
PANCARDI
Svalbard
Barents Sea
Atlantic Ocean
Caledonides
Pechora Basin
Timanides
East-European Craton
Variscides
Alps
Carpathians
PANCARDI
Pericaspian Basin
Black Sea
Caspian Sea
Mediterranean

# PANCARDI

## Dynamics of Ongoing Orogeny

*by Čestmír Tomek (Salzburg) and PANCARDI colleagues*

The Pannonian Basin, Carpathian arc, Dinaride (PANCARDI) system offers an outstanding opportunity to study the interaction of asthenospheric and lithospheric processes and their mutual dependencies during volcanic arc and related fore- and back-arc basin development. The evolution of the highly arcuate Carpathians is driven by the interrelated processes of subduction, slab roll-back, plate boundary retreat into a continental embayment, asthenospheric up-welling, and lateral extrusion of the eastern Alps and Dinarides-Balkan orogens. The arc is unique in providing a snapshot of still-active, soft collision between the Carpatho-Pannonian and Eurasian plates. Another remarkable feature of the region is the interplay of contraction, strike-slip and extension which led to the formation of the Pannonian Basin, with the coeval radial displacements of nappes and the progression of volcanism during formation of the Carpathian arc. This scenario and the seismicity in the Vrancea zone, apparently related to slab detachment, provide key constraints on the relative role of lithospheric and asthenospheric driving mechanisms during orogeny.

The PANCARDI region, with its subaerial exposure and large existing data base, provides a ready opportunity for gathering new information critical to our understanding of orogen dynamics.

Within the context of a multidisciplinary investigation of the whole lithosphere, PANCARDI has a particular focus on the following main goals:

1) Reconstructing the Neogene to Quaternary evolution of the arc-basin system, with kinematic and palaeomagnetic constraints contributing to the palinspastic restoration of the orogen.
2) Relating the long-term processes of subduction, arc formation and basin development to the neotectonics and the on-going seismicity, providing a basis for seismic hazard assessment and earthquake engineering in this densely populated area.
3) Understanding the origin of the nearly vertical Vrancea slab, as it is defined by seismicity in the mantle below the foothills of the eastern Carpathians.
4) Establishing the Miocene to Recent magmatic history of the Carpathian arc; defining the sources of the calc-alkaline and alkaline magmas that were coupled in time and space to the west-to-east progression of deformation in the foreland fold and thrust belt.
5) Understanding the chemical evolution of the mantle lithosphere beneath the Pannonian Basin and the relative importance of subduction and plume-related processes.
6) Assessing the significance of collisional thickening, extensional unroofing and lateral extrusion in the eastern Alps and Dinarides for Pannonian Basin development.

### Introduction

On-going orogeny in central Europe is dramatically expressed today in the rise of the Alps and Carpathians and the earthquakes of the Vrancea zone. Understanding the driving mechanisms for this tectonism requires knowledge of lithosphere-asthenosphere relationships beneath the region and how these have changed during the Cenozoic. Today's expression of the neotectonics is only a snapshot of an orogenic process which started in the Mesozoic; it involved Palaeogene continental collision in the eastern Alps and the Balkans and Neogene subduction further east, with the development of the Carpathian volcanic arc and back-arc Pannonian Basin. This complex interplay of Alpine and Dinaric collisions and inferred lateral extrusions, Carpathian subduction and Pannonian extension, provide the scenario for EUROPROBE's PANCARDI project (Fig. 2.1). An integrated multidisciplinary analysis of the four main tectonic elements, the Carpathian arc, the Pannonian back-arc basin and the eastern Alpine and the Dinaride collision zones, provides the basis for a palinspastic reconstruction of their Cenozoic evolution – the essential background for interpreting the on-going tectonics.

## Development of the Research Plan

Research institutes from Austria, Bulgaria, Canada, Croatia, Czech Republic, Denmark, France, Germany, Greece, Great Britain, Hungary, Italy, Poland, Romania, Slovakia, Slovenia, Switzerland, the Ukraine and USA are involved in the PANCARDI project. The science plans for PANCARDI have been developed at several workshops in Warsaw (1991), Bad Herrenalb (1993), Csopak (1993), Covasna (1994) and Stará Lesná (1995). The project involves the territories of ten countries and protocols establishing the basis for collaborative research have been signed by several eastern and central European research institutions.

## Geological Framework

The Carpathian arc and Pannonian back-arc basin are interrelated components of the Mediterranean arc-basin complex (Fig. 2.2). Much of the latter is submarine and the entirely subaerial PANCARDI region is therefore particularly favourable for new integrated geoscientific investigations. The PANCARDI region has been studied for more than a century and there is a wealth of existing geological, geochemical and geophysical data, some of which has not previously been available to the international community. Milestones for the present understanding of the geology were Lugeon's (1903) recognition of the nappe structures in the Carpathians and Uhlig's (1907) interpretation of Cenozoic thrusting of the Carpathian flysch belt over the East-European Craton. Stille (1953) connected the eastern Carpathian Neogene volcanism with the subduction of continental crust. The classical period of pre-plate tectonic geology culminated in an excellent book summarising the Carpathians by Andrusov (1968). Thereafter, Roman (1970) recognised active oceanic subduction in the southeastern Carpathians and Bleahu et al. (1973) published the first plate tectonic interpretation of the entire Carpathian arc. Mahel's (1974) initial tectonic map of the Carpathian-Balkan mountain system is still widely used. Burchfiel (1980) emphasised the close links between the dynamic evolution of the Carpathians, the eastern Alps and the Pannonian Basin; and in 1984, a landmark volume on Romanian geology was published by Sandulescu.
A fundamental new understanding of the processes leading to the formation of these Mediterranean arc-basin systems was triggered by a series of papers by Horvath and Royden (see Royden et al., 1983 and Royden and Horvath 1988). Recently, Ratschbacher et al. (1991) have developed the extrusion hypothesis, explaining the escape of the eastern Alps into the

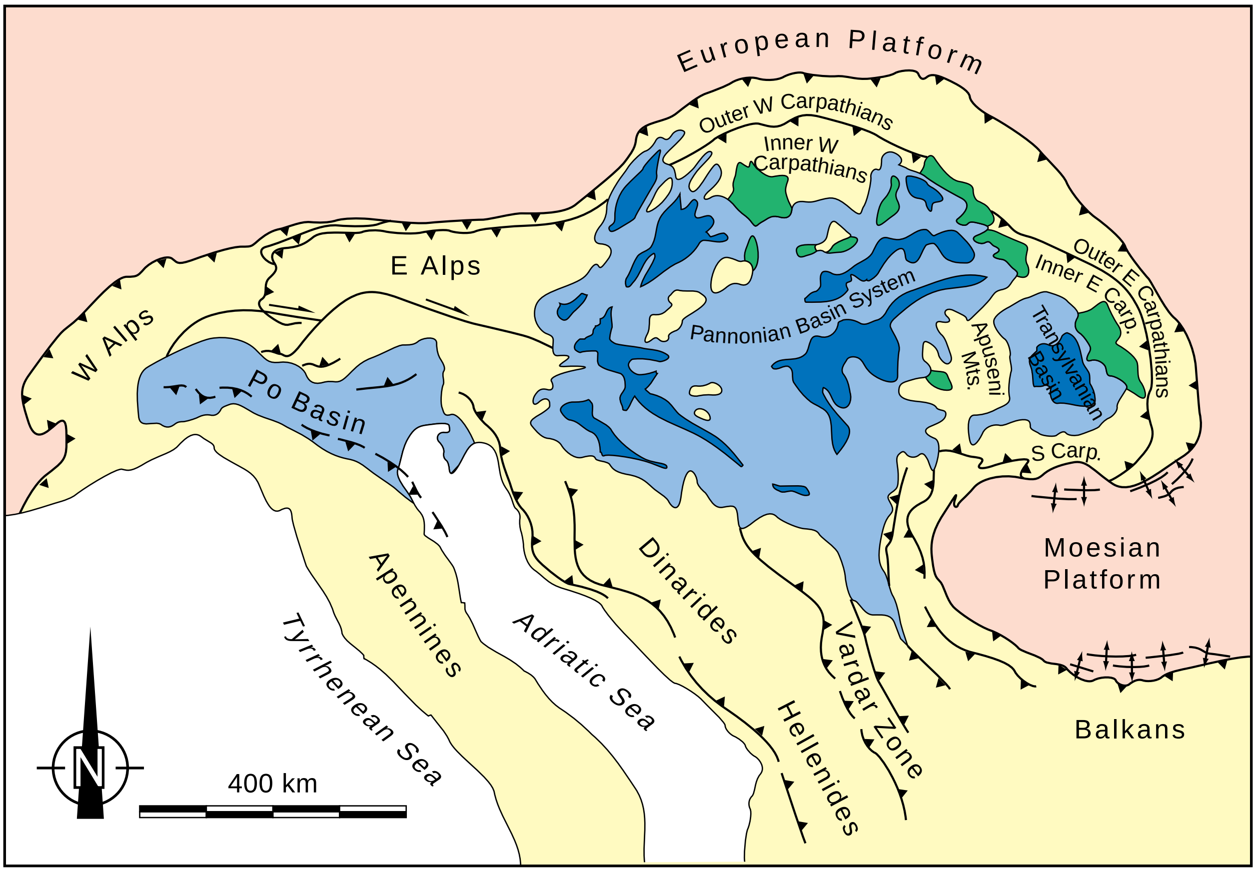


*Figure 2.1: Main tectonic elements of PANCARDI. Yellow: Alpine orogenic arcs; intermediate blue: Neogene basin fill; dark blue: Quaternary basin fill; green: Neogene volcanics.*

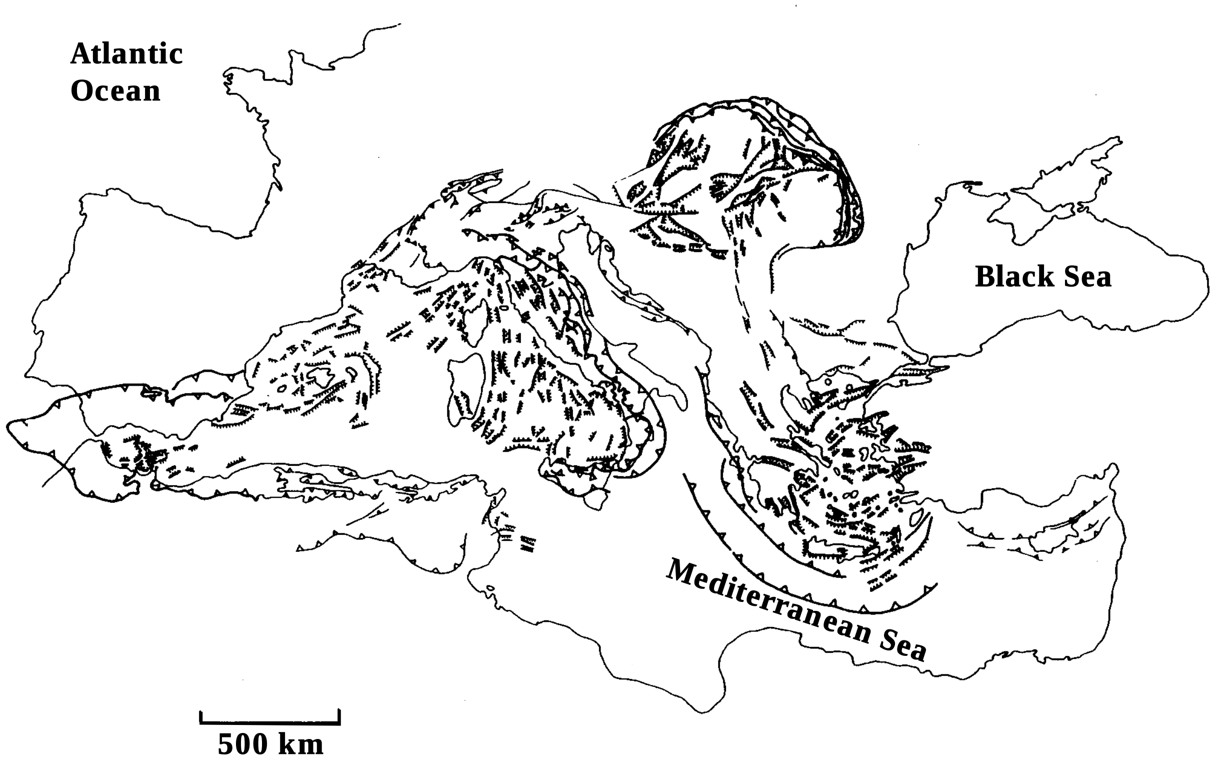


*Figure 2.2: Miocene to Quaternary thrust and extensional faults in the Mediterranean Region (from Royden, 1988).*

Carpathian area during Neogene subduction.

### The Carpathian arc

The Carpathian Mountains extend over a distance of nearly 1500 km and curve through an arc of over 250°. Accretion to the European foreland started in the west in the Oligocene and progressed eastwards, with accompanying arc volcanism, during the Neogene. The historical seismicity of the Vrancea zone in Romania is inferred to be the final expression of the progressive subduction, slab roll-back and plate boundary retreat that were responsible for the evolution of the arc. This focus of seismic activity in Romania represents the most severe seismic hazard in Europe today; every century, there are highly destructive events with about ten earthquakes of magnitude greater than 6.0 (Fig. 2.3).

The shape of the Carpathian arc was apparently dictated by the Mesozoic geometry of an embayment in the European passive margin. A flexural foredeep basin developed first in western areas near Vienna and migrated eastwards; the youngest successions in the basins are 18 Ma in the west and 11 Ma in the southeast. Thrust over the foredeep strata is an accretionary wedge of Mesozoic and Tertiary flysch (the Moldavides), which can be followed over the entire length of the arc. None of the overlying tectonic units have a similar distribution, being derived from two essentially different Alpine complexes. Whereas the other Mediterranean arc-basin systems developed by extension of single collisional orogens, the inner Carpathians contain components of two different pre-Oligocene mountain belts. The western Carpathians have a similar pre-Oligocene history to that of the eastern Alps to which they are connected; they consist of three Alpidic zones and one related to the Dinarides. In contrast, the internides of the eastern and southern Carpathians are composed of thrust sheets derived from early and mid Cretaceous orogens that can be followed southwards around the Moesian "bend" into Bulgaria and the Balkans (Fig. 2.1).

The three Alpidic zones of the western Carpathians were formed by a succession of oceanic subduction and collisional events occurring in Late Jurassic to Early Cretaceous, Late Cretaceous and Palaeogene. Deformation started in the south and migrated northwards. The earlier Mesozoic events are recorded in the Meliata and related zones (Middle and Upper Austro-Alpine; the names of the zones vary from country to country), the late Mesozoic events in the South Penninicum, and the Early Tertiary events in the Rhenodanubian and Magura zones ("Palaeogene Accretionary wedge" in Fig. 2.5). To the south of these Alpidic terranes are located the South Alpine (Bakony) and Dinaric (Bukk) zones, composed of Adriatic shelf carbonates and Tethyan ophiolites, respectively. Whereas the internides in the eastern and southern Carpathians, represented by the Danubian, Bucovinian and Transylvanian nappes, were stacked by the Mid to Late Cretaceous, all of the Alpidic and Dinaric terranes, which compose the upper plate in the western Carpathians, were only amalgamated by the Oli-

gocene.
Subduction-related calc-alkaline volcanism accompanied formation of the Carpathian arc. This magmatism, considered to result from the interaction between fluids derived from the subducted ocean crust and the overlying mantle, started in the Miocene in the west and migrated eastwards throughout the Miocene and Pliocene, in step with the timing of arc accretion along the European margin. In the west, this volcanism was widespread; further east, it is confined to a narrow belt following the curvature of the arc. Thus, the Carpathians provide a classic example of accretion and magmatism, related to subduction.
The deep crustal structure of the western Carpathian arc has been imaged by three regional near-vertical reflection seismic profiles in the Czech and Slovak Republics (Figs. 2.4 and 2.5). The southern margin of the European basement is seen bending down toward the south into the Carpathian subduction system. Gravity anomalies along the arc are related to a thick prism of accreted flysch and molasse sediments.
Beneath the eastern Carpathians, the historical seismicity is well-defined within the limited Vrancea area, apparently related to a near vertical zone with a cross-section of 10 km NW-SE by 60 km NE-SW (Fig. 2.6). Earthquake activity is concentrated at shallow (crustal) and intermediate (60-180 km) depths; an enigmatic seismic gap exists between 40-60 km. It is speculated that the Vrancea Seismic Zone is related to a more-or-less detached lithospheric slab, perhaps the final expression of Carpathian subduction along the European margin.

### The Pannonian Basin

Subduction of European lithosphere, with associated northward and eastward thrusting of the Moldavide Nappes ("Neogene accretionary wedge" in Fig. 2.5), was accompanied by back-arc extension and development of the Pannonian Basin. The extension was heterogeneous and diachronous, and involved conjugate systems of transtensional faults. It is speculated that the style of extension at depth was partially controlled by the geometry of the older thrust systems. Marine deposition was rapid during particularly active extension in the early-mid Miocene; this was followed by thermal subsidence and continued sedimentation in a variety of connected depocentres. Neogene strata are up to 8 km thick.
Within the Pancardi system, the Pannonian Basin is geophysically quite distinct, with high heat flow re-

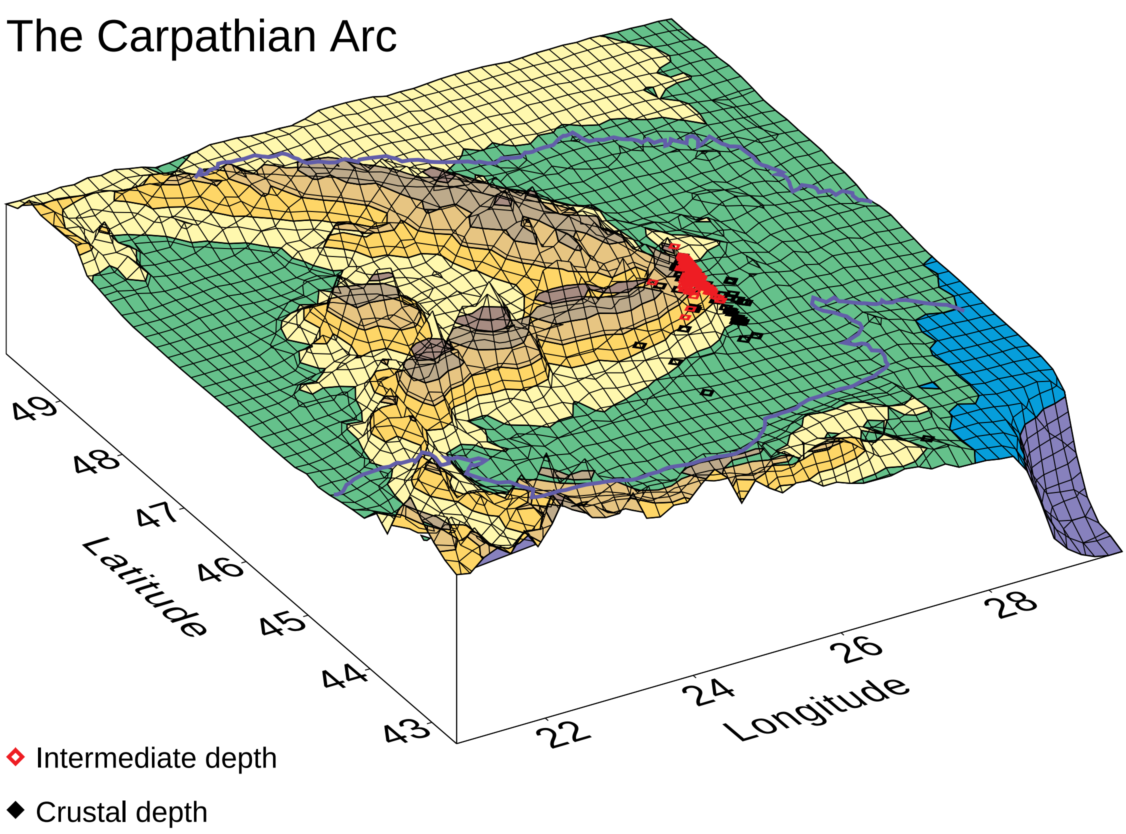


*Figure 2.3: Distribution of earthquake centres in the Carpathians. Open squares represent crustal events, red squares the intermediate depth Vrancea earthquakes concentrated in a narrow area of 20x60 km. Magnitudes of these events range from 5.0 to 7.5.*

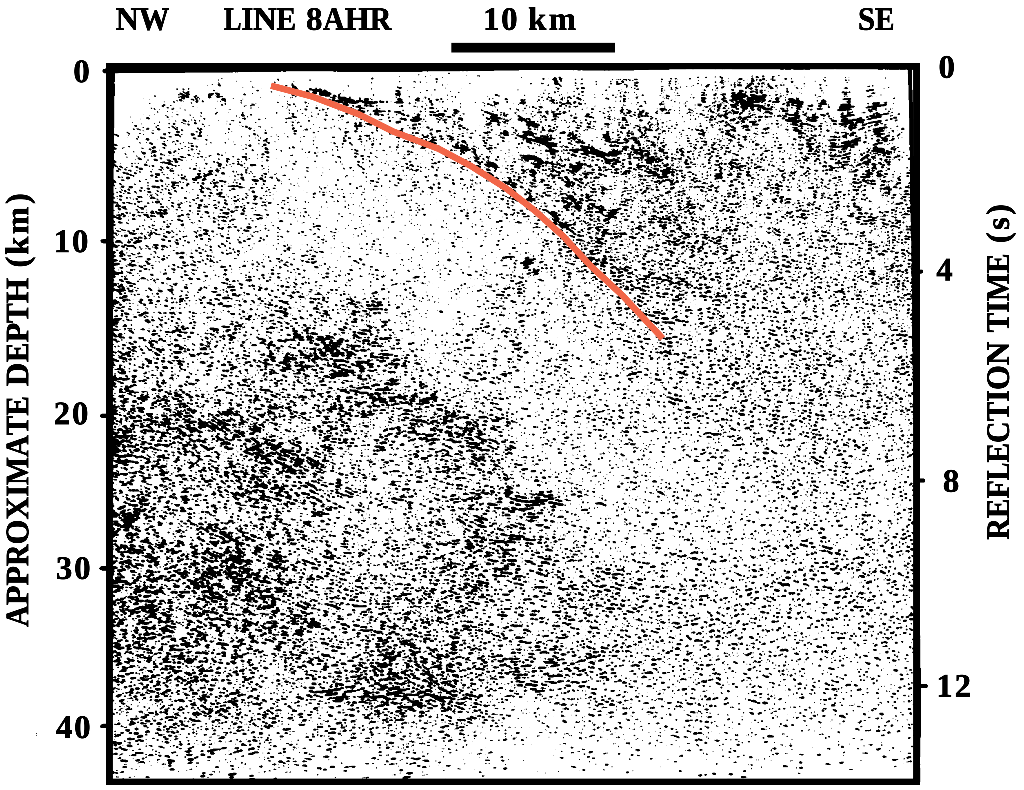


*Figure 2.4: Example of a time migrated CMP profile across the Western Carpathians (profile 5 on Fig. 2.5; modified after Tomek and Hall, 1993). The red line indicates the main Carpathian thrust.*

lated to asthenosphere up-welling and a regional positive gravity anomaly. Late Miocene and younger magmatism is alkaline and may be plume-related. The basin provides an exceptional opportunity for investigating the chemical evolution of mantle lithosphere, thanks to the widespread occurrence of spinel and garnet lherzolite xenoliths in the alkaline basalts.

East of the Pannonian Basin and a marginal horst (the Apuseni Mountains, Fig. 2.1), lies an anomalous smaller basin that has neither high heat flow nor a significant gravity anomaly. This, the Transylvanian basin (Fig. 2.1), contains 4 km of Miocene strata which comprises today a mountainous region, standing 500 m above the level of the Pannonian Basin.

### The Eastern Alps

Mesozoic and Cenozoic convergence of Europe and Africa culminated in the late Eocene in collision, crustal thickening and rise of the Alpine mountain chain. Already in the Mesozoic, the Austro-Alpine nappes (Fig. 2.5), derived from the African passive margin, had been thrust over southern Penninic oceanic assemblages. In the Eocene, the nappes were emplaced onto the Rheno-Danubian flysch and all three together were then displaced further northwards over the Helvetic flysch and shelf sediments onto the foreland molasse. These allochthons are now found arched over the Tauern window, a major antiform of late Oligocene to Recent age. Rise of the Tauern window (Fig. 2.5) has been accompanied by axial extension and extrusion of eastern Alpine allochthons towards Pannonia. Thus, whereas the Oligocene and earlier history recorded in the internide allochthons of the western Carpathians is very similar to that of the thrust sheets in the eastern Alps, the subsequent history is fundamentally different and provides a focus for PANCARDI research.

### The Dinarides

The Dinaride mountains compose the southwestern margin of the PANCARDI system. Together with the Hellenides, they compose a SW and S-verging thrust system. The outer (southern) Dinarides are similar to the southern Alps, being dominated by Mesozoic carbonate platform successions that were deformed after the Eocene and are today being thrust southwards onto the Adriatic plate. The inner Dinarides, extending northwards to the edge of the Pannonian Basin, consist of three major tectonic units. From south to north these are the Pindos Oceanic domain, an internal carbonate platform and the Vardar oceanic domain. The Pindos and associated units comprise pelagic sequences with associated ophiolites of Mesozoic age and Cretaceous to early Tertiary flysch that were thrust in the Eocene onto the

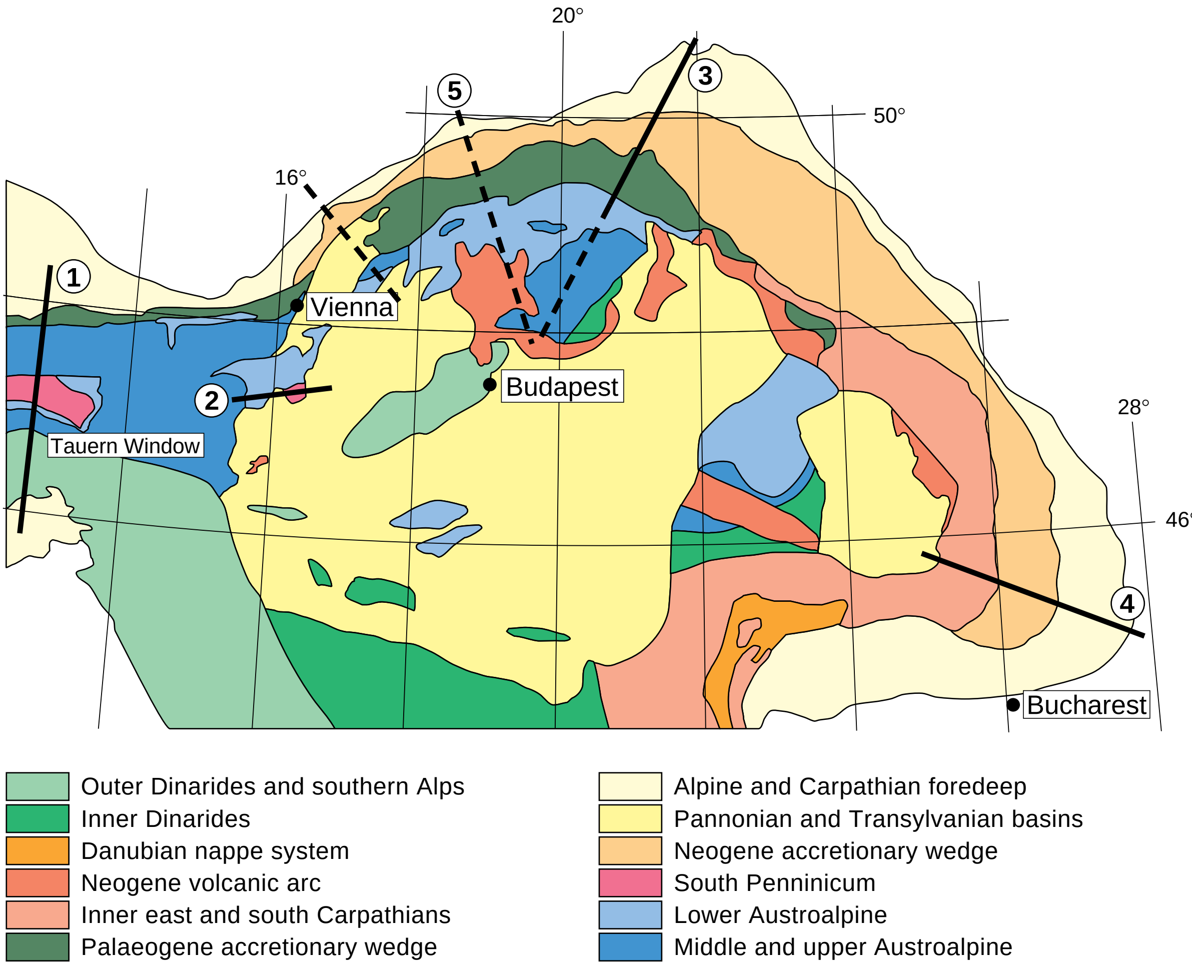


*Figure 2.5: Tectonic map of the Carpathian-Pannonian basin region with existing (dashed) and planned reflection seismic profiles.*

outer Dinaride domain. The internal Mesozoic carbonate-platform/continental-rise, including Variscide elements, separates the Pindos from another ophiolite-bearing allochthon derived from the Tethys Ocean. This oceanic Vardar association extends northwards beneath the southern margin of the Pannonian Basin. Dinaride extension also appears to contribute to the development of the Pannonian Basin.

## General Evolutionary Model

Evolution of the Carpathian and Dinaride orogens was governed by the interaction of the Afro-Arabian plate with the Eurasian plate and intervening continental terranes. Jurassic and Early Cretaceous opening of the Central Atlantic, entailing major sinistral translations between Europe and Africa, induced convergence and collision of the Italo-Dinaride block and intra-Carpathian terranes with each other. This early tectonism represents the onset of orogenic activity in the PANCARDI area. During the Late Cretaceous northward convergence of Africa with Europe, space constraints increased in the Alpine-Carpathian domain. This resulted in progressive closure of Mesozoic oceanic and para-oceanic basins, incorporation of intervening continental terranes into the evolving orogenic system and step-wise progradation of subduction. By Senonian-Palaeocene times, compressional stresses were exerted on the forelands of the eastern Alps and the Carpathians, as indicated by the inversion of Mesozoic rifts and the reactivation of major wrench faults. In the Oligo-Miocene, continued compressional deformation of the European foreland gave rise to imbrication of external crystalline massifs (as seen in the central Alps and the southern Carpathians). This is taken as evidence for 'hard' collision with the European margin. In contrast, external basement imbrication appears to play a subordinate role, being largely absent in the northern and eastern Carpathians. This speaks for 'soft' collision of the orogen with these forelands.

Palaeogene and particularly Neogene progressive consolidation of the Carpatho-Dinaride orogen, was apparently accompanied by eastward displacement of intra-Carpathian lithospheric blocks (terranes) and major lateral translations between them. This appears to have been an effect of 'hard' collision-induced indentation in the Alpine region and lateral

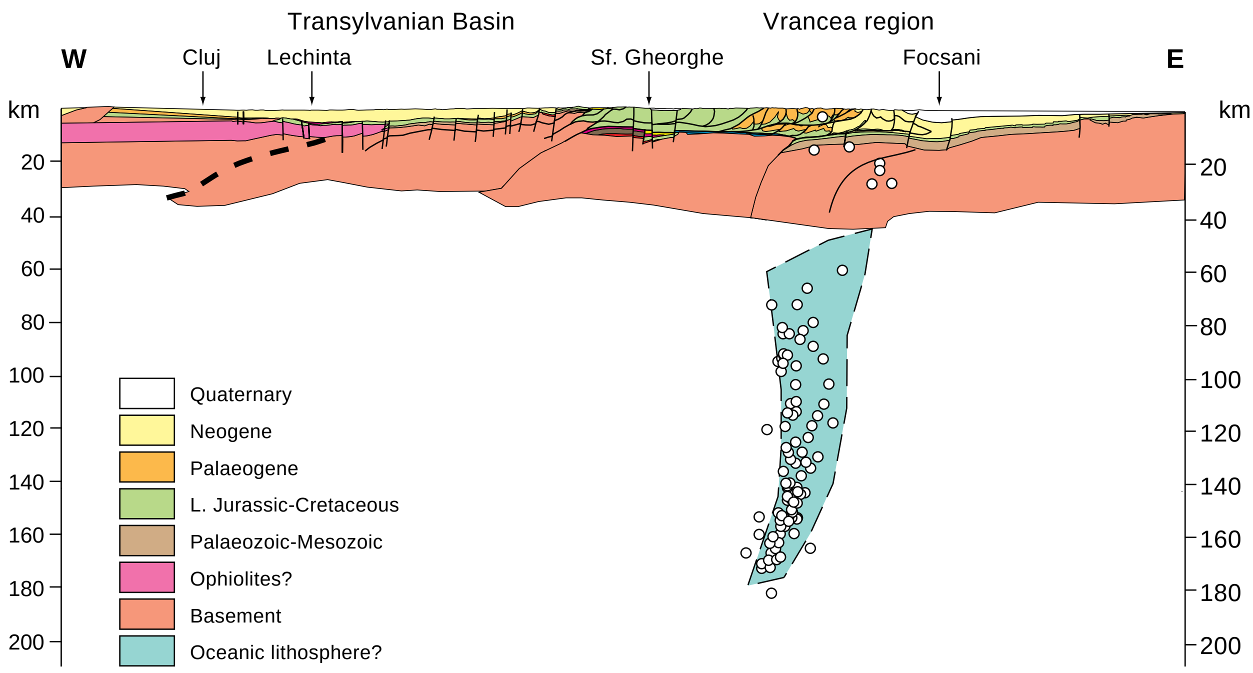


*Figure 2.6: Hypothetical lithospheric cross-section through the eastern Carpathians along profile 4 (Fig. 2.5). The open circles indicate earthquake hypocentres. Compiled by H.-G. Linzer, from Stefanescu (1994), Sandulescu (1984) and Oncescu (1984, 1987).*

mass escape, as well as of subduction-induced plate boundary retreat and slab roll-back into the Carpathian continental embayment. The Cenozoic evolution of the Carpatho-Dinaride system was accompanied by the development and deformation of inter-arc basins, such as the Transylvanian basin, and the evolution of the Neogene Pannonian back-arc basins. The on-going seismicity in the Vrancea zone appears to be the final expression of Carpathian subduction and arc accretion.

## Outstanding Features

The PANCARDI system has much in common with other arc-basin complexes in the Mediterranean area and even the western Pacific. Common to all of these is the development of fore-arc basins characterised by thin-skinned tectonics in response to rapid (5-10 cm/year), short-lived (c. 10 Ma) subduction. Andesitic and tholeiitic volcanic rocks are concentrated in the arcs, behind which developed back-arc extensional basins. However, there are a number of outstanding features that make PANCARDI particularly favourable for new research initiatives.

1) The subaerial exposure of the entire system allows the comprehensive geological, geochemical and geophysical studies necessary for modelling arc-basin evolution. In particular, it will promote an understanding of the complex interrelationships between thrusting, strike-slip and normal faulting during arc development.
2) The well-defined concentration of historical seismicity in the Vrancea zone provides a unique opportunity to study asthenosphere-lithosphere relationships and analyse source mechanisms of mantle earthquakes.
3) Studies of stress distribution and neotectonics in the Vrancea area and their relationship to the seismicity, particularly the crustal earthquakes, should provide a basis for defining seismic hazard and, in collaboration with engineers, contribute to disaster mitigation.
4) The Pannonian Basin alkaline magmatism provides a unique opportunity for studying the chemical evolution of the mantle lithosphere and the relationships between asthenospheric up-welling during back-arc extension and subsequent plume-related volcanicity.
5) The well-defined temporal and spatial correlation of andesitic arc volcanism and Carpathian arc accretion with accompanying Pannonian Basin extension, provides particularly favourable circumstances for investigating the origin of subduction-related volcanism.
6) The eastern Alps and western margin of the Pannonian Basin provide an excellent natural laboratory for studying the relationships between collisional thickening of the lithosphere, extensional unroofing and lateral extrusion (escape).

# PANCARDI RESEARCH

1. Vrancea zone seismology and tomography *(Bucharest [NIEP, U, RAS], Karlsruhe [U], Strasbourg [EOPG], Nice [CNRS], Potsdam [GFZ]).*

There is a high probability for a major earthquake in the Vrancea zone within the next few years. Understanding and quantification of the seismogenic potential of the region and proposing measures for hazard mitigation is an important goal of PANCARDI that may have immediate impact on society. Seismologic research will be devoted to a better understanding of the interaction of mantle and crustal seismicity and to processes in the subducting oceanic plate itself. A seismic tomography experiment will aim to obtain a high resolution 3-dimensional image of the mantle beneath the eastern Carpathian portion of the arc (Fig. 2.7). This experiment will provide detailed velocity information on the lithosphere and asthenosphere beneath the Vrancea area and details on the propagation of seismic waves, thus providing important boundary conditions for the prediction of hazard parameters.

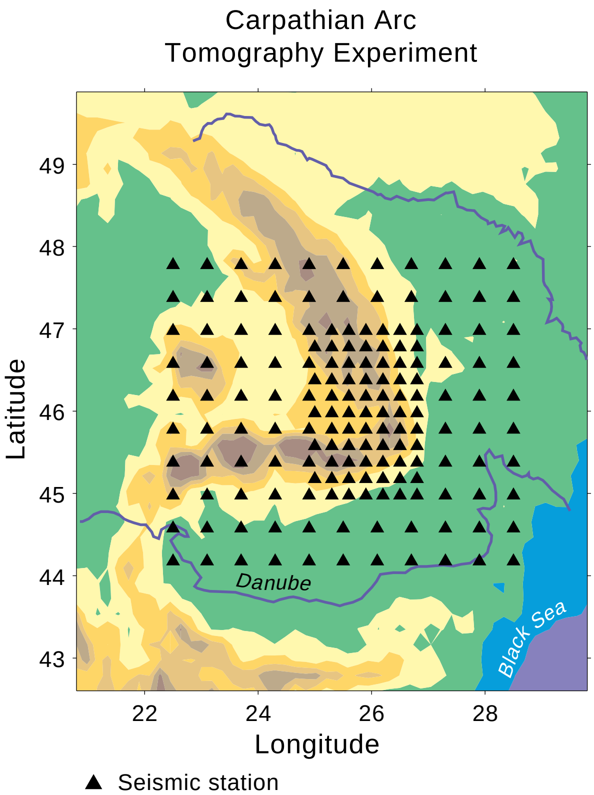


*Figure 2.7: Planned array of seismic stations for the teleseismic tomography experiment.*

2. Stress pattern of the Vrancea area and active tectonics in the eastern Carpathians *(Karlsruhe [U], Bucharest [U, RAS], Potsdam [GFZ], Budapest [U]).*
The eastern and southern boundaries of the west European stress province are not well known. An area of particular interest is the Vrancea seismic zone. New investigations will allow distinctions between different models that have been developed to explain the tectonic evolution, thermal field, uplift and subsidence pattern, and present-day tectonics of the PANCARDI area. In addition to direct stress measurements in boreholes, the NAVSTAR Global Positioning System will be used to derive the on-going deformation pattern; it will be supported by gravimetric measurements. A geodetic network consisting of 20 to 25 stations will be installed. Repeated GPS and gravity measurements will be made, along with analysis of the deformation.

3. Deep seismic profiling and sounding in the Vrancea region *(Bucharest [NIEP, U], Karlsruhe [U], Potsdam [GFZ]).*
The crustal-scale geometry of the eastern Carpathians and its foredeep in the Vrancea area will be studied by deep seismic profiling and sounding methods. A CMP profile recorded to at least 20s is proposed to start in the eastern parts of the Transylvanian basin and cross eastwards over the anomalously deep Focsani foreland basin, east of the orogenic arc (Fig. 2.5, profile 4). Due to the importance of the Focsani basin for the reconstruction of the subduction and collision in this area, the CMP profile will be aimed at imaging the sedimentary sequence as well as the deeper crustal structure. Near-vertical reflection seismic profiling will be accompanied by wide-angle reflection and refraction experiments in order to derive the elastic wave velocity distribution in this most active tectonic region.

4. Deep seismic reflection profiling in the eastern Carpathians of Poland and the Slovak Republic *(Bratislava [DSIG], Cracow [PGI], Warsaw [PAS, PGI], Salzburg [U]).*
Whereas subduction continues in the Vrancea area today, it ended in other parts of the eastern Carpathians about 10 Ma ago. A joint Slovak-Polish experiment images the foreland and back-arc basins as well as the thrust sheet complex in the northwestern part of the eastern Carpathians (Fig. 2.5, profile 3). Defining the characteristics of the suture between the upper Carpatho-Pannonian and lower European plates, as well as the structure of the Oligo-Miocene accretionary

wedge, are the main goals of this experiment. The Slovakian part of the line (110 km) has been completed and the Polish experiment is prepared for 1997-98.

5. Deep seismic profiling in the eastern Alps *(DEKORP, CROP, Salzburg [U], Leoben [U], Innsbruck [U], Budapest [U, ELGI], Zürich [ETH]).*
Two deep seismic reflection lines are needed to investigate the main problems of the tectonic evolution of the eastern Alps (Fig. 2.5, profiles 1 and 2). A c. 200 km long profile, crossing the Tauern Window from Germany via Austria to Italy, should focus on the evolution of the Tauern Window. Aspects to be investigated will include the Tertiary Alpine thrusting, extension and indentation of the Adriatic subplate. A shorter (c. 100 km) E-W line across the boundary between the Alps and the Pannonian Basin will aim at reconstructing the style of extension of the Rechnitz metamorphic core complex. These two profiles are essential for estimating the collisional shortening across the eastern Alps and for testing the extrusion hypothesis for the formation of the Carpathian arc. Plans for the first profile are being developed by DEKORP and supported by EUROPROBE.

6. Deep seismic sounding in the Ukrainian Carpathians *(Milan [U], Kiev [IG]).*
Several deep seismic sounding lines, which were acquired during the sixties and seventies in the PANCARDI area, will be interpreted with modern methods. The most important line passes from the Ukrainian Shield, via the Ukrainian Carpathians, into the eastern part of the Pannonian Basin. A necessary condition for the use of modern data treatment and interpretation techniques is the digitisation of the field data that was recorded on paper. New sophisticated software has been developed in Milan for the digitisation procedure.

7. New Atlas of deep seismic reflection profiles of the Slovak and Czech western Carpathians *(Bratislava [DSIG], Salzburg [U], St. John's [U]).*
About 1200 km of deep seismic reflection profiles were recorded in the western Carpathians between 1982 and 1993 (see an example in Fig. 2.4). Reprocessing will include new migration and coherency filtering of all lines. A Seismic Atlas is being prepared for publication in 1998.

8. Gravity field of the PANCARDI region *(Corvallis [U], Bucharest [U], Bratislava [DSIG], Salzburg [U]).*
This subproject will involve the first analyses of the gravity field of the entire Carpathian arc. New work will focus on the tectonically active southeastern and southern Carpathians, where a new precise Bouguer anomaly map is available for Romania. Of specific interest will be an investigation of deep lithospheric density variations and their relation to structures in the Vrancea region, where coordination with the teleseismic tomography experiment is planned.

9. Palaeomagnetic constraints of the Tertiary Carpathian evolutionary model *(Budapest [ELGI], Köln [U], Bratislava [DSIG], Warsaw [PGI], Bucharest [U]).*
Palaeomagnetic studies will form an important basis for better understanding the Cenozoic evolution of the Carpathian arc. This project will aim at an integrated investigation of the entire PANCARDI region. It

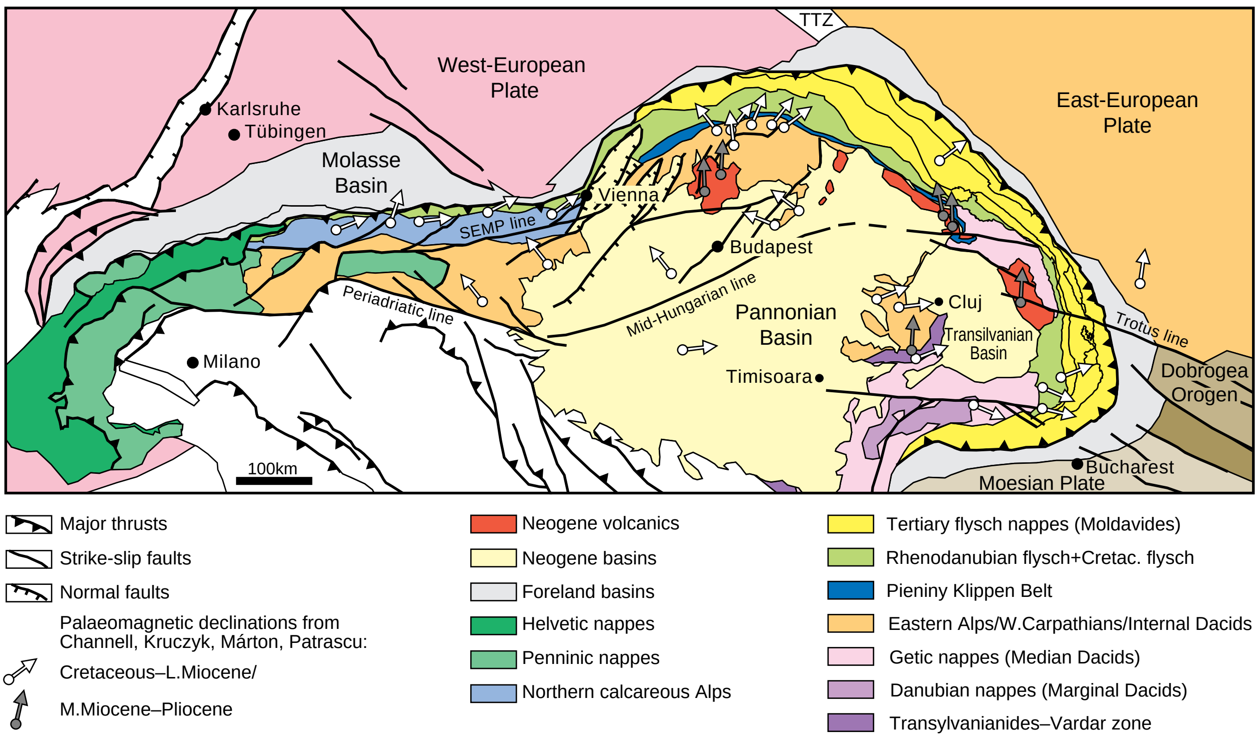


*Figure 2.8: Existing palaeomagnetic data in the PANCARDI region (from Linzer, 1996).*

will be necessary to collect new data at the eastern boundary of the Alps in Slovenia, in the western Carpathians of Poland and Slovakia, and in the Romanian Carpathians. Existing data indicate that differential movements have occurred between blocks (Fig. 2.8). New work will define the block rotations during their displacement into the Carpathian embayment.

10. Palaeobiogeographical reconstruction of the Mesozoic Tethyan and Penninic basins *(Cracow [PAS], Budapest [U], Bucharest [U], Athens [U], Bratislava [U, DSIG], Kiev [IGS], Sofia [BAS], Prague [CGS]).*
Palaeobiogeographical investigation is a powerful tool for reconstructing palaeo-oceanic basins, yielding important information that is complementary to palaeomagnetic techniques. The internal units of the PANCARDI region belong to different Tethyan or Penninic Mesozoic zones and, in order to recognise their Neogene assemblage and interplay, their provenance has to be determined. Based on detailed taxonomic, palaeoecologic and stratigraphic analyses of the fauna, the palaeoenvironments and palaeogeographic origin of the different Carpathian, Dinaric and eastern Alpine zones will be reconstructed.

11. Electrical resistivity structures of Pannonian and Carpathian crust and upper mantle *(Sopron [HAS], Uppsala [SGU, U], Potsdam [GFZ], Bucharest [GIR]).*
Low resistivity structures in the lithosphere are mainly related to areas of high temperature and strong shear motions. In the crust both graphite and saline fluids may be concentrated in shear zones of fossil and active tectonic regions, forming zones of high conductivity. Moreover, deeper low resistivity anomalies may be associated with the asthenosphere. A large data set of existing magnetotelluric soundings will be compiled within this subproject. New measurements are planned in the southeastern Pannonian Basin of Hungary and in the Vrancea earthquake area. The results of this large-scale magnetotelluric investigation will help to quantify lithospheric thickness variations and to determine the lithospheric thermal field.

12. Geothermal field and fluid flow in the Pannonian and Transylvanian basins *(Bucharest [RAS], Aarhus [U], Copenhagen [U], Budapest [U], Bratislava [DSIG], Prague [CAS]).*
Thermal studies provide fundamental constraints on thermomechanical models of lithospheric evolution and lithosphere-asthenosphere interaction. The evo-

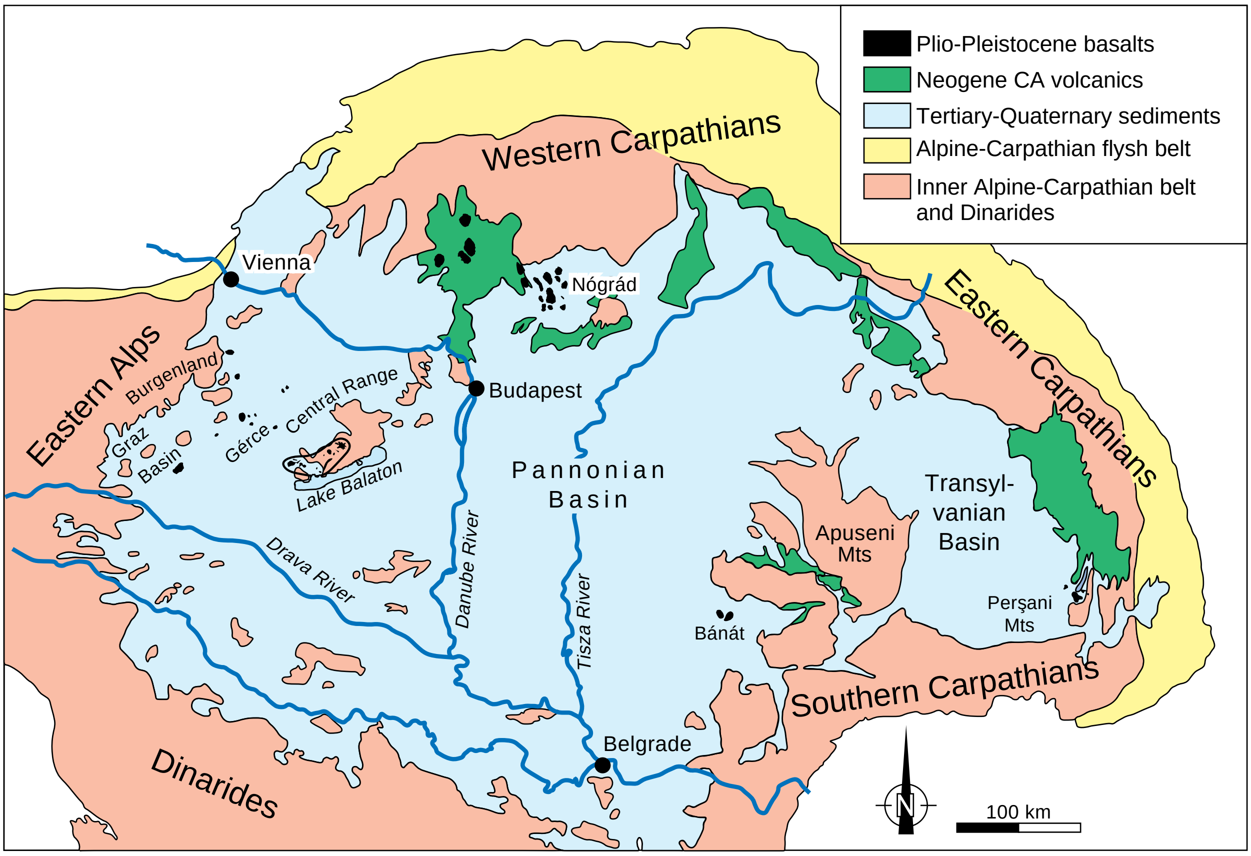


*Figure 2.9: Tertiary to Recent volcanism in the PANCARDI region. From Embey-Isztin et al. (1993).*

lution of the Pannonian and Transylvanian basins will be studied in order to determine the heat flow history of the area. Since shallow processes like erosion, sedimentation and fluid flow may influence strongly the near surface thermal field, special emphasis will be devoted to modelling the fill and fluid flow in the basins. The study includes a review of existing data and acquisition of new data, including borehole temperatures, rock thermal properties, formation pressures, homogenisation temperatures of fluid inclusions, and vitrinite reflectance data.

13. Magmatic processes in the PANCARDI region *(London [BC], Florence [U], Bucharest [GIR], Budapest [HAS, U], Bratislava [DSIG, U], Pisa [U], Debrezen [HAS], Sofia [BAS], Urbino [U]).*

Magmatism in the PANCARDI area (Fig. 2.9) occured in response to two different Neogene tectonic regimes: subduction and extension. The relation between the sources of these two magma series is not yet known. Main targets of the subproject are to 1) establish the magmatic history of the arc, 2) determine the source(s) of the calc-alkaline and alkaline magmas and the interaction between these sources, and 3) investigate the extent to which the mantle has been affected by subduction. Volcanic rocks related to Cenozoic subduction and extension will be sampled and analysed. In particular, concentrations of High Field Strength and rare earth elements will be determined. Equally important will be information from the radiogenic (Sr, Nd, and Pb) isotopic characteristics, in order to characterise the source of these rocks. Furthermore, state-of-the-art laser-fluorination analyses of $\delta^{18}O$ values in separated minerals will be used to constrain the amount of crustal contamination in the magmas.

14. Geochemical characterisation of the Pannonian Basin mantle lithosphere *(Leeds [U], London [BC], Florence [U], Budapest [HNM], Pisa [U], Leoben [U]).*

Our knowledge of the chemical composition and mineralogy of the lithospheric mantle is derived mainly from spinel and garnet lherzolite xenoliths enclosed in alkali basalts and kimberlites. Mantle xenoliths in late Miocene-Quaternary alkali basalts of the Pannonian Basin are especially suitable for this study. A systematic trace element and Sr-Nd-Pb isotopic study of mantle xenoliths along a northwest-southeast transect across the Pannonian Basin will be undertaken. Evidence for sequential metasomatism of the subduction-modified mantle will be sought. This will provide important insights into the geodynamic evolution of the Pannonian Basin. Specific objectives of this study are to 1) document the extent of fluid-induced metasomatic enrichment of the Pannonian Basin lithospheric mantle, 2) characterise the two distinct types of fluid metasomatism (subduction-related and plume-related), and 3) use the above data to place constraints on the timing of upwelling of the mantle plume beneath the Pannonian Basin.

15. Kinematic constraints for Carpathian evolution *(Amsterdam [VU], Basel [U], Bratislava [DSIG], Brno [CGS], Bucharest [U], Budapest [U], Cluj-Napoca [U], Ljubljana [SGS], Lvov [NASU], Salzburg [U], Tübingen [U], Vienna [U], Belgrade [GI]).*

A combination of methods (structural geology, sedimentary facies analysis, comparative stratigraphy, quantitative basin modelling and the interpretation of geophysical data) is crucial for unravelling the dynamics of processes that governed the formation of the highly curved Carpathian mountain belt. Kinematic constraints will be provided by applying the modern tools of structural geology by eight teams in different zones of the PANCARDI region (southern Carpathians: Basel, Bucharest, Cluj-Napoca and Tübingen; eastern and central Carpathians: Amsterdam, Bratislava, Bucharest, Lviv, Tübingen and Vienna; western Carpathians and eastern Alps: Bratislava, Brno, Budapest, Ljubljana, Salzburg, Tübingen and Vienna).

16. Geochronology by fission track and Ar/Ar isotope studies *(Salzburg [U], Tübingen [U], Budapest [HAS], Bucharest [U]).*

Analyses of Neogene to Recent dynamic processes in the PANCARDI area have to account for the Mesozoic and Palaeogene history and discriminate between the younger and older tectonic processes. New Ar/Ar isotope studies will focus on the internal parts of the western and eastern Carpathians, aiming at dating low-temperature mylonite zones. In addition, fission track analysis will play a key role in solving problems concerning the thermal regime of evolving sedimentary basins and for dating the age of extensional faulting, characteristically accompanied by a jump in cooling ages across fault zones.

17. Quantitative modelling of basin evolution and thermomechanical evolution of deforming lithosphere *(Amsterdam [VU], Bucharest [U], Lvov [NASU, WUGE], Budapest [U], Bratislava [U], Salzburg [U], Warsaw [PGI], Cambridge [MIT]).*

Quantitative modelling of basin evolution will integrate geophysical and geological data in the reconstruction of the thermomechanical structure and flexural evolution of the lithosphere underlying the Carpathian arc and Pannonian Basin. Modelling will be based on detailed knowledge of stratigraphy, monitoring the interplay of thrusting in the external part of the arc system and extension in the back-arc area. Flexural basins in the foreland and extensional fore-arc and back-arc basins will be modelled in the southern, central and western Carpathians. This subproject focuses on fundamental questions concerning the dynamics of the deep tectonic processes that controlled and still affect the PANCARDI system and their relation to basin formation.

18. Step-wise, 3-D palinspastic restoration of the PANCARDI system *(Basel [U], Tübingen [U], Salzburg [U], Bucharest [U], Budapest [U], Bratislava [DSIG, U], Cracow [PAS], Vienna [U], Lausanne [U], Zagreb [U]).*
The Pannonian Basin is surrounded by the Dinarides, eastern Alps and Carpathian arc. Based on detailed structural and stratigraphic analysis of these orogens and their forelands and hinterlands, carried out in different PANCARDI projects, paleotectonic-paleogeographic maps will be reconstructed for progressively older times. These will be palinspastically restored in order to model the Cenozoic development of the entire eastern Alpine-Carpathian-Dinaric orogenic system and Pannonian-Transylvanian basin complex with its basement. This analysis will provide the foundation for a better understanding of the geodynamic processes which governed the evolution of the Carpathian arc.

19. The Alps-Dinarides connection *(Basel [U], Neuchâtel [U], Lausanne [U], Amsterdam [VU], Zagreb [INA, U], Sarajewo [U], Budapest [U]).*
Large amounts of Alpine shortening extend into and are transfered to the Dinarides. However, this connection is still poorly understood. A fundamental change in nappe transport direction near the Alps-Dinarides transition led to the northern termination of the Dinaridic ophiolite belt. This study will specifically adress: 1) the structure, kinematics and amount of shortening within the external Dinarides (seismic and field data), 2) the northern end of the Dinarides ophiolite belt and its relation to the Alpine-Carpathian ophiolites (magmatic, metamorphic and tectonic processes; palinspastic reconstructions), and 3) the formation of the southern margin of the Pannonian basin and its pre-Miocene substratum (seismic interpretation, borehole evidence, basin modelling).

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