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The pre-Alpine geodynamic evolution of the Southern Alps: a short summary

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1. Introduction

The Alps are a collage of tectonic units derived from ancient continental margins and intervening Mesozoic ocean basins. Their continental basement units preserve signatures of Palaeozoic and pre-Palaeozoic orogenies; their Alpine history records both Cretaceous and Tertiary orogenic movements, and along their eastern boundary their structures are interfering with those of the Dinarides and the Carpathians.

Within the Alps, the Southern Alps of which the Dolomites are an integral part, are in a particular position. They form the retrowedge of the upper plate of the Alpine subduction, and their south-vergent thrusts are of much more limited extent than in the nappe stack to the north, from which they are separated by the peri-Adriatic (Insubric) fault system. In the Southern Alps, thrusting was from north to south, parallel to the strike of the older, Mesozoic continental margin units that are still in their original palaeotectonic position relative to each other. Mesozoic faults were mainly reactivated as Alpine transfer faults.

Palaeogeographically, the Southern Alps were part of the Adriatic microcontinent or Adriatic promontory of Emile Argand, bordering the Alpine-Mediterranean Tethys to the southeast; therefore they share much of their Mesozoic history with the external Apennines and the external Dinarides and their Adriatic foreland. Within this larger area, the Southern Alps probably represent the best-preserved Mesozoic continental margin with a transect from the proximal margin in Friuli in the east to the ocean-continent transition in the Canavese zone north of Torino in the west. The excellent outcrops, exposing even lower crustal rocks in the west allow us to reconstruct the tectono-sedimentary evolution from the Variscan orogeny to the latest, Pliocene, thrusting events.

2. The Variscan basement

In the Southern Alps, the Permo-Mesozoic, non- or locally anchimetamorphic sediments overlie different crustal levels of the Variscan edifice along a Late Carboniferous (Westphalian) unconformity. The metamorphic grade increases from east to west, i. e. from deep burial diagenesis and anchimetamorphism in the Palaeozoic sediments in the external Variscan zone in the east (Carnic Alps) to amphibolite-grade in the internal zone (Strona-Ceneri zone) in the west. These deeper levels of the Variscan crust preserve the radiometric signatures of a possibly Proterozoic («Cadomian») orogeny and of Ordovician («Caledonian») metamorphism and granite intrusion. During Variscan subduction, this older arc was underplated by a Carboniferous accretionary complex containing slivers of ocean-

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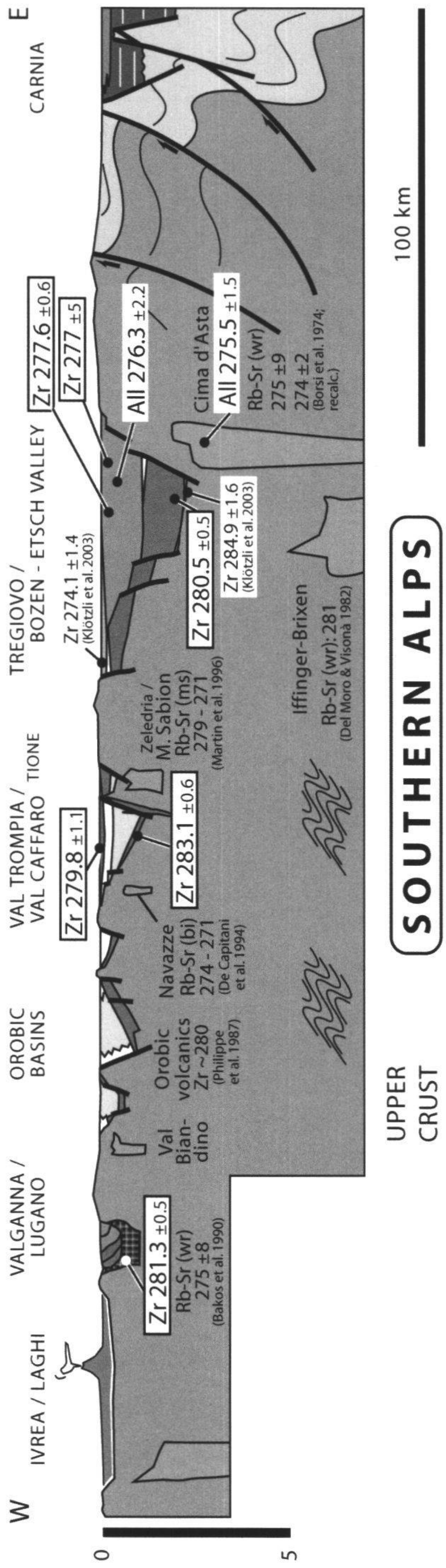

Fig. 1: Palinspastic east-west cross-section of the Early Permian crust of the Southern Alps with U-Pb zircon (Zr) and allanite (All) age data; after Schaltegger & Brack (2007). Reproduced by permission of Springer-Verlag, Heidelberg.

ic crust and mantle (Handy et al. 1999). Exhumation and erosion of this complex assemblage must predate the Permian magmatic and metamorphic events, because the Upper Carboniferous-lowermost Permian sediments directly overlie the amphibolite-grade rocks. At the very end of the Variscan orogeny, the crust appears to have re-equilibrated to normal crustal thickness.

3. Early Permian extension and magmatism

After the Variscan orogeny, the South-Alpine crust underwent extension in the Early Permian, leading to the formation of sedimentary basins accompanied by widespread silicic volcanism. Basin formation and magmatism were closely related to each other and occurred during a short time span between 285 and 275 million years (Fig. 1; Schaltegger & Brack 2007). In the western Southern Alps, the silicic magmatism is coeval with mafic intrusions in the lower crust of the Ivrea Zone. High heat flows are reflected by granulite-facies metamorphism, and magmatic underplating by basaltic melts led to migmatization and the generation of silicic melts in the lower crust that were emplaced in the upper crust (Baveno Granite) or rose to the surface forming large caldera complexes (Bolzano and Lugano «porphyries»). The asymmetric, intra-continental basins were the site of alluvial and lacustrine deposition (Collio Formation), and the geodynamic setting may be compared to that of the modern Basin-and-Range province of the western United States.

Early Permian magmatic underplating by basaltic melts can be observed in those places where within the Alpine nappe edifice lower crustal rocks are exposed, e. g. in the Campo nappe (Sondalo), the Malenco Complex, the Dent Blanche nappe (Arolla Series) or the Sesia zone. It has been proposed that Early Permian extension and accompanying magmatic activity might represent the first rifting phases that led to the opening of the Alpine Tethys; however, shallow intrusions of Early Permian granites and accompanying volcanicity are widespread phenomena all over Variscan Europe, their underpinnings, however, are rarely or not exposed at all. We may thus speculate that the European post-Variscan lower crust may have undergone a similar evolution. Magmatic underplating and advection of melts into the crust may have occurred rather during, possibly continental-scale, transtensional movements across a broad belt covering much of post-Variscan Europe (Handy & Zingg 1991; Schaltegger & Brack 2007) than during early Tethyan rifting (e. g. Winterer & Bosellini 1981).

4. From the Mid-Permian transgression to Triassic subsidence and magmatism

A mid-Permian unconformity spans about 10 to 15 million years of non-deposition and erosion. During the mid-Permian, the volcanic edifices of Borgomanero, Lugano and Bolzano were levelled and in the Late Permian a sedimentary wedge developed onlapping the Lower Permian deposits and the basement from the southeast: The related time-transgressive marine ingression from the east (Palaeo-Tethys) reached the eastern Southern Alps during the Late Permian (evaporites of Bellerophon Formation), central Lombardy in the late Early Triassic and the western southern Alps in early Anisian times (see Fig. 3 in Schaltegger & Brack 2007).

After an interval of differential subsidence and local uplift in the early-middle Anisian, massive subsidence during late Anisian-early Ladinian times provided the accommodation space for the carbonate buildups of the Dolomites (and the Bergamasc Alps), that were separated by deep basins with first pelagic, later mass flow and volcanic deposits infilling the relief between the atolls (Fig. 2; Bosellini 1984: Brack & Rieber 1993; Bosellini et al. 2003; Schlager this volume). In the Dolomites, estimates of maximum subsidence for the early Ladinian interval range from ~ 650 m/10^6 years to ~ 850 m/10^6 years (Emmerich et al. 2005); in the late Ladinian to early Carnian, these basins were partially inverted by transpressive movements whose structures were cut by late Ladinian-early Carnian igneous rocks (Doglioni 1987; Castellarin et al. 1988). The extremely high subsidence rates and the short-lived syn-sedimentary transpressional tectonics are as puzzling as is the character of the magmatic rocks in the Dolomites area. The oldest volcanic rocks are late Anisian tuffs of rhyolitic to rhyodacitic composition, that appear to be derived from a belt of mid-Triassic volcanics (rhyolites, rhyodacites, andesites) below the Po Plain, whereas in the north, in the Dolomites area, the Ladinian igneous rocks show a basaltic and basaltic-andesitic composition with a clear calcalkaline, shoshonitic trend (Castellarin et al. 1988). Such a zonation and the same calcalkaline trend are observed all along the Dinarides from the Dolomites to Serbia and beyond (Fig. 3; Bébien et al. 1978). Both, massive subsidence and igneous activity occurred over a short period of less than 10 million years and their current interpretations are highly divergent. Two scenarios are actually discussed: (1) a general strike-slip setting, and (2) a subduction-related volcanic arc setting:

(1) The close juxtaposition of syn-sedimentary compressional structures and subsiding basins as well as the high subsidence rates could indicate the close neighbourhood of transpressional flower structures and local pull-apart basins (Doglioni 1987). The calcalkaline trend could in this case be an older arc signature inherited from earlier subduction (Sloman 1989). The Ladinian age would approximately coincide with the early evolution of the Maliac-Meliata Ocean, and the volcanic episode could be related to extension associated with its opening. Indeed, mid-Triassic extensional basins are

found in the Adriatic foreland of the Dinarides (Franciosi & Vignolo 2002), and the thick Triassic sequences of the external Dinarides and of the eastern Southern Alps may reflect thermal subsidence following the opening of this ocean.
(2) Bébien et al. (1978) and Castellarin et al. (1988) interpreted the magmatic rocks as part of a volcanic arc on continental crust related to subduction of a segment of Palaeo-Tethys (Bébien et al. 1978, Castellarin et al. 1988) or of young lithosphere of the (Hallstatt-) Maliac-Meliata Ocean (Fig. 3; Brack et al. 1999). The evidence for Triassic subduction, in particular for a west-directed subduction of Palaeozoic or Triassic ocean crust, is, however, meager, and the short-lived igneous activity does not argue for deep-reaching subduction. So there is, at the moment, no entirely satisfactory explanation.

5. Late Triassic - Middle Jurassic extension and the formation of a continental margin

In the late Carnian, a marked relative sea-level fall associated with the input of siliciclastic and volcanic detritus caused the extinction of most of the carbonate platforms, and the realm of the Southern Alps was covered by first terrigenous, evaporitic and lesser carbonate sediments (Raibl Group), then by peritidal dolomites (Hauptdolomit, Dolomia Principale). These deposits were part of a larger continental margin wedge onlapping onto local basement highs and interfingering with the Germanic facies realm to the north and west, but open to a marine, oceanic area to the east (Figs. 3 and 4).
At the end of the Triassic, the continental crust of the westernmost Southern Alps may have been in near to isostatic equilibrium, whereas in the east, thermal subsidence of the western Maliac-Meliata margin may have

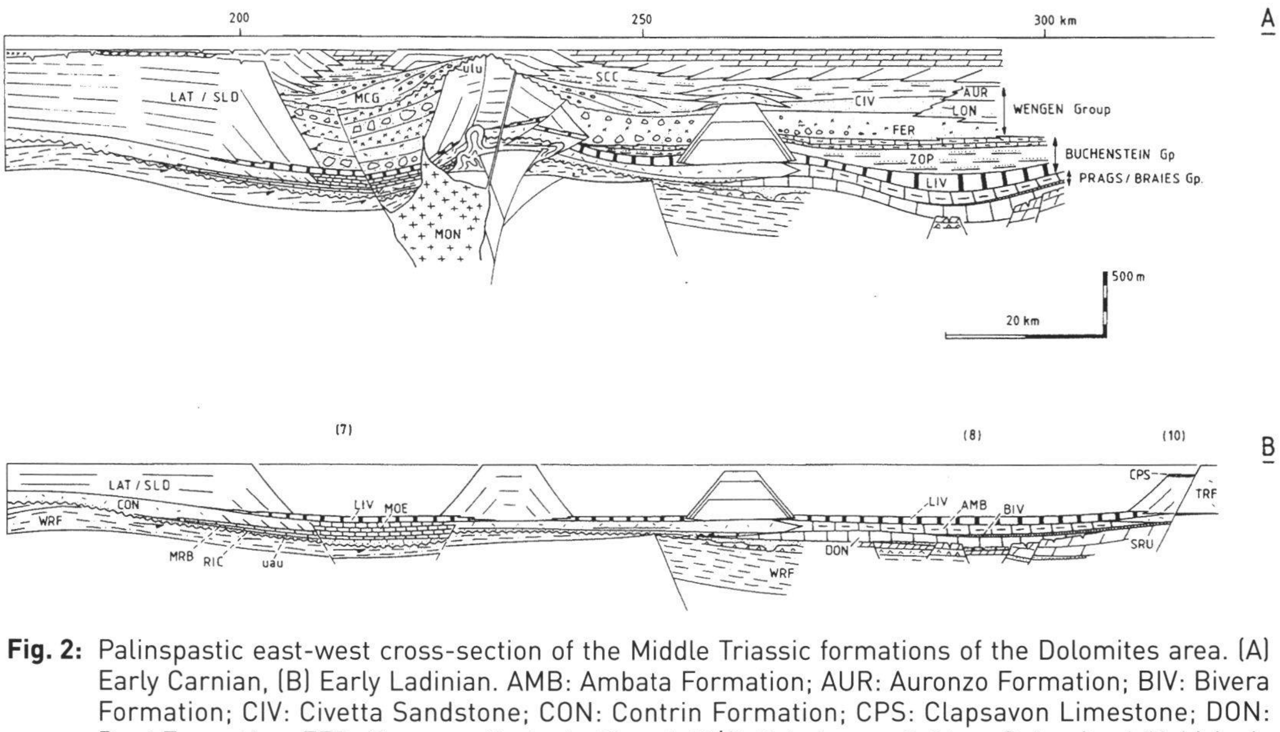

Fig. 2: Palinspastic east-west cross-section of the Middle Triassic formations of the Dolomites area. (A) Early Carnian, (B) Early Ladinian. AMB: Ambata Formation; AUR: Auronzo Formation; BIV: Bivera Formation; CIV: Civetta Sandstone; CON: Contrin Formation; CPS: Clapsavon Limestone; DON: Dont Formation; FER: Fernazza Hyaloclastites; LAT/SLD: Latemar-Schlern Dolomite; LIV: Livinallongo Formation; LON: Longiarin Sandstone; MGC: Marmolada Conglomerate; MOE: Moena Formation; MON: Monzoni and Predazzo intrusives; MRB: Morbiac Limestone; RIC: Richthofen Conglomerate; SCC: basinal Cassian Formation; SRU: upper Sarl Dolomite; TRF: Tiarfin Dolomite; WRF: Werfen Group; ZOP: Zoppè Sandstone; uau: Upper Anisian unconformity; ulu: Upper Ladinian unconformity; from Brack & Rieber (1993).

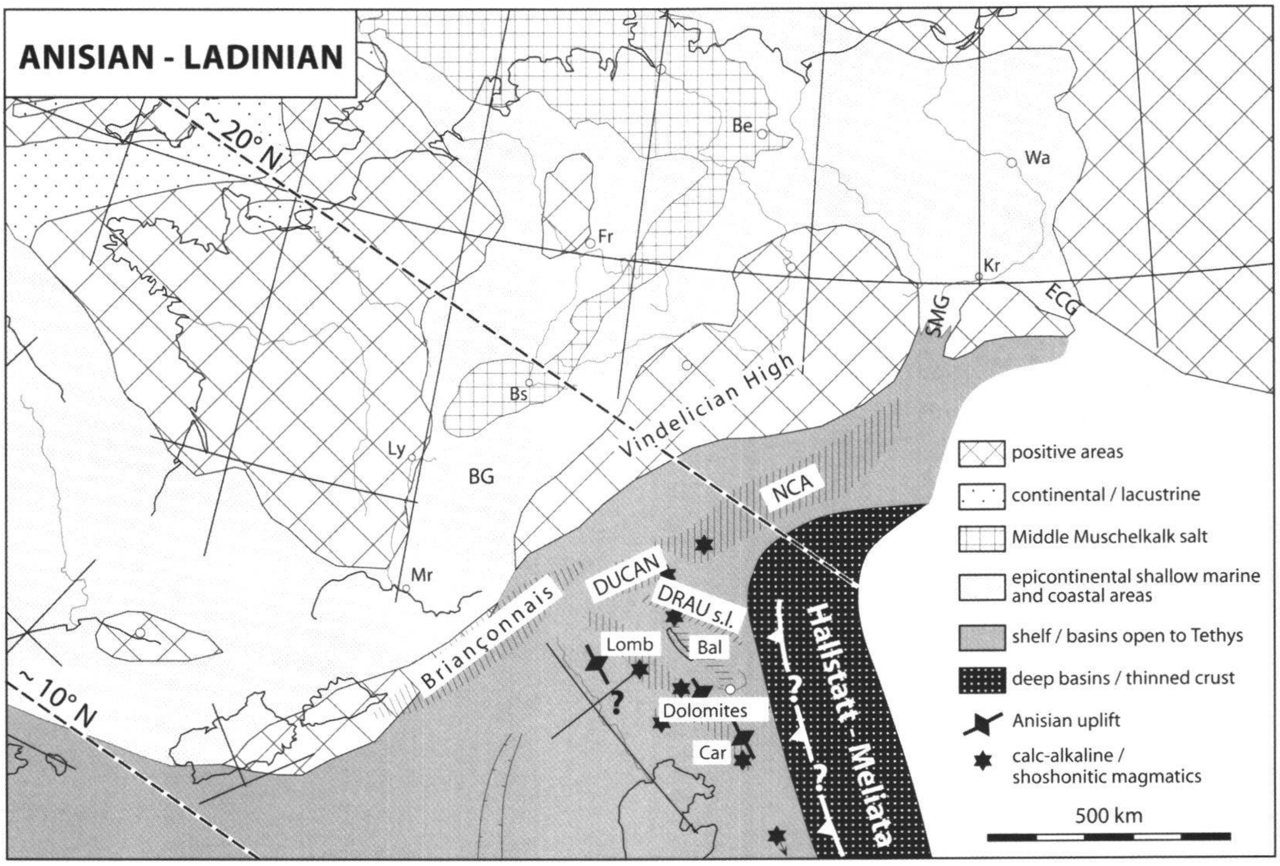

Fig. 3: Simplified Middle Triassic palaeogeography. In this interpretation, the late Anisian to early Carnian calcalkaline magmatism is related to short-lived, southwestward subduction along the border of the evolving Hallstatt-Meliata(-Maliac) Ocean. Bal: Balaton; BG: Burgundy Gateway; Car: Carnia; ECG: Eastern Carpathian Gateway; NCA: Northern Calcareous Alps; Lomb: Lombardy; SMG: Silesian-Moravian Gateway; from Brack et al. (1999).

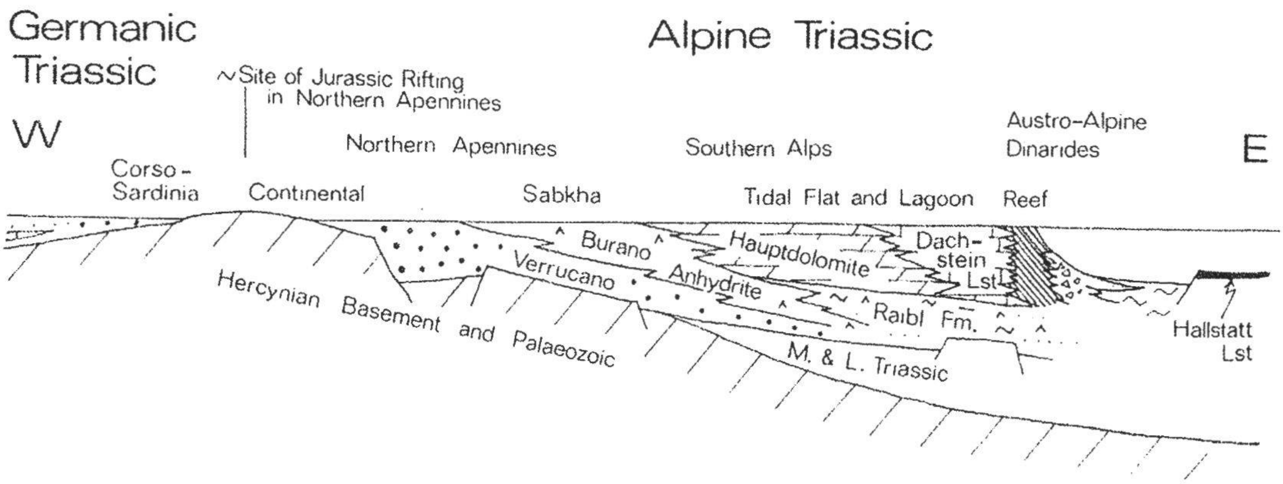

Fig. 4: Palaeographic profile through the Triassic deposits along a transect from the eastern South-Alpine-Austroalpine area to the western Southern Alps and the Northern Apennines. The section combines areas now occurring in different tectonic units into one palinspastic profile in order to show the general arrangement of facies realms; after Bosellini (1973) and Laubscher & Bernoulli (1977).

been the cause for ongoing Triassic subsidence (Manatschal et al. 2007). In the late Norian, a new evolution began: sedimentary basins developed in Lombardy and Friuli, up to ~ 10 km wide, in which thick sequences of fault-derived coarse resediments and fine-grained, organic carbon-rich limestones and dolomites were deposited. The shape of the individual basins suggests a left-lateral strike-slip component (Bertotti et al. 1993, their Fig. 4). During the Rhaetian, extension continued, however, because sedimentation kept up with differential subsidence, the faults had hardly a morphological expression. In the Early Liassic, strain was gradually concentrated along a few major crustal faults, and the major provinces of the evolving South-Alpine margin came into being (Fig. 5; Bertotti et al. 1993). Early (Liassic) rift basins were more or less symmetrical with the listric faults soling in the mechanically weak middle crust. With cooling and embrittlement of the already thinned crust, the focus of rifting shifted to the western-

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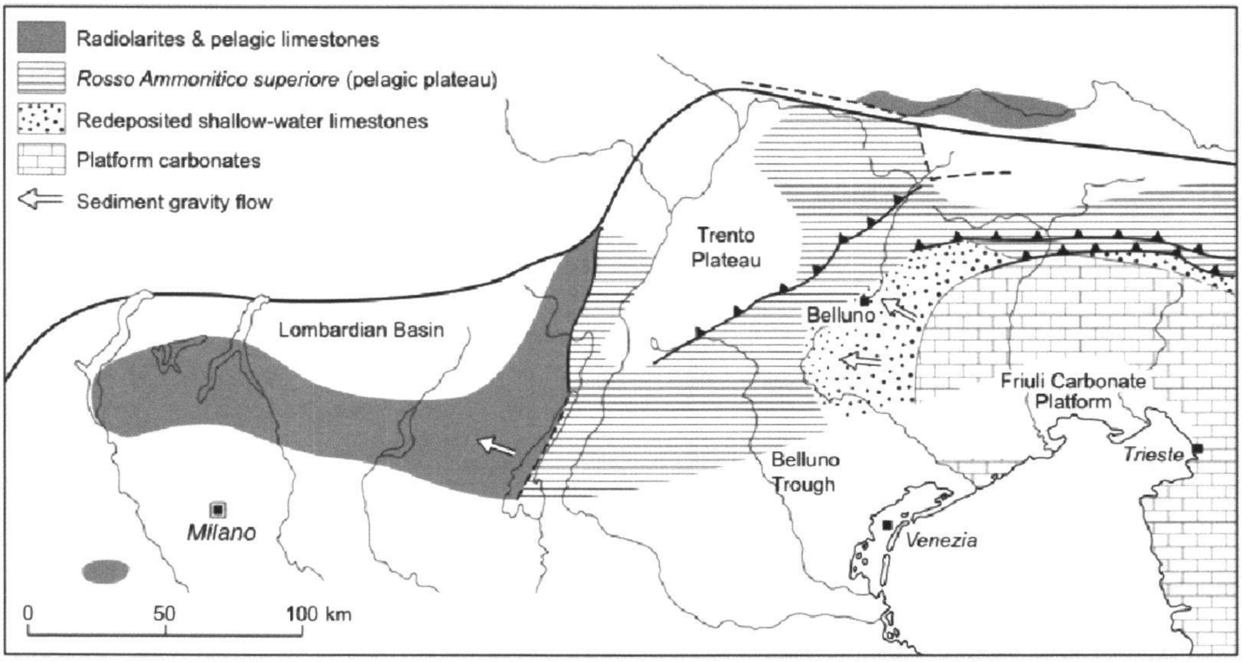

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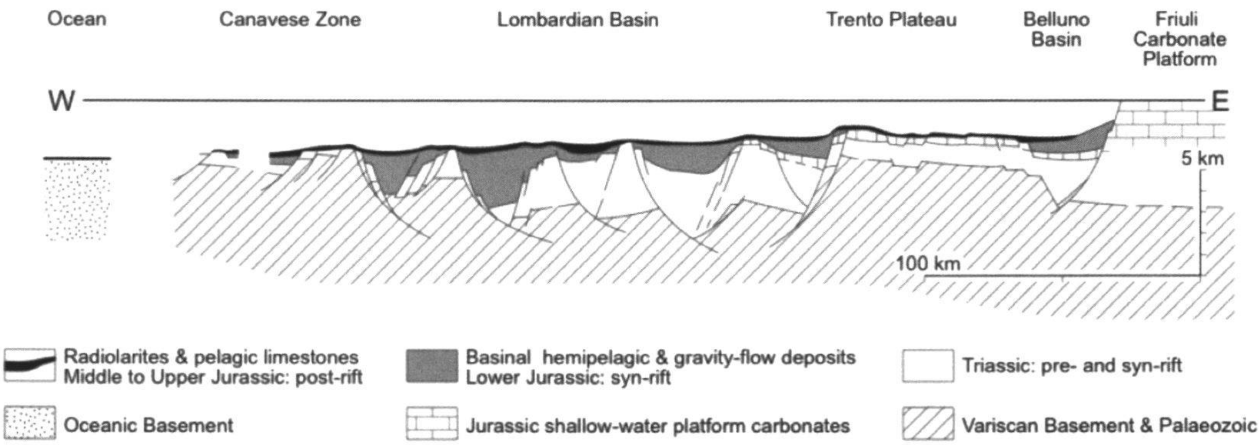

Fig. 5: (a) Palaeogeographic map of the Southern Alps for the Late Jurassic, not palinspastically corrected; after Winterer & Bosellini (1981). (b) Palinspastic cross-section through the South-Alpine continental margin for Late Jurassic times, after Bernoulli et al. (1979), modified.

most Southern Alps, and lower crustal (Canavese zone) and mantle rocks (Piemont zone) became exhumed to the seafloor along a system of low-angle detachment faults (Ferrando et al. 2004, and references therein). This evolution is conspicuously similar to that of the Cretaceous non-volcanic Iberian margin west of Portugal (Manatschal & Bernoulli 1999).

The post-rift history of the South-Alpine margin was characterized by prolonged thermal subsidence contemporaneous with the opening of the Liguria-Piemonte segment of the Alpine Tethys. The margin sank to bathyal depth as suggested by the encroachment of deep oceanic facies onto the distal margin in the west (Canavese, Lombardian Basin); the Trento High, of which the Dolomites were now part and which persisted as a carbonate platform into the early Middle Jurassic, was submerged forming an isolated, current-swept pelagic plateau, and only the Friuli area remained as a Bahamian-type carbonate platform throughout the Cretaceous (Fig. 5). From the Middle Jurassic to the Early Cretaceous, increasing water depth and palaeoceanographic changes determined the facies of the increasingly sediment-starved margin, culminating in the deposition of the Middle-Upper Jurassic radiolarites in Lombardy.

In Early Cretaceous times, the Cretaceous orogeny of the Eastern Alps began to influence the sedimentation in the Southern Alps. In the «Neocomian» (Puez Marls) and in the Aptian-Albian, hemipelagic marls were deposited, finally the Upper Cretaceous flysch deposits in the north reflect the early orogenic (pre-Gosau) movements in the Austroalpine realm. This Alpine tectonic evolution of the Southern Alps is the topic of the contribution by Doglioni (this volume).

6. Conclusions

During its post-Variscan, Mesozoic evolution, the area of the future Southern Alps underwent three phases of extension: (1) post-Variscan extension in the Early Permian that was accompanied by high-temperature, granulite-facies metamorphism and magmatic underplating by basaltic melts in the deep crust, and basin formation, shallow intrusion of granitoids and volcanic extrusions (e. g. Bolzano) in the shallow crust; (2) extension, probably combined with transtension and transpression, and shoshonitic igneous activity in the Middle Triassic in the eastern Southern Alps that most probably were related to the evolution of the young Maliac-Meliata Ocean to the east; (3) Late Triassic to Middle Jurassic extension that led to the formation of a new passive continental margin, segmented by basins and plateaus, and the opening of the Alpine Tethys to the west. These different «phases» of extension are not obviously related to each other although pre-existing faults may have played a major role in the localization of strain during the later tectonic evolution, whereas the different thermo-tectonic events may have determined the future rheology of the crust.

Acknowledgments

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