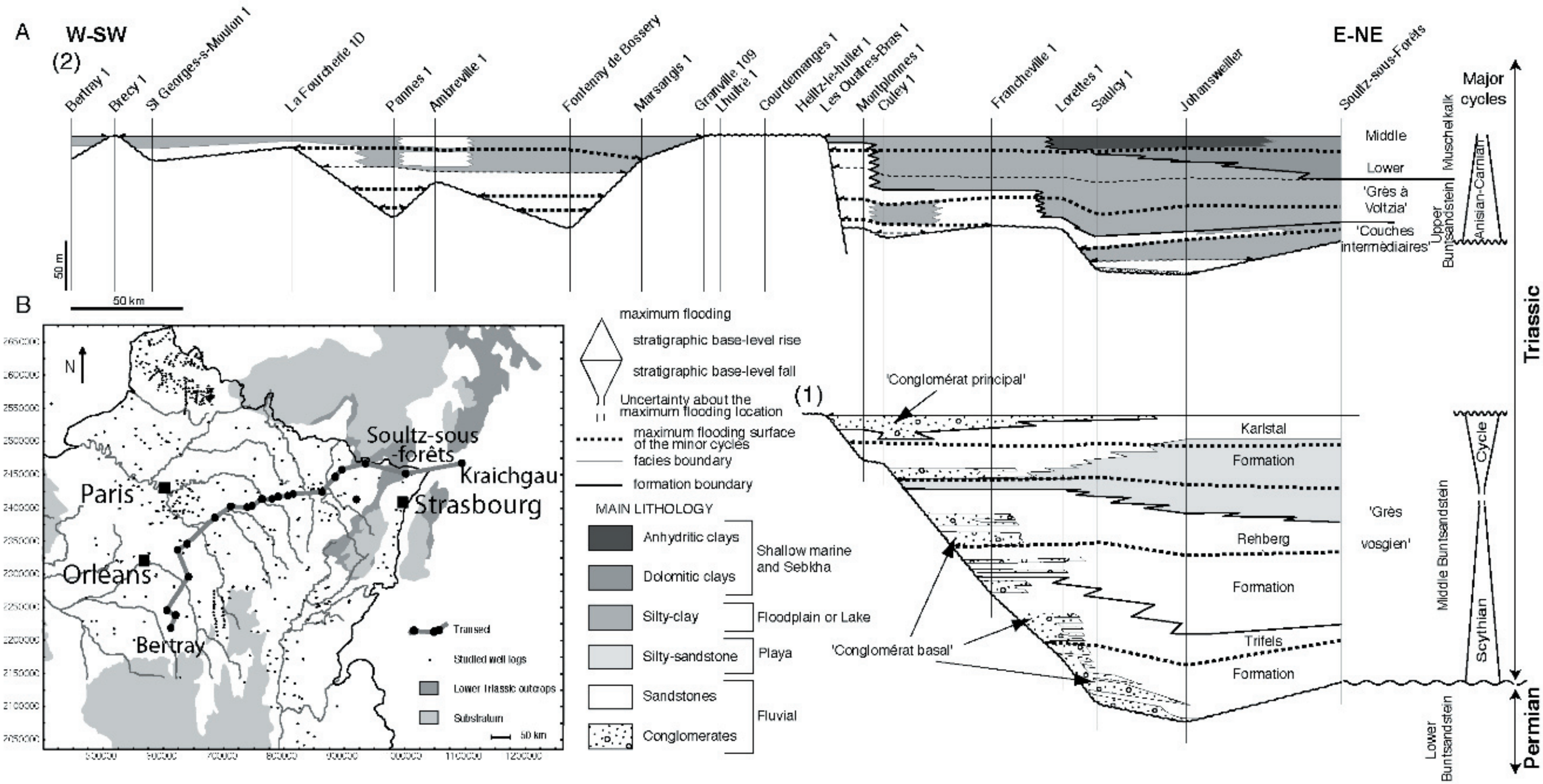

Fig. 2.- A) Sedimentary geometry and lithology of the Lower Triassic stratigraphic cycles, along a transect between the area south of Orléans (Bertray well) and the Rhine Graben (Soultz-sous-Forêts well) inferred from well-log analysis: (1) Correlations from Variscan basement or pre-Triassic deposits to the Hardegsen unconformity, (2) Correlations from the Hardegsen unconformity to the basal anhydrite bed of the "Couches grises" Formation defined in the eastern part of the Paris Basin (middle part of the Middle Muschelkalk, Table 1). (B) Transect location. (Modified after Bourquin *et al.*, 2006)

Fig. 2.- A) Geometrías y litología de los ciclos estratigráficos del Triásico Inferior, a lo largo del transecto entre el área Sur de Orleáns (sondeo de Bertray) y el Graben del Rin (sondeo de Soultz-sous-Forêts) deducidas del análisis de los testigos de sondeo: (1) Correlación desde el basamento Variscico o los depósitos pre-Triásicos a la discordancia Hardegsen, (2) Correlación desde la discordancia Hardegsen a la capa de anhidrita de la base de la Formación "Couches grises" definida al este de la Cuenca de Paris (parte media del Muschelkalk medio, Table 1). (B) Localización del transecto. (Modificado de Bourquin *et al.*, 2006)

i) disconformity overlain by quartz-conglomerate; ii) apparent transition; or iii) angular unconformity produced by intra-Permian tilting (Durand, 2006). Where an apparent transition occurs, as on the Gonfaron area sections, the PTB was sometimes assumed to be at the top of a spectacular paleosol (Cournut, 1966; Toutin-Morin, 1986), but it is now clear that this paleosol is located in flood-plain deposits intercalated between Triassic channel sandstones (Durand, 2006).

2.3. Spain

In the Castilian branch of the Iberian Ranges, it is generally accepted that the PTB lies somewhere in the lower part of the Cañizar Sandstone Formation, or in the coeval Hoz de Gallo Conglomerate and Rillo de Gallo Sandstone formations making up the lower (and major) part of the "Buntsandstein *sensu stricto*" (López-Gómez *et al.*, 2002; Arche *et al.*, 2004; López-Gómez *et al.*, 2005). In fact, the Hoz de Gallo Conglomerate comprises two distinct lithostratigraphic units separated by a discontinuity (Ramos, 1979; Arche and López-Gómez, 2005) whose importance has been underestimated before this study.

West of Molina de Aragon, at the entrance of the La Hoz gorge on the Gallo River, the lower conglomeratic unit, yields Permian palynomorphs (Ramos and Doubinger, 1979), and locally passes upwards into sandstone beds capped by a silcrete. However, a few hundred metres downstream (behind the hermitage), these beds are eroded, so that the two conglomeratic units of the Hoz de Gallo Conglomerate are in direct contact. Thus, the slightly angular unconformity highlighted here, which can also be seen in the landscape (Fig. 3), could well correspond to the PTB, as proposed for the first time by Ramos (1979). Because of this, it would seem illogical to include both conglomerates in the same formation. Consequently, and to avoid any confusion, we propose to call the upper conglomerate the "Chequilla Conglomerate Member" of the Cañizar Formation (Table 1). In the classical locality of Chequilla, where this member is very well exposed, it is the only unit present above the Variscan basement. Everywhere it passes upwards rather rapidly but more or less transitionally into the typical sandstones of the Cañizar Fm.

In the Aragonian Branch, "Buntsandstein" sedimentation began with the alluvial fan and lacustrine deposits of the Araviana Unit attributed to the Late Permian (Arche *et al.*, 2004). The top of this unit is characterized by an unconformity, which are overlain by Tierga Unit dated as Anisian from palynological data. Like this, in the Aragonian Branch, a hiatus of sedimentation of all the Lower Triassic is observed (Diez *et al.*, 2007) and the hiatus corresponding to the PTB would be longer than in the Castilian Branch (Table 1).

The Balearic Islands are also believed to belong to the domain where the age of the Buntsandstein ranges from "Thuringian" to Anisian (Broutin *et al.*, 1992; Arche *et al.*, 2002). Nevertheless, in Minorca, the lowermost Buntsandstein unit (B1) is a quartz conglomerate lying above a clear unconformity marking the top of a siliclastic formation yielding Permian palynomorphs (Gómez-Gras and Alonso-Zarza, 2003). The quartz conglomerate unit deserves further study since it resembles the Chequilla Conglomerate, or even the basal conglomerate of Provence and Sardinia. Since no conglomerate occurs in Majorca, the contact between dated Permian and Triassic formations appears transitional as in the Gonfaron area (Provence). Moreover, since the Triassic succession is thinner than in Minorca, the hiatus corresponding to the local PTB would be longer, in a more marginal setting (Table 1).

2.4. Italy (NW Sardinia)

In Nurra, a thick Permian-Triassic siliciclastic group crops out over a relatively limited area, and shows remarkable similarities with formations in the distal part of the Provence Trough (around Toulon harbour) in southeast France. This comparison allows us to consider both areas as parts of the same basin, which initially faced each other in close proximity (Cassinis *et al.*, 2003).

Otherwise, as in many other areas of limited exposure, the Nurra unit provides an excellent example of different "Buntsandstein concepts", more or less well defined, that are likely to create serious problems in palaeogeographic reconstructions. Sciunnach (2001) applied the term "Buntsandstein" only to the upper part (units 3 and 4) of the "Verrucano Sardo" (Gasperi and Gelmini, 1980) which encompasses all the post-Autunian siliciclastic succession. The so-called "Lower Buntsandstein" of Sciunnach (*i.e.* Cala del Vino Formation, Cassinis *et al.*, 2003) can be correlated with the Permian St-Mandrier Formation (more than 700 m thick) of the Toulon area (Fig. 2). Costamagna and Barca (2002) use the term "Buntsandstein" for the whole "Verrucano Sardo". Conversely, Cassinis *et al.* (2003), use the same concept as in Provence, restricting the "Buntsandstein" to the uppermost part of the succession starting from the "Conglomerato del Porticciolo".

2.5. Bulgaria

In NW Bulgaria, the Petrohan terrigenous Group can be regarded as the "Buntsandstein" facies of the Peri-Teth-

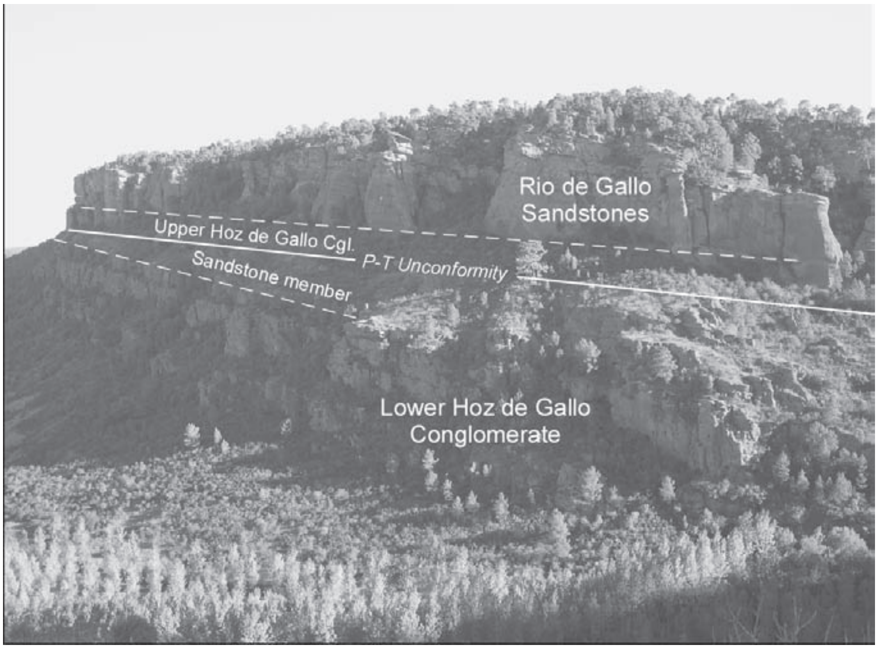

Fig. 3.- Angular unconformity within the Hoz de Gallo conglomerate. View from the left side of the Gallo river towards SE, over the entrance of the Hoz gorge (Corduente, SW of Molina de Aragon, Spain).

Fig. 3.- Discordancia angular en los conglomerados de Hoz de Gallo. Vista desde la orilla izquierda del Rio Gallo hacia el sureste, sobre la entrada de la garganta de Hoz de Gallo (Corduente, SW de Molina de Aragon, España)

yan (*i.e.* autochtonous) Lower Triassic (Zagorchev and Budurov 1997). It usually includes a basal oligomictic siliceous conglomerate (Table1), and its uppermost part contains marine intercalations of Spathian age (Belivanova, 2000). The picturesque landscapes developed on the thick Belogradchik Sandstones resemble those of the Cañizar Fm. in NE Spain or the "Grès vosgien" Fm. in NE France. According to Zagorchev and Budurov (1997), the basal hiatus could correspond to a major part of the Lower Triassic, whereas Yanev *et al.* (2001) consider it to be related rather to the Upper Permian.

3. Early Triassic sedimentation in the European basins

The Triassic is a period of transition associated with the beginning of the break-up of the Pangean supercontinent and the development of the Mesozoic basins, in a globally warm and dry climate (Ziegler, 1990; Frakes *et al.*, 1992; Dercourt *et al.*, 1993; Lucas, 1999, Golonka and Ford, 2000; Reinhardt and Ricken, 2000; Boucot and Gray, 2001).

In the Central Europe Basin, *i.e.* the Germanic Basin, the Buntsandstein is mainly represented by two fluvial styles: (i) large bed-load sand sheets associated with ephemeral-lake deposits, characterizing the Lower and Middle Buntsandstein (*i.e.* "Scythian": Röhling, 1991; Aigner and Bachmann, 1992), which pass upwards into (ii) fluvial systems bordering an evaporite sabkha or shallow sea, typical of the Upper Buntsandstein (*i.e.* upper "Scythian" to middle Anisian: Durand, 1978; Courel *et al.*, 1980; Durand *et al.*, 1994).

3.1. Germanic Basin

Detailed stratigraphic studies on the western margin of the Germanic Basin and a comparison with other parts of this basin allow us to propose correlations of the Triassic "Buntsandstein" on either side of the Rhine Graben (Fig. 4; Bourquin *et al.*, 2006).

At the beginning of the Early Triassic (Induan), the sedimentation area was restricted to the central part of the Germanic Basin: the Lower Buntsandstein formations, which characterize a playa system, do not have any equivalents on the western margin of the basin (Geluk, 2005). Succeeding marginal-marine evaporites these deposits express the regressive tendency of the uppermost Zechstein ("Bröckelschiefer" = Fulda Formation), which continues into the Lower Buntsandstein (Aigner and Bachmann, 1992; Aigner *et al.*, 1999). The slightly angular unconformity at the base of the Upper "Bröckelschiefer" was caused by non-deposition or erosion of the uppermost Zechstein at the basin margin (Röhling, 1991, Szurlies *et al.*, 2003).

During the lower Olenekian (Smithian), in the northwestern peri-Tethys domain, fluvial deposits are preserved in a large endoreic basin under arid climatic conditions (Fig. 5). In the western part of the Germanic basin, the sedimentation is characterized by braided fluvial systems passing laterally, toward the central part, into more or less ephemeral lakes (Richter-Bernburg, 1974; Röhling, 1991; Aigner and Bachmann, 1992; van der Zwan and Spaak, 1992; Geluk, 2005) and aeolian deposits (Clemmensen, 1979; Ulicny, 2004). In the northern Germanic Basin, alluvial fan deposits are described that are fed by catch-

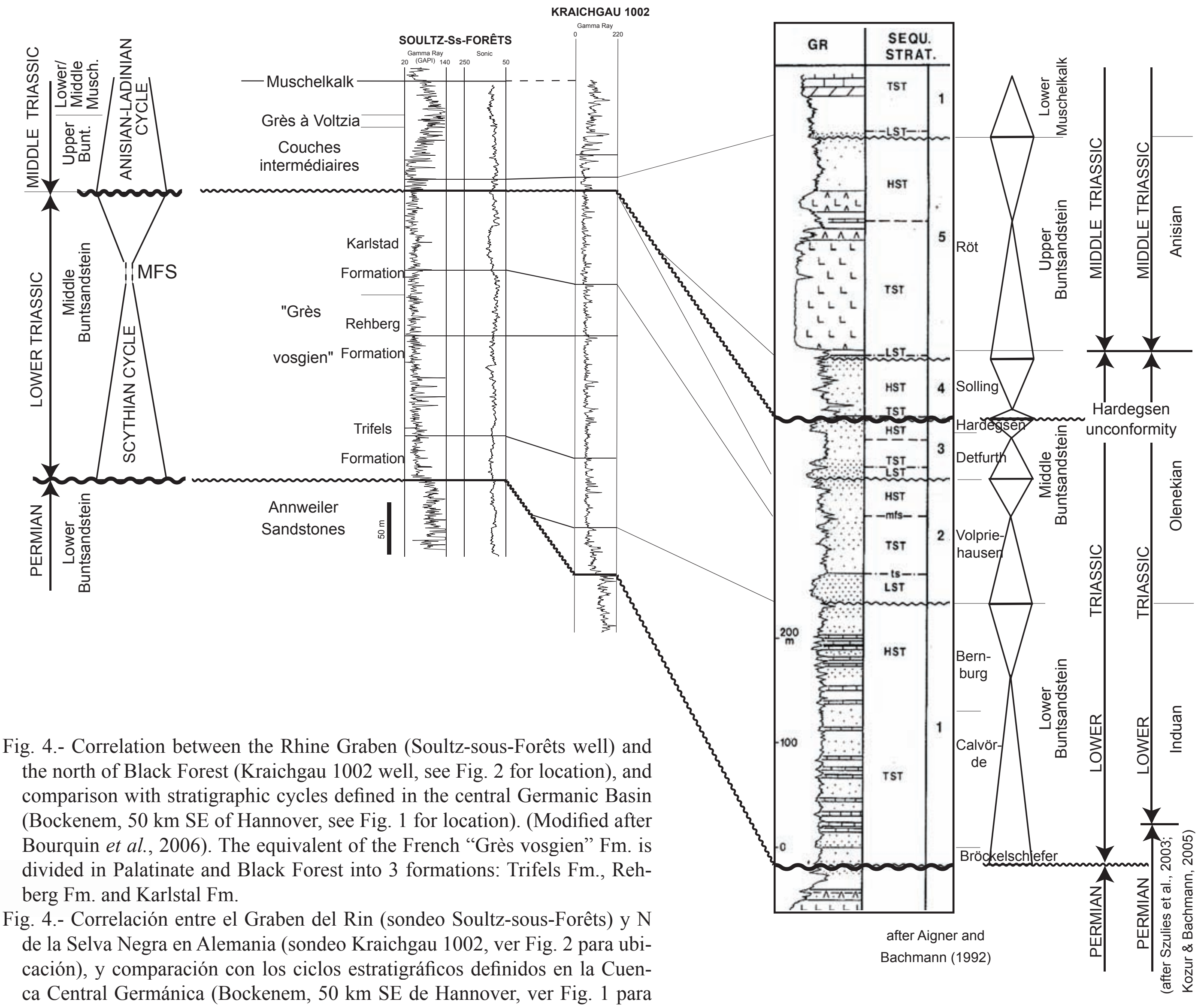

Fig. 4.- Correlation between the Rhine Graben (Soultz-sous-Forêts well) and the north of Black Forest (Kraichgau 1002 well, see Fig. 2 for location), and comparison with stratigraphic cycles defined in the central Germanic Basin (Bockenem, 50 km SE of Hannover, see Fig. 1 for location). (Modified after Bourquin *et al.*, 2006). The equivalent of the French "Grès vosgien" Fm. is divided in Palatinate and Black Forest into 3 formations: Trifels Fm., Rehberg Fm. and Karlstal Fm.

Fig. 4.- Correlación entre el Graben del Rin (sondeo Soultz-sous-Forêts) y N de la Selva Negra en Alemania (sondeo Kraichgau 1002, ver Fig. 2 para ubicación), y comparación con los ciclos estratigráficos definidos en la Cuenca Central Germánica (Bockenem, 50 km SE de Hannover, ver Fig. 1 para ubicación). (Modificado de Bourquin *et al.*, 2006). El equivalente de la Formación"Grès vosgien" en Francia se divide, en el Palatinado y Selva Negra en tres formaciones: Fm. Trifels, Fm.Rehberg y Fm. Karlstal

ment areas from the Fennoscandian Massif (Goldsmith *et al.*, 2003). At the southwestern margin of the Germanic basin, combined sedimentological and well-log studies show that sandstones ("Grès vosgien") and conglomeratic facies ("Conglomérat basal" and "Conglomérat principal") were deposited on a very large alluvial plain that onlapped the basement topography (Durand, 1978; Durand *et al.*, 1994; Bourquin *et al.*, 2006). The facies analysis allows us to recognize deposits laid down by a major bed-load river within an arid alluvial plain without vegetation. The arid climate prevailing in the sedimentation area is attested by the presence of many wind-worn pebbles and cobbles (ventifacts), not only concentrated in the conglomeratic layers, but also scattered here and there throughout the "Grès vosgien" Fm. (Durand *et al.*, 1994).

The fluvial channels seem to be very wide, and they are divided during low-water stages into numerous distributaries separated by temporary islands with aeolian deposits and ephemeral ponds that allowed only a very limited development of subaquatic life. Although many distributaries display periods of inactivity that reflect their ephemeral character, the occurrence of deflation lags bounding the fluvial systems in the middle of the "Grès vosgien" Fm. indicates frequent wind reworking of fluvial deposits. The upper "Grès vosgien" Fm. is essentially characterized by playa-lake deposits (Karlstal Formation in the Palatinate) that directly overlie the basement to the west. These deposits mark the maximum flooding episode of the first major cycle, which is well recognized on well-log data in the Early Triassic succession (Fig. 4). The maximum flooding surface (MFS) of the major stratigraphic cycle defined in the Paris Basin appears equivalent to the MFS observed within the Volpriehausen Formation (Aigner and Bachmann, 1992; Aigner *et al.*, 1999), where brackisch-marine fauna is present in the central part of the Germanic Basin (Richter-Bernburg, 1974, Roman, 2004). At the basin scale, the sandstones facies that developed after this playa episode show a progradational pattern. The upper part of the "Conglomérat principal" Formation does not exceed a thickness of 20 m on outcrops in the Vosges area, and shows a great extension to the east. In Lorraine, the top of the Middle Buntsandstein is marked by a major sedimentary break associated with a period of by-pass and development of the first paleosols (*i.e.* "Zone limite violette", Müller, 1954; Ortlam, 1967; Gall *et al.*, 1977). This episode could be coeval with the deposition of the Hardegsen Formation, where the evidence of biological activity (ichnites, rhizolites and palynomorphs) rules out any correlation with the "Conglomérat principal" Fm. laid down under arid conditions. The 'Conglomérat principal' Fm. rarely occurs at outcrop north of the Vosges Massif, near the German Frontier. Here, it is truncated by a major discontinuity referred to as the "Hardegsen unconformity", which even cuts locally into the "Grès vosgien" Fm. This unconformity expresses the onset of one of the most pronounced extensional tectonic events observed in the German Triassic (Trusheim, 1961, 1963; Wolburg, 1968; Röhling, 1991).

Above the Hardegsen unconformity, the Triassic deposits show an onlap relationship, which implies some tectonic activity just before the renewal of fluvial sedimentation. Moreover, the siliciclastic material includes micas, large feldspars and, angular quartz that provide evidence for reactivation of the source area. The fluvial sedimentation shows an enhanced development of floodplains with preservation of paleosols. The only biostratigraphic evidence in this Upper "Buntsandstein" cycle is provided by the "Grès à Voltzia", where macrofauna and palynoflora allow the attribution of a lower to middle Anisian age according to location (Durand and Jurain, 1969; Gall, 1971). The "Grès à Voltzia" evolves eastwards and upwards into deposits with increasingly marine affinity ("Grès coquillier" and "Complexe de Volmunster", "Dolomie à Myophoria orbicularis"). This fluvial system is a lateral equivalent of marine deposits attributed to the Lower Muschelkalk in Germany (Fig. 4), and is preserved in an exoreic basin. Fluvial systems appear to collapse suddenly at the beginning of the evaporitic episode corresponding to the Middle Muschelkak ("Couches rouges", "Couches grises" and "Couches blanches"), which precedes the deposition of marine carbonates during the Ladinian (Table 1). The vertical passage from the "Couches intermédiaires" to the Ladinian marine limestones characterizes a general backstepping trend, in which the maximum flooding surface (MFS) is located at the top of the "Calcaires à Cératites" Formation dated as Ladinian (Duringer and Hagdorn, 1987).

3.2. Southeast France

The deposits referred to as "Buntsandstein" are much thinner (maximum 80 m) in the Provence Trough than in the northern Vosges area. Along the basin axis, a basal quartz conglomerate up to 8 m thick ("Poudingue de Port-Issol" Formation) overlies the sub-"Buntsandstein" unconformity that is thought to represent the PTP. The vast majority of the pebbles are well rounded by long fluvial transport, but many display secondary ridges and facets shaped by wind-blown sand (ventifacts). The contact with the main unit ("Grès de Gonfaron" Formation) is very sharp and marked by the sudden appearance of caliche nodules, sometimes reworked and sometimes *in situ*. These mainly fluvial sandstones pass upwards, in the more distal area (Toulon), into terminal fan and playa deposits. Besides the caliche horizons, there is relatively frequent evidence of biological activity, *e.g.*: vegetation-induced primary sedimentary structures (Rygel *et al.*, 2004) and trace fossils, mainly corresponding to invertebrate burrows (*Scoyenia*, *Beaconites*, *Phycodes*, *Arenicoloides*, etc). Nevertheless, the only palaeontological remains that enable dating of this unit are palynomorphs from the uppermost part, which allow the assignment of an early Anisian age (Adloff, *in* Durand *et al.*, 1989). Occasional occurrences of tetrapod footprints have also been recorded. Although these trace fossils are much less constraining for age determination than palynomorphs, their stratigraphic ranges nonetheless encompass the early Anisian (Demathieu and Durand 1991).

3.3. Spain

The most important expression of Early Triassic sedimentation in Spain is represented by the Cañizar Formation (or its equivalents). This unit is characterized by amalgamated sequences of braided systems that are almost devoid of fines and lacking any palaeoflora except at the top (López-Gómez and Arche, 1994). As redefined above, its basal unit (Chequilla Conglomerate Member) is composed of conglomerates yielding ventifacts (Durand, *in* Arche and López-Gómez, 2005). The Cañizar Fm. is capped by paleosols and iron-rich crusts that represent a break in sedimentation with subaerial emergence of regional extent. This major hiatus is attributed to part of the early Anisian stage by López-Gómez and Arche (1994).

In the Aragonian Branch, the basal part of the Triassic succession is made up of the fluvial Tierga and Calcena units, which pass upwards into the marine deposits of the Muschelkalk Calcareous Group. The basal fluvial units are attributed to braided rivers with floodplain deposits (Diez *et al*., 2007). The palynomorphs allow us to date these fluvial deposits as Anisian (Diez *et al.,* 1996a, 1996b; Diez, 2000; Diez *et al*., 2007). As observed in this part of Spain, sedimentation above the PTB only resumed during the Anisian, after a stratigraphic break encompassing all of the "Scythian".

Closely comparable associations are also characteristic of the earliest Triassic palynofloras found in the upper Buntsandstein of the southern Catalonian Pyrenees (Broutin *et al.*, 1988), and NW Sardinia (Pittau, 2002).

3.4. Italy (NW Sardinia)

In the Cala Viola area (Nurra), above the PTB, the "Conglomerato del Porticciolo" Formation (Cassinis et al., 2003) is composed of well-rounded vein-quartz pebbles and cobbles. Cassinis *et al* (2003) have observed scarcely reworked and even *in situ* ventifacts (paleoreg) in this formation, as well as an eolian dune remnant. Together with the entire stratigraphic framework, these observations are used as an argument for correlating this unit with the "Poudingue de Port-Issol" in Provence. Curiously, these clear indications of arid conditions are not taken into account in a recent study claiming to show that red beds do not form under dry climates, while assuming all the Permian-Triassic deposits of this locality are of Late Permian age (Sheldon, 2005). The upper unit ("Arenarie di Cala Viola" Formation) also displays many features in common with the 'Grès de Gonfaron', in particular: a very sharp basal contact showing truncation of previous sedimentary structures and caliche nodules the upper part of a subsurface unit (in Cugiareddu well) which can be correlated with the "Arenarie di Cala Viola" yielded a palynomorph assemblage of early Anisian age (Pittau, 2002).

3.5. Bulgaria

The Triassic succession here also seems to begin with basal conglomerates, which contain many ventifacts at several localities. By comparison with the Germanic Basin data, this tends to suggest a general lack of lowermost Triassic strata, with basal facies occurring in various different settings. On the Noevtsi section (Kraishte Unit), the thin (0.5-2 m) unnamed basal conglomerate is sharply overlain by the palaeosol-rich sandstones of the Murvodol Formation. By contrast, the basal conglomerate of the Smolyanovtsi section (Prebalkan Unit) shows an upward transition into the thick Belogradchik Formation (up to about 200 m), devoid of any pedogenic features.

4. Correlation and discussion

At the scale of Western Europe we clearly show that, except from the Central Germanic Basin, an unconformity can be observed between the Permian and the Triassic deposits. The main question is the age of the earliest Triassic sediments. Except for the Germanic Basin, there is a total lack of typically "Scythian" fossils, and the oldest biochronological evidence yielded by these rocks are palynomorphs, found more or less high in the sections, that provide an early Anisian age. In the particular instance of the Lodève basin (Languedoc, SE France), the very basal bed of the "Buntsandstein" contains palynomorphs ascribed to the middle Anisian (Broutin *et al.*, 1992; Diez, 2000).

Within the Germanic Basin, rocks of Induan and Olenekian age have been recognized by magnetostratigraphy (Szurlies, 2004) and biostratigraphy (Kozur and Bachmann, 2005; see also discussion *in* Durand, 2006).

In other respects, recent studies from paleoenvironmental reconstructions allow us to simulate climate conditions during the Olenekian period (Péron *et al.,* 2005). The present study is focused on Western Europe, where sedimentological and stratigraphic data can be used to check the results of climate simulation against geological data. The main result is that climatic conditions in the sedimentary basins were very arid, while the sediment and water supply came from the adjacent relief (Fig. 6). Although these arid conditions prevailed at the European scale, seasonal changes are inferred in North Africa, showing alternating periods of aridity and precipitation. In this context, we can readily explain the presence of aeolian features (dunes or ventifacts) at a large scale.

On the western margin of the Germanic Basin, the Triassic deposits formed under arid conditions are attributed mainly to the lower Olenekian, *i.e.* Smithian (Durand, 2006). They are made up of 300 m of sandy alluvium laid down by a major braided river in an arid basin with some aeolian and very few floodplain deposits, lacking any paleosols ("Conglomérat basal", "Grès vosgien" and "Conglomérat principal").

Above this arid fluvial facies, the upper Olenekian, *i.e.* Spathian, is marked by a major sedimentary break characterized by the formation of a planation surface and preservation of the lowermost paleosols, followed by the tectonically induced Hardegsen unconformity. During

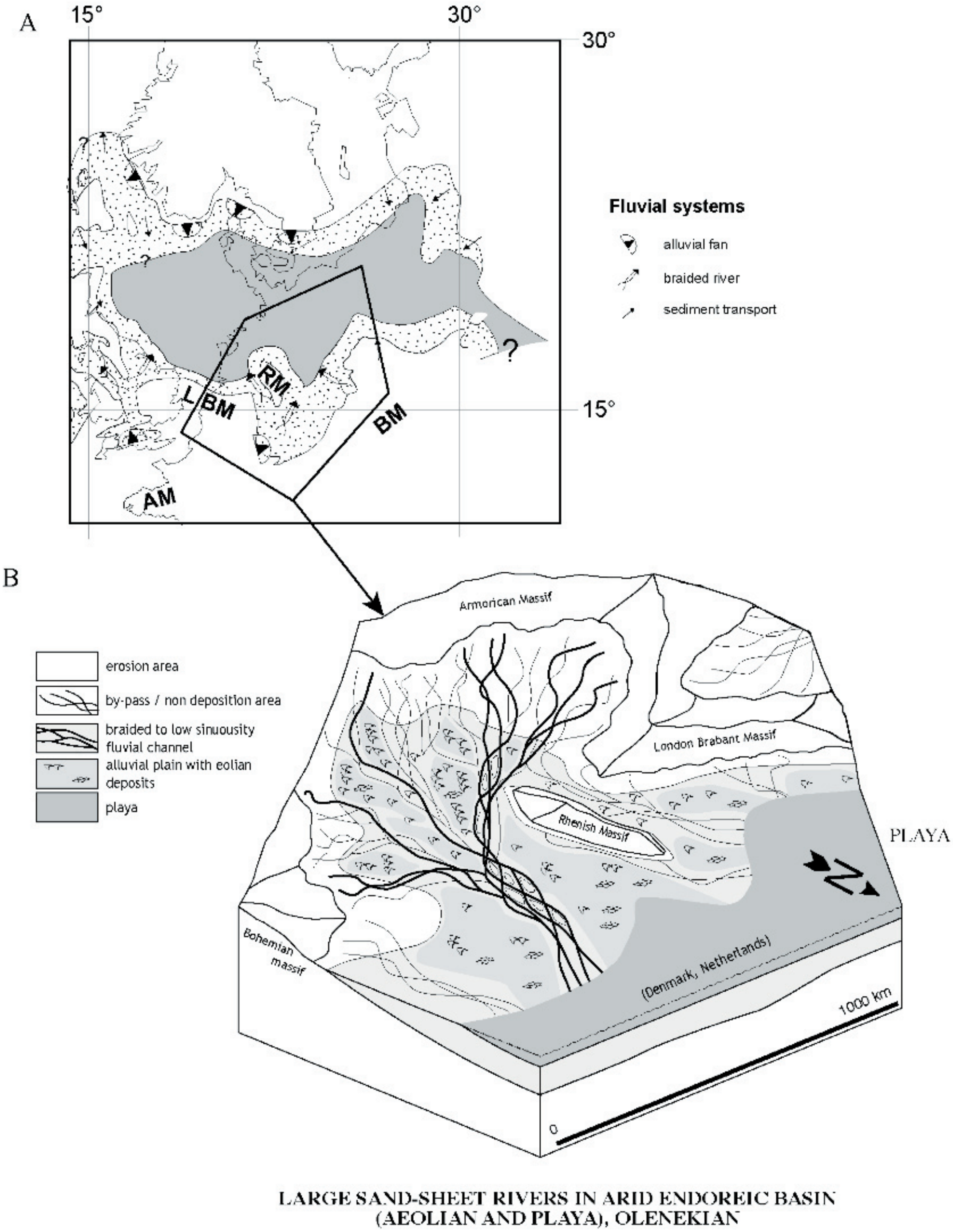

Fig. 5.- (A) Palaeogeographic map of southern part of the German Basin with superimposed palaeoenvironments and fluvial systems (modified after Péron *et al.*, 2005). VC: Varisan Chain; BM: Bohemian Massif; RM: Rhenish Masssf; LBM: London Brabant Massif. (B) Olenekian paleoenvironmental reconstruction of the western part of the Germanic Basin (Bourquin *et al.,* 2006).

Fig. 5.- (A) Mapa paleogeográfico de la parte sur de la Cuenca Germánica mostrando los paleoambientes y sistemas fluviales sobreimpuestos (a partir de Péron *et al*, 2005). VC: Cadena Variscica; BM: Macizo Bohémico; RM: Macizo Renano; LBM: Macizo Londres Brabante. (B) Reconstrucción paleoambiental de la parte occidental de la Cuenca Germánica.

the Hardegsen Phase, a major structural event occurred in NW Europe (Geluk and Röhling, 1997), leading to the formation of rift systems in NW Germany (Best *et al.*, 1983; Röhling, 1991). In the Germanic Basin, the base of the Solling Formation corresponds to the erosional interval of the Hardegsen unconformity, during which 100 m of Middle Buntsandstein deposits were locally eroded (Aigner and Bachmann, 1992). Moreover Geluk (1998) shows that the base of the Solling Formation becomes progressively younger to the west, accompanied by a decrease in thickness. In the present study, this formation appears to be missing due to non-deposition or erosion. The Solling sandstones preserved in the basin could be equivalent to an episode of sediment by-pass at the basin margin (Bourquin *et al.*, 2006). Above the Solling Formation, the Röt Formation, corresponding to evaporitic marine and sabkha deposits, representing the earliest Triassic occurrence of halite deposition in the Germanic Basin. In the western part of the Germanic Basin, after the major Hardegsen unconformity, the Triassic fluvial suc-

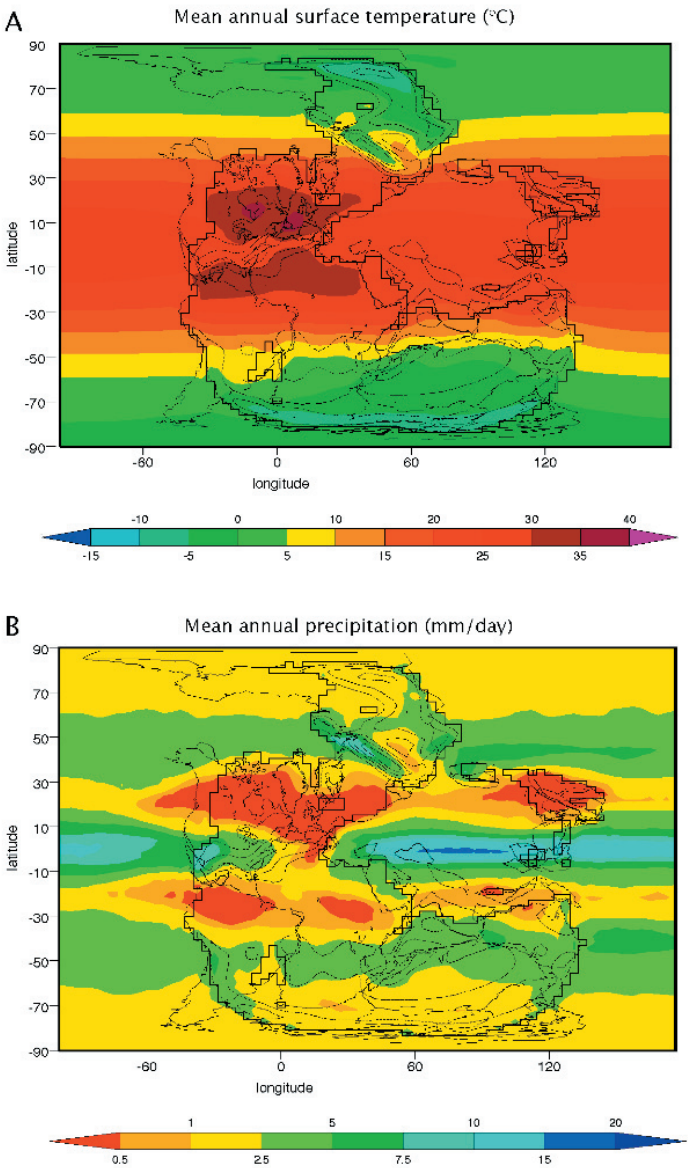

Fig. 6.- Climate simulations for the Early Triassic (Olenekian). (After Péron *et al.*, 2005)

Fig. 6.- Simulaciones climáticas para el Triásico Inferior (Olenekiense). (A partir de Péron *et al.*, 2005)

cession is characterized by a major retrogradational trend from fluvial deposits (from low sinuosity rivers with well developed floodplain and paleosol, "Couches intermédiaires" and "Grès à Voltzia"), dated as Anisian, to shallow marine deposits of the Ladinian (Durand, 1978; Bourquin *et al.*, 2006), reflecting the connection of the Germanic Basin with the Tethys Ocean (Dercourt *et al.*, 1993). These fluvial systems are the lateral equivalents of sabkha and marine environments in the Central Germanic Basin.

In the other western Europe peri-Tethyan basins (Table 1), the Permian-Triassic boundary corresponds to an unconformity that is overlain either by conglomerates containing ventifacts (followed by fluvial sandstones sometimes rich and sometimes totally lacking in paleosols) or directly by fluvial sandstones with the first occurrence of paleosols, and then plants debris and palynomorphs.

In Spain, in the Castilian Branch of the Iberian Range, the hyper arid event, attributed herein to the Smithian, is recorded in the lower part of the Cañizar Formation; the top is marked by hiatuses and paleosols, which are possibly partly coeval with the German "Röt". Within the Hoz del Gallo section, at about the first two thirds of the Rillo de Gallo Fm. (*i.e.* Canizar Fm) appears a condensed zone, about 3 m thick, with several weakly developed paleosols. The sudden drop in textural maturity from this level upwards could be regarded as a result of the Hardegsen movements in the catchment area, because a similar evolution is known in NE France, from the "Zone limite violette" paleosols to the "Couches intermédiares" Formation (Table 1). In the Aragonian Branch, a gap is observed corresponding to the entire lower Triassic; the Permian-Triassic boundary is overlain by fluvial siliciclastics, including floodplain deposits and plant remains dated as Anisian.

In SE France (Provence) and in NW Sardinia, the "Poudingue de Port-Issol" and "Conglomerato del Porticciolo" formations can be attributed to the end of the arid lower Olenekian episode. Both conglomerates are overlain by fluvial sandstones with caliche nodules, which are dated as lower Anisian in their upper part. The top boundary of this conglomerate is sharp and could correspond to the Hardegsen unconformity.

In Bulgaria, the relationship of the thin basal conglomerate of the Noevtsi section with the overlying sandstones is reminiscent of the "Poudingue de Port-Issol" in Provence or the "Conglomerato del Porticciolo" in Nurra. By contrast, the basal conglomerate of the Smolyanovtsi section, which passes upwards into the Belogradchik Formation, strongly evokes, by its setting, the "Basal conglomerate" of the "Grès vosgien" in NE France or the Chequilla Member of the Cañizar Formation in central Spain, and thus could be a little older than that of Noevtsi (Table 1).

5. Conclusions

From this review of the "Buntsandstein" of several European basins we can characterize the Permian Triassic boundary and the onset of early Triassic sedimentation at the west European scale. We clearly show that, except from the Central Germanic Basin, an unconformity can be observed between the Permian and the Triassic. The main question is the age of the earliest Triassic sediments. Except in the Germanic Basin, there is a total lack of typically "Scythian" fossils, and the oldest biochronological markers provided by these series are palynomorphs yielding an early Anisian age.

In the other western Europe peri-Tethyan basins (Table 1), the Permian-Triassic boundary corresponds to an unconformity that is overlain either by conglomerates containing ventifacts (followed by fluvial sandstones sometimes enriched and sometimes totally lacking in paleosols) or directly by fluvial sandstones with the first occurrence of paleosols, and then plant debris and palynomorphs. On the western margin of the Germanic Basin, the arid climate Triassic deposits are attributed mainly to the lower Olenekian, *i.e.* Smithian. Fluvial deposits with ventifacts (formed under arid conditions) are also described in other west European basins. Hence, this arid event seems not to be isolated in continental areas, but reflects arid climate conditions at the scale of Western Europe, as indicated by the climate simulation (Fig. 6). Moreover, an early Triassic arid episode is now indicated at the margins of Tethys (in the Lombardy Alps, Cassinis *et al.*, this issue).

Thus, the lack of typically Early Triassic fossils can be explained not only by slow recovery after the Permian-Triassic biologic crisis (López-Gómez *et al.*, 2005), but also by a true stratigraphic break during the Early Triassic (*i.e.* Induan) and/or by climatic conditions that were unfavourable for the development of flora and fauna during the lower Olenekian (*i.e.*'desert' environments). The early Triassic arid episode could have a global origin as suggested by recent studies on early Triassic ammonoids (Brayard *et al.*, 2006). Furthermore, it should be noticed that even in South Africa, last research provides evidence of a vegetated landscape during the earliest Triassic, and conversely of an aphytic interval from that time up to the Middle Triassic (Gastaldo *et al.,* 2005).

The careful recognition of unconformities and the use of sedimentary indicators of clearly arid climate provide us powerful tools for correlation, within non-marine succession that are devoid of any biostratigraphic markers, at least on the scale of the West European Plate.

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