plagioclase+hornblende of the amphibolite facies, from the definition of Eskola (1939). In the Central Alps, the staurolite, index mineral of the amphibolite facies, is unfortunately too rare for being a useful marker of this facies. The age of the temperature culmination event of the metamorphism of the Lepontine gneiss dome is between 38-35 Ma (Hunziker et al. 1992, Steck & Hunziker 1994).
The regional occurrence of the Eocene high pressure metamorphism (dated by Rubatto et al. 1998 and Amato et al. 1999) in the Zermatt-Saas Fee, Antrona, Monte Rosa and Etirol Levaz units is based on the observations by Bearth (1962, 1973), Dal Piaz & Ernst (1978) and Colombi (1989). The regional occurrence of the Late Cretaceous eclogite facies (Hunziker et al. 1992, Ruffet et al. 1997, Rubatto et al. 1999) and geenschist facies in the Sesia Zone is based on the work of Compagnoni et al. (1977), Chabloz (1990), Halter (1992), Simic (1992), Marclay (1999) and our own observations. A rime of 1-2 km of greenschist and anchi zonal rocks follows the Canavese Line in the Ivrea zone (Steck & Tièche 1976).

2.2 The Variscan and pre-Variscan evolution

G.M. Stampfli, J. von Raumer, G.D. Borel & F. Bussy

After the review of the Alpine history of the western Alps, a Permian continental fit of the Mediterranean and Alpine region can be elaborated (fig 14). On this canvas, Variscan terrains can be replaced, and a attempt at unravelling their geodynamic evolution can be proposed. We present first a general geodynamic plate tectonic model in order to define the main elements, then we move to the pre-Variscan and Variscan history in more detail

2.2.1 The proposed model (fig.15) *(see Stampfli et al. 2001d, and references therein)*

Generally speaking one finds important geodynamic similarities in the Variscan terrains of Europe. The explanation of the present complexity should not be sought in a complex plate tectonic scenarios involving numerous oceanic realms, on the contrary, and in view of the parallels in evolution, a simple model is preferable.

We propose a continuous southward subduction of oceanic realms under the Gondwanan border, starting already in the Late Precambrian, which triggered the detachment of three main terrains. First Avalonia in the Early Ordovician, then the Gothic terrain in Late Silurian, promptly followed by the Hunic terrain in Early Devonian (fig.16).
The accretionary processes of these terrains to Laurentia-Baltica show a more differentiated history, which is the source of the observed complexities. If for the Avalonia super-terrain things turned out to be quite simple with a classical collision of an active margin and a passive one, a more complex scenario is necessary to explain the Variscan collage. In order to respect parallels of evolution found in different parts of the Gothic terrain, we propose that areas affected by the mid-Devonian HP phase were located on the leading accretionary edge of this terrain, whereas areas not affected by this major eo-Variscan event were located on the PaleoTethys passive margin of the terrain (Stampfli et al. 2000; Stampfli et al. 2001d). This eo-Variscan mid-Devonian event is related to accretion of buoyant material derived from Laurussia and subduction of a peri-Laurussian ocean, whereas further east the event is related to a collision with an island-arc system.

To explain the subsequent large scale mixture of these two domains (active and passive margins), large scale lateral displacements have to be evoked. Most hercynologists would agree with the latter proposal (*e.g.* Matte 1991) but most of them would place these translations in a context of collision. What we propose here is a context of displacement of terrains in a still active margin, the translations being accompanied by transtensional and tranpressional events leading to the opening of Gulf

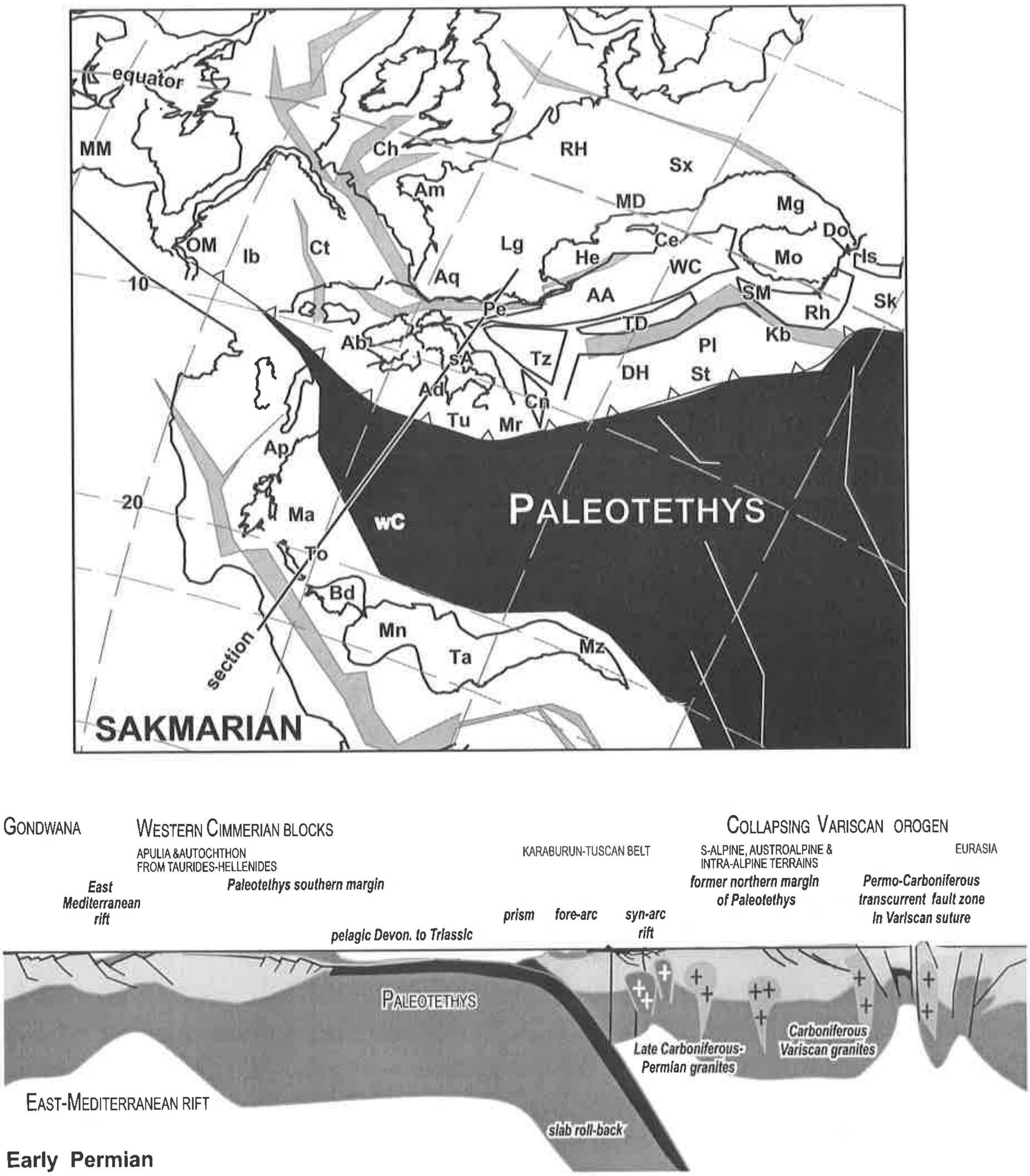
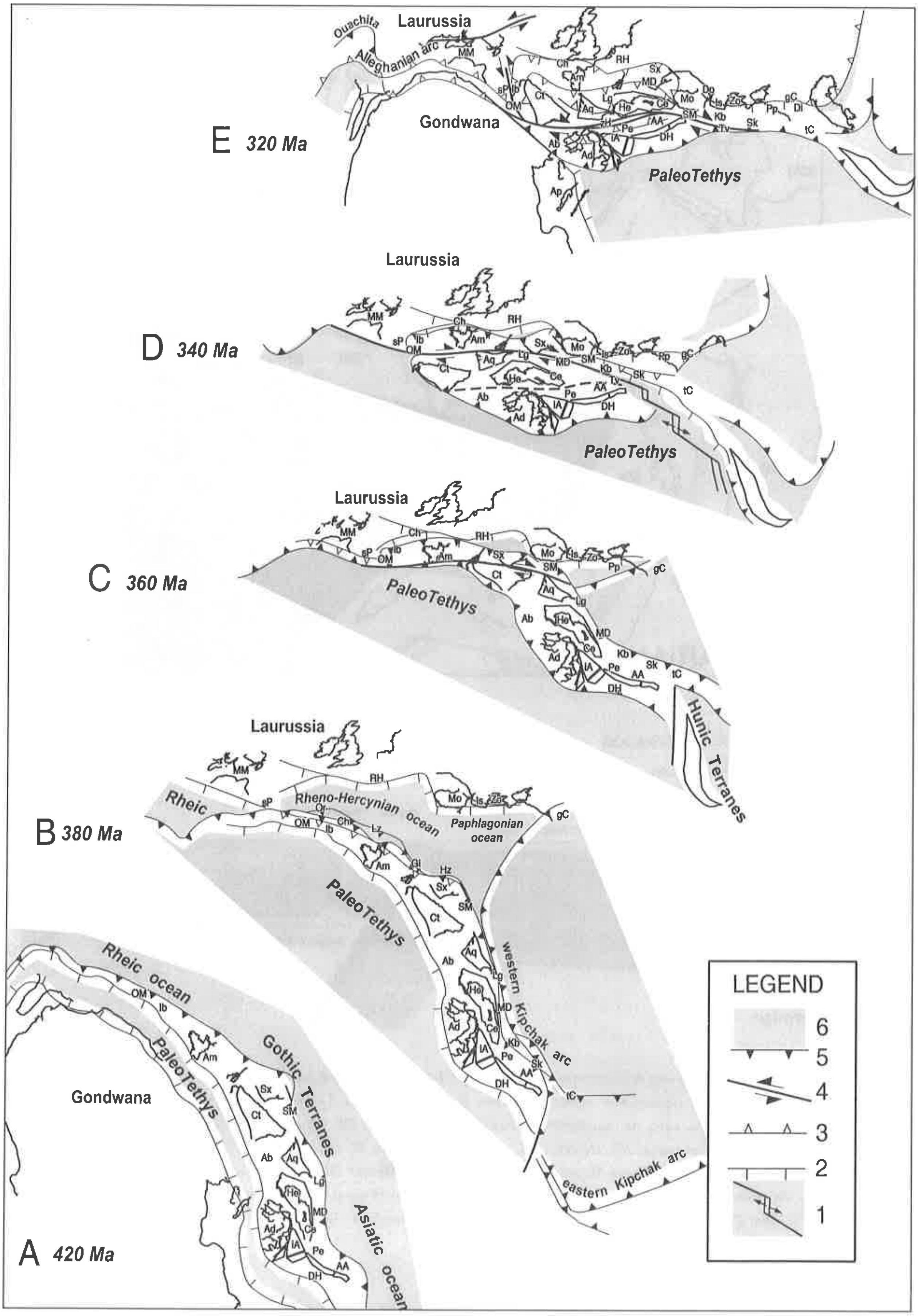


Fig.14 - Early Permian (Sakmarian) reconstruction of the western Tethyan realm modified from Stampfli et al. (2001a), rift zones are shown in grey; and lithospheric cross-section across the western part of PaleoTethys. Legend: AA, Austro-Alpin; Ab, Alboran; Ad, Adria s.str.; Am, Armorica; Ap, Apulia s.str.; Aq, Aquitaine; Bd, Beydaghlari; Ce, Cetic; Ch, Channel ; Cn, Carnic-Julian; Ct, Cantabria; DH, Dinarides-Hellenides; Do, Dobrogea; He, Helvetic; iA, intra-alpine terrain; Ib, Iberia, central; Is, Istanbul; Kb, Karaburun; Lg, Ligerian; MD, Moldadubian; MM, Meseta-Meguma; Mn, Menderes; Mo, Moesia; Mr, Mrzlevodice fore-arc; Mz, Munzur Dag; OM, Ossa-Morena; Pe, Penninic; Pl, Pelagonian ; Rh, Rhodope; RH, Rheno-Hercynian; sA, south Alpine; Sk, Sakarya; SM, Serbo-Macedonian; St, Sitia; Sx, Saxo-Thuringian ; Ta, Taurus, s.l.; TD, Trans-Danubian; To, Talea Ori; Tu, Tuscan ; Tz, Tizia; wC, western-Crete (Phyl-Qrtz); WC, West-Carpathian.


E 320 Ma
Ouachita
Laurussia
Alleghanian arc
Gondwana
PaleoTethys
MM
Ch
RH
Sx
MD
Am
sP
Ib
OM
Ct
Aq
Lg
He
Ce
Mo
Do
Is
Zo
Pp
gC
Dl
SM
Kb
Tv
Sk
tC
zH
Pe
AA
IA
DH
Ab
Ad
Ap
D 340 Ma
C 360 Ma
Hunic Terranes
B 380 Ma
Rheic
Rheno-Hercynian ocean
Paphlagonian ocean
Or
Lz
Gi
Hz
western Kipchak arc
eastern Kipchak arc
A 420 Ma
Rheic ocean
Gothic Terranes
Asiatic ocean
LEGEND
6
5
4
3
2
1

of California type oceans and in other places to the building up of cordilleras.

During the building up of the Carboniferous cordillera two scenarios developed. The westward evolution is towards a continent-continent collision where the accreted terrains got squeezed between Laurussia and Gondwana, this is the prevailing scenario for the Alleghanian regions. The other scenario, eastward, is a continuation of subduction and a generalised roll-back of the Paleotethyan slab. This, in turn, generated the opening of numerous back-arc basins and oceans starting in the Early Permian and until the Middle Triassic closure of the PaleoTethys oceanic domain (see above and fig. 4A).

Post collisional Permo-Carboniferous granites found for example in Morocco (*e.g.* Amenzou & Badra 1996) should be related to slab detachment when major crustal attenuation through generalised extension is not documented. In other western European regions, "post collisional" Permo-Carboniferous granites (as found in the Alps, see field trips 1 and 2) should be related either to slab detachment or the collapse of the cordillera or both, but not really to post collisional processes, the final collision being far away in time and space. Effectively, from Sicily to the Caucasus the final closure of PaleoTethys took place during the eo-Cimmerian cycle, and the closure of back-arc oceans issued from the PaleoTethys slab roll-back finally took place only in Cretaceous times (fig. 4 and 5).

2.2.2 What pieces of the model are to be found in the Alps?

The pre-Variscan elements

Comparing pre-Variscan relics hidden in the Variscan basement areas of Central Europe, the Alps included, large parallels between the evolution of basement areas of future Avalonia and its former peri-Gondwanan eastern prolongations (*e.g.* Cadomia, Intra-Alpine Terrain) become evident (von Raumer et al. 2001, and references therein). Their plate-tectonic evolution from the Late Proterozoic to the Late Ordovician is interpreted as a continuous Gondwana-directed evolution. Cadomian basement, late Cadomian granitoids, late Proterozoic detrital sediments and active margin settings characterize the pre-Cambrian evolution of most of the Gondwana-derived microcontinental pieces. Also the Rheic ocean, separating Avalonia from Gondwana, should have had, at its early stages, a lateral continuation in the former eastern prolongation of peri-Gondwanan microcontinents (*e.g.* Cadomia, Intra-Alpine Terrain). Subduction of an oceanic ridge (ProtoTethys) triggered the break-off of Avalonia, whereas in the eastern prolongation, the presence of the ridge may have triggered the amalgamation of volcanic arcs and continental ribbons with Gondwana (Ordovician orogenic event).

In this general picture the different future Alpine basement units are no exceptions. All four domains, the External, the Penninic, the Austroalpine and the South-Alpine domains, represented by a multitude of outcrop areas,

Fig.15 - Plate tectonic model for the origin and evolution of the pre-Variscan units preserved in the European Variscan mountain chain modified from Stampfli et al. (2001d). 1 spreading ridge; 2 passive margin; 3 sutures; 4 strike-slip fault; 5 subduction zone; 6 oceanic lithosphere. AA, Austro-Alpine; Ab, Alboran; Ad, Adria; Am, Armorica; Ap, Apulia; Aq, Aquitaine; Ce, Cetic; Ch, Channel; Ct, Cantabria; DH, Dinarides-Hellenides; Do, Dobrogea; gC, great Caucasus; Gi, Giessen; He, Helvetic; Hz, Harz; iA, intra-alpine; Ib, central-Iberia; Is, Istanbul; Kb, Karaburun; KT, Karakum-Turan; Lg, Ligerian ; Lz, lizard; MD, Moldanubian; MM, Meguma-Meseta Mo, Moesia; OM, Ossa-Morena; Or, Ordenes; Pe, Penninic; Pp, Paphlagonian; RH, Rhenohercynian; Sk, Sakarya; SM, Serbo-Macedonian; sP, south Portuguese; Sx, Saxo-Thuringian; tC, trans-Caucasus; Tv, Tavas; zH, zone Houillère; Zo, Zonguldak.

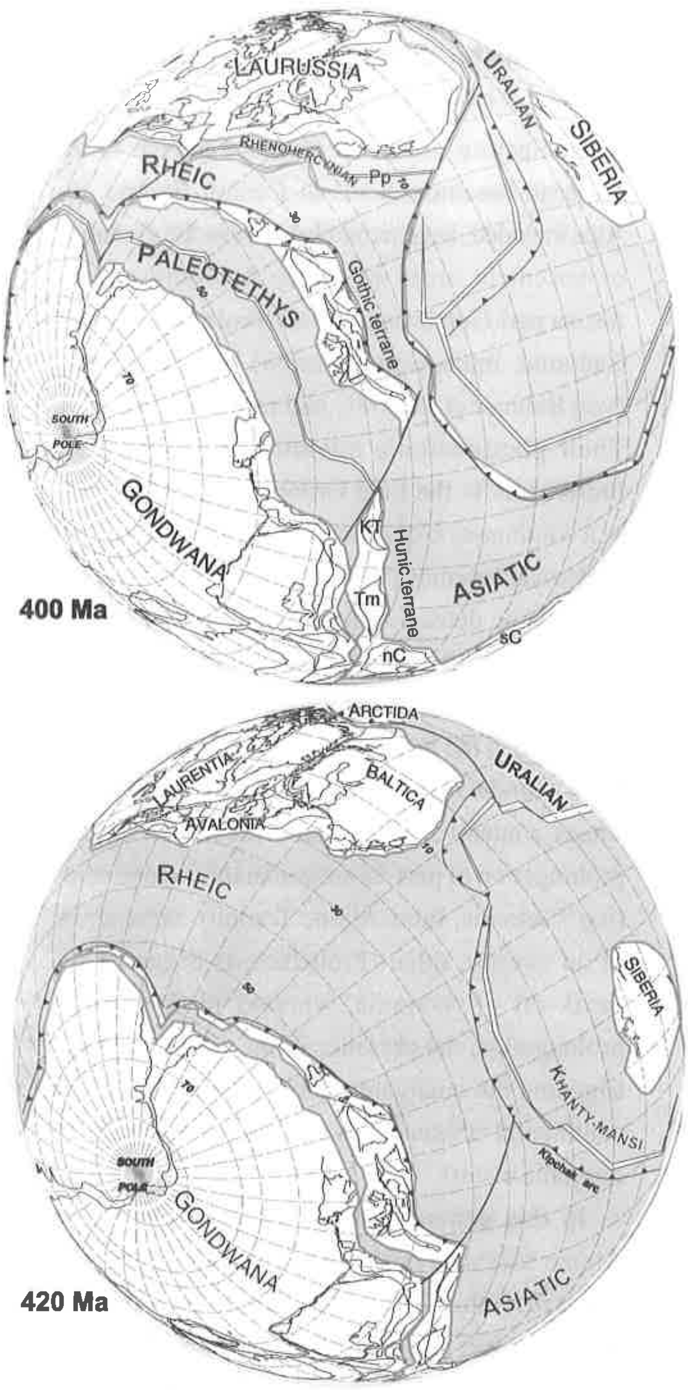


Fig.16 - Global reconstruction for the Late Silurian and the Early Devonian, showing the location of the Hunic and Gothic terrains. The 420Ma projection is centered on present-day latitude 10N, longitude 25E, the 400Ma projection on 10N, 20E. Pp, Paphlagonian ocean; KT, Karakum-Turan; Tm, Tarim; nC, North-China; sC, South-China.(Modified from Stampfli and Borel in press).

without distinction, include relicts testifying their former location at the Gondwana margin (von Raumer et al. 1998), but there is no specific basement characterizing one of the four Alpine realms. They have to be seen as puzzle stones including relicts from different plate tectonic situations depending on their former relative location during the plate tectonic evolution from the Late Precambrian to the Ordovician.

Cadomian basement and Late Cadomian granitoids could have been present, but have to be proven, and Late Proterozoic detrital sediments and active margin settings characterize locally the pre-Cambrian evolution of these Gondwana-derived microcontinental pieces. The mostly metamorphic counterparts of detrital sediments characterizing the Gondwana shelf and/or Cambrian rift basins are widely distributed. As said above, subduction of an oceanic ridge (ProtoTethys) triggered the break-off of Avalonia, whereas its presence, in the eastern prolongation of Avalonia – the future basement areas composing the basement of the Alps, may have triggered the amalgamation of volcanic arcs and continental ribbons with Gondwana, thus leading to a short Middle Ordovician orogenic event. Renewed Gondwana directed subduction led to the opening of PaleoTethys (fig.16). The great difficulties to understand such pre-Variscan events do not only result from the Alpine juxtaposition of small pieces, but also from the Variscan evolution, transforming most of these pieces to lower to middle crust elements.

The Variscan elements

Introduction

As we have seen above and depending on their former location at the Gondwana margin, the Variscan basement may contain, besides the complex Variscan (and Alpine) overprint, relicts of Cadomian basement, Late Proterozoic volcanic arcs, subsequent stages of accretionary wedges and back-arc rifting and spreading. The evolution of these terrains was guided by the diachronous subduction of the ProtoTethys oceanic ridge under different segments of the Gondwana margin. This subduction triggered the emplacement of magmatic bodies and the formation of back-arc rifts, some of them becoming major oceanic realms (Rheic, PaleoTethys). Consequently, the drifting of Avalonia is followed since the Silurian and after a short Ordovician orogenic event, by the drifting of middle European and Alpine domains accompanied by the opening of PaleoTethys.

The slab roll-back of the Rheic ocean is viewed as the major mechanism for the drifting of the European Variscan terrains, this, in turn, generated a large slab-pull force responsible for the opening of major rift zones within the passive Eurasian margin (Rhenohercynian ocean). Therefore, the first mid-Devonian Variscan orogenic event is viewed as the result of a collision between terrains detached from Gondwana (Gothic and Hunic terrains) and terrains detached from Eurasia (fig.15). Subsequently, the amalgamated terrains collided with Eurasia in a second Variscan orogenic event in Visean times, accompanied by large scale lateral escape of major parts of the accreted margin. Final collision of Gondwana with Laurussia did not take place before Late Carboniferous and was responsible for the Alleghanian orogeny.

PaleoTethys evolution

The PaleoTethys is more or less completely ignored by classical hercynology, therefore it is important to present here the main lines of its geodynamic evolution. The opening of PaleoTethys is relatively well constrained on an Iranian transect (Alborz range, North Iran; Stampfli 2000) representing the southern Gondwanan margin of the eastern branch of the ocean. Late Ordovician to Early Devonian flood-basalts, rift shoulder uplift in the Silurian followed by the onset of thermal subsidence in the Devonian, point to a Late Ordovician/Silurian rifting phase. Sea-floor spreading took place in the Late Silurian or Early Devonian and the rift shoulders were completely flooded by Late Devonian time, following generalised thermal subsidence of the passive margin. From Late Devonian until Middle Triassic, a carbonate-dominated passive margin developed. A similar evolution is found in the Cimmerian part of Turkey (for details see references in Stampfli 1996, and Göncüoglu & Kozur 1998), and most likely of Apulia, however in Apulia the information does not go deeper than the Permian.

The northern margin of the PaleoTethys ocean is well represented in the middle part of the Gothic terrains (*e.g.* southern Alps: Schönlaub & Histon 1999; Tuscan Paleozoic, Sardinia, Betic: cf. Stampfli 1996) also characterised by a Late Ordovician-Early Silurian clastic and often volcanic syn-rift sequence (Silurian flood basalts are also known in Sardinia). Thermal expansion and related erosion and tilting took place in Silurian time and is often wrongly related to the Taconic event (Tollmann 1985). Open marine conditions are found since the Silurian and are represented by graptolitic facies; a more generalised flooding took place in the Early Devonian and marked the onset of widespread thermal subsidence related to sea-floor spreading. On the northern margin, the Visean usually marks the onset of generalised flysch deposition, often accompanied by volcanic activity. We regard this major change as representing the general collage of the different terrains to Eurasia to form the Variscan cordillera. It also marks the onset of PaleoTethys subduction and the transformation of the margin from passive to active, shortly followed by subduction of its mid-oceanic ridge certainly responsible for a large part for the high temperature Variscan metamorphism.

Accretionary sequences related to this subduction are little known, most likely because important subduction erosion took place during the cordillera stage as observed nowadays along the South-

American active margin. Potential Paleotethyan accretionary sequences are located in the southern part of the Variscan orogen and in all cases completely metamorphosed and intruded by subsequent Late Carboniferous granites and usually involved in eo-Cimmerian and Alpine deformations. However, pelagic Late Carboniferous to Early Triassic sediments of Paleotethyan origin are found in Sicily, the Dinarides, Hellenides and Taurides (Kozur et al. 1998; Kozur & Stampfli 2000), and, in Chios (Greece) and Karaburun (Turkey), Silurian and Devonian pelagic sequences have been found (Kozur 1997; Kozur 1998). These sequences clearly show that the remnant Paleotethys ocean was located south of the Alpine domain and separated the Variscan cordillera from Gondwana up to the Late Permian opening of Neotethys and the subsequent final closure of Paleotethys in Carnian times (fig. 4).

This closure speeded up through the opening in the former Variscan cordillera of major rift zones, some of them finally leading to the opening of back-arc marginal oceans (Meliata, Maliac, Pindos).

Variscan metamorphic massifs and intrusives in the western Alps

In the general picture given above for the Variscan evolution, the main Alpine realms (Helvetic, Penninic, Austroalpine, Southern Alps) again have to be replaced at their original location after separation from Gondwana and their stepwise approach towards Laurussia. Consequently, they have no specific evolutions characterising their Alpine situation, but they obey to the tectonic evolution from the Silurian to the Late Carboniferous, being laterally aligned until their Alpine juxtaposition. In the Alpine transect (*e.g.* fig. 3), they appear as basement nappes, separated in many cases by their Mesozoic cover. The general Alpine shortening brought them up to the surface, where they appear as dome like structures surrounded by Mesozoic cover.

Consequently, Variscan metamorphism and magmatism are the mirror of a pre-Alpine tectonic zonation, appearing in many locations as the main overprint, giving to the pre-Variscan lithologies described above the typical aspect of Variscan basement areas, as known all over Europe. Zones of distinct metamorphic grades from lower greenschist facies to high amphibolite facies and granulite facies were tectonicaly juxtaposed, and different magmatic pulses intruded into the strongly sheared and folded rock units. Such rocks will be presented during the field trips in the Aiguilles Rouges and Mont Blanc domains (Ft 1) and in the Penninic basement (Ft 4 & 5).

Rift related deposits (Houiller, Permian basins)

The presence of major transcurrent faults creating intra-mountain basins and the opening of Gulf of California type oceans within the Variscan cordillera influenced the distribution of sedimentary troughs in Central and Southern Europe during the Carboniferous and, again, the Alpine basement areas (Helvetic, Penninic, south Alpine and AustroAlpine domains) cannot be excluded from these tectonic events. The cordillera collapse certainly characterises Late Carboniferous Early Permian times in the Alpine part of the Variscan orogen. Extensional processes initiated already in Middle Carboniferous times and were related to major lateral displacement of the accreted terrains and juxtaposition of units showing quite different metamorphic conditions as found in the Penninic basement of the western Alps (Giorgis et al. 1999) (fig.17).

An example of such a feature are the Salvan-Dorénaz graben in the Helvetic domain (field trip 1 & 2) or the Zone Houillère (Cortesogno et al. 1993) of the Penninic domain (field trip 4 & 5), where extension might have led to local emplacement of E-MORB type extrusives (Cannic 1996) recently dated as Late Carboniferous (Schärer et al. 2000). Continuing extension in Permian times created new grabens (sometimes with gabbro emplacement) in the Alpine domain locally grading to Early-Middle Triassic clastic/carbonate deposits. Similar mafic emplacement and basin development are known in the Penninic, Austro-alpine (Thöni & Jagoutz 1993) and Adriatic domain (Tuscan Carboniferous basins, *e.g.* Englebrecht 1997). These basins aborted and never evolved as oceanic domains, but their thermal subsidence or local inversion is responsible for the Triassic paleogeography of these regions as well as for the final location of the Alpine Tethys rift.

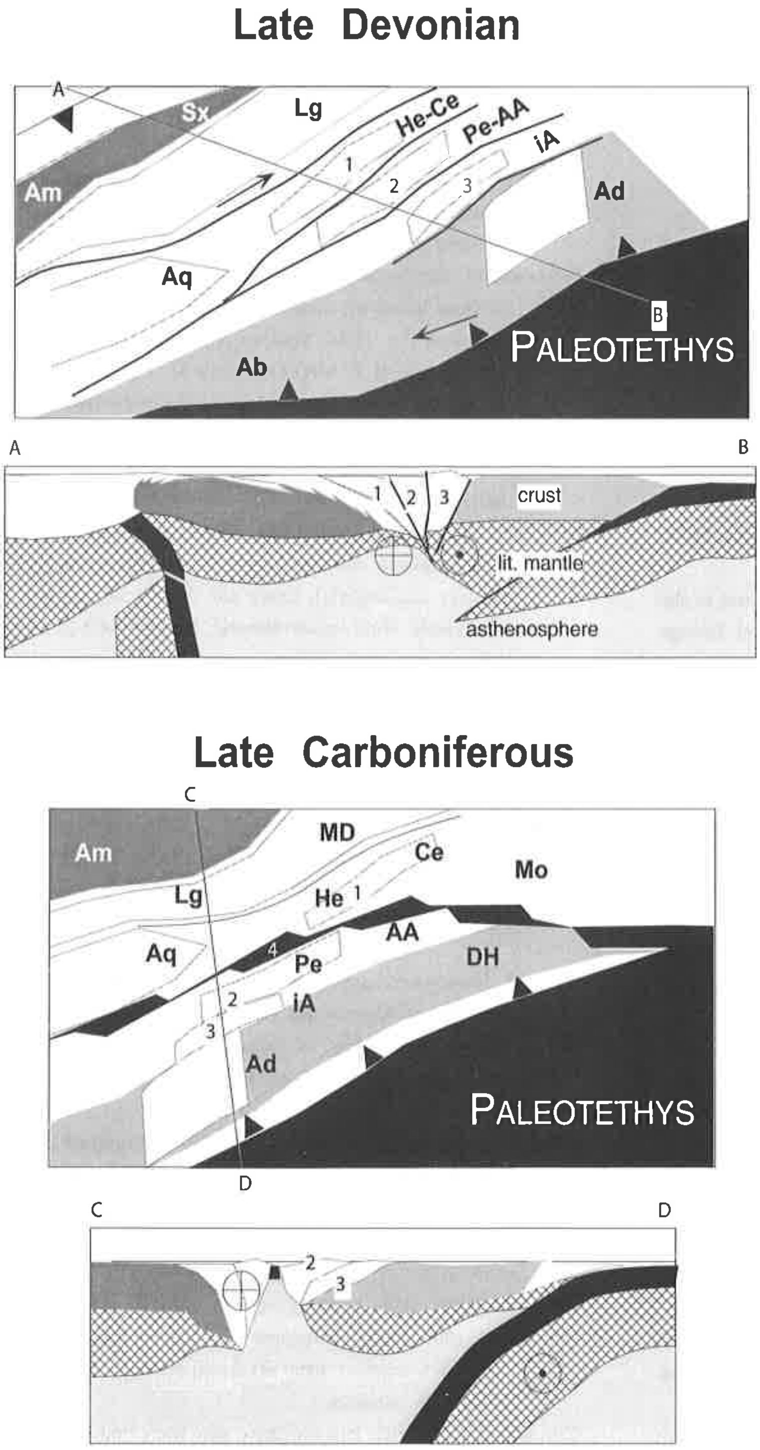


Fig.17 - Late Devonian and Late Carboniferous schematic evolution of the European Variscan domains, modified from Giorgis et al. (1999): AA, Austro-Alpine; Ab, Alboran; Ad, Adria (3); Am, Armorica; Aq, Aquitaine; Ce, Cetic; DH, Dinarides-Hellenides; He, Helvetic (1); iA, intra-alpine; Lg, Ligerian ; MD, Moldadubian; Mo, Moesia; Pe, Penninic (2); 4, zone Houillère rift.

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