PERMIAN FLORAS OF THE SOUTHERN ALPS

HENK VISSCHER[1], HANS KERP[2], JOPIE A. CLEMENT-WESTERHOF[1] and CINDY V. LOOY[1]

Key words – Megaflora; Cuticles; Permian; Southern Alps; Italy.

Abstract – Permian plant megafossils are long since known from various parts of the Southern Alps. These fossils were traditionally mainly used for age estimates of continental formations. However, floras with well preserved cuticles on the basis of which natural species, genera and families could be recognised, also contributed towards a much better understanding of late Palaeozoic gymnosperms.

A short introduction is followed by an updated synthesis of the plant fossils discovered until now in the region. The floras from the Collio Formation in the upper Val Trompia (Brescia) and the Tregiovo Formation in the upper Val di Non (Trento-Bolzano), and from the overlying Upper Permian Val Gardena red beds, east of the Adige Valley are discussed.

Parole chiave – Macroflora; Cuticole; Permiano; Alpi Meridionali; Italia.

Riassunto – La presenza di piante permiane è da lungo tempo nota in vari settori della Alpi Meridionali. Tradizionalmente, questi fossili furono essenzialmente utilizzati per stimare l'età delle formazioni continentali. Tuttavia, flore con ben preservate cuticole in base alle quali specie naturali, generi e famiglie potevano essere riconosciute, contribuirono pure ad una assai migliore conoscenza delle gimnosperme tardo-paleozoiche.

Dopo una breve introduzione segue una aggiornata sintesi delle piante fossili finora rinvenute nell'area considerata. In particolare, vengono discusse le flore della Formazione di Collio in alta Val Trompia (Brescia), della Formazione di Tregiovo nell'alta Val di Non (Trento-Bolzano), nonché quelle sovrastanti, tardo-permiane, delle Arenarie rosse di Val Gardena, presenti ad est della Val d'Adige.

THE PRE-VERRUCANO LOMBARDO / PRE-VAL GARDENA FLORAS

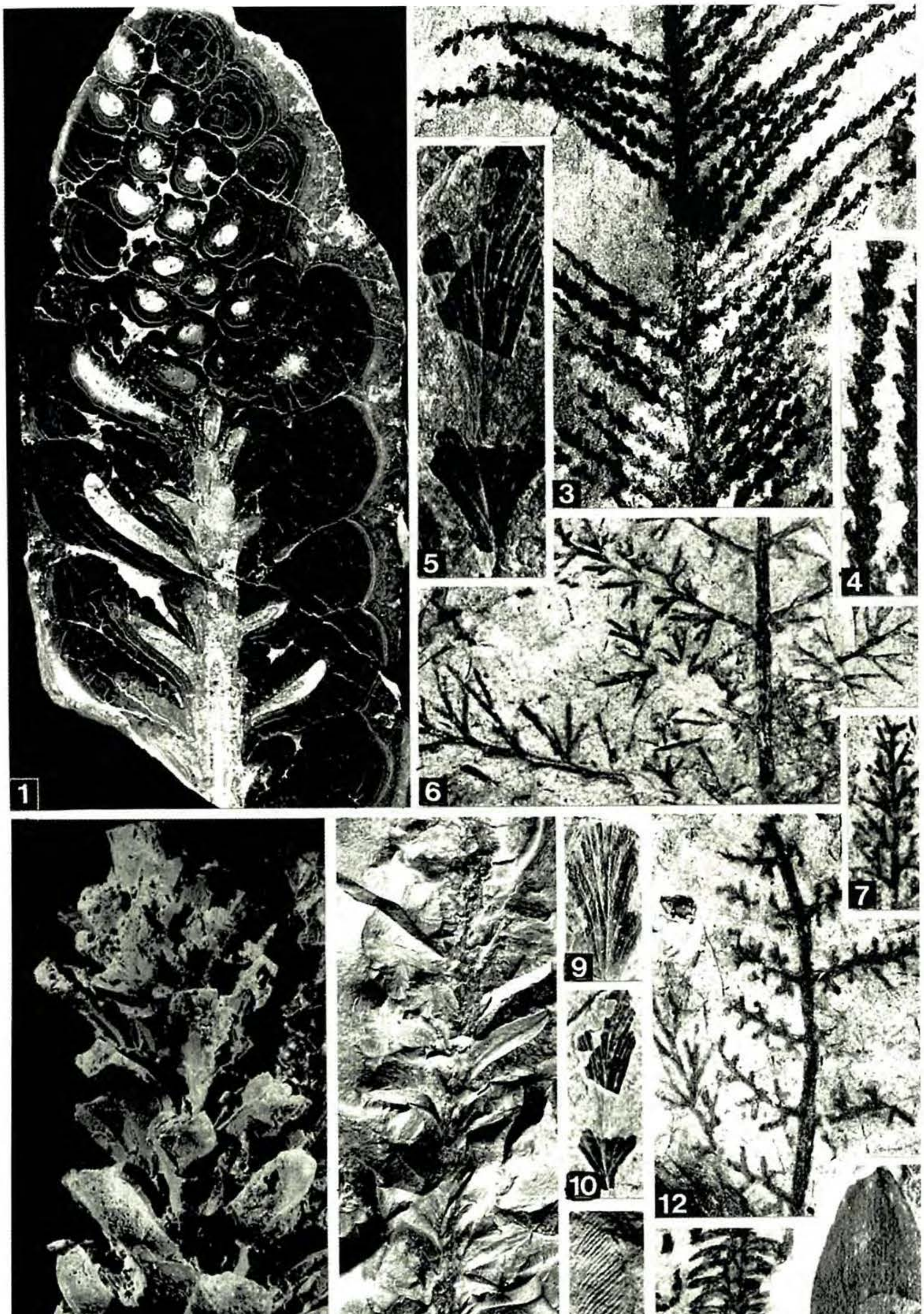
Plant fossils from the Collio and Tregiovo formations underlying the Verrucano Lombardo and Val Gardena formations were first described more than a century ago (*e.g.*, Geinitz, 1869). The age of these floras has been discussed repeatedly and age assessments varied from Late Carboniferous to "Middle" Permian. The most recent account on these megafloras was published by Remy & Remy (1978) who dated these floras as respectively "middle to higher Saxonian" and "higher Saxonian". In recent years a third flora was described from the Ponteranica Conglomerate in the Orobic Alps (Kerp *et al.*, 1996). None of these localities has yielded a really rich and diverse flora. Conifers are the dominant elements in all these three floras. However, unlike the situation in the Val Gardena flora (see below), precise identifications are strongly hampered by the lack of cuticles, which are of essential importance for the recognition of late Palaeozoic conifer taxa; morphologically very similar species of conifers can often only be distinguished on the basis of their epidermal characteristics.

The Collio flora

The flora of the Collio Formation in the upper Val Trompia consists according to Remy & Remy (1978) of six taxa and a number of unidentifiable conifer (and ginkgophyte?) remains: *Sphenopteris suessii* (Pl. I, Figs 6, 7), *S. kukukiana* (Pl. I, Fig.12), *S. patens*, *"Sphenopteris"* cf. *interrupte-pinnata*, *Hermitia* (al. *Walchia*) *geinitzii* (Pl. I, Figs 3, 4) and *Walchiostrobus* sp.

Two of these taxa are only known from the Collio Formation (*S. suessii*, *H. geinitzii*) whereas *S. kukukiana* and *S. patens* were originally described from the German Zechstein. The single specimen illustrated as *"Sphenopteris"* cf. *interrupte-pinnata* (Geinitz, 1869; Remy & Remy, 1978) is very fragmentary preserved; this taxon was originally described from the Permian Copper Sandstone of the Ural Mountains (Russia). None of the

[1] Lab. Palaeob. Palyn., Utrecht Univ., Budapestlaan 4, 3584 CD Utrecht, The Netherlands.
[2] Geol.-Paläont. Inst., Forschungsstelle f. Paläobotanik Westf. Wilh.-Univ., Hindemburgplatz 57, 48143 Münster, Germany.


1
2
3
4
5
6
7
8
9
10
11
12
13
14

sphenopterids is known from the classical Rotliegend. *Walchiostrobus* is a conifer cone originally described by Sordelli (1896) as *Curionia triumpilina* and assigned to *Walchiostrobus* by Florin (1940). Conifer foliage types are reminiscent of *Hermitia* (al. *Walchia*) *germanica* (Pl. I, 13), *H. gallica*, *Culmitzschia* (al. *Lebachia*) *laxifolia* and *Otovicia* (al. *Walchia*) *hypnoides*. These foliage types are normally found in the typical Rotliegend. However, forms similar (or identical) to the latter species are also known from the lower Upper Permian of the Arabian Peninsula. As already mentioned, these taxonomic assignments are only tentative because no cuticles are known.

The Tregiovo flora

According to Remy & Remy (1978), the flora of the Tregiovo Formation in the upper Val di Non, between the Bolzano and Trento provinces includes, apart from various conifer remains, *Lodevia* (al. *Callipteris*) cf. *nicklesii* (Pl. I, Figs 5, 9, 10) and *Lesleya* (al. *Taeniopteris*) *eckardtii* (Pl. I, Fig. 11). Of the first species, that was originally described from the Lower Permian of Lodève (Southern France), only a few incomplete pinnules have been found, whereas the second record refers to a single small fragment only; this latter taxon is a typical Zechstein element. More common are conifer remains. A variety of forms, ranging from very small-leaved types attributed to *Otovicia hypnoides* to large-leaved ones attributed to *Ullmannia frumentaria* (Pl. I, Fig. 8) has been recorded. Although also here identifications are still tentative due to the lack of cuticles, morphological similarities with these essentially Early respectively Late Permian species are striking. Other conifer taxa from the Tregiovo Formation have been compared with *Walchia piniformis*, "*Walchia*" *stricta* and *Quadrocladus*. Isolated large, broad, apparently non-decurrent leaves showing prominent parallel lines (stomatal rows?), previously assigned to *Lepeophyllum* or *Culmitzschia* (Remy & Remy, 1978) might well represent isolated *Ortiseia leonardii* leaves, well-known from the Val Gardena Formation (see below).

The Ponteranica flora

The Ponteranica Conglomerate near Gerola Alta in the western Orobic Alps has yielded a conifer species that was described as *Cassinisia orobica* (Kerp *et al.*, 1996). This conifer has very robust axes and with up to 2.5 cm long leaves. Most remarkable is their three-dimensional preservation in stromatolites (Pl. I, Fig. 1; Freytet *et al.*, 1996). Naturally formed casts are exact lifetime replicas of these Permian conifers (Pl. I, Fig. 2).

The age of the Collio and Tregiovo Formations

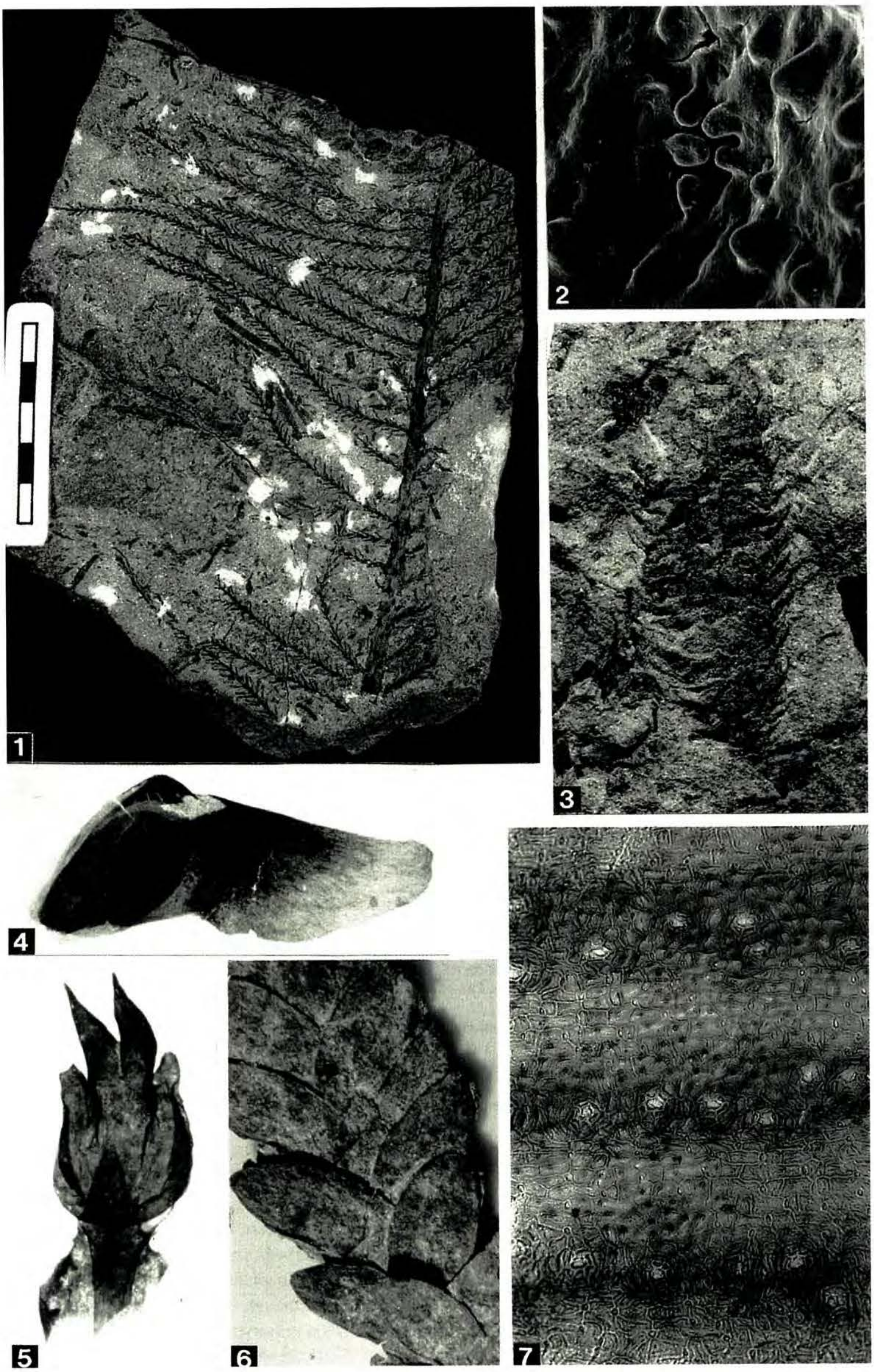
The age of the Collio and the presumably time-equivalent Tregiovo Formation has been discussed for more than a century. Initially these discussions were based exclusively on the megafloras, in later years palynological data have become available. Although both megafloras are rather poor in species and more material still should be studied, they both seem to include taxa which are so far only from the typical Zechstein. However, it should be noted that the ranges of taxa are still imperfectly known as most of the western and middle European Permian is either missing or unfossiliferous. Therefore, stratigraphical ranges of megaplant taxa in this particular time interval are very still poorly known. The most recent palynological data suggest a late Artinskian -?early Ufimian, respectively a Kungurian -Ufimian age for the Collio and the slightly younger Tregiovo Formation (Cassinis & Doubinger, 1991a, b; Barth & Mohr, 1994), which is in accordance with the ages estimated by Remy & Remy (1978) on the basis of the macrofloras. The palynological assemblages from the Tregiovo Formation seem to be younger than those from the marine Amanda Formation recognized in boreholes in the northern Adriatic Sea and probably corresponding to the *Neoschwagerina* (fusulinid) Zone (Sartorio & Rozza, 1991).

THE VAL GARDENA FLORA

Notably in the western Dolomites and in the Vicentinian Alps, grey interbeds in the Val Gardena Formation are sometimes rich in plant fragments of variable size and preservation. Although regularly reported since the second part of the 19th century, larger well-preserved plant fossils are rare. According to early identifications, the fossil as-

Plate I

1. *Cassinisia orobica*, polished section of a stromatolite showing a conifer in the centre. Pizzo Tre Signori, western Orobic Alps; Ponteranica Conglomerate. x 1.
2. *Cassinisia orobica*, natural siltstone cast. Pizzo Tre Signori, western Orobic Alps; Ponteranica Conglomerate. x 1.8.
3. *Hermitia* (al. *Walchia*) *geinitzii*. Monte Colombine; Collio Fm. x 1.
4. Detail of Fig. 3. x 2.
5. *Lodevia* (al. *Callipteris*) *nicklesii*. Exact locality unknown, between Trento and Bolzano; Tregiovo Fm. x 2.
6. *Sphenopteris suessii*. Monte Colombine; Collio Fm. x 1.
7. Idem. x 1.
8. *Ullmannia frumentaria*. ?Tregiovo; Tregiovo Fm. x 1.
9. *Lodevia* (al. *Callipteris*) *nicklesii*. Exact locality unknown, between Trento and Bolzano; Tregiovo Fm. x 1.
10. Same specimen as Fig. 5. x 1.
11. *Leslya* (al. *Taeniopteris*) *eckardtii*. ?Tregiovo; Tregiovo Fm. x 1.
12. *Sphenopteris kukukiana*. Monte Colombine; Collio Fm. x 1.
13. *Hermitia* (al. *Walchia*) cf. *germanica*. Monte Dasdana; Collio Fm. x 1.
14. Isolated conifer leaf, showing similarities with *Ortiseia leonardii* leaves. Exact locality unknown, between Trento and Bolzano; Tregiovo Fm. x 2.


1
2
3
4
5
6
7

semblages seemed to include coniferous foliage of both the Late Carboniferous-Early Permian genus *Walchia* and the Late Permian and Triassic genera *Ullmannia* and *Voltzia*. Based on foliage with preserved cuticle from the Western Dolomites, the only well-described element was the coniferous form-genus *Ortiseia* (Florin, 1964).

In contrast to the rare megafossils, bulk-macerated samples of siltstones that are rich in plant debris, may yield cuticle residues from which large numbers of small (usually <1 cm) but excellently preserved plant remains can be isolated (compare Pl. III) These cuticular fragments are dominated by conifer remains and include both vegetative and reproductive structures, such as isolated leaves, minute twigs, ovuliferous dwarf shoots, seeds and microsporophylls. In addition, one may note remains of pteridosperms. This material has been the basis for a detailed taxonomic study of the principal elements of the Val Gardena flora.

In gymnosperms the epidermal structure, as reflected in the plant cuticles, may vary according to family, genus and species, and hence proves to be of great potential in natural classification. Like in extant taxa, reproductive organs provide the most successful characters for delimiting natural genera and families. In absence of organic connection, cuticle analysis provides a reliable alternative for the necessary correlation of vegetative foliage and reproductive organs.

Through detailed comparative cuticle analysis it was possible to recognize three distinctive species within *Ortiseia* (Clement-Westerhof, 1984), viz. *O. leonardii* (Pl. II, Fig. 7) *O. visscheri* (Pl. II, Fig. 6) and *O. jonkeri* (Pl. II, Figs 1, 3; Pl. III, Figs 2, 5, 6, 8). The species could be described in terms of characteristics of vegetative structures as well as the organization of ovuliferous and polliniferous organs. The form-genus *Ortiseia* thus became "promoted" (Visscher *et al.*, 1986) to the status of a natural genus. It could be demonstrated that the ovules are characterized by the presence of a pollen/archegonial chamber, indicating the existence of zoidogamy among early conifers. The polliniferous organs yield distinctive pollen grains that correspond to the palynological form-genus *Nuskoisporites*. Size and wall organization indicates that the pollen grains represent prepollen, *i.e.* microspores of extinct zoidogamous seed plants that have not yet developed the capacity to produce a distal haustorial pollen tube (Poort *et al.*, 1997).The results of the work on *Ortiseia* formed a basic step towards a natural concept for the family Walchiaceae (Clement-Westerhof, 1984, 1988; Kerp *et al.*, 1990).

In the Val Gardena Formation, natural coniferous genera other than *Ortiseia*, include *Majonica* (*M. alpina*; Pl. II, Figs 4, 5; Pl. III, Fig. 3), *Dolomitia* (*D. cittertiae*) and *Pseudovoltzia* (*P. liebeana*; Pl. III, Fig. 7, *P. sjerpii*). These genera have been reconstructed with the aid of cuticle analysis on the basis of rich vegetatitive and fertile plant fragments (Clement-Westerhof, 1987). Particularly because of a common characteristic organization of ovuliferous dwarf-shoots, the three genera have been included in a separate family, the Majonicaceae. Polliniferous organs of *Majonica* yield pollen grains that belong to the palynological form-genus *Lueckisporites*.

As far as the coniferous remains are concerned, the detailed reconstruction of natural genera demonstrates that the composition of the flora of the Val Gardena Formation is different from what is assumed in earlier literature . The dominant conifers are *Ortiseia*, *Majonica*, *Dolomitia*, and *Pseudovoltzia*, rather than *Walchia*, *Ullmannia*, and *Voltzia*.

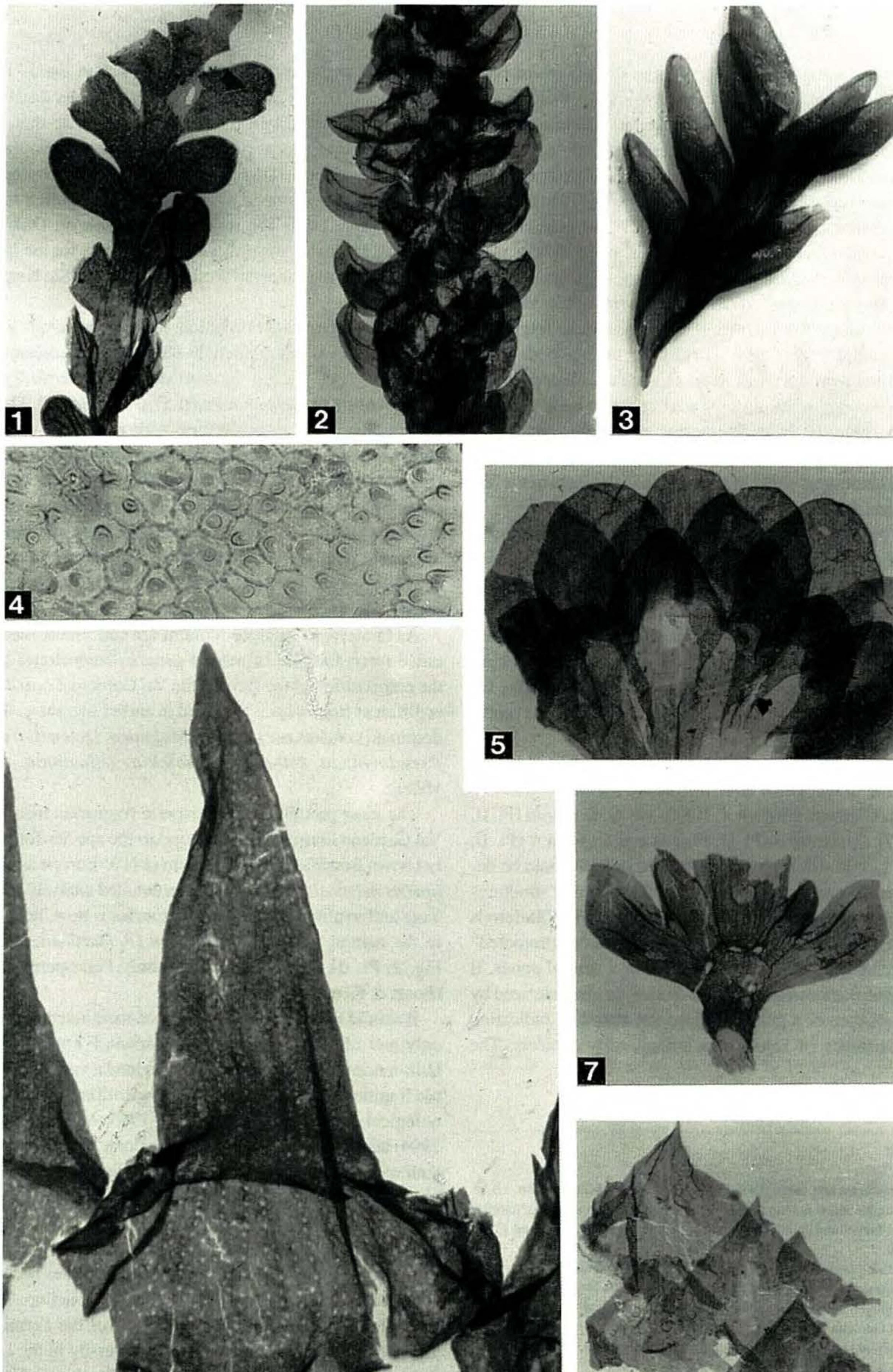
The most prominent pteridosperm fragments from the Val Gardena Formation correspond to the species formerly known from the Zechstein Basin of NW-Europe as *Callipteris martinsii*. On the basis of a detailed analysis of foliage and ovuliferous organs, this species is now included in the natural genus *Peltaspermum* (*P. martinsii*; Pl. II, Fig. 2; Pl. III. Figs 1, 4) of the family Peltaspermaceae (Poort & Kerp, 1990).

It should be realized that the above-mentioned taxa are only part of the flora of the Val Gardena Formation.The bulk-macerated plant material has yielded a variety of fertile fragments that have not yet been identified. Also palynological assemblages (*e.g.* Klaus, 1963; Massari *et al.*, 1994) testify to a much more diverse flora. Yet, because of their natural status, the plant taxa so far described from the Val Gardena Formation, are important links in the reconstruction of gymnosperm evolution.

It is now generally agreed that the age of the Val Gardena flora is Late Permian. All recognized species become extinct at or close to the Permian-Triassic junction. This extinction illustrates the profound effect of the Permian-Triassic biotic crisis on gymnosperm diversity in the Late Palaeozoic Euramerican floral realm (Visscher & Brugman, 1988; Visscher *et al.*, 1996; Poort *et al.*, 1997).

Plate II

1. *Ortiseia jonkeri*, lateral shoot system. Cortiana, Val Gardena Fm. x 0,65.
2. *Peltaspermum martinsii*, SEM outer leaf surface showing papillae and one stoma (compare Pl. III, 4). Butterloch, Val Gardena Fm. x 700.
3. *Ortiseia jonkeri*, polliniferous cone. Recoaro, Val Gardena Fm. x 2,2.
4. *Majonica alpina*, seed. Butterloch, Val Gardena Fm. x 4,4.
5. *Majonica alpina*, ovuliferous dwarf shoot, abaxial view. Butterloch, Val Gardena Fm. x 5,2.
6. *Ortiseia visscheri*, shoot ultimate order. Taubenleck, Val Gardena Fm. x 3,5.
7. *Ortiseia leonardii*, cuticle showing stomatal rows. Butterloch, Val Gardena Fm. x 130.



REFERENCES

BARTH S. & MOHR B.A.R., 1994. Palynostratigraphically determined age of the Tregiovo sedimentary complex in relation to radiometric emplacement ages of the Atesina volcanic complex (Permian, Southern Alps, N Italy). *N. Jb. Geol. Paläont. Abh.*, 192: 273-292.

CASSINIS G. & DOUBINGER J., 1991a. Artinskian to Ufimian palynomorph assemblages from the central Southern Alps, Italy, and their regional stratigraphic implications. *Contributions to Eurasian Geology, Intern. Congr. Permian System of the World, Perm, Russia.* Occ. Publ. ESRI, N.S., 8b: 9-18.

CASSINIS G. & DOUBINGER J., 1991 b. On the geological time of the typical Collio and Tregiovo continental beds in the Southalpine Permian (Italy), and some additional observations. *Atti Ticin. Sci. Terra*, Pavia, 34: 1-20.

CLEMENT-WESTERHOF J.A., 1984. Aspects of Permian palaeobotany and palynology. IV. The conifer *Ortiseia* Florin from the Val Gardena Formation of the Dolomites and the Vicentinian Alps (Italy) with special reference to a revised concept of the Walchiaceae (Göppert) Schimper. *Rev. Palaeobot. Palynol.*, 41: 51-166.

CLEMENT-WESTERHOF J.A., 1987. Aspects of Permian palaeobotany and palynology. VII. The Majonicaceae, a new family of Late Permian conifers. *Rev. Palaeobot. Palynol.*, 52: 375-402.

CLEMENT-WESTERHOF J.A., 1988. Morphology and phylogeny of Paleozoic conifers. In: Beck C.B. (ed.), *Origin and Evolution of Gymnosperms*. Columbia Univ. Press, New York: 298-337.

FLORIN R., 1940. Die Koniferen des Oberkarbons und des Unteren Perm. *Palaeontographica, B*, Stuttgart, 85: 729 S., Lief. 5.

FLORIN R., 1964. Über *Ortiseia leonardi* n.gen. et sp., eine Konifere aus den Grödener Schichten in Alto Adige (Südtirol). *Mem. Geopalaeont. Univ. Ferrara*, 1: 3-11.

FREYTET P., KERP H. & BROUTIN J., 1996. Permian freshwater stromatolites associated with the conifer shoots *Cassinisia orobica* Kerp *et al.* - a very peculiar type of fossilization. *Rev. Palaeobot. Palynol.*, 91: 85-105.

GEINITZ H.B., 1869. Über fossile Pflanzenreste aus der Dyas von Val Trompia. *N. Jb. Min. Geol. Paläontol.*, 1869: 457-461.

KERP J.H.F., POORT R.J., SWINKELS H.A.J.M. & VERWER R., 1990. Aspects of Permian palaeobotany and palynology. IX. Conifer-dominated Rotliegend floras from the Saar-Nahe Basin (? Late Carboniferous-Early Permian; SW-Germany) with special reference to the reproductive biology of early conifers. *Rev. Paleobot. Palynol.*, 62: 205-248.

KERP H., PENATI F., BRAMBILLA G., CLEMENT-WESTERHOF J.A. & VAN BERGEN P.F., 1996. Aspects of Permian palaeobotany and palynology. XVI. Three-dimensionally preserved stromatolite-incrusted conifers from the Permian of the western Orobic Alps (northern Italy). *Rev. Palaeobot. Palynol.*, 91: 63-84.

KLAUS W., 1963. Sporen aus dem südalpinen Perm. *Jb. Geol. Bundesanst.*, 106: 229-363.

MASSARI F., NERI C., PITTAU P., FONTANA D. & STEFANI C., 1994. Sedimentology, palynostratigraphy and sequence stratigraphy of a continental to shallow-marine rift-related succession: Upper Permian of the eastern Southern Alps (Italy). *Mem. Sci. Geol.*, Padova, 46: 119-243.

POORT R.J. & KERP J.H.F., 1990. Aspects of Permian palaeobotany and palynology. XI. On the recognition of true peltasperms in the Upper Permian of western and central Europe and a reclassification of species formerly included in *Peltaspermum* Harris. *Rev. Palaeobot. Palynol.*, 63: 197-225.

POORT R.J., CLEMENT-WESTERHOF J.A., LOOY C.V. & VISSCHER H., 1997. Aspects of Permian palaeobotany and palynology. XVII. Conifer extinction in Europe at the Permian-Triassic junction: Morphology, ultrastructure and geographic/stratigraphic distribution of *Nuskoisporites dulhuntyi* (prepollen of *Ortiseia*, Walchiaceae). *Rev. Palaeobot. Palynol.*, 97: 9-39.

REMY W. & REMY R., 1978. Die Flora des Perms im Trompia-Tal und die Grenze Saxon/Thüring in den Alpen. *Argum. Palaeobot.*, 5: 57-90.

SARTORIO D. & ROZZA R., 1991. The Permian of Amanda 1bis well (Northern Adriatic Sea). *Giorn. Geol.*, Ser. 3, 53: 187-196.

SORDELLI F., 1896. Studî sulla vegetazione di Lombardia durante i tempi geologici. Atti della Fondazione Scientifica Cagnola, Milano, 14: 298 pp.

VISSCHER H., BRINKHUIS H., DILCHER D.L., ELSIK W.C., ESHET Y., LOOY C.V., RAMPINO M.R. & TRAVERSE A., 1996. The terminal Paleozoic fungal event: evidence of terrestrial ecosystem destabilization and collapse. *Proc. Natl. Acad. Sci. USA*, 93: 2155-2158.

VISSCHER H. & BRUGMAN W.A., 1988. The Permian-Triassic boundary in the Southern Alps: a palynological approach. In: Cassinis G. (ed.), *Proc. Field Conf. on "Permian and Permian Triassic boundary in the South Alpine segment of the Western Tethys, and additional regional reports"*. IGCP Proj. No. 203. Mem. Soc. Geol. Ital., 34 (1986): 121-128.

VISSCHER H., KERP J.H.F. & CLEMENT-WESTERHOF J.A., 1986. Aspects of Permian palaeobotany and palynology. VI. Towards a flexible system of naming Palaeozoic conifers. *Acta Bot. Neerlandica*, 35: 87-99.

Plate III

1. *Peltaspermum martinsii*, foliage. Butterloch, Val Gardena Fm. x 6.
2. *Ortiseia jonkeri*, shoot ultimate order. Taubenleck, Val Gardena Fm. x 10.
3. *Majonica alpina*, shoot. Butterloch, Val Gardena Fm. x 3.
4. *Peltaspermum martinsii*, leaf cuticle. Butterloch, Val Gardena Fm. x 270.
5. *Ortiseia jonkeri*, ovuliferous dwarf shoot. Butterloch, Val Gardena Fm. x 9.
6. *Ortiseia jonkeri*, leaf main axis. Butterloch, Val Gardena Fm. x 10.
7. *Pseudovoltzia liebeana*, ovuliferous dwarf shoot, abaxial view. Butterloch, Val Gardena Fm. x 4.
8. *Ortiseia jonkeri*, microsporophyls. Butterloch, Val Gardena Fm. x 10.

THE BELLEROPHON-WERFEN BOUNDARY IN THE WESTERN DOLOMITES (ITALY) - PETROGRAPHICAL STUDIES AND A NEW INTERPRETATION

CLAUDIO BERETTA [1] and SERGIO RADRIZZANI [2]

Key words – Bellerophon-Werfen Boundary; Depositional Evolution; Dolomites; Italy.

Abstract – Analysis of some detailed sections at the transition between the Bellerophon and Werfen Fms. in the western Dolomites has made possible a new interpretation of the formational boundary. In particular the Tesero (Fiemme Valley) and Seres (Badia Valley) sections were chosen, being representative of proximal and distal palaeogeographical conditions respectively. The boundary is located at the base of the thick bed containing the first oolitic levels and overlying a thin black organic-rich shaly layer. The criteria enabling us to reach this new interpretation are:
– a progressive and continuous evolution of the petrographical and sedimentary characteristics of the microfacies in the thick bed;
– a sharp morphological break on the outcrops.
The different phases of the depositional evolution in the studied interval can be correlated on a regional scale; these have already been recorded but their boundaries are in part reinterpreted here both in terms of location and meaning.

Parole chiave – Limite Bellerophon-Werfen; Evoluzione deposizionale; Dolomiti; Italia.

Riassunto – Lo studio di dettaglio di alcune sezioni al passaggio tra le formazioni a Bellerophon e di Werfen nelle Dolomiti occidentali ha permesso di proporre una nuova interpretazione per il limite formazionale. In particolare sono state scelte le sezioni di Tesero (Val di Fiemme) e di Seres (Val Badia), rispettivamente rappresentative di condizioni paleogeografiche prossimali e distali. Il limite viene ubicato alla base del banco che contiene i primi livelli oolitici, in corrispondenza di un sottile livello pelitico nero e bituminoso. I criteri che permettono di arrivare a questa nuova interpretazione sono i seguenti:
– una progressiva e continua evoluzione dei caratteri petrografici e sedimentari all'interno del banco;
– un netto stacco morfologico in affioramento.
Le differenti fasi dell'evoluzione sedimentaria nell'intervallo esaminato sono correlabili a scala regionale; queste fasi sono già note in letteratura, ma i loro limiti vengono qui in parte reinterpretati, sia per posizione che per significato.

INTRODUCTION

This paper deals with a new interpretation of the Bellerophon-Werfen boundary through the study of two representative sections in the Dolomites area: the Tesero section (Fiemme Valley) and the Seres section (Badia Valley) (Beretta, 1999) (Fig. 1).

This boundary, in previous studies, was generally discussed together with the Permian-Triassic chronostratigraphical boundary; the two boundaries are in fact very close and for many years were even considered to coincide.

For the Dolomites area, before the fundamental paper by Bosellini (1964), this boundary was not defined so clearly (Leonardi, 1935) because of the presence of transitional beds between two distinct lithological complexes (Upper Permian Bellerophon Fm. and Triassic "Werfenian"). Accordi (1958) located the boundary at the base of the *Claraia* marls in the Bletterbach-Butterloch section, lying above limestones and marly limestones; this author used the terms "fiemmazza" and "badiota" facies to label the two main lithological types of the Bellerophon Fm. The *Claraia* beds were also considered the base of the Werfen also in the Trento area (Venzo, 1955, 1962; Panizza, 1963), whereas the underlying thick oolitic limestones (about 20m) were assigned to the Upper Permian Bellerophon Fm.

Bosellini (1964) first recorded a mainly oolitic interval (from 20cm to 7-8m) in several sections of the Dolomites. This interval, initially defined "transitional" and then as the "Tesero Oolitic Horizon" (TOH), was considered the base of the Triassic Werfen Fm. The TOH always begins with a 15cm to 1m thick oolitic bed; its absolute base, in some sections, consists of facies representing the initial

[1] Beretta C., Dipartimento per lo Studio del Territorio e delle sue Risorse, Università di Genova, Corso Europa 26, 16132 Genova, Italy.
[2] Radrizzani S., Via Europa 28, 20097 San Donato Milanese, Milano, Italy.

phase of oolite production, *i.e.* bio- and intraclastic limestones followed by "coated grain" limestones and then by the first small oolites.

For Assereto *et al.* (1973) the boundary was defined by a disconformity (or unconformity) at the base of the TOH. A hiatus was in fact recognised, based on biostratigraphical data: the *Comelicania* beds, present at the very top of the Bellerophon Fm. in the eastern Southern Alps, were correlated with the *Comelicania* beds of lower Dorashamian age found in the Transcaucasia, whereas the oolitic beds were considered of Lower Triassic age. Details on lithology at the boundary were not shown, but the Tesero section was included in the area where the TOH directly overlies the "fiemmazza" facies of the Bellerophon Fm.

Farabegoli & Viel (1982) considered the boundary as transgressive in the Trento-Val Sugana area. The TOH shows at the base, above bioturbated dolomitic mudstones of the Bellerophon Fm., thin black marls with volcanic pebbles and then fossiliferous mudstones interbedded with fine sandstones (80cm) before the appearance of an oolitic level (50cm).

Subsequently the criterion of locating the boundary at the base of the first oolitic bed was instead chosen for the Dolomites, and also for the Trento-Val Sugana area, by many authors, including: Ghetti & Neri (1983), Neri & Pasini (1985), Broglio Loriga *et al.* (1986), Noè (1987), Broglio Loriga *et al.* (1988) and Buggish & Noè (1988). All these authors define the transition between the two formations as very gradual.

More recently the Permian-Triassic succession was also interpreted in terms of sequence stratigraphy; the B-W boundary, *i.e.* the base of the first oolitic level, falls in the middle of a PAC (punctuated accretionary cycle) for Wignall & Hallam (1992), or in the middle of a transgressive system track bounded by erosional surfaces (the only remnant of a third-order cycle) for Noè & Buggish (1994). This boundary, for Massari *et al.* (1994), Massari & Neri (1997), Massari & Neri (in Cassinis *et al.*, 1998) and Neri (in Cassinis *et al.*, 1999), corresponds instead to the boundary between the two basal parasequences (CU cycles) of a third-order cycle.

The evolutionary facies trend and morphological characters led Cirilli *et al.* (1998) to locate the boundary, in the Seres section, at the base of a sequence in the middle of which the first oolites appear. Beretta (1999) confirmed the validity of this interpretation from other sections of the Dolomites as well, also using petrographical and geochemical data.

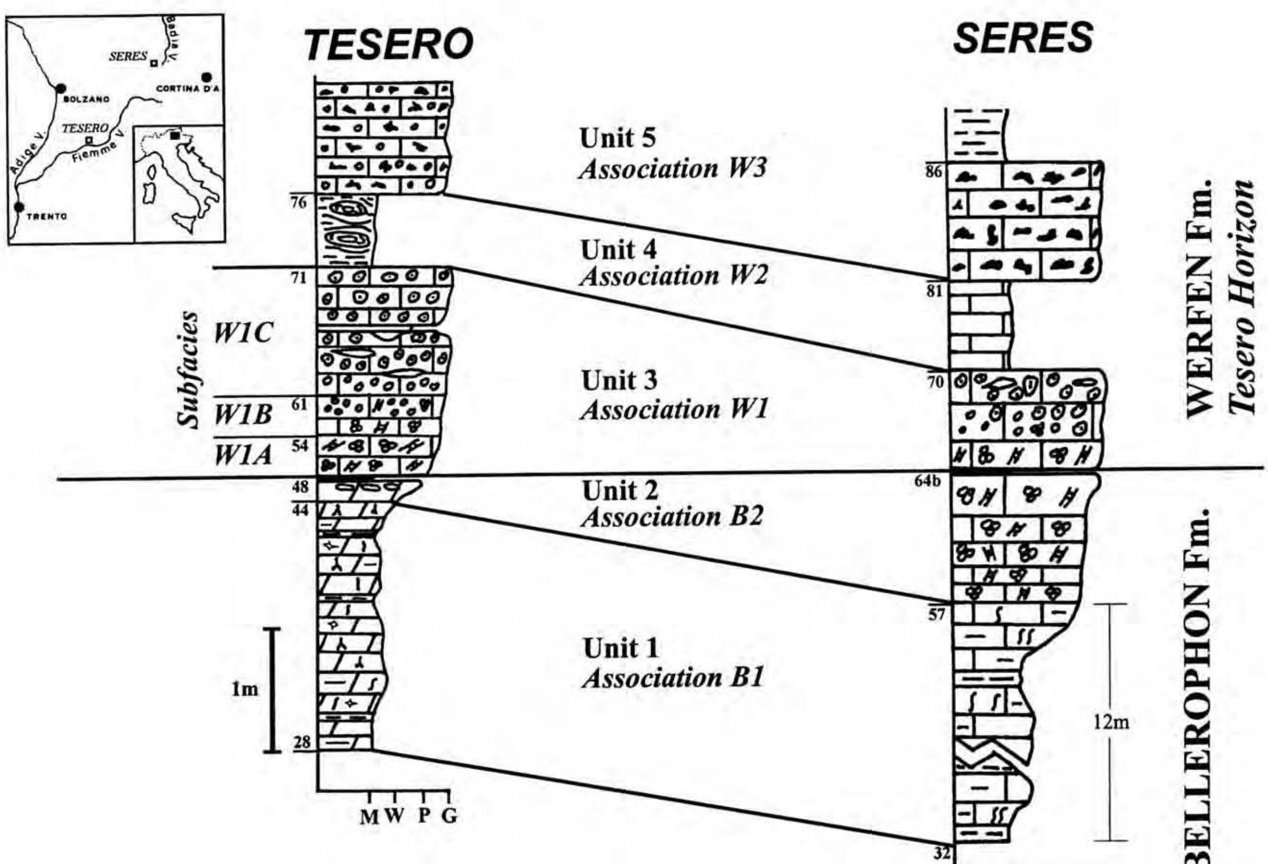


Fig. 1 – Correlation of the Tesero and the Seres sections. Lithologies clearly correspond to the description in the text.

LITHOSTRATIGRAPHY AND FACIES ASSOCIATIONS (FIG. 1)

Tesero Section: Lithostratigraphy

BELLEROPHON Fm.

Unit 1: Tes28 to Tes44 (2.40 m): The interval is dominated by grey-hazel dolomitic beds (2-10cm thick), marly and slightly vacuolar, with thin interlayers of bituminous clays. Bioturbations are frequent, with peculiar subvertical burrows, interpreted as root traces.

Unit 2: Tes45 to Tes48 (20cm): This consists of nodular, compact, grey-yellowish dolomitic beds, 2-5cm thick, showing a rapid transition to a marly black layer at the top; this level, rich in organic matter, is 7-10cm thick and more calcareous and nodular in the upper part.

WERFEN Fm.- TESERO HORIZON

The Tesero Horizon is about 8m thick here, but we will describe the lower 3m only. A sharp morphological boundary separates the TOH from the underlying unit.

Unit 3: Tes49 to Tes71 (2m): The base consists of dark grey, compact limestones in a 40cm thick bed, subdivided into six levels by stylolites or very thin pelites. Light grey limestones, in a 40cm layer resting on a wavy surface, overlie this interval. It is made up of five beds: the two lower ones are bioclastic whereas the upper ones (32cm) are oolitic; these beds are lenticular, separated by stylolites and with a clear low-angle lamination. The same characteristics are also present in the overlying grey oolitic limestones (60cm), with mudstone lenses and channels at the top. A 10cm thick packstone-wackestone separates these layers from a thick bed (50-80cm) of grey-hazel oolitic limestones at the top of the unit.

Unit 4: Tes72 to Tes76 (70cm to 1.1m): This unit shows different lithologies (and different thicknesses) with rapid lateral variations. Variously shaped microbialitic mud mounds are in fact laterally replaced by close interbeddings of grey-hazel mudstone (2-7cm thick) and marls (up to 3-4cm thick). Thin dark to yellowish marls and mudstones are sometimes interbedded in the mud mounds. Unit 4 is overlain by a very thick bed (up to 1m) of grey oolitic and/or intraclastic limestones, which forms the base of the middle and upper parts of the TOH.

Tesero Section: Petrographic-sedimentological analysis and facies associations

Detailed analysis has allowed us to identify different petrographical-sedimentary facies associations in the lithostratigraphic units.

BELLEROPHON Fm.

Association B1 (Tes32 to Tes44): Bioturbated mudstones and mudstone-wackestones prevail. The rare allochems are represented by bioclasts only (algae and bivalve fragments, gastropods and rare foraminifers). Thin microbialitic laminations are present in the upper part. Dolomite and calcite after anhydrite and gypsum pseudomorphs have been observed. The matrix consists of non-homogeneous dolomicrite, often pelletoidal.

Association B2 (Tes45 toTes48): This is mainly represented by wackestone-packstones characterised by an abundance of silt-sized peloids and algal fragments. Level Tes47 shows an increase in the terrigenous content and the presence of nodules of different lithologies: a) packstone-wackestones with echinoid and algae fragments, a high content of clay, organic matter, silty quartz grains, oxides and sulphides; this petrographic facies is also found in nodules at the top of the overlying black layer; b) unsorted detrital packstone-grainstone, with bioclasts (algae, bivalve and echinoid fragments, foraminifers), oomoldic oolites (Ø=100-200 microns), micritic oolites (with bioclastic nuclei or formed by micritic laminae only; Ø up to 500 microns); 10-15% of the constituents consist of terrigenous silty-sandy grains (quartz, muscovite and feldspar).

WERFEN Fm.- TESERO HORIZON

Association W1 - Three subfacies can be identified within this association.

Subfacies W1A (Tes49 to Tes54): This consists of packstones and rudstones, with packstone-grainstones at the top. Allochems are represented by bioclasts only (echinoid and algae fragments and foraminifers are more frequent). The rudstone levels are characterised by iso-oriented echinoid fragments, an increase of marly-clayey influx and a pseudo-flaser type structure. The bioclasts show, towards the top, a slight decrease in size and an increase in roundness; they are also more packed, better sorted and generally thinly coated. The matrix consists of non-homogeneous micrite. The echinoid fragments are always surrounded by a large syntaxial sparitic rim.

Subfacies W1B (Tes55 to Tes61): Interbedded packstones, grainstone-packstones and floatstones (0.5 to 2cm thick) prevail, although grainstones are rare. The bioclasts (mainly algae, then echinoid fragments, foraminifers, gastropods, bivalves and ostracods) prevail in the basal layers (up to Tes58) and in floatstones and detrital packstones; these are interbedded in the oolitic sediments, which gradually predominate from Tes58 onwards. At first oolites are oomoldic, small (Ø=100-200 microns) and surficial; numerous micritic peloids of similar size are present. Larger (Ø=0.4-0.5 mm) and complex oolites, spherical and mainly micritic, gradually replace the ever-present oomoldic ones towards the top. In the lower levels, as in the immediately underlying ones, bioclasts are thinly coated, more rounded and packed and better sorted. A few layers with finer bioclasts and marly clasts can also be noted. The matrix, where present, is micritic. The oomoldic oolites most probably derive from dissolution of aragonitic peloids and a further crystallisation of fine to medium equigranular sparite in the intragranular voids. These peloids originate from direct precipitation from oversaturated marine waters and characterise the initial phases of oolitic deposition. Three sparitic cementing generations can be observed here. The beds are subdivided into centimetre-thick layers by frequent and high amplitude columnar stylolites, mainly subparallel to the bedding surface. A second less evident stylolytic system overlaps the low-angle lamination. Similar characteristics can be noted in the overlying layers.

Subfacies W1C (Tes62 to Tes71): This is mainly composed of grainstones, with a few interbedded floatstones, mudstones and packstone-wackestones. Oolites are dominant among the allochems: grain-size (Ø from 0.5 to 1mm), complexity, proportion of aggregated and botryoidal forms, and sorting all increase towards the top. Micritic and oomoldic oolites and those with bioclastic/terrigenous nuclei are all present together; the former are no longer present at the top of the interval. Bioclasts are frequent in floatstones only, where a few irregular and millimetre-sized intraclasts (reworked oolitic grainstone) have also been observed. Some levels (Tes67 and Tes71) show a transition from oolitic grainstone at the base to oolitic and/or bioclastic floatstone, and to mudstone at the top. The micritic matrix, where present, is non-homogeneous.

Association W2 (Tes72 to Tes76): mudstones and mudstone-wackestones prevail. The few bioclasts are often transformed into microsparitic ghosts. Several strata show a microsparitic to finely sparitic, irregular, pervasive, anastomosing reticule, entrapping the pelletoidal and non-homogeneous micritic matrix. These characteristics are generally referred to the diagenesis of an original microbialitic/trombolitic texture (Bourque, 1997; Baud *et al.*, 1997).

Association W3 (Tes77 to Tes92): The basal part of the association only, where unsorted coarse grainstones and packstone-grainstones prevail, is described here. The allochems consist of bioclasts, small oomoldic oolites, large intraclasts and micritic algal peloids. The micritic matrix is mainly non-homogeneous or pelletoidal. Grainstones and packstone-grainstones show two sparitic cementing generations.

Seres section: Lithostratigraphy

BELLEROPHON Fm.

Unit 1: S32 to S57 (12m): This consists of interbedded grey-yellowish bioturbated marly limestones and marls. Bed thicknesses vary from 10-20cm to 60-70cm in both lithologies; the bedding shows irregular surfaces and nodular structures.

Unit 2: S58 to S64b (1.1m): This consists of compact grey-blackish limestones and is characterised by the disappearance of bioturbation. Bed thickness varies from 10-20cm in the lower part to 30cm towards the top. The top of the unit consists of a 3-5cm black organic-rich marly layer that marks the boundary with the overlying Werfen Fm.

WERFEN FORMATION - TESERO HORIZON (4.90m)

We will describe here only the lower 2.60m of the TOH.

Unit 3: S65 to S70 (85cm): The base consists of a 50-cm-thick bed, subdivided into at least six layers by low-amplitude stylolites; the first 20cm are made up of dark limestones, the upper 30cm of greyish oolitic limestones. Two other oolitic beds follow, separated by high-amplitude stylolites and with scattered micritic lenses.

Unit 4: S71 to S81 (75cm): This consists of fine light-grey limestones, in 8-10cm thick beds, resting on an undulating surface.

Unit 5: S82 to S86 (1m): This consists of compact greyish coarse limestones, in irregular or lenticular beds, 20 to 35cm thick. This unit is overlain by light-grey micritic limestones, in thick to very thick beds (25-35cm to 1m).

Seres section: Petrographical-sedimentological analysis and facies associations

BELLEROPHON Fm.

Association B1 (S32 to S57): Bioturbated wackestones and packstones prevail, mudstones are subordinate and grainstones are rare. Bioclasts are dominant (bivalves and ostracods, then algae and miliolids among others). Oncolites can be observed in some layers. Some grainstones and packstones show iso-oriented bioclasts. A bioclastic silty-arenitic fraction is also common and characterises the biocalcarenitic levels. The micritic matrix is more uniform in the mudstone layers than in the coarser ones. The grainstones are characterised by eogenetic meteoric-phreatic cements.

Association B2 (S58 to S64b): Bioclastic packstones and packstone-grainstones prevail; large algae fragments, highly diversified foraminifers and algal peloids are the more frequent allochems. Packstones are commonly characterised by iso-orientation of the bioclasts, pseudo-flaser textures and the constant presence of a bioarenitic fraction. Bioclasts show a strong diagenetic compaction. The black marly layer at the top has a high organic fraction that almost completely obliterates the compositional and textural characteristics, similar to those of the underlying levels. The micritic matrix is generally scarce and non-homogeneous.

WERFEN FORMATION - TESERO HORIZON

Association W1 (S65a to S70): The base is composed of bioclastic packstone-wackestones and packstone-grainstones (S65a and b) similar to those described for the upper part of the Ass. B2. The bioclasts are mainly represented by highly diversified foraminifers, algae fragments and algal peloids. Level S65c is a bioclastic grainstone with few oomoldic oolites; the grains are well rounded here, less sorted and thinly coated. The upper part of the association consists of oolitic grainstone; bioclasts (foraminifers and gastropods) are rare and present mainly in the lower layers. Oolites are at first small (Ø = 0.2-0.3mm), oomoldic and surficial, micritic or with bioclastic nuclei; they are well sorted and, upwards, are gradually larger (Ø from 0.4 to 0.8-1mm) and more complex, with the micritic and oomoldic types prevailing; at the top, aggregated ooids and botryoidal forms are frequent, together with a few bioclasts and large calcarenitic intraclasts.

Association W2 (S71 to S81): This consists of mudstones, with closed and narrow undulating laminae; very rare ostracods are the only skeletal grains. Irregular, elongated and oriented micritic intraclasts are observed in the wackestones, infilling isolated microchannels in the central part of the interval. The terrigenous content (up to 3%) is formed by quartz grains (Ø 0.2-0.3mm) and by mica lamellae (up to 10mm). The matrix is micritic, brown and homogeneous.

Association W3 (S82 to S86): This is represented by intraclastic grainstones only. The intraclasts are microsparitic and have a rounded irregular shape; they are often fractured, sometimes iso-oriented. Skeletal grains (gastropods and ostracods) are quite rare.

CORRELATIONS AND DEPOSITIONAL EVOLUTION

The depositional environment across the boundary between the Bellerophon Fm. and the Werfen Fm. (Tesero Horizon) developed through the phases described below (Fig. 1).

Regressive (low energy) phase: Ass. B1 deposited, at Seres, in a shallow-water, low-energy, sheltered environment. Conditions of lowest energy and restricted water circulation are reached at the top of the association. Some levels, showing eogenetic meteoric-phreatic cements, could indicate a near intertidal environment. This association, in the central-eastern Dolomites, may be defined as "Low Energy Badiota Facies"; it represents a widespread regressive episode, already documented (Broglio Loriga *et al.*, 1988). At Tesero the characteristics of Ass. B1 point to inter/supratidal, clearly hypersaline conditions, then to a shallower and more restricted environment in relation to the underlying sediments. On the basis of these characteristics, the Ass. B1 of the two sections can be correlated to a good extent.

Transgressive phase - Black Level - Basal Oolitic Bed

Transgression and Black Level: The Seres section shows, from the very base of Ass. B2, a gradual and constant increase in the energy level: a strong current regime dominates the shallow waters and subtidal environment. At the top theAss. B2 shows a black organic-rich marly level. At Tesero the "fiemmazza" facies of the Bellerophon Fm. ends with about 10cm of dolomites showing a facies of higher hydrodynamic energy. This interval has only recently been recorded by one of the authors (Beretta, 1999). A black organic-rich marly layer is present at the top of this section too. Ass. B2 therefore show a good degree of correlation in both the sections. The black layer is found in many sections of the area and can be considered synchronous on a regional scale. The abundance and size of woody remains of continental origin, the palynological content (Cirilli *et al.*, 1998) and frequent terrigenous clasts indicate maximum proximity at the top of Ass. B2. This datum fits well, at least at Seres, with the interpretation of Ass. B2 as a CU and shallowing-up cycle. The Black Level is chosen as the boundary between the Bellerophon and the Werfen Fms; furthermore it does not represent a discontinuity in the evolution of the petrographic-sedimentary microfacies.

Basal Oolitic Bed: The lower part of this thick bed (Ass. W1) is always formed by bioclastic layers with rounded and coated grains, peloids and rare small oolites at the top. The oolitic layers in a strict sense follow with a gradual evolution; towards the top, the ooids increase in size and complexity. A reverse grading trend in oolitic sediments has been recorded from bars (Persian Gulf; Loreau & Purser, 1973), and from prograding shoals (Bahamas; Bathurst, 1975). A comparison with these modern areas enables us to interpret the Basal Oolitic Bed as an elementary CU cycle. The environment varies from subtidal to intertidal with even higher hydrodynamic levels. At Seres the succession is rather "clean". At Tesero, frequent muddy and/or bioclastic interbeddings are instead present among the oolitic beds; furthermore the top oolitic layer is slightly different in relation to the underlying ones, with poorer sorting and lower hydrodynamic levels. However, the frequent lateral facies variations lead us however to hypothesise, for the whole Oolitic Bed, an environment in which various constituents accumulated; these elements derived from surrounding areas of oolitic and/or bioclastic production (bars, dunes, less restricted platforms) in diverse and differentiated sedimentary conditions. This Bed shows a regional distribution, with thickness decreasing eastwards: 2m at Tesero (50cm of the "non-oolitic" lower part) and 85cm at Seres (20cm "non-oolitic"). This bed is considered to be a record of a very rapid transgression which lasted a few thousand years only and, as a consequence, was synchronous throughout the area.

Mudstones (low energy) and Microbasaltic phase: The basal oolitic phase was followed by a period of low hydrodynamism over the whole Dolomites; microbialitic or stromatolitic structures are in some places associated with this phase (Ass. W2). At Tesero intertidal microbialitic bodies are interbedded with mudstones and pelitic layers, typical of tidal ponds. The transition between Ass. W1 and Ass. W2 is sharp, but at Tesero a depositional continuity seems to be present. This phase can be considered synchronous on a regional scale too.

Deepening phase – Storm Facies: An accurate analysis of this interval is beyond the scope of this study; we can simply note that it consists of sediments typical of muddy bottoms (below the fair-weather wave-base) with interbeddings of oolitic layers (also intra- and bioclastic); the latter do not show the typical reverse grading of the Basal Oolitic Bed, but are totally unsorted; this is interpreted as being due to basinwards storm sedimentation.

CONCLUSIONS AND INTERPRETATION OF THE FORMATIONAL BOUNDARY

The Basal Oolitic Bed, over the whole area of the Dolomites, shows a continuous evolution of the petrographical-sedimentary characteristics; this evolution, in our opinion, does not make it possible to locate formational or sequence boundaries inside the Bed. This event, if compared with present-day depositional areas, may actually represent an interval of a few thousand years.

For all these reasons, we consider it more appropriate to locate the Bellerophon-Werfen formational boundary at the base of the Basal Oolitic Bed.

If the said time-span is correct, the meaning of bio- and chronostratigraphical events in this interval should also be reconsidered, as the resolution of these dating methods is clearly lower.

This Bed, moreover, is part of an evolutionary trend that begins in the upper Bellerophon Fm. and continues in the Werfen Fm. without evident depositional discontinuities. This interpretation is in contrast with the more traditional location of the formational boundary and the more recent sequence stratigraphy interpretations (see Introduction). We can instead confirm that the interpretation proposed by Cirilli *et al.* (1998) for the Seres section is valid on a regional scale. Further confirmation can be drawn from other sections also; their description, with detailed petrographical (cathodoluminescence, SEM-EDS analyses), biostratigraphical and isotopic geochemistry data, will be the subject of a paper currently in preparation.

REFERENCES

ACCORDI B., 1958. Contributo alla conoscenza del Permiano medio-superiore della zona di Redagno (Bolzano). *Annali Univ. Ferrara*, 3 (2): 37-47.

ASSERETO R., BOSELLINI A., FANTINI SESTINI N. & SWEET W.C., 1973. The Permian-Triassic boundary in the Southern Alps (Italy). In: Logan A. & Hill L.V.(eds), *The Permian and Triassic Systems and their mutual boundary.* Can. Soc. Petroleum Geol., Mem. 2: 176-199.

BATHURST R.G.C., 1975. *Carbonate sediments and their diagenesis.* Elsevier: 658 pp.

BAUD A., CIRILLI S. & MARCOUX J., 1997. Biotic response to mass extinction: the lowermost Triassic microbialites. Ancient stromatolites and microbialites - Part XIII. *Facies*, Erlangen, 36: 238-242.

BERETTA C., 1999. Stratigrafia (bio- e lito), correlazioni stratigrafiche, ricostruzione paleoambientale e paleogeografica delle formazioni al passaggio Permo-Trias nell'area dolomitica. *Tesi di Dottorato, Univ. Genova.*

BOSELLINI A., 1964. Stratigrafia, petrografia e sedimentologia delle facies carbonatiche al limite Permiano-Trias nelle Dolomiti Occidentali. *Mem. Mus. St. Nat. Venezia Trid.*, 15 (2): 59-110.

BOURQUE P.A., 1997. Finely cristalline carbonate mounds: cryptic communities, petrogenesis and ecological eonation. Carbonate mud mounds and biogenic mounds, Part XVI. *Facies*, Erlangen, 36: 250-253.

BROGLIO LORIGA C., FONTANA D., MASSARI F., NERI C., PASINI M. & POSENATO R., 1986. The Upper Permian sequence and the P/T boundary in the Sass de Putia Mt. (Dolomites) In: Italian IGCP 203 Group (ed.), *Permian and Permian-Triassic boundary in the South Alpine segment of the Western Tethys. Field Guide-Book*, S.G.I. & IGCP Proj. 203, July 1986: 79-99.

BROGLIO LORIGA C., NERI C., PASINI M. & POSENATO R., 1988. Marine fossil assemblages from Upper Permian to Lowermost Triassic in the Western Dolomites (Italy). In: Cassinis G. (ed.), *Proc. Field Conf. on: Permian and Permian-Triassic boundary in the South-Alpine segment of the Western tethys, and additional regional reports. Brescia, 4-12 July 1986.* Mem. Soc. Geol. Ital., 34 (1986): 5-44.

BUGGISCH W. & NOÈ S., 1988. Upper Permian and Permian-Triassic boundary of the Carnia (Bellerophon Formation, Tesero Horizon, Northern Italy). In: Cassinis G. (ed.), *Proc. Field Conf. on: Permian and Permian-Triassic boundary in the South-Alpine segment of the Western tethys, and additional regional reports. Brescia, 4-12 July 1986.* Mem. Soc. Geol. Ital., 34 (1986): 91-106.

CASSINIS G., AVANZINI M., CORTESOGNO L., DALLAGIOVANNA G., DI STEFANO P., GAGGERO L., GULLO M., MASSARI F., NERI C., RONCHI A., SENO S., VANOSSI M. & VENTURINI C., 1998. Synthetic Upper Palaeozoic correlation charts of selected Italian areas. *Atti Ticin. Sci. Terra*, Pavia, 40: 65-120.

CASSINIS G., CORTESOGNO L., GAGGERO L., MASSARI F., NERI C., NICOSIA U. & PITTAU P. (Coordinators), 1999. *Stratigraphy and facies of the Permian deposits between Eastern Lombardy and the Western Dolomites - Field Trip Guidebook.* The Continental Permian, Intern. Congr., 15-25 September 1999, Brescia. Earth Sci. Dept., Pavia University, Pavia: 157 pp.

CIRILLI S., PIRINI RADRIZZANI C., PONTON M. & RADRIZZANI S., 1998. Stratigraphical and palaeoenvironmental analysis of the Permian-Triassic transition in the Badia Valley (Southern Alps, Italy). *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 138: 85-113.

FARABEGOLI E. & VIEL G., 1982. Litostratigrafia della Formazione di Werfen (Trias inf.) delle Dolomiti occidentali. *L'industria mineraria*, 6: 3-14.

GHETTI S. & NERI C., 1983. La Formazione di Werfen (Trias inferiore) della Valsugana (Trento). *Studi Trentini Sc. Nat. (Acta Geol.)*, Trento, 60: 135-164.

LEONARDI P., 1935. Il Trias inferiore delle Venezie. *Mem. Ist. Geol. R. Univ. Padova*, 11: 136 pp.

LOREAU J.P. & PURSER B.H., 1973. Distribution and ultrastructure of Holocene ooids in the Persian Gulf. In: Purser B.H. (ed.), *The Persian Gulf Holocene carbonate sedimentation and diagenesis in a shallow epicontinental sea.* Springer Verlag: 279-328.

MASSARI F. & NERI C., 1997. The infill of a supradetachment (?) basin. The continental to shallow-marine Upper Permian succession of Dolomites and Carnia (Italy). *Sediment. Geol.*, 110: 181-221.

MASSARI F., NERI C., PITTAU P., FONTANA D. & STEFANI D., 1994. Sedimentology, palynostratigraphy and sequence stratigraphy of a continental to shallow-marine rift-related succession: Upper Permian of the Eastern Southern Alps (Italy). *Mem. Sci. Geol.*, Padova, 46: 119-243.

NERI C. & PASINI M., 1985. A mixed fauna at the Permian-Triassic boundary - Tesero section, Western Dolomites (Italy). *Boll. Soc. Paleont. Ital.*, 23 (1): 113-117.

NOÈ S., 1987. Facies and paleogeography of the marine Upper Permian and of the Permian-Triassic boundary in the Southern Alps (Bellerophon Formation, Tesero Horizon). *Facies*, Erlangen, 16: 89-142.

NOÈ S. & BUGGISCH W., 1994. Sequence stratigraphy in Late Permian and lowest Triassic of the Southern Alps (Dolomites, Northern Italy) with special regards to the Permian/Triassic Boundary. *J. Geol* ., 137 (2): 297-318.

PANIZZA M., 1963. Sezione stratigrafica permo-werfeniana della "Terra Rossa" (Monte Marzola, Trento). *Studi Trentini Sc. Nat. (Acta Geol.)*, Trento, 40 (3): 329-361.

VENZO G.A., 1955. Il Permiano superiore nei dintorni di Egna (A. Adige) e le sue dolomie calcaree a tessitura oolitica. *Mem. Mus. St. Nat. Venezia Trid.*, 10 (3): 1-14.

VENZO G.A, 1962. Geologia della regione dalla confluenza Val di Cembra-Val d'Adige all'altipiano di Lavazè, Trentino-Alto Adige. *Mem. Mus. St. Nat. Venezia Trid.*, 14 (1): 7-228.

WIGNALL P.B. & HALLAM A., 1992. Anoxia as a cause of the Permian/Triassic mass extintion: facies evidences from northern Italy and the Western United States. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 93 (1/2): 21-46.

THE FUNES/VILLNÖSS BASIN: AN EXAMPLE OF EARLY PERMIAN TECTONICS, MAGMATISM AND SEDIMENTATION IN THE EASTERN SOUTHERN ALPS (NE ITALY)

LUCA BENCIOLINI [1], M. ELIANA POLI [1], DARIO VISONÀ [2] and ADRIANO ZANFERRARI [1]

Key words – Eastern Southern Alps; Permian; Athesian Volcanic District.

Abstract – The Funes Basin is an intermontane basin located in the northern Dolomites. At present, because of Neoalpine compressional tectonics, it is exposed for 2 km in a NE-SW direction and for about 3 km in an E-W direction. The basin is filled by up to 500 m thickness of andesitic lavas, which roughly thin eastwards and are replaced by up to 200 m of pyroclastic – mainly agglomerate – deposits. Stratigraphical, sedimentological and tectonic data indicate that the evolution of the Funes Basin was controlled by normal faults. No evidence of transcurrent tectonics was observed. An Early Permian age for the Funes Basin is suggested by the presence of lenses of Ponte Gardena Conglomerate within andesitic lavas and agglomerates, and by the calcalkaline cogenetic nature of the andesites of Funes and the Permian volcanics of the neighbouring Athesian Volcanic District.

Parole chiave – Alpi Meridionali orientali; Permiano; Distretto Vulcanico Atesino.

Riassunto – Il bacino di Funes è un bacino intramontano affiorante nella porzione settentrionale delle Dolomiti. Attualmente, a causa dell'intensa tettonica compressiva neoalpina, affiora solo per circa 2 km in direzione NE-SW e per circa 3 km in direzione E-W. Il bacino è riempito da lave andesitiche per uno spessore massimo di 500 m. Nella porzione orientale del bacino le lave sono rapidamente sostituite da potenti depositi di agglomerati cui si intercalano depositi alluvionali (per uno spessore massimo di circa 300 m). I dati sinora raccolti indicano che l'evoluzione del bacino di Funes è stata guidata da faglie normali; nessuna evidenza di tettonica trascorrente è stata sinora osservata. La presenza di lenti di Conglomerato di Ponte Gardena sia nelle lave che nei depositi piroclastici e l'affinità compositiva fra le andesiti di Funes e le vulcaniti del Distretto Vulcanico Atesino, suggeriscono che il bacino di Funes si sia evoluto durante il Permiano inferiore.

INTRODUCTION

During Late Carboniferous and Early Permian times, the central-eastern Southern Alps were the centre of intense volcanic activity linked to the formation of a series of intermontane basins and cauldrons (Massari, 1988; Cassinis *et al.*, 1997 and refs therein). The geometry, stratigraphy and evolution of such basins are important tools in deciphering the Late Paleozoic tectonic setting of the eastern Southern Alps. Up to now two contrasting scenarios have been proposed: i) a Late Variscan dextral transtensional regime (*e.g.* Cassinis & Perotti, 1994); and ii) opening of the Mesozoic Tethys (*e.g.* Selli, 1998).

The Funes Valley, located on the left side of the Isarco/Eisack river near Chiusa/Klausen, provides a good opportunity of understanding the structural relationships between the basal volcanic sequence of the " Athesian Volcanic District" (AVD), its coeval terrigenous volcaniclastic cover and the underlying Variscan metamorphic basement.

GEOLOGICAL SETTING

The Funes Valley is located in the westernmost part of the eastern Southern Alps (Fig.1), at the northern margin of the "Dolomitic sinclinorium" (Doglioni, 1987). The valley is located in the footwall of a Neogene north-vergent backthrust system (Val di Funes and Passo delle Erbe backthrusts according to Doglioni, 1987, and Ring & Richter, 1994).

This valley cross-cuts the Variscan metamorphic basement and its basal terrigenous and volcanic cover of Late Carboniferous to Permian age, showing their original structural and stratigraphical relationships. In the study area, the stratigraphic succession starts with the Variscan metamorphic rocks consisting of prevailing metapelitic and metapsammitic rocks of Early Paleozoic age (Bressanone Phyllite, Val Digon Fm. and Eores Quartzite), with interbedded acidic (Comelico Porfiroids, Caradocian) and basic (Gudon Fm., Early Silurian?) metavolcanic layers (Poli *et al.*, 1996).

[1] Dipartimento di Georisorse e Territorio, Università di Udine, via Cotonificio 114, I-33100 Udine, Italy.
[2] Dipartimento di Mineralogia e Petrologia, Università di Padova, Corso Garibaldi 37, I-35137 Padova, Italy.

The metamorphic thermal peak is Visean in age (350 Ma; Del Moro *et al.*, 1980), and white mica cooling ages suggest a date of approx. 320 Ma for cooling below 350°C (Hammerschmidt & Stöckhert, 1987; Meli & Klötzli, 1997).

In the central-eastern Southern Alps, the deposition of clastic continental sequences of the "basal conglomerates" (Upper Carboniferous-Lower Permian) testifies the uplift and the erosion of the greenschist-facies Variscan basement as from the Late Carboniferous at least (Krainer, 1989).

During the Early Permian the magmatic activity began; the intrusion of the Bressanone Granodiorite (282 Ma±14; Del Moro & Visonà, 1988) and of coeval diorites (Luson, Chiusa) was followed by the deposition of the AVD sequence (D'Amico & Del Moro, 1988; Barth *et al.*, 1994; Di Battistini *et al.*, 1989; Rottura *et al.*, 1998). The deposition of the Ponte Gardena Conglomerate preceded and/or accompanied the AVD emplacement. Finally, the deposition of the Val Gardena Sandstone in Tatarian times (Massari *et al.*, 1994) sealed both the volcanics and the effects of the tectonism of Early Permian age.

THE FUNES BASIN

A geological sketch-map of the study area is shown in Fig. 2, while the tectonostratigraphic relationships are summarised in the sections of Fig. 3.

Abrupt lateral variations in the stratigraphic succession reflect intense tectonic activity during the deposition of the volcanosedimentary sequence, which reaches a maximum thickness of 500 m. The deepest portion of the volcanic sequence crops out in the Mittermühl locality where, however, Quaternary cover hides the underlying metamorphic basement. Here, andesite block-lavas, altered by hydrothermal fluids and intruded by basaltic-andesite dykes, crop out. In contrast, on Hauben/Mt. Cappello, at the top of the series, the andesite lavas have an amygdaloidal pyroxene-phyric texture. The irregularly-shaped elongated amygdales, usually filled with chalcedony, testify to both the magma high vapour-phase content of the magma, and the intensity of the late-stage magmatic activity.

Thin, discontinuous layers of quartz-rich, biotite-bearing tuffs with rhyodacitic lapilli are interbedded in the andesite lavas. Near Tiso/Teis, tuffs directly overlie the metamorphic basement, here strongly deformed and intruded by sets of dykes.

Andesites and basaltic-andesite dykes always intrude the andesite lavas. Petrographical and geochemical analyses on andesite dykes reveal their low- to high-K orogenic andesite nature (Table I and Fig. 4). The similarity with the neighbouring Chiusa epiplutonic diorite is also demonstrated. The same composition was obtained for the lava flows and block-lavas, as already found for all the Permian lavas of the AVD (Rottura *et al.*, 1998).

The andesite lavas reduce in thickness eastwards where they are replaced and covered by up to 200 m thick agglomerates and breccias. Along the northern margin of the basin, agglomerates and breccias directly overlie the metamorphic basement.

Agglomerates are chaotic and heterometric with clasts of prevailing andesitic composition, but clasts of rhyolites or rhyodacites as well as the underlying metamorphic basement can be locally found. Graded and cross-bedded metre-scale quartz-rich lenses of tuffaceous arenites or microrudites are sometimes present. Locally some reddish clay lenses were found. Bodies of

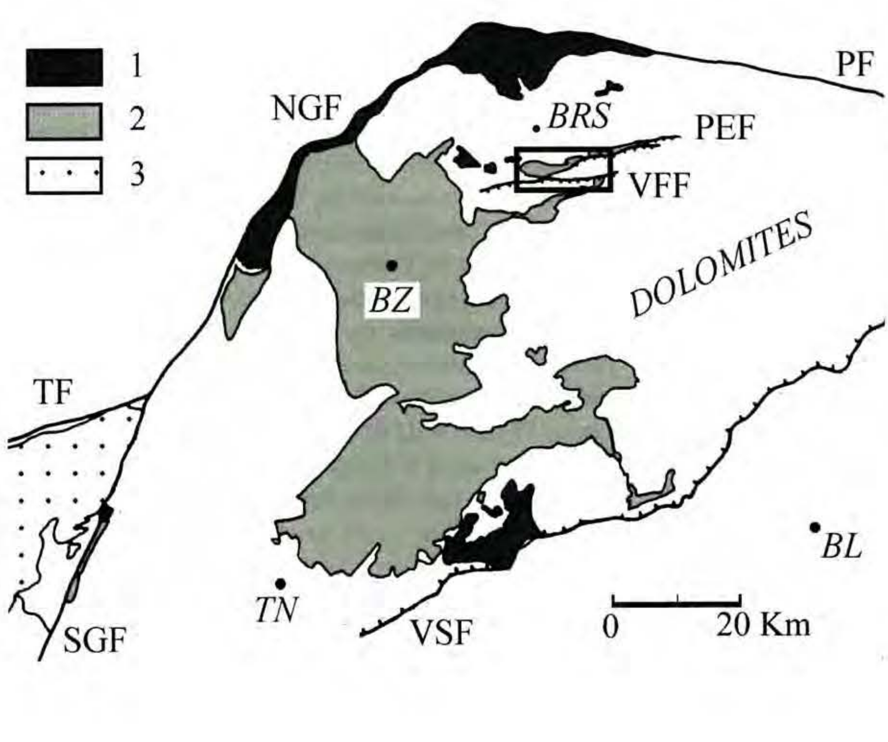


Fig. 1 – Location of the study area (rectangle) in the eastern Southern Alps. Distribution of the volcanic and plutonic rocks is shown. 1) Permian plutonics; 2) Permian volcanics of Athesian Volcanic District (AVD); 3) Oligocene Adamello pluton; NGF: North Giudicarie Fault; PEF: Passo delle Erbe Fault; PF: Pusteria Fault; SGF: South Giudicarie Fault; TF: Tonale Fault; VFF: Val di Funes Fault; VSF: Valsugana Fault. *BL*: Belluno; *BRS*: Bressanone/Brixen; *BZ*: Bolzano/Bozen; *TN*: Trento.

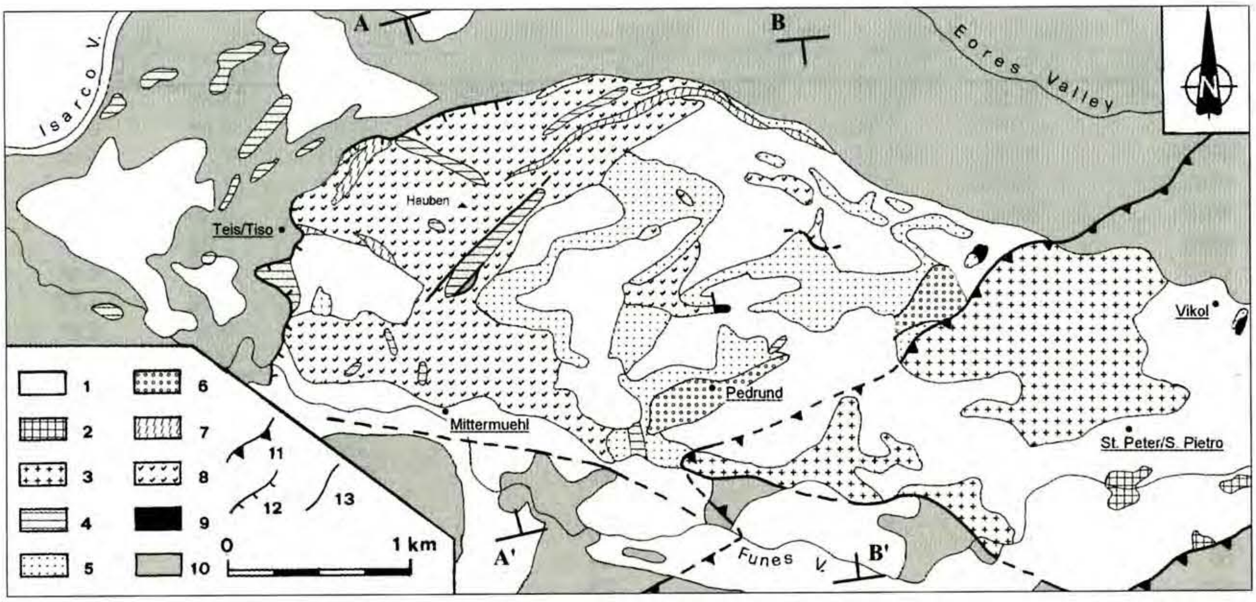


Fig. 2 – Geological sketch-map of the study area (location in Fig. 1). 1) Quaternary cover; 2) Val Gardena Sandstone; 3) rhyolites and rhyodacites; 4) andesitic to basaltic-andesitic dykes; 5) agglomerates; 6) Pedrund unit; 7) tuffs; 8) andesitic lavas; 9) Ponte Gardena Conglomerate; 10) metamorphic basement; 11) Neogene thrust; 12) Permian normal fault; 13) fault. A-A' and B-B': traces of geological sections in Fig. 3.

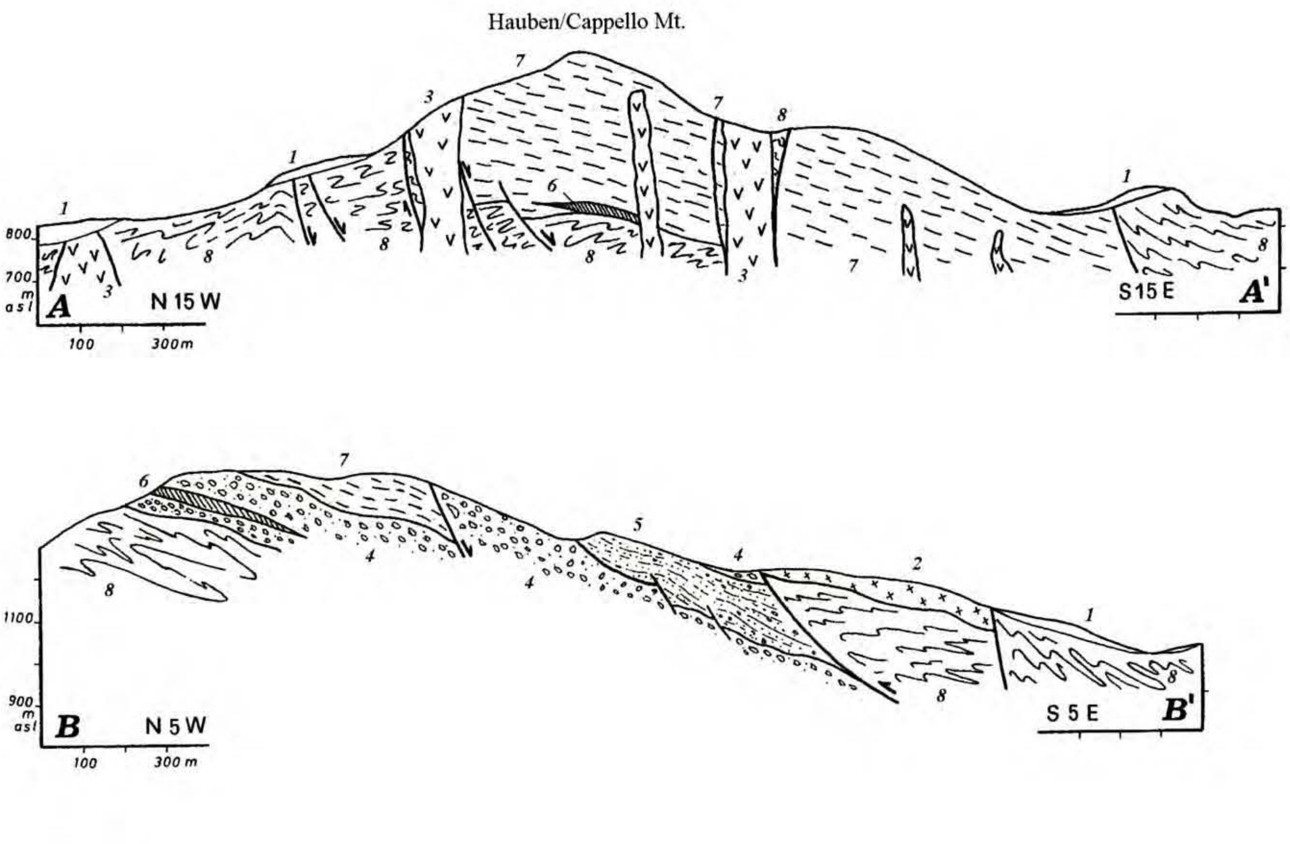


Fig. 3 – Geological cross-sections (*location in Fig. 2*). Legend: 1) Quaternary cover; 2) rhyolites and rhyodacites; 3) andesitic to basaltic-andesitic dykes; 4) agglomerates; 5) Pedrund unit; 6) tuffs; 7) andesitic lavas; 8) metamorphic basement.

Sample	TPZ6	TPZ19	TPZ30	TPZ48	TPZ53	TPZ63	TPZ54	86-4
Rock type	L 2	L 2	L 1	D 2	L 1	L 2	D 2	D 1
SiO2 (wt%)	55.45	55.76	56.69	55.41	56.36	53.70	53.38	56.91
TiO2	0.74	0.80	0.93	0.80	0.93	0.80	0.94	0.71
Al2O3	15.18	17.11	17.02	16.73	17.03	17.33	17.05	16.34
Fe2O3*	8.04	7.35	7.29	7.64	7.33	7.78	7.75	7.49
MnO	0.13	0.13	0.16	0.14	0.10	0.16	0.16	0.13
MgO	7.20	4.12	3.91	4.96	4.25	5.44	5.32	4.47
CaO	9.23	9.46	7.90	8.59	7.84	9.16	9.87	6.94
Na2O	1.68	1.61	1.90	1.67	1.94	1.74	1.52	1.73
K2O	0.45	0.63	2.30	0.48	2.20	0.35	0.37	2.21
P2O5	0.13	0.14	0.19	0.17	0.19	0.15	0.20	0.11
Total	98.23	97.11	98.29	96.59	98.17	96.61	96.56	97.04
LOI	1.74	2.90	1.61	3.37	1.73	3.79	3.41	3.11
Mg #	63.94	52.61	51.51	56.25	53.45	58.07	57.62	54.17
Cr (ppm)	640	248	220	206	222	300	234	277
Ni	80	27	45	34	45	32	28	18
Co	30	21	19	21	23	25	24	43
V	172	132	146	156	153	179	165	179
Cu	24	19	16	19	19	21	18	20
Pb	13	15	16	13	14	11	14	14
Zn	85	85	82	158	86	90	92	91
Rb	19	11	95	13	99	10	11	96
Ba	311	369	403	462	355	247	304	406
Sr	482	1387	312	839	311	775	935	199
Ta	0.76	0.83	0.97	0.82	0.92	0.85	0.92	0.98
Nb	9.3	9.9	28.7	10.0	11.8	10.3	11.8	8.9
Hf	3.87	4.22	4.32	4.00	3.82	3.74	4.02	3.47
Zr	148	160	172	158	171	149	172	134
Y	24	25	27	25	25	25	26	24
Th	8.94	9.73	10.1	10.4	10.3	9.32	9.42	9.00
U	1.73	1.89	2.04	1.85	1.9	1.66	1.81	1.85

Table I – Major and trace element contents for lavas (L) and dykes (D) of andesite (1) and basaltic andesite (2) composition in the study area.

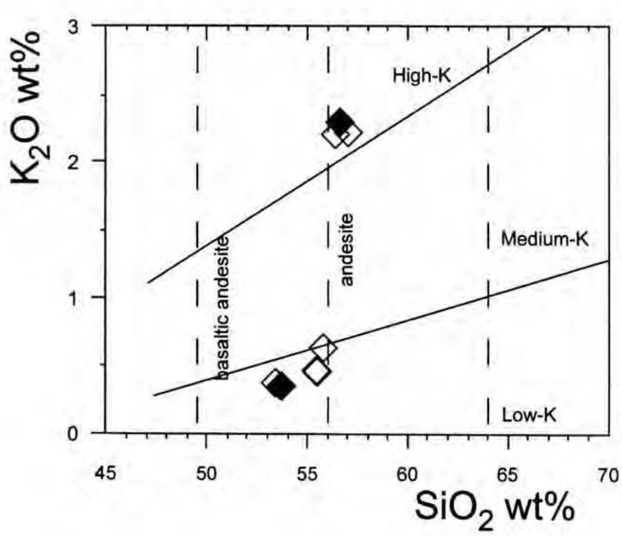


Fig. 4 – K_2O vs silica classification diagram (Rickwood, 1989) for lavas (open diamond) and dykes (filled diamond). According to Bargossi *et al.* (1981) and Di Battistini *et al.* (1989), lavas and dykes both show low to high K_2O contents.

chaotic andesitic breccias suggest a proximal location.

Decimetre to metre-scale lenses of conglomerates and breccias composed of fragments derived from the underlying low-grade basement (Ponte Gardena Conglomerate) are sometimes interbedded within the pyroclastic deposits.

Between Miglanz and St. Valentin/St. Valentino, alluvial terrigenous sediments (the *Pedrund unit*) replace the agglomerates. From the bottom to the top, thin layers of red to green arenites and red pelites pass into polygenic conglomerates (clasts of andesites, phyllites, phyllitic mica-schists, quartzites and scarce rhyolites) crop out. A clear stratification is emphasised by decimetre-thick units of microrudites and red arenites. Some caliche-rich horizons in pelites and graded or cross-bedded arenites are observed in this unit.

On top of the volcanosedimentary sequence, rhyolites, rhyodacites and rhyolitic ignimbrites have been emplaced tectonically. This volcanic unit overthusts both the sedimentary units (*Pedrund unit* and agglomerates) and the metamorphic basement.

STRUCTURAL ANALYSIS

Compressional tectonics. The present structural setting of the study area is linked to the Neogene tectonic event (Doglioni, 1987; Castellarin *et al*., 1992; Ring & Richter, 1994). Low- to middle-angle NNW-vergent backthrusts, a general tilting to the SSE and the inversion of some inherited normal faults are ascribed to this event.

Moreover, along the Funes creek (Fig. 2), a subvertical WNW-ESE trending fault separates the metamorphic basement from the volcanosedimentary succession. According to Doglioni (1987) and Ring & Ricther (1994), it should correspond to a segment of the Funes Line, the major Neoalpine backthrust in the northern Dolomites. This fault is actually cut by the NE-SW trending NNW-vergent thrusts, and its fault zone shows evidence of a polyphase tectonic history and very different structural features with respect to the NNW-vergent backthrusts.

Extensional tectonics. The western edge of the basin is well preserved and exposed near Tiso. Here the metamorphic basement is characterised by: i) NE-SW and NW-SE trending andesitic and basaltic-andesite dikes (Fig. 5a), ii) N-S to NE-SW trending subvertical extensional fractures and sulphide- or barite-bearing veins; such veins also intrude andesitic-fault-breccias along NE-SW normal faults; iii) "fluidisation" breccias (*sensu* Reynolds, 1954). Locally a N 50°-trending dyke cross-cut by another trending N 160° was observed. In contrast, no dyke, vein or other extensional structure was observed in the rhyolite and rhyodacite lavas.

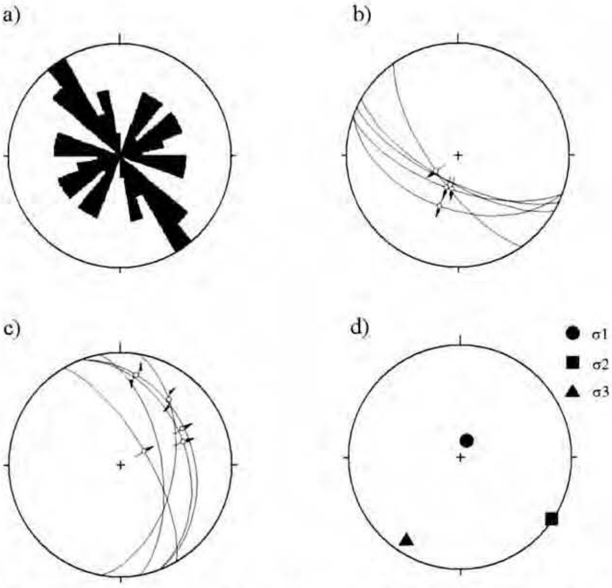


Fig. 5 – Selected structural data collected in the Funes Basin. a) Strike of andesitic dykes. Dataset: 37, interval: 10°, max: 13,51°; b) attitude and vector displacement of normal listric faults in the metamorphic basement. Dataset: 5; c) attitude and vector displacement of synsedimentary normal faults in the Pedrund unit; d) calculated stress field for Permian normal faults.

Also, the northern margin of the Funes Basin was tectonically active during the volcanism, as suggested by the presence of a set of WNW-ESE trending andesitic dykes, NW-SE trending and SW-dipping normal faults in the metamorphic basement (Fig. 5b), and a lens of agglomerates directly overlying the metamorphic basement. At least within the *Pedrund unit*, synsedimentary metre-scale faults trending NNW-SSE and dipping ENE were observed (Fig. 5c).

Both NW-SE and NNW-SSE normal faults are consistent with a pure extensional stress field with horizontal, NE-SW trending σ_3 and σ_1 subvertical (Fig. 5d).

FIRST RESULTS

These data indicate the presence in the northern Dolomites of an intermontane basin that at present is exposed for 2 km in a NE-SW direction and for about 3 km in an E-W direction. A Neoalpine NNW-vergent thrust at the eastern edge and a WNW-ESE-striking subvertical fault at the southern edge prevent a correct evaluation of the original width of the basin.

The Funes Basin is filled by up to 500 m thickness of andesitic lavas which roughly thin eastwards and are replaced by up to 200 m of pyroclastic – mainly agglomerate – deposits. A 100 m-thick, pelitic to ruditic alluvial sequence, showing NNW-SSE-trending synsedimentary normal faults, is interbedded within the upper part of the agglomerates.

East-dipping normal faults, andesitic dykes and hydrothermal veins, N-S to NE-SW trending, mark the well-preserved western edge of the basin.

Stratigraphic, sedimentological and tectonic data indicate that the evolution of the Funes Basin was controlled by normal faults. No evidence of transcurrent tectonics was observed.

An Early Permian age for the Funes Basin is suggested by the presence of lenses of Ponte Gardena Conglomerate within andesitic lavas and agglomerates and by the calcalcaline cogenetic nature of the Funes andesites and the Permian volcanics of the neighbouring Athesian Volcanic District.

In order to determine the precise age of formation of the Funes Basin, isotopic dating of zircons from the andesites is in progress.

Acknowledgements – We thank Prof. G. Cassinis for critical reading of the manuscript and useful suggestions. Special thanks to Robert and Christine Pernthaler for their hospitality and kindness. Research was sponsored by M.U.R.ST. grant (COFIN 1997).

REFERENCES

BARGOSSI G.M., D'AMICO C., DI BATTISTINI G. & LANDINI F., 1981. Le K-andesiti inferiori atesine tra Nogaré e Serso (Trento). *Rend. Soc. Ital. Mineral. Petrol.*, 37: 719-738.

BARTH S., OBERLI F. & MEIER M., 1994. Th-Pb versus U-Pb isotope systematic in Allanite from co-genetic rhyolite and granodiorite: implication for geochronology. *Earth and Planet. Sci. Lett.*, 124: 149-159.

CASSINIS G. & PEROTTI C., 1994. Interazione strutturale permiana tra la linea delle Giudicarie ed i bacini di Collio, Tione e Tregiovo (Sudalpino centrale, NE Italia). *Boll. Soc. Geol. Ital.*, 112 (1993): 1021-1036.

CASSINIS G., PEROTTI C. & VENTURINI C., 1997. Examples of late Hercynian transtensional tectonics in the Southern Alps (Italy). In: Dickins J.M. (ed.), *Late Palaeozoic and Early Mesozoic Circum-Pacific Events and Their Global Correlation*. Cambridge Univ. Press: 41-50.

CASTELLARIN A., CANTELLI L., FESCE A.M., MERCIER J.L., PICOTTI V., PINI G.A., PROSSER G. & SELLI L., 1992. Alpine compressional tectonics in the Southern Alps. Relationships with the N-Appenines. *Annales Tectonicae*, 6: 62-94.

D'AMICO C. & DEL MORO A., 1988. Permian and Triassic Rb-Sr dating in the Permian rhyodacitic ignimbrites of Trentino (Southern Alps). *Rend. Soc. Ital. Mineral. Petrol.*, 43: 171-180.

DEL MORO A., SASSI F.P. & ZIRPOLI G., 1980. Preliminary results on the radiometric age of the hercynian metamorphism in the South-Alpine basement of the Eastern Alps. *N. Jb. Geol. Paläont. Mh.*, 12: 707-718.

DEL MORO A. & VISONÀ D., 1988. The epiplutonic Hercynian Complex of Bressanone (Brixen, Eastern Alps, Italy). Petrologic and radiometric data. *N. Jb. Mineral. Abh.*, 145: 66-85.

DI BATTISTINI G., GALLO F., GIAMMETTI F. & VERNIA L., 1989. Permian andesites from Val d'Isarco and Val di Funes volcanic sequence (Bolzano, northern Italy). *Mineral. Petrogr. Acta*, 32: 123-137.

DOGLIONI C., 1987. Tectonics of the Dolomites. *J. Struct. Geol.*, 9 (2): 181-193.

HAMMERSCHMIDT K. & STÖCKHERT B., 1987. A K-Ar and $^{40}Ar/^{39}Ar$ study on white micas from the Brixen Quartzphyllite, Southern Alps. *Contrib. Mineral. Petrol.*, 95:181-193.

KRAINER K., 1989. Composition and evolution of Lower Permian molasse sediments (Ponte Gardena Conglomerate) at the base of the Bolzano Volcanic Complex, Southern Alps. *N. Jb. Geol. Paläont. Mh.*, 7: 400-424.

MASSARI F., 1988. Some thoughts on the Permo-Triassic evolution of the South-alpine area (Italy). *Mem. Soc. Geol. Ital.*, 34 (1986): 179-188.

MASSARI F., NERI C., PITTAU P., FONTANA D. & STEFANI C., 1994. Sedimentology, palynostratigraphy and sequence stratigraphy of a continental to shallow-marine rift-related succession: Upper Permian of the Eastern Southern Alps (Italy). *Mem. Sci. Geol.*, 46: 119-243.

MELI S. & KLÖTZLI U., 1997. Preliminary geochronological results on the pre-Variscan metavolcanics of the Eastern Southalpine basement. *Plinius*, 18: 144-145.

POLI M.E., VISONÀ D. & ZANFERRARI A., 1996. Il basamento varisico delle Dolomiti. *78^ Riunione estiva Soc. Geol. Ital., S.Cassiano (BZ), 16-18 settembre 1996*, vol. Riassunti, 4 pp.

REYNOLDS D.L., 1954. Fluidization as a geological process and its bearing on the problem of intrusive granites. *Am. J. Sci.*, 252: 577-614.

RICKWOOD P.C., 1989. Boundary lines within petrologic diagrams which use oxides of major and minor elements. *Lithos*, 22: 247-263.

RING U. & RICHTER C., 1994. The Alpine structural evolution of the Eastern Southalpine basement. *J. Geol. B.-A.*, 137: 187-196.

ROTTURA A., BARGOSSI G.M., VISONÀ D. & TRANNE C.A., 1998. Petrological and geochemical evidence on the origin and significance of the Permian magmatism in the central-eastern Southern Alps. *Mem. Soc. Geol. Ital.*, 53 (1998): 9-21.

SELLI L., 1998. Il lineamento della Valsugana fra Trento e Cima d'Asta: cinematica neogenica ed eredità strutturali permo-mesozoiche nel quadro evolutivo del Sudalpino orientale. (NE Italia). *Mem. Soc. Geol. Ital.*, 53 (1998): 503-541.

«NATURA BRESCIANA» Ann. Mus. Civ. Sc. Nat., Brescia, MONOGRAFIA N. 25, 2001: 139-148

UPPER PALEOZOIC AND TRIASSIC CONTINENTAL DEPOSITS OF SARDINIA: A STRATIGRAPHIC SYNTHESIS

AUSONIO RONCHI [1]

Key words – stratigraphy; paleontology; Sardinia; Upper Paleozoic basins.

Abstract – Recently, a team of Italian and French geologists renewed field research on some (late) post-Variscan terrigenous and volcanic sequences in Sardinia.
From stratigraphical, paleontological, petrological and geochemical investigations, two main volcanic and sedimentary cycles appear so far confirmed.
In the older cycle (cycle 1), Late Carboniferous to Early Permian in age, a number of narrow, fault-bounded subsiding basins developed.
Mostly during the Early Permian ("Autunian") these troughs, which presently crop out in different parts of Sardinia, were characterised by both alluvial-to-lacustrine sediments, with differing lithofacies, and calcalkaline, mainly effusive, intermediate-to-acidic products. These latter volcanics were also distributed in large volumes outside the basin areas, covering a large part of the island.
The deposits pertaining to the second cycle (cycle 2) crop out in a restricted number of sites in northwestern as well as central to southwestern Sardinia.
They consist of fossil-barren alluvial, coarse-to-fine clastic red beds, followed upwards, after an unconformity, by the Buntsandstein, which is biostratigraphically related to late Olenekian(?)-early Anisian and late Anisian ages.
Furthermore, in Nurra, the presence of alkaline volcaniclastic products in the relatively older red beds allows the correlation of the second cycle with similar deposits cropping out in southern France and the Catalonian Pyrenees, generally ascribed to the late Early Permian to early Late Permian (*i.e.* to the "Saxono-Thuringian" *p.p.* of authors), with which Sardinia was linked during post-Variscan times.

Parole chiave – stratigrafia; palaeontologia; Sardegna; bacini tardo-paleozoici.

Riassunto – In questi ultimi anni, un gruppo di ricercatori italiani e francesi ha analizzato in dettaglio alcune delle più importanti successioni vulcaniche e sedimentarie (tardo-) postercíniche della Sardegna. Ciò ha permesso di acquisire nuovi dati stratigrafici, paleontologici e petrografici, confermando l'esistenza nell'isola di almeno due grandi cicli vulcanici e sedimentari. Durante il primo fra questi (ciclo 1), databile tra il Carbonifero superiore e il Permiano inferiore, una fase trascorrente interessò la catena varisica ormai sollevata, dando luogo alla formazione di piccoli e incisi bacini transtensivi. Soprattutto nel Permiano inferiore ("Autuniano"), queste fosse continentali, presenti in varie zone dell'isola, furono caratterizzate da una sedimentazione alluvio-lacustre, con facies molto differenti l'una dall'altra, e da prodotti magmatici, principalmente effusivi, ad affinità calcalcalina. Tali prodotti magmatici risultano ampiamente diffusi anche in zone extrabacinali di varie aree della Sardegna. Le successioni attinenti al secondo ciclo (ciclo 2) affiorano molto più limitatamente delle precedenti e precisamente nella zona nordoccidentale, sudoccidentale e centrale dell'isola. Esse sono caratterizzate da *red beds* alluvionali con caratteri sedimentologici e tessiturali diversi, con presenza di fossili solo nelle porzioni sommitali, che richiamano il Buntsandstein europeo e facenti passaggio all'ambiente marino del Muschelkalk. La correlazione di questi ultimi sedimenti con dati di sondaggio permetterebbe di assegnare loro un'età compresa tra l'Olenekiano?-Anisico inferiore e l'Anisico superiore. Intercalate nella parte basale dei *red beds* del secondo ciclo, ma solo nella Nurra, si trovano prodotti vulcanoclastici a carattere alcalino; ciò porterebbe a riferire l'insieme di questi depositi ad un'età permiana superiore, in base a confronti con le analoghe successioni della Francia meridionale e dei Pirenei catalani, cui la Sardegna era in quel tempo unita.

GENERAL FRAMEWORK

The aim of this paper is to show the current state of research on the Upper Carboniferous to Permian and Triassic sedimentary and volcanic sequences of Sardinia.

In this regard, the fieldwork recently carried out by a group of researchers on some Late Paleozoic basins of the island will be reviewed in the light of the relatively new data.

On the basis of stratigraphical, paleontological, petrographical and radiometric data, two major volcanosedimentary cycles can be recognised in the post-Variscan deposits of Sardinia. The older one (cycle 1) is Late Carboniferous to Early Permian *p.p.* in age, whereas the younger cycle

[1] Dipartimento di Scienze della Terra, Università di Pavia, Via Ferrata 1, 27100, Pavia, Italy.

(cycle 2) spans from Early Permian *p.p.* (post-"Autunian") to Middle Triassic (Anisian). The latter cycle was also defined as "Permo-Triassic" by some authors (*e.g.* Gasperi & Gelmini, 1980; Fontana *et al.*, 1982; Cassinis, 1996; etc.).

At the beginning of the first cycle, a (trans)tensional tectonic phase affected the Variscan basement, giving birth to a number of small intramontane, fault-bounded subsiding basins, of which the most remarkable crop out presently in various parts of the island (Fig. 1). They are the well-known basins of Lu Caparoni-Cala Viola (NW Sardinia), Seui-Seulo (Central Sardinia), Perdasdefogu, Escalaplano and Lago di Mulargia (SE Sardinia), Guardia Pisano and San Giorgio (SW Sardinia). Clear evidence of Upper Carboniferous deposits occurs only in the ?Westphalian D to Stephanian sediments of the last-mentioned basin (Cocozza, 1967; Del Rio, 1973; Fondi, 1979; Del Rio & Pittau, 1999).

Investigations seem to suggest an early structuration of the local basins in the Perdasdefogu and Seui areas, in a NE-SW trend. Subsequently, but probably still during the Early Permian, these troughs underwent major extensional tectonism, along with NW-SE to NNW-SSE oriented faulting, which generated a horst-and-graben framework. This structural trend, which is generally known as "Hercynian" in Sardinia, corresponds exactly to the major late-Hercynian (or late-Variscan) transcurrent faults (such as those of Posada and Mt. Grighini) and to the (late) post-Variscan dyke swarm cropping out in the western part of the island.

At that time, close to the Carboniferous-Permian boundary but mainly during the beginning of the Early Permian (Autunian of French authors), these troughs were characterised by both alluvial-to-lacustrine sedimentation and calcalkaline intermediate-to-acidic magmatism.

Due to the tectonic activity and the related subsidence, the Lower Permian volcanosedimentary infills of the various basins show thicknesses ranging from just a few metres to almost 400 m (see *e.g.* Broutin *et al.*, 1996). The repeated volcanic activity, mainly in the form of lava flows or shallow intrusions within the basin fill, and of pyroclastic flow and fall deposits originating from nearby volcanic centres, greatly contributed to the variations in basin sequences both in thickness and facies. This explains why precise correlation, even between successions cropping out in adjoining basins, has so far been hampered.

The rich paleontological record (macro- and microfloras, and rarely ostracods, stromatolites, algae and amphibians) yielded by these sediments allows the confirmation of an Early Permian (Autunian) age for most of these sequences.

The second cycle is, at present, clearly developed in northwestern Sardinia (Nurra), and probably in a few areas in central to southwestern regions of the island. It followed a stratigraphic gap of unknown duration and is represented by alluvial red beds, which are intercalated with tuffs and ignimbrites of alkaline composition in Nurra (markedly only at Monte Santa Giusta). This new volcanic and sedimentary period was seemingly connected with a more extensional regime and overlies the first cycle of Lower Permian deposits.

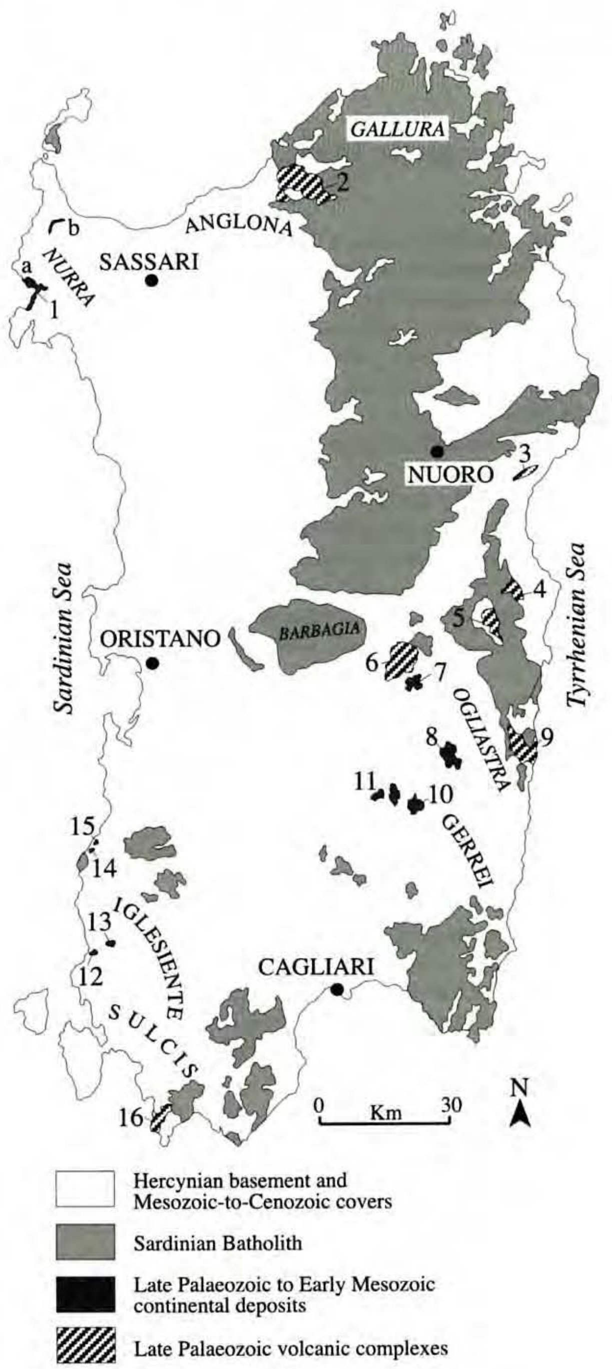


Fig. 1 – Location of the main late- to post-Hercynian sedimentary and volcanic sequences of Sardinia. 1. a: Lu Caparoni-Cala Viola Basin; b: Monte Santa Giusta. 2. Li Reni-Azzagulta. 3. Galtellì. 4. Baunei. 5. Villagrande-Strisaili. 6. Monte Perdedu-Monte Alastria. 7. Seui-Seulo. 8. Perdasdefogu. 9. Monte Ferru di Tertenia. 10. Escalaplano. 11. Lago di Mulargia. 12. Guardia Pisano. 13. San Giorgio. 14. Punta Acqua Durci. 15. Tuppa Niedda. 16. Teulada.

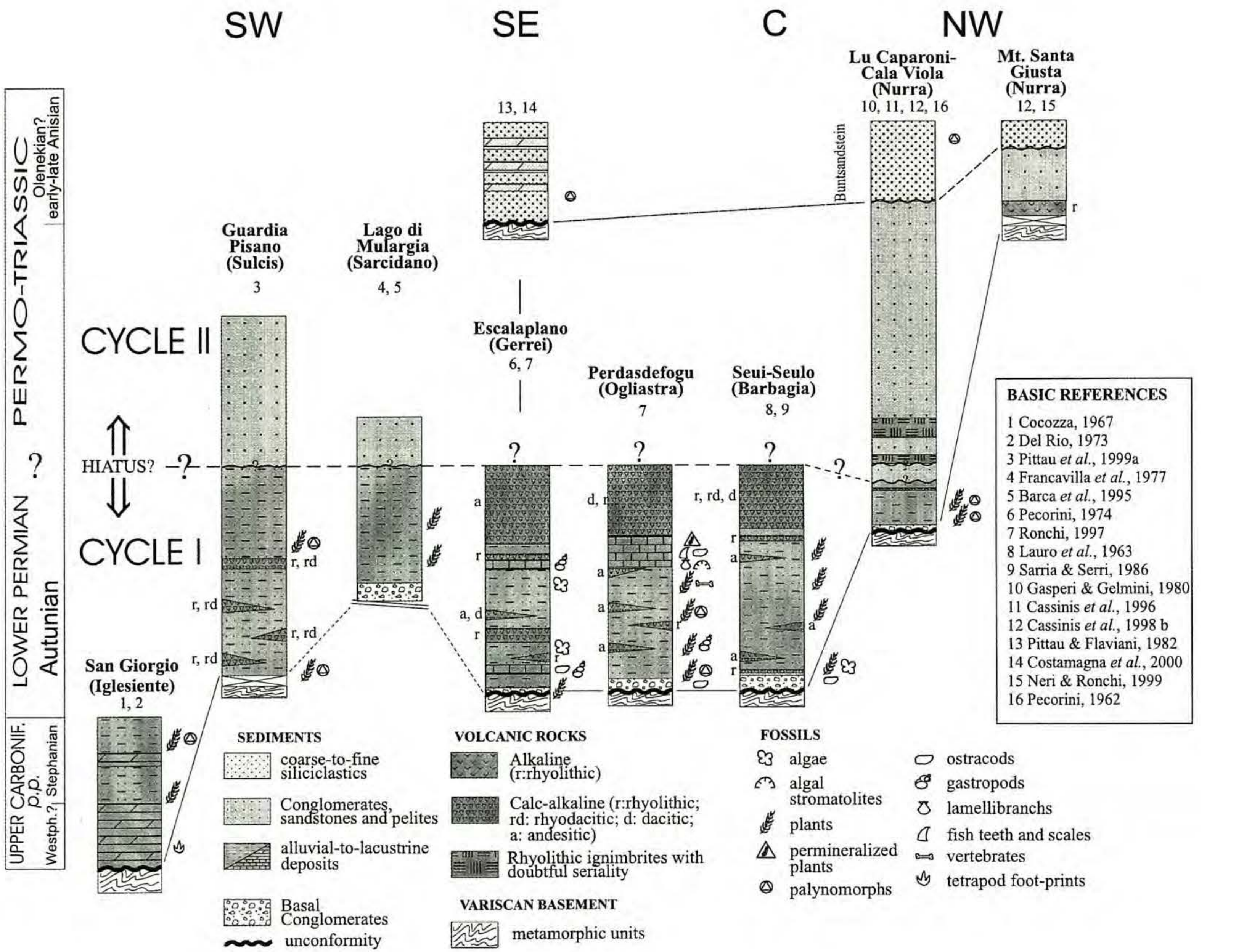


Fig. 2 – Correlation scheme among the Late Paleozoic volcano-sedimentary sequences of Sardinia. Vertical distances are not time- or thickness-related.

A clear unconformity between the two aforementioned cycles has not so far been observed at any of the previously cited basin localities. However, the abrupt facies changes in the two volcanosedimentary sequences suggest fundamental changes both in the structural regime and in the depositional environment. Furthermore, a marked angular unconformity between the Autunian and the "Saxonian-Thuringian" is recorded in various west-Mediterranean continental regions (*e.g.* Broutin *et al.*, 1994) from which the primary Corsica-Sardinia block moved subsequently towards the present-day Tyrrhenian.

According to some authors (*e.g.* Cassinis *et al.*, 1996, 1998a; Fontana *et al.*, this volume), the Lu Caparoni-Cala Viola Permian-Triassic detrital sequence ends with Buntsandstein-type deposits of early-to-late Anisian age (Pittau, 1999). These can be correlated by lithofacies and microfloristic associations with the Cugiareddu-drilled red beds (NW Sardinia) (Pittau Demelia & Flaviani, 1982) and with the southwest Campumari and southeast Escalaplano outcrops (Pittau Demelia & Del Rio, 1980; Pittau *et al.*, 1999b; Costamagna *et al.*, 2000).

STRATIGRAPHICAL CONSTRAINTS

Although the Late Paleozoic troughs of Sardinia developed in a similar intracontinental scenario, marked by a basin-and-swell landscape, their respective sequences greatly differ in thickness, extent and facial development. An extensional regime governed all these troughs, producing block-faulting and transtensional/transpressional movements. The environmental conditions of each basin were typical either of small lakes or of swamp ponds, from some centimetres to some metres in deep, and periodically exposed.

Hereafter, a brief stratigraphic synthesis of the most significant Upper Paleozoic basins of Sardinia are outlined. In Fig. 2, the investigated Upper Carboniferous to Middle Triassic successions of the island are shown.

First cycle

The first cycle is generally ascribed to "Autunian" times, apart from the (?)Westphalian C-Stephanian deposits which have been discovered only in southwestern Sardinia

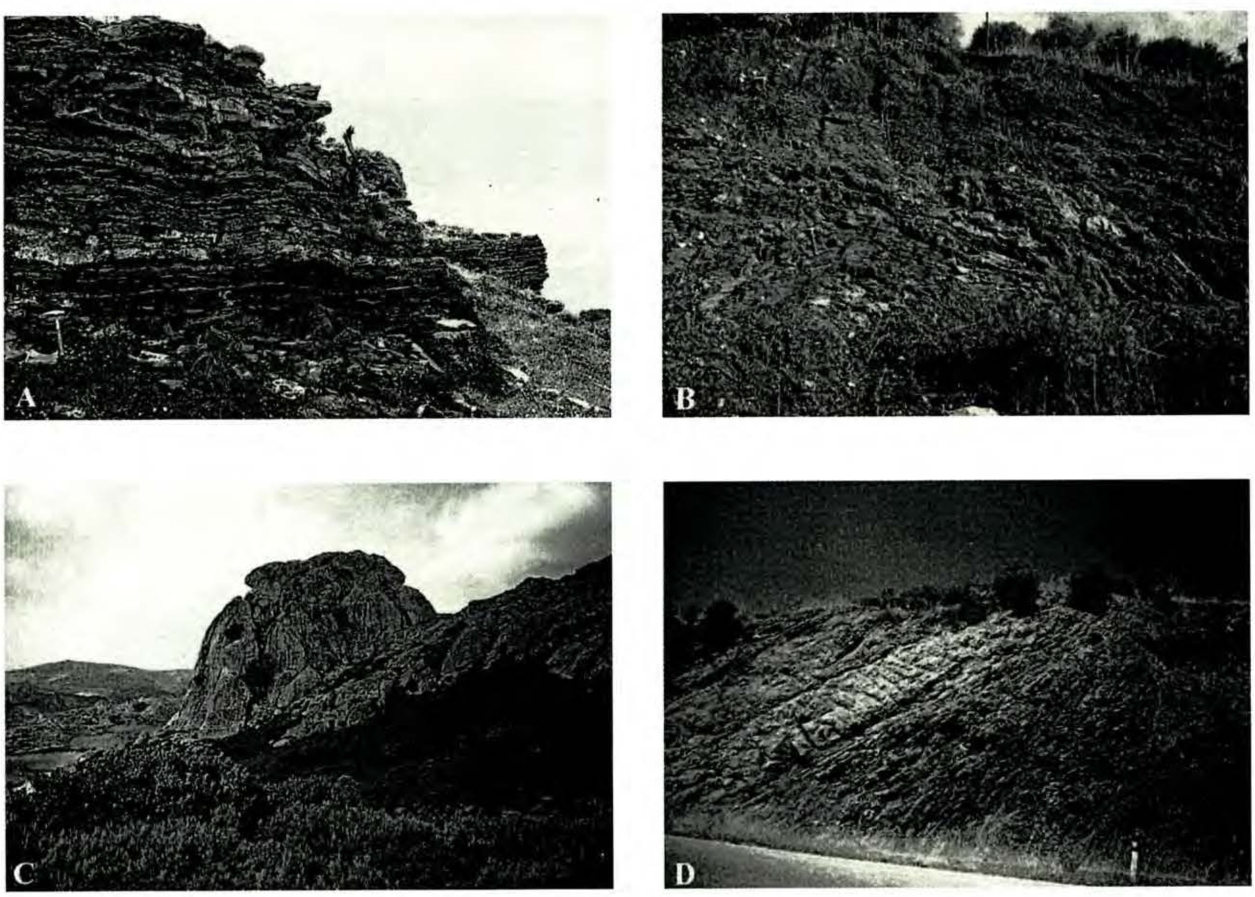


Fig. 3 – Representative examples of the first-cycle sequences in Sardinia. A: alternating dolostones, limestones and silicified carbonates (Perdasdefogu Basin, Ogliastra); B: coarse-to-fine red siliciclastics (Basal Conglomerate) disconformably overlying the Variscan basement (Escalaplano Basin, Gerrei); C: the subvolcanic rhyolitic dome of Monte Taddì (Seui Basin, Barbagia di Seulo); D: Lower Permian coarse to fine clastics in tectonic contact with the Variscan basement (Lago di Mulargia, Sarcidano).

(San Giorgio Basin, Iglesiente and Tuppa Niedda, Arburese). This cycle normally begins, in all the troughs, with more or less coarse basement breccias (Basal Conglomerates) unconformably overlying the Cambrian to Lower Carboniferous Variscan substratum (Fig. 3b, d). Alluvial-to-lacustrine, fossiliferous, mainly dark, shaly-to-sandy sediments follow, together with frequent volcanic (lavas) and volcaniclastic products (ignimbrites, pyroclastic fall deposits and breccias).

Locally, intercalations of conglomerates, lacustrine carbonates (up to 70 m in the Perdasdefogu Basin) with frequent silicification phenomena, anthracite deposits and pedological as well as diagenetic nodules occur (Ronchi, 1997 *cum bibl.*) (Fig. 3a). From most of these basins, *i.e.* Lu Caparoni-Cala Viola (Pecorini, 1962; Gasperi & Gelmini, 1980), Seui-Seulo (Lauro *et al.*, 1963; Sarria & Serri, 1987), Lago di Mulargia (Francavilla *et al.*, 1977; Barca *et al.*, 1995a), Guardia Pisano (Barca *et al.*, 1992; Pittau *et al.*, 1999a) and from other minor outcrops (Barca *et al.*, 1995b), the finer laminated sediments yielded abundant macrofloras and palynomorphs. In the Perdasdefogu Basin, other significant paleontological data such as permineralised plants, amphibians, algal stromatolites, ostracods and fish remains have also been highlighted. During the last century, many studies on the "Carboniferous-Permian" Sardinian macrofloras were performed (*e.g.* Comaschi Caria, 1959; Spano, 1976). Recently, according to Broutin (in Ronchi *et al.*, 1998; Broutin & Ronchi, 1999) the palynological assemblage of Perdasdefogu is qualitatively and quantitatively similar to that of Lu Caparoni Fm.; he relates these forms to the "A3" Biozone of Doubinger (1974) for the "Autunian" of Europe. Furthermore, according to Barca *et al.* (1992) and Pittau *et al.* (1999a), the well-preserved microflora of Guardia Pisano allow correlation with the Stephanian-Autunian of Western Europe, the Wolfcampian of the North American Midcontinent and the Ghzelian-Asselian of the Donetz and Ural basins.

In Sardinia, the first cycle generally ended with a major deposition of volcanic rocks, represented by rhyolitic and dacitic ignimbrites, lava flows and domes (Traversa, 1979; Lombardi *et al.*, 1974; Cortesogno *et al.*, 1998). Widespread magmatic basins also developed in various parts of Sardinia, where the sedimentary record appears reduced or missing. As in other western Mediterranean regions, the first-cycle fossil content shows that it ranged from the Late Carboniferous to the first part of the Early Permian; this age assessment is also confirmed by the calcalkaline volcanics found within and/or on top of these sedimentary sequences. However, we cannot exclude the possibility that this igneous activity continued up to the beginning of the Late Permian, as some radiometric dating may suggest (see *e.g.* Cozzupoli *et al.*, 1971; Edel *et al.*, 1981b; Tab. 1). This cycle is unconformably overlain by post-Autunian to Middle Triassic clastics in Nurra (and dubiously in Sarcidano and Sulcis) and by both Middle Jurassic and Eocene deposits in central to southeastern Sardinia (Barbagia, Ogliastra and Gerrei).

Second cycle

The second cycle consists of red azoic siliciclastic deposits (the so-called "Verrucano sardo" *Auct.*), which are mainly widespread in the Lu Caparoni-Cala Viola area (Nurra in northwestern Sardinia – Fig. 4a). In southeastern (Lago di Mulargia in Sarcidano – Fig. 4b) and southwestern Sardinia (Guardia Pisano in Sulcis) there are also similar, but less thick, alluvial coarse-grained deposits, which still require comparison with the Nurra sequence. Their chronostratigraphical attribution is hampered by the lack of fossils and the absence of reliable radiochronometric data (see Table 1).

Furthermore, the age of the Lu Caparoni-Cala Viola Basin (Nurra), alluvial to coastal plain sequence is still a matter of debate. In this area, the first-cycle Autunian plant-bearing sediments, *i.e.* the Lu Caparoni Formation *Auct.* is (disconformably?) overlain by mature white quartz-conglomerate fan deposits (unit 1 *sensu* Gasperi & Gelmini, 1980). The above units, presently both ascribed to the same cycle (Cassinis & Ronchi, 1997; Fontana *et al.*, this volume) are probably disconformably capped (without any clear evidence so far) by a fining-upwards sequence, up to some 200 m thick (units 2 and 3 of Gasperi & Gelmini, 1980), which is in turn followed by some 50 m of Buntsandstein-like deposits. This last portion (unit 4 *sensu* Gasperi & Gelmini, 1980), which can clearly be correlated to the Buntsandstein of Provence, begins with a metres-thick quartz conglomerate. In this context, in fact, significant boreholes in Permian and Triassic deposits were drilled a little to the east of Cala Viola (Lotti, 1931) and north of this area, near to Cugiareddu (Pomesano Cherchi, 1968), helping to unravel the chronostratigraphical and depositional problems. The whole fossil-barren red beds have historically been attributed to the second, Permian-Triassic cycle (Vardabasso, 1966; Gandin *et al.*, 1977; Gasperi & Gelmini, 1980; Fontana *et al.*, 1982).

The presence of some macroflora imprints (*Equisetum* cfr. *mougeotii*) led Pecorini (1962) to attribute the top of the aforementioned sequence to a doubtful Early Triassic age. Recently, Pittau (1999) ascribed these deposits to an ?Olenekian-early Anisian to late Anisian interval on the basis of lithostratigraphical correlations with similar sporomorph-bearing rocks in the Cugiareddu Well (see also Pittau Demelia & Flaviani, 1982). Concerning the stratigraphy as well as the petrography of sediments and volcanic rocks of the whole sequence, they have been analysed in detail by Cassinis *et al.* (1996, 1998b) and Fontana *et al.* (this volume).

At Monte Santa Giusta (Nurra), about 60 metres thickness of clastic deposits of uncertain age are poorly exposed at the base of the Muschelkalk and Keuper sequence (Fontana *et al.*, this volume). These authors correlates this succession with the Lu Caparoni-Cala Viola red beds (see also the inferred correlation made by Gasperi & Gelmini, 1980), explaining its reduced thickness as related to the structural height of the basement or to a slow subsidence rate. Acidic welded tuffs with alkaline affinities crop out at the base of the cited sediments (Lombardi *et al.*, 1974, Cassinis *et al.*, 1996; Cortesogno & Gaggero, 1999b). In a recent study, mainly dealing with the Muschelkalk and Keuper transgressive deposits, Carrillat *et al.* (1999) attributed the whole siliciclastic succession at the base of Monte Santa Giusta to a Lower Triassic to Anisian interval.

MAGMATISM

The voluminous late- to post-Variscan magmatic products, cropping out in Sardinia over more than 8000 km^2, have always been considered a decisive tool in the better understanding of the geological evolution of the island during the Late Paleozoic.

For this reason, studies dealing with this issue are numerous (*e.g.* Vardabasso, 1939; Traversa, 1979; Lombardi *et al.*, 1974; Atzori & Traversa, 1986; Cortesogno *et al.*, 1998). Also, geochronological and geochemical studies were carried out recently by various authors on the Permian-Triassic dykes, cutting through the Variscan intrusives and metamorphic basement all over the eastern part of the island (Atzori & Traversa, 1986; Vaccaro *et al.*, 1991; Traversa & Vaccaro, 1992).

The volcanic products pertaining to the first cycle show a calcalkaline affinity, which has been variously interpreted by some researchers as the consequence of a poorly constrained active margin with a volcanic arc, located in the Ligurian-Provencal area (Cabanis, in Broutin *et al.*, 1994, and references therein), and by others as due to partial melting processes at the mantle-crust interface (Cortesogno *et al.*, 1998). This magmatism affected all the Early Permian basins of Sardinia, although it consists of large volumes mainly distributed in extrabasinal areas, particularly on the eastern side of Sardinia. From north to south, it gave birth to broad volcanic complexes or calderas, like those of Li Reni-Azzagulta in Gallura (Traversa, 1979 *cum bibl.*; Del Moro *et al.*, 1996), Monte Perdedu-Monte Alastria in Barbagia di Seui (Cozzupoli & Lombardi, 1969; Cozzupoli *et al.*, 1971), Monte Ferru di Tertenia in Ogliastra, and Capo Teulada in Sulcis (Lombardi *et al.*, 1974).

Within the Lower Permian basins, acidic to intermediate volcaniclastic deposits as well as rhyolitic to rhyodacitic domes, lava flows and dykes are always associated with siliciclastic deposits (see the recent works of Cassinis *et al.*, 1998a; Cortesogno *et al.*, 1998; Cortesogno & Gaggero, 1999a). Commonly, the first-cycle volcanic activity began with acid explosives and major volumes of andesitic lavas with columnar joints and chaotic breccias (Seui, Escalaplano, Perdasdefogu), followed locally by dacitic lavas (Perdasdefogu) and dykes, and rhyolitic dykes and ignimbrites (Seui, Perdasdefogu). In the Seui Basin, spectacular updoming of dacitic to rhyolitic magmatic bodies also occurs (Calzia *et al.*, 1999) (Fig. 3c). In some sequences, like those of Escalaplano (Pecorini, 1974; Ronchi, 1997), the volcanic products largely dominate the strictly sedimentary units, but mostly they are intercalated with the sediments and occur as lens-shaped volcanic breccias, stratified cinerites and tuffs, hyaloclastites, lava plugs and sills. Stratigraphical and recent radiometric data generally place this volcanic activity during the Early Permian.

In contrast, an alkaline affinity was stated for the first

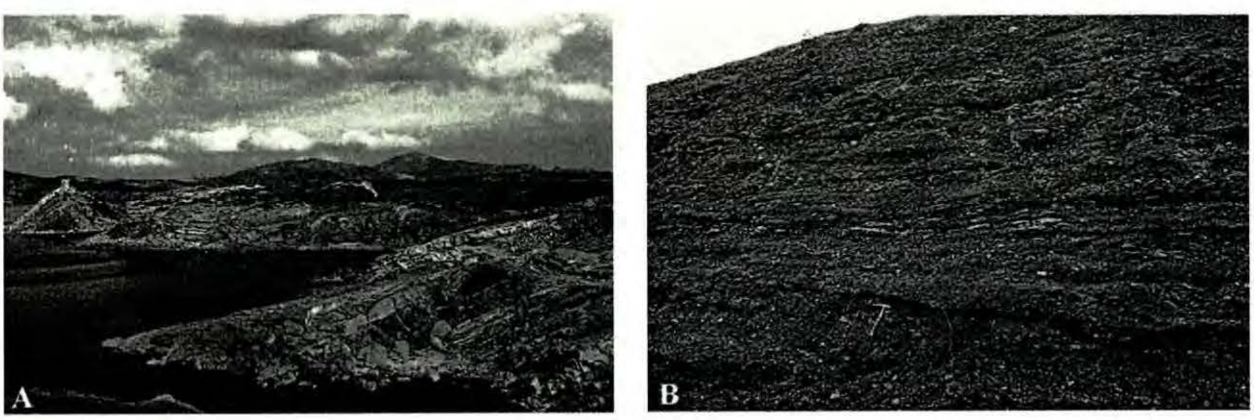


Fig. 4 – Two examples of the second-cycle continental deposits. A: the Permo-Triassic siliciclastic sequence near Cala Viola (Nurra); B: channelled red alluvial deposits near Lago di Mulargia (Sarcidano).

REGION	SITE	AGE	ISOTOPIC METHOD	ROCK TYPE	AUTHOR
NW SARDINIA (Nurra)	Mt. Santa Giusta	197+/- 6Ma 204+/- 6Ma	K-Ar (WR) "	alkaline rhyolitic ignimbrite	Lombardi *et al.*, 1974
		297+/-9 Ma 244+/-9 Ma 296+/-8 Ma	K-Ar (Bt) K-Ar (Fs) K-Ar (Bt)	rhyolitic ignimbrite	Edel *et al.*, 1981
N-NE SARDINIA (Gallura-Anglona)	Azzagulta-Li Reni	247+/- 7Ma 211+/- 6Ma 226+/- 6Ma 258+/- 7Ma 267+/- 7Ma 262+/- 9Ma 249+/- 7Ma 260+/- 9Ma	K-Ar (WR) K-Ar (Fs) K-Ar (Fs) K-Ar (Fs+Q) K-Ar (Fs+Q) K-Ar (Q+ Fs) K-Ar (Fs+Q) K-Ar (Fs+Q	rhyolitic ignimbrite	Edel *et al*, 1981
	Coghinas Valley-Aggius	286+/-3Ma 288+/-3Ma 288+/-11Ma	Rb-Sr (Ms) Rb-Sr (Bt) Rb-Sr (WR)	arkosic sandstone " rhyolitic ignimbrite	Del Moro *et al.*, 1996
		268+/-8 Ma 289+/-9 Ma	Rb-Sr (WR) "	intermediate dyke	Vaccaro *et al.*, 1991
(Goceano)	Concas	273+/-9 Ma 282+/-9 Ma 280+/-9 Ma 210+/-115 Ma	Rb-Sr (WR) Rb-Sr (WR) Rb-Sr (WR) Rb-Sr (WR)	dyke	Vaccaro *et al.*, 1991
	Mt. Lerno	281+/-10 Ma	Rb-Sr (WR)	dyke	Vaccaro *et al.*, 1991
(Baronie)		291+/-9 Ma	Rb-Sr (WR)	dyke	Vaccaro *et al.*, 1991
CENTRAL-E SARDINIA (Barbagia)	Sorgono	298+/-9 Ma	Rb-Sr (WR)	dyke	Vaccaro *et al.*, 1991
	Galtellì (Orosei)	268+/-10 248+/-9 275+/-11 238+/-11 280+/-7Ma	K-Ar (WR) " " " "	rhyolitic ignimbrite	Cozzupoli *et al.*, 1984
	Mt. Perdedu-Mt. Alastria	260+/-5Ma 212+/-5Ma	K-Ar (WR) "	quartzlatitic subvolcanite	Cozzupoli *et al.*, 1971
	Seui-Seulo	255+/-5Ma 250+/-5Ma 262+/-5Ma	" " "	rhyolitic ignimbrite	
		255+/-6Ma 265+/-5Ma	" "	Trattalas Diorite	
		220+/-4Ma 225+/-5Ma 250+/-6Ma 255+/-8Ma	" " " "	rhyolitic lava	
		259+/-7Ma 261+/-8Ma	K-Ar (Pl) K-Ar (Fs)	ignimbrite ignimbritic tuff	Edel *et al.*, 1981
(N Ogliastra)	Talana-Villagrande Strisaili	301+/-8Ma 281+/-10 Ma 308+/-11 Ma	K-Ar (Bt+Cl) K-Ar (Pl) K-Ar (Pl)	dyke ignimbrite "	Edel *et al.*, 1981
		235+/-7 Ma 228+/-5 ma 251+/-5 Ma	K-Ar (WR) " "	rhyolitic ignimbrite	Lombardi *et al.*, 1974
		289+/-9 Ma	Rb-Sr (WR)	intermediate dyke	Vaccaro *et al.*, 1991
CENTRAL-SE SARDINIA (S Ogliastra)	Baunei	281+/-10 Ma 291+/-11 Ma 137+/-9 Ma 290+/-5Ma	K-Ar (Pl) K-Ar (Pl) K-Ar (Fs+Q) K-Ar (Cl+Bt)	ignimbrite	Edel *et al.*, 1981
	Perdasdefogu	220+/-5Ma 218+/-6Ma	K-Ar (WR) "	quarzlatitic lava (dacite)	Lombardi *et al.*, 1974
	Escalaplano	230+/-5Ma 197+/-7Ma	K-Ar (WR) "	latitic lava (andesite)	Lombardi *et al.*, 1974
		295+/-8Ma	K-Ar (Bt)	andesite	Edel *et al.*, 1981
	Mt.Ferru di Tertenia	223+/-7Ma	K-Ar (WR)	rhyolitic ignimbrite	Lombardi *et al.*, 1974
		211+/-8Ma 252+/-8Ma	K-Ar (Fs+Q) K-Ar (Pl)	ignimbrite	Edel *et al.*, 1981
SW SARDINIA (Sulcis)	Capo Teulada	260+/-5Ma 228+/-6Ma	K-Ar (WR) "	rhyodacitic lava quartzlatitic lava	Lombardi *et al.*, 1974
	Guardia Pisano	295+/-Ma	SHRIMP	rhyolitic lava	Pittau et al., 1999

Table 1 – Radiometric data for the Late Paleozoic volcanic rocks and dykes of Sardinia.

time by Lombardi *et al.* (1974) for the volcanic deposits intercalated within the second sedimentary cycle of Nurra.

This change to a typically anorogenic character has been related by some authors to a post-Variscan global plate reorganisation (Cortesogno *et al.*, 1998). Such straightforward affinity is partly confirmed by recent works, but only for Monte Santa Giusta volcaniclastics (Cassinis *et al.*, 1996; Cortesogno & Gaggero, 1999b). In contrast, the porphyric pebbles included in unit 2 of Lu Caparoni-Cala Viola Basin (Gasperi & Gelmini, 1980), as well as the pyroclastic rocks cropping out at the base or intercalated in the same part of the second cycle, show a calcalkaline petrographic affinity which could be «either primary or induced by important secondary depletion of mobile elements» (Cortesogno & Gaggero in Cassinis *et al.*, 1996 and 1998b).

GEOCHRONOLOGICAL DATA AND AGE PROBLEMS

Many isotopic age analyses have been performed on the Upper Paleozoic volcanic rocks (mostly using K/Ar and Rb/Sr methods) at various sites in Sardinia (Cozzupoli *et al.*, 1971, 1984; Lombardi *et al.*, 1974; Edel *et al.*, 1981; Del Moro *et al.*, 1996). These rocks have shown differing ages which span from the Late Carboniferous to the Late Triassic, and these discrepancies probably derive from alteration processes (Table 1).

Even if Sardinia seems not to have been strongly affected by Alpine orogenic events, the calculated ages spread over a time span of more than 150 Ma (see also the schematic tables in Fontana *et al.*, 1982; Beccaluva *et al.*, 1985; Gelmini, 1985). Furthermore, it appears very difficult to compare data gathered using different isotopic techniques and based on whole rock or single mineral analyses. In the opinion of some authors, the late- to post-Variscan volcanic activity developed in two different periods: 250-260 Ma and 210-230 Ma for Fontana *et al.* (1982), around 250 and 280 Ma for Gelmini (1985), and 340-275 Ma and 275-235 Ma for Broutin *et al.* (1994).

In contrast with these authors, Edel *et al.* (1981) stated that the Upper Paleozoic volcanic products are almost contemporaneous and referable to an older calcalkaline cycle (late Westphalian-early Stephanian) and a younger one with alkaline affinities (Stephanian).

In the light of the modern reliability criteria, quality data appear to be those gathered by Cozzupoli *et al.* (1984) on the Galtellì ignimbrites (284±15 Ma), Del Moro *et al.* (1996) on the Gallura rhyolites (288±11 Ma), and Pittau *et al.* (1999a) on the rhyolitic-rhyodacitic lavas intercalated in the Guardia Pisano sequence (295±5 Ma, SHRIMP). These measurements are in good agreement with macro- and microfloral associations, which point to a basal Permian age for the bulk of the first-cycle sequences. Geochronological Rb/Sr and Ar-Ar age determinations on whole rocks and mineral separates were also performed on a great number of Late Paleozoic dykes throughout the island (Vaccaro *et al.*, 1991).

For these authors and for Atzori and Traversa (1986), this type of magmatism in Sardinia was largely heterochronous, both preceding and following the Permian effusive activity. The dyke activity probably occurred during two phases: the first one, represented by calcalkaline, normal to high potassium and peraluminous anatectic lithotypes, developed during two different stages, at 298-289 Ma and 270 Ma; the second phase, which is represented almost exclusively by basaltic products and rare peraluminous rhyolitic dykes (subalkaline and transitional types are found in central-southern Sardinia, while alkaline types are restricted to the north), shows ages of approximately 230 Ma.

The geochronology of the second cycle is more doubtful and, conversely with respect to the preceding cycle, is not controlled by a paleontological record. As previously stated, the alkaline affinity of Monte Santa Giusta ignimbrites prompts comparison with the Late Permian ("Saxonian-Thuringian") activity developed in other western Mediterranean areas, like Corsica and Provence.

As shown, the evolution and timing of the Late Paleozoic to Middle Triassic sequences of Sardinia may not be properly unravelled until new isotopic dating measurements or paleontological discoveries are made.

Acknowledgements – The author acknowledges Prof. G. Cassinis (Università di Pavia) for the basic impulse of this research, and is grateful also to Prof. P. Pittau (Università di Cagliari), L. Cortesogno and L. Gaggero (Università di Genova), J. Broutin (Paris 6), and E. Sarria (Progemisa S.p.A.) for useful discussions and suggestions. This work has been carried out with a post-doctoral grant (Università di Cagliari), CNR and MURST (Università di Pavia) funds. Proff. G. Cassinis and S. Barca (U. Cagliari) are also acknowledged for their careful and appreciated review of the paper.

REFERENCES

ATZORI P. & TRAVERSA G., 1986. Post-granitic Permo-Triassic dyke magmatism in eastern Sardinia (Sarrabus *p.p.*, Barbagia, Mandrolisai, Goceano, Baronie and Gallura). *Period. Mineral.*, 55: 203-231.

BARCA S., DEL RIO M., & PITTAU DEMELIA P., 1992. Lithostratigraphy and microfloristic analysis of the fluvial-lacustrine Autunian basin in the Sulcis area (south-western Sardinia, Italy). In: Carmignani L. & Sassi F. P. (eds), *Contribution of the Geology of Italy, with special regard to the Palaeozoic basements.* IGCP project No. 276, Newsletter, Siena, 5: 45-49.

BARCA S., CARMIGNANI L., ELTRUDIS A. & FRANCESCHELLI M., 1995 a. Origin and evolution of Permo-Carboniferous basin of Mulargia Lake (south-central Sardinia, Italy) related to the Late-Hercynian extensional tectonics. *C. R. Acad. Sci. Paris*, 321, ser. IIa: 171-178.

BARCA S., COSTAMAGNA L. G. & DEL RIO M., 1995 b. Affioramenti permo-carboniferi e mesotriassici fra Porto Piscinas e Punta Acqua Durci (Arburese, Sardegna SW). *Boll. Soc. sarda Sci. Nat.*, Sassari, 30: 1-11.

BECCALUVA L., CIVETTA L., MACCIOTTA G. & RICCI C., 1985. Geochronology in Sardinia: results and problems. *Rend. Soc. Ital. Mineral. Petrol.*, 40: 57-72.

BROUTIN J. & RONCHI A., 1999. The Lower Permian deposits of Punta Lu Caparoni. Palaeontological data. Excursion 4: The Permian and Triassic stratigraphic record in northwestern Sardinia (Nurra). In: Cassinis G., Cortesogno L., Gaggero L., Pittau P., Ronchi A. & Sarria E. (Coordinators), *Late Palaeozoic continental basins of Sardinia. Field trip guidebook.* Intern. Field Conf. on "The continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations", 15-25 Sept. 1999, Brescia: 98-101.

BROUTIN J., CABANIS B., CHATEAUNEUF J-J & DEROIN J-P., 1994. Evolution biostratigraphique, magmatique et tectonique du domain paléotéthysien occidental (SW de l'Europe): implications paléogeographiques au Permien inférieur. *Bull. Soc. géol. France*, 165/2: 163-179.

BROUTIN J., CASSINIS G., CORTESOGNO L., GAGGERO L., RONCHI A. & SARRIA E., 1996. Research in progress on the Permian deposits of Sardinia (Italy). *Permophiles*, 28: 45-48.

CALZIA P., CASSINIS G., RONCHI A. & SARRIA E., 1999. The Early Permian Seui Basin: stratigraphy and volcanism. Stratigraphy. Excursion 3. In: Cassinis G., Cortesogno L., Gaggero L., Pittau P., Ronchi A. & Sarria E. (Coordinators), *Late Palaeozoic continental basins of Sardinia. Field trip guidebook.* Intern. Field Conf. on "The continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations", 15-25 Sept. 1999, Brescia: 87-89.

CARRILLAT A., MARTINI A., ZANINETTI L., CIRILLI S., GANDIN A. & VRIELYNCK B., 1999. The Mushelkalk (Middle to Upper Triassic) of the Monte di Santa Giusta (NW Sardinia): sedimentology and biostratigraphy. *Eclogae geol. Helv.*, 92: 81-97.

CASSINIS G., 1996. Upper Carboniferous to Permian stratigraphic framework of Southwestern Europe and its implications- An overview. In: Moullade M. B. & Nairn A. E. M. (eds), *The Fanerozoic geology of the World. I. The Paleozoic, B.* Elsevier: 110-167.

CASSINIS G. & RONCHI A., 1997. Upper Carboniferous to Lower Permian continental deposits in Sardinia (Italy). *Geodiversitas*, 19/2: 217-220.

CASSINIS G., CORTESOGNO L., GAGGERO L., RONCHI A. & VALLONI R., 1996. Stratigraphic and petrographic investigations into the Permo-Triassic continental sequences of Nurra (NW Sardinia). *Cuad. Geol. Iberica*, spec. issue, 21: 149-169.

CASSINIS G., AVANZINI M., CORTESOGNO L., DALLAGIOVANNA G., DI STEFANO P., GAGGERO L., GULLO M., MASSARI F., NERI C., RONCHI A., SENO S., VANOSSI M. & VENTURINI C., 1998 a. Synthetic Upper Palaeozoic correlation charts of selected Italian areas. *Atti Ticin. Sci. Terra*, Pavia, 40: 65-120.

CASSINIS G., CORTESOGNO L., GAGGERO L. & RONCHI A., 1998 b. Osservazioni preliminari sulle successioni continentali permiane della Sardegna. *Rend. Ist. Lomb. Accad. Sci. e Lett.*, B., 130: 177-205.

COCOZZA T., 1967. Il Permo-Carbonifero del bacino di San Giorgio (Iglesiente, Sardegna sud-occidentale). *Mem. Soc. Geol. Ital.*, 6: 607-642.

COMASCHI CARIA I., 1959. Le piante fossili della Sardegna. *Mem. Riv. Ital. Paleont. Stratigr.*, 7: 176 pp.

CORTESOGNO L. & GAGGERO L., 1999 a. Permian continental basins of Sardinia: intra- and extra-basinal magmatic activity. In: Cassinis G., Cortesogno L., Gaggero L., Pittau P., Ronchi A. & Sarria E. (Coordinators), *Late Palaeozoic continental basins of Sardinia. Field trip guidebook.* Intern. Field Conf. on "The Continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations", 15-25 Sept. 1999, Brescia: 27-30.

CORTESOGNO L. & GAGGERO L., 1999 b. The Permian and Triassic calc-alkaline volcanic activity in Nurra. Excursion 4: The Permian and Triassic stratigraphic record in northwestern Sardinia (Nurra). In: Cassinis G., Cortesogno L., Gaggero L., Pittau P., Ronchi A. & Sarria E. (Coordinators), *Late Palaeozoic continental basins of Sardinia. Field trip guidebook.* Intern. Field Conf. on "The Continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations", 15-25 Sept. 1999, Brescia: 110-111.

CORTESOGNO L., CASSINIS G., DALLAGIOVANNA G., GAGGERO L., OGGIANO G., RONCHI A., SENO S. & VANOSSI M., 1998. The Post-Variscan volcanism in Late Carboniferous-Permian sequences of Ligurian Alps, Southern Alps and Sardinia. *Lithos*, 45: 305-328.

COSTAMAGNA L.G., BARCA S., DEL RIO M. & PITTAU P., 2000. Stratigrafia, paleogeografia ed analisi di facies deposizionale del Trias del Sarcidano-Gerrei (Sardegna SE). *Boll. Soc. Geol. Ital.*, 119: 473-496.

COZZUPOLI D. & LOMBARDI G., 1969. Le facies eruttive della Barbagia di Seulo e Seui (Nuoro). La serie del M.te Perdedu. *Quaderni Ist. di Petrografia*, Roma, 6: 116 pp.

COZZUPOLI D., DISCENDENTI A., LOMBARDI G. & NICOLETTI M., 1971. Cronologia K-Ar delle manifestazioni eruttive del settore di Seui-Seulo (Barbagia, Sardegna). *Period. Mineral.*, 40: 113-124.

COZZUPOLI D., GERBASI G., NICOLETTI M. & PETRUCCIANI C., 1984. Età K-Ar delle ignimbriti permiane di Galtellì (Orosei, Baronie-Sardegna orientale). *Rend. Soc. Ital. Mineral. Petrol.*, 39: 471-477.

DEL MORO A., DI PISA A. & OGGIANO G., 1996. Relationship between an Autunian volcano-sedimentary succession and the Tempio Massif granites (Northern Sardinia). Geochronological and field constraints. *Plinius*, 16: 94-95.

DEL RIO M., 1973. Palinologia di un livello Permo-Carbonifero del bacino di San Giorgio (Iglesiente, Sardegna sud-occidentale). *Boll. Soc. Geol. Ital.*, 92: 485-494.

DEL RIO M. & PITTAU P., 1999. The Upper Carboniferous of the San Giorgio Basin. Excursion 1. In: Cassinis G., Cortesogno L., Gaggero L., Pittau P., Ronchi A. & Sarria E. (Coordinators), *Late Palaeozoic continental basins of Sardinia. Field trip guide-*

book. Intern. Field Conf. on "The Continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations", 15-25 Sept. 1999, Brescia: 37-43.

DOUBINGER J., 1974. Etudes palynologiques dans l'Autunien. *Rev. Paleobot. Palynol.*, 17: 21-38.

EDEL J. B., MONTIGNY R. & THUIZAT R., 1981. Late Palaeozoic rotations of Corsica and Sardinia: New evidence from paleomagnetic and K-Ar studies. *Tectonophysics*, 79: 201-223.

FONDI R., 1979. Orme di microsauri nel Carbonifero superiore della Sardegna. *Mem. Soc. Geol. Ital.*, 20: 347-356.

FONTANA D., GELMINI R. & LOMBARDI G., 1982. Le successioni sedimentarie e vulcaniche carbonifere e permo-triassiche della Sardegna. In: Carmignani L., Cocozza T., Ghezzo C., Pertusati P. C. & Ricci C. A. (eds), *Guida alla geologia del Paleozoico sardo, Guide geologiche regionali.* Mem. Soc. Geol. Ital., 18: 183-192.

FONTANA D., NERI C., RONCHI A. & STEFANI C., this volume. Stratigraphic architecture and composition of the Permian and Triassic siliciclastic succession of Nurra (northwestern Sardinia). In: Proc. of the *Intern. Field Conf. on "The continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations"*, 15-25 Sept. 1999, Brescia.

FRANCAVILLA F., CASSINIS G., COCOZZA T., GANDIN A., GASPERI G., GELMINI R., RAU A., TONGIORGI M. & VAI G.B., 1977. Macroflora e datazione di alcuni affioramenti (tardo) - postercinici presso il Lago di Mulargia (Sardegna sud-orientale). In: Vai G.B. (ed.), *Boll. Gruppo di Lavoro sul Paleozoico, Escursione in Sardegna*, 2: 31-33.

GANDIN A., GASPERI G. & GELMINI R., 1977. Il passaggio Permo-Trias in Sardegna. In: Vai G.B. (ed.), *Boll. Gruppo di Lavoro sul Paleozoico, Escursione in Sardegna*, 2: 35-37.

GASPERI G. & GELMINI R., 1980. Ricerche sul Verrucano. 4. Il Verrucano della Nurra (Sardegna nord-occidentale). *Mem. Soc. Geol. Ital.*, 20 (1979): 215-231.

GELMINI R., 1985. A paleogeographycal reconstruction of the Permo-Triassic circumtyrrenian area. *Boll. Soc. Geol. Ital.*, 104: 561-74.

LAURO G., NEGRETTI G. C. & SBARACCANI M., 1963. Contributo alla conoscenza delle formazioni permiane di Seui (Barbagia, Sardegna). *Giorn. Geologia*, 31: 281-309.

LOMBARDI G., COZZUPOLI D. & NICOLETTI M., 1974. Notizie geopetrografiche e dati sulla cronologia K-Ar del vulcanismo tardo-paleozoico sardo. *Period. Mineral.*, 43: 221-312.

LOTTI B., 1931. Relazione generale riassuntiva dei tre sondaggi per la ricerca del carbone paleozoico nei piani di Alghero. *Boll. R. Uff. Geol.*, LVI/6: 5-15.

NERI C. & RONCHI A., 1999. The Buntsandstein deposits of Mt. Santa Giusta. Excursion 4: The Permian and Triassic stratigraphic record in northwestern Sardinia (Nurra). In: Cassinis G., Cortesogno L., Gaggero L., Pittau P., Ronchi A. & Sarria E. (Coordinators), *Late Palaeozoic continental basins of Sardinia. Field trip guidebook.* Intern. Field Conf. on "The continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations", 15-25 Sept. 1999, Brescia: 108-109.

PECORINI G., 1962. Nuove osservazioni sul Permico della Nurra (Sardegna nord-occidentale). *Atti Acc. Naz. Lincei, Rend. Cl. Sci. fis. mat. e nat.*, ser. 8, 32: 377-380.

PECORINI G., 1974. Nuove osservazioni sul Permo-Trias di Escalaplano (Sardegna sud-orientale). *Boll. Soc. Geol. Ital.*, 93: 991-999.

PITTAU P., 1999. The Triassic succession of northwestern Sardinia: data from the subsurface. Excursion 4: The Permian and Triassic stratigraphic record in northwestern Sardinia (Nurra). In: Cassinis G., Cortesogno L., Gaggero L., Pittau P., Ronchi A. & Sarria E. (Coordinators), *Late Palaeozoic continental basins of Sardinia. Field trip guidebook.* Intern. Field Conf. on "The continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations", 15-25 Sept. 1999, Brescia: 106-107.

PITTAU DEMELIA P. & DEL RIO M., 1980. Pollini e spore del Trias medio e del Trias superiore negli affioramenti di Campumari e di Ghiscera Mala (Sardegna). *Boll. Soc. Paleont. Ital.*, 19 (2): 241-249.

PITTAU DEMELIA P. & FLAVIANI A., 1982. Aspects of the palynostratigraphy of the Triassic Sardinia sequences (Preliminary report). *Rev. Palaeobot. Palynol.*, 37: 329-343.

PITTAU P., DEL RIO M., PUTZU T. & BARCA S., 1999 a. The Permian of Guardia Pisano basin (Sulcis). Excursion 1. In: Cassinis G., Cortesogno L., Gaggero L., Pittau P., Ronchi A. & Sarria E. (Coordinators), *Late Palaeozoic continental basins of Sardinia. Field trip guidebook.* Intern. Field Conf. on "The Continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations", 15-25 Sept. 1999, Brescia: 44-57.

PITTAU P., DEL RIO M. & RONCHI A., 1999 b. The Middle Triassic of Escalaplano (Central Sardinia). Excursion 2. In: Cassinis G., Cortesogno L., Gaggero L., Pittau P., Ronchi A. & Sarria E. (Coordinators), *Late Palaeozoic Continental Basins of Sardinia, Field Trip Guidebook.* Intern. Field Conf. on "The Continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations", 15-25 Sept. 1999, Brescia: 65-72.

POMESANO CHERCHI A., 1968. Studio bio-stratigrafico del sondaggio Cugiareddu nel Trias e Permico della Nurra (Sardegna nord-occidentale). *Ist. Geol. e Paleont. Univ. Cagliari*, 61: 7-51.

RONCHI A., 1997. I prodotti sedimentari e vulcanici dei bacini permiani di Escalaplano e Perdasdefogu nella Sardegna sudorientale: stratigrafia e loro inquadramento nell'evoluzione tardo-paleozoica del settore sudeuropeo. *Tesi di Dottorato,* Univ. di Parma: 231 pp.

RONCHI A., BROUTIN J., DIEZ B., FREYTET P., GALTIER J. & LETHIERS F., 1998. New paleontological discoveries in some Early Permian sequences of Sardinia. Biostratigraphic and paleogeographic implications. *C. R. Acad. Sci. Paris,* 327: 713-719.

SARRIA E. & SERRI R., 1986. Tettonica compressiva tardo paleozoica nel bacino antracitifero di Seui (Sardegna Centrale). *Rend. Soc. Geol. Ital.*, 9: 7-10.

SPANO C., 1976. Nuovo contributo alla conoscenza delle piante del Paleozoico della Sardegna. *Rend. Seminari Fac. Sci. Univ. Cagliari*, 46: 385-433.

TRAVERSA G., 1979. Permian volcanism in Sardinia. F.P. Sassi (ed.): *Newsletter 1, IGCP Project n. 5*: 127-140.

TRAVERSA G. & VACCARO C., 1992. REE distribution in the Late Hercynian dikes from Sardinia. In: Carmignani L. & Sassi F.P. (eds)., *Contributions to the geology of Italy, with special regards to the Palaeozoic basements.* IGCP N. 276, Newsletter, 5, Siena: 215-226.

VACCARO C., ATZORI P., DEL MORO A., ODDONE M., TRAVERSA G. & VILLA I.G., 1991. Geochronology and Sr isotope geochemistry of late-Hercynian dykes from Sardinia. *Schweiz. mineral. petrogr. Mitt.*, 71: 221-230.

VARDABASSO S., 1939. Der Permische Vulkanismus in Sardinien. *Geol. Rdsch.*, 48: 159-172.

VARDABASSO S., 1966. Il Verrucano sardo. Atti del Symposium sul Verrucano. *Soc. Tosc. Sc. Nat.*, Pisa Sett. 1965: 293-310.

«NATURA BRESCIANA» Ann. Mus. Civ. Sc. Nat., Brescia, MONOGRAFIA N. 25, 2001: 149-161

STRATIGRAPHIC ARCHITECTURE AND COMPOSITION OF THE PERMIAN AND TRIASSIC SILICICLASTIC SUCCESSION OF NURRA (NORTHWESTERN SARDINIA)

DANIELA FONTANA [1], CLAUDIO NERI [2], AUSONIO RONCHI [3] and CRISTINA STEFANI [4]

Key words – Stratigraphy; red beds; arenite composition; Sardinia; Permian-Triassic.

Abstract – This work represents a preliminary revision of the terrigenous Permian and Triassic stratigraphic successions of the Nurra region (northwestern Sardinia). On the basis of lithostratigraphical, sedimentological and petrographic evidence, supported by scattered and rare biostratigraphical data, the whole post-Variscan succession has been subdivided into the following units: I) the "Punta Lu Caparoni Formation" (PLC), made by the traditional alluvial-to-lacustrine deposits and upwards by a whitish succession which corresponds to the unit 1 of Gasperi & Gelmini, 1980; II) a volcanic-bearing unit of problematic geochemistry, scarcely cropping out in the Lu Caparoni-Cala Viola area and well-documented in the Monte Santa Giusta section, where shows an alkaline composition; III) a clastic unit of reddish conglomerates, sandstones and minor pelites, rich in volcanic-derived clasts; as in the Monte Santa Giusta, this unit represents a fining-upwards sequence, evolving from alluvial fan/braided river settings to meandering river and coastal plain deposits, and corresponds to units 2 and 3 of Gasperi & Gelmini (1980); IV) an upper clastic unit, separated from the underlying deposits by a marked disconformity. It comprises a basal quartz conglomerate grading upwards into reddish sandstones and minor pelites, showing alternating fluvial and tidal influx.
Scarce biostratigraphical data allow us to relate the base of the investigated siliciclastic succession to the Early Permian ("Autunian" Auct.) and the top to an Olenekian (?)-early Anisian to late Anisian time, but do not allow a chronostratigraphical classification, unit by unit, of the whole sequence and the evaluation of the duration of hiatuses at the main unconformities.

Parole chiave – Stratigrafia; *red beds*; composizione delle areniti; Sardegna; Permiano-Triassico.

Riassunto – Questo lavoro fornisce una revisione preliminare della successione permiana e triassica della Nurra dal punto di vista stratigrafico, sedimentologico e composizionale. Sulla base di nuovi dati di campagna, gli autori propongono di suddividere la successione in quattro unità principali: I) la "Formazione di Punta Lu Caparoni" (PLC), che oltre ai tradizionali depositi alluviolacustri comprende, per la prima volta, la sovrastante unità clastica, di colore biancastro, già denominata come unità 1 da Gasperi & Gelmini (1980); II) uno o più corpi vulcanici, rappresentati da ignimbriti e tufi a composizione riolitica, spesso molto alterati. Questi prodotti affiorano sia ad un livello stratigrafico imprecisato tra la PLC e la successione rossastra permiana e triassica di Lu Caparoni-Cala Viola e sia, benchè la correlazione tra i rispettivi episodi vulcanici risulti tuttora incerta, alla base della sezione di Monte Santa Giusta; III) la successione soprastante, che corrisponde alle unità 2 e 3 di Gasperi & Gelmini (1980), è costituita da conglomerati e arenarie fluviali, con abbondanti clasti di origine vulcanica. In base ai dati forniti dalla sezione di Monte Santa Giusta, per quanto condensata e lacunosa, si può ritenere che le unità 2 e 3 di Gasperi & Gelmini (1980) costituiscano un'unica sequenza fining-upward, con transizione da facies braided a facies meandriformi e quindi di piana costiera; IV) l'unità silicicla̍stica superiore (unità 4 di Gasperi & Gelmini, 1980) è discordante sulla successione precedente; la discordanza è marcata da un banco conglomeratico ricco in ciottoli di quarzo provenienti dal basamento metamorfico. Verso l'alto passa ad arenarie a stratificazione incrociata bipolare e successivamente a siltiti ed arenarie fini con influssi alternativamente fluviali e tidali.
Il limite con i soprastanti depositi del Muschelkalk è graduale e parzialmente visibile nella sezione di Monte Santa Giusta, mentre a Cala Viola la successione si trova in contatto tettonico con i sedimenti del Keuper.
I dati composizionali indicano contributi prevalenti dal basamento metamorfico e dalle vulcaniti permiane. Con la deposizione dell'unità sommitale (IV), arenarie e conglomerati mostrano un'elevata maturità tessiturale e composizionale, con un consistente incremento nella quantità di quarzo.
Sulla successione in esame sono disponibili solo rari dati cronostratigrafici. La parte inferiore della "Formazione di Punta Lu Caparoni" è datata al Permiano inferiore ("Autuniano" *Auct.*) in base al contenuto macrofloristico e palinologico; la parte superiore dell'unità IV a Cala Viola ha fornito flore mal conservate (*Equisetum* cfr. *mougeotii*). Le associazioni palinologiche rinvenute nel pozzo Cugiareddu, entro depositi clastici probabilmente correlabili con l'unità IV, indicherebbero la presenza dell'Olenekiano(?)-Anisico inferiore e dell'Anisico superiore.

[1] Dipartimento di Scienze della Terra, Università di Modena, Largo S. Eufemia 19, 41100 Modena, Italy.
[2] Dipartimento di Scienze Geologiche e Paleontologiche, Università di Ferrara, Corso Ercole I d'Este 32, 44100 Ferrara, Italy.
[3] Dipartimento di Scienze della Terra, Università di Pavia, Via Ferrata 1, 27100 Pavia, Italy.
[4] Dipartimento di Geologia, Paleontologia, Geofisica, Università di Padova, Via Giotto 1, 35137 Padova, Italy.

INTRODUCTION

In the Nurra region (northwestern Sardinia), a post-Variscan continental succession, represented by terrigenous deposits intercalated with volcaniclastic products, is discontinuously exposed (Fig. 1). It has been the subject of a number of studies: Lotti (1931), Oosterbaan (1936), Moretti (1959), Pecorini (1962), Vardabasso (1966), Gasperi & Gelmini (1980), Fontana *et al.* (1982), Gelmini (1985), Cassinis *et al.* (1996, 1998a, 1998b) and Neri *et al.* (1999). The present study concerns the stratigraphy, sedimentology and composition of such a red-bed succession, in the Alghero area, between Punta Lu Caparoni to the north and Cala Viola to the south (Fig. 1).

Gasperi & Gelmini (1980) provided the first lithostratigraphical classification of the succession, subsequently accepted by most researchers (*e.g.*, Cassinis *et al.*, 1996, 1998a, 1998b). According to their classification, the whole post-Variscan and sub-Muschelkalk (using the terminology of Owen, 1987) terrigenous succession has been divided into a thin, discontinuous formation (Punta Lu Caparoni Fm.), Early Permian in age, and in a terrigenous sequence, 200-300 m thick. The terrigenous sequence is in turn divided into four informal units: unit 1 comprises mainly quartz conglomerates and coarse whitish sandstones; unit 2 consists of reddish conglomerate and sandstones, with clasts of volcanic and metamorphic rocks; unit 3 consists of grey sandstones with tabular and trough cross-stratification, alternating with upward-increasing red siltstones; unit 4 begins with coarse quartz conglomerate and grades into fine to medium-grained sandstones.

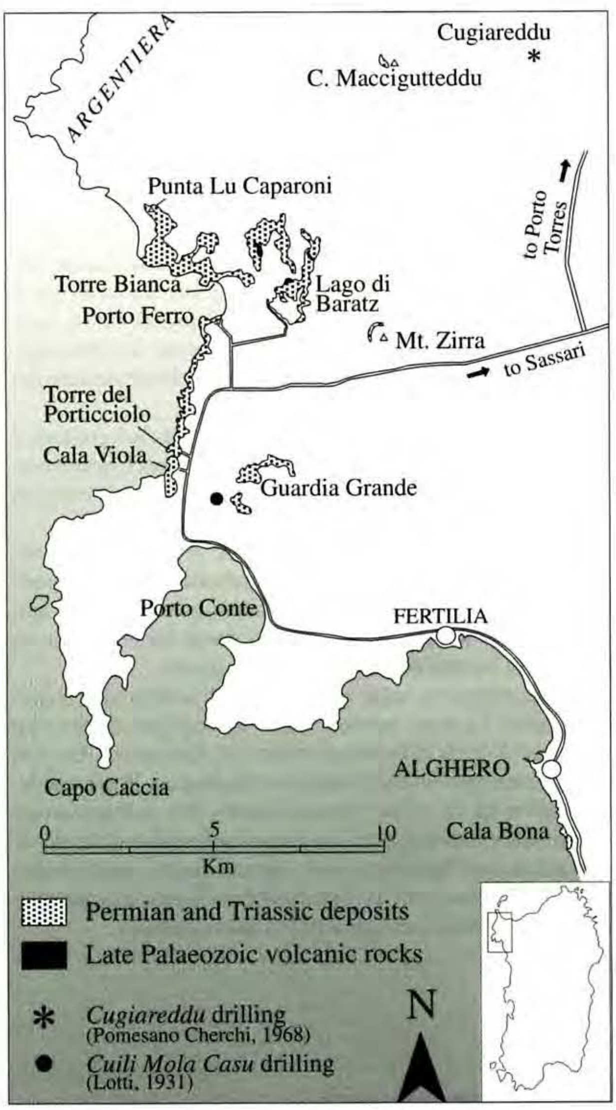


Fig. 1 – Location map of the main outcrops of the Permian and Triassic deposits in the Nurra region.

The vertical transition from these siliciclastic deposits into the Middle Triassic carbonates (Muschelkalk) is not exposed over a great part of the investigated area, mainly due to tectonics, with the remarkable exception of Monte Santa Giusta (Carrillat *et al.*, 1999; Neri & Ronchi, 1999) and of the Cugiareddu borehole (Pomesano Cherchi, 1968).

The biochronostratigraphical data are poor, and limited to the basal and upper portions of the succession; the base (Punta Lu Caparoni Fm. *s.s.*) yields plant remains and palynomorphs of Early Permian ("Autunian") age. The upper portions of unit 4 (*sensu* Gasperi & Gelmini, 1980) contain a scattered and poorly preserved paleoflora (*Equisetum* cfr. *mougeotii*, reported by Pecorini, 1962) indicating a presumed Olenekian(?)-early Anisian to late Anisian, on the basis of two differing palynological associations of the top of the Permian and Triassic sequence, from the Cugiareddu well (Pittau Demelia & Flaviani, 1982; Pittau, 1999). A considerable time-span is encompassed by these two age-data points; we have tried to achieve new biostratigraphical data through a systematic sampling of the rare grey pelite horizons intercalated into the sequence, for palynological study, but without appreciable results. Thus, the stratigraphic gap associated with the unconformity between units 3 and 4 of Gasperi & Gelmini (1980) cannot be estimated.

An attempt has been made by Cassinis *et al.* (1996, 1998a) and Neri *et al.* (1999) to correlate the Permian and Triassic succession of Nurra to the "Two Tectonosedimentary Cycles" model proposed by the Italian IGCP 203 Group (1986) for the South-Alpine area. Unfortunately, the poor biostratigraphical data and the fact that boundaries between units 1, 2 and 3 have not been observed in the field, prevent such a correlation. We need more data on bounding unconformities (real or presumed) and their ages.

However, research recently carried out by the authors may lead to a new lithostratigraphical subdivision for the

Permian and Triassic succession of the Nurra region, as documented in the following sections (note that we use the numbers 1, 2, 3 and 4 to indicate units of Gasperi & Gelmini, 1980 and roman numerals I, II, III and IV for new units from this work). Since an important sector of the study area (*i.e.*, the steep sea-cliff south and west of Punta Lu Caparoni) has not yet been investigated, we do not propose new formation names here.

STRATIGRAPHY

Punta Lu Caparoni section

According to the lithostratigraphy of Gasperi & Gelmini (1980), this section, about 45 m thick, consists, of two units, separated by a marked disconformity. They are the Punta Lu Caparoni Fm. and unit 1 of the Permian and Triassic terrigenous succession.

The first unit (Figs 2 and 3) begins with a poorly sorted conglomerate, about 1 m thick, mainly consisting of angular clasts derived from the local phyllitic basement.

Dark-grey laminated shales, siltstones and fine-grained

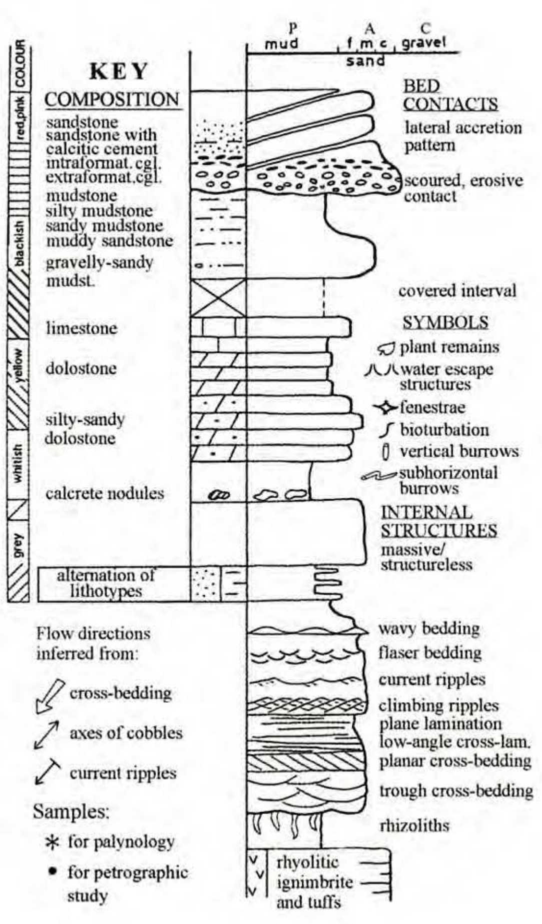


Fig. 2 – Legend of symbols for Figs 3, 5, 6 and 7.

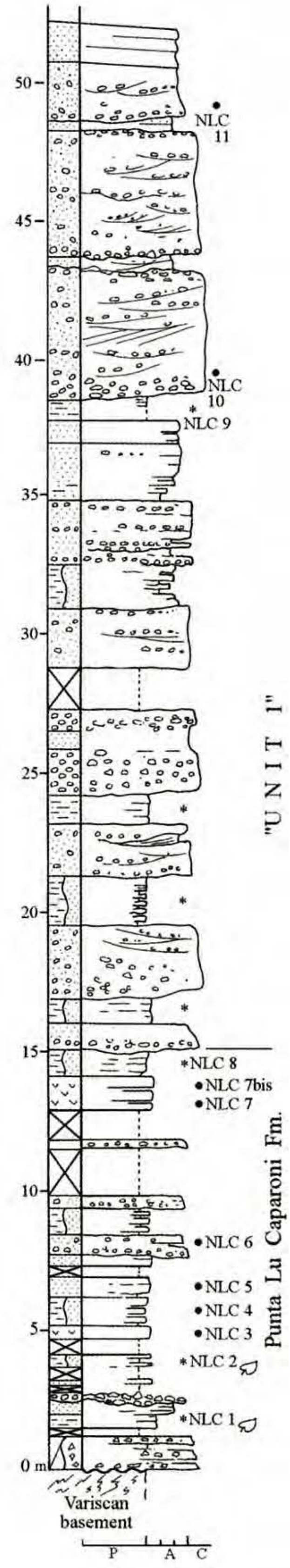
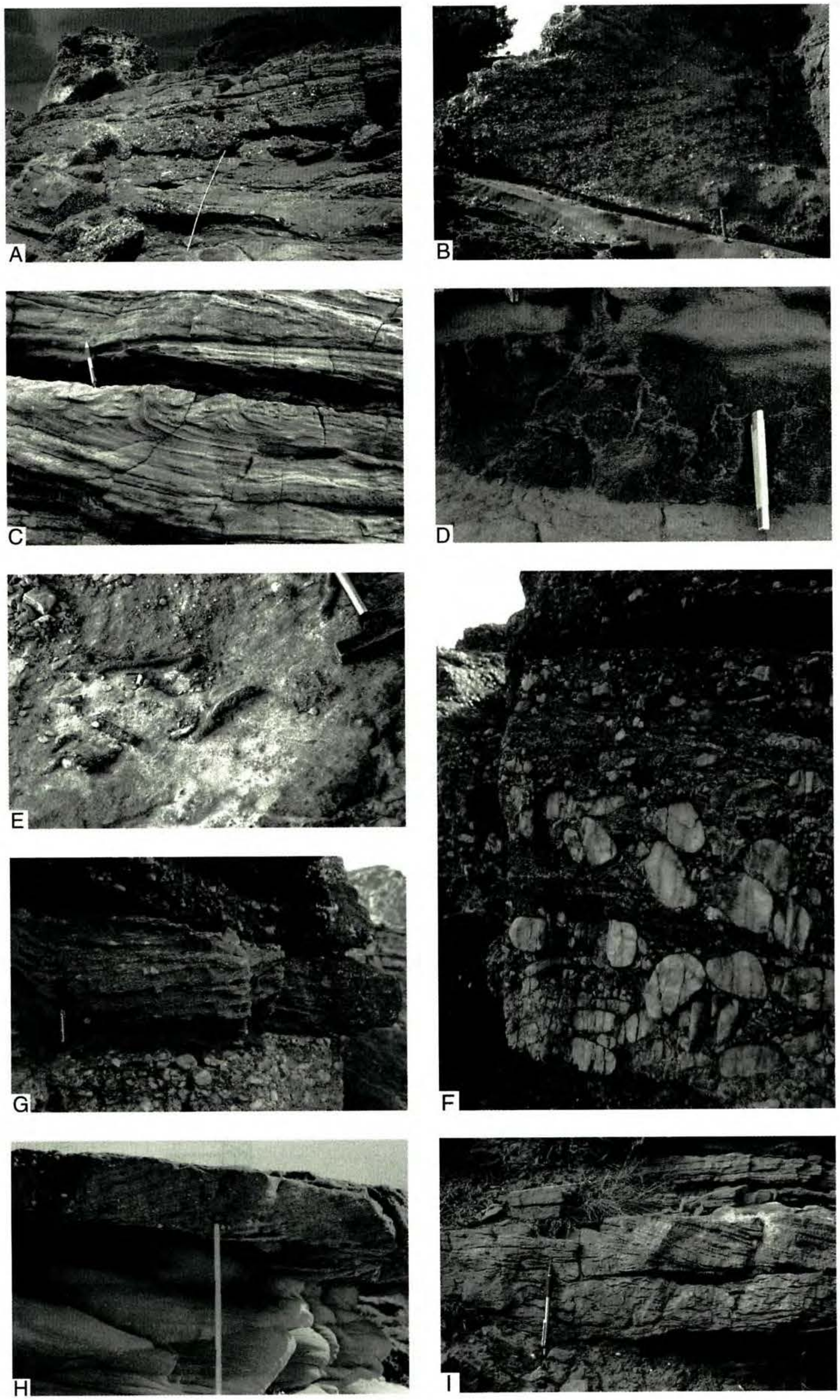


Fig. 3 – Stratigraphic section of Punta Lu Caparoni (symbols as in Fig. 2); Unit 1 and Lu Caparoni Fm. *sensu* Gasperi & Gelmini, 1980.



sandstones are present upwards. Two main fossil-bearing horizons occur in this part of the section, about 5 m thick, yielding Autunian macrofloras and palynomorphs of Early Permian age (Pecorini, 1962; Broutin *et al.*, 1996, 1999).

The following tract of Punta Lu Caparoni Fm. (about 10 m thick) is discontinuously exposed. However, it does show some decimetre- to metre-scale conglomerate intercalations, with clasts of quartz and phyllites, alternating with sandstones and siltstones. Yellowish and grey massive fines, constituting decimetre- to metre-thick horizons with ferruginous crusts at the top, also occur: they are interpreted as kaolinised cinerites, and the crusts may represent pedogenic horizons.

Similar deposits also occur in the lower and middle part of the overlying unit 1 of Gasperi & Gelmini (1980), alternating with quartz-conglomerates and coarse sandstone bodies, increasing in thickness upwards. These coarse-grained bodies typically have scoured, erosional lower boundaries and marked lateral variations in thickness, mainly due to the deepness of scouring.

The strongly channelised bodies, separated by considerable amounts of fines, grade upwards into laterally-continuous conglomerate and coarse sandstone units, several metres thick, with trough cross-bedding. The uppermost part of the section is represented by a sandstone body showing a lateral accretion pattern.

Evidence of volcanic activity in these upper deposits is clearly represented by high percentage of embayed quartz and volcanic rock fragments, as well as by fine volcaniclastics.

Facies interpretation. A possible interpretation of such a vertical evolution of the facies pattern may be the following:

– A fluvial-lacustrine environment may be suggested for the lowermost part of the section, dominated by siltstones rich in plant remains. The basin was probably small in size; other deposits cropping out in the Nurra region and referred to as the Punta Lu Caparoni Fm. were probably laid down in separate, endoreic basins.

– Coarse sandstone to conglomerate bodies, progressively increasing in thickness, encroach on the sandy-pelite lacustrine deposits; each coarse-grained body has a disconformable base, so it is difficult to indicate a major-rank disconformity, separating the Punta Lu Caparoni Fm. *sensu* Gasperi & Gelmini (1980) from the overlying unit 1.

Finally, the tabular cross-bedded bodies may indicate the presence of a widely-distributed braided-river environment, possibly followed upwards by a meandering-river regime (Fig. 3). Unfortunately, we lack biostratigraphical data to support the continuity between the two above units.

Torre Bianca section

In the Torre Bianca area the deposits corresponding to unit 2 of Gasperi & Gelmini (1980) crop out with good exposures. A continuous tract more than 50 m thick can be observed, but its lower and upper boundaries are not exposed. Moreover, considerable tectonic deformation (faulting) separates this section from other outcrops in the area.

The section has not been measured in detail, but carefully examined and documented by photos and drawings of the main facies. Spectacular outcrops show the facies model of this tract, mainly dominated by braided river depositional settings (Figs 4A and 4B).

The main lithofacies are represented by conglomerates and conglomeratic coarse sandstones, with clasts deriving both from the "porphyric" volcanics and the metamorphic Variscan basement (quartz, minor phyllites). Depositional structures consist of metre-sized trough cross-bedding and, subordinately, tabular cross-bedding forming sets up to a metre thick; they probably record longitudinal bars (Fig. 4B).

Torre del Porticciolo and Cala Viola sections

The Torre del Porticciolo and Cala Viola sections (Figs 5 and 6) have been measured along the coastline between Cala del Turco and Cala Viola. Both sections may be subdivided into two units, separated by an impressive unconformity, and corresponding to units 3 and 4 of Gasperi & Gelmini (1980) respectively. Only the upper part of unit 3 crops out, and this makes defining the relationship with the underlying units problematic. Unit 4 crops out from the base, but its upper portion is cut by faults. In fact, this unit at Cala Viola is overlain, through a tectonic contact, by Keuper evaporites and dolomites.

The lower unit (unit 3) is represented by grey-green to

Fig. 4 – A: sedimentary facies in the Torre Bianca area. Cross-cutting conglomeratic bodies represent braided-river dominated setting; B: thick (about 1.20 m) conglomeratic body with planar, cross-bedding probably showing the frontal accretion of a longitudinal bar. Torre Bianca section; C: water escape structures on low-angle parallel lamination in the arenites of Torre del Porticciolo section. These deposits represent a laterally-accreted channel fill; D: reddish floodplain deposits containing rhizoliths in the upper part of Torre del Porticciolo section; E: cylindrical, featureless, variably oriented burrows on a stratigraphic surface in the uppermost part of a channel body, Cala Viola section; F: sheet-like massive conglomerate bank with well rounded, imbricated quartz cobbles underlying the base of the upper unit in the Torre del Porticciolo section; G: tabular cross-lamination in the granule-cobble-bearing arenites at the top of the conglomerate bank. Unit 4 in the Torre del Porticciolo section; H: planar cross-bedding in the lower part of unit 4 in the Torre del Porticciolo section; I: flaser and wavy-bedded body cut by a small cross-bedded (lateral accretion?) channel-fill. Upper part of the Cala Viola section.

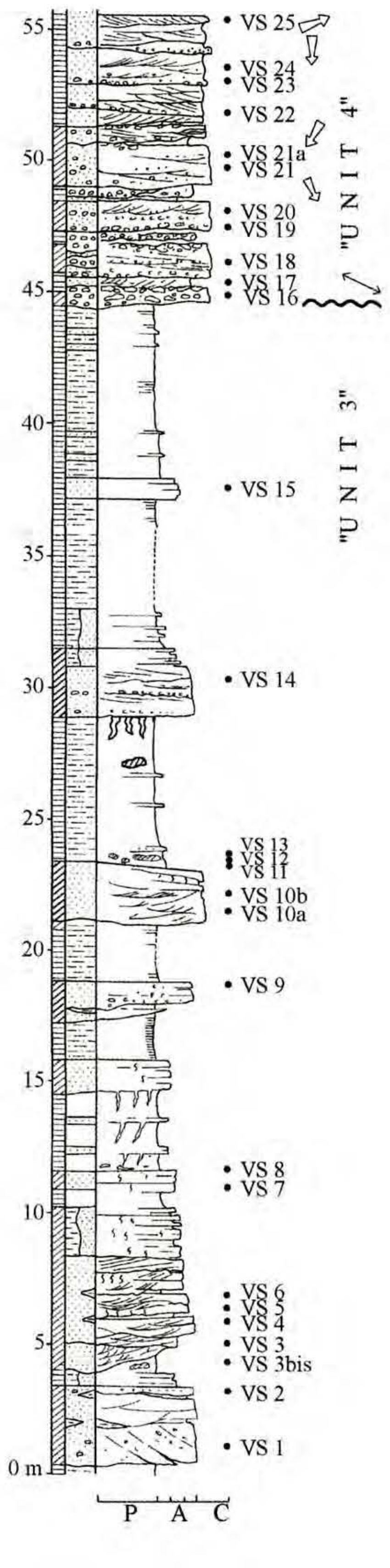


Fig. 5 – Stratigraphic section of Torre del Porticciolo (see Fig. 2 for legend); Units 3 and 4 *sensu* Gasperi & Gelmini, 1980.

brown channelised arenitic bodies decreasing in thickness and lateral continuity upwards in the section, interbedded with reddish pelites (Figs 5 and 6). Sandstones are commonly medium- to coarse-grained, with sparse quartz pebbles, and form lenticular channel-fills, with a marked erosional base cutting into structureless (with the exception of pedogenic features) reddish siltstones and pelites. Arenitic bodies show a complex internal organisation, with trough- and planar cross-bedding and minor, lens-shaped, intercalations of reddish pelites (Figs 5 and 6). From the outcropping base of the sections (in particular, in the Torre del Porticciolo area), the channel-fills show clinostratified sets indicating lateral accretion (Fig. 4C). Sets are 20-30 cm thick, dipping at 25°-30°, and are separated by thin red pelitic interlayers. The internal structures of sandstone beds within the channel-fills include trough cross-bedding and low-angle to parallel lamination, accompanied by climbing ripple cross-lamination and water-escape structures (Fig. 4C).

Sheet-like sandstones with scarce lateral persistence are also present, intercalated with the channel-fill bodies; they display planar cross-bedding and parallel lamination. These arenitic layers become more frequent in the upper part of the unit, where silty-pelitic bodies increase in thickness.

Colour mottling and other pedogenetic features such as rhizoliths and carbonate concretions are frequent in the pelitic intervals, and become more abundant in the thicker layers (Fig. 4D). Bioturbation, common both in red pelites and in fine- to medium-grained sandstones, is represented by horizontal and vertical tubes on the set surfaces (Fig. 4E).

Facies interpretation. The overall facies model may indicate a sinuous (meandering?) channel complex for the lower part of the section, at least in the Torre del Porticciolo area. The thick reddish pelite horizons intercalated between channel-fills are interpreted as flood plain deposits on which pedogenic transformations took place. Geometry and sedimentary structures suggest that sheet-like arenitic layers intercalated within siltstones are crevasse-splay deposits. The main feature of the upper part of the unit is the very low lateral continuity of arenitic bodies (ribbon-like channel-fills) and the prevalence of pelites.

The upper unit (unit 4) overlies unit 3 through a distinctly disconformable contact and a sharp change in facies. The lowermost part of the unit, 6-8 m thick, consists of a sheet-like conglomerate bank of regional extension, internally subdivided into decimetre- to metre-thick sets with erosional bases; conglomerates are usually matrix-supported, with well-rounded, imbricated (a-axis), cobble-grade clasts made almost exclusively of quartz (Fig. 4F). Planar and trough cross-bedded sets of microconglomerate and coarse sandstone are intercalated.

The conglomerate bank grades upwards into a unit, 5-6 m thick, of pebbly coarse sandstones; they show planar and trough cross-bedding, frequently with tangential basal contacts and opposite dips of the laminae (Figs 4G and 4H).

The upper part of unit 4 crops out only in the Cala Viola section (Fig. 6); it is represented by medium-grained reddish arenites, with subordinate pelites, forming metre-sized flaser-bedded sets, locally evolving upwards into horizontal to low-angle laminated or trough cross-bedded thin sandstone layers (Fig. 4I). Metre-thick fining-upwards channel-fills occur at different levels. The uppermost part of the succession contains numerous small, 30-50 cm thick, erosive sand bodies with little lateral persistence; they are frequently rich in tabular-shaped to rounded intraclasts.

Facies interpretation. Facies analysis suggests that the basal coarse-grained conglomerate sheet was deposited within a braided fluvial system, probably during a tecton-

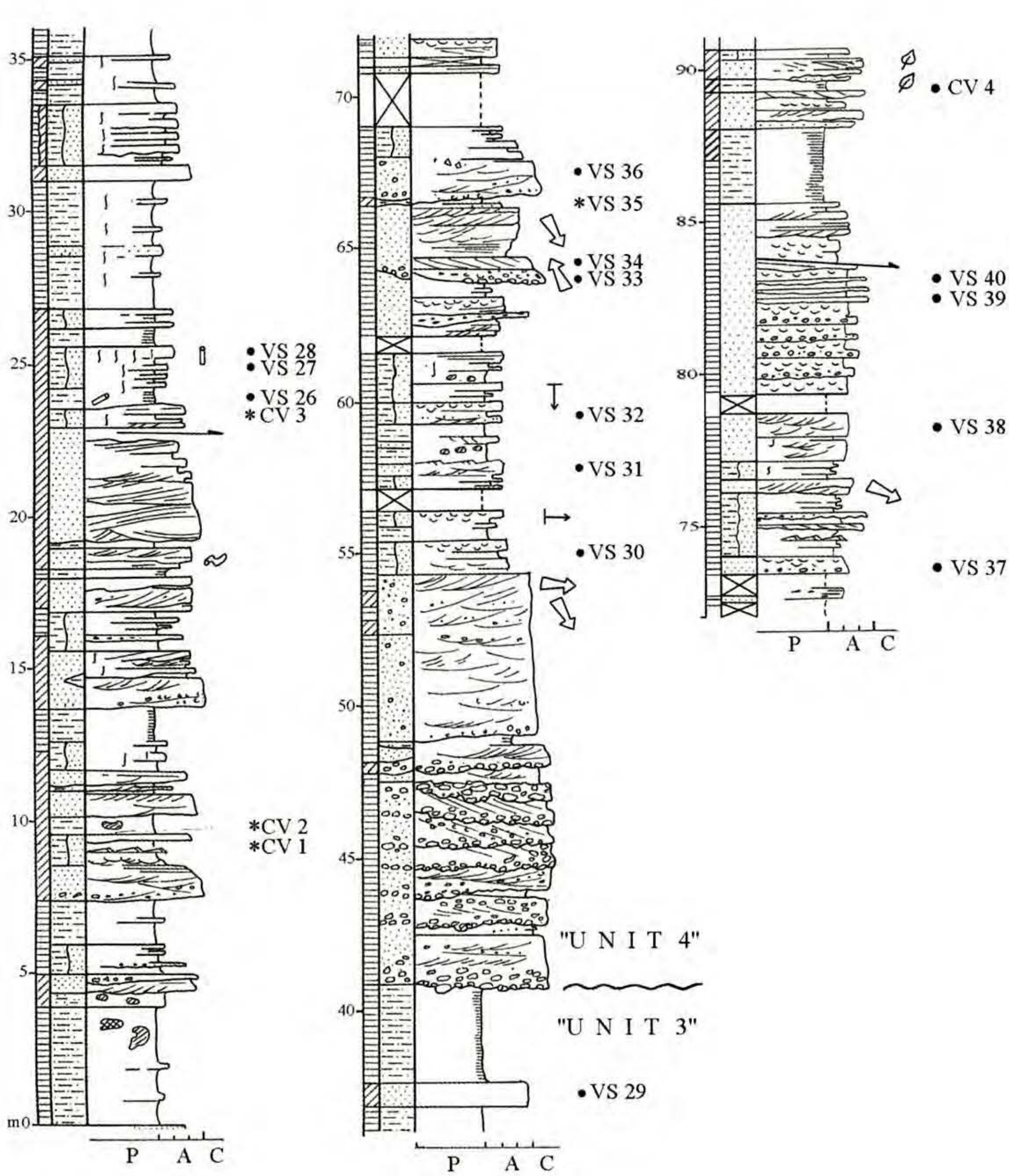


Fig. 6 – Stratigraphic section of Cala Viola (see Fig. 2 for legend); Units 3 and 4 *sensu* Gasperi & Gelmini, 1980.

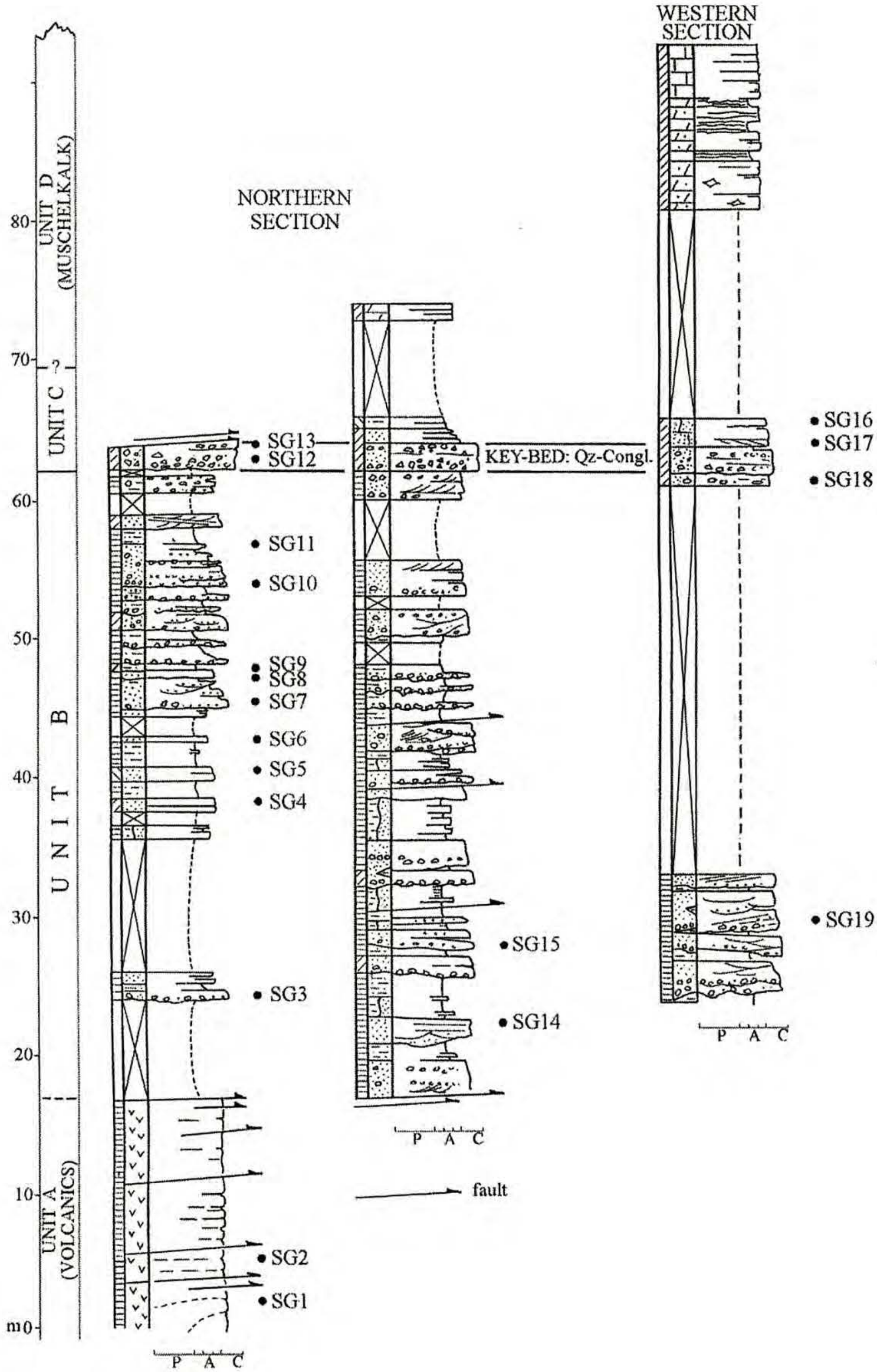


Fig. 7 – Monte Santa Giusta sections (see Fig. 2 for legend).

ically induced lowstand phase of the base level. The peculiar clast composition suggests a rejuvenation of the source area and a new phase of sedimentation after a long period of non-deposition. The presence of tidal sedimentary structures in the upper part of the unit might also suggest the progressive establishment of a transgressive setting in a coastal environment.

Monte Santa Giusta sections

Two sections (Fig. 7), representative of the sub-Muschelkalk succession, both poorly exposed, have been examined on the northern and western slopes of Monte Santa Giusta. They have been subdivided by Neri & Ronchi (1999) into the following units:

A) This unit is only recorded in the northern section and consists of volcanic products (ignimbrites), heavily weathered and tectonised. The rocks are made of reddish, roughly stratified "porphyries", with quartz and feldspar phenocrysts surrounded by an aphanitic matrix. Better-preserved volcanic rocks crop out just some tens of metres north of the section, but widespread cover masks their relationships with the sedimentary units (Lombardi *et al.*, 1974; Cassinis *et al.*, 1996).

B) Poorly exposed conglomerates with clasts deriving from both the Variscan basement and volcanics, sandstones and pelites, mainly reddish in colour. Although their fluviatile nature is evident, detailed facies analysis is prevented by the poor exposures. The thick, isolated, conglomerate/coarse sandstone body of the western section (Fig. 7), quite well-exposed, may have corresponded to a braided river setting.

C) The base of the unit consists of a light grey to whitish quartz conglomerate, a few metres thick, easily recognised and correlatable all around Monte Santa Giusta, and thus regarded as a key marker bed. It is overlain by a thin, poorly exposed silty-sandy succession.

D) This represents the base of the Muschelkalk and consists of dolostones with a high terrigenous content, silt to sand-sized, alternating with stromatolitic dolomites. The terrigenous content and the degree of dolomitisation decrease upwards, and fossiliferous fine-grained limestones become the main lithofacies.

Despite their poor exposure and relatively "condensed" nature, according to the authors, the sections of Monte Santa Giusta represent the key to understanding the Permian and Triassic succession of the Nurra region. If the volcanics occurring at the base of the northern section are correlatable with the volcanics intercalated in the lower part of unit 2 of the Porto Ferro-Lake Baratz area (Lombardi *et al.*, 1974), the conclusions may be:

– Unit B of Monte Santa Giusta correlates with units 2 (*p.p.*) and, possibly, 3 of Gasperi & Gelmini (1980).

– The quartz conglomerate of unit C may correlate, on the basis of lithofacies and stratigraphical setting, with the basal conglomerate of unit 4 *sensu* Gasperi & Gelmini (1980) in the Torre del Porticciolo and Cala Viola sections.

However, the observed multiple faults in the Monte Santa Giusta sections could be responsible of the above "condensed" and/or incomplete succession, and to explain the apparent lack of unit 3, *e.g.* possibly emphasised by the pulse of intra-Permian tectonic movements.

Furthermore, while some lithofacies affinities between the sedimentary units of the Monte Santa Giusta and Lu Caparoni-Cala Viola areas could be inferred, problems arise if we attempt to strictly compare the volcanic units in the differing successions.

LITHOSTRATIGRAPHICAL REVISION

The above-reported stratigraphical and sedimentological data allow a partial review of the lithostratigraphic classification of Gasperi & Gelmini (1980); however, due to the numerous uncertainties, we have not introduced new formation or other hierarchic names, as suggested by the stratigraphic codes. A formal lithostratigraphy will be provided when further investigations on the relatively continuous sections cropping out in the steep cliffs south of Punta Lu Caparoni, in great part only approachable from the sea, clarify these relationships and the nature of boundaries between units 1, 2 and 3 of Gasperi & Gelmini (1980).

At present, the post-Variscan and sub-Muschelkalk succession could be re-organised into the following units (Fig. 8):

I) "Punta Lu Caparoni Formation" (PLC), reviewed to include the clastic unit 1, with clasts derived both from the metamorphic basement and volcanic sources.

II) A volcanic "complex", traditionally ascribed to the lower part of unit 2. It crops out clearly in the Monte Santa Giusta section and is also documented in the Cugiareddu (Pomesano Cherchi, 1968) and Cuili Mola Casu wells (Lotti, 1931), where two "porphyrite" horizons occur, alternating with coarse clastic deposits with volcanic pebbles. According to the literature (Lombardi *et al.*, 1974; Cassinis *et al.*, 1996) and field observations of the authors, other volcanic outcrops also occur in the Nurra region (*e.g.*, Casa Satta, northeast of Lake Baratz), presumably at the base of unit 2, but we are not able to confirm their occurrence and stratigraphical setting. The stratigraphic relationships and the correlation between the two episodes of volcaniclastic activity (presumed calcalkaline at Lu Caparoni-Cala Viola area, and alkaline at Monte Santa Giusta, respectively) reported in the Nurra region by Lombardi *et al.* (1974), Cassinis *et al.* (1996) and Cortesogno & Gaggero (1999) are, at present, unclear.

However, the importance of volcanics is documented by the great amount of porphyric pebbles and cobbles in the conglomerates and conglomeratic sandstones of the unit 2 of Gasperi & Gelmini (1980).

III) A clastic unit of conglomerates, sandstones and minor pelites, rich in volcanic-derived clasts (units 2 *p.p.* and 3 of Gasperi & Gelmini), discontinuously cropping out along the coastline from Torre Negra to Porto Ferro. Although the contact with the overlying unit 3 has not been observed, the overall facies pattern suggests that units 2 and 3 may form a single, major fining-up sequence, evolving upwards from alluvial fan/braided river to coastal plain settings.

IV) This corresponds to unit 4 of Gasperi & Gelmini (1980) and lies disconformably on the underlying unit (but with no possibility of estimating the duration of the hiatus) and grades upwards into the carbonate deposits of the Muschelkalk.

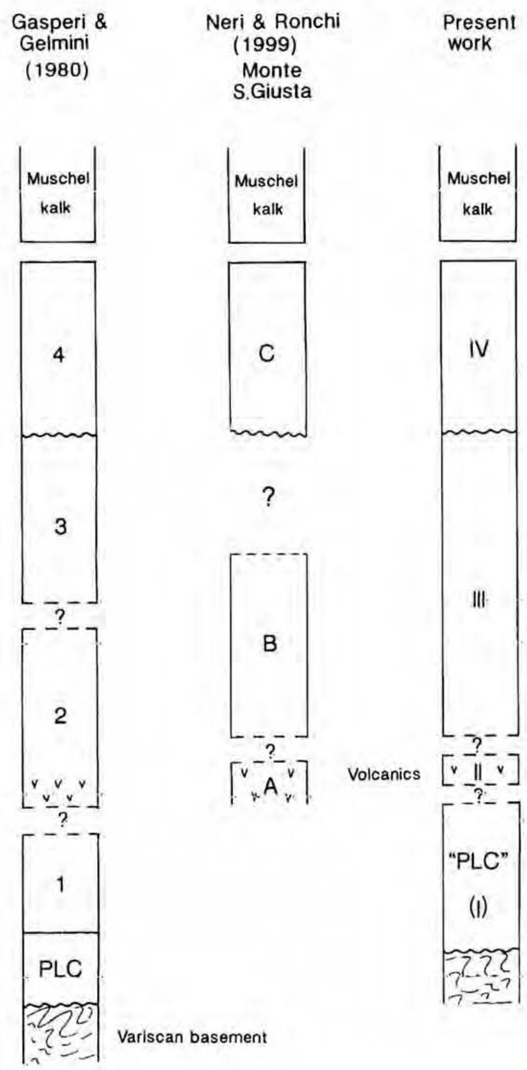


Fig. 8 – Comparison among the lithostratigraphic schemes of the Permian and Triassic succession of the Nurra region according to Gasperi & Gelmini (1980), Neri & Ronchi (1999) and that proposed in the present work. PLC: Punta Lu Caparoni Fm.

COMPOSITION OF ARENITES

The compositions of 50 selected samples of arenites and microconglomerates from the Torre del Porticciolo-Cala Viola stratigraphic sections were examined to determine the provenance of the detritus and to show the diagenetic overprinting.

The most common clast types in the examined samples are monocrystalline quartz grains (with slightly to highly undulose extinction and, in some cases, deformation bands and lamellae). Polycrystalline quartz, with a wide variety of subgrain sizes and fabrics, show frequently undulose extinction and crenulate crystal boundaries. Other types of terrigenous clasts include volcanic and low-grade metamorphic rocks. Volcanic rock fragments are acidic vitric and porphyric rocks; phenocrysts of quartz with resorbed embayments are common, but other phenocrysts are preserved only as ghosts of original grains. Micron-sized inclusions of opaque minerals cause the cloudiness of most of these fragments. The groundmass is commonly deformed between grains to form pseudomatrix. Silicified porphyries are also present, composed of quartz phenocrysts in a groundmass of microcrystalline and mesocrystalline quartz. Low-grade metamorphic rock fragments include: microcrystalline and mesocrystalline quartz rocks with fine crystals of mica, quartz-sericite schist, quartz-albite and quartz-albite-muscovite phyllites.

Detrital potassium feldspars (mainly perthitic) occur in very small amounts in samples of unit 3. Mica (muscovite) is abundant in fine-grained arenites and siltstones; mica flakes have an evident preferred alignment, except in bioturbated samples.

Various types of intraclasts, such as carbonate nodules composed of numerous small dolomite rhombs and mudstone clasts, are locally abundant in the upper succession (units III and IV).

The abundance of ductile rock fragments in some arenites, chiefly volcanic rocks which are highly susceptible to mechanical compaction, produces large amounts of pseudomatrix.

Modal analyses from this work and from previous studies (Cassinis *et al.*, 1996) are reported in Fig. 9. Samples are litharenites to quartzarenites and show a clear compositional trend due to the progressive enrichment of quartz from the basal to the upper units.

As for the provenance of the detrital material, rock types in arenites and conglomerates of the basal successions (vein quartz showing various degrees of strain, quartz-mica schist and phyllites, porphyries and silicified porphyries) indicate contributions from both the Hercynian basement and Permian volcanites. Sediments from the upper successions (units III and IV) show a higher textural and compositional maturity, with a noticeable increase in quartz content. In particular, arenites and conglomerates of unit IV are made up almost exclusively of quartzose grains, and most of these grains are fragments of vein quartz. Thus, the detritus of the upper unit is chemically stable and mechanically durable and could be the residue left after an intense chemical weathering and a long period of mechanical abrasion.

Post-depositional events recognised in the examined samples include: - kaolinite cementation; - formation of iron oxides; - mechanical compaction; - quartz cementation; - Fe-calcite cementation; - dolomite/ankerite cementation; - pressure solution, - recrystallisation of clay to sericite and illite, and - precipitation of calcite in fractures.

The ages of many of these events are not well constrained. Hematite forms a red pigment that stains fine-grained constituents and partly or completely engulfs and surrounds some coarse grains. Kaolinisation of acidic volcanic fragments is common, kaolinite also occurs as pore-filling cement.

The most common cement is quartz. Quartz overgrowths are present in most of the arenite samples and range from a trace to about 10%. Large quartz overgrowths are especially notable in the coarser arenites of unit IV. Margins of quartz grains have dust rings, generally of iron oxides. Pressure solution has destroyed or obscured the morphology of parts of some grains. The scarcity of quartz cement in fine-grained arenites and siltstones may reflect the almost complete loss of primary porosity by ductile grain deformation prior to the time of cementation by quartz. As for the source of silica for the quartz cement, certainly there has been sufficient pressure solution of quartzose grains in conglomerates and sandstones to furnish it.

Diagenetic carbonates are Fe-calcite (mainly in lower samples) and dolomite and ankerite (in the upper samples); they occur as patches in some of the arenites and locally replace parts of detrital grains. Fractures developed after uplift were filled with sparry iron-free calcite .

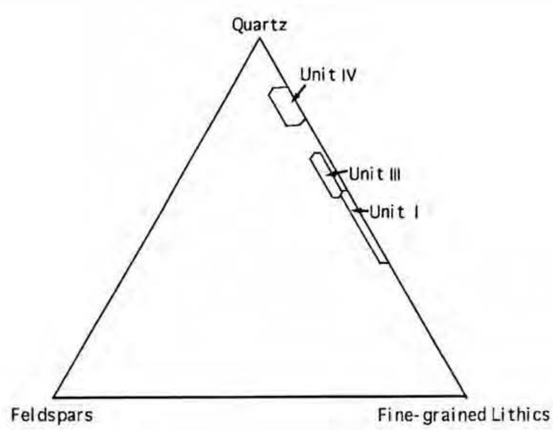


Fig. 9 – Compositional plot of the examined Permian and Triassic arenites from Nurra (from this work and from Cassinis *et al.*, 1996).

CONCLUDING REMARKS

Based on detailed lithostratigraphical, sedimentological and petrographical data, supported by scattered and rare biostratigraphical evidence, a preliminary revision of the terrigenous Permian and Triassic successions of the Nurra region (northwestern Sardinia) has been attempted. The whole post-Variscan continental succession has been subdivided, from bottom to top, into the following horizons:

I) "Punta Lu Caparoni Formation". This formation, already instituted by Gasperi & Gelmini (1980) to indicate vertically and laterally discontinuous alluvial-to-lacustrine deposits, has been reviewed here to also include the overlying clastic succession (unit 1 of Gasperi & Gelmini, 1980).

II) Volcanic unit, documented in the Monte Santa Giusta section, the drillings of the Cugiareddu and Cuili Mola Casu Wells, and, according to the literature and field observations of the authors, in the Lake Baratz area. Its significant original extent is documented by the large amount of volcanic pebbles in the conglomerates and conglomeratic sandstones of the overlying unit.

III) A clastic unit of conglomerates, sandstones and minor pelites, weathered and reddish in colour, rich in volcanic-derived clasts. It crops out discontinuously along the shore from Torre Negra-Torre Bianca to Porto Ferro and in the Lake Baratz area. Based on our data, we interpret this unit (corresponding to units 2 and 3 of Gasperi & Gelmini, 1980) as a single major fining-upwards sequence, evolving from alluvial fan/braided river settings to meandering river and coastal plain deposits.

IV) The upper clastic unit consists of reddish sandstones and minor pelites, showing alternating fluvial and tidal influx. The basal contact is marked by an evident disconformity. The base of the unit, well exposed in the Torre del Porticciolo and Cala Viola area, consists of a quartz conglomerate, followed upwards by cross-bedded sandstones. This unit corresponds to unit 4 of Gasperi & Gelmini (1980). The upper contact with the Muschelkalk deposits is, even if partly covered, transitional in the Monte Santa Giusta section, while at Cala Viola it has been faulted out.

As for the provenance of the detrital material, rock types in arenites and conglomerates of the basal successions indicate contributions from the Hercynian basement and Permian volcanic rocks. Moving upwards in the successions, sediments show a higher textural and compositional maturity. In particular, arenites and conglomerates of unit IV are made almost exclusively of quartzose grains (vein quartz). This type of detritus is chemically stable and mechanically durable and could be the residue left after an intense mechanical abrasion and/or chemical weathering.

Although few biostratigraphical data are available, based on scattered macroflora and palynomorphs occurrence, they allow us to relate the base of sequence to the Early Permian ("Autunian") and the top to an Olenekian(?)-early Anisian to late Anisian time, but do not allow a zonation of the whole sequence or an evaluation of the duration of hiatuses at the main unconformities.

Acknowledgements – This work has been supported by MURST and CNR grants (Universities of Ferrara, Modena, Padova and Pavia). The authors are grateful to F. Massari for the useful discussions and suggestions on facies and depositional settings, and to G. Cassinis and P. Pittau respectively for collaboration and contribution on stratigraphical and biostratigraphical problems of the Permian and Triassic sequence in the Nurra region. G. Cassinis and M. Durand (U. Nancy) are acknowledged for their careful review of the paper.

REFERENCES

BROUTIN J., CASSINIS G., CORTESOGNO L., GAGGERO L., RONCHI A. & SARRIA E., 1996. Research in progress on the Permian deposits of Sardinia (Italy). *Permophiles*, 28: 45-48.

BROUTIN J., DIEZ J.-B & RONCHI A., 1999. The Lower Permian deposits of Punta Lu Caparoni. Palaeontological data. Excursion 4: The Permian and Triassic stratigraphic record in northwestern Sardinia (Nurra). In: Cassinis G., Cortesogno L., Gaggero L., Pittau P., Ronchi A. & Sarria E. (Coordinators), *Late Palaeozoic Continental Basins of Sardinia, Field Trip Guidebook*. Intern. Congr. on "The continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations". 15-25 Sept. 1999, Brescia: 98-101.

CARRILLAT A., MARTINI A., ZANINETTI L., CIRILLI S., GANDIN A. & VRIELYNCK B., 1999. The Muschelkalk (Middle to Upper Triassic) of the Monte di Santa Giusta (NW Sardinia): sedimentology and biostratigraphy. *Eclogae geol. Helv.*, 92: 81-97.

CASSINIS G., CORTESOGNO L., GAGGERO L., RONCHI A. & VALLONI R., 1996. Stratigraphic and petrographic investigations into the Permo-Triassic continental sequences of Nurra (NW Sardinia). *Cuad. Geol. Iberica*, spec. issue 21: 149-169.

CASSINIS G., AVANZINI M., CORTESOGNO L., DALLAGIOVANNA G., DI STEFANO P., GAGGERO L., GULLO M., MASSARI F., NERI C., RONCHI A., SENO S., VANOSSI M. & VENTURINI C., 1998 a. Syntethic Upper Palaeozoic correlation charts of selected Italian areas. *Atti Ticin. Sci. Terra*, Pavia, 40: 65-120.

CASSINIS G., CORTESOGNO L., GAGGERO L. & RONCHI A., 1998 b. Osservazioni preliminari su alcune successioni continentali permiane della Sardegna. *Rend. Ist. Lomb. Accad. Sci. e Lett.*, B., 130 (1996): 177-205.

CORTESOGNO L. & GAGGERO L., 1999. The Permian and Triassic calc-alkaline volcanic activity in Nurra. Excursion 4: The Permian and Triassic stratigraphic record in northwestern Sardinia (Nurra). In: Cassinis G., Cortesogno L., Gaggero L., Pittau P., Ronchi A. & Sarria E. (Coordinators), *Late Palaeozoic Continental Basins of Sardinia, Field Trip Guidebook*. Intern. Congr. on "The continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations". 15-25 Sept. 1999, Brescia: 110-111.

FONTANA D., GELMINI R. & LOMBARDI G., 1982. Le successioni sedimentarie e vulcaniche carbonifere e permo-triassiche della Sardegna. In: Carmignani L., Cocozza T., Ghezzo C., Pertusati P. C. & Ricci C. A. (eds), Guida alla Geologia del Paleozoico sardo, Guide geologiche regionali. *Mem. Soc. Geol. Ital.*, 18: 183-192.

GASPERI G. & GELMINI R., 1980. Ricerche sul Verrucano. 4. Il Verrucano della Nurra (Sardegna nord-occidentale). *Mem. Soc. Geol. Ital.*, 20 (1979): 215-231.

GELMINI R., 1985. A paleogeographical reconstruction of the Permo-Triassic circumthyrrenian area. *Boll. Soc. Geol. Ital.*, 104: 561-574.

ITALIAN I.G.C.P. 203 GROUP (ed.), 1986. Field Guide-book of Permian and Permian-Triassic boundary in the South-Alpine segment of the Western Tethys. Brescia: 180 pp.

LOMBARDI G., COZZUPOLI D. & NICOLETTI M., 1974. Notizie geopetrografiche e dati sulla cronologia K-Ar del vulcanismo tardopaleozoico sardo. *Period. Mineral.*, 43: 221-312.

LOTTI B., 1931. Relazione generale riassuntiva dei tre sondaggi per la ricerca del carbone paleozoico nei piani di Alghero. *Boll. R. Uff. Geol.*, LVI, 6: 5-15.

MORETTI A., 1959. Carta Geologica d'Italia alla scala 1:100.000, F° 179 "Porto Torres". *Servizio Geologico d'Italia.*

NERI C. & RONCHI A., 1999. The Buntsandstein deposits of Mt. Santa Giusta. Excursion 4: The Permian and Triassic stratigraphic record in northwestern Sardinia (Nurra). In: Cassinis G., Cortesogno L., Gaggero L., Pittau P., Ronchi A. & Sarria E. (Coordinators), *Late Palaeozoic Continental Basins of Sardinia, Field Trip Guidebook*. Intern. Congr. on "The continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations". 15-25 Sept. 1999, Brescia: 108-109.

NERI C., RONCHI A., CASSINIS G., FONTANA D. & STEFANI C., 1999. The Permo-Triassic succession of Cala Viola-Porto Ferro. Stratigraphy, sedimentology and sandstone petrography. Excursion 4: The Permian and Triassic stratigraphic record in northwestern Sardinia (Nurra). In: Cassinis G., Cortesogno L., Gaggero L., Pittau P., Ronchi A. & Sarria E. (Coordinators), *Late Palaeozoic Continental Basins of Sardinia, Field Trip Guidebook*. Intern. Congr. on "The continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations". 15-25 Sept. 1999, Brescia: 102-105.

OOSTERBAAN A.M., 1936. Étude géologique et paléontologique de la Nurra avec quelques notes sur le Permien et le Trias de la Sardaigne meridionale. *Thesis* Univ. Utrecht: 130 pp.

OWEN D.E., 1987. Usage of stratigraphic terminology in papers, illustrations and talks. *J. sediment. Petrol.*, 57 (2): 363-372.

PECORINI G., 1962. Nuove osservazioni sul Permico della Nurra (Sardegna nord-occidentale). *Atti Accad. naz. Lincei, Rend. Cl. fis. mat. e nat.*, sez. VIII, 32: 377-380.

PITTAU P., 1999. The Triassic succession of northwest Sardinia: data from the subsurface. Excursion 4: The Permian and Triassic stratigraphic record in northwestern Sardinia (Nurra). In: Cassinis G., Cortesogno L., Gaggero L., Pittau P., Ronchi A. & Sarria E. (Coordinators), *Late Palaeozoic Continental Basins of Sardinia, Field Trip Guidebook.* Intern. Congr. on "The continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations". 15-25 Sept. 1999, Brescia: 106-107.

PITTAU DEMELIA P. & FLAVIANI A., 1982. Aspects of the palynostratigraphy of the Triassic Sardinia sequences (Preliminary report). *Rev. Palaeobot. Palynol.*, 37: 329-43.

POMESANO CHERCHI A., 1968. Studio bio-stratigrafico del sondaggio Cugiareddu nel Trias e Permico della Nurra (Sardegna nord-occidentale). *Ist. Geol. e Paleont. Univ. Cagliari*, 61: 9-51.

VARDABASSO S., 1966. Il Verrucano sardo. *Atti del Symposium sul Verrucano*. Pisa, Sett. 1965, Soc. Tosc. Sci. Nat., 293-310.

A PERMIAN MARINE SEDIMENTARY RECORD IN THE FARMA VALLEY (MONTICIANO-ROCCASTRADA RIDGE, SOUTHERN TUSCANY)

MAURO ALDINUCCI [1], FABIO SANDRELLI [1], ENRICO PANDELI [2] and ANNA GANDIN [1]

Key words – Continental rifting sedimentation; Brachiopods; Permian; Southern Tuscany.

Abstract – A new Permian, fossiliferous siliciclastic unit (Poggio alle Pigne Quartzite) has been recognised in the Farma Valley between the Carboniferous Carpineta Formation and the Civitella Formation of probable Early Triassic age. It represents part of the rare evidence for Permian marine sedimentation in Tuscany, documented by the occurrence in the upper part of the Poggio alle Pigne sequence, of brachiopods which can be related to Strophalosicea, probably *Tschernyschewia typica*.

The Poggio alle Pigne Quartzite represents a transgressive cycle, probably related to an early stage of continental-rifting activity before the beginning of the Alpine Cycle which led to the fragmentation of the Hercynian continent and the subsequent opening of the Mesozoic Tethys.

Parole chiave – Rifting Continentale; Brachiopodi; Permiano; Toscana Meridionale.

Riassunto – Nella valle del Farma, in Toscana meridionale, è stata riconosciuta una nuova successione silicoclastica fossilifera di età permiana, la Quarzite di Poggio alle Pigne, compresa tra la Formazione di Carpineta, di età carbonifera, e la Formazione di Civitella di probabile età triassica. Questa successione rappresenta uno dei rari esempi di sedimentazione permiana marina in Toscana. I fossili rinvenuti sono brachiopodi strophalosicei, probabilmente riferibili a *Tschernyschewia typica*, di ambiente marino neritico.

La successione di Poggio alle Pigne rappresenta un episodio trasgressivo probabilmente connesso con le fasi distensive precedenti l'inizio del ciclo alpino.

INTRODUCTION

In the Farma Valley, near Poggio alle Pigne, Permian brachiopods have been found within a siliciclastic succession previously assigned to the Triassic (Aldinucci *et al.*, 1999). This new unit, so far unrecognized, was mapped as the basal part of the unfossiliferous Civitella Formation, which in the Monticiano Roccastrada Ridge is the oldest member of the Verrucano Group (Costantini *et al.*, 1987). In the Northern Apennines the Paleozoic and Scythian-Carnian successions belong to the deepest units of the tectonic pile (Tuscan Metamorphic Units) which are affected by Alpine low-grade metamorphism in the green-schist facies (Franceschelli *et al.*, 1986; Conti *et al.*, 1991; Elter & Pandeli, 1993 *cum bibl.*).

In Tuscany, these epimetamorphic successions mainly crop out in the Middle Tuscan Ridge, extending from Alpi Apuane to Monte Leoni, on Elba Island, and in Monte Argentario (Fig. 1).

The Monticiano-Roccastrada Ridge, a segment of the Middle Tuscan Ridge south of the Arno River, ranging from Montagnola Senese to Monte Leoni, is deeply cut from west to east by the Farma River. The Farma Valley is a key area for the stratigraphy of the Permo-Carboniferous to Carnian in Tuscany. This time interval is particularly important in the tectono-sedimentary evolution of the Tuscan domain because it includes the transition from the late-/post-Hercynian extensional events to the Alpidic continental rifting (Rau & Tongiorgi, 1974; Bagnoli *et al.*, 1979; Gattiglio *et al.*, 1989; Rau, 1990; Pandeli *et al.*, 1994; Pandeli, 1998, 1999).

Many authors have discussed the stratigraphy, sedimentology, and textural and compositional features of the Triassic siliciclastic metasediments of the Tuscan Domain (Verrucano *Auct.*: Rau & Tongiorgi, 1974; Canuti & Sagri, 1974; Deschamps *et al.*, 1983; McBride *et al.*, 1987; Franceschelli *et al.*, 1987 *cum bibl.*; Costantini *et al.*; 1987), whereas data for the Permian successions are

[1] Dipartimento di Scienze della Terra, via Laterina 8, 53100 Siena, Italy.

[2] Dipartimento di Scienze della Terra, via La Pira 1, 50121 Firenze, Italy, and Centro di Studio di Geologia dell'Appennino e delle catene perimediterranee (CNR), via La Pira 4, 50121 Firenze.

scarce (Pasini & Vai, 1997; Pandeli, 1998). In fact the known Permian successions are:

– metasiliciclastics, graphite-rich lacustrine San Lorenzo Formation *pp.* (Rau & Tongiorgi, 1974) and coastal-neritic Rio Marina Formation *pp.* (Bagnoli *et al.*, 1979) which represent the "Autunian" interval of the Late Carboniferous - Early Permian sedimentary cycle;

– hematite-rich, polymictic metarudites (Asciano breccia and conglomerate: Rau & Tongiorgi, 1974; Torri breccia and conglomerates: Costantini *et al.*, 1998), and volcanic-rich metasiliciclastics (Castelnuovo red-sandstone: Bagnoli *et al.*, 1979; Pandeli *et al.*, 1991; Borro del Fregione siltstone: Costantini *et al.*, 1998; Pandeli, 1998) which are related to a semi-arid continental environment of probable Middle/Late Permian age;

– graphite-rich marine metasiliciclastics and carbonates in the Monte Amiata subsurface ("Formation C": Elter & Pandeli, 1991) which contain early Late Permian (Kubergandian: Pandeli & Pasini, 1990) fossils.

The finding in the Farma Valley, north of Poggio alle Pigne, of a siliciclastic succession (Poggio alle Pigne Quartzite) bearing Late (?) Permian fossils adds new data to our knowledge of the Late-Paleozoic in Tuscany.

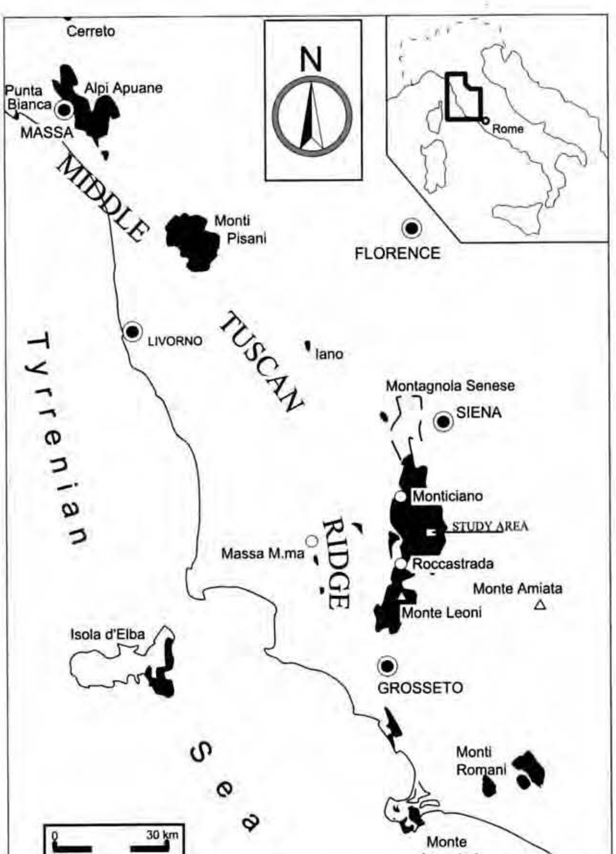


Fig. 1 – Regional distribution of the Paleozoic-Triassic siliciclastic metasediments (in black color) of the Northern Apennine.

GEOLOGICAL SETTING

In Southern Tuscany the Paleozoic to Carnian formations belong to the tectonic Monticiano-Roccastrada Unit which consists of two tectonic subunits: the Montepescali-M.Quoio-Iano (internal) sub-Unit and the M. Leoni-Montagnola Senese (external) sub-Unit (Costantini *et al.*, 1987). The Monticiano-Roccastrada Unit underwent two Alpine tectonometamorphic events in the lower greenschist facies, and later weak folding (Costantini *et al.*, 1987; Franceschelli *et al.*, 1986; Elter & Pandeli, 1993; Bertini *et al.*, 1991).

The Poggio alle Pigne Quartzite is part of the Monte Leoni-Montagnola Senese sub-Unit which in the study area consists of two lithostratigraphic units (Costantini *et al.*, 1987): the Paleozoic Group and the Verrucano Group (Fig. 2).

The Paleozoic Group includes from bottom to top:

a) the Carpineta Formation: graphite-rich metasiltite and phyllite with carbonate-siltitic/limonitic nodules and Upper Visean-Lower Namurian fossils (Redini, 1941; Cocozza, 1965; Pasini, 1978b, 1980a, 1980b; Pasini & Winkler Prins, 1981);

b) the Farma Formation: alternating turbiditic metasandstone and metasiltstone with dark-grey phyllite intercalations and locally with carbonate megabreccias (known as Lower Moscovian Sant'Antonio Limestone) and metacalcarenites of Upper Moscovian age (Cocozza, 1965; Pasini, 1978a, 1980a, 1980b).

The Carpineta Formation and the Farma Formation, which were deformed during a pre-Alpine event (probably related to the "Asturian phase" of the Hercynian Orogeny: Costantini *et al.*, 1987), are unconformably overlain by the Verrucano Group, currently regarded as representing the inception of sedimentation connected with the continental-rifting that led to the fragmentation of the Hercynian continent, at the beginning of the Alpine Cycle (Cassinis *et al.*, 1979).

The Verrucano Group consists of three formations which are, from bottom to top:

a) the Civitella Formation: i) greenish to light grey, massive to poorly graded quartz-metaconglomerates; ii) well-sorted, medium- to coarse-grained greenish to light-grey quartzite with local quartz-metaconglomerate lenses and green/purple metasiltstone intercalations; iii) green and purple metasiltstone and phyllite with interbedded quartzite. The inferred age of this unfossiliferous unit is Early Triassic, although a Late Permian age for its basal part cannot be dismissed (Costantini *et al.*, 1987).

b) the Monte Quoio Formation: purple metasiltstone, phyllite and quartzite with thick lens-shaped intercalations of purplish metaconglomerate ("anageniti" *Auct.*) characterised by the presence of pebbles of white and pink quartz, and subordinately of whitish and purple quartzite and rare carbonate. Fossils of Scythian-Early Anisian (Cocozza *et al*, 1975) and uppermost Carboniferous-Early Permian age (Engelbrecht *et al.*, 1989) have been found within the carbonate clasts in the Farma Valley. As a consequence, the age of this unit has been ascribed to the Middle Triassic (Cocozza *et al.*, 1975);

c) the "Anageniti minute" Formation: alternating whitish to pink, finegrained quartz-metaconglomerate ("micro-anagenite" *Auct.*), whitish-pink to purple quartzite and purple metapelite, often arranged in fining-upwards sequences. Owing to the lack of fossils, a probable Ladinian age has been proposed for this formation on the ground of its stratigraphic position beneath the Carnian Tocchi Formation (Azzaro *et al.*, 1976; Costantini *et al.*, 1980).

POGGIO ALLE PIGNE QUARTZITE

The fossiliferous siliciclastic succession crops out in the valley of the Farma River, to the southeast of the villages

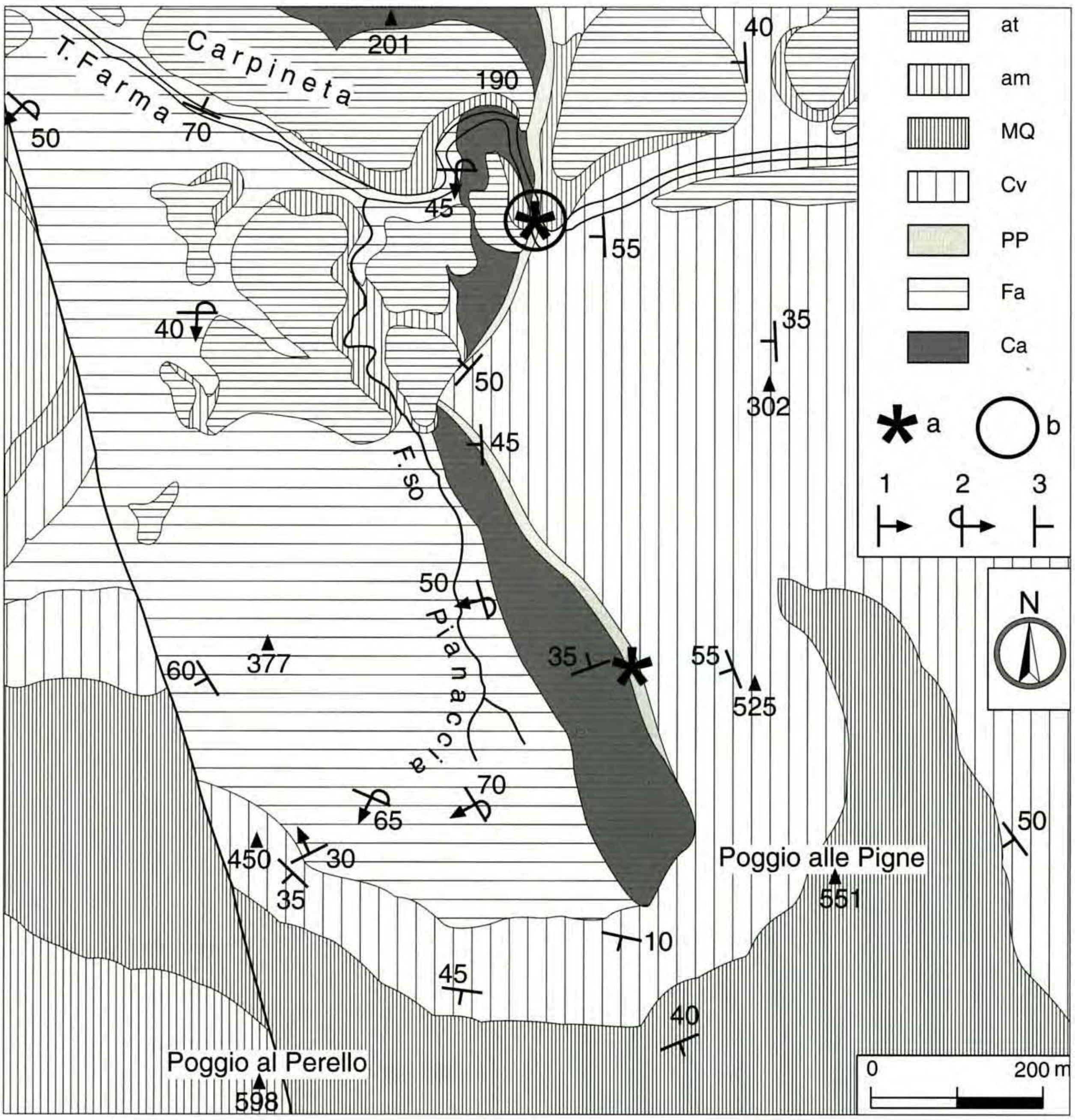


Fig. 2 – Geological map of the Poggio alle Pigne area, after Costantini *et al.*, 1987, modified: a – fossiliferous sites; b – type section; at – alluvial terraces; Am – Anageniti minute Fm.; MQ – Monte Quoio Fm.; Cv – Civitella Fm.; PP – Poggio alle Pigne Quartzite; Fa – Farma Fm.; Ca – Carpineta Fm.; 1 – facing of bedding; 2 – reversed bedding; 3 – strike and dip of bedding.

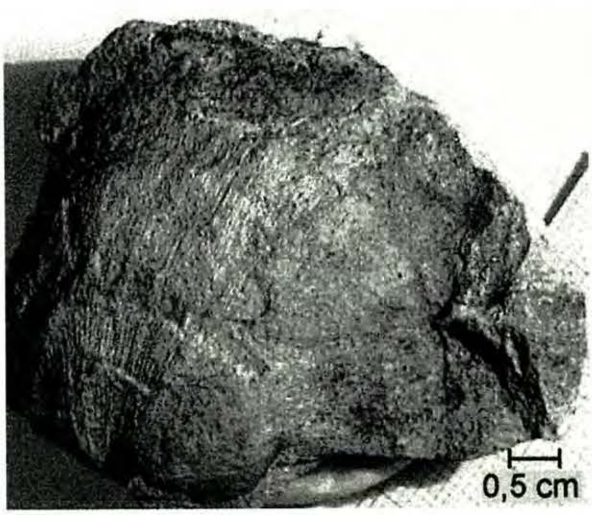
Iesa and Solaia. In particular the outcrops are located on the western slope of Poggio alle Pigne hill (Fig. 2).

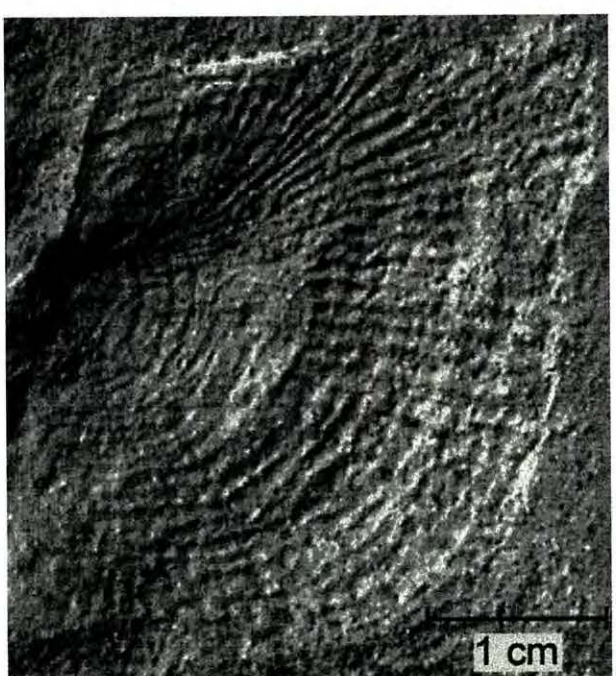
The Poggio alle Pigne Quartzite is stratigraphically interposed between Civitella Formation (Verrucano Group), at the top, and Carpineta Formation (Paleozoic Group), at the bottom.

The lower contact is not well exposed, but at the cartographic scale, an unconformable and probably erosional surface separates the Poggio alle Pigne Quartzite from the underlying black silty phyllites of Carpineta Formation, which was previously deformed during the "Asturian event" of the Hercynian Orogeny. The contact with the overlying metaconglomerates of the Civitella Formation is clearly erosional, although no angular unconformity is recognisable.

The Poggio alle Pigne Quartzite contains, in the uppermost sandstone bed, a monotypical Strophalosiacean brachiopod assemblage represented by moulds of *Tschernyschewia* shells (Figs 3, 4), whose features are similar to the type species of the genus, *Tschernyschewia typica*, occurring in the Upper Permian of Armenia, also reported from Salt Range, Pakistan (B. Wardlaw: pers. comm.).

The investigated section of the Poggio alle Pigne Quartzite was measured in detail along the southern bank of the Farma River, and is composed of two fining-upwards sequences (Fig. 5) whith a total thickness of about 4 m:





Figs 3, 4 – Mould of valves of *Tschernyschewia* shell.

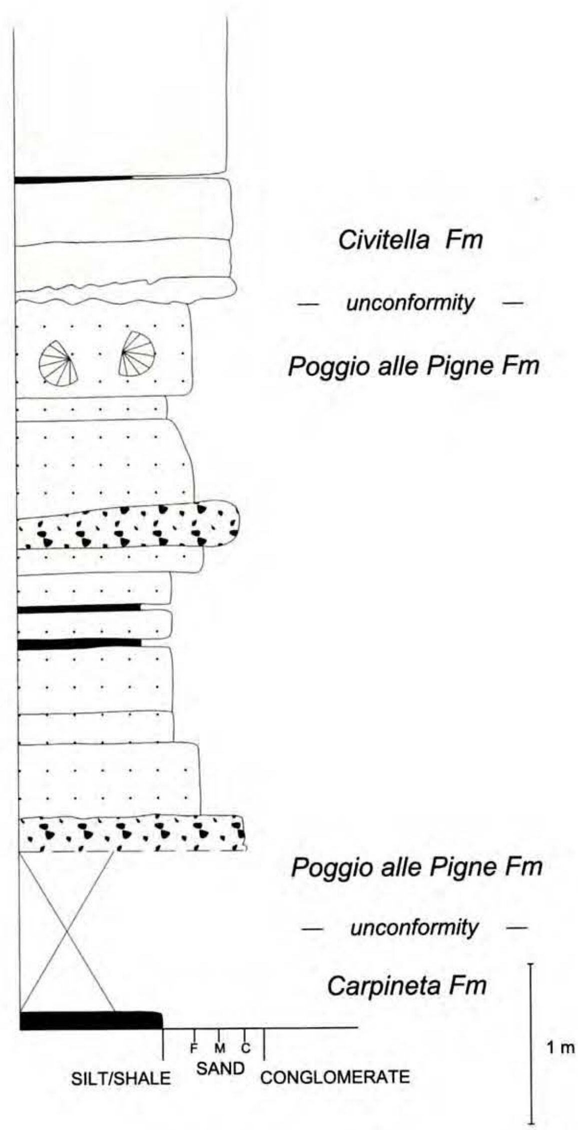


Fig. 5 – Poggio alle Pigne section.

– the lower sequence consists of a basal, polygenic, finegrained conglomerate followed by medium-to finegrained, well sorted quartzitic sandstone with grey to black siltstones and rare phyllitic interbeds;
– the upper sequence starts with a polygenic finegrained conglomerate followed by a medium- to finegrained, well sorted sandstone.

The lack of lateral continuity of the type section is due to the poor conditions of exposure. Nevertheless, at the outcrop scale, the bedding geometry appears to be mainly tabular and the contacts between the layers are sharp, but not erosional, except for the basal conglomerate of the upper sequence which is lenticular and rests with an evident erosional contact, on the lower quartzite.

The composition of the conglomerate beds consists of sub-rounded, white quartz clasts (up to 2 cm) and sub-angular lithic clasts (phyllite, siltstone/finegrained quartzite, radiolarite). The matrix, made up mostly of fine-sand- to silt-sized quartz and white mica, is generally poorly represented.

The sandstones correspond to finegrained quartzite, characterised by the total lack of feldspars and the occurrence of a minor amount of detritic white mica.

DISCUSSION

The finding of Late (?) Permian fossils in the Poggio alle Pigne Quartzite represents the first evidence of an Upper Paleozoic succession along the Monticiano-Roccastrada Ridge. In fact, the youngest Paleozoic unit in this area is represented by the Upper Westphalian-Cantabrian *Spirifer*-bearing shale which unconformably caps the Sant'Antonio Limestone, south of the Farma Valley.

The occurrence of well-preserved moulds of brachiopod shells scattered in the sandstone testifies to a neritic environment. Moreover, the mineralogical composition of the sandstones points to a cratonic provenance for the terrigenous material, whereas the frequency of the conglomerates of lithic clasts associated with the subrounded quartz pebbles suggests that at least part of the source area was not far from the coast and probably affected by block faulting.

The relationships of the Poggio alle Pigne Quarzite with the mixed siliciclastic/carbonate deposits of the Kubergandian "Formation C" recognised in the Monte Amiata deep drillings (Elter & Pandeli, 1991; Pandeli & Pasini, 1990), and with the possible Middle Permian continental siliciclastics (*e.g.* Castelnuovo red sandstone, Asciano breccia and conglomerate) and volcanics (*e.g.* Iano porphyric schists) still remain undefined.

If the Poggio alle Pigne Quartzite represents the stratigraphic cover of the Middle Permian red beds, then a Late Permian transgression in Tuscany would be documented for the first time. This transgression may be related to an early episode of continental rifting (possibly due to dextral megashears affecting the southern part of the Hercynian continent: Rau, 1990) which pre-dated the beginning of the Verrucano sedimentation.

Aknowledgements – We wish to thank Marco Venturini and Leonardo Casini for their help in collecting the fossils in the field. Financial support for this paper was provided by the Italian MURST 1997 Project (A. Gandin), Siena University FAR Grant (F. Sandrelli), and CNR (Centro di Studio di Geologia dell'Appennino e delle catene Perimediterranee).

REFERENCES

ALDINUCCI M., GANDIN A., PANDELI E. & SANDRELLI F., 1999. A Pre-Carnian marine transgression recorded in the Civitella Formation (Verrucano Group) in the Monticiano-Roccastrada Ridge, Southern Tuscany, Italy. *Intern. Congr. on "The continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations". 15-25 Sept. 1999, Brescia*, Earth Sci. Dept., Pavia University, Pavia, Abstracts: 85-87.

AZZARO E., COCOZZA T., DI SABATINO B., GASPERI G., GELMINI R. & LAZZAROTTO A., 1976. Geology and petrography of the Verrucano and Paleozoic formations of Southern Tuscany and Northern Latium (Italy). In: Falke H. (ed.), *The Continental Permian in Central, West, and South Europe,* Proc. NATO Adv. St. Inst. held at the Johannes Gutenberg University, Mainz, F.R.G., 23 Sept. - 4 Oct., 1975, Ser. C, Vol. 22: 181-195.

BAGNOLI G., GIANELLI G., PUXEDDU M., RAU A., SQUARCI P. & TONGIORGI M., 1979. A tentative stratigraphic reconstruction of the Tuscan Paleozoic Basement. *Mem. Soc. Geol. Ital.*, 20: 99-116.

BERTINI G., CAMELI G.M., COSTANTINI A., DECANDIA F.A., DI FILIPPO M., DINI I., ELTER F.M., LAZZAROTTO A., LIOTTA D., PANDELI E., SANDRELLI F. & TORO B., 1991. Struttura geologica fra i Monti di Campiglia e Rapolano Terme (Toscana Meridionale): stato attuale delle conoscenze e problematiche. *Studi Geologici Camerti*, vol. spec. 1: 155-178.

CANUTI P. & SAGRI M., 1974. Ambiente di sedimentazione e provenienza dei clasti nelle Anageniti del Verrucano (Appennino Settentrionale). *Boll. Soc. Geol. Ital.*, 93: 661-704.

CASSINIS G., ELTER G., RAU A. & TONGIORGI M., 1979. Verrucano: a tectofacies of the Alpine-Mediterranean Southern Europe. *Mem. Soc. Geol. Ital.*, 20: 135-149.

COCOZZA T., 1965. Il Carbonifero nel gruppo Monticiano-Roccastrada (Toscana). *La Ricerca Scientifica, Rend.*, 8/3: 1-38.

COCOZZA T., LAZZAROTTO A. & PASINI M., 1975. Segnalazione di una fauna triassica nel conglomerato di Monte Quoio (Verrucano del Torrente Farma – Toscana meridionale). *Riv. Ital. Paleont. Stratigr.*, 81/4: 425-436.

CONTI P., COSTANTINI A., DECANDIA F.A., ELTER F.M., GATTIGLIO M., LAZZAROTTO A., MECCHERI M., PANDELI E., RAU A., SANDRELLI F., TONGIORGI M. & DI PISA A., 1991. Structural frame of Tuscan Paleozoic: a review. *Boll. Soc. Geol. Ital.*, 110: 523-541.

COSTANTINI A., GANDIN A., MATTIAS P. P., SANDRELLI F. & BRUNI T., 1980. Un'ipotesi per l'interpretazione paleogeografica della Formazione di Tocchi. *Mem. Soc. Geol. Ital.*, 21: 203-216.

COSTANTINI A., DECANDIA F. A., LAZZAROTTO A. & SANDRELLI F., 1987. L'Unità di Monticiano-Roccastrada fra la Montagnola Senese e il Monte Leoni (Toscana Meridionale). *Atti Ticin. Sci. Terra*, Pavia, 31: 382-420.

COSTANTINI A., ELTER F. M., PANDELI E. & SANDRELLI F., 1998. Geologia dell'area di Iano (Toscana meridionale, Italia). *Boll. Soc. Geol. Ital.*, 117: 187-218.

DESCHAMPS Y., DAGALLIER G., MACAUDIÈRE J., MARIGNAC C., MOINE B. & SAUPÉ F., 1983. Le gisement de pyrite-hématite de Valle Giove (Rio Marina, Ile d'Elbe, Italie) (Contribution à la connaissance des gisements de Toscane - I). *Schweiz. mineral. petrogr. Mitt.*, 63: 149-165.

ELTER F.M. & PANDELI E., 1991. Structural features of the metamorphic Paleozoic-Triassic sequences in deep geothermal drillings in the Mt. Amiata area (SE Tuscany, Italy). *Boll. Soc. Geol. Ital.*, 110: 511-522.

ELTER F.M. & PANDELI E., 1993. Alpine tectono-metamorphic framework of the Tuscan Paleozoic (Southern Tuscany, Italy). *Annales Tectonicae*, VII/1: 71-84.

ENGELBRECHT H., KLEMM D.D. & PASINI M., 1989. Preliminary notes on the tectonics and lithotypes of the "Verrucano *s.l.*" in the Monticiano area (southern Tuscany, Italy) and finding of fusulinids within the M.te Quoio Fm. (Verrucano Group). *Riv. Ital. Paleont. Stratigr.*, 94/3: 361-382.

FRANCESCHELLI M., LEONI L., MEMMI I. & PUXEDDU M., 1986. Regional distribution of Al-silicates and metamorphic zonation in the low-grade Verrucano metasediments from the Northern Apennines, Italy. *J. Metam. Geol.*, 4: 309-321.

FRANCESCHELLI M., LEONI L. & SARTORI F., 1987. Geochemistry and mineralogy of detritic rocks from Verrucano type-sequences of Northern Apennines (Monti Pisani and Punta Bianca), Italy. *Rend. Soc. Ital. Mineral. Petrol.*, 42: 13-31.

GATTIGLIO M., MECCHERI M. & TONGIORGI M., 1989. Stratigraphic correlation forms of the Tuscan Paleozoic Basement. *Rend. Soc. Geol. Ital.*, 12: 247-257.

MCBRIDE E.F., PICARD M.D., FONTANA D. & GELMINI R.,1987. Sedimentology, petrography and provenance of the Triassic Verrucano Group, Monte Argentario (Tuscany, Italy). *Giorn. Geol.*, ser. 3ª, 49/2: 73-92.

PANDELI E., 1998. Permo-Triassic siliciclastic sedimentation in the Northern Apennines: new data from the Iano metamorphic inlier (Florence). *Mem. Soc. Geol. Ital.*, 53: 185-206.

PANDELI E., 1999. Tectono-sedimentary evolution of the Tuscan area from the late Autunian to the Carnian: a review. *Intern. Congr. on "The continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations"*. 15-25 Sept. 1999, Brescia, Abstracts: 131-133.

PANDELI E. & PASINI M., 1990. Fusulinidi permiani nella successione metamorfica del sottosuolo del M. Amiata, Toscana Meridionale (Italia). *Riv. Ital. Paleont. Stratigr.*, 96/1: 3-20.

PANDELI E., BERTINI G. & CASTELLUCCI P., 1991. The tectonic wedges complex of the Larderello area (Southern Tuscany – Italy). *Boll. Soc. Geol. Ital.*, 110: 621-629.

PANDELI E., GIANELLI G., PUXEDDU M. & ELTER F.M., 1994. The Paleozoic basement of the Northern Apennines: stratigraphy, tectono-metamorphic evolution and alpine hydrotermal processes. *Mem. Soc. Geol. Ital.*, 48: 627-654.

PASINI M., 1978 a. Further paleontological records from the Upper Paleozoic outcrops of the Farma Valley. In: Tongiorgi M. (ed.), *Report on Tuscan Paleozoic*. C.N.R., Rapp. Interno Sottopr. Energia Geotermica, Prog. Fin. Energetica, Pisa: 35-39.

PASINI M., 1978 b. *Edmondia Scalaris* (M'coy, 1844) e *Phestia* cf. *attenuata* (Fleming, 1828) nella Formazione di Carpineta (Paleozoico Superiore della Toscana Meridionale). *Riv. Ital. Paleont. Stratigr.*, 84/4: 849-864.

PASINI M., 1980 a. I Fusulinidi della Valle del Torrente Farma (Toscana Meridionale). *Mem. Soc. Geol. Ital.*, 20: 323-342.

PASINI M., 1980 b. Gli Archeodiscidi dell'affioramento di Poggio alle Pigne nella Valle del Torrente Farma (Toscana Meridionale). *Mem. Soc. Geol. Ital.*, 20: 343-346.

PASINI M. & VAI G.B., 1997. Review and updating of the Moscovian to Artinskian marine rocks in peninsular Italy. *Geodiversitas*, 19/2: 187-191.

PASINI M. & WINKLER PRINS C.F., 1981. Carboniferous brachiopods from the locality Poggio alle Pigne in the Farma Valley (Southern Tuscany, Italy). *Riv. Ital. Paleont. Stratigr.*, 86/3: 459-468.

RAU A., 1990. Evolution of the Tuscan Domain between the Upper Carboniferous and Middle Triassic: a new hypothesis. *Boll. Soc. Geol. Ital.*, 109: 231-238.

RAU A. & TONGIORGI M., 1974. Geologia dei Monti Pisani a Sud-Est della Valle del Guappero. *Mem. Soc. Geol. Ital.*, 13: 227-408.

REDINI R., 1941. Rinvenimento di Antracolitico nel gruppo Monticiano-Roccastrada. *Boll. Soc. Geol Ital.*, 60: 331-334.

1.2. OTHER REGIONS

«NATURA BRESCIANA» Ann. Mus. Civ. Sc. Nat., Brescia, MONOGRAFIA N. 25, 2001: 171-180

THE LATE PERMIAN ALKALINE MAGMATISM OF THE CINCO VILLAS MASSIF (WESTERN PYRENEES, SPAIN): A RECORD OF THE LATE-VARISCAN EVOLUTION OF THE PYRENEES

ESTHER LASHERAS ADOT [1], MARCELIANO LAGO SAN JOSÉ [1], CARLOS GALÉ BORNAO [2], ENRIQUE ARRANZ YAGÜE [2] and ANDRÉS GIL IMAZ [2]

Key words – basalts; dolerites; Late Permian; Western Pyrenees.

Abstract – A basic, primary magmatism, with subalkaline to alkaline affinity, is exposed in three Upper Permian outcrops in the Cinco Villas Massif (CVM; Western Pyrenees, Spain) in the form of basaltic sills, interbedded into clastic sediments.
These basalts are cogenetic (and probably coeval) with doleritic dykes emplaced into Upper Paleozoic rocks in the southern sector of the CVM.
This mantle-derived magmatism is poorly fractionated, as shown by its petrology and geochemistry, especially the rare earth elements.
The emplacement of this anorogenic magmatism is related to late Variscan distension, making it clearly different from the Late Carboniferous - Early Permian orogenic calcalkaline magmatism.
The studied Upper Permian magmatic rocks are the earliest expression of Alpine magmatic activity in the Pyrenees, prior to the Triassic tholeiitic magmatism.

Parole chiave – basalti; doleriti; Permiano superiore; Pirenei occidentali.

Riassunto – Il presente lavoro tratta del magmatismo basico, ad affinità da subalcalina ad alcalina, inerente a tre affioramenti tardo-permiani del Massiccio di Cinco Villas (CVM; Pirenei occidentali, Spagna) sotto forma di *sill* basaltici interstratificati con sedimenti clastici. Questi basalti sono geneticamente connessi (e probabilmente coevi) con i dicchi doleritici posti, nel settore meridionale dello stesso Massiccio, entro rocce riferite al Paleozoico superiore. Il magmatismo di derivazione mantellica è scarsamente frazionato, come si desume dalle composizioni petrologica e geochimica essenzialmente delle terre rare. La comparsa e la messa in posto di questo magmatismo anorogenico fu legato alla distensione tardo-varisica, che l'ha reso chiaramente differente dal magmatismo calcalcalino orogenico di età compresa tra il Carbonifero superiore e il Permiano inferiore. Il magmatismo tardo-permiano in esame rappresenta la primissima espressione dell'attività magmatica alpina nei Pirenei, prima del magmatismo tholeiitico triassico.

INTRODUCTION

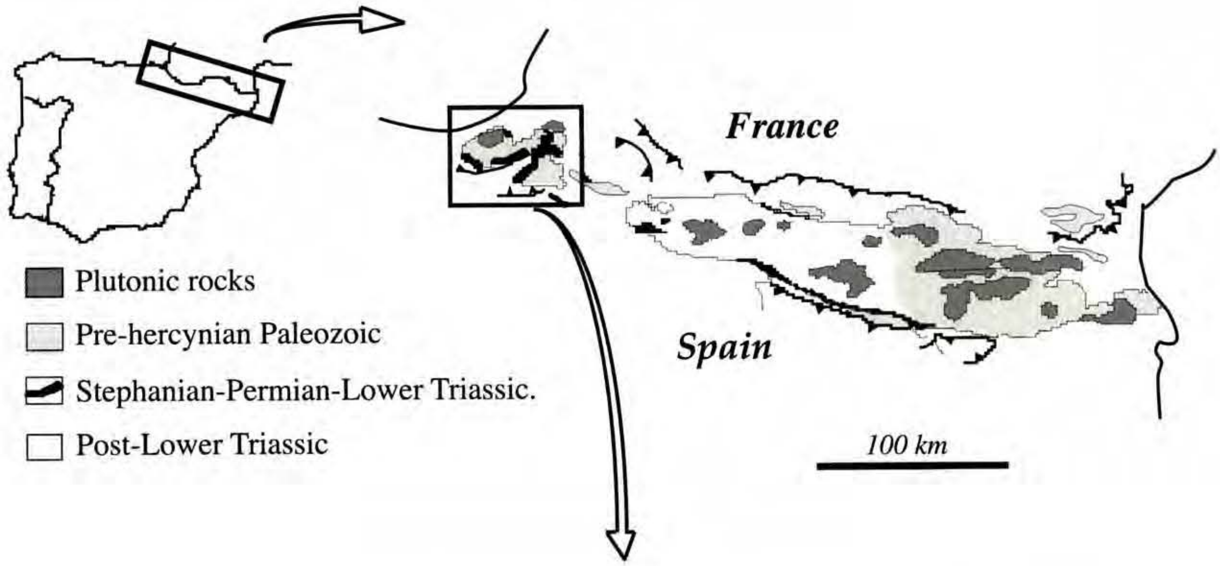
The study of continental deposits with interbedded igneous rocks in selected outcrops of Upper Permian basins is one of the best tools for gaining knowledge of this important time interval, and allows comparison and correlation between different outcrops considered representative of Late Variscan geology in several European areas. Cassinis (1996) provided a synthesis of the information available on the Late Carboniferous and Permian basins of southwestern Europe, underlining the need for studies to complete a detailed paleogeographical and geological scheme for Permian times. In this context, the Cinco Villas Massif (CVM; Navarra, Western Pyrenees, Spain) provides new compositional and age information for three Upper Permian outcrops, affected by a post-Autunian to pre-Buntsandstein magmatism.

The first data about this magmatism in the CVM (Fig. 1) came from Le Fur-Balouet (1985) and Cabanis & Le Fur-Balouet (1989), who studied its petrography in the Larrun and Yanci-Aranaz areas, and Innocent *et al.* (1994), who studied the magmatism cropping out in the Larrun Basin, in the context of Late Variscan magmatic episodes of the Pyrenees. In this paper, we deal with the composition and emplacement age of this magmatism (not studied by previous authors), represented in three Permian outcrops (Larrun, Mendaur and Ibantelli) and also by cogenetic doleritic dykes in the Yanci-Aranaz area.

GEOLOGICAL SETTING

The studied outcrops are situated in the westernmost part of the Pyrenean Axial Zone (PAZ), in a Paleozoic geological unit known as the Cinco Villas Massif (CVM; Fig. 1). The CVM is isolated from the rest of the PAZ by a crustal-scale

[1] Departamento de Química y Edafología, Universidad de Navarra, 31080 Pamplona, Spain.
[2] Departamento de Ciencias de la Tierra, Universidad de Zaragoza, 50009 Zaragoza, Spain.



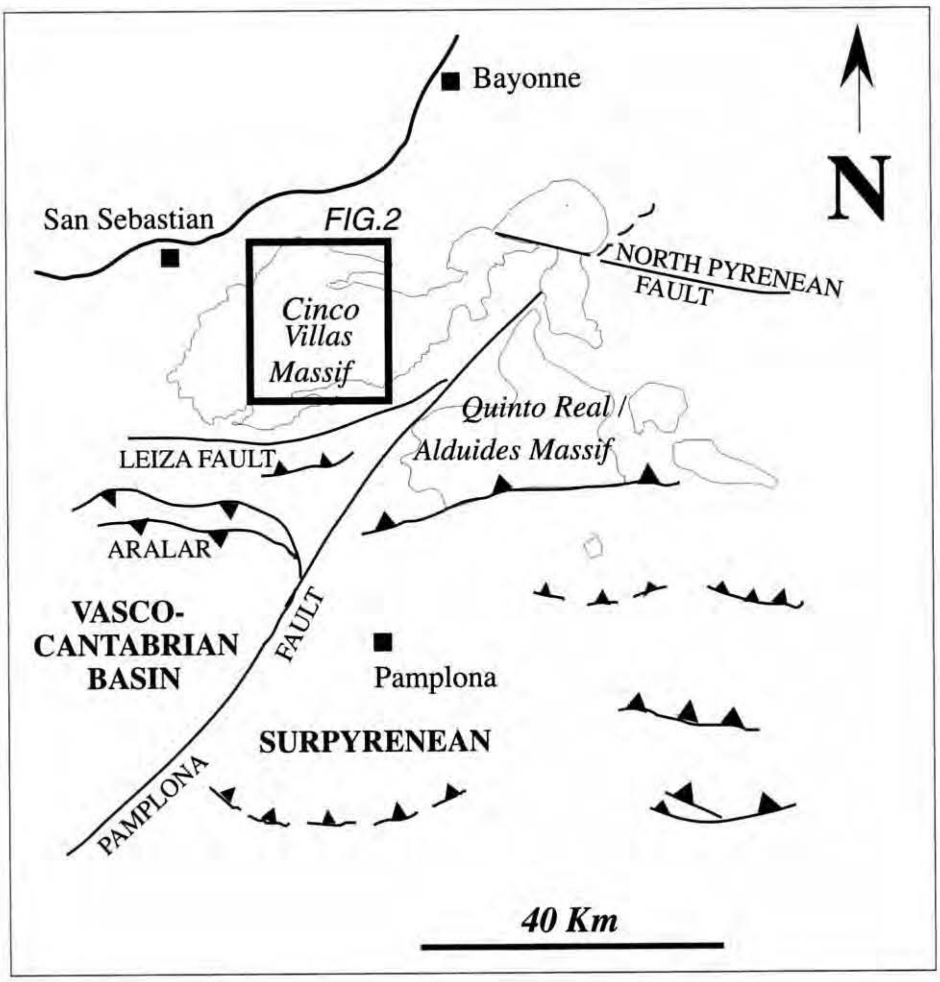


Fig. 1 – Geographical and geological location map for the studied area.

structure (ECORS Pyrenees Team, 1988), the Pamplona Fault, which also affected the North Pyrenean Fault (NPF). The Pamplona Fault divides the NPF into two sectors (eastern and western); these two sectors show different stratigraphic and structural features, as demonstrated when the CVM (located to the west) and the Alduides-Quinto Real Massif (in the eastern sector) are compared. The Leiza Fault, which has been considered to be a continuation of the NPF, is the southern limit of the CVM. The CVM is mainly composed of Devonian and Carboniferous rocks (Fig. 2), which were affected by the Variscan and Alpine orogenies (Martínez-Torres, 1997). The easternmost part of the CVM (also known as the "Allochtonous Unit") is affected by several Variscan thrust sheets; in contrast, the western part of the CVM ("Autochthonous Unit") was unaffected by Variscan thrusts. Late Permian magmatism in the CVM is represented by:

1) basaltic sills, emplaced into sedimentary materials in three areas of Permian rocks (Larrún, Ibantelli and Men-

daur); the base of the Permian sedimentary pile lies unconformably on the Variscan basement, while Buntsandstein facies materials overlie the Permian sedimentary rocks and basaltic sills.

2) doleritic dykes, injected into the Variscan rocks of the western and central sectors of the CVM.

The three Permian outcrops (Larrún, Ibantelli and Mendaur; Fig. 3A, B and C) share some features in common: a) their stratigraphical record, comprising pelites and microconglomerates, equivalent to those described by Gisbert (1981) for the "Unidad Roja Superior" (URS, Upper Red Unit, Upper Permian); b) the occurrence of basaltic sills (two to four events); and c) Buntsandstein facies Triassic rocks (Lucas *et al.*, 1980) resting unconformably on the Permian sequence. Stratigraphic sections for these outcrops are shown in Figs 4A (Larrun), 4B (Ibantelli) and 4C (Mendaur). The microconglomerates seem to be re-

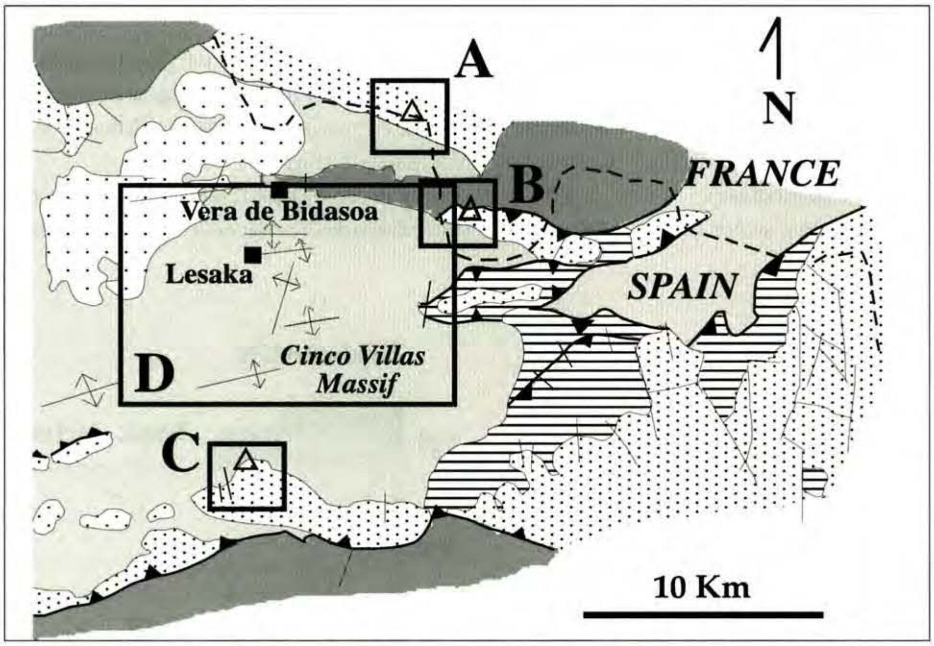


Fig. 2 – Geological map of the Cinco Villas Massif. Capital letters indicate the areas detailed in Fig. 3.

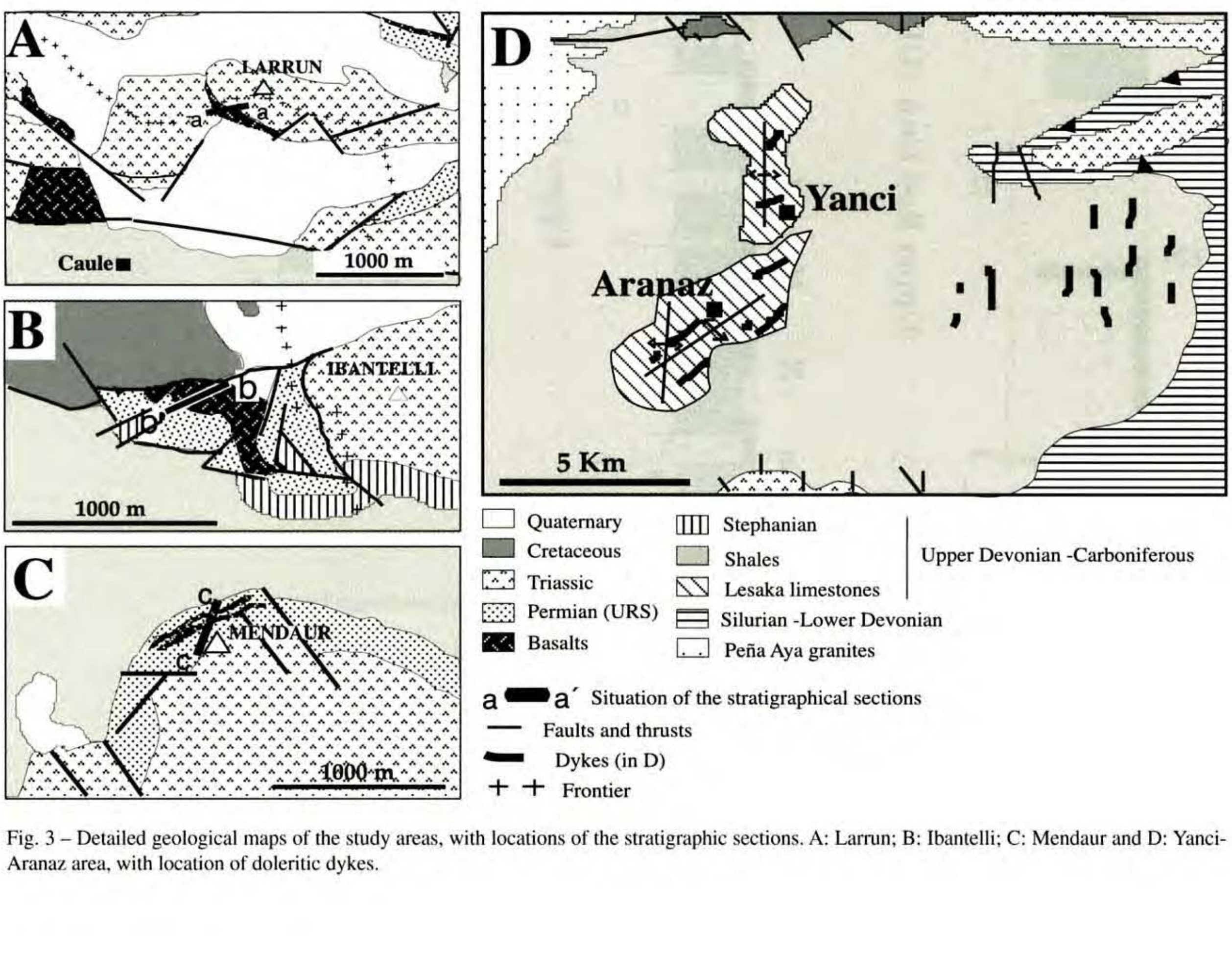


Fig. 3 – Detailed geological maps of the study areas, with locations of the stratigraphic sections. A: Larrun; B: Ibantelli; C: Mendaur and D: Yanci-Aranaz area, with location of doleritic dykes.

lated to basin-opening events, as is suggested by the occurrence of basaltic sills just above each microconglomerate layer (see Fig. 4C). Pelite fragments are included within, and partially disaggregated into, the basalt, suggesting emplacement under a thin layer of unconsolidated sediment of nearly constant thickness and over a large area, as deduced from the lack of contact metamorphism and lava structures. In some cases (lowermost sill in Larrún, of almost 120 m thickness), gravitational settling of crystals is observed (olivine concentrates at the base of the sill, while the top of the sill is richer in plagioclase).

Doleritic dykes crop out in Yanci-Aranaz sector (D in Fig. 2; Fig. 3D), emplaced in carbonate rocks (Lesaka limestones, Upper Famennian-Westphalian; Heddebaut, 1975).

AGE AND EMPLACEMENT CONDITIONS

The emplacement of the basaltic sills, took place at the same time as the deposit of the URS and before the sedimentation of Buntsandstein facies materials, as can be deduced from their stratigraphic position (Fig. 4).

Taking into account the lack of dykes injected into Triassic (or later) materials and the cogenetic character of these

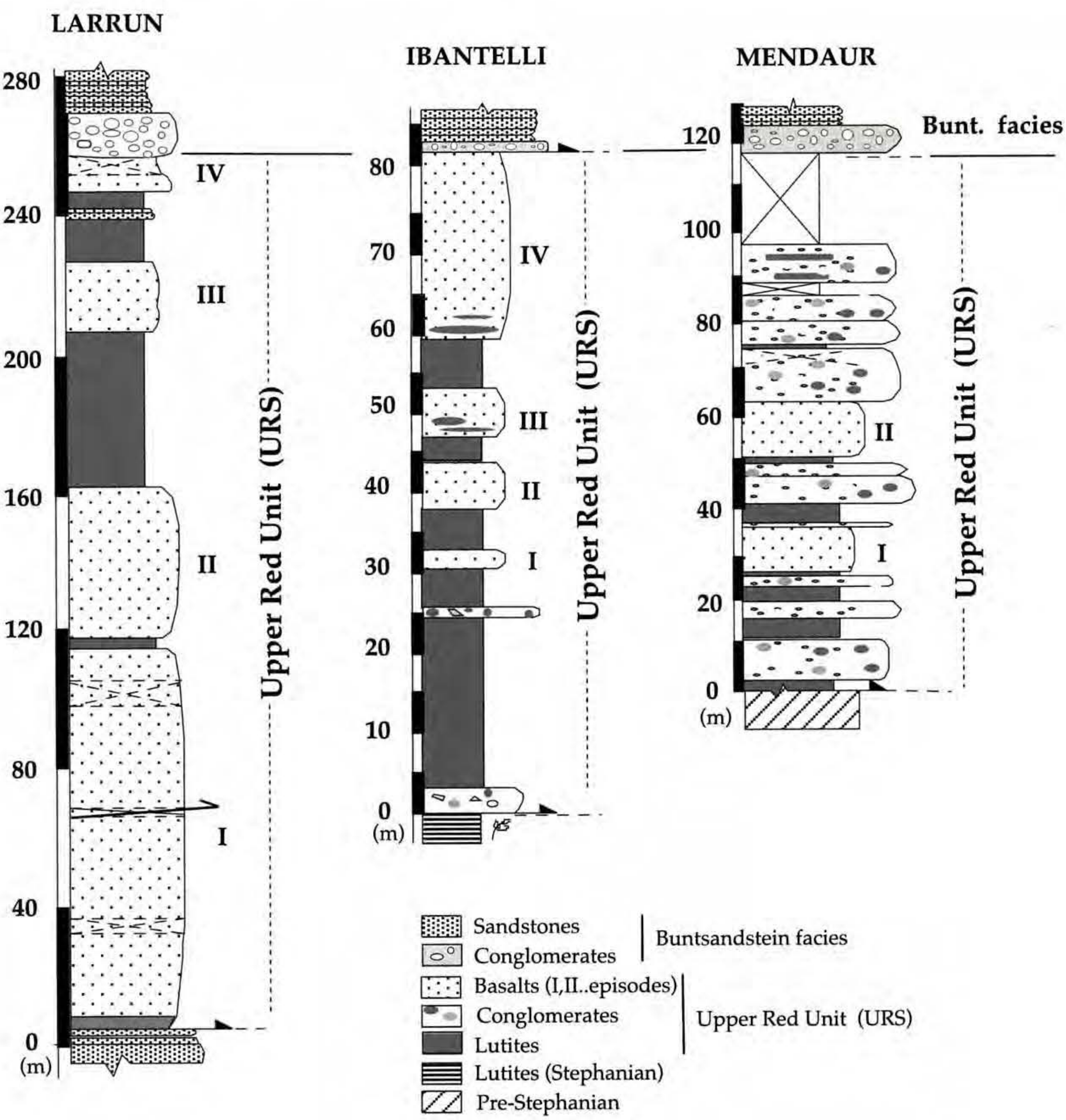


Fig. 4 – Stratigraphic sections for the three studied Permian basins.

dykes with respect to the basaltic sills deduced from their mineral and whole rock-compositions, the emplacement of both sills and dykes can be considered as coeval, favoured by reactivation of the Late Variscan strike-slip WNW-ESE trending fractures (Lucas & Gisbert, 1996; Arthaud & Matte, 1975; Carreras & Capellá, 1994).

The orientations of basins and hypabyssal dykes in the Pyrenees were controlled, during Permian and Triassic times by the sinistral transcurrent movement of the NPF (or the equivalent strike-slip faults at that time) in the western and central Pyrenees, and by dextral shear movement of NE-SW faults in the eastern Pyrenees, as indicated by Lucas & Gisbert (1996; Fig. 5A). These structures were still active in the early Triassic, controlling the evolution of the intracontinental Triassic basins.

The strike of the dykes cropping out in the Yanci-Aranaz area shows a bimodal distribution, with N-S and NE-SW directions (Fig. 5B). The angle between the two sets of dykes is coincident with that indicated in Fig. 5A for basins and dykes in the western Pyrenees, although slightly rotated. This change in orientation of the studied dykes, with respect to that proposed by Lucas & Gisbert (1996), can be related to the counter-clockwise rotation of Iberia during Alpine times.

If the Late Variscan transtensional regime is considered, the formation of subsiding half-graben basins, filled with thick sedimentary piles and basaltic injections (favoured by the extensional regime; Fig. 5C), is a reasonable model for the development of Permian basins.

PETROLOGY AND GEOCHEMISTRY OF SILLS AND DYKES

The basalts (sills) display a variety of textures, but the most

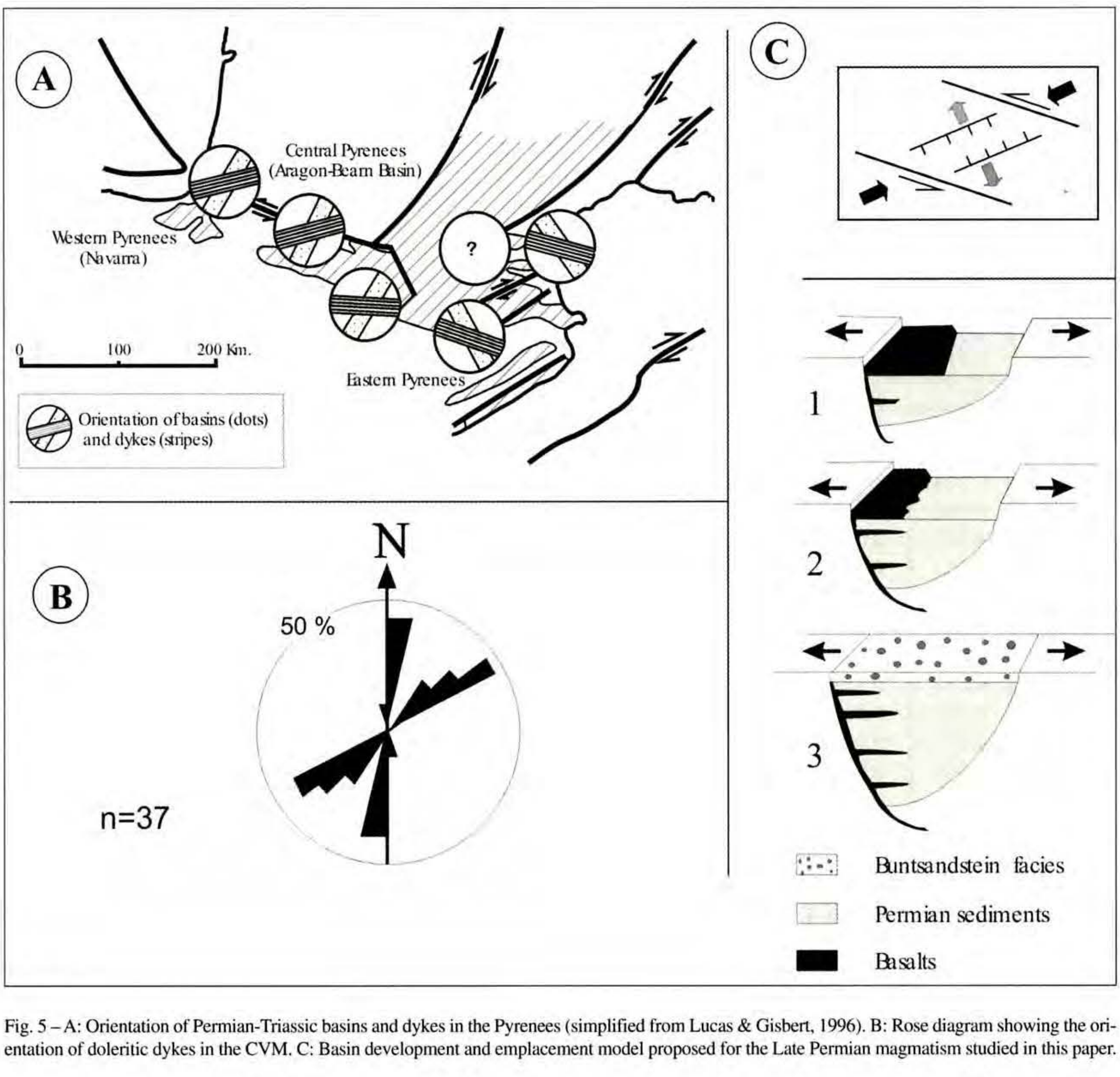


Fig. 5 – A: Orientation of Permian-Triassic basins and dykes in the Pyrenees (simplified from Lucas & Gisbert, 1996). B: Rose diagram showing the orientation of doleritic dykes in the CVM. C: Basin development and emplacement model proposed for the Late Permian magmatism studied in this paper.

common types are hypocrystalline-porphyritic, and rich in vesicles (filled by chlorite and/or carbonates). The main primary minerals are olivine (always altered), Ti-augite and plagioclase feldspar. The modal proportions of these mineral can vary, and two rock types can be defined (olivine-pyroxene basalt, rich in plagioclase and olivine-plagioclase basalt, without pyroxene) in Larrun, but only one (olivine-plagioclase basalt) in Ibantelli and Mendaur.

The dolerites (dykes) have doleritic and/or ophitic textures and two rock-types can be defined: Ti-augite-rich dolerites and plagioclase-rich (An_{63-57}) dolerites, with minor Ti-augite (less than 10%).

The study of mineral compositions in sills and dykes is frequently hindered by the alteration of olivine and plagioclase; accordingly, we have focused our study on clinopyroxene compositions. A selection of clinopyroxene analyses is shown in Table I. These compositions correspond to Ti-rich augite (Fig. 6A), near the diopside-augite boundary, and their evolution is defined by positive correlations of Na *vs*. $*Fe^{3+}$ (Fig. 6B; $*Fe^{3+}$ stands for the estimated value of Fe^{3+}, following the algorithm of Droop, 1987). and Al *vs* Ti (Fig. 6C) The progressive increase in Ti and Na (reaching their highest concentrations at the end of the crystallisation) is consistent with the evolution of an alkaline magma, as

	Basalts					Dykes				
SiO_2	48,763	49,380	48,299	47,881	50,029	47,879	47,818	47,959	48,008	48,304
TiO_2	2,437	1,733	1,948	2,023	2,460	2,626	2,422	2,476	2,574	1,836
Al_2O_3	3,340	2,321	2,723	2,969	3,427	5,255	4,919	4,035	4,341	3,418
V_2O_3	0,203	0,176	0,128	0,135	0,202	0,201	0,229	0,254	0,222	0,113
Cr_2O_3	0,014	0,000	0,089	0,106	0,000	0,242	0,129	0,047	0,082	0,070
Fe_2O_3	2,813	4,073	4,758	5,066	1,158	3,055	4,756	2,753	3,646	5,312
MgO	12,568	13,065	13,453	13,553	13,120	0,031	0,002	0,000	0,000	0,056
CaO	21,080	21,597	21,576	21,583	21,593	12,117	13,236	12,549	12,962	11,406
MnO	0,212	0,250	0,296	0,242	0,143	22,468	22,236	21,841	20,820	22,023
FeO	8,074	6,754	5,484	4,665	8,564	0,191	0,293	0,283	0,224	0,330
CoO	0,000	0,014	0,000	0,000	0,000	4,888	4,560	6,831	7,688	7,530
NiO	0,000	0,000	0,000	0,080	0,000	0,034	0,000	0,000	0,000	0,002
ZnO	0,000	0,098	0,000	0,000	0,063	0,030	0,020	0,020	0,045	0,035
SrO	0,000	0,000	0,000	0,000	0,020	0,000	0,000	0,000	0,000	0,000
Na_2O	0,595	0,544	0,453	0,492	0,470	0,495	0,518	0,450	0,423	0,640
K_2O	0,016	0,008	0,000	0,000	0,010	0,004	0,000	0,000	0,008	0,000
TOTAL	**100,115**	**100,011**	**99,207**	**98,795**	**101,259**	**99,517**	**101,139**	**99,498**	**101,044**	**101,077**
Si	1,836	1,859	1,829	1,818	1,854	1,780	1,772	1,813	1,792	1,817
Ti	0,069	0,049	0,056	0,058	0,069	0,073	0,068	0,070	0,072	0,052
Al	0,148	0,103	0,122	0,133	0,150	0,230	0,215	0,180	0,191	0,152
V	0,006	0,005	0,004	0,004	0,006	0,006	0,007	0,008	0,007	0,003
Cr	0,000	0,000	0,003	0,003	0,000	0,007	0,004	0,001	0,002	0,002
Fe^{3+}	0,080	0,115	0,136	0,145	0,032	0,085	0,133	0,078	0,102	0,150
Mg	0,705	0,733	0,760	0,767	0,725	0,001	0,000	0,000	0,000	0,001
Ca	0,850	0,871	0,876	0,878	0,858	0,727	0,731	0,707	0,721	0,640
Mn	0,007	0,008	0,010	0,008	0,004	0,895	0,883	0,884	0,833	0,888
Fe^{2+}	0,254	0,213	0,174	0,148	0,266	0,006	0,009	0,009	0,007	0,011
Co	0,000	0,000	0,000	0,000	0,000	0,152	0,141	0,216	0,240	0,237
Ni	0,000	0,000	0,000	0,002	0,000	0,001	0,000	0,000	0,000	0,000
Zn	0,000	0,003	0,000	0,000	0,002	0,001	0,001	0,001	0,001	0,001
Sr	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Na	0,043	0,040	0,033	0,036	0,034	0,036	0,037	0,033	0,031	0,047
K	0,001	0,000	0,000	0,000	0,001	0,000	0,000	0,000	0,000	0,000
TOTAL	**4,000**	**4,000**	**4,000**	**4,000**	**4,000**	**4,000**	**4,000**	**4,000**	**4,000**	**4,000**
WO	46,810	47,740	48,150	48,750	45,501	47,981	46,539	46,680	43,748	46,112
EN	38,830	40,170	41,770	42,590	38,461	38,968	38,538	37,311	37,890	33,223
FS	14,370	12,090	10,080	8,660	16,038	13,050	14,923	16,009	18,362	20,666

Table I – Selected clinopyroxene compositions for basalts and dolerites (dykes). *Fe3+ stands for the calculated value for Fe3+ , following the algorithm of Droop, 1987.

can be deduced from a plot of compositions on a Ti *vs* (Ca+Na) diagram (Leterrier *et al.*, 1982; Fig. 6D).

The whole-rock chemical analyses (on 17 basalts and 9 dolerites; selected data are shown in Table II) were carried out at the Universities of Oviedo (major elements and some of the trace elements by XRF) and Granada (rest of the trace elements, including REE, by ICP-MS). Chemical compositions of all the analysed samples show their sub-alkaline affinity (Fig. 7). On the other hand, Ti enrichment with respect to V (consistent with the Ti enrichment in clinopyroxene), high contents of alkalis, P_2O_5 and Ta, together with relatively low values for Y and Sr (Table II and Fig. 9), argue for an alkaline affinity. The cogenetic character of the sills and dykes can be inferred from the good positive, almost linear, correlations between incompatible elements, as shown by Ta *vs* La (Fig. 8A), Th/Ta *vs* Th/Hf (Fig. 8B), Sm/Nd *vs* Th (Fig. 8C) and Lu/La *vs* Ce (Fig. 8D) diagrams.

Trace element contents (averages of Larrún, Ibantelli, Mendaur and dykes; Table II) have been normalised to N-

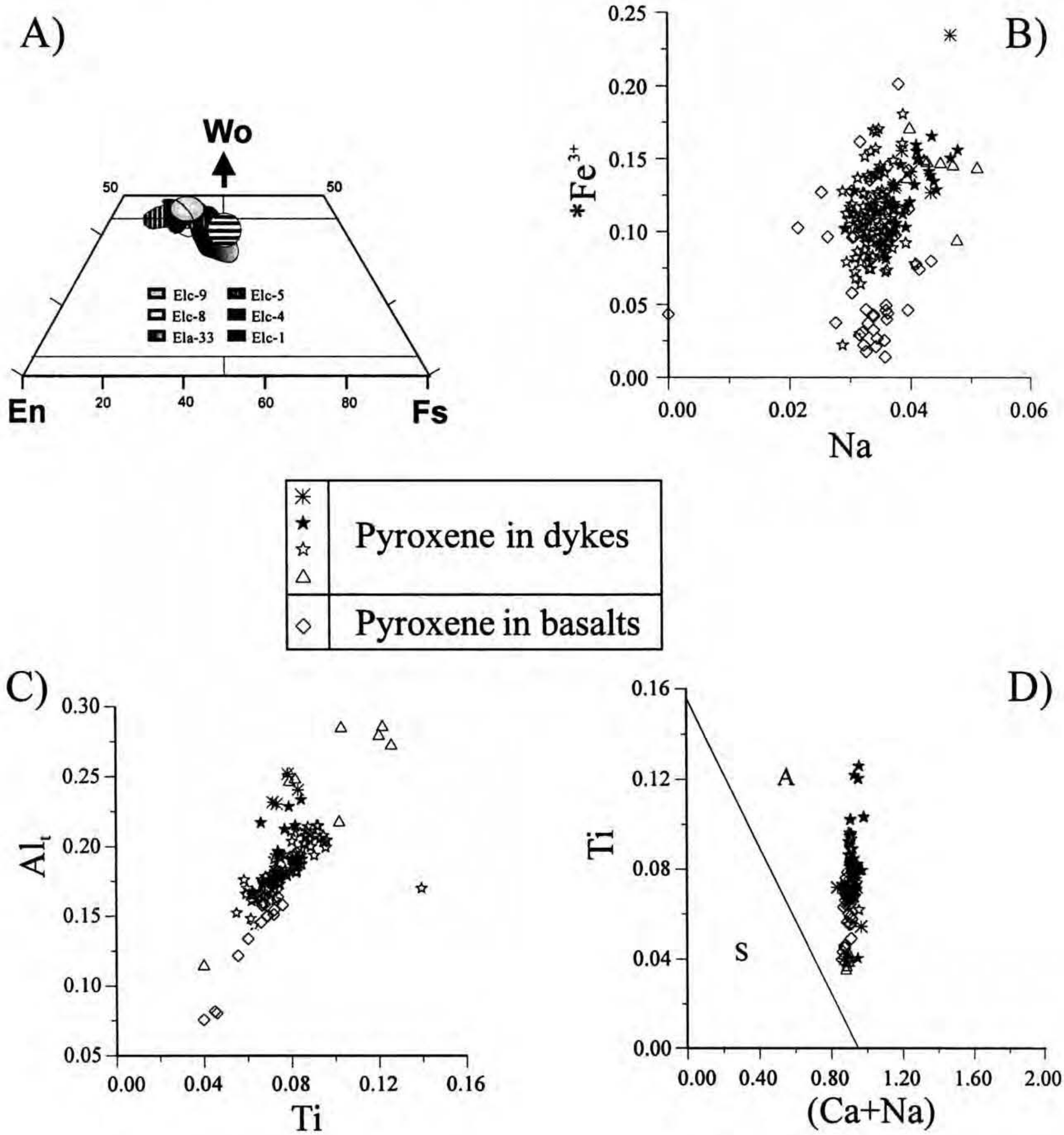


Fig. 6 – Clinopyroxene compositions of basalt and dolerite. A: Classification diagram (Morimoto *et al.*, 1988). B: *Fe3+ *vs* Na diagram. C: Al *vs* Ti diagram and D: Ti *vs* (Ca+Na), according to Leterrier *et al.*, 1982, where A: alkaline domain and S: subalkaline domain.

MORB values (Saunders & Tarney, 1984). The resulting patterns (Fig. 9) indicate the existence of an evolutionary trend (increasing differentiation) from the Ibantelli basalts

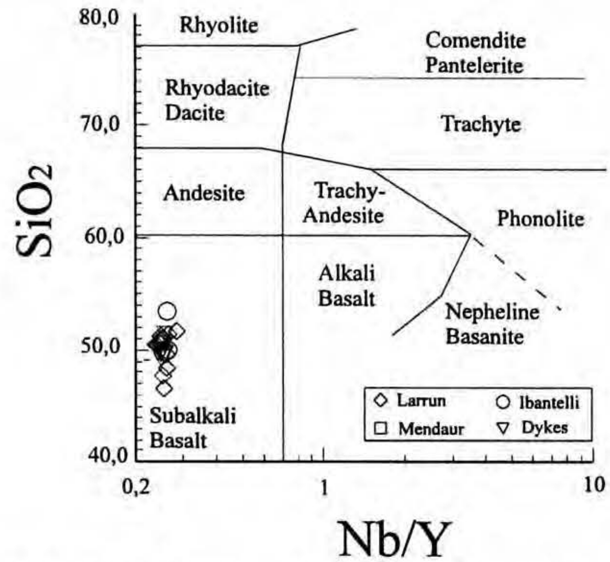


Fig. 7 – SiO_2 *vs* Nb/Y classification diagram (Winchester & Floyd, 1976). All the analysed samples fall in the subalkaline basalt field.

to the Mendaur basalts; this sequence is in good agreement with that obtained by petrographical criteria.

On the other hand, the unexpectedly high values for Th, La and Ce can be explained by crustal contamination processes, which can also be inferred from the Ba, Sr and Rb contents, although these elements may also be affected by alteration processes. Finally, a mantle origin is proposed for the magma, taking into account its unevolved composition and the isotopic ratios $^{87}Sr/^{86}Sr$ (0.706-0.710) and $^{143}Nd/^{144}Nd$ (0.5123-0.5125) obtained by Innocent *et al.* (1994) on Larrun basalts. These authors also suggest that the CVM magmatism can be considered as coeval with that of the Anayet area (Central Pyrenees).

CONCLUSIONS

Three Permian outcrops, located in the CVM (Western Pyrenees), show a sedimentary record supplemented by interbedded basaltic sills, which are cogenetic with doleritic dykes emplaced in other areas of the CVM. Basalts and dolerites evolved from a basic mantle-derived magma, with subalkaline to alkaline affinities, as can be deduced from the

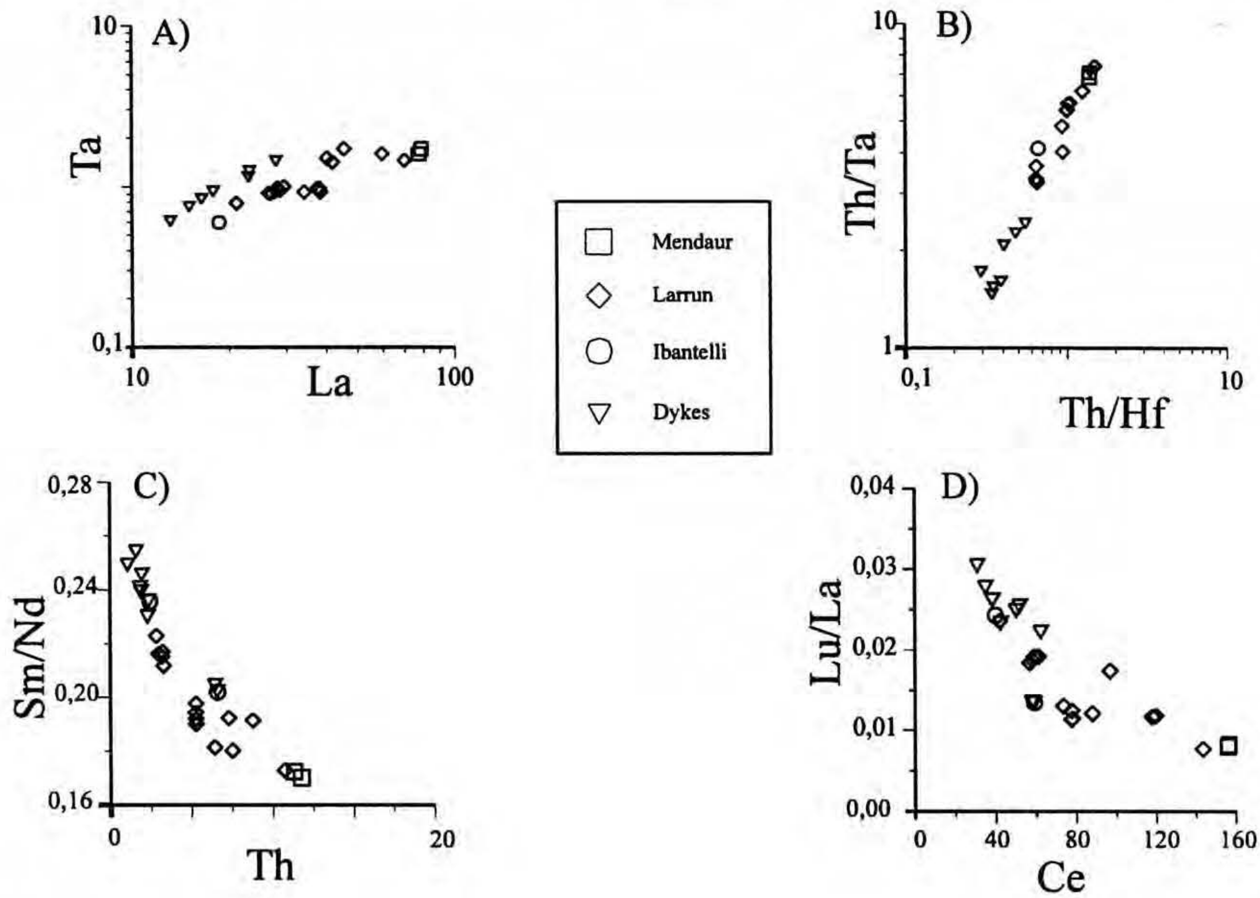


Fig. 8 – Compositions of basalts and dolerites, plotted on variation diagrams for incompatible elements and their ratios. The fairly good correlation of data points suggest the cogenetism of both basalt and dolerite.

	Larrun n=14	Ibantelli n=1	Mendaur n=2	Dykes n=9
SiO_2	46,78	46,54	49,07	46,85
TiO_2	2,02	1,48	2,34	1,95
Al_2O_3	17,16	17,69	16,54	16,82
Fe_2O_3	10,41	8,98	10,75	9,97
MnO	0,10	0,09	0,11	0,15
MgO	7,24	8,24	6,40	6,40
CaO	3,91	6,30	2,48	6,77
Na_2O	4,07	3,75	3,78	3,88
K_2O	1,52	0,41	0,16	1,03
P_2O_5	0,45	0,25	0,63	0,35
LOI	5,76	6,16	7,37	5,22
TOTAL	99,42	99,89	99,60	99,39
Li	109,22	110,40	177,98	47,00
Rb	16,08	9,32	3,12	33,64
Cs	2,64	2,76	8,19	1,74
Be	1,88	0,98	2,09	2,19
Sr	233,67	313,20	65,19	523,36
Ba	314,73	225,36	77,38	170,00
Sc	28,25	29,83	23,86	29,24
V	179,37	181,53	149,80	179,63
Cr	144,87	261,00	56,92	157,31
Co	34,94	32,89	36,22	36,51
Ni	40,02	30,65	24,28	73,35
Cu	33,77	16,50	14,55	42,13
Zn	226,58	134,37	227,09	83,54
Ga	19,64	17,47	22,31	18,96
Y	39,01	26,88	42,89	36,35
Nb	17,38	8,47	22,19	15,05
Ta	1,15	0,60	1,66	0,99
Zr	247,29	146,98	332,15	211,52
Hf	5,81	3,70	8,30	4,67
Mo	1,21	0,70	1,25	1,26
Sn	4,00	2,37	2,85	4,51
Tl	0,06	0,02	0,03	0,19
Pb	15,98	23,59	12,80	7,30
U	0,99	0,62	1,90	0,68
Th	6,17	2,46	11,54	2,91
La	38,59	18,63	78,37	21,27
Ce	82,18	39,98	156,19	47,65
Pr	9,62	5,09	18,58	6,21
Nd	37,53	20,44	69,28	25,95
Sm	7,44	4,82	11,86	6,01
Eu	1,81	1,64	2,37	1,65
Gd	7,07	4,98	9,56	6,10
Tb	1,11	0,82	1,44	0,99
Dy	6,87	5,08	8,20	6,20
Ho	1,45	1,09	1,74	1,31
Er	3,86	2,98	4,60	3,50
Tm	0,58	0,46	0,68	0,53
Yb	3,55	2,92	4,22	3,16
Lu	0,53	0,45	0,64	0,47

Table II – Average whole-rock chemical compositions for basalts (Larrun, Ibantelli, Mendaur) and dolerites (dykes).

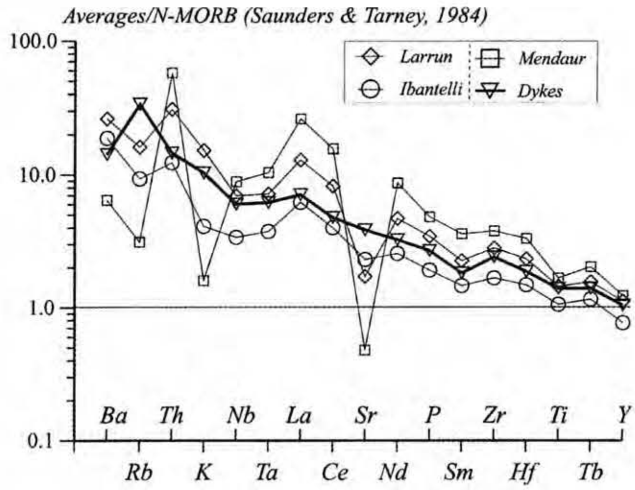


Fig. 9 – N-MORB-normalised spider diagram of average compositions for basalts (Larrun, Mendaur, Ibantelli) and dolerite. See text for interpretation and further explanation.

Ti enrichment in the clinopyroxene and the high contents of P, Ta and Ti in whole-rock compositions. The cogenetic character of the sills and dykes can be inferred from their incompatible trace element ratios and REE patterns, which also show the existence of an evolutionary trend from Ibantelli basalts (the less evolved) to Larrun, and finally to Mendaur basalts (with minor modal olivine).

This magmatism, related to the late-Variscan extensional strike-slip regime, can be considered coeval with that in the Anayet area (Central Pyrenees; Innocent *et al.*, 1994). These Late Permian alkaline magmatic episodes, associated with basin-opening events, represent the first expression of the extension-related Mesozoic magmatism, clearly different from the Variscan magmatism under a transpressional regime (Late Carboniferous-Early Permian), with calcalkaline affinities and a dominant crustal signature. Post-Autunian magmatic episodes are only expressed in central (Anayet; Innocent *et al.*, 1994) and western (CVM, this paper) sectors of the Pyrenees. The available data for the CVM Upper Permian magmatic units are not sufficient to ascertain whether they share the same protolith (the same kind of mantle), or similar melting rates, or both. On the other hand, the emplacement conditions observed for the CVM magmatism are singular and, in this context, the CVM could be considered as a key reference area for the Late Permian magmatism in the Pyrenees.

Acknowledgements – This work is included in the objectives of, and supported by, the PB98-1604 DGICYT project of the Ministerio de Educación y Cultura of Spain. The authors wish to thank B. Bonin and L. Cortesogno for their constructive reviews and criticism, which have greatly improved the original manuscript.

REFERENCES

ARTHAUD F. & MATTE PH., 1975. Les décrochements tardi-hercyniens du sud-ouest de l'Europe: géometrie et essai de reconstitution des conditions de la déformation. *Tectonophysics*, 25: 139-171.

CABANIS B. & LE FUR-BALOUET S., 1989. Les magmatismes stéphano-permiens des Pyrénées marqueurs de l'évolution géodynamique de la chaîne. *Bull. Cent. Rech. Explor.-Prod. Elf-Aquitaine*, 13: 105-130.

CARRERAS J. & CAPELLÁ I., 1994. Tectonic levels in the Palaeozoic basement of the Pyrenees: a review and a new interpretation. *J. Struct. Geology*, 16 (11): 1509-1524.

CASSINIS G., 1996. Upper Carboniferous to Permian stratigraphic framework of South-western Europe and its implications-An overview. In: Moullade B.M. & Nairn A.E.M.(eds), *The Phanerozoic Geology of the World: I. Paleozoic, B.* Elsevier: 110-180.

DROOP G.T.R., 1987. A general equation for estimating Fe^{3+} concentrations in ferromagnesian silicates and oxydes from microprobe analyses, using stoichiometric criteria. *Mineral. Mag.*, 51: 431-435.

ECORS PYRENEES TEAM, 1988. The ECORS deep reflection seismic survey across the Pyrenees, *Nature*, 331: 508-510.

GISBERT J., 1981. Estudio geológico-petrológico del Estefaniense-Pérmico de la Sierra del Cadí (Pirineo de Lérida): diagénesis y sedimentología. *Ph. D. Thesis, Universidad de Zaragoza*: 314 pp.

HEDDEBAUT C., 1975. Études géologiques dans les massifs paléozoiques basques. *Bull. Bur. Rech. Géol. Min.*, IV (I): 5-30.

INNOCENT C., BRIQUEU L. & CABANIS B., 1994. Sr-Nd isotope and trace element geochemistry of late Variscan volcanism in the Pyrenees: magmatism in post-orogenic extension? *Tectonophysics*, 238: 161-181.

LE FUR-BALOUET S., 1985. Les sécuences palévolcaniques du domaine pyrénéen depuis le Stéphano-Permien jusqu'au Crétacé: essai d'identification basé sur l'étude géochimique des elements en traces. *Thesis 3º cycle, Université Paris VI*: 320 pp.

LETERRIER J., MAURY R.C., THONON P., GIRARD D. & MARCHAL M., 1982. Clinopyroxene composition as a method of identification of the magmatic affinities of paleovolcanic series. *Earth and planet. Sci. Lett.*, 59: 139-154.

LUCAS C. & GISBERT J. (Coord.), 1996. Carbonifère Supérieur - Permien. Chap. 8. In: Barnolas A. & Chiron J.C. (eds), *Synthèse géologique et géophysique des Pyrénées*, Ed. BRGM-ITGE, vol. 1: 340-359.

LUCAS C., DOUBINGER J. & BROUTIN J., 1980. Premières datations palynologiques dans les grès triasiques des Pyrénées. *C. R. Acad. Sci.* (Paris), sér. D, 291 (6): 517-520.

MARTÍNEZ-TORRES L.M., 1997. Transversal a la cuenca Vasco-Cantábrica: introducción a la estructura y evolución geodinámica. *Guia de campo de la IX Reunión de la Comisión de Tectónica de la SGE*: 121 pp.

MORIMOTO N., FABRIES J., FERGUSON A. K., GINZBURG I. V., ROSS M., SEIFERT F. A., ZUSSMAN J., AOKI K. Y. & GOTTARDI G., 1988. Nomenclature of Pyroxenes. *Bull. Mineral.*, 111: 535-550.

SAUNDERS A.D. & TARNEY J., 1984. Geochemical characteristic of basaltic volcanism within back-arc basins. In: Kokelaar B.P. & Howells M.F. (eds), *Marginal basin geology*. Spec. Publ. Geol. Soc. London, 16: 59-76.

WINCHESTER M.A. & FLOYD P.A., 1976. Geochemical magma type discrimination, application to altered and metamorphosed basic igneous rocks. *Earth and planet. Sci. Lett.*, 28: 459-469.

«NATURA BRESCIANA» Ann. Mus. Civ. Sc. Nat., Brescia, MONOGRAFIA N. 25, 2001: 181-187

THE PERMIAN CALC-ALKALINE MAGMATISM OF THE IBERIAN BELT (SPAIN): AN UPDATED SYNTHESIS

MARCELIANO LAGO SAN JOSÉ [1], ANDRÉS GIL IMAZ [1], ANDRÉS POCOVÍ JUAN [1], ENRIQUE ARRANZ YAGÜE [1] and CARLOS GALÉ BORNAO [1]

Key words – magmatism; calcalkaline; hypabyssal; Iberian Belt; Permian.

Abstract – The Upper Stephanian-Permian calcalkaline magmatism of the Iberian Belt is represented by hypabyssal intrusions (sills and dykes) and, less commonly, by pyroclastic deposits, emplaced into Permian sedimentary basins, which are conformably overlain by Buntsandstein facies materials Andesitic compositions dominate, with minor basalts and rhyolites. Stratigraphical, paleontological and radiometric age data, together with tectonic criteria, indicate that, in relation to the movement of NNW-SSE and NW-SE trending faults, this magmatism was emplaced in several stages during the Late Stephanian and Early Permian. The least evolved types (basalt) were derived from the upper mantle, but the original magma composition was modified by interaction with crustal materials, as deduced from the inclusion of granitoid and high-grade metapelitic enclaves, partially or completely assimilated into andesite. These enclaves also provide evidence of deep fractures and, furthermore, they suggest hybridisation between the original magma and crustal restite-rich partial melts.

Parole chiave – magmatismo; calcalcalino; ipo-abissale; Catena Iberica; Permiano.

Riassunto – Il magmatismo calcalcalino tardo-stefaniano e permiano della Catena Iberica è contraddistinto da intrusioni ipo-abissali (in filoni-strato e dicchi) e, meno comunemente, da prodotti piroclastici, collocatisi in bacini sedimentari permiani, che sono ricoperti in concordanza da depositi a facies di Buntsandstein. Si hanno in prevalenza rocce a composizione andesitica, e subordinatamente basalti e rioliti. Datazioni stratigrafiche, paleontologiche e radiometriche, nonché criteri tettonici, indicano che questo magmatismo, in relazione al movimento di faglie orientate NNW-SSE e NW-SE, si mise in posto a più riprese durante il tardo-Stefaniano e il Permiano inferiore. I tipi meno evoluti (basalti) provennero dal mantello superiore, ma la compozione primaria del magma fu modificata a seguito di un'interazione avvenuta con materiale crostale, come si può dedurre dalla presenza di inclusi granitoidi e metapeliti d'alto grado, parzialmente o completamente assimilati dai magmi andesitici. Questi "enclaves" suggeriscono anche l'esistenza di profonde fratture, così come un'ibridizzazione tra il magma primario e parziali fusi crostali ricchi in restite.

INTRODUCTION

The Permian calcalkaline magmatism of the Iberian Belt is remarkably interesting due to: 1) the great number - nearly 1000 mapped outcrops- of subvolcanic intrusive bodies (sills and dykes); 2) all the members of a typical calcalkaline trend being exposed, andesite being the dominant rock type; 3) its epizonal emplacement into upper crustal sedimentary rocks ranging in age from Cambrian to uppermost Permian ("Thuringian"), 4) emplacement through basement fractures which favoured fairly rapid ascent of the magma; 5) the significant volume of crustal enclaves (granitoid rocks and metapelites); 6) the interaction between a mantle component and crustal materials, indicated by assimilation processes that affected metapelitic enclaves and finally, 7) in several Permian basins of the Iberian Belt, pyroclastic deposits – coeval with the hypabyssal rocks – include fossil plants, which facilitates paleontological dating of these materials.

GEOLOGICAL FRAMEWORK

The Iberian Belt is an intraplate orogen, located in the NE of the Iberian Peninsula (Fig. 1) and divided into two sectors: the western sector is known as "Rama Castellana" and the eastern as "Rama Aragonesa". Both sectors are affected by Alpine structures which are compatible with reactivation of the main Variscan faults of the Paleozoic basement. Most of these faults acted as NW-SE and NNW-SSE trending strike-slip faults, several kilometres in length, in response to the Variscan structuration of the belt (Capote, 1983).

Calcalkaline magmatism occurred in the Iberian Belt

[1] Departamento de Ciencias de la Tierra, Universidad de Zaragoza, 50009 Zaragoza, Spain.

during the late Stephanian-Permian interval, and was related to the opening of sedimentary basins, controlled by steeply dipping normal faults that affected the Paleozoic basement. Pyroclastic deposits are interbedded in the Stephanian-Permian succession, which unconformably overlies the pre-orogenic materials and, in the studied outcrops, is overlain by Upper Permian and Lower Triassic terrigenous sediments (Lago *et al.*, 1992).

These pyroclastic deposits crop out at Sauquillo de Alcázar (Figs 1A and 2; Lago & Pocoví, 1991 a), Fombuena (Figs 1B and 2; Conte *et al.*, 1987), locally over the top of the Ojos Negros sill (Figs 1C and 2; Lago *et al.*, 1994), Orea (Figs 1D and 2; Lago *et al.*, 1995), Atienza (Fig. 1L; Hernando *et al.*,1980) and Rillo de Gallo (Figs 1I and 2; Ramos *et al.*, 1976). In all these sectors, they are interbedded within sedimentary layers containing fossil plants which indicate an "Autunian" age (Lago *et al.*, 1991, 1995; Lago & Pocoví, 1991 a, b; Conte *et al.*, 1987); this age agrees with those obtained by K/Ar radiometric dating for andesites in Fombuena (292 ± 2.5 Ma; Conte *et al.*, 1987) and Atienza (287 ± 12 Ma; Hernando *et al.*, 1980). Thus, the magmatic episode took place during Late Stephanian and Early Permian times and, in any case, prior to the Buntsandstein facies sedimentation.

Hypabyssal intrusions (sills and dykes) are widely exposed in the Iberian Belt, especially at the SE sector of the Rama Aragonesa (Torres, 1989; Torres *et al.*, 1993); the largest volumes crop out at the Sierra de Albarracín (Rama Castellana; Lago *et al.*, 1993, 1996). In all cases, these intrusions have three features in common: a) andesite - both basaltic and amphibole-bearing - is the main rock type; basalt (*e.g.* Ojos Negros, Fig. 1C) and rhyolite (*e.g.* outcrops at Ateca – Fig. 1J – and NW Montalban Anticline – Fig. 1K) being less frequent; b) intrusion took place in several events, as deduced from the interference of andesite dykes crosscutting more differentiated intrusions; and c) they are all cogenetic. An absolute K/Ar age determination was made on biotite from the Loscos gabbro (Fig. 1H; Lago *et al.*, 1991) giving a 293 Ma (late Stephanian-early Permian) emplacement age. This finegrained gabbro is cut by andesite dykes

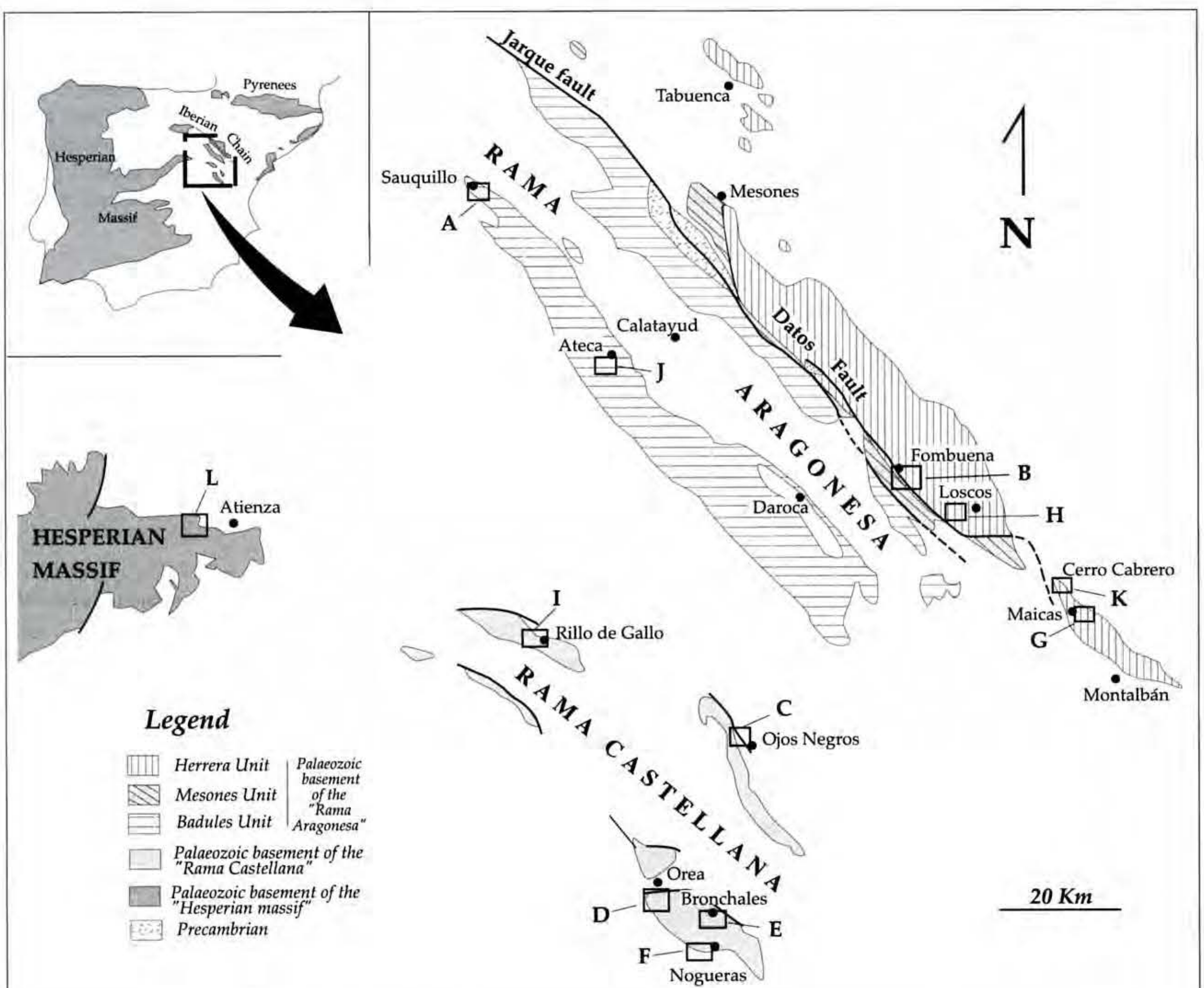


Fig.1 – Geological sketch map of the Iberian Belt, with location of the outcrops cited in the text.

which are cogenetic with all the other studied andesitic intrusions and pyroclastic materials.

MINERAL COMPOSITION AND GEOCHEMISTRY

Most of the igneous bodies (both hypabyssal and pyroclastic) are pervasively affected by secondary alteration processes, and only a few intrusions preserve their original mineral associations almost unaltered. These are the Ojos Negros basalt (Lago *et al.*, 1994), the Loscos gabbro (Lago & Conte, 1989) and some andesites from the Montalban Anticline (Torres, 1989; Torres *et al.*, 1993). The study of their mineral composition (by electron microprobe) and petrology, provides the basis for the definition of the main rock types (Fig. 3). A detailed chemical study

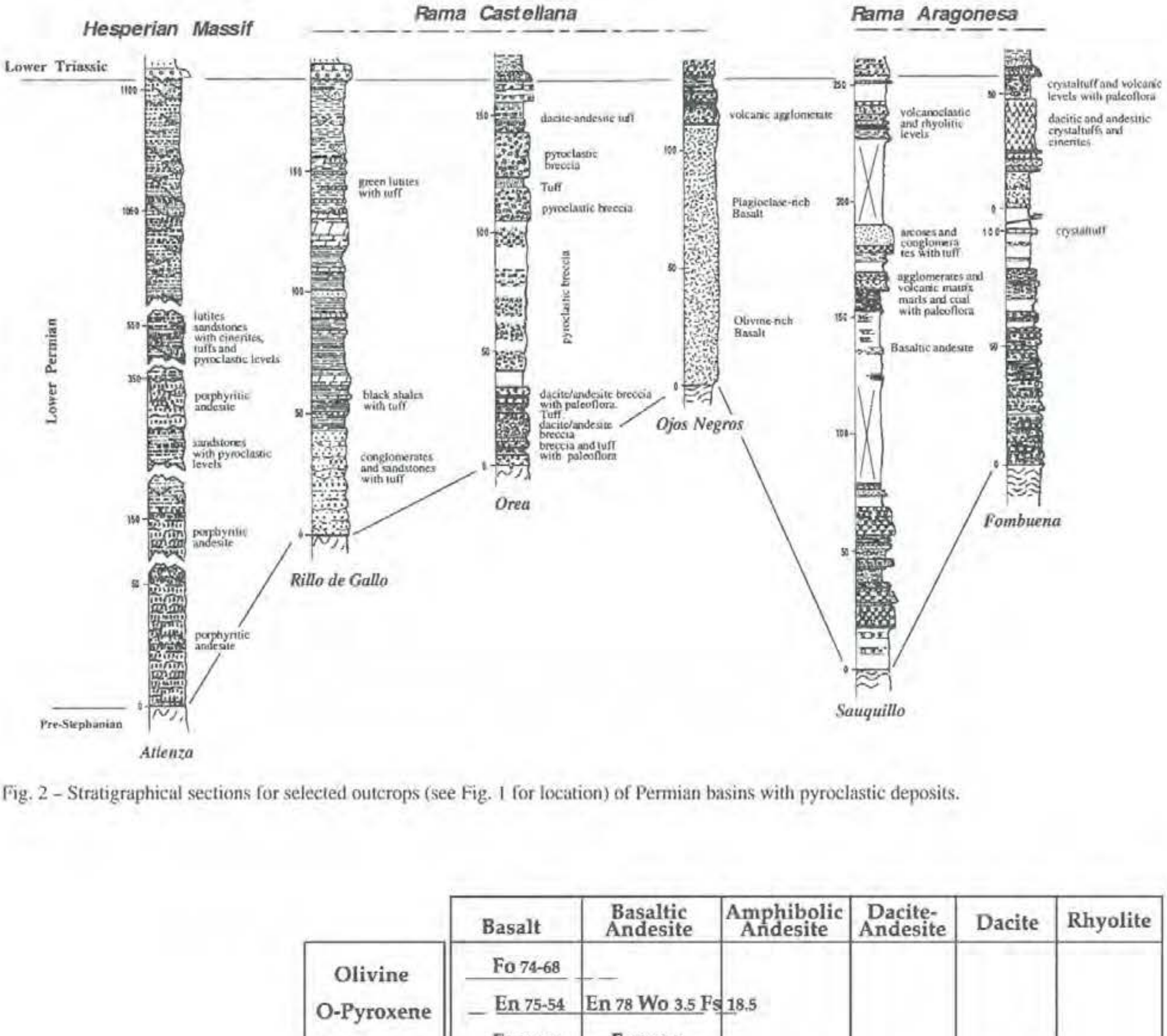


Fig. 2 – Stratigraphical sections for selected outcrops (see Fig. 1 for location) of Permian basins with pyroclastic deposits.

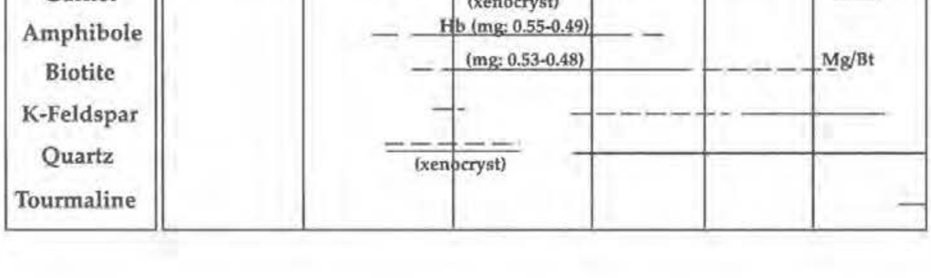


Fig. 3 – Crystallisation sequence for hypabyssal rock-types.

of the ortho- and clinopyroxene and amphibole has also been carried out and the results of this study, together with that of the whole rock geochemical compositions obtained by XRF and ICP-MS- (Table 1) indicate a calcalkaline affinity (Lago *et al.*, 1989 a).

The basalts show a hypocrystalline porphyritic texture, characterised by olivine (Fo_{73-68}), clinopyroxene ($Fs_{8.8}$ to $Fs_{11.8}$) and plagioclase (An_{83-72}) zoned phenocrysts. Basaltic (=pyroxene-bearing) andesite is hypocrystalline and porphyritic, with scarce isolated orthopyroxene crystals ($En_{78}Wo_3Fs_{19}$ on average), clinopyroxene ($En_{50}Wo_{40}Fs_{10}$ on average) and plagioclase (An_{81-27}) crystals as main mineral phases. Amphibole (hornblende) is a minor phase. Quartz xenocrysts are common in these rocks.

samples	M-und. N = 5	M-dif. N = 3	Ojos Negros N = 5
SiO2	52.540	53.700	51.000
TiO2	0.796	0.900	0.803
Al2O3	15.820	16.267	16.120
Fe2O3	7.178	6.937	6.698
MnO	0.128	0.113	0.122
MgO	5.622	5.010	5.176
CaO	7.890	6.980	10.532
Na2O	1.726	2.277	2.102
K2O	0.778	1.177	1.452
P2O5	0.120	0.143	0.128
L.O.I.	6.540	5.417	5.558
*mg**	0.641	0.622	0.638
Total	99.134	98.917	99.691
Li	76.600	60.667	38.800
B	36.400	35.667	45.600
Sc	24.020	20.900	27.960
V	137.400	126.667	207.600
Cr	214.000	180.000	406.000
Co	18.600	18.333	21.800
Ni	18.200	27.000	135.800
Cu	16.460	17.833	35.860
Zn	63.180	67.967	109.760
Rb	27.200	43.333	39.200
Sr	238.600	212.000	268.800
Y	17.600	17.333	23.000
Zr	128.400	148.333	112.400
Nb	9.600	9.667	3.600
Ba	124.200	201.667	273.200
La	18.140	21.233	18.180
Ce	36.820	43.533	36.980
Pr	4.560	5.300	4.220
Nd	18.060	20.400	17.900
Sm	4.220	4.800	3.520
Eu	1.114	1.277	1.152
Gd	4.080	4.700	3.360
Tb	0.540	0.633	0.560
Dy	3.720	4.000	3.800
Ho	0.700	0.730	0.662
Er	2.040	2.133	1.940
Yb	1.960	2.033	2.020
Lu	0.276	0.293	0.216
Hf	2.960	3.633	2.760
Tl	0.300	0.433	0.380
Th	5.120	5.867	4.520
U	1.680	1.600	1.400

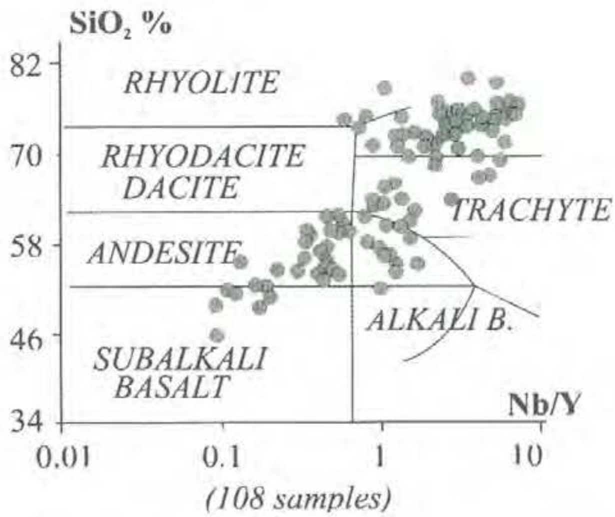


Fig.4 – %SiO_2 vs Nb/Y classification diagram (Winchester & Floyd, 1976).

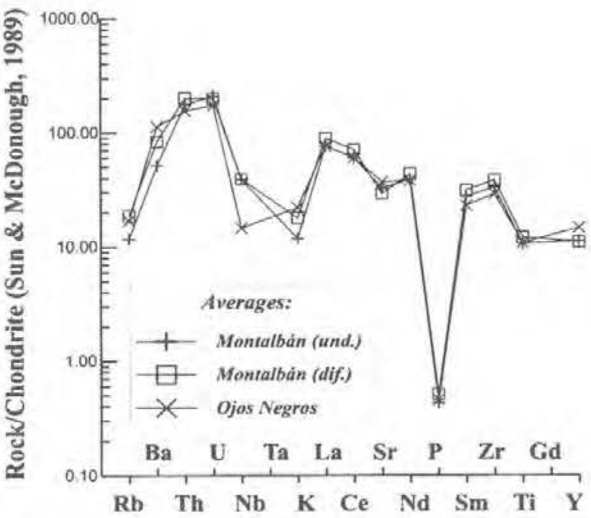


Fig. 5 – Multi-element, chondrite-normalised plot for the average compositions in Table 1. Depletions in P, Nb and K are clearly shown. See text for further details.

Table 1 – Average compositions of selected non-evolved rocks, representative of the studied magmatism. M-und: Pyroxene andesite from Montalban anticline; M-dif.: Amphibole andesite from Montalban Anticline. Ojos Negros: Ojos Negros basalt.

The amphibole andesite is hypocrystalline and porphyritic, with minor clinopyroxene, plagioclase (An_{70-20}) and amphibole (hornblende, with Mg^* values ranging from 0.52 to 0.48) as the main mineral phases. Garnet xenocrysts (Alm_{70-60}) are frequent. They occasionally show zoning and reaction rims, showing their instability within the andesitic magma and some degree of re-equilibration of the original metamorphic composition.

The dacite is composed of plagioclase, alkali feldspar, biotite and quartz, with minor amphibole. Finally, the mineral association in the rhyolite (both massive and fluidal varieties) is composed of alkali feldspar, albite, quartz and very scarce Fe-rich (schorl) tourmaline crystals.

Averaged whole-rock chemical compositions for selected samples – representative of the least evolved members of the calcalkaline trend – are shown in Table 1. A SiO_2 *vs* Nb/Y plot of all the available data (Fig. 4) supports the calcalkaline affinity and displays an almost continuous trend from basalt to rhyolite. A chondrite-normalised multi-element plot (chondritic values after Sun & McDonough, 1989) for the compositions in Table 1 shows negative anomalies for Nb, K and P, together with enrichments for Ba, Th, U, LREEs (La, Ce, Sm and Nd) and Zr (Fig. 5).

When normalising REE contents to chondrite (Boynton, 1984), enrichments in LREEs with respect to HREEs, as well as fractionation from basalt to andesite (Fig. 6), is clearly shown; these patterns are in good agreement with other trace element data (Ni: 136 ppm in basalt and <30 in andesite; Cr: 406 ppm in basalt and <200 ppm in andesite, for a Mg^* (= Mg/Mg+Fe) average value of 0.64). The observed REE patterns are typical of a calcalkaline trend, with anomalous enrichment in LREEs (La, Ce and Nd) and Th. These enrichments in incompatible elements can be related to the important contribution of crustal materials to the original basic magmas. In spite of the lack of other evidence (*i.e.* radiogenic isotope ratios), the origin of these basic magmas can be placed in the upper mantle since: 1) there is no evidence of Variscan basic crustal melts for the Iberian Belt and 2) all the rocks fit on to a calcalkaline trend.

CRUSTAL ENCLAVES AND THEIR SIGNIFICANCE

Two kinds of deep-basement enclaves occur in this magmatic unit: a) granitoids and b) metapelites.

Granitoid enclaves (granite, syenite and aplite, all rich in almandine garnet -Alm_{70-60}-) are common in the hypabyssal intrusions of the Rama Aragonesa (*e.g.* Maicas, Monforte de Moyuela and Vistabella; Lago *et al.*, 1991). The particularly interesting outcrop of an andesite dyke near Maicas (Fig. 1G; Lago *et al.*, 1987) contains an uncommon accumulation (up to 30% of the intrusion volume) of granitoid, metamorphic and sedimentary enclaves, which have several features in common: a) their long axis is clearly oriented, being almost parallel to the base of the andesite dyke; b) contacts between enclaves (granite-granite, granite-aplite, etc) are frequent and c) reaction rims can be observed between some of the enclaves and their host, giving rise to a hybrid rim surrounding the whole enclave.

Metapelite enclaves are also frequent; they show variable degrees of assimilation, from a thin reaction rim to complete assimilation, producing garnet (almandine) xenocrysts as relicts of the original enclaves. Two outcrops are specially rich in this kind of enclave: a) Maicas (Fig. 1G), in which biotite – sillimanite – spinel – plagioclase ± corundum ± garnet metapelitic enclaves are very common (Serra *et al.*, 1997 a), and b) the dacite outcrop at Noguera (Sierra de Albarracín; Fig.1F). In this case, metamorphic enclaves display reaction rims, granoblastic and decussate textures, and in most cases they preserve relicts of an original foliation, defined by biotite and amphibole, and two cleavages. The high-grade mineral association is composed of: biotite - sillimanite - spinel (± garnet [Alm_{72-63}] ± corundum), and also plagioclase (An_{60-33}), which is a late poikiloblastic phase, usually including spinel and/or biotite crystals (Serra *et al.*, 1997 b).

Garnet xenocrysts (Alm_{70-61}) are common in both hypabyssal intrusions (sills and dykes) and pyroclastic deposits (*e.g.* Fombuena; Conte *et al.*, 1987). They are relicts of otherwise completely assimilated metapelitic enclaves; this interpretation is also supported by the clear correlation, for each outcrop, between the quantity of garnet

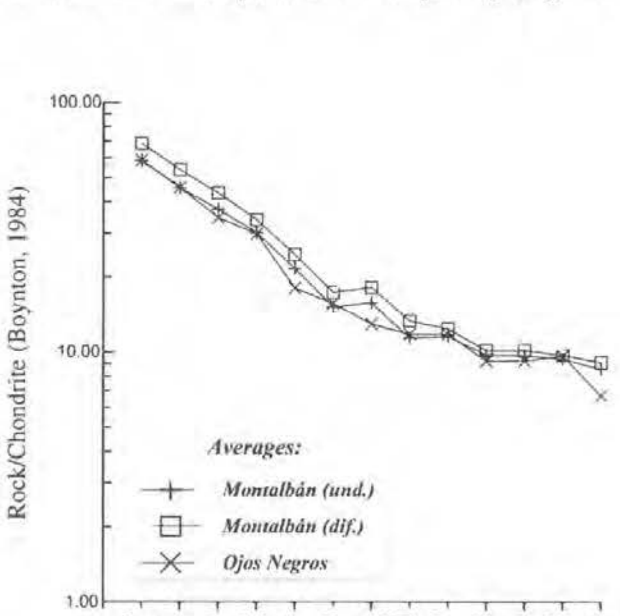


Fig. 6 – REE chondrite-normalised plot for the average compositions in Table 1. See text for further details.

xenocrysts and that of partially assimilated metapelitic enclaves (Lago *et al.*, 1989 b).

The occurrence of high-grade metapelitic enclaves and granitoid fragments within this magmatic unit provides evidence for a) the great depths of the magmatic conduits and b) the interaction between a magma originating in the upper mantle, and lower-middle crustal materials, which were partially or completely assimilated, modifying the original composition of the calcalkaline magma. At this stage, we cannot rule out the possible formation of restite-rich crustal melts that partially hybridised the basaltic magma, giving rise to more evolved andesitic and dacitic compositions.

CONCLUSIONS

The late Stephanian-Permian calcalkaline magmatism of the Iberian Belt, represented by hypabyssal intrusions (with dominance of andesite over basalt and rhyolite) and pyroclastic deposits, was controlled by the Late Variscan extensional regime which was responsible for the formation of deep, crustal-scale faults. This geodynamic framework made possible the ascent of a calcalkaline magma which was eventually emplaced in the form of hypabyssal intrusions (favoured by structural or stratigraphic discontinuities) and pyroclastic deposits which are interbedded into the sedimentary infill of Permian sedimentary basins, limited by normal faults. The primitive composition of the basic magma, derived from the upper mantle, was modified by interaction with lower-crustal materials (now expressed as granitoid and metapelitic enclaves, frequently assimilated) which were carried up by the magma during its ascent and emplacement.

Acknowledgements – The authors wish to thank L. Cortesogno and B. Bonin for their constructive reviews and criticism, which helped to improve the original manuscript.

REFERENCES

BOYNTON W. V., 1984. Geochemistry of the rare earth elements meteorite studies. In: Henderson (ed.), *Rare earth element geochemistry*. Elsevier: 63-114.

CAPOTE R., 1983. La tectónica de la Cordillera Ibérica. In: *Libro Jubilar J. M. Ríos*, Instituto Geológico y Minero de España, Madrid: 108-120.

CONTE J.C., GASCÓN F., LAGO M. & CARLS P., 1987. Materiales Stephano-Pérmicos en la fosa de Fombuena (Provincia de Zaragoza). *Bol. Geol. Minero*, XCVIII (IV): 460-470.

HERNANDO S., SCHOTT J.J., THUIZART T. & MONTIGNY R., 1980. Age des andesites et des sediments interstratifiés de la région d'Atienza (Espagne): étude stratigraphique, géochronologiques et paléomagnétique. *Soc. Géol. Bull.*, 32: 119-128.

LAGO M. & CONTE J. C., 1989. Petrología y Geoquímica. In: E. Hoja Magna. 1:50.000, nº 466 (Moyuela), *ITGE*, Madrid: 91-101.

LAGO M. & POCOVÍ A., 1991 a. Petrología y Geoquímica. In: E. Hoja Magna, 1:50.000, nº 380 (Borobia), *ITGE*, Madrid: 70-75.

LAGO M. & POCOVÍ A., 1991 b. Petrología. In: Hoja nº 40 (Daroca), E. 1:200.000, *ITGE*, Madrid: 205-214.

LAGO M., ENRIQUE P., POCOVÍ A. & VAQUER R., 1987. Occurrence and characteristics of granitoids xenoliths in calc-alkaline dykes of a variscan massif of the Iberian Chain (NE Spain). *Symp. "Granites and their surroundings" (Verbania)*. Soc. Ital. Mineral. Petrol., Suppl. 59: 118 pp.

LAGO M., AMIGÓ J. M., TORRES J. A., BAMBÓ C., HIDALGO M. A. & POCOVÍ A., 1989 a. Características composicionales y geotermométricas de piroxenos en rocas calco-alcalinas, Stephaniense-Pérmico, del sector de Loscos y el Anticlinal de Montalbán (Provincia de Teruel). *Bol. Soc. Esp. Mineralogía*, 12 (1): 59-60.

LAGO M., TORRES J. A., BAMBÓ C., HIDALGO M. A. & POCOVÍ A., 1989 b. Características composicionales de xenocristales de granates en rocas calco-alcalinas, Stephaniense-Pérmico, del sector de la Depresión axial del Cámaras y el Anticlinal de Montalbán (Provincia de Teruel). *Bol. Soc. Esp. Mineralogía*, 12 (1): 61-62.

LAGO M., POCOVÍ A., ZACHMANN D., ARRANZ E., CARLS P., TORRES J. A. & VAQUER R., 1991. Comparación preliminar de las manifestaciones magmáticas, calco-alcalinas y stephaniense-pérmicas, de la Cadena Ibérica. *Cuad. Lab. Xeolóxico de Laxe*, 16: 95-107.

LAGO M., ALVARO J., ARRANZ E., POCOVÍ A. & VAQUER R., 1992. Condiciones del emplazamiento, petrología y geoquímica de las riolitas, calco-alcalinas y stephaniense-péermicas, en las cadenas ibéricas. *Cuad. Lab. Xeolóxico de Laxe*, 17: 187-198.

LAGO M., AUQUÉ L., ARRANZ E., GIL A. & POCOVÍ A., 1993. Caracteres de la fosa de Bronchales (Stephaniense-Pérmico) y de la turmalinización asociada a las riolitas calco-alcalinas (Provincia de Teruel). *Cuad. Lab. Xeolóxico de Laxe*, 18: 65-79.

LAGO M., ARRANZ E., POCOVÍ A., VAQUER R. & GIL A., 1994. Petrología y geoquímica de los basaltos calco-alcalinos, Autuniense, de Ojos Negros (Cadena Ibérica oriental, Teruel). *Bol. Geol. Minero*, 105 (6): 73-81.

LAGO M., GIL A., ARRANZ E., BASTIDA J. & POCOVÍ A., 1995. Emplazamiento, petrología y geoquímica del complejo volcanoclástico de Orea (Guadalajara, Cadena Ibérica occidental). *Cuad. Lab. Xeolóxico Laxe*, 20: 195-212.

LAGO M., GIL A., POCOVÍ A., ARRANZ E., BASTIDA J., AUQUÉ L. & LAPUENTE M.P., 1996. Rasgos geológicos del magmatismo Autuniense en la Sierra de Albarracín (Cadena Ibérica occidental). *Cuad. Geol. Ibérica*, 20: 139-157.

RAMOS A., DOUBINGER J. & VIRGILI C., 1976. El Pérmico inferior de Rillo de Gallo (Guadalajara). *Acta Geol. Hispánica*, XI (3): 65-70.

SERRA J., LAGO M. & VAQUER R., 1997 a. Los diques andesíticos del sector N del Anticlinal de Montalbán y sus enclaves (Cordillera Ibérica oriental). *Bol. Soc. Españ. Mineralogía*, 20-A: 45-46.

SERRA J., LAGO M. & VAQUER R., 1997 b. Los enclaves metamórficos de las daciandesitas de la Sierra de Albarracín (Cordillera Ibérica occidental). *XIVª Reun. Geol. do Oeste Peninsular*, Vila Real, Portugal: 231-236.

SUN S. S. & MCDONOUGH W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders A. D. & Norry M. J. (eds), *Magmatism in ocean basins*. Geol. Soc. London, Spec. Pub., 42: 313-345.

TORRES J.A., 1989. Estudio petrológico, geoquímico y de aprovechamiento industrial del magmatismo calco-alcalino, Stephaniense-Pérmico, en el Anticlinal de Montalbán (Provincia de Teruel). *M. Sc. Thesis*, Univ. de Zaragoza: 528 pp.

TORRES J. A., LAGO M., ARRANZ E., VAQUER R. & POCOVÍ A., 1993. Estudio geoquímico del magmatismo calco-alcalino, Autuniense, del Anticlinal de Montalbán (Cadena Ibérica oriental, Teruel). *V° Congr. Geoquímica España*: 54-59.

WINCHESTER M. A. & FLOYD P.A., 1976. Geochemical magma type discrimination, application to altered and metamorphosed basic igneous rocks. *Earth and planet. Sci. Lett.*, 28: 459-469.

«NATURA BRESCIANA» Ann. Mus. Civ. Sc. Nat., Brescia, MONOGRAFIA N. 25, 2001: 189-202

THE PERMIAN OF SOUTHERN FRANCE: AN OVERVIEW

JEAN-PAUL DEROIN[1] (coordinator), BERNARD BONIN[2], JEAN BROUTIN[3], BRUNO CABANIS[4], JEAN-JACQUES CHÂTEAUNEUF[5], RENÉE DAMOTTE[6], MARC DURAND[7] and GEORGES GAND[8]

Key words – Continental deposits; intramontane basins; macro- and microflora; tetrapod footprints; ostracod; calcalkaline episode; alkaline episode; magmatic suite; "Autunian"; "Saxonian"; "Thuringian".

Abstract – This paper deals with the recent advances in stratigraphy, magmatism and paleogeography of the Permian areas of southern France (French Pyrenees, Massif Central, Provence, Corsica, French Alps), especially since the publication of the Synthèse des Bassins Permiens Français (Châteauneuf & Farjanel, 1989). The lithological successions of the basins have been dated using essentially macroflora, microflora, footprints, crustaceans, insects, and some radiometric ages. The comparison between the different basins reveals significant variations in the time of deposition of the red beds during the Permian and the earliest Triassic. In contrast, the Early Permian seems to be well-defined by the "Autunian" biostratigraphic content.

The geodynamic setting of the studied area shows two contrasting magmatic episodes. The first episode is mainly high-K calcalkaline, its geochemical properties providing evidence for a significant crustal component. At the beginning of the second episode, the magmatic suites became abruptly alkaline. This second episode derived from an OIB source replacing the older lithospheric source with minor crustal contribution, and it is mainly represented by alkaline rocks showing widespread distribution (Morocco, Catalonia, Pyrenees, Corsica-Sardinia, Provence, the Alps).

In many areas (Corsica, Pyrenees, Massif Central, etc.), supplementary evidence for a mid-Permian tectono-magmatic event, reflected by the magmatic episode at 270 Ma, is marked by an angular unconformity at the base of the "Saxonian" and sometimes by slight tectonic movements.

Parole chiave – Depositi continentali; bacini in tramontani; macro- e microflora; impronte di tetrapodi; ostracodi; episodio calcalcalino; episodio alcalino; serie magmatica; "Autuniano"; "Sassoniano"; "Turingiano".

Riassunto – Questo lavoro espone i recenti avanzamenti compiuti in stratigrafia, magmatismo e paleogeografia nelle aree permiane della Francia meridionale (Pirenei francesi, Massiccio Centrale, Provenza, Corsica, Alpi Francesi), soprattutto a partire dalla pubblicazione relativa alla "Sintesi dei Bacini Permiani Francesi" (Châteauneuf & Farjanel, 1989). Le successioni litologiche dei bacini sono state datate ricorrendo essenzialmente allo studio della macroflora, microflora, impronte di vertebrati, crostacei e insetti, ed ai risultati di alcune età radiometriche. Il confronto tra i diversi bacini rivela significative variazioni di età dei *red beds* durante il Permiano e l'inizio del Trias. Al contrario, il Permiano inferiore sembra essere ben definito dal contenuto biostratigrafico dell'"Autuniano". L'assetto geodinamico dell'area studiata mostra due contrastanti episodi magmatici. Il primo episodio è essenzialmente calcalcalino, con alto contenuto in K, e le sue proprietà geochimiche forniscono evidenze di una significativa componente crostale. All'inizio del secondo episodio, la serie magmatica divenne improvvisamente alcalina. Questo secondo episodio provenne da una sorgente OIB che sostituì, con un apporto crostale minore, la più vecchia sorgente litosferica, ed è soprattutto rappresentato da rocce alcaline che assumono un'ampia distribuzione geografica (Marocco, Catalonia, Pirenei, Corsica-Sardegna, Provenza, Alpi). In molte aree (Corsica, Pirenei, Massiccio Centrale, ecc.), l'evidenza supplementare di un evento tettono-magmatico medio-permiano, che è riflesso dall'episodio magmatico di 270 Ma, è segnato da una discordanza angolare alla base del "Sassoniano" e talora da deboli movimenti tettonici.

[1] Université Michel de Montaigne, Institut EGID Bordeaux 3, F-33607 Pessac cedex.
[2] Université de Paris-Sud, Département des Sciences de la Terre, F-91405 Orsay cedex.
[3] Université Pierre et Marie Curie, Paris VI, Paléobotanique, F-75252 Paris cedex 2.
[4] Université Pierre et Marie Curie, Paris VI, Géochimie, F-75252 Paris cedex 2.
[5] BRGM, BP 6009, F-45060 Orléans cedex 2.
[6] Université Pierre et Marie Curie, Paris VI, Micropaléontologie, F-75252 Paris cedex 2.
[7] Université Henri Poincaré, Nancy I, Sciences de la Terre et UMR G2R, F-54506 Vandœuvre cedex.
[8] Université de Dijon, UMR 5561, du CNRS, Centre Sciences de la Terre, 6, boulevard Gabriel, F-21100 Dijon.
1 to 8: Association des Géologues du Permien (France).

INTRODUCTION

Southern France and Corsica constitute intracontinental terranes, part of the large Variscan orogen that resulted from the collision between the African and the North European plates and extended from the Appalachians to the Urals (Fig. 1). These terranes were subjected during the entire Permian period to post-collisional and pre-oceanic extensional episodes, resulting in contrasting magmatic, sedimentary and tectonic regimes (Bonin *et al.*, 1993, 1998). The Late Paleozoic deposits of southern France (Châteauneuf & Farjanel, 1989) are mainly continental sandstones, pelites, and volcanosedimentary rocks, as in the other intramontane basins of Spain (Martinez-García, 1983; Sopeña *et al.*, 1988, 1993; Pieren *et al.*, 1995; Gand *et al.*, 1997c) and Italy (Cassinis *et al.*, 1992, 1995; Broutin *et al.*, 1994; Cassinis, 1996). In southern France, the corresponding Permian outcrops are located in the Pyrenees, at the edges of the French Massif Central, in Provence, in Corsica, and in the Alps. In addition, many boreholes have found generally assumed Permian deposits below the Mesozoic cover in Aquitaine and in the South East Basin: Languedoc, Provence and Dauphiné.

At the end of the 19th century, Munier-Chalmas and de Lapparent defined two continental stages in the Lower Permian deposits: the Autunian, from the Autun Basin, Burgundy, and the Saxonian by analogy with the red facies known in Saxony. These stages labeled, on the one hand, the dominantly greyish and highly fossiliferous strata overlying the Stephanian deposits and, on the other hand, the dominantly reddish and poorly fossiliferous strata overlying the former. The use of these names has been abandoned in the framework of the international time scale which rejects any non-marine stratotype. As the terms were also used in the lithostratigraphic sense, for example by many mining geologists, one of us suggested the use of "*Autunian*" and "*Saxonian*" only as groups, namely lithostratigraphic units next in rank above formation (Gand *et al.*, 1997 c). Very recently, Broutin *et al.* (1999) showed that the paleontological content of the "*Autunian*" of the Autun Basin dated from the latest Ghzelian to early Sakmarian. Therefore, they proposed to keep up the "*Autunian*" chronostratigraphic sense for any continental Permian deposits which could be characterised by the Autunian flora.

The third Permian continental stage defined by Renevier also at the end of the 19th century, namely the Thuringian, has always been considered as equivalent to the German Zechstein (Upper Permian).

DESCRIPTION OF THE PERMIAN OUTCROPS

French Pyrenees

The Paleogene orogeny of the Pyrenees exhumed the oldest part of the belt in the central domain (*Zone primaire axial*). On both French and Spanish sides, the Upper Paleozoic and Mesozoic series have been strongly folded and faulted. The Permian deposits of the Pyrenees (Lucas, 1985) consist of thick red beds comprising conglomerates, sandstones, and pelites, the volcanic rocks associated with the sediments being very common. They are located along the external part of the "Alpine" belt. From west to east, we distinguish (Table 1a): the Basque deposits of La Rhune and Bidarray areas, the Haut Béarn deposits of the Ossau Massif (linked to the Anayet area in Aragon, Spain) and to the east of the belt a number of small outcrops in Hautes-Pyrénées department (Aure valley), Ariège department (Labastide de Sérou, Niort, Sainte-Colombe), and Pyrénées-Orientales department (Ségure, Durban, Baixas) namely Roussillon deposits in Table1a.

The Permian in the Pyrenees was characterised by five volcanic episodes described by Bixel (1984, 1988). Unfortunately, no cross-section shows the superimposition of the five events. The descriptions of the different stages are mainly based on the geochemistry of the magmatic products intercalated in the lithostratigraphic succession. A first episode dated from Late Carboniferous-Early Permian is well-exposed in the Ossau area. Aluminous rhyolites dated from 278 Ma (Innocent *et al.*, 1994) and calc-alkaline dacites dated from 272 Ma are intercalated within the Ossau Fm. A third episode is only revealed in the easternmost part of the belt, notably in the Baixas cross-section. The fourth and fifth alkaline episodes are well-exposed in

Fig. 1 – Location of the Permian deposits of Southern France and surrounding areas.
a. Variscan basement; b. Exposed Permian deposits; c. Main Late-Variscan faults; d. Main Alpine thrusts.
Numbers refer to the Permian outcrops:
Main Permian outcrops of Southern France. 1 to 5 French Pyrenees: 1. La Rhune, 2. Bidarray, 3. Haut-Béarn (Ossau), 4. Aure Valley, 5. Roussillon (Baixas); 6 to 11 Southern Massif Central: 6. Saint Sauves d'Auvergne, 7. Brive, 8. Rodez, 9. Saint-Affrique, 10. Lodève, 11. Prades (Largentière); 12 and 13 Provence: 12. Toulon-Cuers, 13. Bas-Argens-Estérel; 14. Corsica (Monte Cintu); 15 to 19 French Alps: 15. Barrot, 16. Argentera, 17. Belledonne, 18. Galibier, 19. Vanoise.
Other Permian deposits of Northern France and surrounding areas. 20. Exeter (England); 21. Carentan (Normandy, France); 22. Mosel (Germany); 23. Saar-Nahe (Germany); 24. Landau (Germany); 25. Seuil de la Haardt (Alsace, France); 26. Schwarzwald (Germany); 27 to 31 Vosges (France): 27. La Plaine-Nideck, 28. Champenay, 29. Saint-Dié, 30. Villé, 31. Ronchamps-Giromagny; 32 to 37 Northern Massif Central (France): 32. Autun, 33. Montreuillon, 34. Decize, 35. Le Creusot, 36. Bourbon-l'Archambault, 37. Bert; 38 to 41 Italian Alps: 38. Southern Alps, 39. Sesia, 40. Dora Maira, 41. Liguria; 42. Sierra de Cadi (Spain).

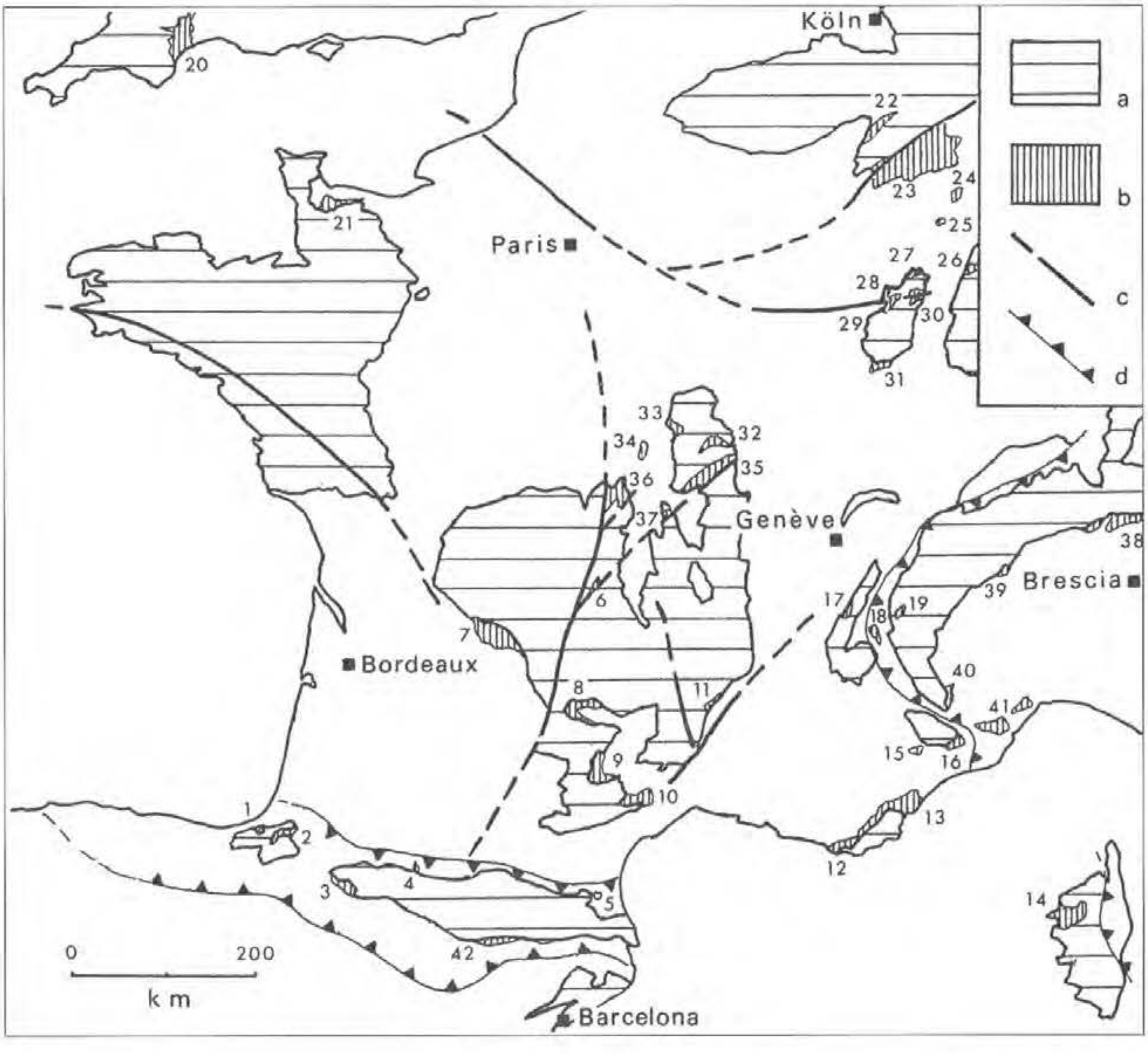
the western part of the Pyrenees, in the Ossau Massif (fourth and fifth) and in the Basque Country (fifth).

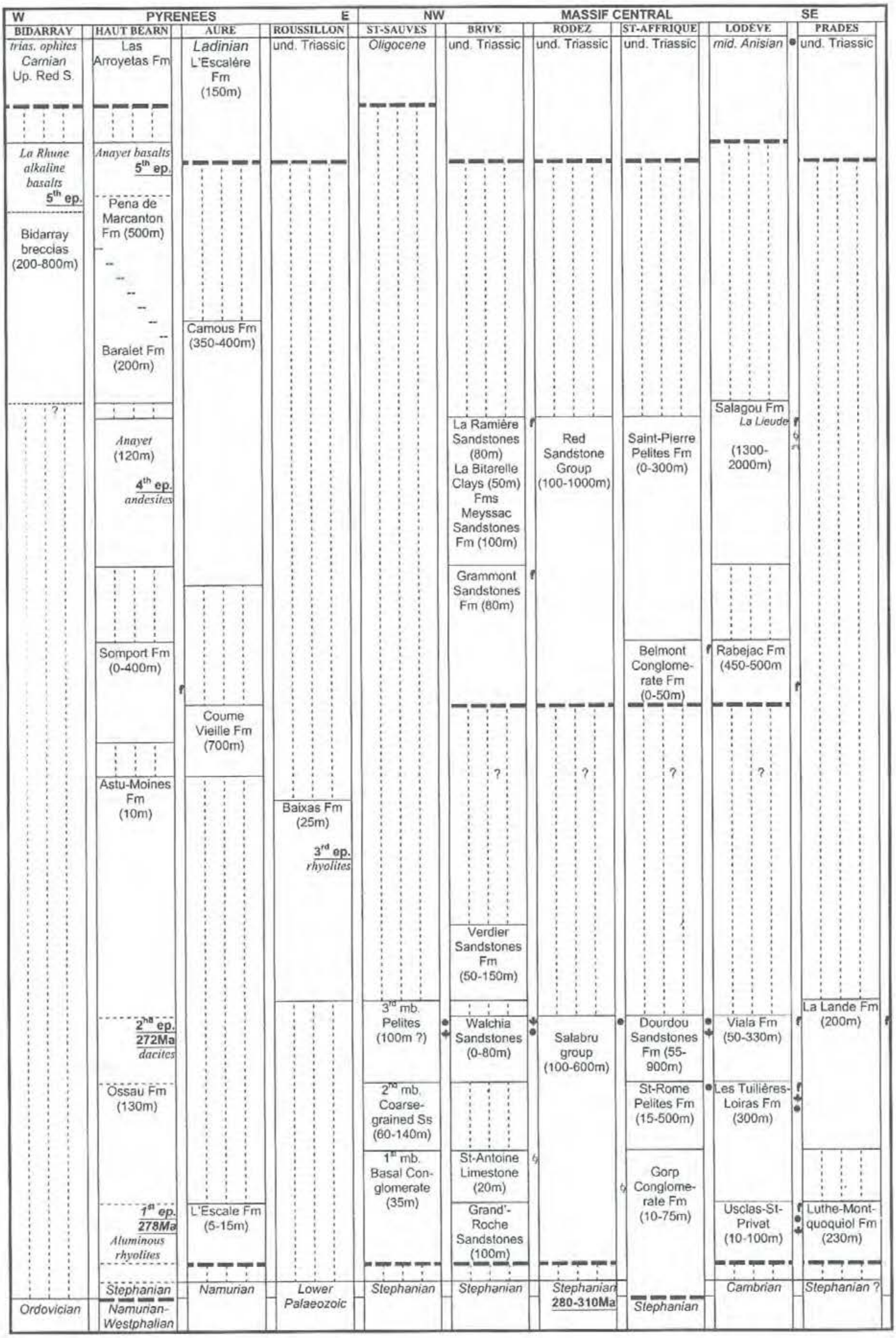
The Pyrenean Permian formations are poor in paleontological evidence. Some microfloras indicate a Stephanian (at the bottom) to Autunian age for the Ossau Fm. Rare footprints have been found by one of us in the Somport Fm. (Gand, 1988). In spite of the absence of fossils, other methods, such as paleomagnetism, indicate a Permian age for some non-fossiliferous series, for example in the Camous Fm. (Schott, 1985).

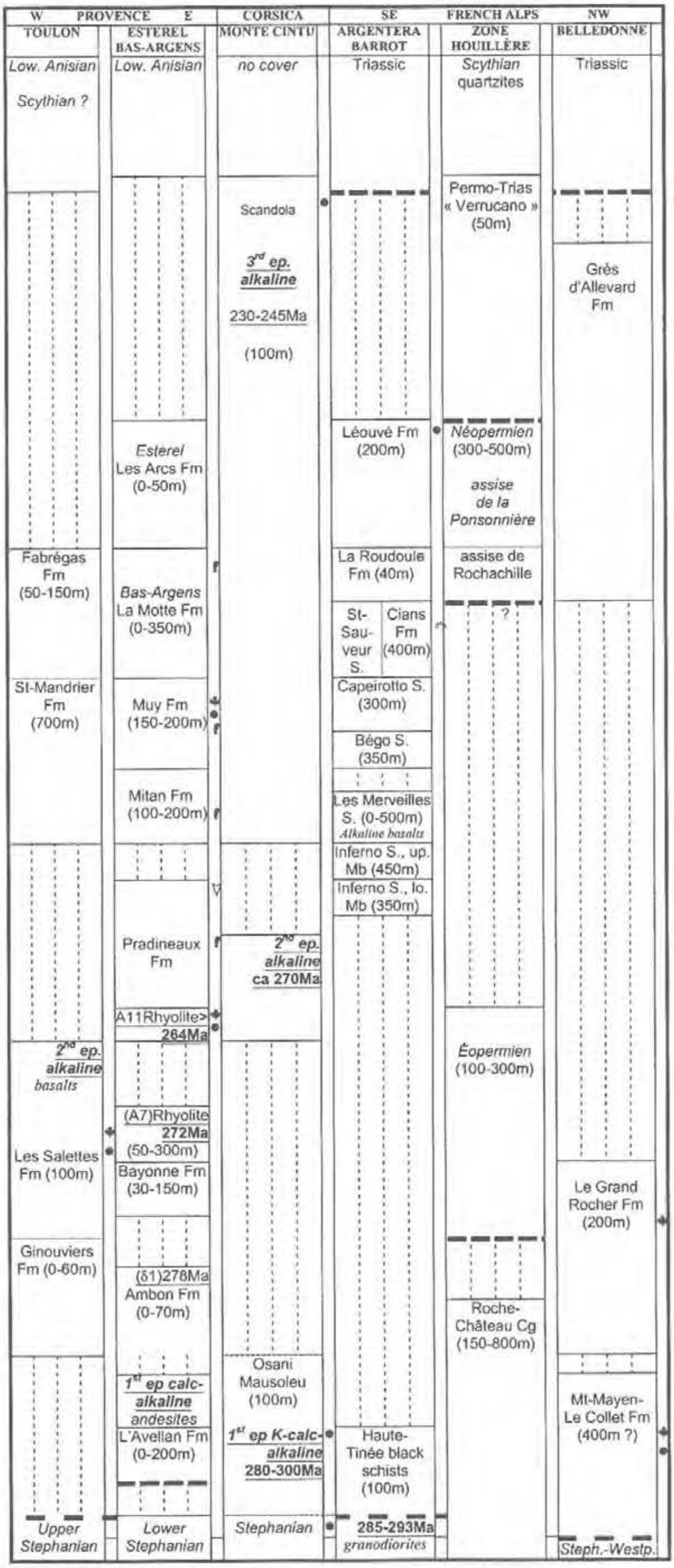
From a structural point of view, the Permian outcrops are mainly – except for the Basque Country – situated in the north of the *Zone primaire axiale* (ZPA), in the so-called *Zone Nord-Pyrénéenne*. In the Central Pyrenees, different settings could be defined. In the Aure Trough, at the northern front of the ZPA, the detrital series is very thick (more than 1,000 m). In contrast, on the Paleozoic North-Pyrenean massifs the Permian deposits are usually thin, but generally present below the base of the Mesozoic formations. Some Permian rocks could also be involved in allochthonous Alpine units, such as the Gavarnie Nappe. All the paleomagnetic data show a considerable rotation for the outcrops of Central and Eastern Pyrenees (Baixas for example), such as the Spanish Permian and Triassic outcrops of Catalonia (between 90 and 100°). Thus, except for the Permian layers of the Basque Country, consistent with a fixed Europe, the Permian deposits were mainly deposited on the mobile block of Iberia.

Edges of the French Massif Central

The Permian deposits of the southern Massif Central are essentially located along its borders: the basins of Brive, Rodez, La Grésigne, Saint-Affrique, Lodève and Prades (Table 1a). One small occurrence appears surrounded by




W
PYRENEES
E
NW
MASSIF CENTRAL
SE
BIDARRAY
HAUT BEARN
AURE
ROUSSILLON
ST-SAUVES
BRIVE
RODEZ
ST-AFFRIQUE
LODÈVE
PRADES
trias. ophites
Carnian
Up. Red S.
Las Arroyetas Fm
Ladinian
L'Escalère Fm (150m)
und. Triassic
Oligocene
und. Triassic
und. Triassic
und. Triassic
mid. Anisian
und. Triassic
La Rhune alkaline basalts
5th ep.
Anayet basalts
5th ep.
Pena de Marcanton Fm (500m)
Bidarray breccias (200-800m)
Camous Fm (350-400m)
Baralet Fm (200m)
Salagou Fm
La Lieude
(1300-2000m)
La Ramière Sandstones (80m)
La Bitarelle Clays (50m)
Fms
Meyssac Sandstones Fm (100m)
Red Sandstone Group (100-1000m)
Saint-Pierre Pelites Fm (0-300m)
Anayet (120m)
4th ep.
andesites
Grammont Sandstones Fm (80m)
Somport Fm (0-400m)
Belmont Conglomerate Fm (0-50m)
Rabejac Fm (450-500m)
Coume Vieille Fm (700m)
Astu-Moines Fm (10m)
Baixas Fm (25m)
3rd ep.
rhyolites
Verdier Sandstones Fm (50-150m)
3rd mb. Pelites (100m ?)
Walchia Sandstones (0-80m)
Salabru group (100-600m)
Dourdou Sandstones Fm (55-900m)
Viala Fm (50-330m)
La Lande Fm (200m)
2nd ep.
272Ma
dacites
Ossau Fm (130m)
2nd mb. Coarse-grained Ss (60-140m)
St-Rome Pelites Fm (15-500m)
Les Tuilières-Loiras Fm (300m)
1st mb. Basal Conglomerate (35m)
St-Antoine Limestone (20m)
Gorp Conglomerate Fm (10-75m)
1st ep.
278Ma
Aluminous rhyolites
L'Escale Fm (5-15m)
Grand'-Roche Sandstones (100m)
Usclas-St-Privat (10-100m)
Luthe-Montquoquiol Fm (230m)
Stephanian
Namurian
Lower Palaeozoic
Stephanian
Stephanian
Stephanian
280-310Ma
Cambrian
Stephanian ?
Ordovician
Namurian-Westphalian
Stephanian



Tables 1a and b

Synthesis of the Permian of Southern France. a) from the Pyrenees to the French Massif Central. b) from Provence-Corsica to the Alps.

A compilation of unpublished results of Châteauneuf & Farjanel (1989), and of:

- for the Pyrenees: Bixel (1984), Bixel & Lucas (1983), Cabanis (1996), Cabanis & Le Fur-Balouet (1989), Innocent *et al.* (1994), Lucas (1985), Lucas & Gisbert-Aguilar (1996) and Schott (1985).
- for the Massif Central: Brive Basin by Feys (1976) and Gand (1991); Rodez Basin by Bourges (1987); Saint-Affrique Basin by Gand (1993 b), Gand *et al.* (1996), Rolando (1988) and Rolando *et al.* (1988); Lodève Basin by Broutin *et al.* (1992), Gand *et al.* (1997a, b, d), Odin (1986) and Schneider *et al.* (1999); Prades Basin by Gand (1993a).
- for Provence: Demathieu *et al.* (1992), Gand *et al.* (1995), Lethiers *et al.* (1993), Toutin (1980), Toutin-Morin (1987, 1992), Toutin-Morin & Bonijoly (1992), Vozenin-Serra *et al.* (1991) and Zheng *et al.* (1991-1992).
- for Corsica: Bonin *et al.* (1987), Cabanis *et al.* (1990), Gondolo (1989), Vellutini (1977).
- for the French Alps: Deroin *et al.* (1996), Vinchon (1984).

Vertical dashed lines represent the stratigraphic gaps. Bold horizontal dashes represent the main discontinuities.

Main biostratigraphic features of each formation

Flora:
(macroflora)
(microflora)

Crustaceans:
(brachiopods: conchostracans, triopsids…)
(ostracods)

Insects

Footprints

the basement, near the Sillon Houiller, at Saint-Sauves-d'Auvergne. The basins are mainly characterised by well-developed red beds cropping out widely above a relatively thin, rhythmically deposited Autunian unit, representing the repeated alternation of torrential with lacustrine deposits. The red beds range in age from Autunian *sensu* Broutin *et al.* (1999) to Upper Permian (*"Thuringian"*). Volcanic rocks are poorly represented in the Brive and Rodez areas but form thick pyroclastic deposits in the Lodève Basin, possibly related to the volcanism of Sardinia, Provence, and Corsica.

Paleontological discoveries have recently been made in the so-called *"Saxonian"* group *sensu* Gand *et al.* (1997d) of the Lodève Basin which was long thought to be non-fossiliferous. Triopsids (*Lepidurus*, *Triops*), conchostracans (associated with triopsids but with a larger vertical distribution), insects (ten orders represented), arthropod tracks and burrows have been identified for the first time (Gand *et al.*, 1997 a, d). Among the triopsids, *Triops* corresponds to a species very close to present-day *Triops cancriformis*. This indicates that these arthropods have evolved little since Permian times. The range of insects suggests Leonardian to early Kazanian ages for part of the Salagou Fm. The Conchostracans are represented by species similar to those described in the "Rotliegende II" *sensu* Schneider *et al.* (1995). They suggest a Kungurian (or Sakmarian) to Tatarian age for the *"Saxonian"* group of the Lodève Basin. In the La Lieude strata the occurrence of conchostracans with ornamentation suggests a Tatarian age for the uppermost part of the Salagou Fm. Other investigations in the Saint-Affrique Permian basin have discovered some triopsids, conchostracans, and insects showing the same fauna as in Lodève (Gand *et al.*, 1997 b).

The intramontane basin of Saint-Sauves-d'Auvergne extends for about 10 km^2. It has been considered as *"Saxonian"* by Brousse (1981) in spite of (or due to ?) the lack of any paleontological data. Unpublished analyses performed by one of us (JJC) provide the first elements for dating this small basin. Spores and palynomorphs from one of the greyish layers of the "Pelites Fm." have shown the spores: *Thymospora* sp., *Spinosporites spinosus*, *S. exiguus*, *Laevigatosporites perminutus*, *Lycospora pusilla*, *Verrucosisporites* sp., *Lophotriletes* sp., *Granulatisporites*; and the pollen grains: undifferentiated smooth Disaccates and Monosaccates, some *Florinites* and *Cordaitina*. At first sight, this microflora could be dated to the Stephanian or the Early Permian, but not the *"Saxonian"*. The solution has been found by using weathering effects (epigenesis of organic matter by pyrite) involving the degradation of the biggest species (Mono- and Disaccates). The high quantity of Disaccate and Monosaccate remains suggests a Permian age, which is in better accordance with the occurrence of the red sandstones than a Stephanian age well-known for coal-deposits along the Sillon Houiller (Singles, Messeix).

In the Permian basin of Largentière, on the southeastern border of the Massif Central where no other Permian strata crop out, the reinterpretation of the post-Carboniferous and pre-Triassic deposits by Gand (1993 a) has shown the presence of two formations: Luthe-Montquoquiol and La Lande Fms. A number of fossils and fossil tracks have been identified including vertebrate footprints, macroflora mainly composed of conifers and callipterids, and many *Scoyenia* beds. Using methods such as the comparison with the same ichnofacies from the Thuringian Forest, a correlation with the Asselian - upper Sakmarian of the marine time-scale has been proposed for the La Lande Fm.

Provence

The Permian basins of Provence (Toutin-Morin in Châteauneuf & Farjanel, 1989) follow one another along the border of the Variscan Maures massif, from the east to the west: Estérel and Bas-Argens, bounded to the north by the Tanneron massif, then Le Luc and Cuers-Toulon, which are partly concealed beneath the Mesozoic cover (Table 1b). Whereas the Upper Carboniferous sediments are confined within a few narrow submeridian troughs, affected by a post-Stephanian compressive phase, each of these Permian grabens trends more or less E-W. The thick continental siliciclastic fills are organised in fining-upwards sequences evolving from fanglomerates (Delfaud & Toutin-Morin, 1993) to meandering stream deposits (Durand, 1993) or playa mudstones where paludal to lacustrine carbonates occur sporadically (Toutin-Morin, 1992). They are interrupted at various levels by felsic or mafic volcanic units, which are mostly developed in the Estérel and Bas-Argens where their cumulative thickness reaches a few hundred metres. It is for the eastern basins that the most stratigraphical data are available (Toutin-Morin *et al.*, 1994 a, b). The oldest deposits (L'Avellan Fm., Estérel) are tilted in a very small ESE-WNW graben and capped by the only volcanics in the area pertaining to the calcalkaline episode; thus an Autunian age *sensu* Broutin *et al.* (1999) is assumed for this formation alone. Above the main marker is the A7-Rhyolite, in the middle part of the series, whose ^{40}Ar-^{39}Ar date is very close to 272 Ma (Zheng *et al.*, 1991-92) fitting well with the age of the Artinskian-Kungurian boundary proposed by Jin Yu-gan *et al.* (1997). Below, the Ambon and Bayonne Fms, devoid of any fossils, are separated by a basalt flow of probable (early?) Artinskian age (278 Ma). Above, the Pradineaux Fm. may constitute a condensed section: the lower part is older than 264 Ma (age of a crossing dyke) but the upper part can be correlated with the lowermost Tatarian of the Russian platform owing to ostracod studies (Lethiers *et* *al.*, 1993). This last result does not seem in conflict with paleobotanical and paleo-ichnological data obtained from the same formation (Gand *et al.*, 1995). Finally, the macro- and microflora yielded by the Muy Fm. (Bas-Argens), very similar to those from the German Zechstein, are the youngest known within the entire French Permian. Westwards correlations become more and more difficult. Nevertheless the ichnofauna found in the uppermost red-siltstone unit of each basin (Pélitique Fm. in Le Luc Basin; Gonfaron Fm. in Cuers Basin, and Fabregas Fm. in Toulon Basin) is nearly identical to the La Lieude association in the Lodève Basin (Demathieu *et al.*, 1992). Around the middle part of the Toulon series, lacustrine laminated limestones and siltstones, deposited in a narrow submeridian half-graben, yield a rich macroflora and a palynological assemblage closely similar to that from the Tregiovo Fm (Southern Alps, Italy) and for which a post-Kungurian ante-Tatarian age can be suggested (Broutin & Durand, 1995). In other respects, the possibility of correlation of the acidic tuffs described in the Saint-Mandrier Fm. (Durand, 1993) and the more distal ones discovered in the Lodève Basin (Nmila *et al.*, 1992) remains to be borne out.

From a structural point of view the Permian basins of Provence are clearly related to N-S distensional conditions (Toutin-Morin & Bonijoly, 1992), but a transcurrent element is shown by the diachronic activity of normal faults expressed by many intra-Permian angular unconformities (Baudemont, 1988). An overall depocentre migration can be traced in an E-W direction. Movement ceased before the end of the Permian and was followed by a long period of pediplanation. The oldest Triassic terrigenous deposits, located in the Toulon area, display paleocurrents in an opposite direction to those from the Permian (Durand *et al.*, 1989; Durand, 1993).

Corsica and neighbouring areas

After the Variscan event, in the continental block now defined by Corsica and Sardinia, a new orogenic event akin to the Alleghanian was accompanied by Upper Carboniferous to Lower Permian magmatic episodes. Several calcalkaline magmatic pulses made up the huge 500 km-long and 50 km-wide Corsican-Sardinian Batholith (Orsini, 1980). The older tonalitic units are interpreted as the result of renewed subduction processes (Finger & Steyrer, 1990). The younger post-collisional plutonic units were coeval with volcanic formations. The compositionally expanded high-K calcalkaline suite comprises cumulates, gabbro, diorite, porphyritic granodiorite and monzogranite, leucomonzogranite (Orsini, 1980), and an andesite-dacite-rhyolite volcanic association (Vellutini, 1977). Trace element and isotopic compositions indicate magmas derived from a depleted mantle source with a subduction component and mixed with crustal products (Cabanis *et al.*, 1990; Cocherie *et al.*, 1994).

The Permo-Triassic alkaline province was built during two episodes. The mid-Permian (270 ± 10 Ma) was a critical period marked by emplacement of numerous complexes. No time interval is substantiated between the latest high-K calcalkaline and the earliest alkaline intrusions at about 280 Ma. After a quiescent period, renewed magmatic activity took place at the Permian-Triassic boundary (245 ± 10 Ma). The magmatic rocks are exposed within caldera volcanoes, dyke swarms and ring complexes. The compositionally expanded suite (Bonin, 1986) encompasses gabbro, monzogabbro, monzonite, syenite, alkali feldspar granite and syenogranite at the subvolcanic level (Platevoet, 1990), scarce basic lava flows and voluminous trachyte-rhyolite ignimbritic flows at the volcanic level (Vellutini, 1977).

Trace-element compositions of dolerite dykes indicate derivation from an OIB source (Cabanis *et al.*, 1990). Metaluminous, slightly peraluminous or highly peralkaline granites exhibit high, yet variable, trace-element contents related to mineral fractionation and volatile transfer through F-rich complexing fluids (Egeberg *et al.*, 1993). Initial Sr isotope ratios range from 0.703 up to 0.737 (Bonin *et al.*, 1987) and εNd from +0.5 down to -5.8 (Poitrasson *et al.*, 1995). Chemical evidence precludes simple mixing processes by crustal contamination of mantle-derived magmas and indicates primary magmas similar to the Ivrea mafic complex (Sinigoi *et al.*, 1994), with an insignificant to minor contribution from old upper crustal units and a varying contribution of lower crust.

The mid-Permian episode can be considered as post-orogenic, namely post-Alleghanian. It is characterised by two magmatic alignments (Bonin *et al.*, 1987), one from Morocco to Catalonia to Corsica-Sardinia to Estérel and Briançonnais to the Southern Alps, and the second from Corsica to Vosges-Schwarzwald to the Oslo Rift, defining a Y-shaped fault system associated with large sinistral shear zones. The Late Permian to Triassic episode was markedly early anorogenic (Bonin, 1990) and was related to an incipient rifting regime in Corsica, Estérel and Catalonia. It heralded the Mesozoic evolution of the western Mediterranean area, and can also be considered eo-Alpine.

Thus, the Permian of Corsica is essentially magmatic in nature (Gondolo, 1989). Only two small outcrops at the western edge of the Monte Cintu caldera have provided paleontological data (Table 1b). In Mausoleu, near the Osani Stephanian basin mined for coal, flora revealed an "*Autunian*" age for sediments intercalated within calcalkaline andesites of the first magmatic episode. In Scandola (Capu Puppiaghia) some microfloras containing *Platysaccus* and *Lueckisporites* provide a Thuringian age for sandstones and lacustrine limestones intercalated within alkaline volcanic rocks of the second episode.

French Alps

The French Alps are located in the westernmost part of the orogen (Table 1b). The main structural Alpine units concerned are: the external zone (*Dauphiné*) and the internal zones (*Briançonnais* and *Valais*). In the Alpine segment of the Variscan belt, the Upper Paleozoic features are often difficult to decipher because of the superimposition of the Cenozoic orogenic episodes. In the external zones, some occurrences of Permian deposits are generally less deformed than their Mesozoic cover above the Triassic gypsum layers, for example in the Belledonne Massif (Deroin *et al.*, 1996). The Permian deposits are better exposed in the southern French Alps, in the Barrot and Mercantour-Argentera areas (Vinchon, 1984). Near Léouvé (Barrot dome) the discovery of *Arctotypus verneti* (Odonata) has provided a "Thuringian" age for the top of the Cians Fm. (Laurentiaux-Vieira & Laurentiaux, 1963). The same age has been proposed for the Léouvé Fm. using palynomorphs.

In the northern Alps, Savoie and Dauphiné, the Late Paleozoic deposits including Upper Carboniferous and Permian strata appear within very narrow troughs, mainly along the Belledonne granitic massif. Near Allevard, the pre-Mesozoic series is composed of a succession of: (i) black shales and coarse-grained sandstones dating from the Westphalian to the Stephanian, using macroflora; (ii) a 200 m thick sequence of sandstones (Grand-Rocher Fm.) including conglomerate and dolomite layers possibly Early Permian in age (some rare macroflora); (iii) sandstones probably Triassic as well as Upper Permian in age corresponding to the Flumet- and Allevard Sandstone Fm.). In the internal zones, the Permian deposits are widely exposed in the Briançonnais (*Zone houillère*), notably in the Vanoise and Galibier areas. Unfortunately, the amount of strain has destroyed any paleontological evidence. Thus, the Permian facies are mainly defined on structural considerations, the typical cross-section showing the "*Éopermien*" or Early Permian overlain by the "*Néopermien*", namely the Late Permian. This megasequence begins with conglomeratic layers (Roche-Château Conglomerates), probably Upper Carboniferous as well as Early Permian in age, and is overlain by the Verrucano facies, reputedly Permo-Triassic. All the "*Permian*" megasequence rests unconformably on Carboniferous or older deposits.

MAGMATISM

Carboniferous to Triassic plutonic activity

Progressive amalgamation of almost all continental terranes into the last Pangaea during the Carboniferous resulted from the complex collisional interactions of two megacontinents, Laurasia to the north and Gondwana to the south. The scattered occurrence of Cadomian ages in south Europe and eastern North America indicate that Gondwana-derived terranes, such as Avalonia, Armorica, Iberia, and so on, collided early with the Laurasia megacontinent (Ziegler, 1986). Collision of the Mid-European Moldanubian terrane with the Intra-Alpine terrane (Stampfli, 1996) resulted in contrasting plutonic episodes (Bonin *et al.*, 1998, and references therein).

In the Moldanubian terrane, the post-collisional magmatic activity consisted of short-lived syntectonic episodes of a few million years, controlled by transcurrent crustal-scale faults. (1) Mg-K-rich magmatic suites, recorded at 345-330 Ma from the External Alps to the Bohemian Massif and at 310 Ma in the Aar Massif, probably derived from a subduction-enriched lithospheric mantle source with crustal contamination. (2) Peraluminous magmas were emplaced along dextral strike-slip faults at 307 Ma in the Mont-Blanc and Aiguilles-Rouges and had dominantly crustal sources, but a mantle contribution is documented by coeval gabbro and mafic microgranular enclaves. (3) The last magmatic episode was post-orogenic and is represented in the Mont-Blanc, Central Aar and Gotthard Massifs by alkali-calcic plutonic suites at 303-292 Ma, and by abundant intermediate to acidic volcaniclastic deposits at 303-299 Ma. Isotopic evidence points to an ultimately mantle source, with an increasing contribution from the upwelling asthenospheric mantle relative to the subcontinental lithospheric mantle source, and to crustal contamination of unknown magnitude. In this intra-continental zone, magmatic activity was poorly developed during the Permian.

By contrast, in the marginal Intra-Alpine terrane, magmatic episodes were largely represented during the Permo-Carboniferous. (1) 340 ± 5 Ma Mg-K-rich magmatic suites in the Pyrenees, Corsica and the western Alps resemble those within the Moldanubian terrane. (2) During the Late Carboniferous and the Early Permian in Morocco, Catalonia, Pyrenees, Corsica-Sardinia, Provence, the Internal Alps (Internal Crystalline Massifs, Briançonnais zone, Austro-Alpine realm and Southern Alps) and south Italy, normal to high-K calcalkaline batholiths and volcanic formations derived from a subduction-enriched lithospheric mantle source with crustal contamination, but partial melting involved smaller amounts of K-rich minerals. Peraluminous anatectic massifs, well-developed in the Velay Dome of the French Massif Central, are also represented. (3) The magmatic suites became abruptly alkaline 280 Ma ago, with no smooth transition from the previous suites, and produced two episodes, the major one at 270 ± 10 Ma in Morocco, Catalonia, the Pyrenees, Corsica-Sardinia, Estérel, and the Internal Alps, and the second minor one at 245 ± 10 Ma in Catalonia, Corsica and Estérel. They derived from an OIB source replacing the older lithospheric source, with minor, yet varying, crustal contribution.

The Triassic (250-200 Ma) was marked by volcanic-plutonic complexes emplaced along fault zones, such as the 245 Ma Matterhorn-Mont Collon-Dents de Bertol transitional suite, the Austro-Alpine realm, the 237-232 Ma Monzoni-Predazzo alkaline complex, the Southern Alps, and the tholeiitic ophites of the Pyrenees. Lastly, a 200 Ma thermal anomaly reset mineral and some whole-rock isotopic clocks.

Permian volcanic activity

Significant volcanism occurred during the Permian and the earlier Triassic in the western Mediterrannean province. Two main episodes, high-K calcalkaline and alkaline, are classically recognised. They correspond to the transition from post-collisional crustal-derived or contaminated magmatism to anorogenic asthenospheric magmatism.

The first episode

The first volcanic episode including andesites, dacites and rhyolites of Early Permian age (290-275 Ma) is high-K calcalkaline with a significant crustal component. It is well-represented in the Pyrenees (Cabanis & Le Fur Balouet, 1989; Innocent *et al.*, 1994; Cabanis, 1996), the Corsica-Sardinia block (Cabanis *et al.*, 1990; Cortesogno *et al.*, 1998) and the Iberian Cordillera. Similar volcanism occurred in the Ligurian and Southern Alps (Barth *et al.*, 1993; Cortesogno *et al.*, 1998; Rottura *et al.*, 1998).

In the Pyrenees and Corsica, geochemical studies show evidence for a crustal component (Cabanis, 1996; Cabanis *et al.*, 1990). Trace-element data from andesites show a strong LILE enrichment, particularly in K, U and Th. The Th/Ta ratio (3-6) is low and differs from the typical orogenic andesite related classically to an actively subducted slab (Cabanis & Thiéblemont, 1988). The strong decrease of compatible elements (Cr, Ni, Sc, Co) with increasing Th (Th considered as a differentiation index) shows that fractional crystallisation involving spinel, olivine and clinopyroxene was the main petrogenetic process. Low La, Ti and P contents in the most basic andesites could be interpreted in terms of an important crustal contribution (Cabanis & Le Fur-Balouet, 1989). These crustal characteristics are well-illustrated in La-Y(Tb)-Nb(Ta) (Cabanis & Lécolle, 1989) in which most of the rock compositions plot within a field intermediate between the typical orogenic andesite field and the non-orogenic basalt field. Similar characteristics have been found in the Ligurian Alps and the Southern Alps (Cortesogno *et al.* 1998; Rottura *et al.*, 1998).

In the Pyrenees, isotopic studies (Gilbert *et al.*, 1994; Innocent *et al.*, 1994) confirm the importance of a crustal component. In the Sm-Nd diagram, the basic andesites of the Ossau caldera (France) and Sierra del Cadi (Spain) plot in the field of Archean to Cretaceous sediments and have the same isotopic composition as the Querigut monzogranite and granodiorite (Ben Othman *et al.*, 1984); their Nd signature yields a low initial eNd of –3 to –9 with very constant Sr isotopic ratios, showing the crustal influence. Very similar results have been found in the Southern Alps (Barth *et al.*, 1993).

The second episode

The second Permian episode (265-235 Ma) corresponds to the emplacement of bimodal volcanic products (basalts-ignimbritic rhyolite) into caldera structures during an extensional regime. It is localised in different areas in the Pyrenees: La Rhune, Ossau-Anayet (Cabanis & Le Fur-Balouet, 1989; Innocent *et al.*, 1994; Cabanis, 1996); Corsica (Cabanis *et al.*, 1990); Estérel (Gondolo, 1989; Poitrasson & Pin, 1998; Lapierre *et al.*, 1999) and Toulon (Leroy & Cabanis, 1993).

In a MORB- normalised spidergram (Pearce, 1982) basalts display a regular decrease from Th to Tb similar to alkaline or transitional basalts. Variable negative anomalies in Ta and Ti suggest a mantle-source still affected by an orogenic component. The variable Th/Ta ratios – close to 3 in Corsica, nearer 1 in the Toulon Basin and Anayet, and 3-8 in La Rhune and Estérel – are consistent with this hypothesis. Constant values of Cr, Ni, Co and Sc with a large increase in Th suggest variable degrees of partial melting in contrast with the fractional crystallisation processes of the first episode.

Isotopic data (Rb-Sr, Sm-Nd) on Pyrenean volcanism (Innocent *et al.*, 1994) agree with the trace-element study. Anayet basalts clearly originate from the melting of the asthenosphere, and La Rhune basalts have Sr and Nd isotopic characteristics similar to the CFB continental tholeiites, and could have heralded the Triassic ophite volcanism.

Position of Permian magmatism in the geodynamic setting

Although considered initially as a continuous process, magmatism actually occurred in discrete episodes accompanying or heralding major geological discontinuities. At the Carboniferous-Permian boundary (ca. 300 Ma), extensive volcanic and associated plutonic activity occurred throughout the area. It consisted of high-K calcalkaline andesite-dacite-rhyolite suites, mostly erupted from fissural vents in intramontane basins, filled with molasse deposits produced by local erosion of high relief. The mid-Permian episode (280-260 Ma) was characterised by largely complete peneplanation and widespread magmatism, yielding the famous red landscapes of the western Mediterranean coasts (Lodévois, Provence basins, etc). Volcanic-plutonic complexes and fissural formations indicate a rapid shift from the older high-K calcalkaline suites, related to the waning post-collisional stages of the Variscan orogeny, to the younger alkali-calcic to alkaline suites, implying new mantle-enriched source(s) and the onset of Pangaea break-up. Lastly, at the Permian-Triassic boundary (ca. 245 Ma) and within the Early Triassic (up to 220 Ma outside the study area), alkaline to peralkaline caldera volcanoes and ring complexes were emplaced within the future passive margins of the Tethyan ocean basin. Evidence for continental dislocation is provided by the large Triassic (ca. 220-200 Ma) thermal anomaly recorded in mineral ages of the older basement rocks.

BIOSTRATIGRAPHY

The stratigraphy of Permian terranes in southern France, Corsica, and the surrounding regions, is essentially based on continental biofossils. As a consequence the correlations with the marine time-scales, international or Tethyan, are not reliable, except in the places where continental and marine deposits are intercalated. Moreover, the continental basins frequently dried up during the Permian, leading to disconformities, gaps and erosion of the deposits, as well as the destruction of biota by oxidation. Imprints or permineralised fragments of macroflora, spores and pollen grains, ostracods and tetrapod footprints, and now conchostracans and insects, are the most important tools to have been used for stratigraphy.

Catalonian Pyrenees

The Permian is crops out near Palenca de Noves, Baro, and along the Pallerols river. The basal conglomeratic or silty sediments have been dated from the Autunian *sensu* Broutin *et al.* (1999) by macroflora (Broutin & Gisbert, 1983). In the same area, above the red Permian facies, the lower Buntsandstein facies which contains a *Lueckisporites* association has been attributed to the Thuringian (Broutin *et al.*, 1988).

Southern edge of the Massif Central

In the Lodève, Saint-Affrique, Rodez, and Largentière Permian basins, plant remains and footprints are abundant. Above the coal-bearing and generally tilted Stephanian (Rodez and Saint Affrique) or the Cambrian basement (Lodève), the Permian sediments have been divided into five formations, on the basis of sedimentological criteria. The biostratigraphic content includes flora and fauna. Macroflora and microflora (spores and pollen grains) essentially are abundant in the grey formations. Systematic studies on the flora are as old as the 18th century. The "*Walchia*" assemblages include a large range of Permian species belonging to the following genera: *Pecopteris, Callipteridium, Rhachiphyllum, Lodevia, Odontopteris, Autunia, Culmitzschia, Ginkgophyllum, Baiera, Arnhartia, Odontopteris, Cordaites* and *Supaia* (Broutin *et al.*, 1992). The age interpretation of such a flora fits very well with the paleo-ichnological results, except for the Usclas-Saint-Privas to Les Tuilières-Loiras Fms which are ascribed to the upper "Autunian". The microfloral content is likewise abundant from the base of the Usclas-Saint-Privas Fm to the middle part of the Viala Fm. It has been divided into three biozones (Lo1 to Lo3) by Doubinger *et al.* (1987), which are successively assigned to the upper "Autunian", the Artinskian and the Thuringian (Ufimian to Kazanian). These microfloral interpretations are in conflict with tetrapod and macroflora data.

The recent paleontological discoveries in the Lodève Basin improved the stratigraphical scheme by means of insects and conchostracans (Gand *et al.*, 1997 d; Nel *et al.*, 1999 a, b; Schneider *et al.*, 1999). These fossils are located in the Salagou Fm. dating from Leonardian to Tatarian (Gand *et al.*, 1997 d). From Schneider *et al.* (1999), the whole Usclas-Saint-Privas-Les-Tuilières-Loiras and Viala Fms could be Asselian in age, and the Rabejac and Salagou Fms could have a Sakmarian-Dzulfian age.

Provence

With the exception of those recently discovered in the Toulon Basin (Broutin & Durand, 1995), the study of which is still in progress, the fossiliferous horizons of Provence are restricted to the eastern basins in the Pradineaux, Mitan, Muy and La Motte Fms. They have yielded vertebrate footprints, macroflora, spores, pollen grains and invertebrate remains (mainly ostracods).

The vertebrate assemblages include the following species: *Hyloidichnus major, Dromopus didactylus, Antichnium salamandroides, Limnopus zeilleri, Varanopus rigidus* and *curvidactylus, Dimetropus latus* and *Laoporus* sp. The macroflora comprises: *Walchia* spp., *Pseudovoltzia* spp., *Sphenopteris kukukiana, Ullmannia Bronni* and *U. frumentaria,* and *Ginkgophytoxylon permiense*. Amongst the palynological content, the following genera are well-represented: *Nuskoisporites, Lueckisporites, Jugasporites, Klausipollenites, Limitisporites, Labiisporites, Taeniaesporites* and *Vittatina*. This last set is assigned to the "Thuringian" (Kazanian to Tatarian). This fits very well with the recent data from ostracods discovered in the Pradineaux Fm., giving an early Tatarian age.

Corsica-Sardinia block

In the Osani area, northwestern Corsica, some fluvial and lacustrine layers are intercalated within the volcanic and pyroclastic deposits of the first calcalkaline episode (Gondolo, 1989). Plant debris of *Calamites, Cordaites* and *Walchia* are associated with the siltstones attributed to the Autunian *sensu* Broutin *et al.* (1999). In the same area, at the edge of Scandola caldera, sandstones and lacustrine mudstones linked to the second volcanic episode contain a

Platysaccus and *Lueckisporites* association, most likely "Thuringian" in age. In Sardinia, new paleontological data (Ronchi *et al.*, 1998) have recently enhanced the dating of "Autunian" sediments in the Guardia Pisano area (Barca *et al.*, 1991). Some additional sections in the north (Lu Caparoni) and the southeast (Perdasdefogu, Escalaplano) have yielded plant remains, spores, pollen grains, algal colonies and ostracods, which have enabled the correlation of such fossiliferous sections not only with others within Sardinia, but also with the eponymous Autun Basin and, further to the west, with the Gerri de la Sal section in Spain.

CONCLUDING REMARKS

1. The Permian of southern France is famous for its volcanic formations, like many other Mediterranean areas. The first magmatic episode is mainly high-K calcalkaline in character, and provides evidence for a significant crustal component. The second episode is mainly alkaline and derived from an OIB source replacing the older lithospheric source with minor crustal contribution. It has a widespread distribution (Morocco, Catalmonia, Pyrenees, Corsice-Sardinia, Provence, Alps). In most areas (Corsica, Pyrenees, Massif Central, etc.) the Permian tectonomagmatic event was reflected by the magmatic episode at 270 Ma and tectonism (Bonin *et al.*, 1993; Broutin *et al.*, 1994; Deroin *et al.*, 1990). The Permian-Triassic boundary is marked by scarce (per)alkaline magmatic complexes (Catalonia, Corsica, Estérel).

2. The Permian sedimentary facies cannot be used as a stratigraphic marker. An example of evident diachronism is provided by the widespread transition from grey to red facies. In other respects carbonate deposits, including stromatolites (Freytet *et al.*, 1999), appear as peculiar facies scattered in space and time (Toutin-Morin, 1992). Complementary studies call into question some correlations between volcanic units; in Le Luc Basin, for instance, a rhyolite believed to be coeval with the A7-rhyolite from the Estérel showed a normal magnetic polarity component (Merabet & Daly, 1986) which was not detected in the typical A7. Even biostratigraphical data give rise to debate. Conclusions based on macroflora, palynomorphs and vertebrate footprints may be in conflict (*e.g.* Broutin *et al.*, 1992), possibly owing to varying ecological and taphonomical conditions (Broutin *et al.*, 1990). That is why there remain many discrepancies in correlations between the different basins of southern France.

3. From a paleogeographical point of view, it is important to emphasise the very close facies relationships displayed on the one hand by the Permo-Triassic siliciclastic sequences in the Toulon Basin (Durand, 1993; Durand *et al.*, 1989), and on the other hand by the "*Verrucano Sardo*" in the Nurra region, NW Sardinia (Cassinis *et al.*, 1996). Furthermore the Autunian paleoflora recently discovered in the black-grey shaly deposits from Perdasdefogu, SE Sardinia, is very similar to the one from the Gerri de la Sal succession, Catalonian Spanish Pyrenees (Ronchi *et al.*, 1998). These data are in full agreement with the paleoposition of the Corsica-Sardinia "block" stretching E-W, in a palinspastic reconstruction such as that proposed by Broutin *et al.* (1994) in a paleogeographical reconstruction based on structural and magmatic data. In such a model, the Permian volcanics of northeastern Corsica are facing those of the Estérel massif, and the southern part of Sardinia is linked with the eastern Pyrenean domain, the Late Paleozoic setting of which is harder to decipher.

REFERENCES

BARCA S., DEL RIO M. & PITTAU P., 1991. The Permian-Carboniferous at Guardia Pisano in the Sulcis area (southwest Sardinia, Italy). In: Cappelli B. & Crotta D., (coord.), *Geologia del basamento italiano*, Univ. Siena: 98-110.

BARTH S., OBERLI F., MEIER M., BLATTNER P., BARGOSSI G.M. & DI BATTISTINI G., 1993. The evolution of a calc-alkaline basic to silicic magma system: Geochemical and Rb-Sr, Sm-Nd, and $^{18}O/^{16}O$ isotopic evidence from the Late Hercynian Atesina-Cima d'Asta volcanic-plutonic complex, northern Italy. *Geochim. Cosmochim. Acta*, 5: 4285-4300.

BAUDEMONT D., 1988. Discordances angulaires multiples dans le Permien de Provence (France). Tectonique extensive antémésozoïque avec effondrements diachrones. *C. R. Acad. Sci. Paris*, 306, sér. II: 149-152.

BEN OTHMAN D., WHITE W.M. & PATCHETT J., 1984. The geochemistry of marine sediments, island arc, magma genesis, and crust-mantle recycling. *Earth and planet. Sci. Lett.*, 94: 1-21.

BIXEL F., 1984. Le volcanisme stéphano-permien des Pyrénées. *D. Sc. Thesis*, Toulouse: 640 pp.

BIXEL F., 1988. Le volcanisme stéphano-permien des Pyrénées Atlantiques. *Bull. Centres Rech. Explor.-Prod. Elf-Aquitaine*, 12 (2): 661-706.

BIXEL F. & LUCAS C., 1983. Magmatisme, tectonique et sédimentation dans les fossés stéphano-permiens des Pyrénées occidentales. *Rev. Géogr. phys. Géol. dynamique*, 24 (4): 329-342.

BONIN B., 1986. *Ring complex granites and anorogenic magmatism.* Studies in Geology, North Oxford Academic, Oxford, and Elsevier, Amsterdam: 188 pp.

BONIN B., 1990. From orogenic to anorogenic settings: evolution of granitoid suites after a major orogenesis. *Geol. J.*, W.S. Pitcher Spec. Issue, 25: 261-270.

BONIN B., PLATEVOET B. & VIALETTE Y., 1987. The geodynamic significance of alkaline magmatism in the Western Mediterranean compared with West Africa. In: Bowden P. & Kinnaird J. (eds), *African geology reviews*. Geol. J., 22: 361-387.

BONIN B., BRÄNDLEIN P., BUSSY F., DESMONS J., EGGENBERGER U., FINGER F., GRAF K., MARRO C., MERCOLLI I., OBERHÄNSLI R., PLOQUIN A., VON QUADT A., VON RAUMER J., SCHALTEGGER U., STEYRER H.P., VISONA D. & VIVIER G., 1993. Late Variscan magmatic evolution of the Alpine Basement. In: Von Raumer J.F. & Neubauer F. (eds), *Pre-Mesozoic geology in the Alps*. Springer-Verlag: 171-201.

BONIN B., AZZOUNI-SEKKAL A., BUSSY F. & FERRAG S., 1998. Alkali-calcic and alkaline post-orogenic (PO) granite magmatism: petrologic constraints and geodynamic settings. *Lithos*, 45: 45-70.

BOURGES P., 1987. Sédimentation alluviale et tectonique extensive dans le Permien du détroit de Rodez Aveyron-France. *Thesis*, Toulouse: 186 pp.

BROUSSE R., 1981. Carte géologique de la France à 1/50 000. Feuille "Bourg-Lastic", 716, BRGM Ed.

BROUTIN J. & DURAND M., 1995. First paleobotanical and palynological data on the "Les Salettes Formation" uppermost Member (Permian Toulon Basin, Southeastern France). *XIIIth Intern. Congr. Carboniferous-Permian*, Krakow, Abstr. vol.: 15-16.

BROUTIN J. & GISBERT J., 1983. Entorno peoclimatico y ambiental de la flora stephano-autuniense del Pirineo Catalan. *C. R. 10ème Congr. Intern. Strat. Géol.Carbon.*, 2: 53-66.

BROUTIN J., DOUBINGER J., GISBERT J. & SATTA-PISANI S., 1988. Premières datations palynologiques dans le faciès buntsandstein des Pyrénées catalanes espagnoles. *C. R. Acad. Sci., Paris*, sér. II, 306: 159-163.

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*, 311, sér. II: 1563-1569.

BROUTIN J., CHÂTEAUNEUF J.J. & MATHIS V., 1992. Permian basins in the French Massif Central: the Lodève basin. *Cah. Micropaléont.*, 7 (1/2): 107-121.

BROUTIN J., CABANIS B., CHÂTEAUNEUF J.J. & DEROIN J.P., 1994. Evolution biostratigraphique, magmatique et tectonique du domaine paléotéthysien occidental (SW de l'Europe): implications paléogéographiques au Permien supérieur. *Bull. Soc. géol. France*, 165 (2):163-179.

BROUTIN J., CHÂTEAUNEUF 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. *Géologie de la France*, 2: 17-31.

CABANIS B., 1996. Tome 1 - Cycle hercynien: le volcanisme Stéphano-Permien. *Synthèse géologique et géophysique des Pyrénées*. BRGM-ITGE eds.: 376-407.

CABANIS B. & LE FUR-BALOUET S., 1989. Les magmatismes stéphano-permiens des Pyrénées marqueurs de l'évolution géodynamique de la chaîne: apport de la géochimie des éléments en traces. *Bull. Centres Explor.-Prod. Elf-Aquitaine*, 13: 105-130.

CABANIS B. & LECOLLE M., 1989. Le diagramme La/10-Y/15-Nb/8, un outil pour la discrimination des séries volcaniques et la mise en évidence des processus de mélange et/ou de contamination crustale. *C. R. Acad. Sci. Paris*, 309: 2023-2029.

CABANIS B. & THIEBLEMONT D., 1988. La discrimination des tholéiites continentales et des basaltes des bassins arrière arc ; proposition d'un nouveau diagramme: le triangle Th-TBx3-Tax2. Essai d'interprétation. *Bull. Soc. Géol. France*, 8, IV(6): 927-935.

CABANIS B., COCHEME J.J., VELLUTINI P., JORON J.L. & TREUIL M., 1990. Post-collisian Permian volcanism in Northwestern Corsica: assesment based on mineralogy and trace element geochemistry. *J. Volc. Geotherm. Res.*, 44: 51-67.

CASSINIS G., 1996. Upper Carboniferous to Permian stratigraphic framework of Southwestern Europe and its implications - An overview. In: Moullade B.M. & Nairn A.E.M. (eds), *The Phanerozoic Geology of the World: I. The Paleozoic, B*. Elsevier: 110-167.

CASSINIS G., TOUTIN-MORIN N. & VIRGILI C., 1992. Permian and Triassic events in the continental domains of Mediterranean Europe. In: Sweet W.C., Yang Zunyi, Dickins J.M. & Yin Hongfu (eds), *Permo-Triassic Events in the Eastern Tethys, Stratigraphy, Classification, and Relations with the Western Tethys*, Cambridge University Press: 60-77.

CASSINIS G., TOUTIN-MORIN N. & VIRGILI C., 1995. A General outline of the Permian continental basins in Southwestern Europe. In: Scholle P.A., Peryt T.M. & Ulmer-Scholle D.S. (eds), *The Permian of Northern Pangea, vol. 2, Sedimentary basins and economic resources*. Springer-Verlag: 137-157.

CASSINIS G., CORTESOGNO L., GAGGERO L., RONCHI A. & VALLONI R., 1996. Stratigraphic and petrographic investigations into the Permo-Triassic continental sequences of Nurra (NW Sardinia). *Cuad. Geol. Iberica*, 21: 149-169.

CHÂTEAUNEUF J.J. & FARJANEL G., 1989. Synthèse géologique des bassins permiens français. *Mém. Bur. rech. géol. min.*, 128: 288 pp.

COCHERIE A., ROSSI P., FOUILLAC A.M., & VIDAL P., 1994. Relative importance of recycled- and mantle-derived material in granitoid genesis: An example from the Variscan batholith of Corsica studied by trace element and Nd-Sr-O isotope systematics. *Chem. Geol.*, 115: 173-211.

CORTESOGNO L., CASSINIS G., DALLAGIOVANNA G., GAGGERO L., OGGIANO G., RONCHI A., SENO S. & VANOSSI M., 1998. The Variscan post-collisional volcanism in Late Carboniferous-Permian sequences of Ligurian Alps, Southern Alps and Sardinia (Italy): a synthesis. *Lithos*, 45: 305-328.

DELFAUD J. & TOUTIN-MORIN N., 1993. Le Rocher de Roquebrune (Var). Un cône alluvial exemplaire permien supérieur de bordure de bassin intramontagneux. *Géologie de la France*, 2: 31-41.

DEMATHIEU G., GAND G. & TOUTIN-MORIN N., 1992. La palichnofaune des bassins permiens provençaux. *Geobios*, 25 (1): 19-54.

DEROIN J.P., BECQ-GIRAUDON J.F. & PROST A.E., 1990. Fracturation tardi-hercynienne et détritisme associé: chronologie des événements dans les massifs granitiques cévenols décrochés par la faille de Villefort (mont Lozère et Borne, Massif central, France). *C. R. Acad. Sci. Paris*, 311, II: 865-871.

DEROIN J.P., GAND G. & GUILLOT F., 1996. Field trip in the northern French Alps. *Guide-book 10[th] annual excursion of the AGP (Assoc.Géol. du Perm.)*, unpublished. (In French).

DOUBINGER J., ODIN B. & CONRAD G., 1987. Les associations sporopolliniques du Permien continental du bassin de Lodève (Hérault, France). *Ann. Soc. Géol. Nord*, 56: 103-109.

DURAND M., 1993. Un exemple de sédimentation continentale permienne dominée par l'activité de chenaux méandriformes: la Formation de Saint-Mandrier (Bassin de Toulon, Var). *Géologie de la France*, 2: 43-55.

DURAND M., MEYER R. & AVRIL G., 1989. Le Trias détritique de Provence, du dôme de Barrot et du Mercantour. *Publ. Assoc. Sédiment. Français*, 6: 135 pp.

EGEBERG A.T., BONIN B. & SØRENSEN H., 1993. The Bonifatto peralkaline granites (NW Corsica): a possible case of evolution through volatile transfer. *Bull. Soc. géol. France*, 164: 739-758.

FEYS R., 1976. Le Permien et la phase saalienne dans le bassin de

Brive (SW de la France). In: Falke H. (ed.), *The Continental Permian in Central, West, and South Europe*. D. Reidel Publishing Company, Dordrecht: 80-90.

FINGER F. & STEYRER H.P., 1990. I-type granitoids as indicators of a Late Paleozoic convergent ocean-continent margin along the southern flank of the central European Variscan orogen. *Geology*, 18: 1207-1210.

FREYTET P., TOUTIN-MORIN N., BROUTIN J., DEBRIETTE P., DURAND M., EL WARTITI M., GAND G., KERP H., ORSZAG F., PAQUETTE Y., RONCHI A. & SARFATI J., 1999. Palaeoecology of non marine algae and stromatolites: Permian of France and adjacent countries. *Ann. Paléont.*, 85 (2): 99-153.

GAND G., 1988. Les traces de Vertébrés tétrapodes du Permien français (paléontologie, stratigraphie, paléoenvironnements). *D. Sc. Thesis*, Dijon: 341 pp.

GAND G., 1991. Première découverte de traces de pas de vertébrés tétrapodes dans le bassin permien de Brive-la-Gaillarde (Corrèze). *Géologie de la France*, 3: 43-51.

GAND G., 1993 a. Les empreintes animales et végétales du bassin permien de Largentière (Ardèche, France). Conséquences stratigraphiques et paléoenvironnementales. *Bull. Soc. hist. nat. Autun*, 146: 8-41.

GAND G., 1993 b. La palichnofaune de Vertébrés tétrapodes du bassin permien de St-Affrique Aveyron: comparaisons et conséquences stratigraphiques. *Géologie de la France*, 3-4: 41-56.

GAND G., DEMATHIEU G. & BALLESTRA F., 1995. La palichnofaune de vertébrés tétrapodes du Permien supérieur de l'Estérel (Provence, France). *Palaeontographica Abt. A*, 235: 97-139.

GAND G., GARRIC J., SCHNEIDER J., SCIAU J. & WALTER H., 1996. Biocoenoses à méduses du Permien français (Bassin de Saint-Affrique, Massif Central). *Geobios*, 29 (4): 379-400.

GAND G., GARRIC J. & LAPEYRIE J., 1997 a. Biocénoses à Triopsidés (Crustacea, Branchiopoda) du Permien du bassin de Lodève (France). *Geobios*, 30 (5): 673-700.

GAND G., GARRIC J., LAPEYRIE J., LAPEYRIE M. & STAPF K., 1997 b. Découverte de chenaux ou de gouttières silto-carbonatés fossilifères inédits dans le Permien du bassin de Saint-Affrique (Aveyron, France). *Bull. Soc. hist. nat. Autun*, 161: 21-38.

GAND G., KERP H., PARSONS C. & MARTINEZ-GARCIA E., 1997 c. Paleoenvironmental and stratigraphic aspects of animal traces and plant remains in Spanish Permian red beds (Peña Sagra, Cantabrian Mountains, Spain). *Geobios*, 30 (2): 295-318.

GAND G., LAPEYRIE J., GARRIC J., NEL A., SCHNEIDER J. & WALTER H., 1997 d. Découverte d'Arthropodes et de bivalves inédits dans le Permien continental (Lodévois, France). *C. R. Acad. Sci. Paris*, 325: 891-898.

GILBERT J.S., BICKLE M.J. & CHAPMAN H.J., 1994. The origin of Pyrenean Hercynian volcanic rocks (France-Spain): REE and Sm-Nd isotope constraints. *Chem. Geol.*, 111: 207-226.

GONDOLO A., 1989. Le volcanisme alcalin permo-triasique du Sud-Est de la France. *Thesis*, Nice: 280 pp.

INNOCENT C., BRIQUEU L. & CABANIS B., 1994. Sr-Nd isotope and trace-element geochemistry of late Variscan volcanism in the Pyrénées: magmatism in post-orogenic extension?. *Tectonophysics*, 238: 161-181.

JIN YU-GAN, WARDLAW B.R., GLENISTER B.F. & KOTLYAR G.V., 1997. Permian chronostratigraphic subdivisions. *Episodes*, 20: 10-15.

LAPIERRE H., BASILE C. & DUPUIS V., 1999. Basaltes et trachytes permiens de l'Estérel (SE France): une série tholéiitique transitionnelle épanchée pendant l'amincicement lithosphérique. *Bull. Soc. géol. France*, 170: 253-265.

LAURENTIAUX-VIERA F. & LAURENTIAUX D., 1963. Découverte d'un Insecte Prodonate dans le Permien des Alpes-Maritimes. *C.R. Acad. Sc. Paris*, 257: 3018-3020.

LEGRAND X., SOULA J.C. & ROLANDO J.P., 1994. The Saint-Affrique Permian basin (southern France): an example of a roll-over controlled alluvial sedimentation during regional extensional tectonics. *Geodinamica Acta*, 7: 103-120.

LEROY S. & CABANIS B., 1993. Le volcanisme permien du bassin de Toulon: un jalon septentrional du volcanisme permien de l'Ouest Méditerrannéen. *Géologie de la France*, 2: 57-66.

LETHIERS F., DAMOTTE R. & SANFOURCHE J., 1993. Premières données sur les ostracodes du Permien supérieur continental de l'Estérel (SE de la France): Systématique, Biostratigraphie, Paléoécologie. *Géol. Méditer.*, XX (2): 109-125.

LUCAS C., 1985. Le Grès rouge du versant nord des Pyrénées. Essai sur la géodynamique des dépôts continentaux du Permien et du Trias. *D. Sc. Thesis*, Toulouse: 267 pp.

LUCAS C. & GISBERT-AGUILAR J., 1996. Carbonifère supérieur-Permien. In: Barnolas A. & Chiron J.C. (eds), *Synthèse géologique et géophysique des Pyrénées, I, Cycle hercynien*, 339-359, BRGM-ITGE: 729 pp.

MARTÍNEZ-GARCÍA E., 1983. El Permico de la Cordillera cantabrica. In: Martínez-Diaz C. (coord.), *Carbonifero y Permico de España*. Oviedo: 391-402.

MERABET N. & DALY L., 1986. Détermination d'un pôle paléomagnétique et mise en évidence d'aimantations à polarité normale sur les formations du Permien supérieurdu Massif des Maures (France). *Earth and planet. Sci. Lett.*, 80: 156-166.

NEL A., GAND G., FLECK G., BETHOUX O., LAPEYRIE J. & GARRIC J., 1999 a. *Saxonagrion minutus* nov. gen. et sp., the oldest damselfly from the Upper Permian of France (Odonatoptera, Panodonata, Saxonagrionidae nov. fam.). *Geobios*, 32 (6): 883-888.

NEL A., GAND G. & GARRIC J., 1999 b. A new family of Odonatoptera from the continental Upper Permian: the Lapeyriidae (Lodève Basin, France). *Geobios*, 32 (1) 63-72.

NMILA A., CABANIS B., LEROY S., HENRIOT O. & MATHIS V., 1992. Découverte de nouveaux horizons tuffiques dans le Permien Rouge supérieur du bassin de Lodève (Hérault, France). Essai de caractérisation du volcanisme. *C. R. Acad. Sci. Paris*, sér. II, 315: 689-696.

ODIN B., 1986. Les formations permiennes Autunien supérieur à Thuringien du "bassin" de Lodève (Hérault, France). *Thesis*, Aix-Marseille: 392 pp.

ORSINI J.B., 1980. Le batholite corso-sarde: anatomie d'un batholite hercynien. Composition, structure, organisation d'ensemble. Sa place dans la chaîne varisque française. *D. Sc. Thesis*, Aix-Marseille III, Marseille: 439 pp.

PEARCE J.A., 1982. Trace elements characteristics of lavas from destructive plate boundaries. In: Thorpe R.S. (ed.), *Andesites: orogenic andesites and related rocks*. Intersci. Publ., Wiley & Sons, Chichester: 525-549.

PIEREN A.P., AREGES J.L., TORAÑO J. & MARTINEZ-GARCIA E., 1995. Estratigrafía y estructura de los materiales permotriásicos del sector Gijón-La Collada (Asturias). *Cuad. Geol. Ibérica*, 19: 309-335.

PLATEVOET B., 1990. Le plutonisme basique et intermédiaire dans le magmatisme anorogénique de Corse. *D. Sc. Thesis*, Paris-Sud, Orsay: 526 pp.

POITRASSON F. & PIN, C., 1998. Extreme Nd isotope homogeneity in a large rhyolitic province: the Esterel Massif, SE France. *Bull. volcanol.*, 60: 213-223.

POITRASSON F., PIN C. & DUTHOU J.L., 1995. The relationship between petrology and Nd isotopes as evidence for contrasting anorogenic granite genesis: example of the Corsican province (SE France). *J. Petrol.*, 36: 1251-1274.

ROLANDO J.P., 1988. Sédimentologie et stratigraphie du bassin permien de Saint-Affrique Aveyron, France. Un exemple de bassin alluvial contrôlé par la tectonique extensive. *Thesis*, Toulouse: 265 pp.

ROLANDO J.P., DOUBINGER, J., BOURGES, P. & LEGRAND, X., 1988.

Identification de l'Autunien supérieur, du Saxonien et du Thuringien inférieur dans le bassin de Saint-Affrique (Aveyron, France). Corrélations séquentielles et chronostratigraphiques avec les bassins de Lodève (Hérault) et de Rodez (Aveyron). *C. R. Acad. Sci. Paris*, 307, sér. II: 1459-1464.

RONCHI A., BROUTIN J., DIEZ J.B., FREYTET P., GALTIER J. & LETHIERS F., 1998. New palaeontological discoveries in some Early Permian sequences of Sardinia. Biostratigraphic and palaeogeographic implications. *C. R. Acad. Sci. Paris*, 327: 713-719.

ROTTURA A., BARGOSSI G.M., CAGGIANELLI A., DEL MORO A., VISONÀ D. & TRANNE C.A., 1998. Origin and significance of the Permian high-K calc-alkaline magmatism in the central-eastern Southern Alps, Italy. *Lithos*, 45: 329-348.

SCHNEIDER J.W., RÖSSLER R. & GAITZSCH B.G, 1995. Times lines of the Late Variscan Volcanism. A holostratigraphic synthesis. *Zbl. Geol. Paläont.*, Stuttgart, I (5-6): 477-490.

SCHNEIDER J.W., KÖRNER F., HOERNES S.T., GAND G., SCHAEBEN H. & KLEEBERG R., 1999. Teil 1: Perm-red beds des Lodève-Beckens: Geochemie, Bio/Lithofazies, Zyklostratigraphie, Klima. *Freiberg (unpublished)*.

SCHOTT J.J., 1985. Paléomagnétisme des séries rouges du Permien et du Crétacé inférieur dans les chaînes pyrénéo-cantabrique et NW ibérique. Implications géodynamiques. *Thesis*, Strasbourg.

SINIGOI S., QUICK J.E., CLEMENS-KNOTT D., MAYER A., DEMARCHI G., MAZZUCHELLI M., NEGRINI L. & RIVALENTI G. 1994. Chemical evolution of a large mafic intrusion in the lower crust, Ivrea Verbano Zone, northern Italy. *J. geophys. res.*, 99: 21575-21590.

SOPEÑA A., LOPEZ J., ARCHE A., PEREZ-ARLUCEA M., RAMOS A., VIRGILI C. & HERNANDO S., 1988. Permian and Triassic rift basins of the Iberian Peninsula. *Dev. Geotect.*, Manspeizer W. (ed.), Amsterdam: 757-786.

SOPEÑA A., DOUBINGER J., RAMOS A. & PEREZ-ARLUCEA M., 1993. Palynologie du Permien et du Trias dans le Centre de la Péninsule Ibérique. *Sci. géol., Bull.*, 48 (1-3): 119-157.

STAMPFLI G.M., 1996. The Intra-Alpine terrain: A Paleotethyan remnant in the Alpine Variscides. *Eclogae geol. Helv.*, 89: 13-42.

TOUTIN N., 1980. Le Permien continental de la Provence orientale (France). *D. Sc. Thesis*, Univ. de Nice, 2 vol.: 594 pp.

TOUTIN-MORIN N., 1987. Les bassins permiens provençaux, témoins de l'orogenèse hercynienne et de l'ouverture de la Téthys dans le Sud-Est de la France. *Ann. Soc. Géol. Nord*, CVI: 183-187.

TOUTIN-MORIN N., 1992. The Permian carbonates in Provence (South-eastern France). *Carbonates and Evaporites*, 7 (2): 108-121.

TOUTIN-MORIN N. & BONIJOLY D., 1992. Structuration des bassins de Provence orientale à la fin de l'ère primaire. *Cuad. Geol. Ibérica*, 16: 59-74.

TOUTIN-MORIN N., BONIJOLY D., BROCARD C., BROUTIN J., CREVOLA G., DARDEAU G., DUBAR M., FERAUD J., GIRAUD J.D., GODEFROY P., LAVILLE P. & MEINESZ A., 1994 a. Notice explicative, Carte géol. France à 1/50 000, feuille Fréjus-Cannes n° 1024. BRGM, Orléans: 187 pp.

TOUTIN-MORIN N., CREVOLA G., GIRAUD J.D., BROCARD C., DARDEAU G., BULARD P.F., DUBAR M., MEINESZ A. & BONIJOLY D., 1994 b. Carte géol. France à 1/50 000, feuille Fréjus-Cannes n° 1024. BRGM, Orléans.

VELLUTINI P., 1977. Le magmatisme permien de la Corse du Nord-Ouest. Son extension en Méditerranée occidentale. *D. Sc. Thesis*, Aix-Marseille: 276 pp.

VINCHON C., 1984. Sédimentogenèse et métallogenèse du Permien du dôme du Barrot (Alpes-Maritimes, France). *D. Sc. Thesis*, Nancy: 244 pp.

VOZENIN-SERRA C., BROUTIN J. & TOUTIN-MORIN N., 1991. Bois permiens du Sud-Ouest de l'Espagne et du Sud-Est de la France. Implications pour la taxonomie des Gymnospermes paléozoïques et la phylogénie des Ginkgophytes. *Palaeontographica Abt. B.*, 221: 1-26.

ZHENG J.S., MERMET J.F., TOUTIN-MORIN N., HANES J., GONDOLO A., MORIN R. & FERAUD G., 1991-1992. Datation ^{40}Ar-^{39}Ar du magmatisme et de filons minéralisés permiens en Provence orientale (France). *Geodinamica Acta*, 5 (3): 203-215.

ZIEGLER P.A., 1986. Geodynamic model for the Palaeozoic crustal consolidation of Western and Central Europe. *Tectonophysics*, 126: 303-328.

«NATURA BRESCIANA» Ann. Mus. Civ. Sc. Nat., Brescia, MONOGRAFIA N. 25, 2001: 203-211

SYNSEDIMENTARY VOLCANISM IN THE LATE CARBONIFEROUS SALVAN-DORÉNAZ BASIN (WESTERN ALPS)

NICOLA CAPUZZO [1] and FRANÇOIS BUSSY [2]

Key words – Western Alps; Aiguilles-Rouges; Late Carboniferous sediments; Salvan-Dorénaz basin; volcanism; fall-out deposits.

Abstract – The Salvan-Dorénaz basin is a NNE-SSW elongated intracontinental trough located in the Aiguilles-Rouges crystalline massif (Western Alps), which formed during the Late Carboniferous post-orogenic evolution of the Variscan fold-belt. Only part of the original basin is preserved with a maximum thickness of 1.5 – 1.7 km of continental sediments, represented by alluvial fan, alluvial plain, lacustrine and river deposits. Four different lithological units formed in response to intrabasinal differential subsidence and tectonic movements: Unit I, at the base, corresponds to the emplacement of the basin and is composed of alluvial fan and braided river deposits; Unit II consists of palustrine and anastomosed river deposits; Unit III comprises meandering river deposits; and Unit IV consists of alluvial fan deposits interfingering with Units II and III and spreading into the fluvial basin from the northwestern margin.
Syndepositional volcanism is documented in the Salvan-Dorénaz basin by different volcanic and volcano-sedimentary layers, for which facies analysis and compositional studies revealed primary as well as reworked characters for these products. In particular, basal subaerial flows and autobreccia deposits are possibly related to the emplacement of a rhyodacitic lava dome along the northwestern margin of the basin.
On the other hand, several tuffs and resedimented volcaniclastic layers found within sediments of Units II and III testify periods of high-explosive volcanism from distant volcanic vents. Facies, petrographical and zircon typological analyses suggest coexistence of different magma sources during synsedimentary volcanism.

Parole chiave – Alpi Occidentali; Aiguilles-Rouges; sedimenti tardo-carboniferi; bacino di Salvan-Dorénaz; vulcanismo; depositi da "fall-out".

Riassunto – Il bacino continentale di Salvan-Dorénaz si imposta nel Carbonifero Superiore sul basamento cristallino del Massiccio dell'Aiguilles-Rouges (Alpi Occidentali) durante la fase post-collisionale dell'orogenesi Varisica. Allungato in direzione NNE-SSW presenta uno spessore massimo di 1.5-1.7 km di depositi continentali costituiti da associazioni di facies di conoide alluvionale, piana alluvionale, lacustri e fluviali. Quattro unità lito-stratigrafiche si formarono in seguito a intensa attività tettonica sindeposizionale e a differenti tassi di subsidenza intrabacinale. L'Unità I, alla base, corrisponde alle fasi iniziali di formazione del bacino ed è composta da facies di conoide alluvionale e di corsi d'acqua intersecantisi; l'Unità II consiste in sedimenti palustri e depositi di fiumi anastomizzati; l'Unità III è caratterizzata da sedimenti di fiumi meandriformi, e l'Unità IV consiste in conoidi alluvionali sviluppatesi dal lato nord-occidentale del bacino, all'interno delle Unità II e III. L'attività vulcanica sinsedimentaria è documentata da vari livelli di vulcaniti e vulcanoclastiti, per le quali l'analisi di facies e lo studio composizionale hanno rilevato caratteri di prodotti sia primari sia rimaneggiati. In particolare, colate subaeree e depositi di autobreccia che affiorano alla base della successione sedimentaria si formarono possibilmente in relazione alla messa in posto, lungo il margine nord-occidentale del bacino, di un duomo vulcanico di composizione riodacitica. D'altra parte, numerosi livelli di cineriti e di vulcanoclastiti presenti nei sedimenti delle Unità II e III testimoniano un vulcanismo altamente esplosivo, proveniente da edifici vulcanici distanti. L'analisi di facies, lo studio petrografico e la tipologia degli zirconi dei diversi prodotti vulcanici suggeriscono coesistenza di varie sorgenti di provenienza del magma.

INTRODUCTION

The Variscan orogeny in Europe is the result of the complex and oblique continental collision between Gondwana to the south and Laurasia to the north. Thrust tectonics and continental subduction led to a thickened continental crust and a Barrowian-type metamorphism culminating during Mid-Carboniferous times in western and southern Europe (Ziegler, 1986; Stampfli, 1996; von Raumer, 1998). Current geodynamic reconstruction for the Carboniferous infers a consolidated continent-continent fold-belt in the western part of the Variscan orogen, whereas its eastern

[1] Geologisch-Paläontologisches Institut, Universität Basel, Bernoullistr. 32, CH-4056 Basel, Switzerland.
[2] Institut de Minéralogie et Pétrographie, Université de Lausanne, BFSH 2, CH-1015 Lausanne, Switzerland.

part would still be characterized as an active margin with oblique subduction of Palaeotethys (Ziegler & Stampfli, 1999 in this volume).

The anti-clockwise rotation of Africa relative to Europe during the Late Carboniferous induced the development of crustal-scale dextral strike-slip zones in the consolidated part of the Variscan belt (Arthaud & Matte, 1977; Ziegler, 1990) (Fig. 1), where post-orogenic readjustment processes of the thickened crust took place (*e.g.* Burg *et al.*, 1994, and reference therein). As a result, numerous strike-slip and pull-apart basins formed in central and southern Europe (Ziegler, 1990; Cassinis *et al.*, 1992; Krainer, 1993). The main characteristics of this post-orogenic development were: (a) regional uplift with erosional processes that reached mid-crustal levels; (b) localized areas of intense tectonic subsidence filled with thick clastic continental series; and (c) widespread intrusive and extrusive magmatism of mantle and crustal derivation (Benek *et al.*, 1996; Bonin *et al.*, 1993; Cortesogno *et al.*, 1998; Bussy *et al.*, in press).

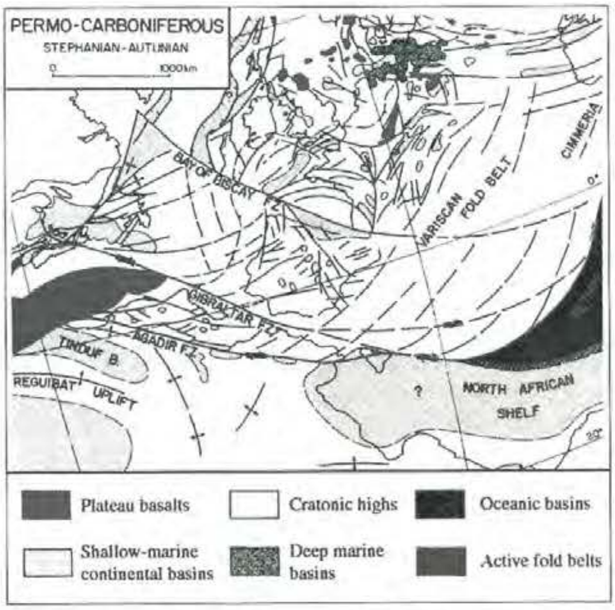


Fig. 1 – Late Carboniferous framework illustrating the western part of the Variscan fold belt, after Ziegler (1990). Abbreviations: B - basin, EUB - El Biot Uplift, FZ - fracture zone.

This volcano-sedimentary cycle is recognized in both the southern and western regions of the European Variscan orogen, for instance the Collio and Tregiovio basins in the Southern Alps (Cassinis & Neri, 1990), Tödi basin in the Aar Massif (Franks, 1966; Schaltegger & Corfu, 1995), Salvan-Dorénaz (Sublet, 1962; Niklaus & Wetzel, 1996) and Pormenaz (Lox & Bellière, 1993; Dobmeier & von Raumer, 1995) basins in the Aiguilles-Rouges massif, Saar-Nahe basin in central Germany (Schäfer & Korsch, 1998). These intramountain and perimountain basins rest on top of the orogenically deformed and erosionally truncated Variscan basement and are fault bounded. They subsided rapidly and were isolated from each other by metamorphic or igneous structural heights. As a general characteristic, they are strongly controlled by the relation between tectonic, volcanic and sedimentary processes.

This first Late Carboniferous-Early Permian tectono-sedimentary cycle is separated from a second Late Permian-Early Triassic post-tectonic cycle by a marked region-

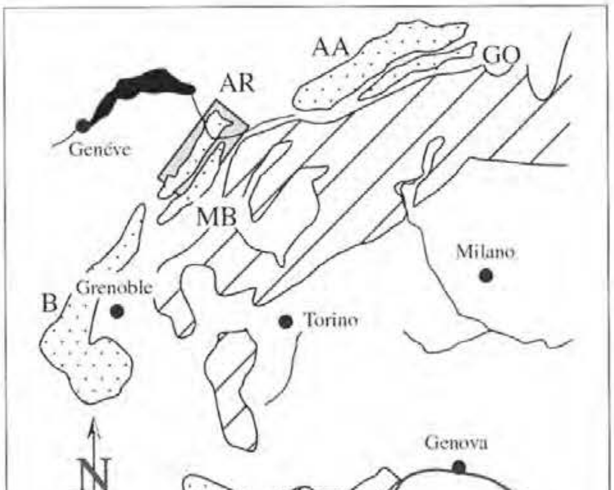


Fig. 2 – Pre-Mesozoic basement in the Alpine External Massifs (stippled). AA: Aar; Go: Gotthard; AR: Aiguilles-Rouges; MB: Mont-Blanc; B: Belledonne; A: Argentera. Study area is shaded.

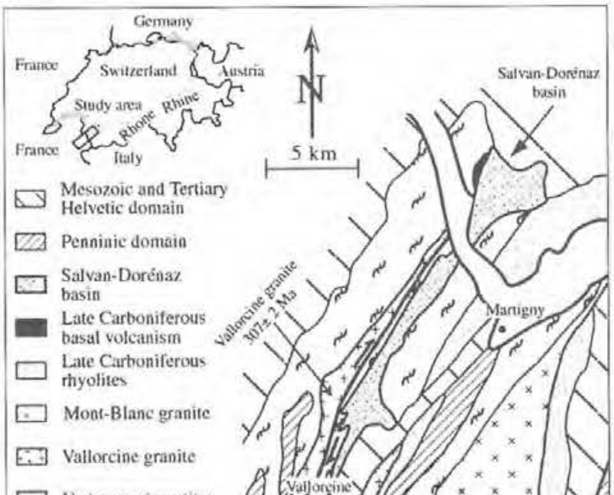


Fig. 3 – Schematic geological map of the northern part of the Aiguilles-Rouges and Mont-Blanc massifs, modified after Brändlein *et al.* (1994); insert show location of the study area.

al unconformity associated with a time-gap of uncertain duration (Italian IGCP Group (ed.), 1986; Cassinis *et al.*, 1988; Massari, 1988).

The aim of this paper is to describe and characterize new evidences of syndepositional volcanism found at different levels of a well-exposed continental sedimentary basin outcropping within the Aiguilles-Rouges massif, which developed during the Late Carboniferous – Early Permian tectono-sedimentary cycle.

REGIONAL GEOLOGICAL SETTING

The Salvan-Dorénaz basin formed during the Late Carboniferous (Late Westphalian – Stephanian; Jongmans, 1960) as an intramountain trough within the crystalline and metamorphic basement of the Aiguilles-Rouges massif. The latter is one of the so-called External Crystalline Massifs of the Alps (Fig. 2), which were part of the internal zone of the Variscan belt (von Raumer, 1998).

The Salvan-Dorénaz basin is a 20 km long by 4 km wide, NNE-SSW oriented trough, bounded by crustal-scale faults (Fig. 3). It hosts 1.5 to 1.7 km in thickness of clastic sediments (Fig. 4) deposited in continental environments. They represent only part of the original series, which were partly obliterated during an intense erosion and peneplanation stage linked to a Late Permian tectonic inversion with possible tilting of the basin (Fig. 5). During Alpine orogeny, the basin was deformed into a complex syncline structure (Pilloud, 1991; Badertscher & Burkhard, 1998), and Alpine metamorphic overprint in the Upper Carboniferous sediments only reached anchizone grades, as documented by illite crystallinity measurements on mudstones by Pilloud (1991).

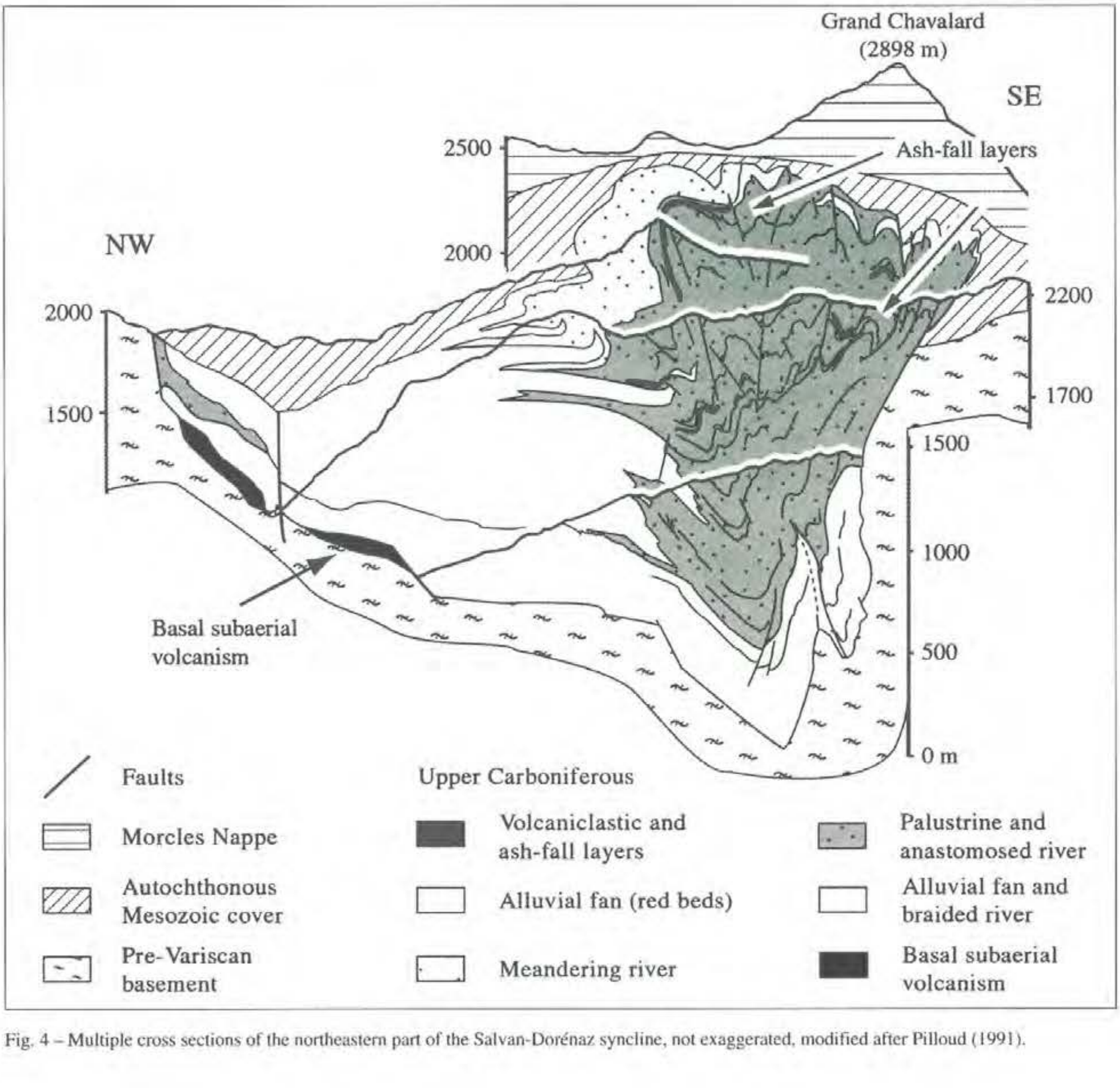


Fig. 4 – Multiple cross sections of the northeastern part of the Salvan-Dorénaz syncline, not exaggerated, modified after Pilloud (1991).

This sedimentary trough displays an asymmetric infill with a shifting depocenter located next to the northwestern side, a thick sedimentary series in comparison to basin area, rapid lateral and vertical facies variations, and high-average subsidence rates. All of these characteristics are typical for basins formed in strike-slip tectonic settings (Nilsen & Sylvester, 1995).

The formation of the Salvan-Dorénaz basin started at the very end of the Westphalian, as indicated by paleo-flora assemblages (Jongmans, 1960) and new radiometric age data on volcanic zircons (Capuzzo & Bussy, 2000). Large amounts of coarse-grained clastic deposits were transported from the northwestern margin via wet alluvial fans with dominant sediment-gravity flow deposits located proximal to sources of clastic material. These mass flow deposits progressively change downstream into high-energy shallow-stream flows characteristic of braided river facies associations.

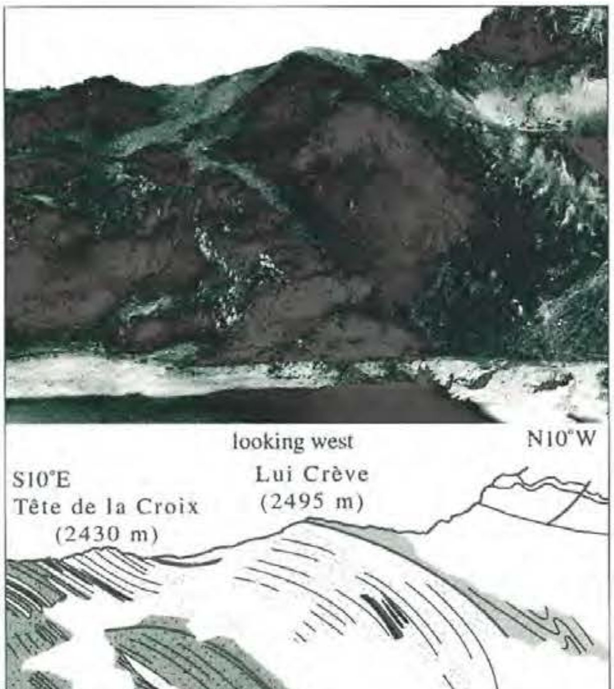


Fig. 5 – Outcrop profile and geological interpretation of the upper part of the Salvan-Dorénaz basin, Montagne de Fully area, illustrating lithologic Unit II and Unit III, and interfingering of the distal part of Unit IV with Unit II and III. The low angular unconformity between Unit III and the transgressive Triassic deposits crops out just below Lui Crève. LC-Late Carboniferous sediments. Description of the different Units in text.

The average grain-size of the sediments drastically decreases up-section. Facies assemblage and architectural elements of Unit II display characteristics of low sinuosity streams with consolidated, fixed banks, which flowed in a mud-dominated and vegetated fluvial plain. In Unit III, on top of the anastomosed river and alluvial plain deposits, the average grain-size of the sediments increases. Typically, channalized architectural elements which are characteristic of meandering fluvial channels occur. They show an increased length/width ratio and lateral accretion surfaces which testify to the migration of the channels along the fluvial valley. Sediments of Unit III are capped unconformably and at low angle by Triassic shallow-marine transgressive facies (Fig. 5).

Unit IV corresponds to dry alluvial fan deposits prograding into and retreating from the upper part of Unit II and Unit III, entering the fluvial system from the northwestern margin of the basin. Coarse-grained conglomerates of mass flow deposits represent proximal areas to the basin margin, while sheet-flood sediments dominate distal parts of the fan. The alluvial fan of Unit IV differs from that of Unit I in its reddish matrix color, possibly due to drained environments during early diagenesis, with localized oxidizing conditions.

SYNDEPOSITIONAL VOLCANISM

Basal volcanism

The initial stage of development of the sedimentary basin is marked by a period of subaerial volcanism ranging in composition from dacites to rhyodacites. It is characterized by variable proportions of coherent and autoclastic scoriaceous volcanic facies, interlayered toward the top with the Upper Carboniferous sediments (Pilloud, 1991; and own observations). The coherent facies consists of solidified lava flows having a porphyritic texture, and typically enclosed by a carapace and floor of autobrecciated products. The latter implies non-explosive fragmentation of the flowing lava commonly affecting the outer surfaces (top, base, sides) of the lava flows (McPhie *et al.*, 1993). The autoclastic facies consists of monomict, clast-supported, matrix poor, and poorly sorted breccias which are composed only of volcanic clasts (Fig. 6A), and produced by the brittle response to stress of the cooler and more viscous outer part of the flow. Typical bread-crust structures are visible in the coarser blocks and in the outer parts of the flows (Fig. 6B) and denote rapid cooling and quenching in the surface environment. These deposits were only found along the northwestern margin of the basin and they have a maximum thickness of 50-70 m, measured in non-continuous sections. They could represent the emplacement of a subaerial lava dome along the faulted margin of the basin. This was a common scenario during the evolution of the Late Palaeozoic first sedimentary cycle (*e.g.* Seui basin, Sardinia, Cortesogno *et al.*, 1998; Collio basin, Southern Alps, Breitkreuz *et al.*, 1999).

In thin section the coherent lava flows display porphyritic textures with large euhedral and subhedral phenocrysts of quartz and plagioclase (Fig. 7A), with subsidiary altered biotite flakes and few k-feldspar dispersed in a microcrystalline groundmass. Accessory minerals such as garnet, apatite, zircon and opaque minerals also occur. Quartz frequently shows perlitic fractures and typical resorption features (Fig. 7A) due to increased SiO_2 solubility during rise and eruption of the magma (McPhie *et al.*, 1993). Coarse-grained garnets are interpreted as xenocrysts pointing to crustal contamination from desegregating wall rocks during intermediate stages of the ascending magma. Fine-grained quartz reaction rims around garnets (Fig. 7B) evidence chemical disequilibrium with the melt. Both pheno- and xenocrysts are frequently cracked as a result of shear during flow and/or pressure release during rise and eruption. Zircons separated from coherent lava flows yielded an U/Pb isotopic age of 308 Ma (Capuzzo & Bussy, 2000), interpreted as the oldest possible age for the emplacement of this subaerial volcanism. Zircon morphology (Pupin, 1980) is typical for crustal derived S-type magmas (Fig. 14).

Numerous rounded volcanic pebbles, texturally and petrographically similar to the basal volcanic deposits, were found in the lower conglomeratic levels of Unit I. In thin section, these rhyolitic pebbles show eutaxitic texture with different welded pumice fragments and devitrified glass shards (Fig. 8); quartz and plagioclase phenocrysts are frequently aligned along flow direction. Coarse-grained garnet xenocrysts also occur. These volcanic rocks were probably erupted as ignimbritic flows in the source areas of detrital material, and subsequently eroded and transported through alluvial fan systems into the Salvan-Dorénaz basin. Their textural and compositional characteristics and their tectonically undeformed fabric suggest

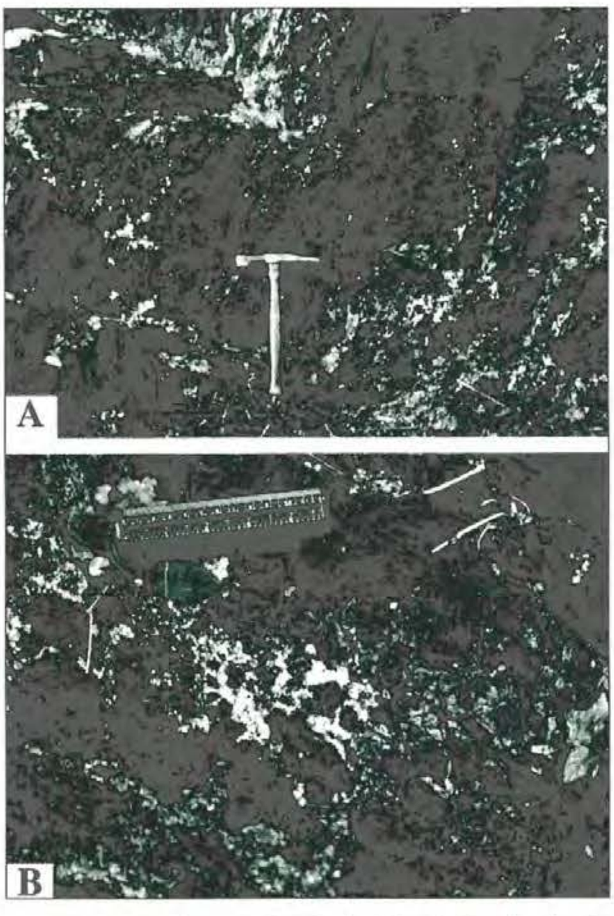


Fig. 6 – A) Autoclastic breccia from the basal rhyodacitic volcanism; B) Bread-crust structure denoting rapid cooling and quenching, from outer part of a volcanic flow. Both photographs were taken in the area of Plex (coord. 113800/570100).

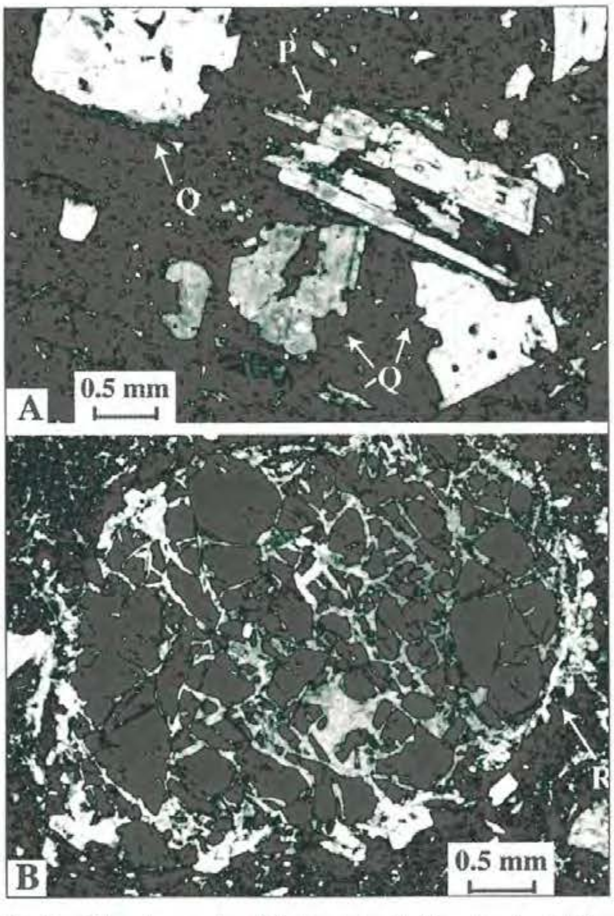


Fig. 7 – Microphotographs of the basal rhyodacitic volcanics. A) Porphyritic texture with resorbed quartz (Q) and broken plagioclase (P) phenocrysts; B) Garnet xenocryst surrounded by a microcrystalline quartz reaction rim (R). Both photographs were taken with crossed polars.

a direct link with the local magmatic pulse represented by the Salvan-Dorénaz basal volcanic deposits and by the shallow-seated Vallorcine granite (Brändlein *et al.*, 1994).

Primary to re-worked volcaniclastic deposits

Several tuff and tuffaceous sandstone layers were recently identified in the alluvial plain and overbank deposits belonging to the Salvan-Dorénaz Units II and III. Their facies and composition revealed both primary and reworked characters.

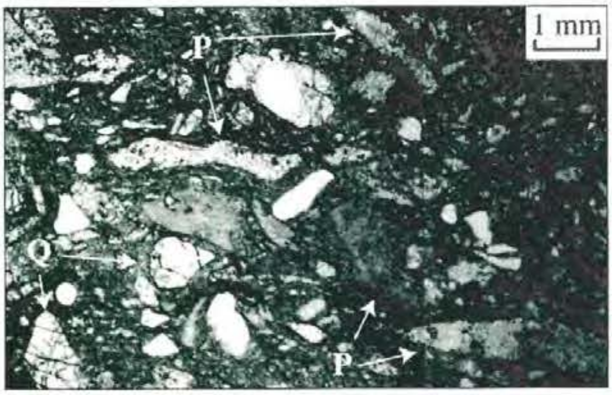


Fig. 8 – Microphotograph of a rhyolitic pebble having eutaxitic texture with broken quartz (Q) and plagioclase phenocrysts and silicified welded pumice (P) fragments. Pebble from Unit I conglomeratic alluvial fan deposits, Trient area (coord. 101175/564435). Plane-polarized light.

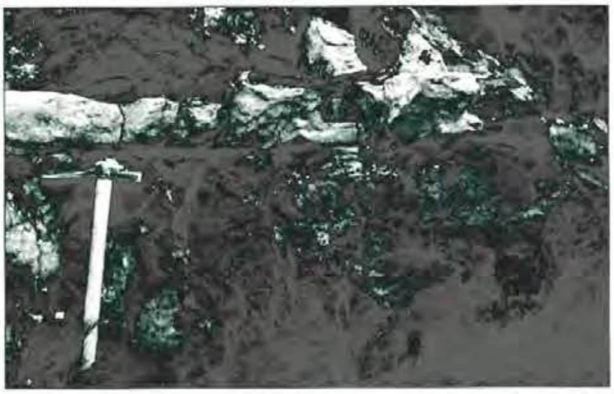


Fig. 9 – Tuff layer deposited from volcanic-ash fallout and intercalated into black alluvial plain mudstone, Montagne de Fully area (coord. 112805/572423). Hammer is 37 cm long.

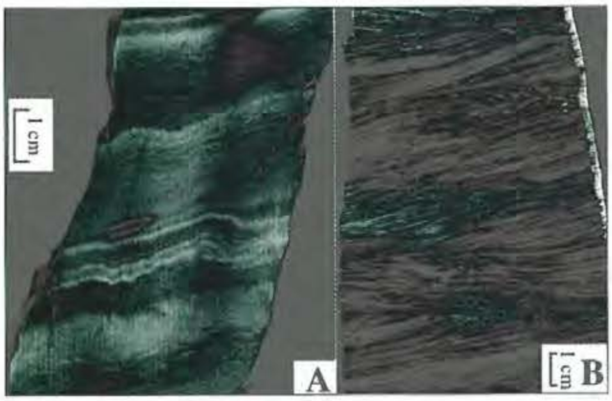


Fig. 10 – A) Delicate planar lamination partly disturbed from water escape structures. Polished surface of a silicified tuff level from the Lac Inférieur de Fully area (coord. 113252/573895); B) Cross-stratification from climbing ripples in a fine-grained volcaniclastic sandstone, Tête du Portail area (coord. 112040/572935).

Tuffs from volcanic fallout

Fine to very fine-grained tuffs range from 5 to 70 cm in thickness and show lateral continuity, mantle bedding, delicate planar laminations and fining-upward tendency (Figs 9 and 10A). They were deposited from volcanic-ash fallout and therefore are considered as primary pyroclastic deposits. They occur within black mudstone and micaceous siltstone characteristic of low energy alluvial plain and shallow lacustrine depositional environments, which allowed for their preservation (Fig. 11A). Therefore they were more frequently found within the alluvial plain and anastomosed river deposits of Unit II. Microscopical analyses revealed that they are mainly composed of a fine-grained matrix with dispersed chloritized glass shards, few fragmented quartz and plagioclase crystals, biotite flakes, and opaque and heavy minerals (Fig. 12A). The cryptocrystalline matrix is intensely silicified and might contain some carbonate patches. The main mineral phases determined with powder X-ray diffraction analyses are quartz, albite, illite and clinochlore, while their Ni vs. Zr/Ti trace element ratio (Winchester *et al.*, 1980) is consistent with a magmatic origin (Fig. 13). Textures and composition all suggest derivation from silica-rich, highly explosive volcanic eruptions from distant volcanic vents, and zircon U/Pb geochronological analyses pro-

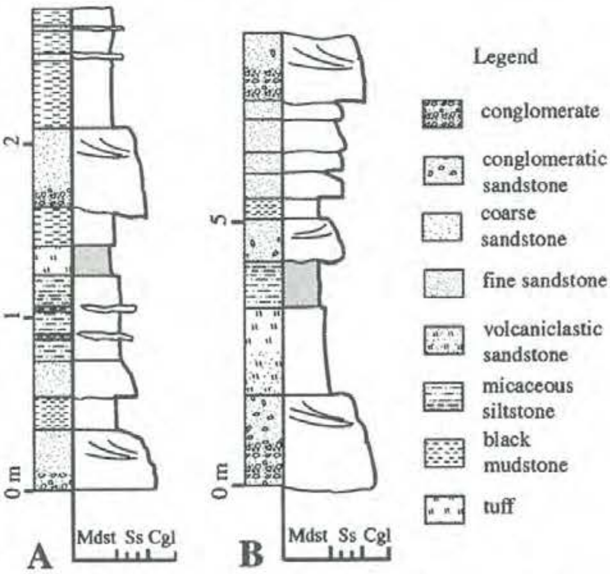


Fig. 11 – A) Stratigraphic section of a tuff layer intercalated into black mudstone. Alluvial plain deposits interbedded with crevasse splays and overbank fines (Unit II). Ash-fall layer shown in Fig. 9. B) Stratigraphic section of a reworked volcaniclastic sandstone in crevasse splay deposits from the upper Unit III, Montagne de Fully area (coord. 114100/572585).

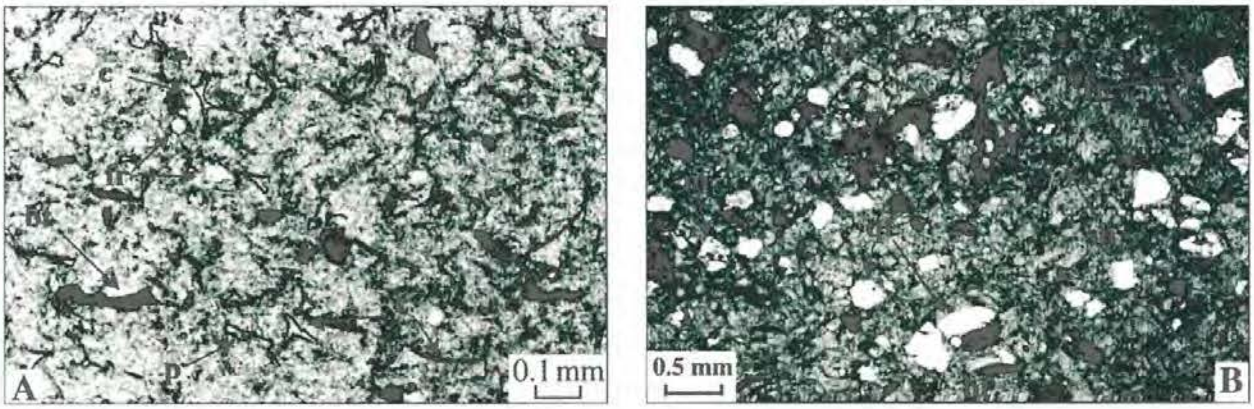


Fig. 12 – A) Microphotograph of a fine-grained tuff layer, mainly composed of light gray fine ash with dispersed cuspate (c) and platy (p) glass shards, few biotite (bt) flakes and plagioclase and quartz crystal fragments (fr); B) Microphotograph of a matrix-supported volcaniclastic layer, composed of glass shards (sh), crystal fragments (fr), biotite flakes (bt), polycrystalline quartz (qt) and metamorphic (m) fragments, denoting their mixed volcanic and detrital nature. Both photographs in plane polarized light.

duced a consistent age for this synsedimentary volcanism at 295 +4/-3 Ma (Capuzzo & Bussy, 2000). Bimodal zircon morphology distribution (Pupin, 1980) suggests derivation from alkaline magma series with crustal contamination (Fig.14).

Volcaniclastic sandstone

Strong volcanic influence during sedimentation is also recorded from several sandstone layers, which consist of mixed volcaniclastic and detrital grains and sometimes provide evidence of reworking by traction currents (Fig. 10B). They range in thickness from 50 to 160 cm and are interbedded with siltstone and sandstone layers interpreted as overbank and crevasse splay deposits (Fig. 11B). They mainly occur within Unit III. Their fabric is matrix- to grain-supported with clastic components mainly derived from volcanic sources. Broken devitrified glass shards, monocrystalline quartz and plagioclase fragments, and biotite flakes are abundant (Fig. 12B), while micaschist and sillimanite-bearing metamorphic clasts, polycrystalline quartz, intensely altered K-feldspar and white mica flakes indicate provenance from detrital sources. Their Ni vs. Zr/Ti trace element ratio (Winchester *et al.*, 1980) is also consistent with a prevalent magmatic origin (Fig. 13).

CONCLUSIONS

The Salvan-Dorénaz basin is a tectono-sedimentary trough, which formed towards the end of the Palaeozoic (Westphalian) within the Aiguilles-Rouges crystalline basement (Western Alps). Different periods of active synsedimentary volcanism occurred during formation and evolution of the Salvan-Dorénaz basin. Basal rhyodacitic flows and autobrecciated products localized along the

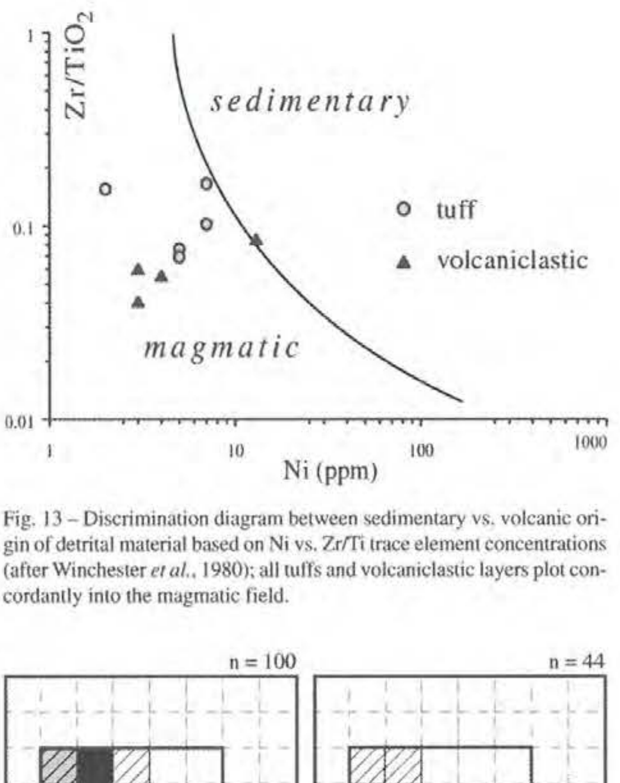


Fig. 13 – Discrimination diagram between sedimentary vs. volcanic origin of detrital material based on Ni vs. Zr/Ti trace element concentrations (after Winchester *et al.*, 1980); all tuffs and volcaniclastic layers plot concordantly into the magmatic field.

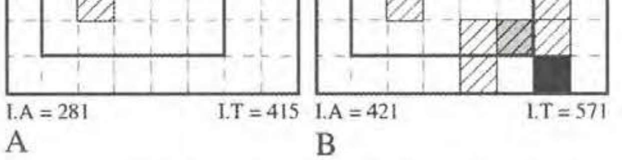


Fig. 14 – Typologic distribution of zircon for the syndepositional volcanism in the Salvan-Dorénaz basin, mean A/T values as in the classification diagram of Pupin (1980). A) basal rhyodacitic volcanism presenting an homogeneous population characteristic of anatectic magmas; B) tuff layer presenting a bimodal distribution of zircons with a maximum in the alkaline magma series.

northwestern margin of the basin were deposited during its initial stage of development. Zircon typology suggests crustal derivation for this subaerial volcanism, while petrographical studies provide evidence of contamination from disintegrating wall-rocks. An estimated age of emplacement at 308 ± 3 Ma was determined from U/Pb geochronological analyses on zircons (Capuzzo & Bussy, 2000). This lower volcanism is possibly associated with a local magmatic phase documented in the Aiguilles-Rouges massif by numerous subvolcanic dykes and by the shallow-seated, anatectic Vallorcine granite (Brändlein *et al.*, 1994), which intruded syntectonically along a dextral transcurrent shear-zone at 307 Ma (Bussy *et al.*, in press). On the other hand, ash-fall and volcaniclastic layers found within alluvial plain and palustrine sediments of Unit II and III testify for high-explosive volcanic eruptions from distant volcanic centers, and a consistent age of 295 +4/-3 Ma was determined from U/Pb geochronological analyses on zircons (Capuzzo & Bussy, 2000). Their zircon typology presents a bimodal distribution, which suggests derivation from alkaline magma series differently contaminated by crustal material. Coeval, highly explosive volcanism is known from the Aar massif in the Central Alpine basement (Schaltegger & Corfu, 1995), and tuff layers associated with this magmatic event have already been described in a Permo-Carboniferous basin located in northern Switzerland (Schaltegger, 1997).

Acknowledgements – This paper presents results from the doctoral thesis of the first author. We are grateful to the Swiss National Science Foundation for the financial support (NC: grants No. 21-43103.95 and 20-50484.97 to A. Wetzel), (FB: grant N°. 21-45650.95 to J. Hernandez). Many thanks to W. Stern for assisting the powder X-ray diffraction analyses and helping in their interpretation and to A. Wetzel for the constructive remarks on the first draft of this paper.

REFERENCES

ARTHAUD F. & MATTE P.H., 1977. Late Palaeozoic strike-slip faulting in Southern Europe and Northern Africa. *Geol. Soc. Am. Bull.*, 88: 1305-1320.

BADERTSCHER N. & BURKHARD M., 1998. Inversion alpine du graben Permo-Carbonifère de Salvan-Dorénaz et sa relation avec le chavauchement de la Nappe de Morcles sus-jacente. *Eclogae geol. Helv.*, 91: 359-373.

BENEK R., KRAMER W., MCCANN T., SCHECK M., NEGENDANK J.F.W., KORICH D., HEUBSCHER H.D. & BAYER U., 1996. Permo-Carboniferous magmatism of the Northeast German Basin. *Tectonophysics*, 266: 379-404.

BONIN B., BRÄNDLEIN P., BUSSY F., DESMONS J., EGGENBERGER U., FINGER F., GRAF K., MARRO C., MERCOLLI I., OBERHÄNSLI R., PLOQUIN A., VON QUADT A., VON RAUMER J., SCHALTEGGER U., STEYRER H.P., VISONA D. & VIVIER G., 1993. Late Variscan magmatic evolution of the Alpine Basement. In: Von Raumer J.F. & Neubauer F. (eds), *Pre-Mesozoic geology in the Alps*. Springer-Verlag : 171-201.

BRÄNDLEIN P., NOLLAU G., SHARP Z. & VON RAUMER J., 1994. Petrography and geochemistry of the Vallorcine granite (Aiguilles-Rouges massif, Western Alps). *Schweiz. mineral. petrogr. Mitteilungen*, 74: 227-243.

BREITKREUZ C., CHECCHIA C., CASSINIS G., CORTESOGNO L. & GAGGERO L., 1999. Dynamic of a Variscan post-orogenic basin in the Southern Alps: sublacustrine SiO_2-rich volcanism and associated mass flows (Collio basin, Italy). *J. Conf. EUG 10*, March 28th - April 1st, Abstract vol.: 294-295.

BURG J.-P., VAN DEN DRIESSCHE J. & BURN J.P., 1994. Syn- to post-thickening extension in the Variscan belt of Western Europe: modes and structural consequences. *Géologie de la France*, 3: 33-51.

BUSSY F., HERNANDEZ J. & VON RAUMER J., in press. Bimodal magmatism as a consequence of the post-collisional readjustment of the thickened Variscan continental lithosphere (Aiguilles-Rouges and Mont-Blanc massifs, Western Alps). *Trans. Royal Soc. Edinburgh.*

CAPUZZO N. & BUSSY F., 2000. High-precision dating and origin of synsedimentary volcanism in the Late Carboniferous Salvan-Dorénaz basin (Aiguilles-Rouges massif, Western Alps). *Schweiz. mineral. petrogr. Mitteilungen*, 80(2): 147-167.

CASSINIS G. & NERI C., 1990. Collio and Tregiovo Permian continental basins (Southern Alps, Italy): a general comparison. *Atti Ticin. Sci. Terra*, Pavia, 33: 11-15.

CASSINIS G., MASSARI F., NERI C. & VENTURINI C., 1988. The continental Permian of the Southern-Alps (Italy). A review. *Z. geol. Wiss.*, 16: 1117-1126.

CASSINIS G., TOUTIN-MORIN N. & VIRGILI C., 1992. A general outline of the Permian continental basins in Southwestern Europe. In: Sweet W.C., Yang Zunyi, Dickins J.M. & Yin Hongfu (eds), Permo-Triassic events and their global correlation. Cambridge Univ. Press: 41-50.

CORTESOGNO L., CASSINIS G., DALLAGIOVANNA G., GAGGERO L., OGGIANO G., RONCHI A., SENO S. & VANOSSI M., 1998. The Variscan post-collisional volcanism in Late Carboniferous-Permian sequences of Ligurian Alps, Southern Alps and Sardinia (Italy): a synthesis. *Lithos*, 45: 305-328.

DOBMEIER C. & VON RAUMER J.F., 1995. Significance of latest - Varisican and Alpine deformation for the evolution of Montagne de Promenaz (Southwestern Aiguilles-Rouges massif, Western Alps). *Eclogae geol. Helv.*, 88 (2): 267-279.

FRANKS G.D., 1966. The development of the limnic Upper Carboniferous of the eastern Aar Massif. *Eclogae geol. Helv.*, 59: 943-950.

ITALIAN IGCP 203 GROUP (ed.), 1986. Permian and Permo-Triassic boundary in the South-Alpine segment of the western Tethys. Field Guidebook. *Field Conf. SGI-IGCP Project 203*, July 1986, Brescia: 180 pp.

JONGMANS W.J., 1960. Die Karbonflora der Schweiz. *Beitr. geol. Karte Schweiz, Neue Folge*: 108.

KRAINER K., 1993. Late and post-Variscan sediments of the Eastern and Southern Alps. In: von Raumer J.F & Neubauer F. (eds), *The Pre-Mesozoic geology in the Alps*. Springer, Berlin: 573-564.

LOX A. & BELLIÈRE J., 1993. Le Silésien (Carbonifère Supérieur) de Pormenaz (Massif des Aiguilles-Rouges): litologie et tectonique. *Eclogae geol. Helv.*, 86 (3): 769-783.

MASSARI F., 1988. Some thoughts on the Permo-Triassic evolution of the South-Alpine area (Italy). In: Cassinis G. (ed.), *Permian and Permian-Triassic boundary in the South-Alpine segment of the Western Thetys, and additional regional reports*. Mem. Soc. Geol. Ital.: 179-188.

MCPHIE J., DOYLE M. & ALLEN R., 1993. Volcanic texture, a guide to the interpretation of textures in volcanic rocks. *CODES*, Univ. of Tasmania: 198 pp.

NIKLAUS P.A. & WETZEL A., 1996. Faziesanalyse und Ablagerungsmilieu der fluviatilen Sedimentfüllung des Karbontroges von Salvan-Dorénaz. *Eclogae geol. Helv.*, 89 (1): 427-437.

NILSEN T.H. & SYLVESTER A.G., 1995. Strike-slip basins. In: Busby C.J. & Ingersoll R.V. (eds), *Tectonics of sedimentary basins*. Blackwell Science, Oxford: 425-457.

PILLOUD C., 1991. Structure de déformation alpines dans le synclinal de Permo-Carbonifère de Salvan-Dorénaz (massif des Aiguilles Rouges, Valais). *Mém. de Géol.* (Lausanne), No. 9: 101 pp.

PUPIN J.P., 1980. Zircon and granite petrology. *Contrib. Mineral. Petrol.*: 73: 207-220.

SCHÄFER A. & KORSCH R.J., 1998. Formation and sediment fill of the Saar-Nahe Basin (Permo-Carboniferous, Germany). *Z. dtsch. geol. Ges.*, 149 (2): 233-69.

SCHALTEGGER U., 1997. The age of an Upper Carboniferous/Lower Permian sedimentary basin and its hinterland as constrained by U-Pb dating of volcanic and detrital zircons (Northern Switzerland). *Schweiz. mineral. petrogr. Mitteilungen*, 77: 101-111.

SCHALTEGGER U. & CORFU F., 1995. Late Variscan "Basin and Range" magmatism and tectonics in the Central Alps: evidence from U-Pb geocronology. *Geodinamica Acta*, 8 (2): 82-98.

STAMPFLI G., 1996. The intra-Alpine terrain: a Paleotethyan remnant in the Alpine Variscides. *Eclogae geol. Helv.*, 89 (1): 13-42.

SUBLET P., 1962. Etude géologique du synclinal Carbonifère de Collonges-Dorénaz (Valais). *Ecoglae geol. Helv.*, 55 (1): 23-76.

VON RAUMER J., 1998. The Palaezoic evolution in the Alps: from Gondwana to Pangea. *Geol. Rdsch.*, 87: 407-435.

WINCHESTER J.A., PARK R.G. & HOLLAND J.G., 1980. The geochemistry of Lewisian semipelitic schists from the Gairloch District, Wester Ross. *Scott. J. Geol.*, 16 (2/3): 165-179.

ZIEGLER P.A., 1986. Geodynamic model for the Palaeozoic crustal consolidation of Western and Central Europe. *Tectonophysics*, 126: 303-328.

ZIEGLER P.A., 1990. Geological Atlas of Western and Central Europe (second and completely revised edition). *Shell Intern. Petroleum Maatschappij BV, The Hague*: 239 pp.

ZIEGLER P.A. & STAMPFLI G.M., 1999. Late Palaeozoic - Early Mesozoic plate boundary reorganization: collapse of the Variscan orogen and opening of Neotethys. Intern. Congr. "*The continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations*". *Brescia, Italy, 15-25 Sept 1999*. Earth Sci. Dept., Pavia University, Pavia, Abstracts: 5-10.

STRATIGRAPHICAL CONSTRAINTS ON MOLASSE DEPOSITIONAL SYSTEMS IN THE PERMO-CARBONIFEROUS SAAR-NAHE BASIN, GERMANY

ANDREAS SCHÄFER [1]

Keywords – European late Variscan sedimentary basin; Permo-Carboniferous; siliciclastics and volcanites; continental depositional environments; strike-slip basin model.

Abstract – The Saar-Nahe Basin formed as an internal rift within the Central European Variscides. It may have communicated with other freshwater basins, interconnected by depositional systems during the Westphalian and the Stephanian in tropical to subtropical latitudes, and in the Rotliegend in arid latitudes; marine deposits are not known. Basin fill of about 7.5 km thickness today, consisting of siliciclastic rocks together with rhyolitic/andesitic volcanic rocks, exhibits a well documented standard for continental stratigraphy of the Central European Permo-Carboniferous.

Parole chiave – bacino sedimentario tardo-varisico europeo; Permo-Carbonifero; rocce silicoclastiche e vulcaniche; ambienti deposizionali continentali; modello di bacino a *strike-slip*.

Riassunto – Il Bacino della Saar-Nahe si formò come un *rift* interno alle Varisidi centro-europee. Esso può aver comunicato con altri bacini d'acqua dolce, collegati da sistemi deposizionali durante il "Westfaliano" e lo "Stefaniano", a latitudini da tropicali a subtropicali, e nel Rotliegende a latitudini aride. Depositi marini sono sconosciuti. Il riempimento del bacino con depositi oggi potenti all'incirca 7.5 Km, che consistono di rocce silicoclastiche e vulcaniti riolitiche/andesitiche, rappresenta un ben documentato standard per la stratigrafia continentale del Permo-Carbonifero centro-europeo.

GENERAL SETTING

The Saar-Nahe Basin is one of the largest and best exposed sedimentary basins within the Variscan orogenic belt in Central Europe (Schäfer, 1989; Korsch & Schäfer, 1991, 1995; Schäfer & Korsch, 1998). It extends over an area of 300 x 100 km, within which it is exposed from underneath the Mesozoic cover by a size over 100 x 40 km. As drill-well evidence and seismic control is extraordinary, a three-dimensional basin model can be constructed.

About 7.5 km thick non-marine molassoid sediments, consisting of 0.5 km Namurian, 2 km Westphalian, 3 km Stephanian, and 2 km Lower Permian Rotliegend strata, were preserved in a wholly structure-controlled setting in the Saxothuringian Zone (Schäfer & Korsch, 1998). The Saar-Nahe Basin is one of the locations of Central Europe, where continental sequences are exposed internal to the Variscan orogen, providing a complete stratigraphic standard for major parts of the Permo-Carboniferous.

STRUCTURE OF THE BASIN

The basin is separated from the Rhenohercynian to the north by the South-Hunsrück Fault, which is part of one of the major Variscan suture zones, running through Central Europe (Fig.1). From the deep-reflection seismic line DEKORP 1C Korsch & Schäfer (1991) argued that the fault plane is more or less planar in shape and steep, cutting most of the continental crust. Also, there are opinions, that, from a previous continental collision (the Rhenohercynian in the N with the E Avalonia continental crust underneath versus the Mid German Crystalline Rise belonging to Armorica with the Saar-Nahe Basin above), the fault plane could be listric (Oncken, 1997).

The basin developed as a dextral strike-slip controlled half-graben with southwestward-oriented oblique transtension (Korsch & Schäfer, 1991, 1995). At the northeastern end of this fault with respect to the Saar-Nahe Basin, well exposed at the surface, shingled alluvial fans demonstrate the dextral strike-slip character of the basin – the youngest fans shingle on top of each other toward the NE (Schäfer & Korsch, 1998). In the subsurface, isopach maps compiled from thick stratigraphic sequences also show a shift of their depocentres from the SW towards the NE.

During its formation as a rift basin, internal to the Variscan orogen during the Permo-Carboniferous, the Saar-Nahe Basin is assumed to have been located in a mountain-

[1] Institute of Geology, University of Bonn, Nussallee 8, 53115 Bonn, Germany.

ous area, (?) some hundreds of metres above sea-level. This could explain the rigid dewatering regime applied throughout the Westphalian (toward the S), the Stephanian (toward the NE), and the Rotliegend (toward the SW) - the latter two running in the Variscan axis. The distance from the sea during the Permo-Carboniferous could have easily been several hundreds of kilometres (Tethys, Biscay). Both topographic height and distance from the sea demand a freshwater regime in the basin. The perennial water-rich depositional environments of the basin formed greyish sediments in a tropical climate during the Westphalian and the Stephanian (from paleomagnetic results the latitude was 10° N in the Stephanian C; Schäfer & Stamm, 1989); in the Rotliegend about 30° N is assumed from the alluvial ephemeral environments and reddish sediments (for an overview see Schäfer & Korsch, 1998).

SEDIMENTS DEPOSITED

The sediment-fill of the Saar-Nahe Basin is siliciclastic in origin (Schäfer & Korsch, 1998).

During the Westphalian (Fig. 2), sediments derived from the Rhenohercynian Schiefergebirge in the north; as a consequence, greywackes formed. These were meandering-fluvial to deltaic sediments in the basin; close to the northern margin, alluvial fans are assumed, although they are not exposed.

From the Stephanian onwards, the source of the sediments was the Moldanubian in the south and southwest of the basin, in the Black Forest, in the Vosges, and in the Massif Central in France (Schäfer, 1986). All basement units provided detritus to form arkoses. The sediment input was fluvial, mostly of a meandering character. Clear-

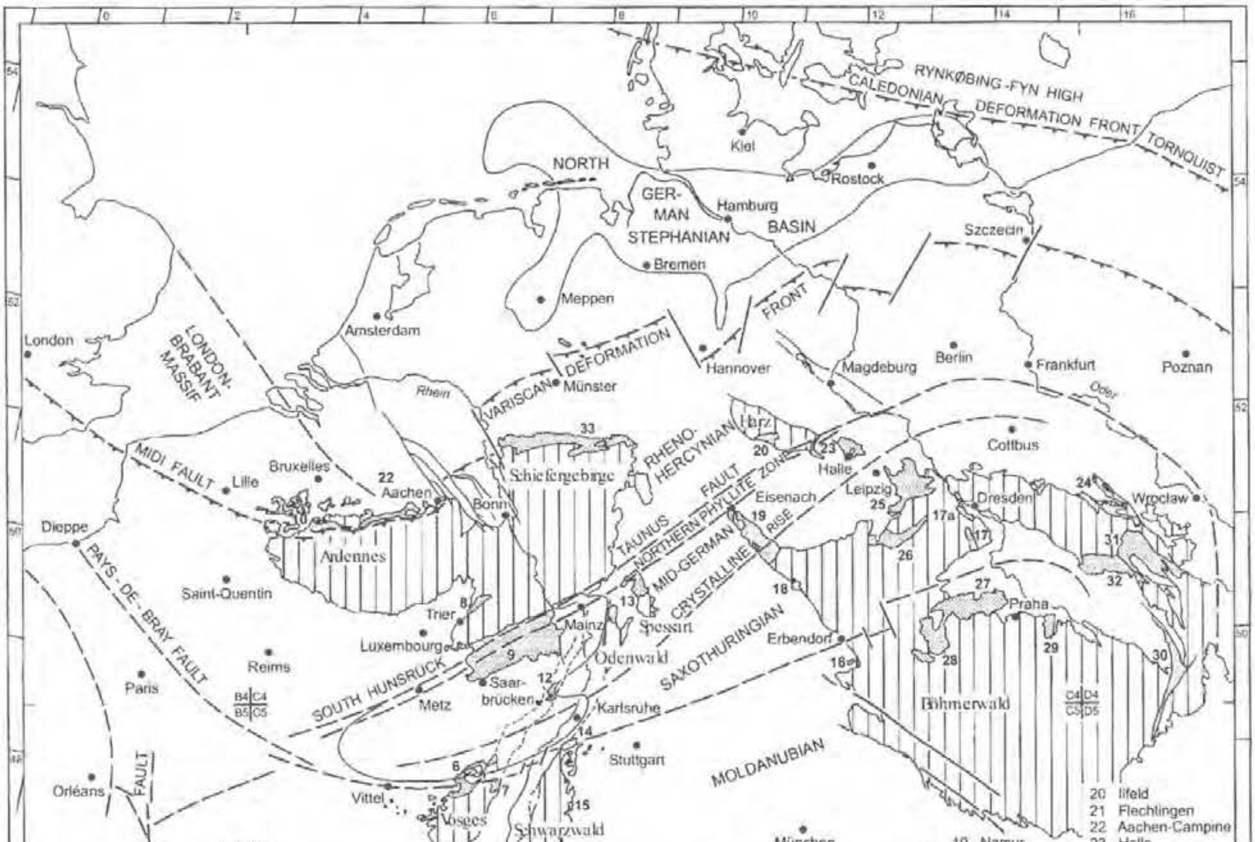


Fig. 1 – Map of Central Europe showing the Variscides together with Permo-Carboniferous continental rocks in surface exposures, mostly part of larger sedimentary basins (modified from Schäfer & Korsch, 1998). The shaded area of the North German Stephanian Basin (Ziegler, 1990) marks the central part of the depocentre of the North German Permo-Carboniferous Basin. The path of the Variscan deformation front is from Franke (1992). The codes B4, B5, C4, C5, D4, D5 are the sheet numbers of the International Geological Map of Europe 1:1,500,000 used for the compilation of this overview.

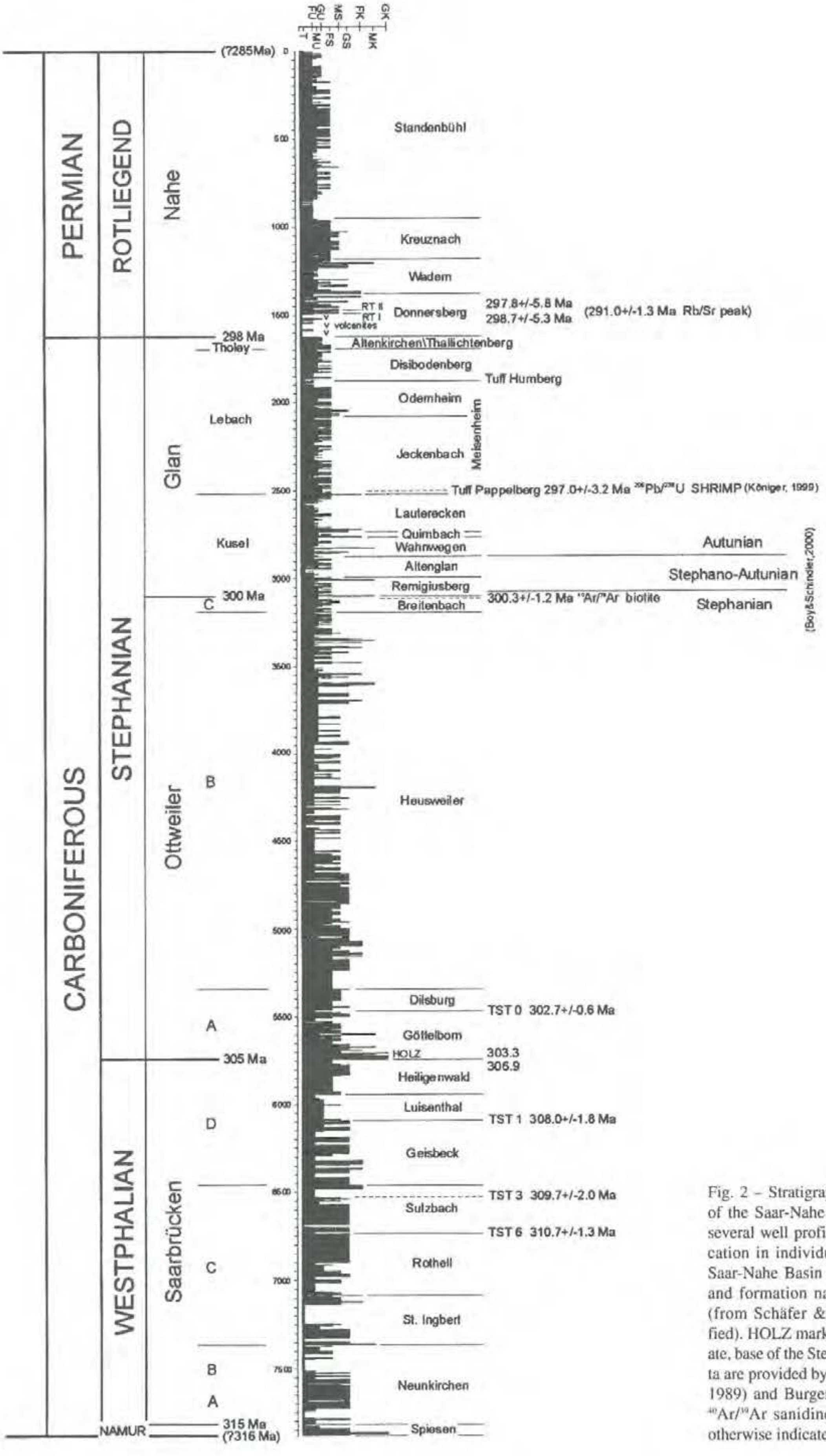


Fig. 2 – Stratigraphical standard section of the Saar-Nahe Basin, compiled from several well profiles, aligned to their location in individual depocentres of the Saar-Nahe Basin with group, subgroup, and formation names, currently in use (from Schäfer & Korsch, 1998; modified). HOLZ marks the Holz Conglomerate, base of the Stephanian. Numerical data are provided by Lippolt & Hess (1983, 1989) and Burger *et al.* (1997) and are $^{40}Ar/^{39}Ar$ sanidine plateau ages, unless otherwise indicated.

ly from orogenic pulses braided-fluvial conglomerate horizons invaded the basin in a stream-channel sedimentation style, providing well-defined lithostratigraphical markers. The Stephano-Autunian sediments were delivered from the Moldanubian in the S and the SW. Thus, they are rich in feldspars and granitic fragments. Also, they contain reworked durable siliciclastics from the Westphalian below. The basin dewatered towards the NE.

Intense Permo-Carboniferous volcanism produced lava flows, rhyolitic tuffs and intrusive rocks (Schwab, 1981, 1987); the volcanic rocks achieved a thickness of about 500 m. The rhyolites were mostly intrusives (Arikas, 1986; Hofmeister & von Platen, 1988; von Seckendorf & Chakraborty, 1993), but also formed volcanic tuffs showing a wide distribution and interacting with fluvial sedimentation (Stollhofen & Stanistreet, 1994). The volcanites were of the same chemistry as known from many other Permo-Carboniferous European continental basins (Plein, 1990; Plein *et al.*, 1995; Breitkreuz & Kennedy, 1999; Schaltegger, 1997). This volcanism was close to the base of the Permian Rotliegend.

Alluvial sedimentation in the Rotliegend above the volcanites (Stollhofen, 1994) was due to a change in basin geometry and the change of climatic conditions to more arid ones as before. Sediment input was from the north by rapid alluvial fans, and in addition from the E and SE where the Saxothuringian and the Moldanubian were eroded (Schäfer & Korsch, 1998).

After a folding event by the end of the Rotliegend, the basin was uplifted in the Cretaceous and the Tertiary. As a consequence, the Meso-Cenozoic overburden and part of the Rotliegend were removed (about 4000 m of bed thickness). The Saar-Nahe Basin became exposed from below the Mesozoic over a third of its surface, as it is known today (Schäfer & Korsch, 1998).

STRATIGRAPHY OF THE BASIN-FILL

Rich coal measures were preserved in the Westphalian and to some extent in the Stephanian as they were formed from the production and decay of tropical floras (Fig. 2). A structural disconformity with considerable loss of strata is obvious between the Westphalian and the Stephanian. The time gap comprises about 2 myr, and it is assumed that the missing Cantabrian stage is located here (Wagner & Winkler Prins, 1994, 1997; Korsch & Schäfer, 1995). The base of the Stephanian is marked by the Holz Conglomerate (HOLZ; Schäfer, 1986; Schäfer & Korsch, 1998).

It has been traditional to determine precise stratigraphic ages in the Saar-Nahe Basin by flora (Germer & Engel, 1989; Kerp, 1996), pollen and spores (Müller & Hoppe, 1996), and also by footprints of sauropods (Boy & Fichter, 1988; Boy & Martens, 1991). From this, the Carboniferous/Permian stratigraphical boundary was posted close below the Dirmingen Conglomerate at the base of the Glan Group. Right below this conglomerate in lacustrine beds of Stepanian C in age, a tuff was preserved, numerically dated to 300.3 +/– 1.2 Ma with a ^{40}Ar/^{39}Ar sanidine plateau age (Burger *et al.*, 1997).

The rhyolitic tuffs associated with the Permo-Carboniferous revealed ^{40}Ar/^{39}Ar sanidine plateau ages of 297.8 +/– 5.8 and 298.7 +/– 5.3 Ma (Lippolt & Hess, 1989). From initiation by Burger *et al.* (1997), Schäfer & Korsch (1998) assigned the stratigraphic boundary between the Carboniferous and the Permian to the Permian volcanites. Also, this age of roughly 298 Ma is about the same as was shown by Claoué-Long *et al.* (1995) and Roberts *et al.* (1995) using SHRIMP zircon ^{206}/Pb/^{238}U ages, determining the Carboniferous/Permian boundary in Australia. This indeed contradicts the international trend to locate the Carboniferous/Permian boundary at 291 – 292 Ma (Wardlaw, 2000). On the other hand, Boy & Schindler (2000) discussed the palaeoecology of fishes and amphibians in lacustrine to fluvial environments close to the Carboniferous/Permian boundary in the Saar-Nahe Basin. On top of the Stephanian C (Breitenbach beds), they inserted a Stephanian D (Remigiusberg to Altenglan beds), a Stephanian D / Autunian transition in the Wahnwegen beds, and the Autunian from the Quirnbach beds onwards. Also, they found reason to correlate the Stephanian D / Autunian boundary with an absolute age of 296 Ma age (probably even 1 or 2 myr older).

DISCUSSION

The continental Saar-Nahe Basin developed as an internal molasse basin of the Permo-Carboniferous. Its subsidence was due to a dextral strike-slip regime that was active during the orogenic shortening of the Variscides, forming an asymmetric half-graben (Korsch & Schäfer, 1991). The calculation of its subsidence strongly depends on stratigraphic markers reliable for dating numerical ages. These markers for most of the Permo-Carboniferous are volcaniclastics, wind-born volcanic tuffs, produced external to the basin and assumed to be provided from the area of the northern Schwarzwald and/or the northern Vosges (Stollhofen, 1994). Some of them are numerically dated (Burger *et al.*, 1997; Königer, 1999). In addition to these, basin-derived rhyolitic tuffs originated from the Donnersberg (in the SE of the exposed part of the basin) and are associated with its intrusion process (Stollhofen, 1994). These tuffs provided the above cited numerical datum of about 298 Ma, as used by Schäfer & Korsch (1998). Yet, using this age, problems are obvious. The numerical age of the tuff in the Breitenbach Formation (Stephanian C) is about 300 Ma (Burger *et al.* 1997). This demands a time span of 2 m.y. for the strata of the Glan Group having a thickness of 2 km (Menning, 1995 a, b; 1999 pers. comm.). In any case, a rather high subsidence rate has to be calculated (Fig. 3; Schäfer & Korsch, 1998).

It should be considered that the Saar-Nahe Basin fill is extremely unbalanced during this period. Consisting of either a large amount of lake beds and meandering rivers versus coarse-grained conglomerates from stream-channels during the Kusel and Lebach Subgroups (Schäfer 1986; Boy & Schindler, 2000), subsidence must have been considerable in the pre-volcanic syn-rift phase (*sensu* Stollhofen, 1994). During the Tholey Subgroup, the basin regained a river-dominated environment with low-sinuosity meanders (Schäfer, 1986). Together with this, the fluvial input changed its direction from the SW to originate now from the Vosges in the south. No longer did it follow the basin axis from the Massif Central in the SW. A structural reorganisation is obvious, which may have been related to the volcanic syn-rift phase (*sensu* Stollhofen, 1994).

Permo-Carboniferous volcanic rocks cover large parts of Central Europe providing a volcanic signal rather short in duration. The rhyodacitic lavas in the North German Rotliegend Basin achieved a thickness of about 2500 m (Plein *et al.*, 1995; McCann, 1999). From these rhyo-

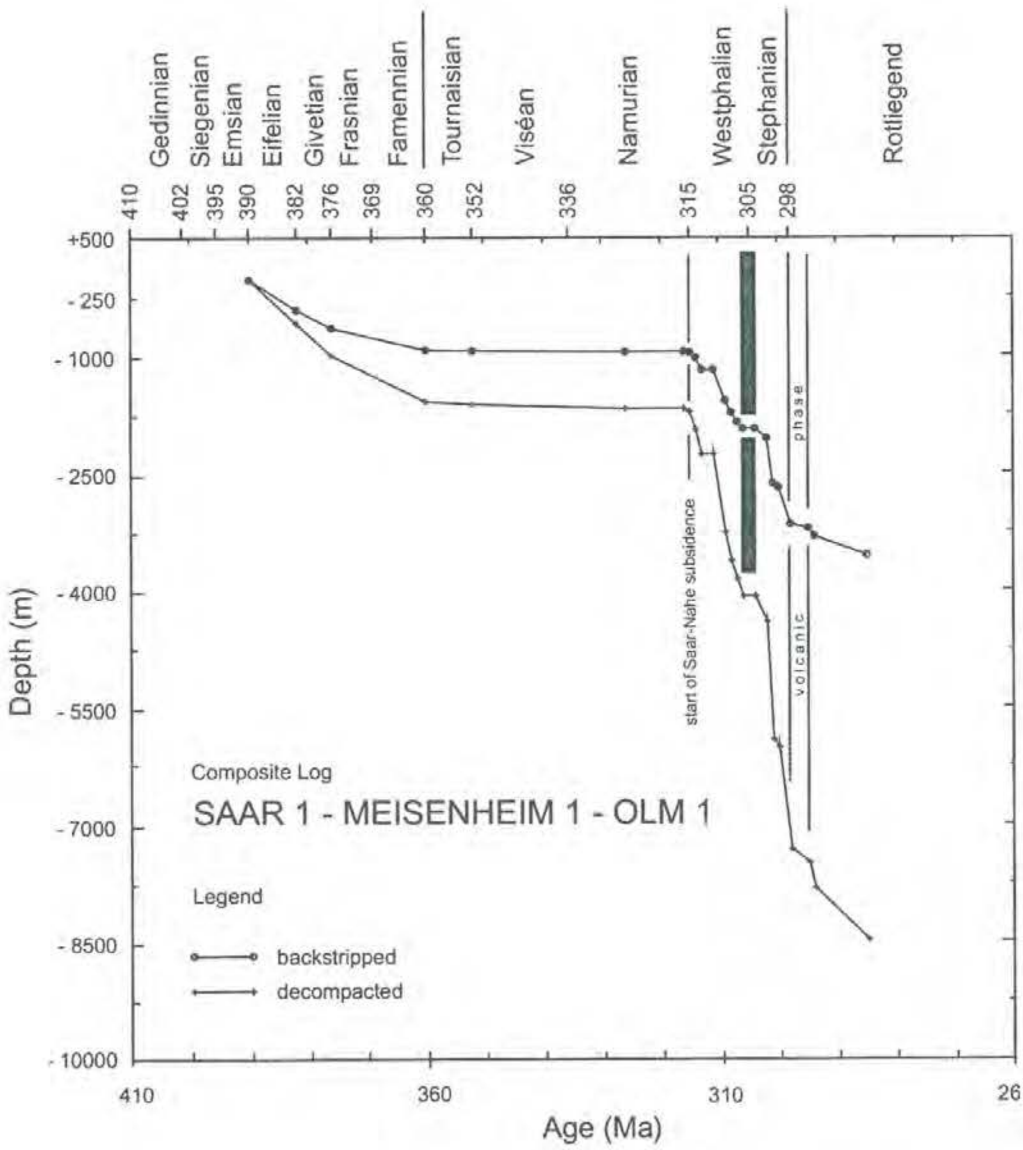


Fig. 3 – The Saar-Nahe Basin subsidence plot is calculated using the backstripping technique (Schäfer & Korsch, 1998). The curves are calculated from stratigraphic data from the wells Saar 1 (Emsian to Stephanian), Meisenheim 1 (Stephanian), and Olm 1 (Stephanian to Rotliegend). The lower curve shows the today's basin-fill, the upper one the structural subsidence of the basin (more details in Korsch & Schäfer, 1995). The horizontal segment at 305 Ma is the discordance due to deformation and erosion at the Westphalian/Stephanian boundary and is emphasised by the dark vertical bar.

dacitic lavas, Breitkreuz & Kennedy (1999) provided numerical ages, ranging from 300 +/– 3 Ma to 297 +/– 3 Ma (SHRIMP zircon ages) each from the centre and the top of the flows respectively, the sample sites being roughly 1.4 km apart from eachother (in well Mirow 1/74). In the North German Rotliegend Basin, from use of the oil industry, the volcanites mark the boundary between the Stephanian and the Rotliegend. In the Thüringerwald Basin, the Carboniferous/Permian boundary is located in a stratigraphical gap between the Möhrenbach and Ilmenau Group, whereby the effusive rhyolites in the Möhrenbach Group have a 296 +/– 5 Ma biotite age which is related to the intrusion of the Ruhla granite (Andreas & Wunderlich, 1998). Boy & Schindler (2000) focussed on a correlation between the Saar-Nahe Basin and the Thüringerwald Basin with palaeoecological findings, and they suggested the use Stephano-Autunian resp. Stephanian D to overcome the inconsistency of biostratigraphical and numerical data. As a consequence, their Stephanian D is different from that used by Schäfer & Korsch (1998) after the suggestion of Doubinger (1956).

Volcanic rocks in the continental Permo-Carboniferous of Central Europe provide stratigraphical markers. Yet, chronostratigraphical ages do not replace biostratigraphical zones. Nevertheless, they provide a chance to correlate between sedimentary basins, distant from each other, and also internal and external to the Variscides.

Acknowledgements – This paper was improved by the thorough reading and comments of Prof. Jean Paul Deroin, Bordeaux, and of one anonymous referee. I appreciate their help.

REFERENCES

Andreas D. & Wunderlich J., 1998. Tektonische Verhältnisse am Westthüringer Quersprung (nordwestlicher Thüringer Wald). II. Spät- und postvariscische Entwicklung an der Reifstieg-Störung und die frühe Entwicklungsphase des Ringgau-Fränkischen Lineamentes. *Beit. Geologie von Thüringen, Neue Folge*, 5: 39-72.

Arikas K., 1986. Geochemie und Petrologie der permischen Rhyolite in Südwestdeutschland (Saar-Nahe-Pfalz-Gebiet, Odenwald, Schwarzwald) und in den Vogesen. *Pollichia-Buch*, Bad Dürkheim, 8: 321 pp.

Boy J.A. & Fichter J., 1988. Ist die stratigraphische Verbreitung der Tetrapodenfährten im Rotliegend ökologisch beeinflußt? *Z. geol. Wiss.*, 16: 877-883.

Boy J.A. & Martens Th., 1991. Zur Problematik chronostratigraphischer Korrelationen im mitteleuropäischen Rotliegend (?oberstes Karbon - Perm). *Newsl. Stratigr.*, 25: 163-192.

Boy J.A. & Schindler Th., 2000. Ökostratigraphische Bioevents im Grenzbereich Stephanium/Autunium (höchstes Karbon) des Saar-Nahe-Beckens (SW-Deutschland) und benachbarter Gebiete. *N. Jb. Geol. Paläont. Abh.*, 216: 89-152.

Breitkreuz Ch. & Kennedy A., 1999. Magmatic flare-up at the Carboniferous/Permian boundary in the NE German Basin revealed by SHRIMP zircon ages. *Tectonophysics*, 302: 307-326.

Burger K., Hess J.C. & Lippolt H.J., 1997. Tephrochronologie mit Kaolin-Kohlentonsteinen: Mittel zur Korrelation paralischer und limnischer Ablagerungen des Oberkarbons. *Geol. Jb.*, A 147: 39 pp.

Claoué-Long J.C., Jones P.J., Foster C., Roberts J. & Makinlay S., 1995. Calibration of late Palaeozoic time. *XIII Intern. Congr. of Carboniferous-Permian, Krakow*, Abstract: p. 24.

Doubinger J., 1956. Contribution à l'étude des flores Autuno-Stephaniennes. *Mém. Soc. Géol. France*, 35: 1-180.

Franke W., 1992. Phanerozoic structures and events in central Europe. In: Blundell D., Freeman T. & Mueller S. (eds): *A continent revealed. The European Geotraverse*. Cambridge University Press: 164-180.

Germer R. & Engel H., 1989. Beiträge zur Biostratigraphie des Saarkarbons. *Courier Forschungs-Institut Senckenberg*, 109: 131-136.

Hofmeister W. & Von Platen H., 1988. Fluid-Interaktionen in basaltisch-andesitischen Gesteinen des Saar-Nahe-Gebietes nach Assimilation von granitisch-rhyolitischem Material. *Fortschr. Mineral.*, 66, Beiheft 1: 66.

Kerp H., 1996. Post-Variscan late Palaeozoic Northern Hemisphere gymnosperms: the onset to the Mesozoic. *Rev. Palaeobot. Palynol.*, 90: 263-285.

Königer S., 1999. Distal ash tuffs in the lowermost Permian of the Saar-Nahe Basin (SW-Germany): distribution, sedimentology, volcanology, petrography, geochemistry, and zircon ages. *Diss.* Univ. Würzburg: 269 pp.

Korsch R.J. & Schäfer A., 1991. Interpretation of DEKORP deep seismic reflection profiles 1C and 9N across the Variscan Saar-Nahe Basin, southwestern Germany. *Tectonophysics*, 191: 127-146.

Korsch R.J. & Schäfer A., 1995. The Permo-Carboniferous Saar-Nahe Basin, south-west Germany and north-east France: basin formation and deformation in a strike-slip regime. *Geol. Rdsch.*, 84: 293-318.

Lippolt H.J. & Hess J.C., 1983. Isotopic evidence for the stratigraphic position of the Saar-Nahe Rotliegend volcanism I. $^{40}Ar/^{40}K$ and $^{40}Ar/^{39}Ar$ investigations. *N. Jb. Geol. Paläont. Mh.*, 12 (1983): 713 – 730.

Lippolt H.J. & Hess J.C., 1989. Isotopic evidence for the stratigraphic position of the Saar-Nahe Rotliegend volcanism III. Synthesis of results and geological implications. *N. Jb. Geol. Paläont. Mh.*, 1989: 553-559.

McCann T., 1999. The tectono-sedimentary evolution of the northern margin of the Carboniferous foreland basin of NE Germany. *Tectonophysics*, 313: 119-144.

Menning M., 1995 a. A numerical time scale for the Permian and Triassic Periods: An integrated time analysis. In: Scholle P.A., Peryt T.M. & Ulmer-Scholle D.S. (eds), *The Permian of Northern Pangea*. Springer, vol. 1: 77-97.

Menning M., 1995 b. Carboniferous and Permian time scale for Central Europe and the timing of the magmatic activity. In: *11th Meeting on Geodynamics of the European Variscides & 2nd Symposium on Permocarboniferous Igneous Rocks*. Geo-ForschungsZentrum Potsdam, October 27th - 29th, 1995 Terra

Nostra, 95 (7) (Alfred-Wegener-Stiftung) Bonn: 97-100.

MÜLLER S. & HOPPE A., 1996. Palynologische Untersuchungen an Unterrotliegend-Seesedimenten nördlich des Donnersberges (Bohrung Oberhausen 1, Saar-Nahe-Becken). *Mainzer geowiss. Mitt.*, 25: 121-143.

ONCKEN O., 1997. Transformation of a magmatic arc and an orogenic root during oblique collision and its consequences for the evolution of the European Variscides (Mid-German Crystalline Rise). *Geol. Rdsch.*, 86: 2-20.

PLEIN E., 1990. The Southern Permian basin and its paleogeography. In: Heling D., Rothe P., Förstner U. & Stoffers P. (eds): *Sediments and environmental geochemistry. Selected aspects and case histories*. Springer: 124-133.

PLEIN E. mit Beiträgen von VAN ADRICHEM BOOGAERT A., BACHMANN G.H., BENEK R., DÖRING H., ELLENBERG J., GAITZSCH B., GAST R., GEBHARDT U., GELUK M., HELMUTH H.J., HOFFMANN N., HOTH K., HUEBSCHER H.D., KLEDITZSCH O., KORICH D., KRAMER W., LÜTZNER H., MARX J., MENNING M., PASTERNAK M., PLEIN E., SCHNEIDER J., SCHRETZMAYR S. & SÜSSMUTH S., 1995. Norddeutsches Rotliegendbecken. Rotliegend-Monographie Teil II. *Courier Forschungsinstitut Senckenberg*, 183: 1-193.

ROBERTS J., CLAOUÉ-LONG J., JONES P.J. & FOSTER C.B., 1995. SHRIMP zircon age control of Gondwana sequences in Late Carboniferous and Early Permian Australia. In: Dunay R.E. & Hailwood E.A. (eds), *Non-biostratigraphical methods of dating and correlation*. Geol. Soc. Spec. Publ., 89: 145-174.

SCHÄFER A., 1986. Die Sedimente des Oberkarbons und Unterrotliegenden im Saar-Nahe-Becken. *Mainzer geowiss. Mitt.*, 15: 239-365.

SCHÄFER A., 1989. Variscan molasse in the Saar-Nahe Basin (W-Germany), Upper Carboniferous and Lower Permian. *Geol. Rdsch.*, 78: 499-524.

SCHÄFER A. & KORSCH R.J., 1998. Formation and fill of the Saar-Nahe Basin (Permo-Carboniferous, Germany). *Z. dtsch. geol. Ges.*, 149: 233-269.

SCHÄFER A. & STAMM R., 1989. Lakustrine Sedimente im Permokarbon des Saar-Nahe-Beckens. *Z. dtsch. geol. Ges.*, 140: 259-276.

SCHALTEGGER U., 1997. The age of an Upper Carboniferous / Lower Permian sedimentary basin and its hinterland as constrained by U-Pb dating of volcanic and detrital zircons (Northern Switzerland). *Schweiz. mineral. petrogr. Mitt.*, 77: 101-111.

SCHWAB K., 1981. Differentiation trends in Lower Permian effusive igneous rocks from the south-eastern part of the Saar-Nahe-Basin (F.R.G.).- In: Depowski S., (ed.), *Intern. Symp. Central European Permian. Jablonna, 27-29 April 1978*, Warschau: 180-200.

SCHWAB K., 1987. Compression and right-lateral strike-slip movement at the Southern Hunsrück Borderfault (Southwest Germany). *Tectonophysics*, 137: 115-126.

SECKENDORF V. VON & CHAKRABORTY S., 1993. Zonierung magnetogener Granate in Rotliegend-Vulkaniten des Saar-Nahe-Beckens: Hinweise auf die Zeitdauer des Vulkanismus. *Beihefte Europ. J. Mineral.*, 5: 274.

STOLLHOFEN H., 1994. Vulkaniklastika und Siliziklastika des basalen Oberrotliegend im Saar-Nahe-Becken (SW-Deutschland): Terminologie und Ablagerungsprozess. *Mainzer geowiss. Mitt.*, 23: 95-138.

STOLLHOFEN H. & STANISTREET I.G., 1994. Interaction between bimodal volcanism, fluvial sedimentation and basin development in the Permo-Carboniferous Saar-Nahe-Basin (south-west Germany). *Basin Research*, 6: 245-267.

WAGNER R.H. & WINKLER PRINS C.F., 1994. General overview of Carboniferous stratigraphy. *Ann. Soc.géol. de Belgique*, 116: 163-174.

WAGNER R.H. & WINKLER PRINS C.F., 1997. Carboniferous chronostratigraphy: Quo vadis? *Proc. XIII Intern. Congr. of Carboniferous - Permian*, Krakow: 187-196.

WARDLAW B.R., 2000. Notes from the SPS Chair. *Permophiles*, 36: 1.

ZIEGLER P.A., 1990. *Geological atlas of Western and Central Europe*. Shell Intern. Petroleum Maatschappij B.V., 2nd ed., Amsterdam: 239 pp.

VARIATION AND PRESERVATION OF *ICHNIOTHERIUM* IN THE TAMBACH SANDSTONE (ROTLIEGEND, THURINGIA)

SEBASTIAN VOIGT [1]

Keywords – tetrapod footprints; *Ichniotherium*; Rotliegend; Thuringia; trackway preservation; ichnotaxonomy.

Abstract – This contribution focuses on the variation of the main trackway characters of *Ichniotherium cottae* Pohlig, 1889 from the Tambach Sandstone. The investigation is based on the detailed description of 22 trackways with nearly 330 tracks of manus and pes, altogether.
As a result, it can be shown that there is strict and direct control of the trackway characters by substrate and gait. Knowledge of the inter-relationships of imprint morphology, trackway pattern, and its controlling factors is of great importance for ichnotaxonomy, and gives new insight into the ecology and environment of the trackmakers.

Parole chiave – impronte di tetrapodi; *Ichniotherium*; Rotliegende; Turingia; conservazione delle piste, icnotassonomia.

Riassunto – Questo contributo s'incentra sulla variazione dei principali caratteri delle piste di *Ichniotherium cottae* provenienti dall'Arenaria di Tambach. La ricerca è basata sulla dettagliata descrizione di 22 piste con quasi 330 impronte di *manus* e *pes*, complessivamente. Ne consegue che si può porre in evidenza che vi è uno stretto e diretto controllo dei caratteri delle piste a seconda della composizione del substrato e dell'andatura degli animali. La conoscenza dei rapporti tra morfologia delle impronte, disposizione delle piste, e loro fattori di controllo è di grande importanza per l'icnotassonomia, e offre nuove prospettive di studio sull'ecologia e sull'ambiente dei *trackmakers*.

INTRODUCTION

For more than 110 years the Tambach Sandstone has been well known as a source of excellently preserved tetrapod tracks. Pabst (1908) gave the first extensive description of tetrapod trackways from the Tambach Sandstone. All trackway slabs come from sandstone quarries in the Bromacker locality, 1.5 km north of Tambach-Dietharz village in the Thuringian Forest of central Germany (Fig. 1).

The Tambach Sandstone represents the middle unit of the Tambach Formation, which is stratigraphically positioned at the base of the Upper Rotliegend, Lower Permian. In addition to the tracks, the recently discovered tetrapod fauna at the Bromacker locality indicates a biostratigraphical position near the base of the Lower Permian, comparable to the Wolfcampian Series of North America (Sumida *et al.*, 1996).

The Bromacker tetrapod tracks are preserved as casts of original imprints at the base of bedded, fine- to medium-grained, reddish-brown sandstones. The sandstones are underlain by thin mudstones, which represent the original surface of trackway formation. The sandstone-mudstone interbedding of the trackway horizon is derived from repeated sheet floods followed by standing-water sedimentation in an intramontane undrained basin (Eberth *et al.*, 2000). The facies of the locality indicates a position near the basin centre (Fig. 1).

ANALYSIS AND MATERIAL

More than 200 trackway slabs have been discovered at the Bromacker locality so far. The biggest slab is 8 metres long. In spite of the abundance of trackway slabs, only five ichnospecies could be differentiated (Haubold, 1998). Approximately 70% of all trackways from the Tambach Sandstone are pentadactyl imprints of the ichnospecies *Ichniotherium cottae* Pohlig, 1885 (Fig. 2). This abundance of material and the obviously varying states of preservation were of prime importance to the analysis of the variability of the ichnospecies. The investigation focused on analysis of the existing interrelationships of the main trackway characters, and the features of the substrate upon which the trackmakers walked. Knowledge of the interrelationships between imprint morphology, trackway pattern and the substrate characteristics is essential in

[1] Martin-Luther University, Institute of Geol. Sc., Domstr. 5 D-06108, Halle, Germany.

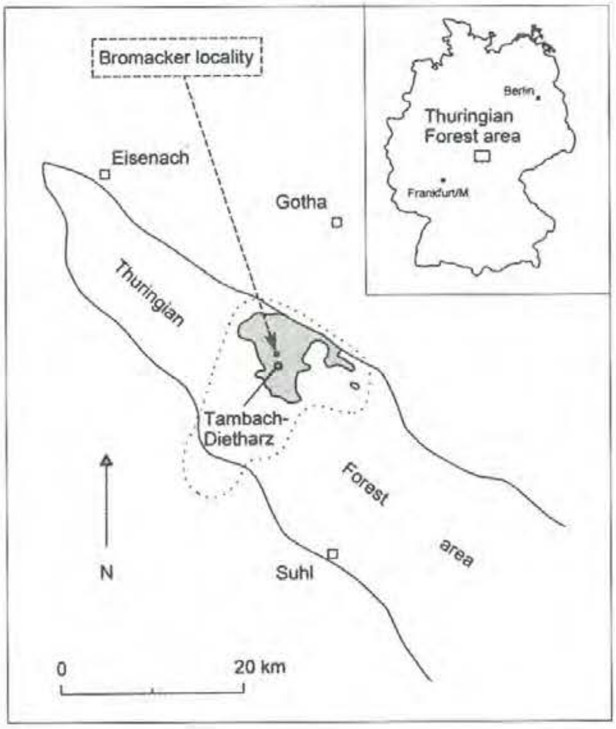


Fig. 1 – The outline of the Thuringian Forest area in central Germany and the Bromacker locality. The extent of the Tambach Formation is shown by the shaded area. The dotted line represents the hypothetical limit of the Tambach Basin (from Haubold, 1985).

Fig. 2 – I. cottae (MNG-1351): The first-discovered trackway slab from the Tambach Sandstone. The trackway is about 1.5 m long and one of the most representative examples of the ichnospecies from the locality.

avoiding the creation of new, unnecessary ichnotaxa. As shown below, there are new indications of the ecological situation of the trackmaker from knowledge of its locomotory behaviour. All results of this work are based on the investigation of 22 longer trackways of *I. cottae* with about 330 single imprints in total. About 2500 measurements have been recorded for a broad-based quantitative analysis (Voigt, 1999).

The vast majority of the investigated trackway material is stored at the Museum der Natur Gotha (MNG). Some other important trackway slabs are stored at the Museum für Naturkunde Berlin (MB).

IMPRINT MORPHOLOGY

Imprint morphology represents the most important characters of a trackway. *I. cottae* from the Tambach Sandstone shows two fundamental differences in imprint morphology. The first relates to the depth and completeness of the imprints. The other relates to certain dimensions of the imprint, especially the relative position and length of the digit V.

The variation in depth and completeness of the imprints is very broad. There are all stages of transition between deep, plantigrade imprints and shallow, unguligrade-like imprints (Fig. 3). The depth and completeness of the imprints are firstly a function of the porewater content of the substrate. This relationship is very close and could be identified on a 2.3 m long trackway which was discovered in summer 1995. The extent and orientation of mudcracks and raindrop impressions on the surface of this trackway slab allows the reconstruction of small-scale palaeotopography in the area of the slab. The extent and orientation of the sedimentary surface structures indicate that the trackmaker went from firm ground on to the soft sediment within a former pool or channel. Depth, completeness and the sharpness of the imprints change systematically in the direction of locomotion. Thanks to the preservation of this special trackway, it is possible to judge the relative consistency of the substrate of all investigated tracks at the time of trackway formation. As a result, the variation of depth, completeness and sharpness of the imprints is first of all controlled by the parameters of the substrate.

As mentioned above, there is variation in the proportions of imprints, too. Firstly, the pes imprints show different types of preservation with regard to the relative position and length of the digit V (Fig. 4). The remarkable lateral shift of the digit V as seen in the photograph on the right (Fig. 4) could be observed only on five of all 22 investigated trackways. An explanation of this kind of variation in imprint morphology is provided by the locomotory behaviour of the trackmakers. Figure 5 shows the locomotory efficiency of all 22 investigated trackways in order from low

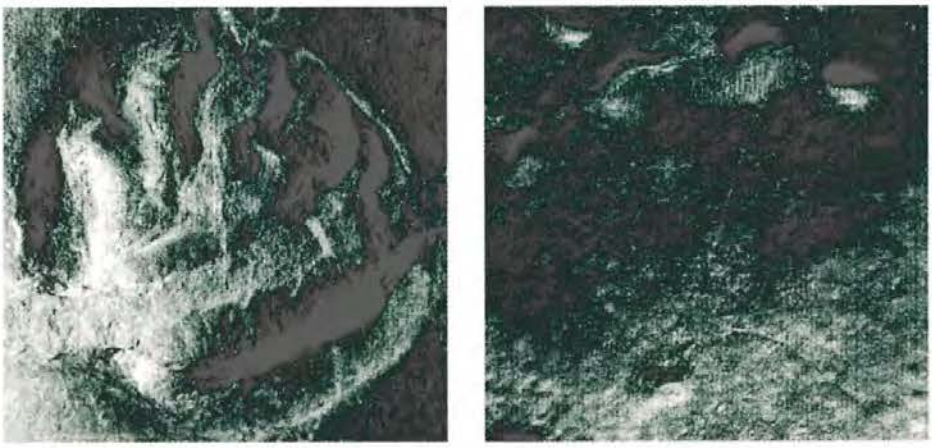


Fig. 3 – Left pes imprints of *I. cottae* to demonstrate the wide differences of preservation in the depth and completeness of the imprints. Illumination on both photographs is from the left. Scale: 5 cm. Left: MNG-10072, right: MNG-1840.

Fig. 4 – Left pes imprints of *I. cottae* to demonstrate the variability of imprint morphology with regard to the relative position and length of the digit V. The Roman numeral 'V' refers to the digit V. Illumination on both photographs is from the left. Scale: 5 cm. Left: MNG-1351, right: MNG-1352.

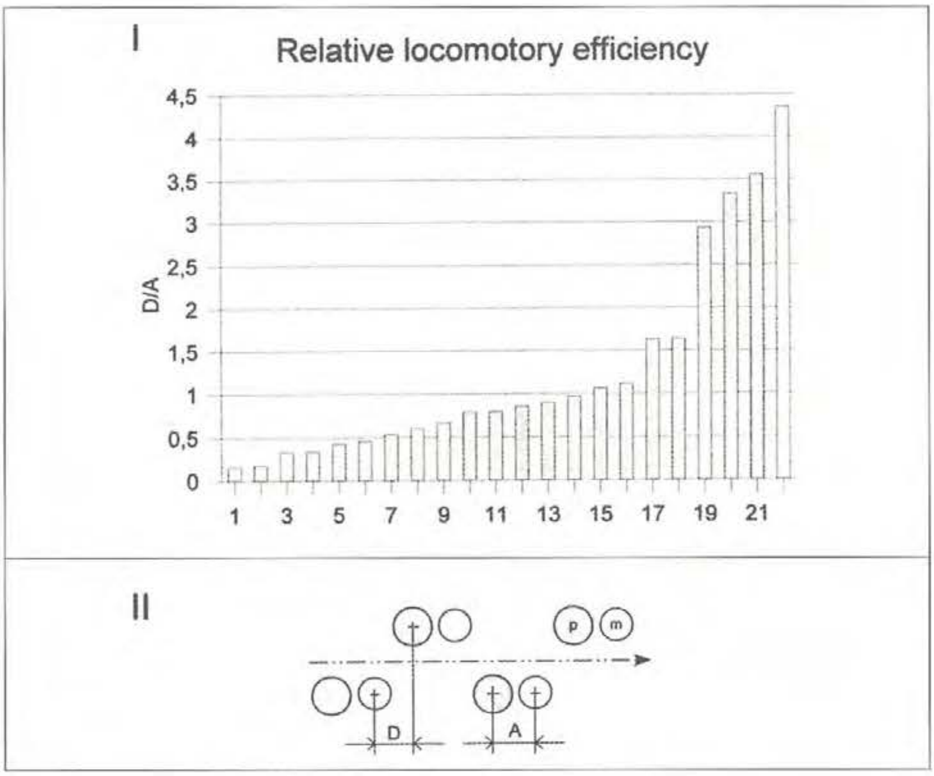


Fig. 5 – I. Graphical representation of the relative locomotory efficiency of all investigated trackways. The relative efficiency of the trackmaker's gait can be calculated from the trackway pattern. The relative locomotory efficiency is given by the ratio D/A. II. The meaning of the measurements D and A is graphically expressed in the lower part of the figure. D refers to the distance between the manus and pes imprint of two successive sets. The measurement A refers to the distance between manus and pes imprint within one set. Abbreviations: p, imprint of the pes; m, imprint of the manus.

to high. The five trackways characterized by a very lateral backward shift of the digit V in the pes imprints all lie at the higher end of the spectrum (numbers 18-22, Fig. 5). Therefore, I speculate that the trackmakers of *I. cottae* were able to change their gait from a more plantigrade to a partially digitigrade gait in order to achieve higher speed and an increased efficiency of locomotion.

TRACKWAY PATTERN AND MEASUREMENT DATA

The second important trackway character, the trackway pattern, is also variable. In the case of *I. cottae*, two extremes in trackway pattern can be observed (Fig. 6). In the first (type 1, Fig. 6), the imprints of manus and pes on the left and right side of the trackway lie nearly opposite one another. In the second (type 2, Fig. 6), the sets of manus and pes of both sides are clearly arranged alternately. All stages of the transition, from an opposite to an alternating arrangement of the trackway pattern, are present. The shift in the trackway pattern coincides with a shift in the trackway measurement data. The trackways of type 1 show a low pace angulation, a large distance between manus and pes, and a low stride-body length ratio. In addition, the type 1 trackways are more irregular. In contrast, the trackways with a clearly alternate pattern similar to type 2 are characterized by a high pace angulation, a small distance between manus and pes, and a high stride-body length ratio. Trackways of type 2 exhibit a more regular trackway pattern.

Moreover, there is a specific relationship between the parameters of the substrate and the trackway pattern type. Trackways with deep, plantigrade, completely preserved imprints show only the type 1 trackway pattern. In contrast, the trackway patterns of the second type could be observed only in trackways with shallow, digitigrade, commonly incomplete imprints. Thus, the gait of the trackmakers was limited by the characteristics of the substrate. The trackmaker achieved a very low speed with a careful and shaky gait on soft sediments, and a high-speed, more agile gait on firmer ground. It can be concluded that the trackmakers of *I. cottae* avoided walking on wet substrates. Most probably, the trackmakers normally lived on firmer substrates.

CONCLUSIONS

The variation analysis of *I. cottae* allows the differentiation between an input of substrate and an input of gait on the main trackway characters. As a result, the general relationship between imprint morphology, trackway pattern, and certain parameters of the substrate can be identified. All observed types of different preservation of *I. cottae* can be explained by the influence of extramorphological parameters, namely the substrate and gait.

Therefore, it is evident that the various preservation types were formed by animals with identical anatomical structures of the hand and foot. Consequently, the tracks of these animals should be assigned only one ichnotaxonomic name.

Moreover, the analysis yields indications to the locomotory behaviour and ecological situation of the trackmakers. The results of the investigation indicate that the trackmakers were fully terrestrial animals that walked preferentially upon firmer, drying, mudcracking surfaces. Consequently, the usual habitat of the trackmakers was not represented by the muddy, wet substrates of the central Tambach Basin plain. The trackmakers of *I. cottae* probably lived in flat upland areas around and away from the small pools and channels of the basin plain, and did not invade the basin plain until an advanced stage of dessication.

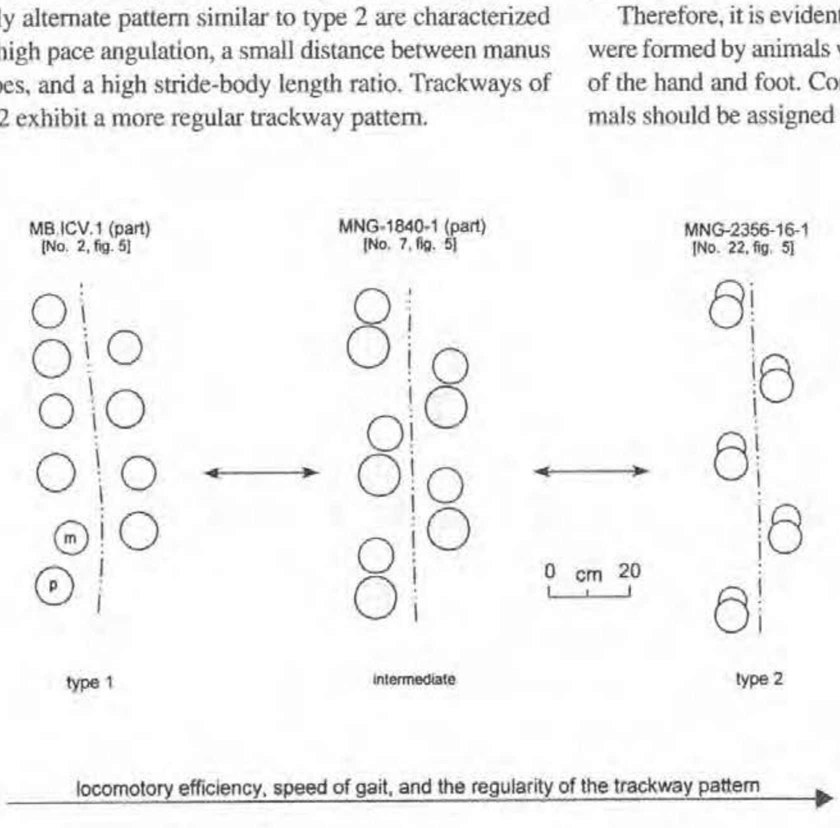


Fig. 6 – The range of the trackway pattern of I. cottae in the Tambach Sandstone represented by three characteristic trackways for each stage. The locomotory efficiency, the speed of gait and the regularity of the trackway pattern increase from left to right. For abbreviations see Fig. 5.

REFERENCES

EBERTH D. A., BERMAN D. S., SUMIDA S. S. & HOPF H., 2000. Lower Permian terrestrial paleoenvironments and vertebrate paleoecology of the Tambach Basin (Thuringia, Central Germany): The Upland Holy Grail. *Palaios*, Waterville, 15(4): 293-313.

HAUBOLD H., 1985. Stratigraphische Grundlagen des Stefan C und Rotliegenden im Thüringer Wald. *Schr. geol. Wiss.*, Berlin, 23: 1-110.

HAUBOLD H., 1998. The Early Permian tetrapod ichnofauna of Tambach, the changing concepts in ichnotaxonomy. *Hallesches Jb. Geowiss.*, B 20: 1-16.

PABST W., 1908. Die Tierfährten in dem Rotliegenden Deutschlands. *Nova Acta Leopoldina*, Halle, 89: 315-480.

POHLIG H., 1885. Saurierfährten in dem Unteren Rotliegenden von Friedrichroda. *Verh. Preuss. Rheinl. u. Westf., Sitzber.*, Bonn, 42: 285-286.

SUMIDA S. S., BERMAN, D.S. & MARTENS T., 1996. Biostratigraphic correlations between the Lower Permian of North America and Central Europe using the first record of an assemblage of terrestrial tetrapods from Germany. *PaleoBios*, Berkeley, 17: 1-12.

VOIGT S., 1999. Analyse zur Variabilität der Tetrapodenfährte *Ichniotherium cottae* aus dem Tambacher Sandstein (Rotliegend, Unterperm, Thüringen). *Unpubl. diploma work*, Univ. Halle: 87 pp.

«NATURA BRESCIANA» Ann. Mus. Civ. Sc. Nat., Brescia, MONOGRAFIA N. 25, 2001: 227-233

PERMIAN EVOLUTION OF THE WESTERN CARPATHIANS, BASED ON THE ANALYSIS OF SEDIMENTARY SEQUENCES

ANNA VOZÁROVÁ[1]

Key words – Permian sedimentary evolution; crystalline basement; collision zones.

Abstract – The Permian sequences of the Western Carpathians are represented by continental, mainly coarse-grained volcanosedimentary formations, the origins of which were ascribed to collision-related transpressional/extensional and extensional sedimentary basins. They originated in time and space as a consequence of the collisional events of the Hercynian orogeny. The result was unevenly consolidated continental crust, which, after a short period of stability, was incorporated again into the Alpine orogenic cycle. The three crustal type fragments of crystalline basement in the Alpine Western Carpathian units were distinguished as: the Central Western Carpathian Crystalline Zone (CWCZ), the Northern Gemeric Zone (NGZ) and the Inner Western Carpathian Crystalline Zone (IWCZ). The main differences between the zones are in the chronological and spatial development of the Late Paleozoic sedimentary basins.
The relicts of two Hercynian zones of distinctly different geodynamic aspects are preserved in the Alpine structure of the Western Carpathians: the internal zone, with termination of collision during the Bretonian-Sudetian events; and the external, with termination of collision during the Asturian phase.

Parole chiave – evoluzione sedimentaria permiana; basamento cristallino; zone collisionali.

Riassunto – Le successioni permiane dei Carpazi occidentali sono essenzialmente rappresentate da formazioni vulcaniche e sedimentarie continentali, la cui origine fu riferita a bacini transpressivi/estensionali connessi a collisione ed a bacini estensionali. Esse si generarono nel tempo e nello spazio a seguito degli eventi collisionali dell'orogenesi ercinica. Il risultato di questi eventi fu la formazione di una crosta continentale non uniformemente consolidata, che, dopo un breve periodo di stabilità, fu di nuovo inclusa nel ciclo orogenetico alpino. Tre frammenti di tipo crostale di basamento cristallino nelle unità dei Carpazi occidentali alpini furono contraddistinti: la Zona Cristallina dei Carpazi centro-occidentali (CWCZ), la Zona Gemmerica settentrionale (NGZ) e la Zona Cristallina dei Carpazi occidentali interni (IWCZ). La principale differenza tra queste zone sta nello sviluppo cronologico e spaziale dei bacini sedimentari tardo-paleozoici.
I resti di due zone erciniche con aspetti geodinamici distintamente diversi sono preservati nella struttura alpina dei Carpazi occidentali: la zona interna, in cui la collisione si concluse durante gli eventi tettonici Bretone-Sudetico, e la zona esterna, in cui la collisione si estinse in concomitanza della fase Asturica.

INTRODUCTION

The kinematic evolution of the Western Carpathian orogenic system occurred during both Variscan and Alpine times. Fragments of newly-formed Epi-Variscan crust were incorporated in the Paleo-Alpine Western Carpathian units as evidenced by repeating subduction/collision and transform fault processes. Like most other collisional belts, the Western Carpathians have been divided into external and internal structural zones. The main difference between the traditionally distinguished zones is in the age of the main Alpine events as well as in the intensity of their deformational and metamorphic effects: (1) the internal zone – the HP/LT Late Jurassic subduction event and Lower/Middle Cretaceous collision, followed by nappe stacking; (2) the external zone – from the Upper Cretaceous/Lower Paleocene to the Oligocene/Lower Miocene subduction/accretion and collisional events. The fragments of the Late Paleozoic sedimentary basin fill are preserved only within the internal zone, as part of the principal Alpine crustal-scale superunits (Fig.1). Relicts of the Upper Carboniferous sedimentary sequences are proven by lithofacial and biofacial data in a relatively wide range of sedimentary environments, from shallow-water to paralic and continental. The Lower Permian sediments confirm only a continental environment as a whole. The Upper Permian facial associations confirm more variability, from continental to sabkha-lagoonal evaporitic formations, as a consequence of the start of a new sedimentary cycle, better developed during the Mesozoic.

[1] Department of Mineralogy and Petrology, Fac. of Nat. Sci., Comenius University, Mlynská dolina pav. G, 842 15 Bratislava, Slovak Republic.

CHARACTERISTICS OF THE BASEMENT

In the Western Carpathians different types of Variscan basement were overstepped by the Upper Carboniferous/Permian sedimentary sequences. Regardless of the age of the metamorphic overprint, the Alpine-Western Carpathian basement can be subdivided into three zones:

1. *The Central Western Carpathian (CWCZ) crystalline zone* composed mainly of metamorphic rocks and huge masses of pre-Mesozoic granitoids. Fragments of pre-Hercynian metamorphic crust are probably also included in this zone. Several pre-Alpine terranes were identified in the CWC-Alpine nappe units (*the Tatra Plate*: the relicts are preserved within the Alpine Tatric, Northern Veporic, Southern Veporic and Zemplinic Units; these substratum fragments were formerly described as the Tatra Terrane, Kohút Terrane and Suspected Ipoltica Terrane – within the Hronic Unit; Vozárová & Vozár, 1996). Nearly all underwent the Hercynian metamorphism during the Early Carboniferous, postdating locally Silurian/Devonian and/or older metamorphic events. The magmatic activity took place in two stages as indicated by Rb-Sr and U-Pb dating, which gave 360-340 Ma and 320-300 Ma; (Cambel & Král, 1989; Cambel *et al.*, 1990). The age of rare post-orogenic A-magmatites corresponds to the Permian (Rb/Sr: 280-250 Ma; Cambel *et al.*, 1989). Geochemical data indicate the operation of subduction system and then collisional tectonics.

2. *The Northern Gemeric Zone (NGZ)*, with relicts of the Visean-Namurian flysch and thrust wedges of pre-Carboniferous oceanic crust. This zone represents a relict of a Hercynian collision suture. Two undated Hercynian terranes, which differ in tectono-metamorphic development (amphibolite vs. greenschist facies) and probably also in the age of protolith, belong to this domain. Their gradual amalgamation took place during the Early Carboniferous because the Uppermost Visean/Serpukhovian, shallow-water carbonate-clastic development was, after a stratigraphic hiatus, unconformably overstepped by the Moscovian marine "molasse". This marine "molasse" unconformably overlies part of the Lower Carboniferous flysch sequence (eastern part of the NGZ), to fix up the Late Variscan thrust sheet structure.

The higher-grade crystalline complex (the Klátov Terrane) consists mainly of amphibolites, subordinate gneisses and metaultramafic rocks. This complex is considered as a partly incomplete ophiolite suite (Hovorka *et al.*, 1984; Spisiak *et al.*, 1985). Findings of regressively overprinted eclogitic rocks lead to the assumption of a polyphase metamorphic P-T path, with high-pressure conditions dur-

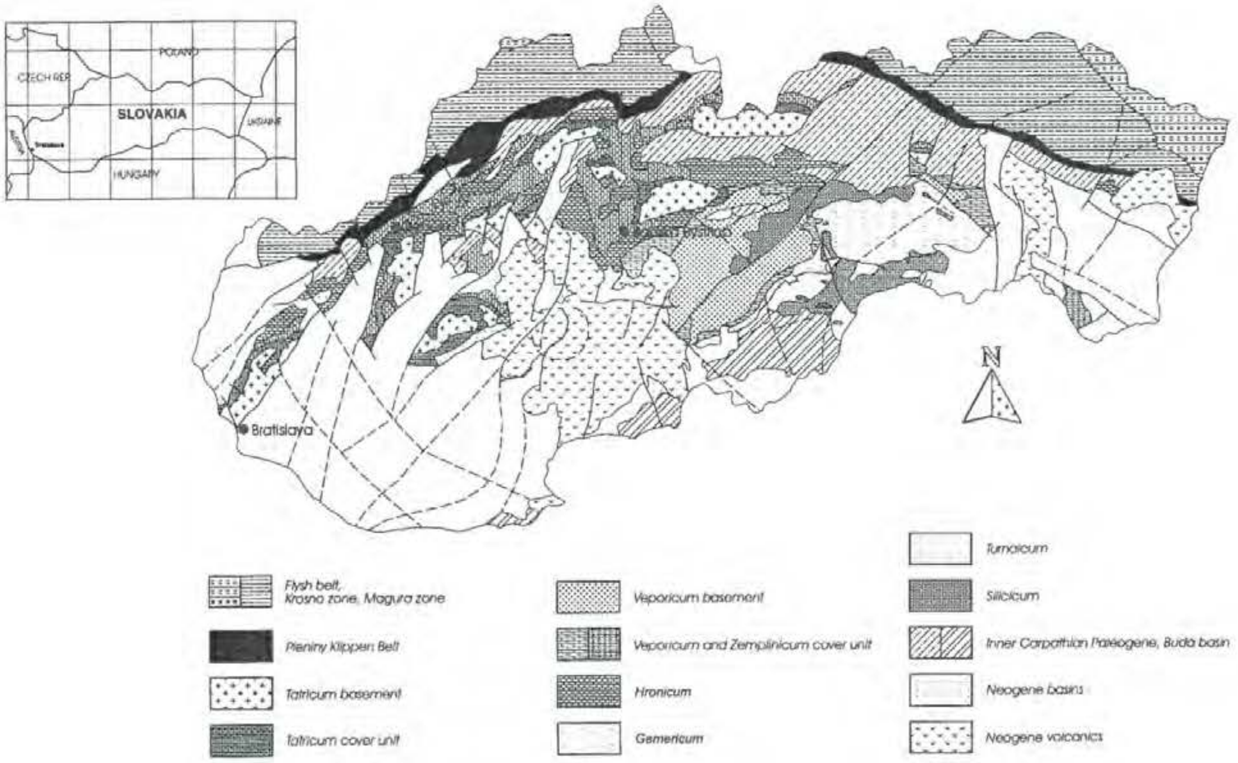


Fig. 1 – Tectonic sketch of the Slovak part of the Western Carpathians.

ing the climax of metamorphism. The low-grade crystalline complex (the Rakovec Terrane) is composed of tholeiitic metabasalts and matavolcaniclastics, associated with smaller amounts of sandy-shaly metasediments and small bodies of gabbro-diorites and metakeratophyres. The magmatic rocks show geochemical characteristics near to E-MORB/OIT basalts (Ivan, 1994).

3. *The Inner Western Carpathian crystalline zone (IWCZ)*, which is subdivided into two subzones – *the Southern Gemeric Subzone (SGS)* and *the Szendrö – Bükk Subzone (SzBS)*. The dominant part of the Southern Gemeric Subzone (corresponding to the *Gelnica Plate*) is composed of the Lower Paleozoic volcanigenic flysch formation and of its Permian-Triassic cover. An enormous mass of volcanogenic flysch comprises distinct turbidity current and other mass-gravity flow sedimentation features. Besides redeposited acid to intermediate volcaniclastic material, derived from the synsedimentary continental magmatic arc, detritus from the subduction complex and fragments of oceanic crust are also present. Regional metamorphism of the SGS basement did not exceed the low-pressure greenschist facies. The SGS Lower Paleozoic flysch sequence was interpreted as a relict of the fore-arc basin related to an active continental margin (Vozárová, 1993).

Within the Szendrö-Bükk Subzone the pre-Carboniferous complexes are preserved only locally. They are represented mainly by the shallow-water to basinal sequences of the passive continental margin of the northern Gondwana promontory (for a precise description see Kovács & Péro, 1983; Fülöp, 1994). The most typical features of both these subzones are the Bashkirian olistostroma flysch complexes. They were reported from the Turnaic Unit in the Inner Western Carpathians (Vozárová & Vozár, 1992) as well as from the Szendrö and Bükk Mts. (Kovács, 1988, 1992). Typically, the Variscan metamorphism of the SzBS Paleozoic complexes is either slight or absent.

LATE PALEOZOIC OF THE CENTRAL WESTERN CARPATHIAN CRYSTALLINE ZONE

The Permian deposits of the CWCZ either gradually develop from the underlying Upper Westphalian-Stephanian formations or unconformably overlie the crystalline basement rocks (Fig. 2). The Lower Triassic deposits disconformably rest on both the above structural stages. The Upper Carboniferous-Permian as well as the Permian sedimentary basins were founded on continental crust. These basins probably formed cratonwards of thin-skinned thrusting, on both the footwalls and hanging walls of crustal-scale reverse faults that ruptured the continental basement. The typical result of deformation was a set of non-marine basins connected by basement uplifts and thin-skinned thrust belts (broken-foreland basins). These retro-arc foreland basins occurred behind the compressional belt, on the thickened continental crust.

The Upper Westphalian-Stephanian sedimentary basins are represented by huge wedges of siliciclastic sediments deposited in continental, fluvial or fluvio-lacustrine and swamp sedimentary environments. These formations are associated with acid to intermediate calcalkaline volcanism. The Upper Westphalian and Stephanian ages are proved by macroflora: *Calamites cistii* Brongn., *Asterophyllites trichomatosus*, *Annularia pseudostelata* Potonie, *Pecopteris cyathea* Schotheim, *Cordaites borassifolius* Sternberg, *Asterotheca miltonii* Artis, *Asterotheca arborescens* Brongn., *Cordaites palmaeformis* Goepp. and *Callipteridium gigas* Guttb. (Nemejc, 1947; Sitár in Planderová *et al.*, 1981; Sitár & Vozár, 1973). The sedimentary regime continued uninterrupted in this basin during Permian times. Distinct changes in climatic conditions took place when the warm and humid climate was replaced by dry and arid conditions.

Generally, the Permian sequences are represented by continental, mainly variegated coarse-grained alluvial fan formations of red-bed type. Integral parts of these formations are volcanic rocks and their volcaniclastics, dominated by calcalkaline rhyolites-dacites, with subordinate andesites and continental tholeiitic andesite-basalts. The Permian sediments indicate very low structural and mineralogical maturity, with provenances from uplifted and tectonically rejuvenated crystalline basement or from dissected magmatic arc (inactive in Permian times, produced by pre-Carboniferous subduction). The prevalent sediments were deposited in alluvial or fluvio-lacustrine and ephemeral lake environments, in semi-arid to arid climatic conditions as indicated by the typical sedimentary facies and absence of fauna and flora. The biostratigraphical data are based on relatively poor finds of pollen and sporomorphs. The Early Permian age is generally documented by the presence of *Potonieisporites* and *Vittatina*. The Upper Permian age is proved by the following microflora assemblage: *Calamospora nathorstii* Klaus, *Klausipollenites* div. sp., *Lueckisporites parvus* Klaus, *L. virkkiae* (Pot.) Klaus, *Monosulcites minimus* Cookson, *Striatites richteri* (Klaus) Jizba, *Limitisporites rectus* Leschik and *Jugasporites lueckuides* Klaus (Planderová, 1973; Planderová *et al.*, 1981).

LATE PALEOZOIC OF THE NORTHERN GEMERIC ZONE

The continental Permian sequences overlie the slightly deformed relicts of the Westphalian peripheral basin fill, as well as all pre-Westphalian crystalline complexes of the NGZ (Fig. 2). The mostly coarse-grained clastic sediments derived from the collisional belt are associated with bimodal andesite-basalt/rhyolite volcanism. The characteristic features are: (1) varicoloured clastic sediments of violet and violet-red; 2) a gradual fining-upwards; 3) cyclicity manifested within the framework of small cycles as well as megacycles; 4) bimodal calcalkaline volcanism. The thickness of the basal formation is extremely variable (from several tens of metres to 350 m). It is composed of pebble material indicating source rocks from the immediate basement. The immature coarse-grained sediments represent fossil mudflows, partly reworked in some places, continued by alluvial, mainly stream channel deposits. An "Autunian" age is proposed because of their position below the main volcanic horizon. The widespread upper part of the Lower Permian ("Saxonian") polyphase volcanic activity manifested the spatial and temporal relationships to the large sedimentary cycles. Sediments are characterised by a low degree of maturity and by a mixture of syngenetic volcanic and non-volcanic detritus. The fining-upwards alluvial cycles, with channel lag, pointbar and floodplain lake facies alternating with playa subenvironments at the topmost part of large cycles, are among the most striking features. The age is inferred from the isotopic analyses of sulphides from the volcanigenic horizons: $^{206}Pb/^{238}U = 263$ Ma; $^{207}Pb/^{235}U = 274$ Ma (Novotný & Rojkovič, 1981). The upper part of the Lower Permian ("Saxonian") was also proved by poor microflora.

The "Autunian-Saxonian" formations are overlain by a relatively mature sandy-conglomerate horizon, with some pebble material derived from the immediate stratigraphic underlier. This could indicate a break in the sedimentation after the "Saxonian", but there is no biostratigraphical evidence to support this assumption. Alluvial, stream-channel deposits prograde upwards to the inland sabkha and near-shore sabkha/lagoonal facies, with the anhydrite-

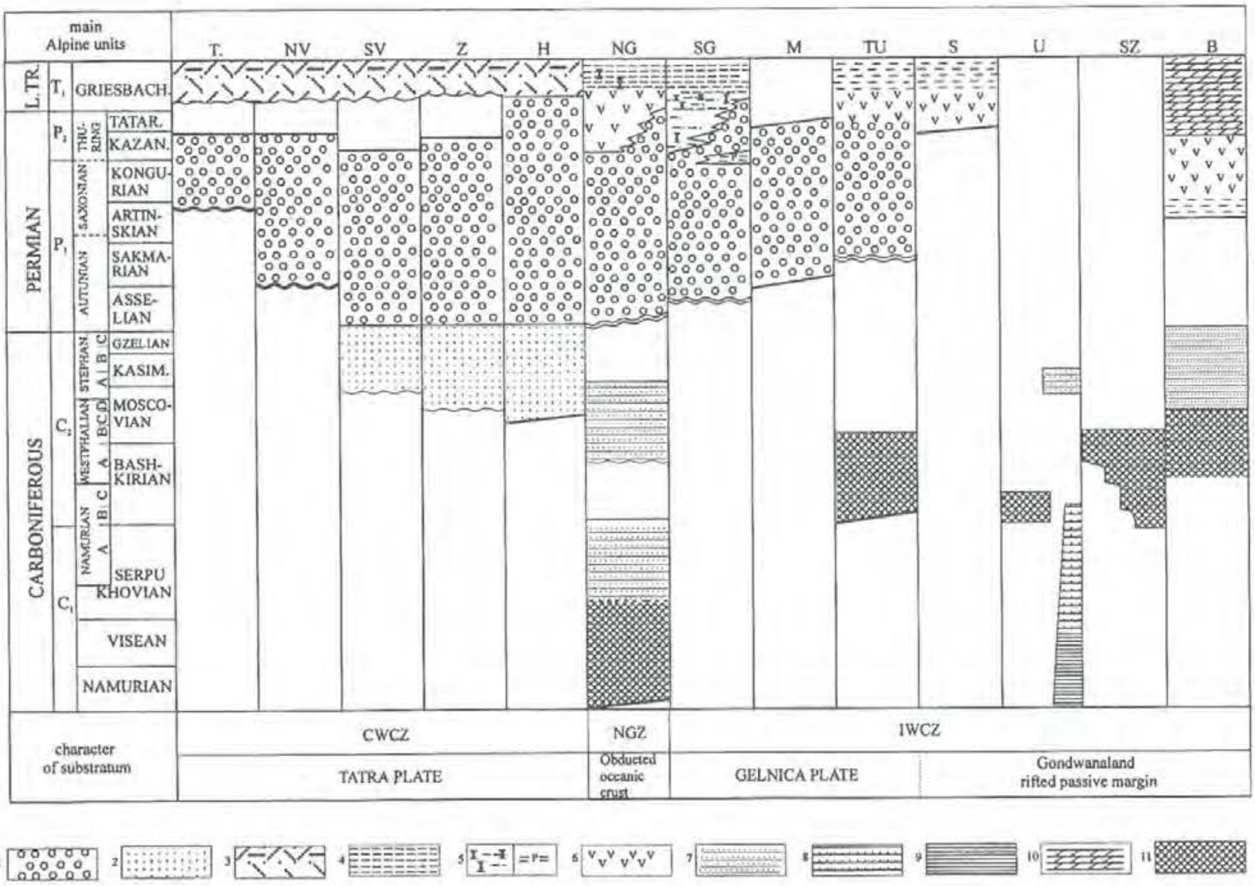


Fig. 2 – Scheme of sedimentary evolution of the Western Carpathians Carboniferous-Permian basins.

1 – continental, prevalently coarse-grained alluvial, alluvial-lacustrine sediments; 2 – continental lacustrine, fluvio-lacustrine sediments with thin coal seams in places; 3 – aeolian, braided alluvium to tidal clastic sediments of greater maturity; 4 – sabkha-lagoonal facies; 5a – lagoonal to shallow-water clastic sediments with thin intercalations of carbonates; 5b – shaley-sandy deposits with thin lenses of phosphorites; 6 – evaporites; 7 – deltaic and shallow-marine clastic deposits, with less carbonates; 8 – shaly-carbonate shelf sediments; 9 – basinal shaly-carbonate sequences; 10 – dolomites, limestones; 11 – flysch: turbidites, olistostrome sequences; disconformity: undulating line; unconformity: double undulating lines; overthrust planes: oblique line. Abbreviations of the main paleo-Alpine units: T – Tatric Unit; NV – Northern Veporic Unit; SV – Southern Veporic Unit; Z – Zemplinic Unit; H – Hronic Unit; NG – Northern Gemeric Unit; SG – Southern Gemeric Unit; M – Meliatic Unit; TU – Turnaic Unit; S – Silicic Unit; U - Uppony Mts.; SZ – Szendrö Mts.; B – Bükk Mts. Abbreviations of the substratum: CWCZ – Central Western Carpathian Crystalline Zone; NGZ – Northern Gemeric Zone; IWCZ – Inner Western Carpathian Crystalline Zone.

gypsum and salt breccia horizons. The isotopic analysis of sulphur (Vozárová, 1997) shows results similar to the data obtained from the Upper Permian to lowest Triassic. There are transitions up to the *Pseudomonotis (Claraia) clarai* (Emmr.) horizon (Griesbachian-?Nammalian).

The Permian sedimentary basin was part of the collision-related foreland basins at the suture zone. The development of this peripheral foreland basin was preceded by the consumption of oceanic crust and, during the first stage of oblique continental collision, by development of an Early Carboniferous remnant ocean basin. Later collisional shortening led to deformation and cannibalisation by uplift and erosion of the early accretionary wedges. The sedimentary infill of the marine Westphalian basin shows evidence of active thrust-faulting in the adjacent collision belt. This can be documented by "clastic wedges" of delta-fan conglomerates. Finally, the extensional faulting on the downgoing rifted continental margin resulted in widespread deposition of coarse-grained nonmarine clastics during the Permian. These clastic red-bed wedges document a large sediment supply from the collision fold-thrust belt. The continual collision during the Permian resulted in the development of a continental sedimentary basin with dominant strike-slip faulting.

LATE PALEOZOIC OF THE INNER WESTERN CARPATHIAN CRYSTALLINE ZONE

The Late Variscan, post-orogenic overstep sequences of the Southern Gemeric Subzone unconformably overlie the Lower Paleozoic crystalline basement of the IWCZ (Fig. 2). Generally, the basal parts of the Lower Permian volcanosedimentary complexes are characterised by a high content of mature mineral detritus. Conspicuous fining upwards is accompanied by a relative decrease in mineralogical maturity of sediments. The whole sequence is subdivided vertically into two large cycles, with the quartzose conglomerate horizons at the base of each and a sandstone-shale member between the two. The stream-channel and sheet-flood deposits with unimodal transport systems predominate. The upper conglomeratic horizon contains detritus from rhyolite-dacite synsedimentary volcanism.

The prograded Upper Permian horizon is a monotonous complex of cyclically alternating sandstones, siltstones and shales. Lenses of carbonatic sandstones and dolomitic limestones with intercalations of shales occur only in its upper part. Exceptionally, thin lenses of phosphatic sandstones and sediments with extremely high contents of albite (albitolites) occur. This sedimentary environment is interpreted as alluvial-lacustrine and lacustrine, with highly alkaline lakes in some places, prograding into the near-shore and lagoonal-sabkha facies at the top. The sediments represent the relicts of sedimentary basin infill, which first developed in a transpressional tectonic regime and prograded to the initial stage of post-Variscan rifting.

The extremely mineralogically mature detritus of the Southern Gemeric Permian formations, allows us to correlate them with other early-Alpine riftogenic tectofacies of the Alpine-Mediterranean domain.

The Early Permian age of the lowermost part of the basal formation is assumed on the basis of microflora, with predominant species of the genera *Potonieisporites, Striatodisaccites, Vittatina sp.* (Planderová, 1980). The Upper Permian date for the uppermost part of the formation was proven on the basis of a cone slice and twig of *Pseudovoltzia liebeana* (Geinitz) Florin, and leaves of the genus *Sphenozamites*, as well as remains of bivalve tests of the genus *Carbonicola* McCoy, 1855 (Šuf, 1963).

The continental red beds unconformably overlying the Bashkirian flysch in the Turnaic Unit are most probably, Upper Permian in age. Upper Permian sediments of the innermost, Szendrö-Bükk Subzone, are represented by the evaporite formation (Silicic Unit). They were spatially connected with a Permian epiplatform, characterised by shallow-marine facies of South Alpine-Dinaric type. The Serpukhovian-Bashkirian turbidite deposits and the Moscovian shallow-marine sedimentary sequences are characteristics of the Szendrö-Bükk Subzone.

DISCUSSION

The typical distribution of the Carboniferous-Permian sedimentary basins and, the lithofacial character of their infill, document the southern polarity of the Hercynian orogeny of the Western Carpathians, responsible for the opposite vergency compared with the Alpine branch (Table 1). Basins originated gradually as a consequence of different stages of collisional events. The beginning of collisional events was connected with the "Bretonian" movements and development of the Lower Carboniferous flysch remnant basin sequences preserved within the Northern Gemeric Unit. Collision continued with the closure of the Lower Carboniferous flysch basin and caused a hiatus during Namurian B-C. The "Sudetian" movements gave rise to the Moscovian marine peripheral basin, whose basal sequences fixed the Lower Carboniferous flysch and both the pre-Carboniferous complexes (fragments of crust with oceanic/supraoceanic affinities). Closure of this basin was connected with Asturian events and is reflected by a hiatus during the Stephanian. The North Gemeric Lower and Upper Permian continental red beds originated under transpressional and extensional tectonic regimes.

The variously evolved basins were established on formerly overthrust continental lithosphere, whose fragments

VARISCAN orogen	INTERNAL						EXTERNAL						
Relics in paleo-Alpine units	T	NV	SV	Z	H	NG	SG	M	TU	S	U	SZ	B
Character of substratum of Late Paleozoic basins	continental crust					thrust wedges of oceanic crust	consuming plate-boundary fore-arc basin filling		disrupted continental crust, attenuated in places				
Tectono-thermal development	Devonian–Carboniferous tectono-thermal activity with maximum deformation, magmatism and metamorphism						weak or no magmatism; metamorphism more advanced than anchimetamorphism/low-temperature greenschist facies						
Main collisional events	Bretonian–Sudetian						Asturian						
Depositional system	continental: Permian Upper Carboniferous marine: shallow-water Moscovian and Serpuchovian deep-water post-Bretonian flysch						continental to sabkha-lagoonal: Permian sabkha to shallow-water: Permian marine: shallow-water Stephanian deep-water post-Sudetian flysch						
Provenance	continental block prov. cut magmatic arc prov. orogen. provenance						continental block provenance mixed with recycled orogen provenance						

Table 1 – Scheme of tectono-sedimentary evolution of the Western Carpathian Carboniferous Permian basin. *Explanation of symbols:* T - Tatric Unit; NV - Northern Veporic Unit; SV - Southern Veporic Unit; Z - Zemplinic Unit; H - Hronic Unit; NG - Northern Gemeric Unit; SG - Southern Gemeric Unit; M - Meliatic Unit; TU - Turnaic Unit; S - Silicic Unit; U - Upponyi Mts.; SZ - Szendrö Mts.; B - Bükk Mts.

are dismembered within the several Alpine mega-units. Continental sedimentation under humid climatic conditions was characteristic of this area during the Late Carboniferous, with relicts preserved within the Zemplinic, Hronic and Southern Veporic Units. Generally, a characteristic feature for this development is gradual progradation into the Permian arid/semi-arid red-bed formations. The sedimentary basins were established in pull-apart and rift-related tectonic settings.

Particular features have been observed in the Permian formations of the Southern Gemeric Unit. Their extremely mineralogically mature detritus, compared with other contemporary sediments of the Western Carpathians, allows their correlation with other early-Alpine riftogenic tectonofacies of the Alpine-Mediterranean Domain. They were most probably areally connected with the Bashkirian flysch depositional zone of the Turnaic Unit (the Turiec Formation, in Brusník Anticline; Vozárová & Vozár, 1992), as well as with the corresponding facies in the SBsZ.

CONCLUSION

Two zones of Hercynian collision at different times were identified in the Western Carpathians on the basis of relict infilled Carboniferous-Permian basins:

– *the internal zone*, in which the collision terminated during "Bretonian-Sudetian" events and resulted in the formation of a syncollisional Lower Carboniferous flysch basin succeeded by a marine Upper Carboniferous and continental Permian peripheral foreland basin (NGZ) as well as the formation of continental Permian back-arc transpressional/transtensional retro-arc basins (CWCZ). With respect to these characteristics, this zone corresponds to the Mediterranean Crystalline Zone as defined by Neubauer & Raumer (1993), comprising the eastern Grauwackenzone and Gurktal thrust system and the Carboniferous of the Noetsch area in the Eastern Alps, the nappe thrust system of the Bucovinian and Ghetic Units in the Eastern and Southern Carpathians in Romania, and part of the Balkanides and Kraishtides in Bulgaria;

– *the external zone*, in which the collision terminated during the "Asturian" events (IWCZ). This zone is represented by the Bashkhirian flysch and the Upper Westphalian/Stephanian marine peripheral foreland basin (relicts preserved only in northern Hungary), and the post-orogenic continental Permian deposits (the Turnaic Unit in Slovakia). This zone was spatially connected with shallow-marine foreland deposits of the Bükk Mts. area in northern Hungary. Generally, this whole external zone could be correlated with the Noric-Bosnian and Betic-Serbian zones distinguished by Neubauer & Raumer (1993).

Ackowledgements – The author is grateful to Prof. Giuseppe Cassinis and anonymous reviewers for their helpful suggestions and critical review of the manuscript. This work was supported by grant No. 1/5153/98 from Slovak Grant Agency VEGA.

REFERENCES

CAMBEL B. & KRÁL J., 1989. Isotopic geochronology of the Western Carpathian crystalline complex: their present state. *Geol. Zborn. Geol. Carpathica*, Bratislava, 40 (4): 387-410.

CAMBEL B., BAGDASARYAN G.P., GUKASYAN R.KH. & VESELSKY J., 1989. Rb-Sr geochronology of leucocratic rocks from the Spišsko-gemerské rudohorie Mts. and Veporicum. *Geol. Zborn. Geol. Carpathica*, Bratislava, 40 (3): 323-332.

CAMBEL B., KRÁL J. & BURCHART J., 1990. *Isotope geochronology of the Western Carpathian crystalline rocks.* Monography. Veda, Bratislava: 183 pp. (In Slovak).

FÜLÖP J., 1994. *Magyarorszägh geologiája. Paleozoikum.* Monography, Vol. 2. Akadémiai Kiadó, Budapest: 445 pp. (In Hungarian).

HOVORKA D., IVAN P. & SPIŠIAK, J., 1984. Nappe with amphibolite facies metamorphism – its position, origin and interpretation. *Mineralia slovaca*, Bratislava, 16: 73-86.

IVAN P., 1994. Early Palaeozoic of the Gemeric Unit (Inner Western Carpathians): Geodynamic setting as inferred from metabasalts geochemistry data. *Mitt. Österr. Geol. Ges.*, Wien, 86: 23-31.

KOVÁCS S., 1988. Olistostromes and other deposits connected to subaquaeous mass-gravity transport in the North Hungarian Paleo-Mesozoic. *Acta Geol. Hung.*, Budapest, 31 (3-4): 263-287.

KOVÁCS S., 1992. Stratigraphy of the Szendrő-Uppony Paleozoic (Northeastern Hungary). In: Vozár J. (ed.), *The Paleozoic geodynamic domain and their alpidic evolution: Western Carpathians, Eastern Alps, Dinarides.* Spec. vol. IGCP No. 276, Dionyz Štúr Inst. Geol., Bratislava, 93-108.

KOVÁCS S. & PÉRO Cs., 1983. Report on stratigraphical investigations in the Bükkium (Northern Hungary). In: Sassi F.P. & Szederkenyi T. (eds), *IGCP No. 5.* Newsletter 5, Szeged-Padova: 58-65.

NĚMEJC F., 1947. Contribution to knowledge of floral remains and stratigraphical division of Permo-Carboniferous of Slovakia. *Rozpravy II. Tř. Čes. Akad. Věd*, Praha, 56 (15): 1-34. (In Czech).

NEUBAUER F. & V. RAUMER J., 1993. The Alpine basement – Linkage between Variscides and East-Mediterranean mountain belts. In: v.Raumer J. F. & Neubauer F. (eds), *Pre-Mesozoic Geology in the Alps.* Springer-Verlag: 641-663.

NOVOTNÝ L. & ROJKOVIČ I., 1981. Uran-mineralization in Western Carpathians. In: Mahel' M. (ed.), *Važnejšie problémy geol. vyvoja a stavby Československa.* Smolenice 1979, Dionyz Štúr Inst. Geol., Bratislava: 327-347. (In Slovak).

PLANDEROVÁ E., 1973. Palynological research in the melaphyre serie on the Choč Unit in the NE part of the Nízke Tatry Mts. between Spišsky Štiavnik and Vikartovce. *Geol. Práce, Správy*, Bratislava, 60: 143-168. (In Slovak).

PLANDEROVÁ E., 1980. New results about age of "Rožňava-Železník Group". *Geol. Práce, Správy*, Bratislava, 74: 113-128. (In Slovak).

PLANDEROVÁ E., SITÁR V., GRECULA P. & EGYÜD K., 1981. Biostratigraphical evaluation of graphite shales of Zemplín island. *Mineralia slovaca*, Bratislava, 13: 97-128. (In Slovak).

SITÁR V. & VOZÁR J, 1973. Die ersten Makrofloren Funde in dem Karbon der Choč Einheit in der Niederen Tatra (Westkarpaten). *Geol. Zborn, Geol. Carpath.*, Bratislava, 24 (2): 441-448.

SPIŠIAK J., HOVORKA D. & IVAN P., 1985. Klátov Group the representative of the Palaeozoic amphibolite facies metamorphites on the Inner Western Carpathians. *Geol. Práce, Správy*, Bratislava, 90: 81-95. (In Slovak).

ŠUF J., 1963. Ergebnisse der geologischen Untersuchungen im Gebiete von Štítnik. *Geol. Práce, Správy*, Bratislava, 27: 63-68. (In Czech).

VOZÁROVÁ A., 1993. Provenance of the Gelnica Group metasandstones and relationship to paleotectonics of sedimentary basins. *Západné Karpaty, sér. met. petrol. miner. geoch., D. Š. Inst. of Geol.*, Bratislava, 16: 7-54. (In Slovak).

VOZÁROVÁ A., 1997. Upper Permian – Lower Triassic evaporites in the Western Carpathians (Slovakia). *Slovak Geol. Mag., D. Štúr Publ.*, Bratislava, 3/97 (3): 223-230.

VOZÁROVÁ A. & VOZÁR J., 1992. Tournaicum and Meliaticum in borehole Brusník, BRU-1, Southern Slovakia. *Acta Geol. Hung.*, Budapest, 35 (2): 97-116.

VOZÁROVÁ A. & VOZÁR J., 1996. Terranes of the West Carpathians-North Pannonian Domain. *Slovak Geol. Mag., Dionyz Štúr Publ.*, Bratislava, 1/96: 61-83.