Pyrenees, Alps, Northern Carpathians, Greater Caucasus: Essay of comparison

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Abstract. A brief analysis of the Alpine evolution and modern structure of the outer chain of the Alpine-Himalayan belt in Europe shows the main features of evolution and structure of these edifices, along with some important differences. The Pyrenees and Greater Caucasus, on the one hand, have much in common, as do the Alps and Carpathians, on the other hand. Transcurrent movements along a fault separating stable Eurasia in the south from the microcontinents detached from Gondwana – Iberia, Apulia, Tiszia and Transcaucasia, played a substantial role in the evolution and formation of these edifices, thus, their origin is due not to a simple orthogonal divergence and convergence, but to transtension and transpression.

Key words: Pyrenees, Alps, Northern Carpathians, Greater Caucasus, geotectonic evolution

Introduction

The Pyrenees, Alps, Northern Carpathians and Greater Caucasus (including the Crimea Mts. and Kopetdagh) form the outer row of young fold-nappe edificies of the Alpine-Himalayan belt in Europe and Western Asia (Fig. 1). The Pyrenees, Alps and Northern Carpathians lie in direct continuation of one another, and the Crimea, Greater Caucasus and Kopetdagh, also form a continuous chain that is displaced relative to the first three, to the south along the Teisseyre-Tornquist lineament, active during all the time of their Alpine evolution (Kopp 1996). Despite this, all four edifices considered in this paper have much in common, not only in their position, but also in their Mesozoic-Cenozoic evolution and in their modern structure. However, notable differences exist between them, especially between the Pyrenees and Greater Caucasus on the one hand, and Alps and Carpathians on the other. The purpose of this paper is just to stress the common features and to show the differences between these edifices and to try to explain some causes of the latter.

Evolution (Table I)

Nature of Pre-Mesozoic basement

All four edifices concerned possess a Pre-Mesozoic metamorphic basement. This basement consists of three main entities:

1) Upper Paleozoic molasse complex, comprising Carboniferous coal-bearing lower molasse and Permian red, coarse, clastic upper molasse, both with some volcanic material, slightly metamorphosed and deformed;

2) Lower Paleozoic carbonate-terrigenous suite, comprising Ordovician-Devonian ophiolites and island arc volcanics, all metamorphosed to the greenschist or amphibolite facies, and participating in a Hercynian nappe structure;

3) Cadomian (Baikalian, Pan-African) metamorphic assemblage, rifted during the Cambrian – Early Ordovician. At the beginning of Late Paleozoic the Alps were situated between the rising Central Europe Variscan orogen and the Gondwana passive margin. The same situation is seen to have occurred in the Greater Caucasus because a Cadomian age now is established for the Dzirula Massif of Georgia (Zakariadze et al. 1998) and could be suggested for the Northern Carpathians, forming the direct continuation of the Alps.

A special case is represented by the southern-slope zone of the Greater Caucasus. There a deep–marine, mainly terrigenous sequence of Devonian or Silurian, to Triassic sediments is developed. It probably represents sediments derived from the continental slope and rise of the epi-Cadomian Gondwana margin and was deformed and slightly metamorphosed at the Triassic-Jurassic border time, during the Early Cimmerian orogeny.

Early Mesozoic quasi – platform cover

After the end of the Hercynian orogeny, the area of all four edifices became for some time a part of the epi-Variscan West European or Scythian platform or, more strictly speaking, of their southern margin. In the Alps, Northern Carpathians and the Greater Caucasus we see in the Triassic a transition from a purely epicontinental, mainly lagoonal and clastic sedimentation to the conditions of an outer carbonate shelf, characteristic of the Austroalpine and Inner Carpathian domain and of the northern slope of the Greater Caucasus.

Rifting stage

By the beginning of the epoch this quiet platformal evolution was interrupted by extension and rifting. This occurred at different times in each of the edifices and had different consequences. In the Alps and Carpathians rifting

Table 1

	PYRENES	ALPS		N. CARPATHIANS		GREATER CAUCASUS	
		N	S	N	S	N	S
N_1^3 - Q					Volcanism	Foredeep formation, Volcanism, Granites	
P_3 - N_1^{1-2}	Foredeep formation, Molasses	Foredeep formations, Molasses, Granites		Foredeep formation, Molasses	Molasses	Foredeep formations Molasses	
K_2 - f_2	Flysch	Flysch	HP/LP metamorphism Flysch	Flysch	Shallow marine deposits	Epicontinental shallow marine deposits	
J_3 - K_1	Black shales, Rifting	Rifting, Spreading Epicontinental shallow marine deposits	HP/LP metamorphism Schistes lustres	Spreading Epicontinental shallow marine deposits	Molasses Neritic and bathyal deposits	Epicontinental shallow marine deposits	Flysch
J_{1-2}			Spreading Neretic a. bathyal deposits			Paralic coal-bearing formation, Volcanics	Black shales, Bimodal volcanics, Rifting
T	Epicontinental lagoonal deposits	Epicontinental lagoonal deposits	Rifting Shallow marine deposits	Epicontinental lagoonal deposits	Rifting, Spreading	Shallow marine deposits	Accumulation of continental slope a. rise, Terrigenous deposits
PZ_2	Molasses, Volcanics, Granites	Molasses, Volcanics, Granites	Molasses + shallow marine deposits, Volcanics, Granites	Molasses, Volcanics, Granites	Molasses, Volcanics, Granites	Molasses, Volcanics, Granites	
PZ_1	Metamorphic complex	Metamorphic complex, Ophiolites	Metamorphic complex	Metamorphic complex, Ophiolites	Metamorphic complex	Metamorphic complex, Ophiolites	
PR_3		Metamorphic complex				Metamorphic complex	

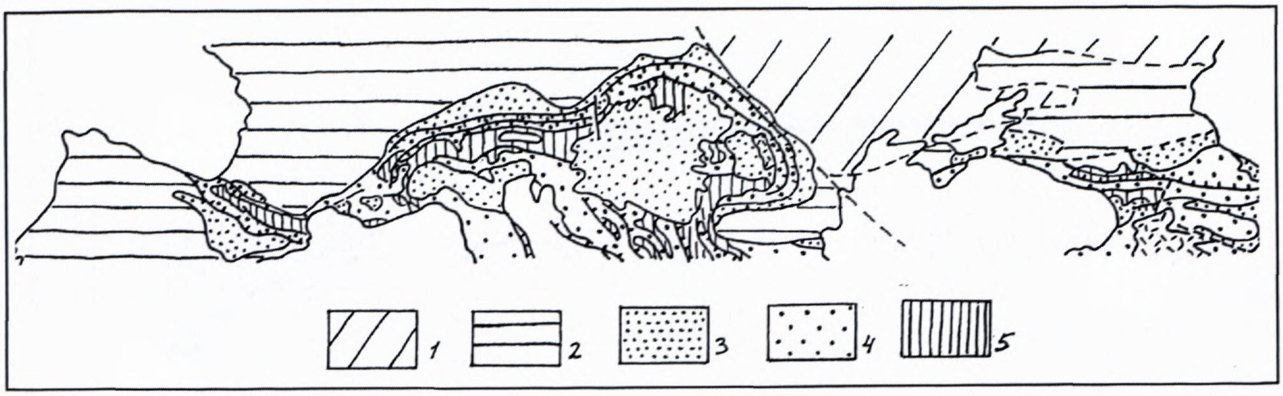

Fig. 1 The outer row of the nappe-fold edifices of the Alpine-Himalyan belt of Europe and Western Asia

already began during mid-Triassic time and led to the differentiation of their sedimentation area into relatively elevated and depressed blocks, with an accumulation in the latter of bathyal carbonate and siliceous (radiolarites) deposits. In the Pyrenees rifting took place during Aptian-Albian time, synchronously with the opening of the Bay of Biscay; this was accompanied by the deposition of black shales. In the Greater Caucasus rifting occurred at the very beginning of the Jurassic and ultimately created the deep marginal basin of the Neotethys, the main trunk of which passed through the central Lesser Caucasus.

Only in the Alps and Carpathians was continental rifting succeeded by spreading, documented by the presence of ophiolites. The rift-drift transition occured most early in easternmost Alps and Western Carpathians, manifested by the development of the Hallstatt-Meliata Ocean during the Middle Triassic. Then came the turn of the Liguro-Piemont Ocean, appearing in the Bathonian after two rifting phases, Hettangian-Sinemurian and Late Toarcian – Middle Jurassic (Froitzheim and Manatschal 1996). Spreading in this oceanic basin lasted until the end of Early Cretaceous. Meanwhile, during the Late Early Cretaceous, another narrower basin with oceanic crust, the Valais Basin appeared, presumably in the western prolongation of the Bay of Biscay and Pyrenees rift. During the Late Jurassic and Early Cretaceous, the Liguro-Piemont Ocean became the site of deposition of the „Schistes lustres" (Bundnerschiefer) formation.

In the Carpathians also, a second narrow oceanic basin (in addition to the Meliata one) was formed by the end of Jurassic. Its scarce remnants are preserved in the form of ophiolite detritus in the Pieniny Klippen belt (Mišík 1978). It disappeared later due to subduction of its crust under the Inner Carpathians.

In the Greater Caucasus rifting continued during the Early and Middle Jurassic but it is doubtful whether there was true spreading. The very thick black shale formation of that age contains volcanics of the spilite-keratophyre type and is similar to the Devonian of the Rhenohercynian zone of the European Variscides. Some basalts are even petrochemically akin to MORB. It seems most probable that extension of the pre-Alpine continental crust led only to its attenuation and transformation into crust of transitional type between continental and oceanic (suboceanic type).

Recently Lomize (1996) proposed a model of the development of the Greater Caucasus Jurassic basin (Fig. 2), based on the Wernicke pure-shear model, originally proposed for the Great Basin structure of the North American Cordillera. It is interesting that the same model was used by Froitzheim and Manatschal (1996) for the Central Alps, but for this domain they were able to show the transition from rifting to spreading.

Beginning of convergence and basin closure

Extension, creating the basins which later became the site of the fold-nappe edifices considered in this paper was followed by convergence and compression, leading, finally, to the closure of these basins and deformation of their infilling.

If we disregard the problematic manifestation of compression in the Greater Caucasus at the end–Middle Jurassic, which allegedly produced a ridge separating the flysch trough of the southern slope from an epicontinental basin of the northern slope, and envisage it rather as an effect of the prolonged rifting-upheaval of the rift shoulder – the earliest true compression began in the Eastern Alps and Inner Carpathians during the second half of the Early Cretaceous – the so called Austrian orogenic phase. This was also the beginning of the HP/LT metamorphism, provoked by the subduction of the Liguro-Piemont oceanic crust under the Apulian and Austroalpine margin (Marchant and Stämpfli 1997). According to these authors, the beginning of the closure of the Liguro-Piemont ocean was connected with the opening of the Valais ocean. This was also the time of the closure of the Meliata-Transylvanian Ocean on the southern border of the Austroalpine microcontinent and its Tiszia eastern prolongation. Subduction of the crust of this ocean already began during the Late Jurassic.

The next compression impulse was manifested in the Alps during the Senonian, and it attained its culmination in the Pieniny Klippen belt in the Carpathians at the Cretaceous/Paleogene border. But these Cretaceous compressive phases did not affect the Pyrenees and probably also the Greater Caucasus, where in the Early Cretaceous a new phase of rifting occured, as well as in the Crimea (Kopp and Khain 1996).

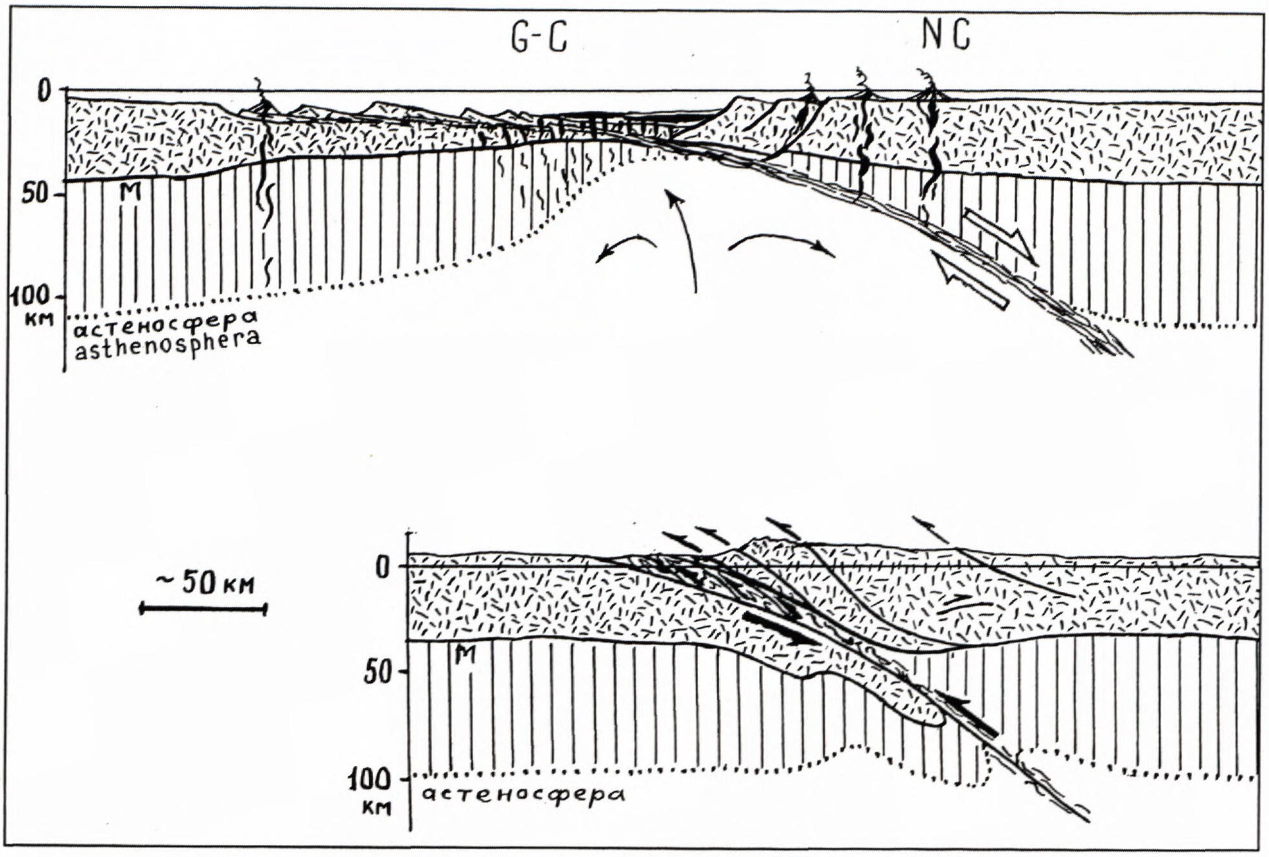

Fig. 2 Evolution of the Greater Caucasus according to Wernicke model (after M. G. Lomize)
GC – greater Caucasus, NC – northern slope

Collision and orogeny

The quiet evolution of the Pyrenees lasted until the Middle Eocene and was succeeded in the Late Eocene by an episode of strong compression as a result of the collision of the Iberian and Eurasian plates – the Pyrenean orogenic phase of Stille. The end-Eocene compression also marked the collision of Apulian and Eurasian plates and was most important in the Alpine tectonic history of the Alps, coinciding with the final creation of a thermal dome in their center that was closely followed by granite plutonism. However, in the Outer Carpathians the deformation only began during the Late Oligocene and attained its culmination during the Middle Miocene. The main phase of compressive deformation was manifested in the Greater Caucasus even later, by the end of Miocene. There is was produced by the northward shift of the Arabian plate after its separation from the African plate and opening of the Red Sea rift. But at the end of the Eocene the Greater Caucasus was already affected by a compressive impulse, leading to the beginning of its inversion, of the formation of molasse basins on its periphery, and of huge olistostromes descending from the flanks of the rising orogen toward these basins.

By the latest Miocene the formation of the fold-nappe mountain edifices of the Pyrenees, Alps and Carpathians, and of their molasse foredeeps was practically completed except for the burst of subaerial volcanism on the southern flank of the Carpathians. In the Greater Caucasus, especially its eastern part, the Pliocene-Quaternary evolution was quite different and very active. The formation of northern foredeeps and southern intermontane basins continued and at the end of the Pliocene and the beginning of the Quaternary strong fold–and–thrust deformation, and even of nappe development took place in the Terek and Kura basins on both flanks of the Greater Caucasus. Also volcanism occurred in its central part and granite intrusions were formed in places. The youngest of these igneous events dated at 2 Ma ago.

Structure

Crustal structure

Among the four edifices considered in this paper, the Pyrenees have the simplest and most symmetric structure. They form an axial ridge with exposures of Paleozoic basement rocks at their flanks composed of Mesozoic and Paleogene rocks that have folds, thrust faults and nappes, directed toward the Aquitaine and Ebro molasse basins to the south. But the magnitude of outward transport was notably larger on the southern than the northern flank.

The structure of the Greater Caucasus is more complicated than that of the Pyrenees. The dominant vergence is southward in the east, in the direction of Kura Basin.

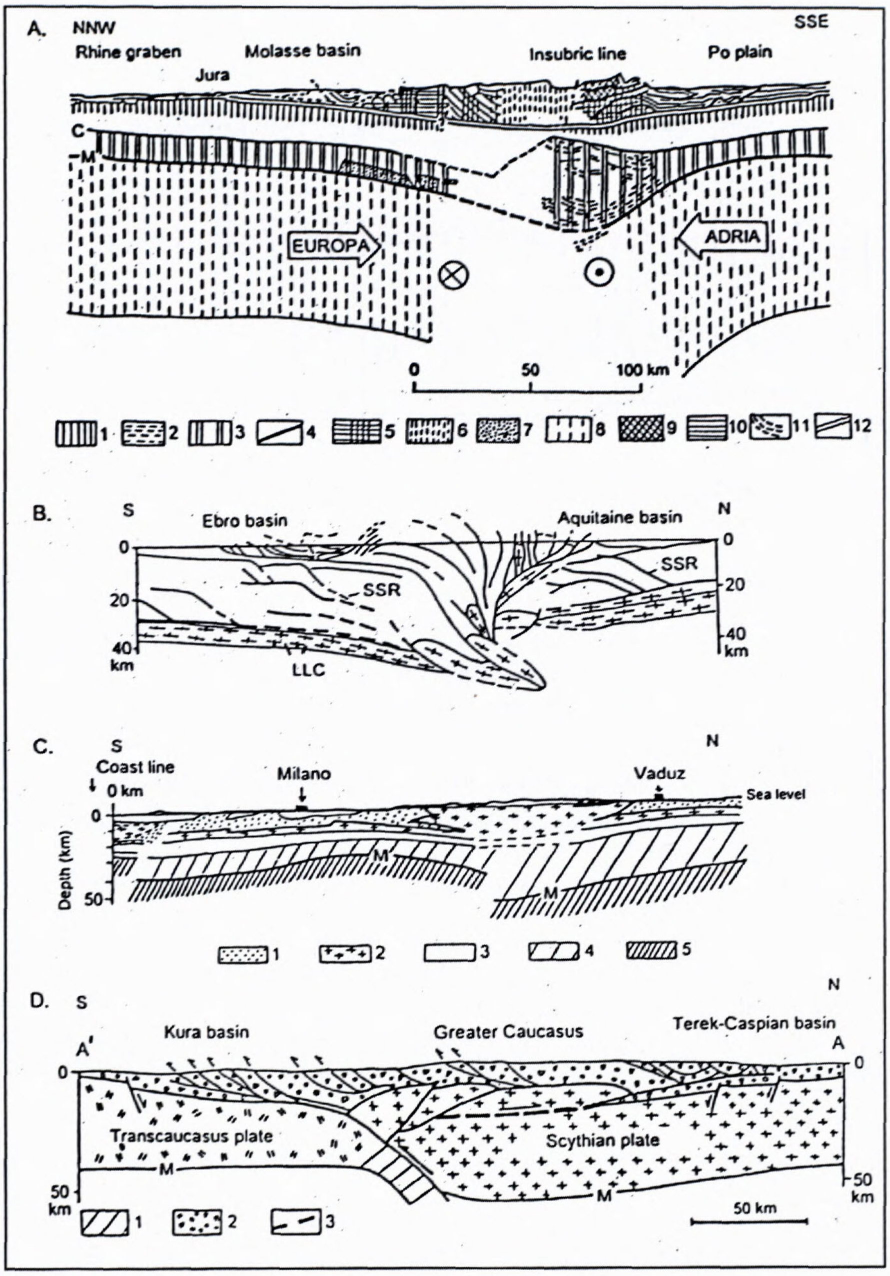

Fig. 3 Deep seismic profiles through some orogenic edificed of the Alpine-Himalayan belt.

***A.** Central Alps, according to the geological interpretation of Laubscher (1994).*
Legend: 1 – crystalline basement of foreland, 2 – Helvetic nappes, 3 – lower crust from refraction, 4 – refraction Moho, 5 – external massifs of Jura phase, 6 – Penninic domain, 7 – European lower crust, 8 – mantle lithosphere, 9 – external massifs of earlier phases, 10 – post-Tortonian, 11 – lower crust imbrications stack, approximate, 12 – Jura phase basal front (brittle-ductile transition).

***B.** Pyrenees, after Choukroune et al. (1990).*

***C.** Alps and Northern Apennines, after Cassonis et al. (1990), highly simplified.*
Legend: 1-3 – upper crust (1 – sediments, 2 – granites), 4 – lower crust, 5 – mantle.

***D.** Eastern Greater Caucasus, after Sobornov (1994).*
Legend: 1 – oceanic crust, 2 – sediments, 3 – wave guide

These was also some retro-thrust faulting at the western and eastern ends of the northern slope. The amount of tectonic transport of nappes on the southern slope attains 70 km. Nappes are also known in the Paleozoic basement; they are north-vergent as opposed to the southerly direction of the vergence of the alpine structure.

The scale of nappe development in the Alps and Carpathians is known; its amplitude is much more than 100 km and the amount of shortening attains several hundred kilometers. These differences between Pyrenees and Greater Caucasus, on the one hand, and the Alps and Carpathians, on the other, are reflected in the shape of the respective orogens – linear in the case of the two former and arcuate, convex toward northwest, north and northeast, of the two latter. And, in their turn, these differences are due to different conditions of plate convergence. This convergence was orthogonal in the case of Pyrenees and Greater Caucasus, with crustal subduction of the Iberian plate under the Eurasian in the Pyrenees and of the Transcaucasian plate also under the Eurasian in the Greater Caucasus. In the case of the Alps the Apulian (Adriatic) plate played the role of indenter, and in the case of Carpathians, the Austroalpine – Tiszia plate, pushed to ENE by the Apulian plate.

Deep structure

From the reflection and refraction profiling of the last decades we now possess adequate representation of the deep lithospheric structure of the Pyrenees, Alps and Western Carpathians, for the Alps we also have a tomographic profile. For the Eastern Carpathians and Greater Caucasus however, only refraction DSS profiles are available. Despite this lack of data, we may infer some analogy with the deep structure of better explored edifices.

It seems that the main common feature of the construction of all edifices, especially the better studied ones, is the structural disharmony between the three principal layers of the lithosphere – the upper crust, the lower crust and the lithospheric mantle. While the lithospheric mantle and lower crust of the lower of the

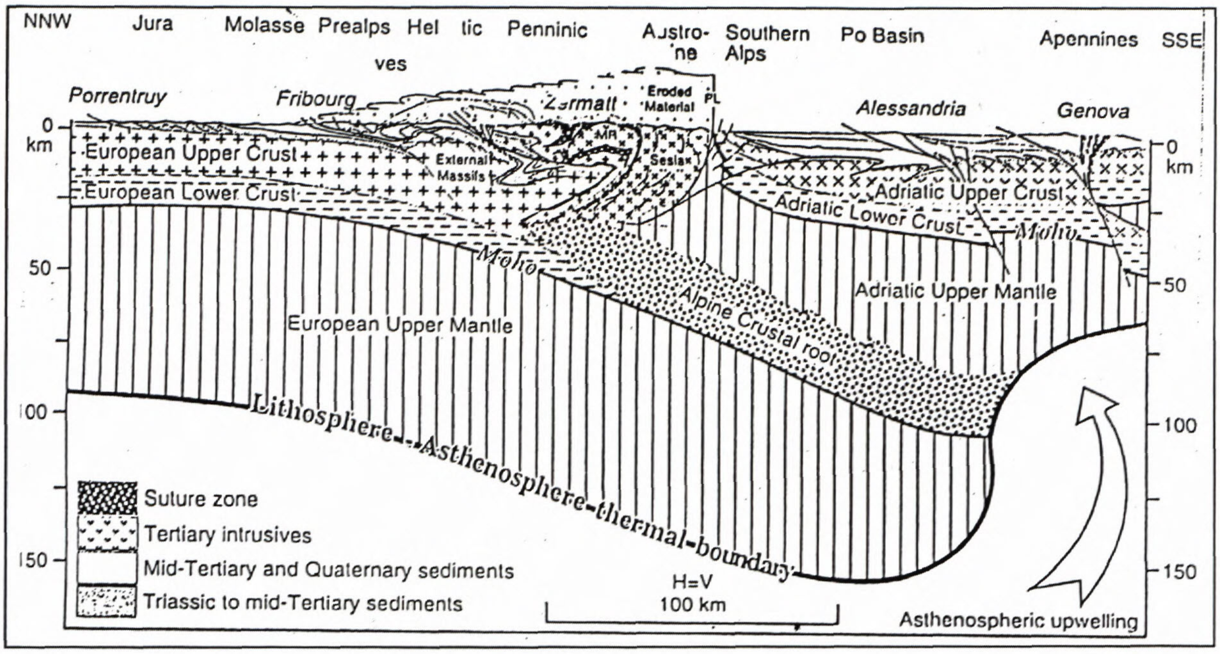

Fig. 4 Lithosperic cross-section along the NFP-20 Western traverse (after Marchant, 1993). MR – Monte Rosa nappe, PL – Periadriatic line

colliding plates were subducted and partly absorbed in the astenosphere, the lower crust of the lower plate was partly squeezed and expulsed up even to the surface, and the upper crust of both plates was piled up, or stacked, thereby producing the antiformal structure of the mountainous edifice. This is most clearly expressed in the Pyrenees and Alps profiles (Figs. 3, 4). In detail, this picture is very complicated, with even some lateral indentation of layers. It must also be stressed that there has been a large amount of the subduction of the European continental crust under the Alps and Carpathians.

Role of strike-slip faulting

The existence of large longitudinal strike-slip faults is well recognized in the Pyrenees; the North Pyrenean fault and the Kopetdagh border fault on the other side of the Caspian Sea are similar structures. These faults are more conspicuous in the Alps and especially in the Carpathians, where they must be invoked to explain the formation of their oroclinal bend and are involved in the evolution of their earlier connection with the oceanic basins of the Alpine and Carpathian domains (Dal Piaz et al. 1995). The sense of movement along these faults changed; it was sinistral until the Mid-Cretaceous and dextral thereafter.

Conclusion (Table II)

All four edifices considered in this essay are situated along the southern margin of the Eurasian lithospheric plate, which was a passive margin during all of their Mesozoic-Cenozoic evolution. The southern border of these edifices at the time of the beginning of their Alpine evolution was represented by microplates – fragments of Gondwana (Africa) – Iberia, Apulia, Transcaucasia. The Austroalpine – Tiszia microplate primarly belonged to Eurasia, but later they played the role of hinterland, with respect to Eastern Alps and Carpathians.

Initially, all four edifices possessed a metamorphic Hercynian-Cadomian basement and, during part of the Mesozoic evolution, acted as a part of the epi-Hercynian West European or Scythian platform. One exception was the actual Greater Caucasus southern slope, which from Devonian or even earlier time showed conditions of continental slope and rise, probably of the Gondwana margin subsided.

This platformal regime was the shortest-lived, it lasted only to the Middle or Late Triassic in the Carpathians (Southern slope), to Early Jurassic in the Greater Caucasus, to Bathonian in the Western and Central Alps and to Aptian in the Pyrenees. Thereafter rifting and destruction of the epi-Hercynian continental crust began and thus led to its extension and to the formation of deep basins on oceanic (Alps, Carpathians) or of transitional – suboceanic (Greater Caucasus) or of attenuated continental (Pyrenees) crusts. A second episode of rifting–spreading took place during the Late Jurassic (Pieniny Klippen Belt) or mid-Early Cretaceous (Valais) in the Carpathians and the Alps, respectively.

The first manifestations of compression were felt in the Carpathians and possibly Greater Caucasus at the end of Middle Jurassic and the Late Jurassic, but an important deformation began in Eastern Alps and Inner Carpathians during mid-Early Cretaceous and was repeated in the Senonian. This compresion was the result of the subduction under the microplates the oceanic crust to the south. These deformations of were followed by the beginning of flysch accumulation, which attained its largest expansion during the Late Cretaceous and Early Paleogene.

Collision began during the Late Eocene in the Pyrenees and in the Alps, during the Late Oligocene–Early Miocene in the Carpathians and during the Miocene in the Greater Caucasus. In the eastern part of the Greater Caucasus, as well as in the Eastern Carpathians, the deformation was renewed at the Pliocene – Quaternary boundary.

The amount of extension, and the width, depth and character of the crust of the original marine basins had a fundamental implication on the future architecture of the orogenic edifices: these determined the degree of shortening and the complexity of this structure. The degree of shortening was approximately 100 km for the Pyrenees, 200-250 km for the Greater Caucasus and several hundreds of kms for the Alps and Carpathians. In this respect, the Alps and Carpathians could be called hypercollision orogens.

Table 2

Edifices Features	PYRENEES	ALPS	N. CARPATHIANS	GREATER CAUCASUS
Initial opening of the Alpine basin	Late Aptian	Bathonian (S) Aptian (N)	Mid-Triassic (S) End-Jurassic (N)	Sinemurian
Nature of basin crust	Attenuated continental	Oceanic	Oceanic	Suboceanic
Ophiolites	Absent	Present	Present	Absent
Time of main deformation	Late Eocene	Late Eocene	Mid-Eocene	Late Miocene
Regional metamorphism	Absent	Present (inc. HP/LT)	Present (inc. HP/LT)	Absent
Alpine granite plutonism	Absent	Present	Present	Present
Shape	Linear	Arcuate	Arcuate	Linear
Vergence	Mainly Southern	Northern	Northern	Southern
Nappe amplitude	n x 10 km	> 100 km	> 100 km	n x 10 km
Sense of plate convergence	EU IB	AP EU	TI EU	EU TR
Recent volcanism	Absent	Absent	Present	Present
Basement	Hercynian	Hercynian + Cadomian	Hercynian + Cadomian	Hercynian (N) + Cadomian (S)

Finally, the important role played by the transcurrent faulting in the evolution of the Alpine edifices considered here must be stressed again.

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