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**Notes**

# The problem of the transition from the Permian to the Triassic Series in southeastern France: comparison with other Peritethyan regions

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**Abstract:** In the French sedimentary basins, widespread alluvial deposits sealing narrow Permian troughs are referred to as 'Buntsandstein'. An Early Triassic age is generally put forward despite a lack of any Scythian biochronological elements. In Provence (Southeast Basin) some doubts remain about the age of the latest Permian deposits, and the oldest Triassic fossils (Anisian palynomorphs) appear in the upper 'Buntsandstein'. Three types of contact occur: disconformity overlain by a quartz-conglomerate, apparent transition, and angular unconformity, according to an increasing basal incompleteness of the 'Buntsandstein'. Whereas the conglomerate was deposited under arid conditions, the overlying fluvial deposits indicate a marked climate change. A transect from France up to the Germanic Basin centre shows that the 'French Buntsandstein' cycle might begin considerably before the end of the Permian; the Early Triassic arid 'event' is Dienerian/Smithian in age; and the Provençal 'basal' conglomerate corresponds to the uppermost part of a coeval subordinate cycle, and thus the underlying sub-Triassic unconformity represents a hiatus estimated at 10–15 Ma. Works in progress confirm that sedimentary climate indicators constitute powerful tools for correlations within non-marine formations devoid of biostratigraphical marker that straddle the Permian–Triassic boundary, at least on the scale of the Western European Plate.

In the three main French sedimentary basins (the Paris, Southeast and Aquitaine basins) the Mesozoic cycle begins, at least in some parts, with widespread alluvial deposits burying relatively narrow Permian troughs, and frequently referred to as the 'Buntsandstein' Group. The basal beds of this 'Buntsandstein' were dated in one place only: above the small Lodève Permian basin, where they yielded a Mid- Anisian palynoflora (Broutin *et al.* 1992). In all other areas where the Middle Triassic was recognized – in the upper part of the 'Buntsandstein' or higher – an Early Triassic age is generally accepted for these red sandy and gravelly units despite the fact that, up to now, no Scythian biochronological indicators have been found. Thus, in actual fact the position of the Permian–Triassic Boundary (PTB) with respect to the sub-'Buntsandstein' unconformity is not straightforward.

For regions stretching further southwest ('North Iberian domain', including the Balearic Islands: Broutin *et al.* 1992) a Late Permian age is adopted for that unconformity, the lower 'Buntsandstein' still yielding 'Thuringian' (*sensu* Visscher 1971) palynofloras. A similar context prevails in the very NE corner of France (Dachroth 1985; Durand *et al.* 1994). Where the non-marine sedimentation seems to have been continuous from the Permian to the Triassic, the PTB is readily believed to coincide with an abrupt change in fluvial style, sometimes related to the global-scale end-Permian extinction (Ward *et al.* 2000). In other regions, it is generally admitted that the sub-'Buntsandstein' unconformity actually fits with the boundary between the Permian and Triassic series. Nevertheless, in both cases the lack of typically Early Triassic fossil remains can be explained either by conditions unfavourable to life and preservation (i.e. 'desert' environments) or by a true stratigraphical gap.

The purpose of this paper is for the first time to test these alternatives on case studies in Provence, where the largest outcrop area of Permian–Triassic deposits in the French Southeast Basin is present (Fig. 1), by using sedimentological climate indicators and step-by-step geometric correlations towards sections that have increasing completeness. These results will be used to tentatively propose a more or less new correlation scheme for other European regions.

## The PTB problem in Provence

On the regional scale there is no difficulty distinguishing the 'Buntsandstein' Group (Fig. 1). Constituting the base of the Mesozoic section, it crops out along a narrow, practically continuous belt from Sanary (SW) to Cannes (NE). It reflects a clear change from local drainage systems in several distinct basins, a characteristic of the Permian palaeogeography, to a single widespread system that is typical of the Triassic,

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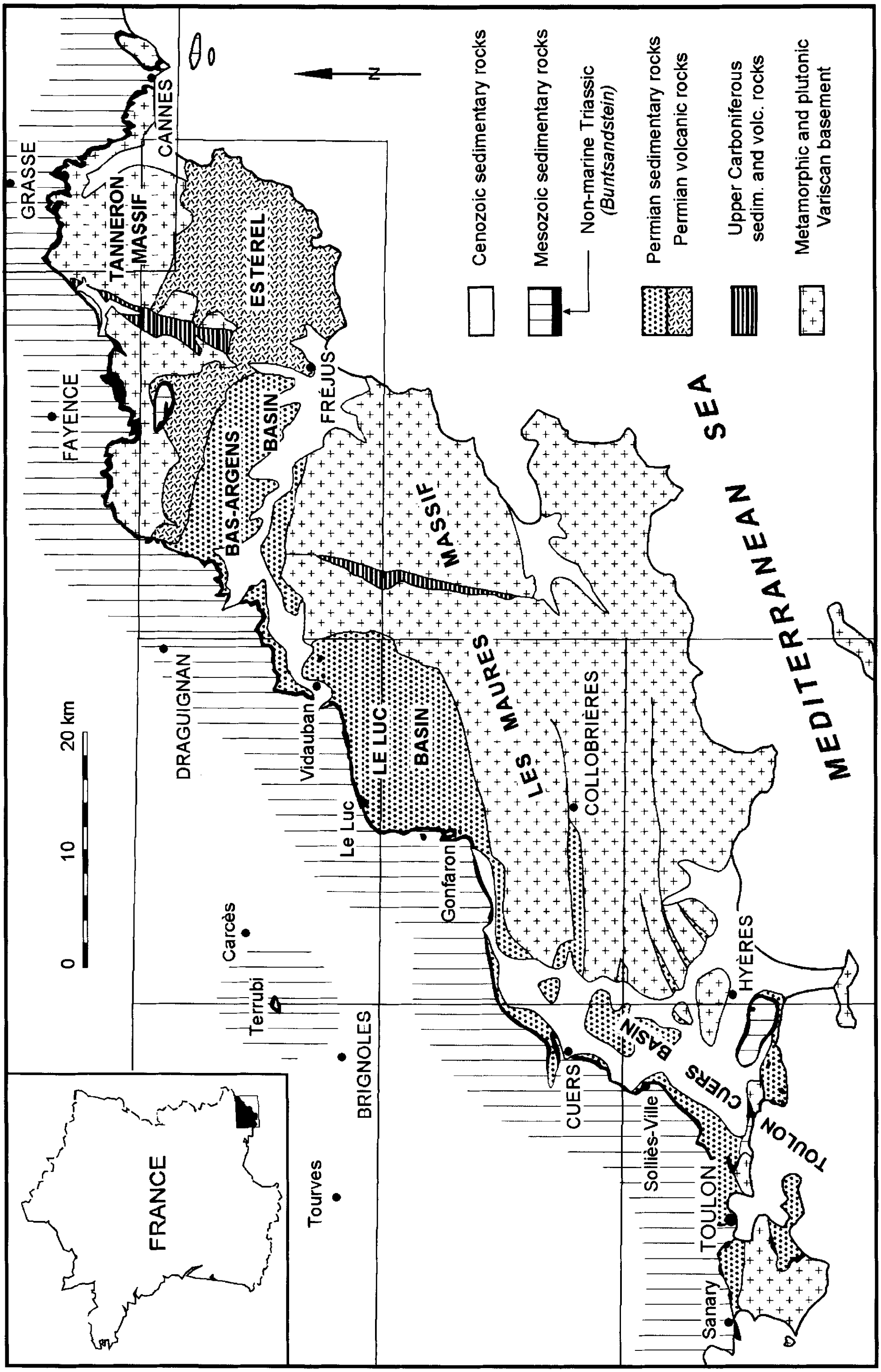
Cenozoic sedimentary rocks
Mesozoic sedimentary rocks
Non-marine Triassic (Buntsandstein)
Permian sedimentary rocks
Permian volcanic rocks
Upper Carboniferous sedim. and volc. rocks
Metamorphic and plutonic Variscan basement
N
0
10
20 km
FRANCE
GRASSE
CANNES
TANNERON MASSIF
ESTEREL
FAYENCE
BAS-ARGENS BASIN
FRÉJUS
MASSIF
LES MAURES
DRAGUIGNAN
Vidauban
LE LUC BASIN
Le Luc
Gonfaron
COLLOBRIÈRES
Carcès
Terrubi
BRIGNOLES
Tourves
CUERS
CUERS BASIN
Solliès-Ville
TOULON
Sanary
HYÈRES
TOULON
MEDITERRANEAN SEA

and thus constitutes the major criterion used to define the 'Buntsandstein' in France. It is noteworthy that the main Triassic palaeocurrents flowed to the SW, along the Maures Massif, that is – at least for the Toulon–Cuers area – in a direction opposite to the Permian palaeoflow (Durand *et al.* 1989; Durand 1993).

## *Dating elements*

The period during which the sub-'Buntsandstein' pediplanation surface, assumed to be the regional PTB, developed is very loosely appraised. On one hand some discrepancies persist between different dating elements from the Permian series, and on the other hand only Mid- Triassic palaeontological data were obtained from the 'Buntsandstein' so far, in its upper part.

Nevertheless, the very local occurrence of the Les Arcs Formation (Fig. 2) – the Permian or Triassic age of which is debatable – provides evidence that the sub-'Buntsandstein' unconformity probably corresponds to a major hiatus. In this connection, it is perhaps useful to report that two independent methods (geometric extrapolation and organic matter study) show that, above the rather nearby Lodève Basin (about 100 km WNW of Toulon), nearly 1500 m of Permian sediments could have been eroded before the Middle Anisian (Lopez *et al.* 2005).

### *Upper part of the Permian series*

The main stratigraphical marker through the Permian basins of Provence is an acidic lava-flow succession called the 'A7 Rhyolite' (Fig. 2). The last and more reliable isotopic dating gives it an age of $272.5 \pm 0.3$ Ma (Zheng *et al.* 1992), which is clearly Kungurian according to the latest geological time scale (Gradstein *et al.* 2004). Its thickness ranges from 150 to 300 m in the Estérel and Bas-Argens basins, but it does not encroach very much on the NE part of the Le Luc Basin.

In the Toulon–Cuers Basin, the sole dated unit in the Permian Series is the lacustrine 'Calcaires du Bau Rouge', which is the uppermost member of the Les Salettes Formation, about two-thirds above its base. It yields well-preserved macroscopic plant remains: *Ullmannia frumentaria* (dominant), *U. bronnii, Pseudovoltzia libeana, Lesleya* (alias *Taeniopteris*) *eckardtii, 'Sphenopteris' dichotoma* and *Odontopteris osmundaeformis*. The palynoflora is composed of scarce microspores, such as *Calamospora* spp. and *Converrucosporites eggeri*, and numerous pollen taxa: *Potonieisporites 'novicus-bhardwaji', Nuskoisporites dulhuntyi, Plicatipollenites* spp., *Vesicaspora–Scheuringipollenites* complex, *Gardenasporites leonardii, Vitreisporites pallidus, Protohaploxipinus microcorpus, Striatoabietites richteri, Lunatisporites* sp., *Lueckisporites virkkiae, Vittatina costabilis, Costapollenites ellipticus*, among others. This palaeofloristic assemblage led to assignment of a 'post-Kungurian / pre-Tatarian' age for the Bau Rouge Member (Broutin & Durand 1995). More precisely, subsequent comparative data (e.g. Poort *et al.* 1997) suggest a Wordian age.

The 'A7 rhyolite' is overlain by the Pradineaux Formation (Fig. 2), up to 200 m thick, which includes detrital to pyroclastic sedimentary deposits, as well as mafic and felsic volcanic-flow intercalations. This formation is the richest in biostratigraphically significant fossils, distributed on three principal levels, but it is developed mainly in the Estérel Basin, where the uppermost part of the Permian and the whole Triassic Series have been removed by Quaternary erosion. On the other hand, primary pinching-out and secondary faults hamper the reconstruction of the actual succession.

The lower fossiliferous beds ('11f unit' of Boucarut 1971) crop out near Agay. These lacustrine shales yielded mainly macrofloral remains such as cf. *Sphenopteris kukukiana*, cf. *Pseudoctenis middridgensis, Ullmannia bronnii, U. frumentaria, Quadrocladus orobiformis* and cf. *Q. solmsii* and cf. *Culmitzschia florinii*; conversely, very few palynomorphs are preserved (only *Lueckisporites virkkiae* and *Nuskoisporites dulhuntyi* were recognized). This assemblage led Visscher (1968) to propose a 'Thuringian age' for that part of the series. In agreement with Menning (1995), it must be emphasized that the term 'Thuringian' is misleading in several respects. For many French geologists it keeps its original sense (Renevier 1874) – equivalent of the Zechstein – whereas in Visscher's opinion it corresponds to the vertical range of *L. virkkiae*, that is, it begins already with the Kazanian (Utting *et al.* 1997, Gorsky *et al.* 2003). In fact, the Agay fossil-bearing beds (Fig. 2) could be only a little younger than those from the Bau Rouge Member (J. Broutin, pers. comm.).

The second fossiliferous beds (Pra Baucous locality) are thin lacustrine limestone layers interstratified with siltstones ('13a unit' of Boucarut 1971). They yielded an ostracode assemblage with *Iniella kutznetskiensis* (Spizharsky 1937), *Paleodarwinula acervalis* (Mandelstam 1956),

**Fig. 1.** Distribution of the non-marine Permian–Triassic outcrop areas in Provence. Fine straight lines are boundaries between sheets of the 'Carte géologique de la France à 1 / 50 000'. Each sheet is referred to by the town name in upper case letters.

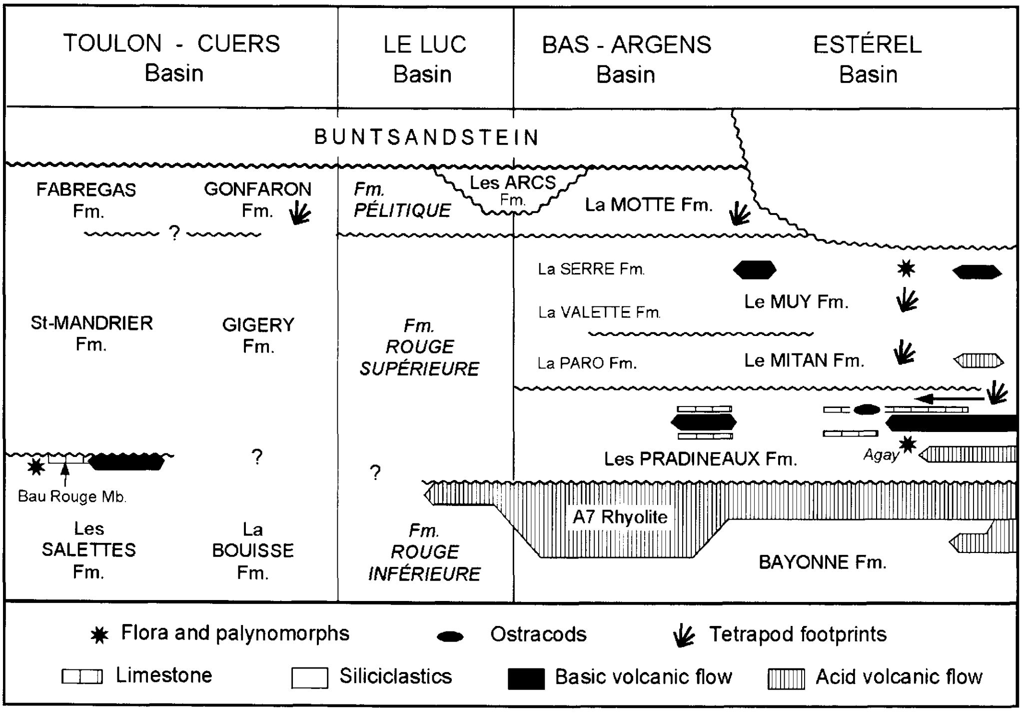


**Fig. 2.** Lithostratigraphical scheme for the upper part of the Permo-Triassic succession in Provence (modified after Toutin-Morin & Vinchon 1989). Without scale.

and *Paleodarwinula alexandrinae* (Belousova 1956). According to the known stratigraphical ranges of these taxa in Russia, this association was assigned to the earliest Tatarian (Lethiers *et al.* 1993); subsequent data show that the last taxon actually seems to be a good marker of the *P. fainaie* Zone, that is, Late Kazanian of the type area (Crasquin-Soleau 2003).

The third fossiliferous beds of the Pradineaux Formation in the Estérel, at a slightly higher level ('13c unit' of Boucarut 1971), are rhyolitic tuffs with fossil ground-surfaces, which, in the town of Saint-Raphaël (St-Sébastien disused quarry), display many tetrapod tracks studied by Gand *et al.* (1995). The ichnotaxon assemblage expresses a more advanced stage of evolution than the Cisuralian ones, but is also distinct from those typical of the Lopingian (Gand & Durand 2006); through the occurrence of the therapsid tracks *Lunaepes* and *Planipes* it can be referred to the 'tapinocephalid stage', which corresponds to the North American Roadian and Wordian (Cassinis *et al.* 2002; Lozovsky 2003).

From the revision of the previous age determinations just carried out, it can be concluded that the Pradineaux Formation as a whole is of Wordian age. The erosional unconformity at the top of the 'A7 Rhyolite' could have been formed during the Roadian.

It is higher in the series that problems persist. The Le Muy Formation provided, in a quarry since filled up, a great deal of coalified plant remains (Germain 1968; Visscher 1968) identified as: *Calamites* sp., *Annularia* sp., *Cordaites* sp., *Ullmannia* cf. *lycopodioides*, *U. bronnii*, silicified woods such as *Ginkgophytoxylon permiense* (Vozenin-Serra *et al.* 1991), and palynomorphs with a quantitative predominance of *Lueckisporites virkkiae*, *Nuskoisporites dulhuntyi* and *Falcisporites zapfei*, as well as *Jugasporites delasaucei*, *Strotersporites richteri* and *Paravesicaspora splendens*. For Visscher (1968) that assemblage is comparable with those from the German Zechstein *sensu stricto* (i.e. Upper Permian), and it is thus regarded as the most recent known so far in the French Permian (Broutin, in Toutin-Morin *et al.* 1994). Conversely, the tetrapod footprint assemblages found in the Le Mitan, Le Muy and even La Motte formations do not differ notably from those of the Pradineaux Formation (Gand & Durand 2006).

Furthermore, the first palaeomagnetic study carried out on the uppermost part of the Permian sedimentary series in Provence (the pelitic La Motte Formation and its equivalents in the Le Luc and Cuers basins) detected a reversed component in about 20% of the samples, and thus referred these formations to the Illawarra Mixed Polarity Superchron (Merabet & Daly 1986). But, it should be emphasized that similar results were also obtained at that time on older sediments and the A7 Rhyolite, whereas more recent works conclude on the contrary that all the Estérel volcanics (including the basalts occurring in Le Mitan and Le Muy formations: Fig. 2) are representative of the Kiaman Reversed Polarity Superchron (Rochette *et al.* 1997) and therefore should be older than 265 Ma (Menning 2001). In fact, several clues suggest that the Estérel rocks might be affected by remagnetization (Vlag *et al.* 1997).

*Triassic 'Buntsandstein'*

The deposits referred to as 'Buntsandstein' are very much less developed in thickness (maximum 80 m). The main part, beginning in many places with pebble beds, is everywhere devoid of any fossils, with the exception of invertebrate traces (*Scoyenia*, *Beaconites*, *Phycodes*, *Arenicoloides*, etc.) deserving further study but without biochronological significance. The only palaeontological elements that enable dating of that unit are palynomorphs from the uppermost part. These are: *Triadispora staplini*, *T. falcata*, *Alisporites grauvogeli*, *Microcacrhyidites fastidoides*, *M. sittleri*, *Pityosporites* sp., *Angustisulcites klausii*, *Voltziacaesporites heteromorpha*, *Illinites kosankei* and *Hexasaccites muelleri* (syn. *Stellapollenites thiergartii*). This assemblage, very close to those found in the Grès à Voltzia Formation of NE France, allows assignment of an early Anisian age (Adloff in Durand *et al.* 1989). Very comparable associations also represent the oldest Triassic palynofloras in the upper Buntsandstein of the southern Catalonian Pyrenees (Broutin *et al.* 1988), and NW Sardinia (Pittau 2002). Occasional occurrences of tetrapod footprints were noted, moreover, although in general rather badly preserved with compared with the Permian ones; they are mostly chirotheroid traces (*Chirotherium*, *Brachychirotherium*) with some *Rhynchosauroides* and *Capitosauroides*. They are much less discriminating than palynomorphs, but their stratigraphical ranges also encompass the early Anisian (Demathieu & Durand 1991).

At the end of this review, one can conclude that neither the presence of the Upper Permian (i.e. Lopingian) nor of the Lower Triassic (i.e. Scythian) are proven in Provence up to now. Other criteria must be used to try to restrict the zone of uncertainty.

## *Outcrop configurations*

Three different main types of contact between the Permian sedimentary deposits and the Triassic 'Buntsandstein' can be observed in the field over a short distance: disconformity overlain by a 'basal' conglomerate, apparent transition, and angular unconformity (Fig. 3). They will herein be called 'Sanary', 'Gonfaron' and 'Vidauban' type respectively.

*The 'Sanary type'*

In most cases, the very even surface regarded as the regional PTB is blanketed with an oligomictic orthoconglomerate composed of exclusively siliceous pebbles (mainly vein quartz, scarce lydites and quartzites) with a variable content of quartz-sand matrix (Fig. 3a) The thickness of this 'Poudingue de Port-Issol'(Glinzbœckel & Durand 1984) is commonly about 1 m and reaches a maximum of 8 m at the type section near Sanary. Sedimentary structures evoke longitudinal bars with lateral sand-wedges in a braided-channel river, and indicate palaeocurrents flowing along the NW border of the present Maures Massif.

The great majority of the pebbles were well rounded by long (polycyclic?) fluvial transport, but many display secondary ridges fashioned by wind-blown sand shortly before their last reworking (Fig. 4). Such clasts are usually known by the German term 'dreikanter', which refers to a specific shape that is never dominant among them, and furthermore can form in a different environment (Jones 1953); this is why the term 'ventifact' (Evans 1911), which can apply to all wind-worn pebbles whatever their shape, should be used in preference. The systematic occurrence of ventifacts in the Poudingue de Port-Issol joined to the lack of transverse supply (as shown by an unexpected decrease of pebble size towards the borders) testify that the depositional area underwent clearly arid conditions; the catchment area of the 'Port-Issol wadi' could be located in mountainous areas farther north (Durand *et al.* 1988, 1989).

Another very important distinctive feature of the Port-Issol Formation is its sharp upper boundary, showing truncation of previous sedimentary structures (see Fig. 3a), and marking an abrupt change in depositional style. The appearance of many indices of biotic activity conveys a climatic evolution into less extreme conditions, of semi-arid type. They are especially caliche nodules (*in situ* and reworked) and, in terminal fan facies of the downstream part (Toulon area), vegetation-induced primary sedimentary structures (Rygel *et al.* 2004). New sediment

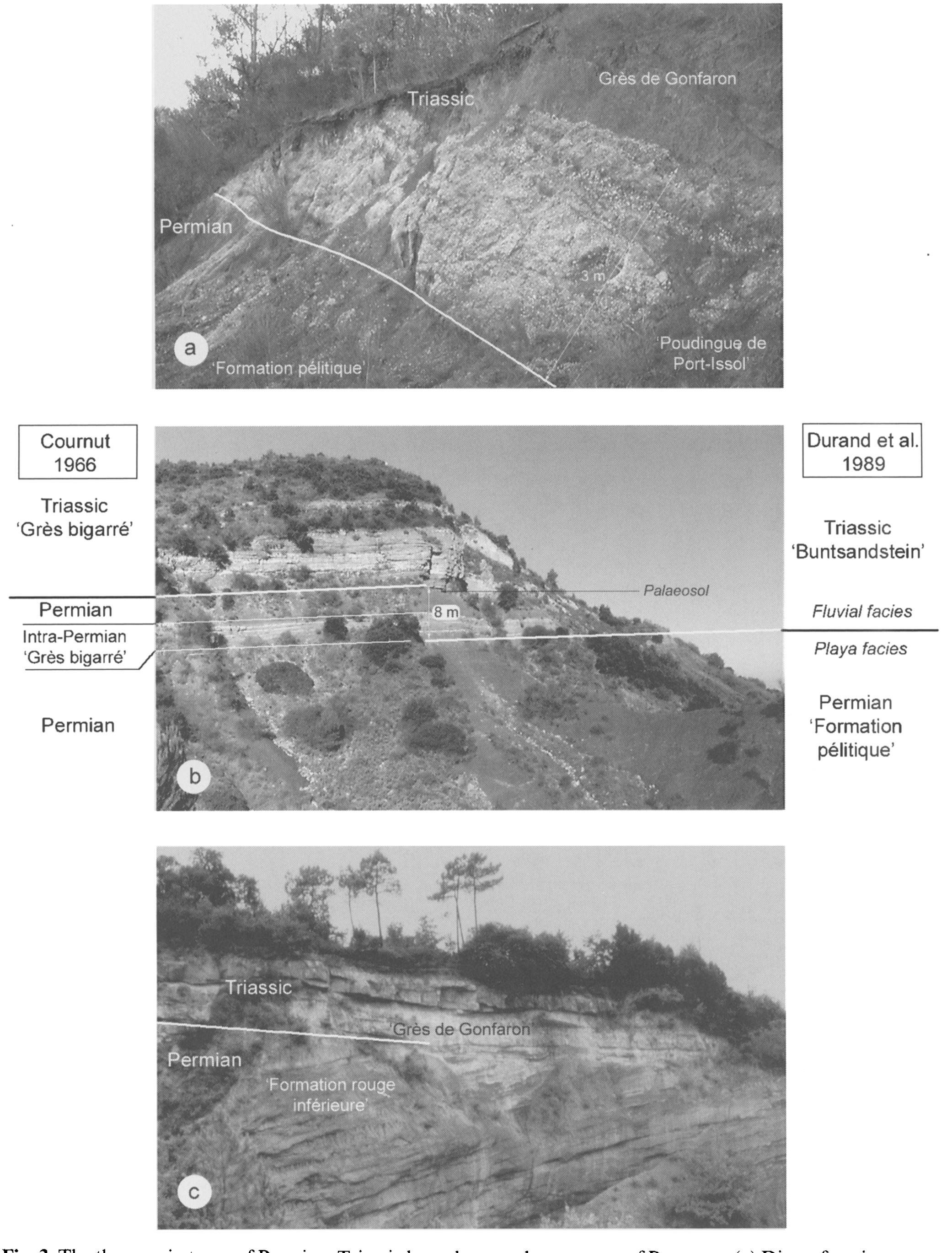


**Fig. 3.** The three main types of Permian–Triassic boundary on the outcrops of Provence. (a) Disconformity overlain by a quartz-conglomerate (Cuers); (b) Apparent transition (Gonfaron); (c) Angular unconformity (La Garduère near Vidauban).

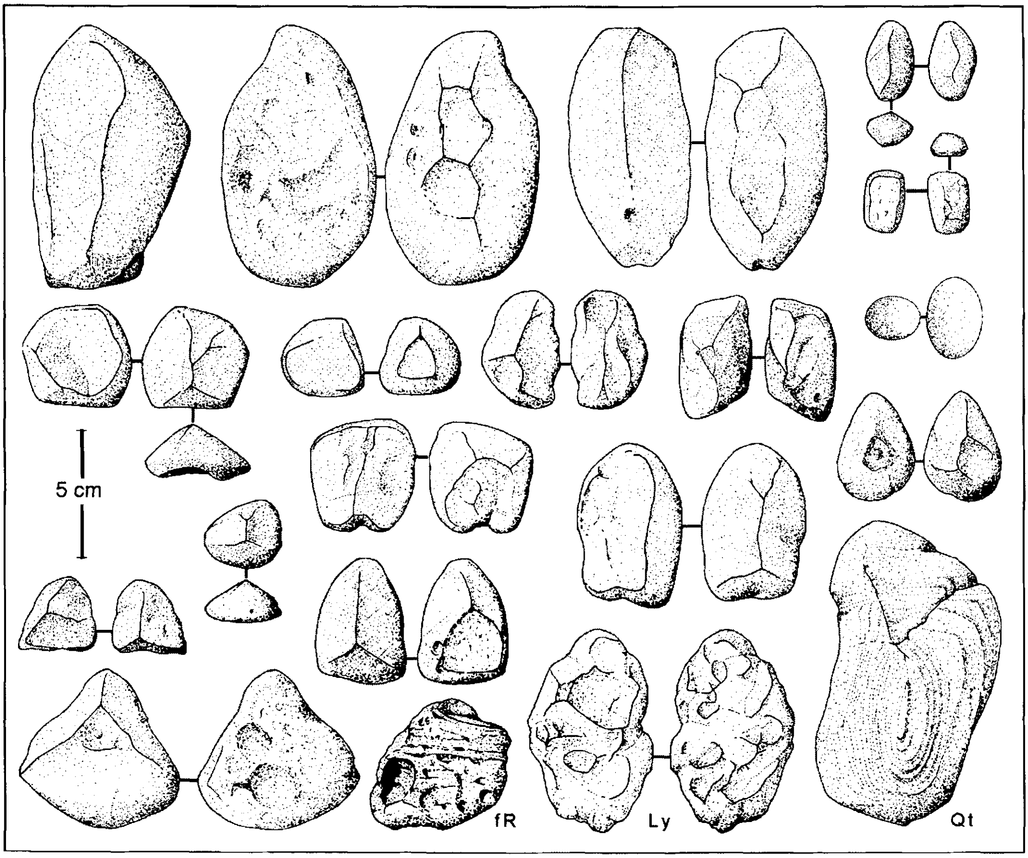


**Fig. 4.** Main types of ventifact from the basal beds of the 'Buntsandstein' of Provence (modified after Durand *et al.* 1989). All these specimens are quartz, except: fR, rhyolite with fluidal structure; Ly, lydite; Qt, quartzite.

supply reached the basin by the Bas-Argens zone, perhaps coming from NE Corsica (Durand *et al.* 1989). The apparently rapid character of the recorded climate change is probably due to only a more or less significant depositional hiatus, as will be seen later. Moreover, several sections in the neighbourhood of Toulon (Fabregas, Solliès-Ville) show the development of a palaeosol at the expense of the uppermost conglomerate layers; in other places (La Garonne beach) the Buntsandstein begins directly with a discontinous dolocrete overlain by a thin conglomerate produced mainly by the reworking of the 'Poudingue de Port-Issol'.

*The 'Gonfaron type'*

Less frequent than the former, this type corresponds to an apparent transition from Permian to Triassic sedimentary deposits because of a lack of any conglomerate. On the Gonfaron outcrops (Fig. 3b), a 'precursory' sandstone facies typical of the 'Buntsandstein' seems to be inserted in Upper Permian red silt-clay deposits ('Intra-Permian *Grès bigarré*' of Cournut 1966; see Fig. 3). For a time, the regional PTB was believed to be located at the top of the uppermost thick silty unit because of the development at this level of a spectacular palaeosol with long, drab-haloed root traces and yellowish subvertical caliche nodules (Cournut 1966; Toutin-Morin 1986). Subsequently, a careful examination of the fine-grained facies revealed significant differences between the lower playa sediments and the upper floodplain deposits. Conversely, the sandstone units are clearly related; they contain particularly subspherical (wind-worn) coarse quartz grains concentrated mostly at the very base of the lower unit. This is why it is currently believed that this level is actually the base of the Triassic Series (Durand *et al.* 1989).

It is clear that an erosional unconformity, which may correspond to a hiatus of several million years, is likely to pass unnoticed much more easily than a variegated palaeosol, even though it is rather moderately developed, such as that described above. Two superimposed lithological units of very different ages can present on the outcrop a 'mimetic' aspect, and it may be that detailed petrographic studies are necessary to differentiate them.

*The 'Vidauban type'*

The least frequent type of appearance of the PTB in Provence is that of an angular unconformity. At the best outcrop (Fig. 3c), SE of Vidauban, the angle between strata of the Permian and Triassic sandstones approximates 20°, and the truncation reached a rather deep level of the Permian Series ('Formation rouge inférieure': Fig. 2). Such an unconformity is not the expression of some latest Permian or earliest Triassic tectonic movements; it results from intra-Permian tilting (Baudemont 1988). There, on the Vidauban swell between the Bas-Argens and Le Luc basins, transtensional deformations generated progressive unconformities, some of which, at a very short distance, are sealed by the uppermost Permian unit in this region ('Formation pélitique').

One can conclude that the three types of contact between the Permian and Triassic series noticed in Provence depend on their location being more and more distant from the axis of the Triassic depositional basin (Fig. 5). Attention must be drawn to the fact that the apparent transition does not correspond to the shorter basal gap.

## The 'Buntsandstein' hyper-arid period

Whereas the other non-marine Triassic siliciclastics of Provence are relatively rich in traces of animal and plant activity, especially caliche nodules (*in situ* and/or reworked) typical of semi-arid soils, the Poudingue de Port-Issol lacks such features. Conversely, it is characterized by the occurrence of numerous, very well-preserved windkanters. The shaping of such gravels could be carried out only on the surface of a ground free from any vegetation during many thousands of years (Wright *et al.* 1991). Thus, it can be inferred that this conglomerate formed during one particular period characterized by hyper-arid climatic conditions. Dating that period would make it possible, on the one hand, to reduce the margin of uncertainty left by biochronological data for the estimate of the age of the regional PTB in Provence and, on the other hand, to attempt correlation with distant regions. That could be carried out starting from a comparison with the series of NE France.

## *Tentative dating*

*The northeastern France context*

To observe, in other localities of France, relationships between Permian and Triassic series very similar to those described in Sanary, it is necessary to move over 500 km northwards to the Lure area (Franche-Comté province), on the southernmost slope of the Vosges Massif (see location on Fig. 7). From there it is possible to follow an evolution in continuity SW–NW (at first towards the axis of the Lorraine Basin, then downstream) as far as the much more complete series of SW Germany (Fig. 6).

The thin Triassic conglomerate with ventifacts that lies directly above the Permian red siltites in the Lure area is nothing other than the 'Conglomérat principal' of the Vosges (Durand

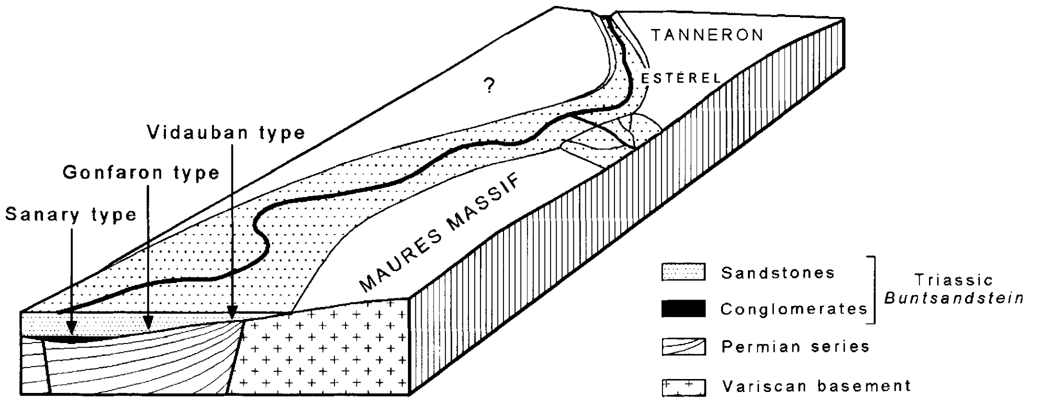


**Fig. 5.** Schematic diagram showing the locations, within a Lower Triassic palaeogeographical context, of the three forms presented by the PTB in Provence. Not to scale.

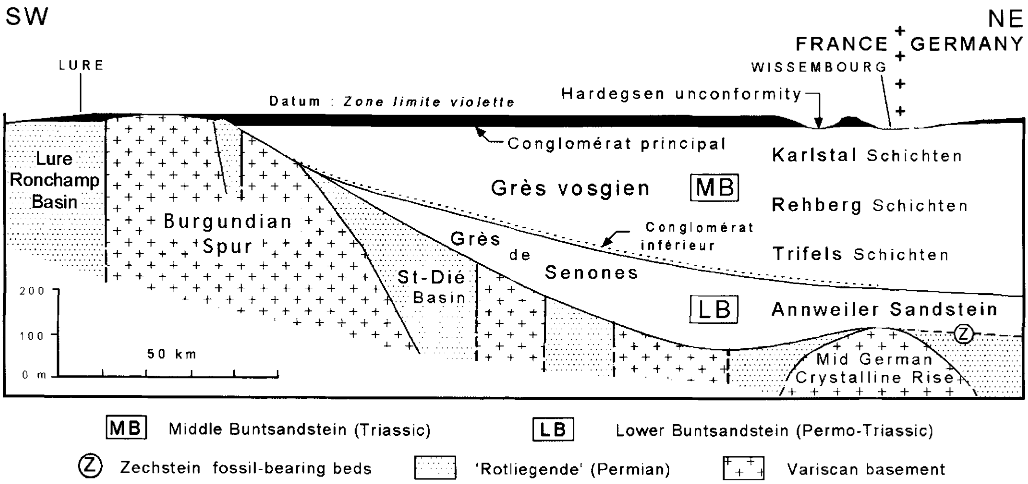


**Fig. 6.** Simplified lithostratigraphical cross-section across the Lower and Middle Buntsandstein of NE France, from Franche-Comté (SW) to Palatinate (NE, Germany) through the Vosges Massif in Lorraine and Alsace.

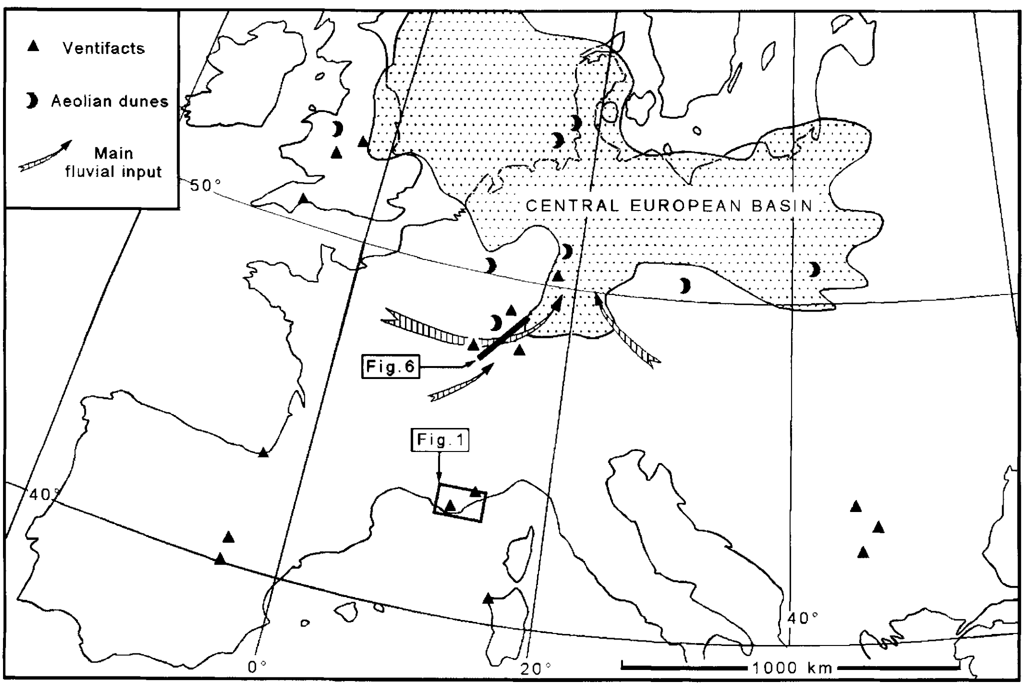


**Fig. 7.** Geographical distribution of the sedimentary features ascribed to the Dienerian–Smithian arid period in SW Europe. Since the maximum extension of coeval deposits is yet known with inadequate precision, only that of the uppermost Permian 'Zechstein', indicating roughly the central part of the Lower Triassic basin, is represented here (dotted area).

1978). On most of the Vosges Massif this unit, generally about 20 m thick, tops a sandy formation ('Grès vosgien') constituting the major part of the Buntsandstein, where remains of large aeolian dunes were seldom preserved by the wandering of fluvial braided channels, and where the pebbly basal member ('Conglomérat inférieur') is already rich in ventifacts (Durand *et al.* 1994). As the same types of pebbles and the same sand fraction characterize the 'Conglomérat principal' and the whole underlying 'Grès vosgien' as well, both formations are considered as part of the same sedimentary cycle, up to 350 m thick, that was entirely deposited during the Buntsandstein arid period; it is referred to as the 'Middle Buntsandstein' by French geologists (Courel *et al.* 1980).

There is, nevertheless, a difference between the setting of the conglomerates in Provence and the Lure area. In the first case the conglomerate remained in the axial part of the basin; in the latter it resulted from an overfilling of the Lorraine Basin, and real divergence on its margin towards the Bresse–Jura Triassic Basin (Durand 1978). But it can be inferred from well-log data that, beneath the Mesozoic cover of the present Paris Basin, the 'Conglomérat principal' does occur upstream from the 'Grès vosgien' depositional area, in a configuration similar to that observed in Provence, about 150 km west of the transect in Figure 6. However, it may be that both conglomerates mark the latest part of the Buntsandstein arid period.

Unfortunately, there is practically no element for direct dating of that period in the French Buntsandstein. The whole Middle Buntsandstein has so far yielded a single body fossil, in the upper 'Grès vosgien': a conchostracan identified as *Cornia* sp. by Kozur (1993), who assumed a Dienerian age. It should, however, be pointed out that this genus is known also from the Smithian (Sludkian Horizon) of the Moscow syneclise (Lozovsky 1993).

The French Middle Buntsandstein is well delimited between two units that present several petrographical and sedimentological characters in common: much lower mineralogical and textural maturity, and presence of palaeosols. Below, under a very sharp boundary, the 'Grès de Senones' (Fig. 6) allows reconstruction of a palaeocurrent system already very comparable with that of the 'Grès vosgien', and rests on various kinds of typically Permian strata ('Rotliegend' of the German geologists) or on the older basement; this is why it is referred to the Lower Buntsandstein. It is devoid of fossils (apart from scarce *Scoyenia*), but near the French–German border the base of its time equivalent 'Annweiler Sandstein' contains a malacofauna that is indicative of the first cycle of the German 'Zechstein' (Forche 1935); thus, the entire Lower Buntsandstein of the Vosges could be Late Permian.

The top of the Middle Buntsandstein is generally marked by a palaeosol complex, with dolocretes and silcretes – the 'Zone limite violette' – which developed in the course of a very long period without noticeable detrital supply following the 'Conglomérat principal' deposition. In most places where this key bed does not occur, one can show that the gap results from a subsequent erosion, having reached the 'Grès vosgien' in places (Durand *et al.* 1994), which very probably corresponds to the Hardegsen disconformity known in many parts of the Triassic Central European Basin (CEB), that is, the Germanic Basin, and formed during the Middle Spathian (Kozur 1999).

Finally, observations limited to NE France do not allow a more precise dating than Early Triassic (Scythian) for the arid period during which formed the conglomerate overlying the sub-Buntsandstein unconformity in Provence.

*Comparison with the central CEB*

The continuity of exposure towards the central part of the Germanic Basin is unfortunately interrupted by the Rhine Graben. On its eastern side the Triassic series is rather more complete, but correlations with NE France and northern Germany as well are still debated. This is why recognition of a time equivalent of the 'French Middle Buntsandstein' was directly sought among the five formations located under the Hardegsen unconformity in the centre of the basin. The required stratigraphical unit was one where no palaeosol was known, but from where conversely the greatest number of aeolian features (ventifacts and sand dunes) were reported, and where non-marine biotas were rare and the least diversified. The best candidate is, without question, the Volpriehausen Formation, especially as it displays the same sequential evolution (Aigner & Bachmann 1992) as the Palatine coeval deposits of the 'Grès vosgien'.

The Volpriehausen Formation yielded several fossil taxa of unequal biochronological interest. The conchostracan fauna is typically Smithian, with the first Spathian element, *Liograpta (Magniestheria) deverta*, appearing in its uppermost part (Kozur 1999, 2003). Miospores are primarily represented by *Densoisporites nejburgii* with subordinate *Endosporites papillatus*, that is: the 'PI' subzone of the *D. nejburgii* Zone (Orłowska-Zwolińska 1985) – that is the 'GTr3' Palynozone (Heunisch 1999) – ascribed to the Smithian stage by its author, the Dienerian by Reitz (1988), and the upper Griesbachian to lower Smithian by Fijałkowska-Mader (1999). Megaspores are usually lacking: 'Barren interzone Ib1' of Fugliewicz (1980). Vertebrates are extremely rare but invaluable; the labyrinthodont *Parotosuchus helgolandicus* was also found in the Torrey Member of the Moenkopi

Formation (SE Utah), which is inserted between ammonoid-bearing units, allowing it to be referred to the Smithian (Lucas & Schoch 2002).

In addition, the Volpriehausen Formation is bracketed between formations richer in palynomorphs. Below, the German 'Lower Buntsandstein' (i.e. Calvörde and Bernburg formations, which are not represented west of the Rhine) is characterized by the *Otynisporites eotriassicus* megaspore Zone beginning in the Late Permian (Fuglewicz 1980). But other palynomorphs were used to define the typically Triassic *Lundbladispora obsoleta – Protohaploxypinus pantii* Zone (Orłowska-Zwolińska 1985), namely the *Endosporites papillatus – Densoisporites playfordi* Zone (Reitz 1988) ≈ 'GTr2' palynozone (Heunisch 1999), belonging mainly to the Griesbachian stage. Kozur (1999) characterizes the whole Lower Buntsandstein by the *Lundbladispora willmotti – Lunatisporites hexagonalis* miospore Zone ranging the entire Induan. Above the Volpriehausen Formation, but still in the Middle Buntsandstein, the *Trileites polonicus – Pusulosporites populosus* megaspore Zone (Fuglewicz 1980) includes a score of taxa. Straddling the Detfurth and Hardegsen formations, the *Densoisporites nejburgii* PII subzone (Orłowska-Zwolińska 1985) = *D. nejburgiii* Zone (Reitz 1988) also has a rich vegetation that already characterizes the lower Spathian.

Recent magnetostratigraphic studies (Szurlies 2004) show that the Volpriehausen Formation is dominated by a reversed polarity record (upper part of his sr2 magnetozone and the entire sr3), with a short normal-polarity interval (sn4) around its lower third, and another (sn5) including the uppermost minor cycle 6 and partly the first of the following Detfurth Formation. It could be that the systematically normal polarities found in the uppermost part of the Middle Buntsandstein on the Beckenhof section (Palatinate) by Burek (1970) belong to the magnetozone sn5. Szurlies (2004) concludes that, in spite of some problems that remain, the Volpriehausen Formation may correlate to the late Dienerian to early Smithian interval; and this is what will be retained herein, in the current state of knowledge, for dating the Early Triassic arid period.

## Correlation potential

It would be beyond the scope of this paper to make a review of all sedimentary features ascribable to the Early Triassic arid period, and Figure 7 does not claim to be exhaustive; it only aims at giving an idea of the wide dispersion of the observation points. Aeolian dune deposits are used, as for Poland and the Czech Republic (Gradziński *et al.* 1979; Uličný 2004), while bearing in mind that they are worse climatic indicators than the ventifacts. At first I will briefly discuss a few cases where recent publications introduce a certain confusion; I will then follow with a short presentation of the most recent results in southern Europe.

Hounslow & McIntosh (2003) suggest, after a palaeomagnetic study, that the ventifact-bearing Budleigh Salterton Pebble Beds (south Devon, United Kingdom) could be of Late Spathian to Early Aegean age (i.e. the same age as the Solling Formation and lower Röt Formation in Germany: Kozur 1999) and extend their conclusion to the 'Conglomérat principal' of the Vosges because both these conglomerates are responses to the same geodynamic events (Smith & Edwards 1991). The last assertion is obvious, but the probable Smithian age of the French conglomerate proposed here is more strongly constrained, which is why both would be better ascribed to the mid-Scythian arid period.

Ptaszyński & Niedźwiedzki (2004) assign the aeolian Tumlin Sandstone (Holy Cross Mountains, Poland) to the Late Permian on the basis of vertebrate track studies. Although aeolian dune deposits are frequent below the Zechstein of the CEB, the combined regional results of palynology (Fijałkowska-Mader 1999) and magnetostratigraphy (Nawrocki *et al.* 2003) show clearly that a correlation with the Volpriehausen Formation, proposed initially by Fuglewicz (1980), is most probable. The reason why ichnology seems to indicate a Permian rather than a Triassic age could be linked with the fact that the European lower and middle Scythian vertebrate footprints are very poorly documented (Demathieu & Haubold 1972; Avanzini *et al.* 2001).

### *Italy*

In Nurra (NW Sardinia), on a relatively limited surface, a thick Permian–Triassic siliciclastic series crops out that shows remarkable similarities to that of the Toulon–Cuers Basin in Provence, allowing us to regard both areas as parts of the same basin, that initially closely faced each other (Cassinis *et al.* 2003). The presence of ventifacts scarcely reworked in the local 'Conglomerato del Porticciolo' is one of the arguments used to correlate this one with the Provençal 'Poudingue de Port-Issol'.

Otherwise, as in many other areas of limited exposure, the Nurra provides an excellent example of different 'Buntsandstein concepts', more or less explained, and likely to create serious problems in palaeogeographical syntheses. Sciunnach (2001) isolates under the name of 'Buntsandstein' the higher part of the 'Verrucano Sardo' (Gasperi & Gelmini 1979), which encompassed all the post-Autunian siliciclastic units. His 'Lower Buntsandstein' (i.e. Cala del Vino Formation: Cassinis *et al.* 2003) can be equated with the St-Mandrier Formation (more than 700 m thick) of the Toulon area (Fig. 2). Costamagna & Barca (2002) call 'Buntsandstein' the whole 'Verrucano Sardo'. Conversely, Cassinis *et al.* (2003), using the same concept as in Provence, restrict the 'Buntsandstein' to the uppermost part, starting from the 'Conglomerato del Porticciolo'.

### *Spain*

It is generally admitted that, in the Castilian branch of the Iberian Ranges, the PTB lies somewhere in the lower part of the Cañizar Sandstones Formation, or its time equivalent, the Hoz de Gallo Conglomerates and Rillo de Gallo Sandstones formations, constituting the lower (and major) part of the 'Buntsandstein *sensu stricto*' (López-Gómez *et al.* 2002; Arche *et al.* 2004). In fact, the Hoz de Gallo Conglomerates include two distinct lithostratigraphical units separated by a discontinuity (Ramos 1979) whose importance has been underestimated. The lower unit, which yields Permian palynomorphs, ends locally with sandstones and then a silcrete, while a few hundred metres further these beds were eroded, so that the two conglomerates are in direct contact. Much further SE the upper conglomerate, yielding ventifacts, is the only unit present and constitutes the basal unit of the Cañizar Formation. This is why it is supposed here that the unconformity in question is an equivalent of that below the 'Grès vosgien' and represents the regional PTB.

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, above the formation yielding Permian palynomorphs, and a clear unconformity, the lower Buntsandstein unit (B1) begins with a quartz conglomerate (Gómez-Gras & Alonso-Zarza 2003) that deserves further study but brings to mind the basal conglomerate of Provence and Sardinia. Since no conglomerate occurs in Majorca, the contact between dated Permian and Triassic formations appears transitional, but as the series is thinner it could be that the local PTB setting correponds to the 'Gonfaron type' and to a hiatus longer than in Minorca.

### *Bulgaria*

In NW Bulgaria the Peri-Tethyan Lower Triassic appears under the Buntsandstein facies (Petrohan terrigenous Group) and usually begins with a basal oligomictic siliceous conglomerate; in its uppermost part occur marine intercalations of Spathian age (Belivanova 2000). For Zagorchev & Budurov (1997), the basal gap could correspond to a major part of the Lower Triassic, whereas for Yanev *et al.* (2001) it would be more related to the Upper Permian. The basal conglomerates recently provided many ventifacts, tending to show a general lack of the lowermost Triassic, but they appear in various settings. On the Noevtsi section (Kraishte Unit), the thin basal conglomerate is abruptly overlain by the palaeosol-rich sandstones of the Murvodol Formation; such a relationship calls to mind that of the 'Poudingue de Port-Issol' in Provence. In contrast, the conglomerate of the Smolyanovtsi section (Prebalkan Unit) passing upwards to the Belogradchik Formation, devoid of any pedogenic features, evokes very much the basal conglomerates of the 'Grès vosgien' or the Cañizar Formation, and thus could be a little older.

## Discussion and conclusions

The 'French Buntsandstein' sedimentary cycle may begin considerably before the end of the Permian. Its basal unconformitiy ('Pfälzer Diskordanz', i.e. Palatine unconformity *sensu* Dachroth 1985) can be followed beneath the whole CEB. It is the 'Altmark unconformity' below the Upper Rotliegend II (Hoffmann *et al.* 1989; Schneider & Gebhart 1993) of northern Germany – where it can come down to the Illawarra Reversal – and below the Silverpit Claystone Formation of the North Sea and the Piła Claystone Formation in Poland (Karnkowski 1994); it also corresponds to the basal unconformity of the Val Gardena Sandstone and the Verrucano Lombardo of the Southern Alps. Intra-Zechstein tectonic movements were limited ('Tubantian' faultings of Geluk 1999). As pointed out by Fuglewicz (1980), the true 'Pfälzic' = 'Palatine' unconformity (i.e. between the Permian and Triassic in Palatinate) is nothing other than the 'Volpriehausen unconformity' below the time equivalents of the 'Grès vosgien' (i.e. Dachroth's 'Lauter' unconformity).

Nevertheless, during the Late Permian most areas in France, and elsewhere in SW Europe, experienced a more or less deep erosion forced by exceptional drops of global sea level (Ross & Ross 1987; Hallam & Wignall 1999; Seidler 2000; Heydari *et al.* 2001), and became only bypass zones for sediments during the earliest Triassic. Therefore, the time gap corresponding to the sub-Triassic unconformity actually encompasses the PTB, and this gap is increasingly long as one approaches the edges of the basin. For the Provence realm, it cannot be excluded that Les Arcs Formation results from the earliest Triassic infilling (transgressive system tract) of a palaeovalley incised during the Late Permian.

The aforementioned scenario seems characteristic of basins open towards the world ocean. Conversely, it is only in closed basins that one can expect a continuity of sedimentation from the Permian to the Triassic. Indeed, the only places on the West European Plate where such a continuity could be proven correspond to the deeper part of the endorheic CEB (Nawrocki 2004).

It must be emphasized that, everywhere in the Northern Hemisphere where such a continuity was demonstrated, the climate seems to have evolved towards rather more humid conditions (e.g. Fuglewicz 1980; Kozur 2003); macroflora is still of a prevailing Permian character and palynoflora shows a transitional nature (Shu & Norris 1999; Lozovsky *et al.* 2001). Nothing indicates a sudden collapse of the terrestrial ecosystem. This is why, when outcrops display an abrupt change in depositional style or palaeoclimatic conditions at the PTB boundary, a more or less significant gap should be suspected.

The first and main Early Triassic arid climatic phase in Europe is of Dienerian–Smithian age. The 'basal' conglomerate of the 'Buntsandstein' in Provence ('Poudingue de Port-Issol') is nothing but the uppermost part of a subordinate cycle corresponding to that phase and is coeval with the middle Buntsandstein of the Vosges. Therefore, the sub-Triassic unconformity represents there a hiatus probably as long as 10–15 Ma, encompassing at least the entire Lopingian and the majority of the Induan.

Much confusion currently exists about the concept of 'Buntsandstein' in certain regions of discontinuous exposure, where a major unconformity may be overlooked. This problem must be borne in mind every time different palaeogeographical domains seem likely to be distinguished. Works in progress confirm that the careful recognition of unconformities and the use of sedimentary indicators of a clearly arid climate constitute powerful tools for correlation within the non-marine rock units, devoid of any biostratigraphical markers, which are straddling the PTB, at least on the scale of the West European Plate.

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