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# The Palaeogene forearc basin of the Eastern Alps and Western Carpathians: subduction erosion and basin evolution

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**Abstract:** Scarce Palaeogene sediment remnants in the Eastern Alps and Western Carpathians are interpreted as remains of a continuous forearc basin. New apatite fission-track geochronological data corroborate mild Paleocene–Eocene exhumation and relief formation in the Eastern Alps. Palinspastic restoration and nine palaeogeographical maps of the Eastern Alps and Western Carpathians ranging from the Paleocene to the Late Oligocene epoch illustrate west to east migration of subsidence in the forearc basin. Subsidence isochrons indicate that oblique subduction of the European plate below the Adriatic plate was responsible for forearc basin migration at a rate of 8 mm $a^{-1}$. The Periadriatic Lineament was formed as a result of shearing by oblique subduction. The Neogene to recent Sumatra forearc basin is an analogue for the evolution of the East Alpine–West Carpathian forearc basin.

**Keywords:** Alps, Carpathians, Palaeogene, fission-track dating, palaeogeography.

Tertiary basin evolution in the Alpine–Carpathian region has been the subject of studies for several decades. Although worldwide recognition was gained by the interpretation of the Pannonian Basin as a Miocene extensional back-arc basin (Royden & Horváth 1988), the geodynamic history of the underlying Palaeogene basins remained obscure. These have been extensively studied through coal, bauxite and hydrocarbon exploration for more than a century. The stratigraphy, on which the present study is based, has been described in detail (major reference works are Oberhauser 1968, 1995; Gross *et al*. 1980; Kopek 1980; Báldi-Beke 1984; Báldi 1986). The subsidence history of the Hungarian Palaeogene Basin (Báldi-Beke & Báldi 1991) was explained as that of either a series of pull-apart basins (Báldi 1986; Royden & Báldi 1988) or a retroarc foreland basin (Tari *et al*. 1993).

Traditionally, the Hungarian Palaeogene Basin and the Central Carpathian Palaeogene Basin were understood to be two separate basins (Nagymarosy 1990), with significantly different basin histories. The first is a coal-bearing basin with thick pelagic infill above a terrestrial to shallow marine sequence; the second is a flysch basin underlain by neritic carbonates (Fig. 1). Studies in the Hungarian Palaeogene Basin concentrated on the terrestrial and shallow-marine part of the succession, justified by economic interests in coal and bauxite. In the Central Carpathian Palaeogene Basin scientific and industrial interest was concentrated mostly on the deep-marine part of the succession (Gross *et al*. 1980), most recently because of hydrocarbon exploration (Soták *et al*. 2001).

The Eastern Alpine–Western Carpathian segment of the Alpine orogen has been divided among 10 countries (Austria, Germany, Italy, Slovenia, Hungary, the Czech Republic, Slovakia, Poland, Ukraine and Romania) since World War I. Hence, geological literature is published in 12 languages (English, French, Russian and various other languages) and map contents often end at state borders. This cultural kaleidoscope hinders mutual understanding, and results from other countries are frequently overlooked. Probably the present paper is not exempt from that.

The purposes of this paper are: (1) to demonstrate that basin evolution in Upper Cretaceous–Eocene time migrated along the active plate margin; (2) to propose a model of the Adriatic upper plate in terms of a forearc basin; (3) to draw analogies with present-day Sumatra. We provide new fission-track data on the uplift of parts of the Eastern Alps.

## Stratigraphy

### *Krappfeld and Hungarian Palaeogene Basin*

Remnants of an almost contiguous set of Eocene–Oligocene basins have been preserved along the southern margin of the Eastern Alps and the Western Carpathians. Although traditionally considered as a separate tectonic unit, we suggest that the Bakony unit (Transdanubian Central Range) of Hungary is an integral part of the West Carpathians, at least during Palaeogene time. The westernmost Krappfeld locality in Carinthia, Austria (Kr in Fig. 1), is underlain by folded Upper Cretaceous marly turbidites. Terrestrial red clay (D'Argenio & Mindszenty 1987) is followed by Lower Eocene (Ypresian) coal measures, overlain either by Lower Eocene *Nummulites* marl or by Lower to Middle Eocene algal carbonate platform sediments. No strata younger than Mid-Eocene age are known (Wilkens 1991).

The Eocene Zala Basin in Hungary is hidden under Neogene cover of several kilometres thickness (ZB in Fig. 1). Hundreds of oil wells penetrate a kilometre-thick calc-alkaline stratovolcanic sequence, which overlies undivided Eocene fossiliferous limestone and is interfingering with Eocene pelagic marl (Kőrössy 1988; Nagymarosy, pers. comm.). K–Ar data scattered around 30 Ma (Benedek 2002) probably indicate thermal overprint by adjacent mid-Oligocene dykes and tonalite intrusions (Balogh *et al*. 1983).

The largest Eocene basin remnant, the Hungarian Palaeogene Basin, extends more than 250 km from the Bakony to the Bükk Mts in Hungary. Palaeogene sedimentation in the Bakony Mts started in early Lutetian (Mid-Eocene) time with terrigenous

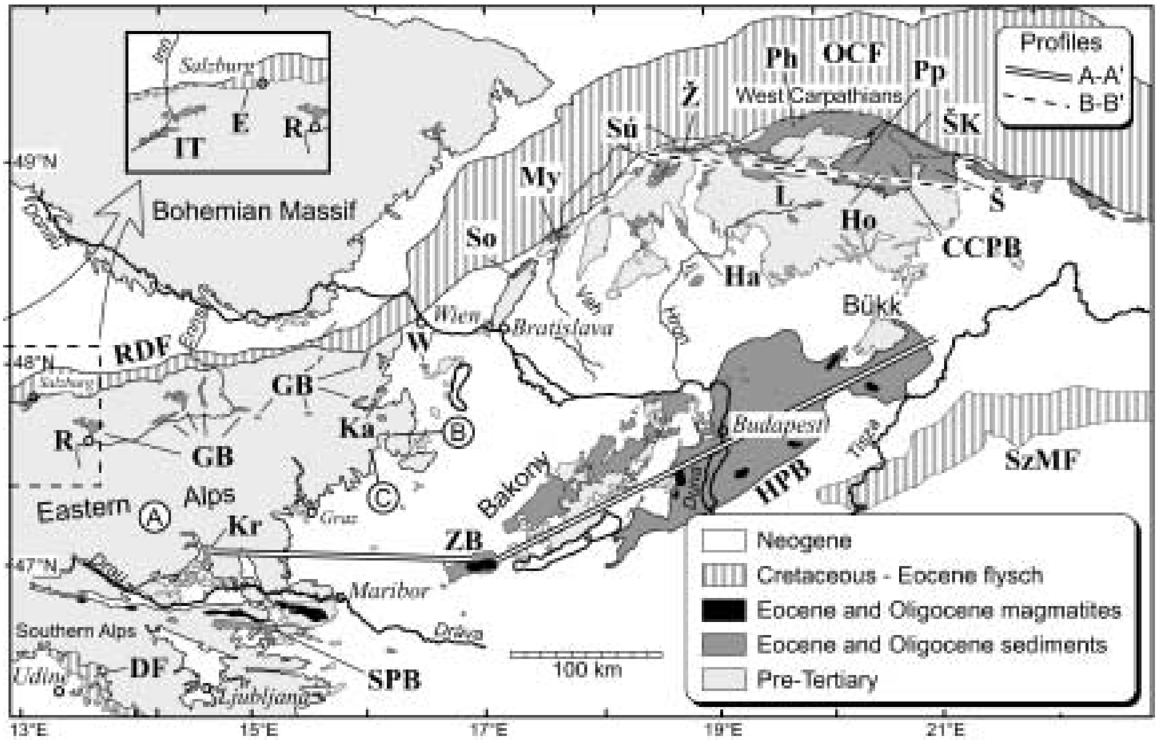


**Fig. 1.** Palaeogene sediments in the Eastern Alps and West Carpathians. Profile A–A′ is shown in Figure 2; B–B′ in Figure 3. A, B and C in circles are localities of the apatite fission-track samples (for results see Fig. 4). Flysch nappes on the lower plate: RDF, Rhenodanubian; OCF, Outer Carpathian; SzMF, Szolnok–Maramureş; DF, Dinaric. Palaeogene basin remnants on the upper plate: IT, Inn Valley Tertiary; E, Eisenrichterstein; GB, Gosau basins; R, Radstadt; Kr, Krappfeld; SPB, Slovenian Palaeogene Basin; Ka, Kambühel; W, Wimpassing; ZB, Zala Basin; HPB, Hungarian Palaeogene Basin; So, Sološnica; My, Myjava; Sú, Súlov; Ž, Žilina; L, Liptov; Ph, Podhale; Pp, Poprad; Ha, Handlová; Ho, Hornád; ŠK, Šambron–Kamenica zone; Š, Šariš; CCPB, Central Carpathian Palaeogene Basin.

clastic rocks (Darvastó Formation: Kecskeméti & Vörös 1975) (Fig. 2). The sequence overlies Upper Triassic to Upper Cretaceous rocks and locally covers Palaeogene karst bauxite deposits (Gánt Formation: Mindszenty *et al*. 1988). The Darvastó Formation passes upward into the neritic Szőc Limestone, rich in larger foraminifers *Alveolina* and *Nummulites*and in red algae (Vörös 1989). The shallow-marine carbonate banks were laterally interrupted by mangrove marshes producing significant coal deposits (Kopek 1980). By the end of the Lutetian, the carbonate factory was drowned, and glauconitic marl and *Globigerina* marl were deposited, topped by turbidites (Báldi-Beke & Báldi 1991). Tuffites are widespread both in the bauxite and in the Priabonian marl (Dunkl 1990, 1992).

Besides the Zala stratovolcano there are further, mostly buried, volcanic centres near Budapest (Velence Hills: Darida-Tichy 1987) and in the Bükk Mts, where volcaniclastic rocks are interfingered with Priabonian carbonates (Baksa *et al*. 1974) (Fig. 1).

The transgression reached the eastern part of the Transdanubian Central Range in the Bartonian, and the Buda Hills and Bükk Mts in the Priabonian (Báldi-Beke 1984). Despite the age difference, the sedimentary succession remained the same: terrestrial clastic rocks with coal measures, shallow marine carbonates, and a transgressive succession of dark shale or bryozoan marl followed by the bathyal Buda Marl and Tard Clay (Fig. 2) (Báldi 1986).

The Lower Oligocene Tard Clay, deposited under anoxic conditions in a sediment-starved basin (Báldi 1984), is an excellent isochronous marker horizon with which to correlate the Hungarian Palaeogene Basin, the Central Carpathian Palaeogene Basin and the sediments of the Carpathian flysch zone. The sudden appearance of reworked Eocene nannofossils in the Tard Clay at the base of the NP 23 zone (Báldi-Beke 1977) dates the onset of the extensive Early Oligocene denudation in the Bakony (Telegdi-Roth 1927). At the end of the Early Oligocene rapid sedimentation of the kilometre-thick Kiscell Clay occurred within $<1$ Ma.

The stratigraphic column displays a heterochronous facies pattern along the basin system: a conspicuous west to east shift of initial neritic deposition and subsequent subsidence to bathyal depth is displayed between Krappfeld and the Bükk Mts (Báldi & Báldi-Beke 1985; Báldi-Beke & Báldi 1991).

## *Central Carpathian Palaeogene Basin*

The Central Carpathian Palaeogene Basin (CCPB) extends along the northern margin of the Central Western Carpathians (Fig. 1). It is underlain by continental crust (a Mesozoic nappe stack). Stratigraphical data indicate a marked shift in the age of sedimentation (Gross *et al*. 1984), not unlike the Hungarian Palaeogene Basin (Fig. 3). Marine deposition started in the westernmost Žilina Basin in the Early Eocene epoch (Samuel 1985), in the Liptov Basin in the Mid-Eocene (Gross *et al*. 1980), in the Poprad Basin in the Priabonian and in the easternmost Šariš Basin as late as the Eocene–Oligocene boundary (Soták 1998*a*, *b*; Janočko & Jacko 1998). Sedimentation started

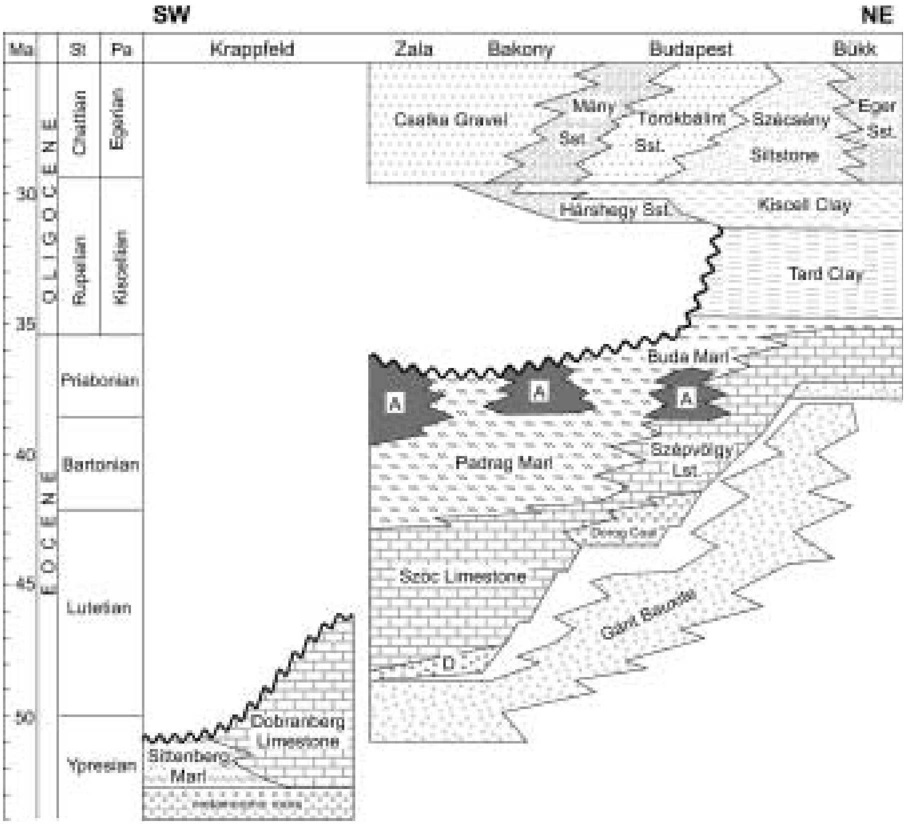


**Fig. 2.** A–A′: Palaeogene lithostratigraphy of Krappfeld and of the Hungarian Palaeogene Basin. A, andesite stratovolcano; D, Darvastó Formation. Both standard (St) and Paratethyan (Pa) stage names are given in the chronostratigraphic scale. (after Báldi-Beke 1984; Báldi 1986; Nagymarosy & Báldi-Beke 1988; Wilkens 1991; Tari *et al*. 1993; Tari 1995; Vass 1995, modified).

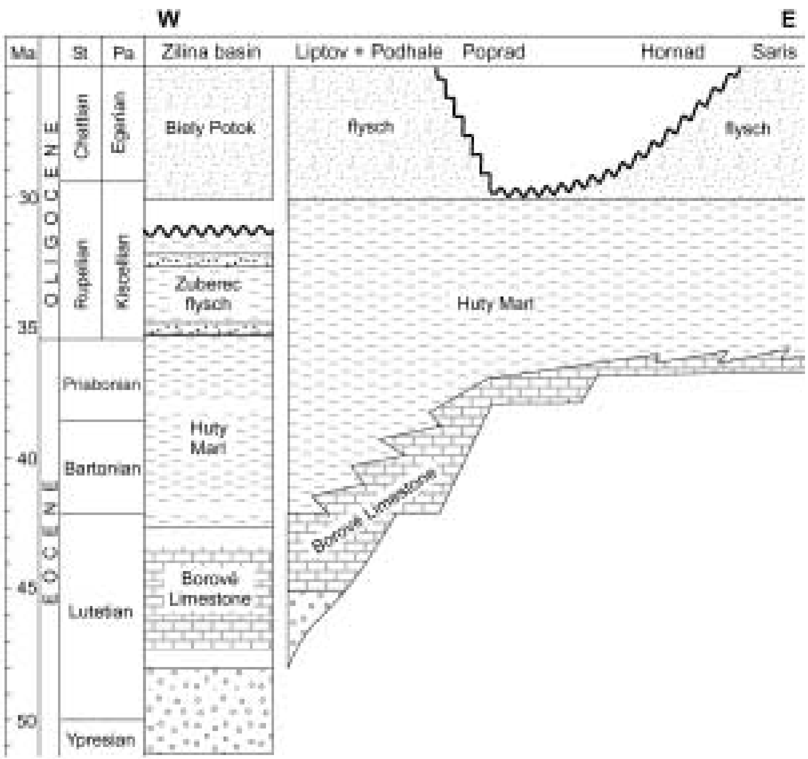


**Fig. 3.** B–B′: Palaeogene lithostratigraphy of the Central Carpathian Palaeogene Basin (after Gross *et al*. 1984; Samuel 1985; Soták 1998*a*, *b*; Bartholdy *et al*. 1999, modified).

with basal conglomerate and breccia, occasionally of considerable thickness, indicating synsedimentary tectonic activity. The lowermost biostratigraphically dated sediments are neritic to shallow bathyal algal–*Nummulites* limestone and *Discocyclina* limestone, overlain by the drowning succession of bryozoan limestone–marl (Borové Formation) (Zágoršek 1992; Bartholdy *et al*. 1999). Subsequent rapid subsidence produced claystone and siltstone (Húty and Zakopane Formations), including sediments referred to as the Menilite facies in the eastern part of the basin, an organic-rich dark shale correlated with the Tard Clay of the Hungarian Palaeogene Basin. A shaly and sandy flysch sequence follows in an upward-coarsening succession (Gross *et al*. 1980; Soták 1998*a*, *b*). Clastic rocks are derived from the Mesozoic basement (Gross *et al*. 1982).

The sedimentary column of the Central Carpathian Palaeogene Basin is truncated; the youngest preserved sediment is lowermost Miocene (NN 1/2). The thickness of the shallow marine formations is up to 150 m, and the bathyal flysch is up to 4 km thick (Soták 1998*a*, *b*; Bezák *et al*. 2000). Vitrinite reflectance, illite crystallinity and fluid inclusion data suggest that there was at least 2 km sediment overburden (Kotulová *et al*. 1998) of unknown age on top of the flysch, which by now has been removed. Fluid pressure was extremely high along the northern margin, in the Šambron zone (150 MPa), with an up to 5 km overburden, and lowest at the southern margin of the Central Carpathian Palaeogene Basin (25 MPa), indicating <1 km overburden. Fluid inclusion palaeotemperatures are surprisingly low: up to 150 °C in the north, and up to 80 °C in the south (Hurai *et al*. 1995). In view of the significant overburden, this suggests low terrestrial heat flow.

### *Gosau basins in the Eastern Alps*

The sedimentary succession on top of the Northern Calcareous Alps is subdivided into the lower Gosau Subgroup (Upper Turonian–Campanian), which is characterized by terrestrial to shallow marine facies associations, and the upper Gosau Subgroup (Santonian–Eocene), which comprises deep-water hemipelagic and turbiditic deposits (Wagreich & Faupl 1994; Faupl & Wagreich 2000; Kurz *et al*. 2001*a*; Wagreich 2001). The shift of rapidly subsiding basins from the NW towards the SE between Santonian and Maastrichtian times is interpreted as a product of subduction erosion (Wagreich 1995).

### *Marginal basins in the Eastern Alps and Western Carpathians*

There are basins of Late Eocene age, e.g. at Oberaudorf in the Inn Valley, and Wimpassing in the Eastern Alps, directly deposited on top of the Mesozoic Alpine nappe pile (IT and W in Fig. 1, respectively). Another Upper Eocene sequence, the reef of Eisenrichterstein (Darga 1990), is in an unclear tectonic position, either below or above the Triassic of the Northern Calcareous Alps near Salzburg (E in Fig. 1). A record of a Lower Oligocene transgression is preserved in the Lower Inn Valley (Ortner & Stingl 2001).

The Little Carpathians host a single Lower Eocene limestone outcrop at Sološnica (deposited on the Mesozoic nappe stack), overlain by the Lower to Middle Eocene pelagic Húty Formation (Gross & Köhler 1991). There is a series of narrow, elongated basins with pelagic sediments lined up along the NE margin of the Western Carpathians. Sedimentary successions ranging from the Upper Cretaceous to the Eocene series are preserved; for example, in the Myjava Hills and in the Periklippen Zone at Žilina, equivalents of the Gosau Group of the Northern Calcareous Alps occur (Salaj & Priechodská 1987; Wagreich & Marschalko 1995).

The Lower Eocene Súlov Basin close to the Pieniny Klippen Belt is a kilometre-thick pile of dolomite gravel, rapidly deposited in a fan (Salaj 1995).

The Upper Eocene–Lower Miocene Šambron–Kamenica zone extends along the northern margin of the Western Carpathians. The Priabonian–Lower Oligocene Šambron Beds are made of pelagic clay, and contain sandstone layers with abundant ophiolite detritus derived from the north (Soták & Bebej 1996). Being thrust onto the autochthonous Central Carpathian Basin, its original basement is unknown (Nemčok *et al*. 1996).

These basins along the margin of the overriding Adriatic plate, especially in the Eastern Alps, display repeated sedimentation and erosion contemporaneous with continuous sedimentation towards the south.

### *Minor basin remnants in the Western Carpathians*

A set of minor Palaeogene basin remnants are found between the Central Carpathian Palaeogene Basin and the Hungarian Palaeogene Basin. Sediments are known from outcrops at Handlová in the Upper Nitra valley and from boreholes around Banská Štiavnica and Banská Bystrica (Samuel 1975; Gross 1978; Gross & Köhler 1994). Sedimentation started in the Late Lutetian (Bartonian) with neritic limestone (Borové Formation), followed by Priabonian and Early Oligocene pelitic, bathyal sedimentation with minor sandstone intercalations (Zuberec Formation). Upper Oligocene–Lower Miocene sandy flysch (Biely Potok Formation) terminates the succession.

## Volcanic chain

There is a Palaeogene magmatic chain along the Periadriatic Fault. It extends from the western Po plain (Fantoni *et al*. 1999) as far as the northeastern Pannonian Basin over *c*. 800 km length (Exner 1976; Baksa *et al*. 1974). Intrusive bodies and up to 2 km thick stratovolcanic edifices of Eocene age are composed of intermediate calc-alkaline rocks. Pyroclastic rocks are preserved in nearly every limestone and sandstone formation of the Hungarian Palaeogene Basin (Szabó & Szabó-Balog 1985; Dunkl 1990, 1992). Fission-track geochronology on zircon from ash layers revealed two intense volcanic periods during Eocene time (at 44 and 39 Ma; Dunkl 1990).

The Oligocene magmatic period (33 to *c*. 28 Ma) yielded numerous tonalite intrusions along the Periadriatic Lineament (Exner 1976), where significant lateral displacement occurred in mid-Oligocene time (Kázmér & Kovács 1985; Tari *et al*. 1995). Magmatism is alternatively attributed to subduction (Kagami *et al*. 1991) or to slab-breakoff magmatism (Von Blanckenburg & Davies 1995; Von Blanckenburg *et al*. 1998).

## Paleocene–Eocene exhumation in the Eastern Alps

Thermochronometers clearly mark two distinct clusters in the cooling ages of the Eastern Alps. The Late Cretaceous (95–70 Ma) 'Eoalpine' cooling–exhumation period can be detected in almost the entire Austroalpine nappe complex by mica Rb–Sr and Ar–Ar thermochronometers (Frank *et al*. 1987). The 'Neoalpine' age cluster (Miocene cooling ages) is typical for the Penninic unit. In the Eastern Alps, ages between these two main events have been usually considered as mixed ages (Frank *et al*. 1987). The Palaeogene thermotectonic event ('Mesoalpine phase') left traces in the pattern of ages mainly in the Central and Western Alps (Escher *et al*. 1997), and also in the Eastern Alps (Liu *et al*. 2001). However, there is further evidence of Eocene cooling and exhumation in the Eastern Alps, as follows.

(1) Remnants of shallow marine Eocene limestone in the central part of the Eastern Alps (Radstadt im Pongau, R in Fig. 1; Trauth 1918) contain siliciclastic material (quartzite pebbles and sand), indicating local erosion. Eocene limestone boulders in the Miocene Kirchberg Basin (K in Fig. 1) (Ebner *et al*. 1991)

and at Wimpassing (W in Fig. 1) (Trauth 1918) are witnesses of Eocene palaeosurfaces.

(2) Eocene white mica Ar–Ar ages were detected along the northern margin and similar zircon fission-track ages were measured along the northern, northeastern and southern margins of the Tauern Window (Dingeldey *et al*. 1997; Handler *et al*. 2000; Liu *et al*. 2001).

(3) There is a marked clustering in the single-crystal apatite fission-track data measured on the Neogene local clastic rocks of the Eastern Alps (Fig. 4; Table 1). This group of Eocene ages means that before the beginning of the Neogene to Recent denudation period, there were already crystalline rock bodies with Eocene cooling ages near the surface (Neubauer *et al*. 1995; Hejl 1997, 1999).

(4) Strongly deformed Gosau sediments overthrust by reactivated pre-Gosau faults indicate important folding and thrusting in the Northern Calcareous Alps in the Eocene epoch (Tollmann 1976). Termination of sedimentation, thrusting, folding and erosion went along with crustal shortening and stacking.

We interpret these data as manifestations of exhumation and relief formation during ‘Early Palaeogene’ time (Neubauer *et al*. 1999, 2000; Wang & Neubauer 2001). This exhumation was weaker than the Eo- and Neoalpine, and thus we find relatively few traces in the mica Ar–Ar and Rb–Sr ages, but the thermally more sensitive apatite fission-track age pattern reflects it well. This orogenic process in the Eastern Alps was the side effect of the collisional, high-relief forming orogenic process of the Western Alps producing a high amount of the siliciclastic sediment.

## Palinspastic restoration

The Palaeogene palaeogeographical base map was constructed from two sources (Fig. 5). The Eastern Alpine segment displays the restored block pattern of Frisch *et al*. (1998, 1999), with the Tauern Window closed. The Western Carpathian and Transdanubian Central Range segment did not undergo extreme Neogene extension like the Eastern Alps. We applied a 30° clockwise rotation to cater for palaeomagnetic declination differences between the Eastern Alps and Western Carpathians (Márton *et al*. 1999, 2000). The Miocene extensional basins, the Vienna Basin, Little Hungarian Plain and Styrian Basins (Tari 1996b), are closed by 30, 80 and 25 km, respectively (Fig. 5). This restoration made the southern border, the Periadriatic–Mid-Hungarian Fault, a straight line. A further 50° clockwise correction for the combined Eastern Alpine–Western Carpathian block (allowed by earliest Miocene counterclockwise rotation data of Márton *et al*. (1999, 2000) and Márton (2001)) both for the Eastern Alps and for the Western Carpathians restores the

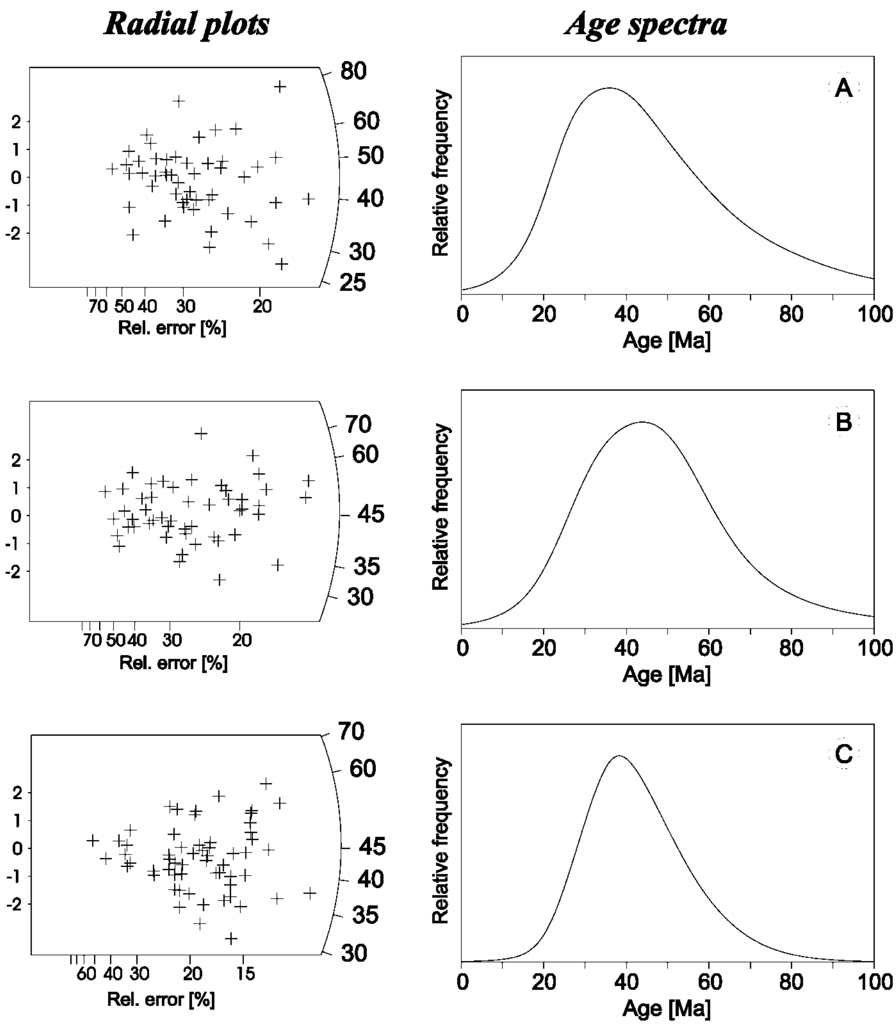


**Fig. 4.** Distribution of apatite single-crystal fission-track ages in Miocene sandstones of the intramontane basins of the Eastern Alps. At left, radial plots show the precision of the individual grain data. Ages on the right of the graph are more precise than those on the left (Galbraith & Laslett 1993). At right, age spectra are plotted according to Hurford *et al*. (1984). Most of the data points fall into the Eocene, proving a marked Paleogene cooling–exhumation period in the Eastern Alps. Localities: A, Schoeder Bach, 50 crystals; B, Boden, 50 crystals; C, Zoebern, 60 crystals.

**Table 1.** *Fission-track geochronological data from selected localities (Fig. 1) in the Eastern Alps*

| Locality | Petrography | Cryst. | Spontaneous $r_s$ ($N_s$) | Induced $r_i$ ($N_i$) | Dosimeter $r_d$ ($N_d$) | $P(\chi^2)$ (%) | Disp. | Fission-track age (Ma $\pm$ 1$\sigma$) |
|---|---|---|---|---|---|---|---|---|
| Schoeder Bach | Sandstone | 50 | 2.59 (1013) | 5.86 (2294) | 5.15 (10041) | <1 | 0.22 | 43.4 $\pm$ 2.4 |
| Boden | Sandstone | 50 | 4.80 (1274) | 8.74 (2322) | 4.57 (4486) | 35 | 0.10 | 46.6 $\pm$ 2.1 |
| Zoebern | Sandstone | 60 | 7.31 (2732) | 15.1 (5653) | 4.66 (9076) | 3 | 0.12 | 42.0 $\pm$ 1.5 |

Cryst., number of dated apatite crystals. Track densities ($r$) are as measured ($\times 10^5$ tracks cm$^{-2}$); number of tracks counted ($N$) shown in brackets. $P(\chi^2)$: probability of obtaining $\chi^2$ value for $n$ degree of freedom (where $n$ = number of crystals − 1). Disp., dispersion calculated according to Galbraith & Laslett (1993). Fission-track central ages calculated using dosimeter glass CN 5 with $\zeta$CN5 = 373.3 $\pm$ 7.1.

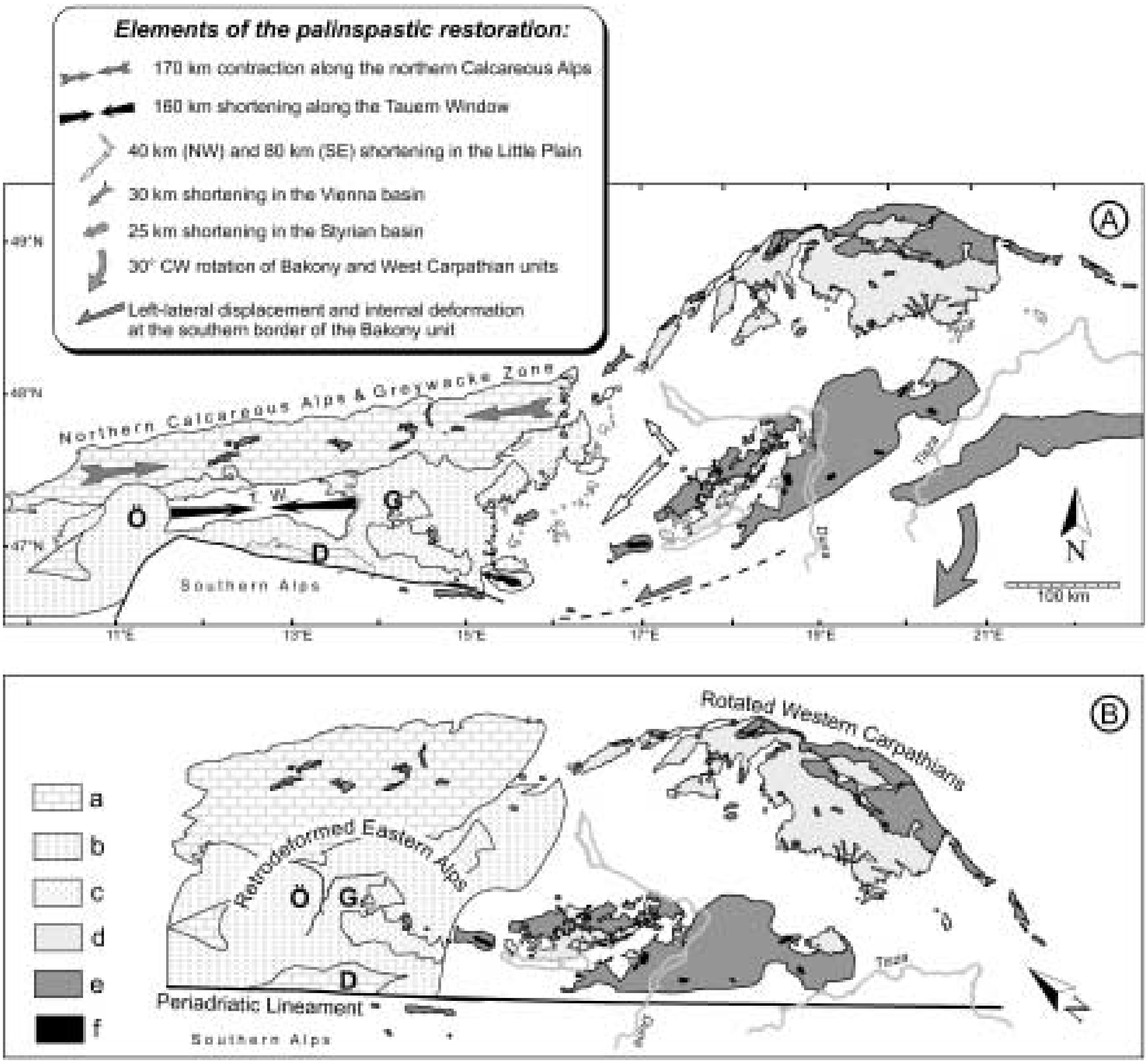


**Fig. 5.** Palinspastic restoration of the Eastern Alps and West Carpathians for the Palaeogene. (**a**) Situation today; (**b**) restored pattern. Ö, Ötztal block; G, Gurktal block; D, Drauzug; T. W., Tauern Window. Legend: a, Upper Austroalpine, partly metamorphosed Palaeo-Mesozoic sedimentary sequences; b, crystalline basement; c, Palaeozoic of Graz and Gurktal complex; d, Palaeo-Mesozoic of the Carpathians; e, Palaeogene basins; f, igneous centres. Magnitude of displacements fromTari (1996*a*, *b*), Frisch *et al*. (1998, 1999) and Márton *et al*. (1999, 2000). No attempt was made to compensate for Neogene deformation within the Carpathians.

Palaeogene NW–SE orientation of the NE margin of the Adriatic microplate.

This reconstruction produced a crustal block of *c*. 200 km width and at least 700 km length, bordered by the Rhenodanubian–Magura flysch on the NE and by the Periadriatic–Mid-Hungarian fault on the SW.

## Palaeogeographical maps (Figs 6–8)

The main idea of the palaeogeographical map series is that the Eastern Alps and Western Carpathians were a forearc basin in Palaeogene time. The maps (Figs 6–8) show land–sea distribution with depth subdivision of the sea wherever possible.

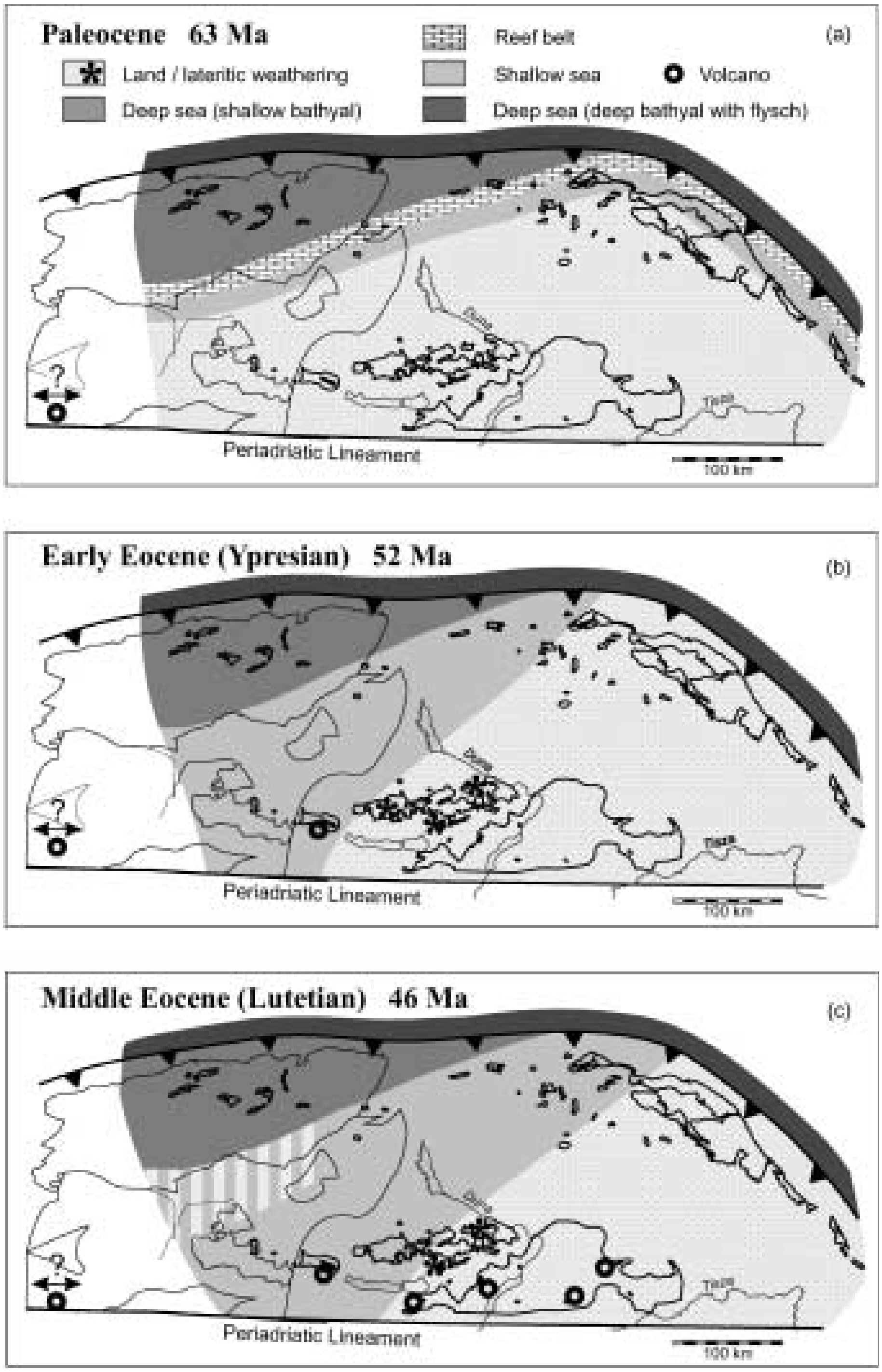


**Fig. 6.** Land–sea distribution in the Eastern Alps and West Carpathians from the Paleocene to Mid-Eocene (Lutetian).

### *Paleocene*

In the Paleocene (63 Ma; chronostratigraphy after Harland *et al*. 1990; Fig. 6a), the area of the Northern Calcareous Alps was covered by bathyal marl and siliciclastic turbidites of the Gosau Group (Wagreich 1995), extending well into the Western Carpathians along its northern margin (Wagreich & Marschalko 1995) as far as the Žilina Basin (Salaj 1995). Along the southern margin of the bathyal basin there was a reef belt (Tragelehn 1996). It extended eastwards along the edge of the Carpathians (Scheibner 1968). A narrow, shallow sea is inferred, in backreef position. Its extent cannot be estimated, because the Paleocene relief of the Alps was low, as suggested by extensive chemical weathering, which helped to produce bauxite formation in the Bakony Mts (Mindszenty *et al*. 1987, 1988). Bauxite is less widespread in the Western Carpathian sector (Zorkovský 1952; Činčura 1990), possibly owing to local uplift resulting in the erosion of Triassic dolomites and deposition in a coarse-grained delta (Salaj 1993).

### *Early Eocene*

In the Early Eocene (52 Ma; Fig. 6b), deep-water marl sedimentation persisted in the Gosau basins of the Northern Calcareous

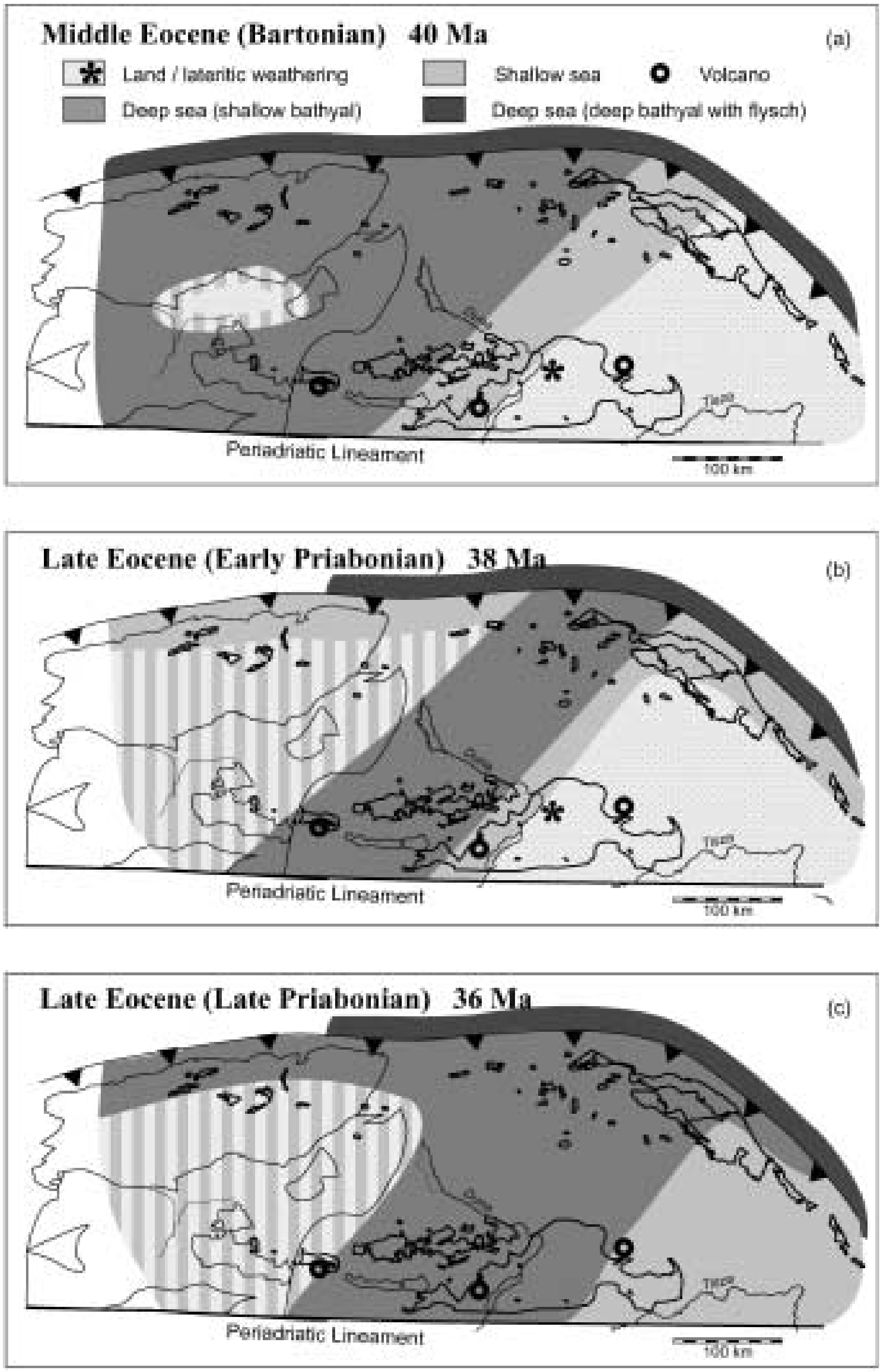


**Fig. 7.** Land–sea distribution in the Eastern Alps and West Carpathians from Mid-Eocene (Bartonian) to Late Eocene.

Alps (Wagreich 1995). The shelf edge was no longer outlined by a reef belt; falling global sea temperature restricted the extensive growth of reef builders (Wood 1999). We suggest that an extensive shallow sea covered the rest of the Eastern Alps (data from Krappfeld) and the westernmost sectors of the Western Carpathians (Žilina). Although the Paleocene low-relief land-scape was inundated by the sea, by the time of subsidence it was dissected and formed a complex topography (e.g. carbonate and coal measures next to each other at Krappfeld). Lack of biostratigraphic data prevents drawing the border between zones with Early Eocene and Middle Eocene start of sedimentation in the Zala region. Terrestrial environments extended through most parts of the Western Carpathians, with continuing bauxite accumulation (Mindszenty *et al.* 1988; Činčura 1990).

## *Early Mid-Eocene*

In the early Mid-Eocene (Lutetian, 46 Ma; Fig. 6c), deep-marine pelagic sedimentation persisted in the Gosau region of the Northern Calcareous Alps. The rest of the Eastern Alps was

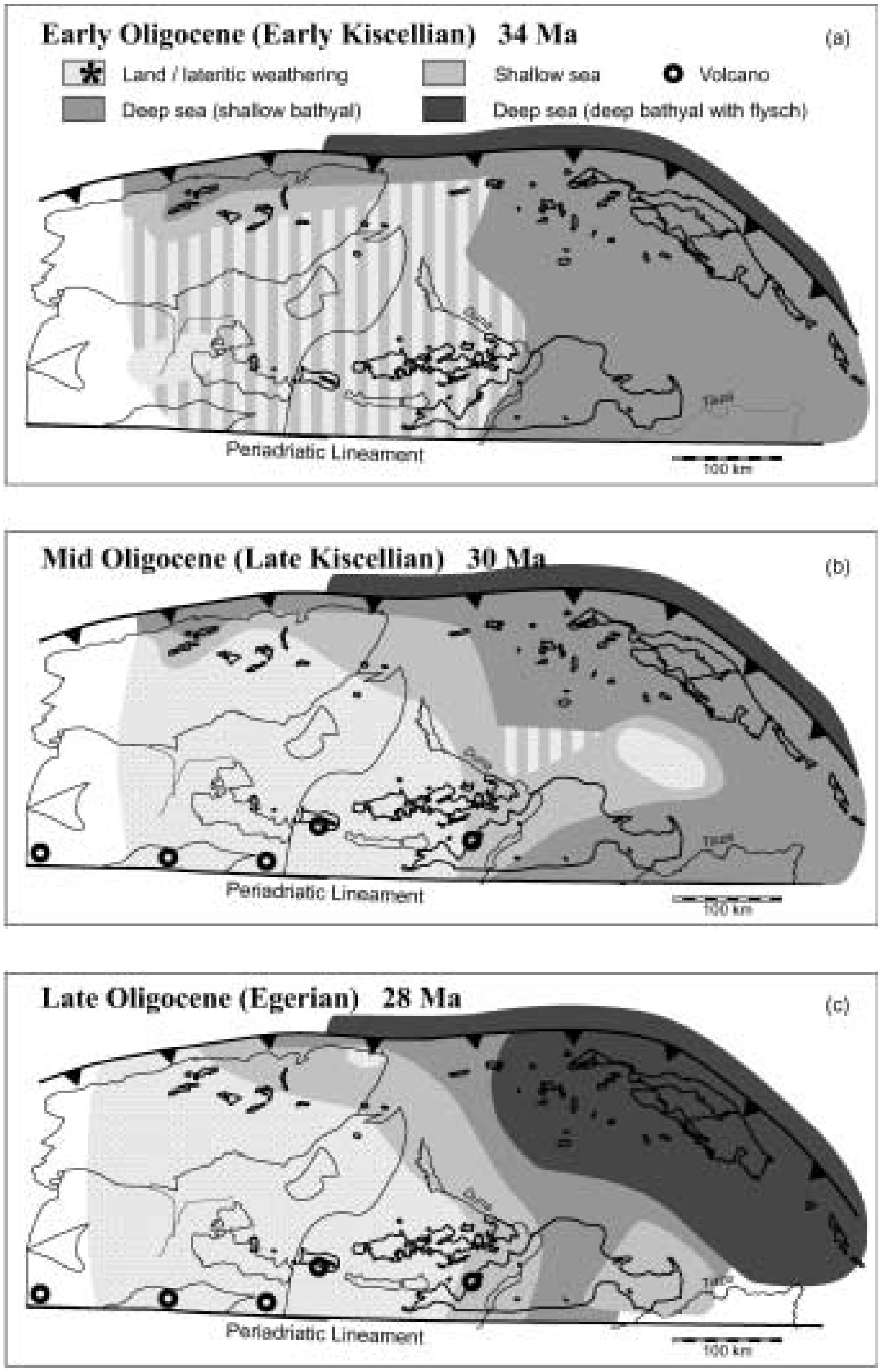


**Fig. 8.** Land–sea distribution in the Eastern Alps and West Carpathians in the Oligocene.

probably covered by shallow marine carbonate- and coal-producing environment as at Krappfeld. The western part of the Transdanubian Central Range was submerged at the beginning of the Lutetian, whereas the eastern part remained land. Submergence was not a simple advancement of the sea on a flat landscape but the inundation of a tectonically dissected and deeply karstified landscape in the Bakony. The eroding Western Carpathian terrain supplied material for thick conglomerates of variable thickness interfingering with carbonate. Although coal measures are extensive in the Bakony, they are subordinate in the Western Carpathian Palaeogene.

### *Late Mid-Eocene*

In the late Mid-Eocene (Bartonian) (40 Ma; Fig. 7a), shallow sea invaded the Bakony plus the western part of the Liptov Basin. The contrast between the internal bauxite- and coal-rich sedimentation and the external carbonate-dominated sedimentary environments persisted. Probably most of the Eastern Alps and western Bakony subsided under deep sea (shallow bathyal Padrag Marl). However, an area within the Eastern Alps was above sea level, shedding Middle Eocene siliciclastic sediments into a carbonate sea at Radstadt. Bojnice, Handlová and Banská Štiavnica in the Western Carpathians display limestone underlain by conglomerate. The eastern part of Liptov Basin subsided: algal limestone with reef structures was deposited. East of Budapest there was still land, with bauxite and coal marshes between the Buda Hills and Bükk Mts.

### *Early Late Eocene*

In the early Late Eocene (Early Priabonian) (38 Ma; Fig. 7b), the external part of the Lower Inn Valley in the Eastern Alps underwent uplift and thick Gosau sediments were eroded. Priabonian limestone was deposited unconformably on Triassic rocks (Lindenberg & Martini 1981), soon to be subsided under deep sea. At the eastern end of the Eastern Alps (Wimpassing) (W in Fig. 1) shallow marine limestone was deposited on the eroded surface of metamorphic rocks. Pebbles in Miocene sediments throughout the Alpine surroundings (Hagn 1981; Ebner & Sachsenhofer 1991) prove that this cover might have been extensive. Most of the Bakony was submerged under a shallow bathyal sea, limited to a narrow belt west of Budapest. Biostratigraphic resolution in the Liptov basin is too low to prove or disprove this arrangement, although facies trends (Gross *et al*. 1980) substantially support it. East of Budapest there was still bauxite and coal deposition. The Šambron zone along the external margin had already subsided under sea level; its evolution did not follow the internal pattern of sedimentation.

### *Late Late Eocene*

In late Late Eocene time (Late Priabonian) (36 Ma; Fig. 7c), the Lower Inn Valley region was under moderately deep sea, whereas marine cover of the rest of the Eastern Alps is questionable. Whereas the shallow bathyal environment was maintained west of Budapest, east of it the landscape was rapidly submerged. Tectonically enhanced subsidence (Fodor *et al*. 1992) produced a thin limestone sequence, overlain by thick shallow bathyal marl. The Poprad, Hornád and Šariš basins were submerged just before the Eocene–Oligocene boundary (Soták 1998a, 1998b), at the same time as the Bükk Mts (Báldi *et al*. 1984). Subsidence to bathyal depth followed rapidly; the Šambron–Kamenica zone was already at a shallow bathyal depth.

### *Early Early Oligocene*

The early Early Oligocene (Early Kiscellian) (34 Ma; Fig. 8a) was the time of initial exhumation of the Tauern Window. The short-term Priabonian sedimentation ceased in the Lower Inn Valley. After a short erosion interval, rapid subsidence started to produce contemporaneous neritic limestone and shallow bathyal marl again (Ortner & Sachsenhofer 1996; Löffler & Nebelsick 2001). Possibly this was the time of exhumation of the Augenstein peneplain in the Northern Calcareous Alps, formed during Priabonian–Early Kiscellian time (Frisch *et al*. 2001). The low relief of the Eastern Alps was subject to erosion, and caves formed in the Northern Calcareous Alps (Kuhlemann *et al*. 2001). Possibly a part of the Western Carpathians was submerged under a bathyal sea, as all the Lower Oligocene localities display anoxic sediments.

### *Late Early Oligocene*

The map for late Early Oligocene time (Late Kiscellian) (30 Ma; Fig. 8b) displays the eroding relief of the Eastern Alps and

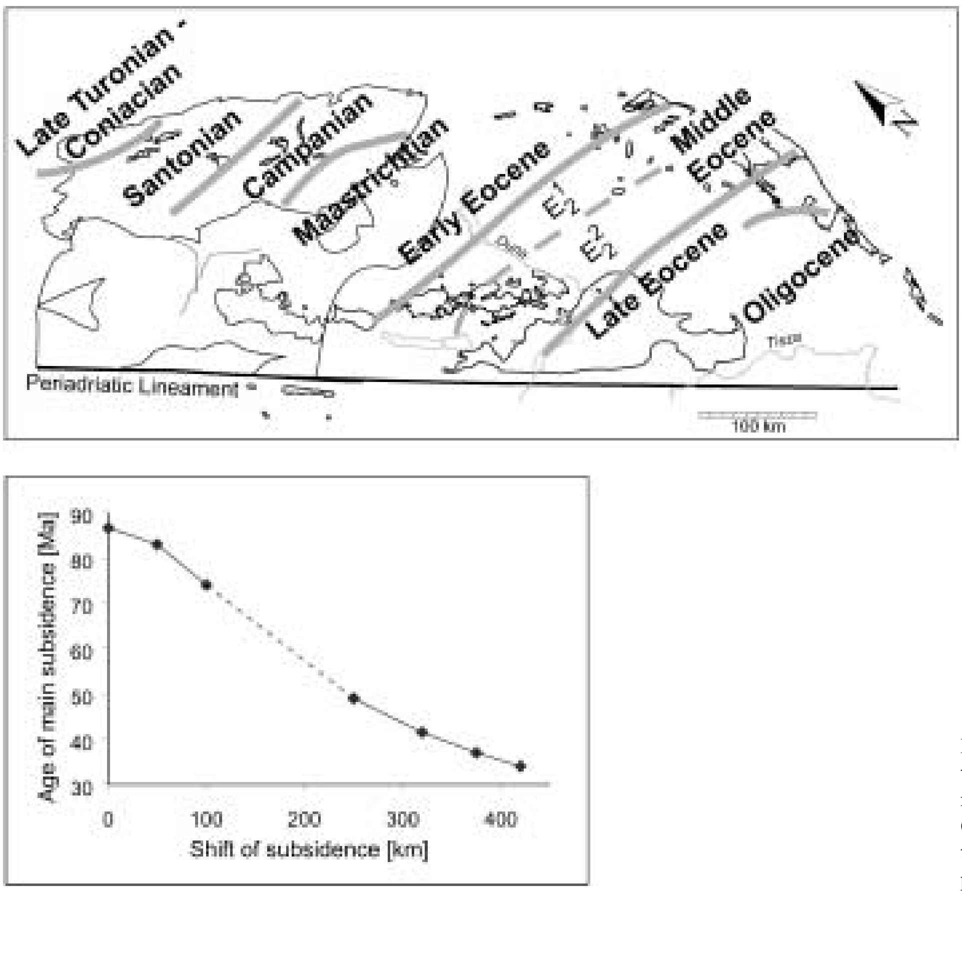


**Fig. 9.** Start of deep marine subsidence (in the Eastern Alps; Wagreich 1995) and marine subsidence (in the West Carpathians; for the various sources see text). About 8 mm a$^{-1}$ shift is encountered perpendicular to the subsidence isochrons.

Bakony during the so-called Early Oligocene denudation (Telegdi-Roth 1927). The general uplift of the Eastern Alps affected the marginal Lower Inn Valley Tertiary sequence, where the Lower Oligocene shallow bathyal Häring Beds are conformably overlain by the late Lower Oligocene shallow marine Unterangerberg Beds (Hagn *et al*. 1981; Ortner & Stingl 2001). Possibly the latter extended eastward along the margin of the Northern Calcareous Alps, with the terrestrial Augenstein sedimentation to its south (Frisch *et al*. 2001). The uplift of the Bakony by at least 2 km (calculating 1 km for water depth and another 1 km for the eroded Padrag Marl) yielded an erosion surface comprising Triassic to Eocene rocks. The shallow marine Hárshegy Sandstone surrounded the area of erosion (Báldi 1986).

At the same time, lagoonal evaporites were deposited in the middle of the Western Carpathians (Vass *et al*. 1979); therefore an island surrounded by lagoons is hypothesized there. The rest of the Western Carpathians was submerged under a bathyal sea (Húty Formation).

### *Late Oligocene*

In the Late Oligocene (Early Egerian) (28 Ma; Fig. 8c), deposition of coarse clastic rocks over most of the region occurred; the Oberangerberg Beds completely filled the Lower Inn Valley basin (Moussavian 1984). Its eastward extension was the terrestrial Augenstein Formation (Kuhlemann *et al*. 2001), interfingering with marine sediments to the north. North of the central and eastern Northern Calcareous Alps the sea floor dropped to bathyal depths. Late Oligocene uplift data for the Eastern Alps (Hejl 1997, 1999; Reinecker 2000) corroborate that it was land, contributing to the thick alluvial sediments of the Csatka Beds in the Bakony (Benedek *et al*. 2001), and supplying the Augenstein Formation in the Eastern Alps to the north (Frisch *et al*. 2001). The Budapest region received shallow marine sands interfingering with the alluvial Csatka Beds (Báldi 1976). Bathyal marl (Schlier) was deposited adjacent to the neritic belt. Bükk was an island in Early Egerian time, topped by a carbonate succession later (Less 1999). The northern part of the Western Carpathians subsided to deep bathyal depth, and kilometre-thick turbidite sediments (Central Carpathian flysch) were deposited. Flysch extended southward as far as the Handlová and Banská Štiavnica localities, but never reached Buda or Bükk.

Four major patterns are displayed in the palaeogeographical map series of Figures 6–8: (1) there is a west-to-east migration of initial basin subsidence in the Eocene (Fig. 9); (2) boundaries separating areas with different timing of subsidence ran oblique to the Periadriatic Lineament and the external margin (Figs 6 and 7), although being perpendicular to the direction of maximum horizontal stress (Fig. 10b); (3) the external margins of the Eastern Alps and Western Carpathians had an active subsidence and uplift history independent of the internal zones; (4) the Oligocene Eastern Alps displayed a systematically higher relief, mostly above sea level, than the Western Carpathians, which were below sea level.

## Sumatra versus the Eastern Alps and Western Carpathians

For a better understanding of the Palaeogene basin evolution in the East Alpine–Western Carpathian orogenic system, the geology of the recent Sumatra forearc basin is briefly reviewed in Table 2.

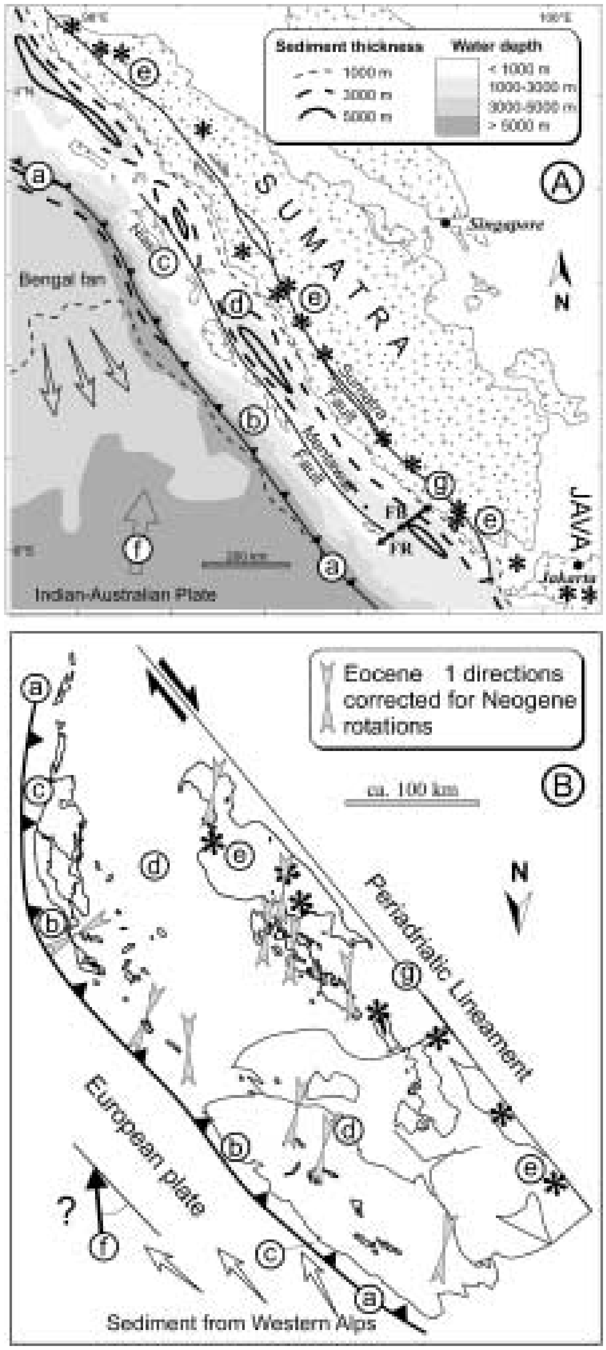


**Fig. 10.** Correlation of (**a**) the recent Sumatran forearc basin (after Hamilton 1979) with (**b**) the Eastern Alps–West Carpathians Palaeogene forearc basin (rotated by 180° to facilitate comparison). Eocene to Early Oligocene stress field (arrows show direction of maximum stress $\sigma_1$), synsedimentary deformation and sediment transport directions within the forearc during the Palaeogene. Sources: Eastern Alps, Peresson & Decker (1997); Vienna Basin, Fodor (1995); Bakony, Bergerat *et al*. (1983) and Csontos *et al*. (1991); Gerecse, Bada *et al*. (1996); Buda Hills, Fodor *et al*. (1992); Bükk, Csontos *et al*. (1991); Central Carpathian Palaeogene, Marschalko (1968, 1978). (See also the review paper of Fodor *et al*. 1999.) This direction is probably close to the subduction direction below the Eastern Alpine–Western Carpathian active margin and is conspicuously perpendicular to the facies boundaries as illustrated in Figures 6–8. FB, forearc basin; FR, forearc ridge; a, trench; b, accretionary wedge; c, forearc ridge; d, forearc basin; e, magmatic arc; f, oblique subduction; g, Sumatra Fault, equivalent to Periadriatic Lineament.

**Table 2.** *Analogous features of the Neogene–Recent Sumatra and the Palaeogene Alpine–Carpathian forearc basins*

| Sumatra | Eastern Alps & Western Carpathians |
|---|---|
| (a) A large subduction system extends from Burma as far as the Banda arc of Indonesia. The northward moving India–Australia plate (Malod *et al.*1995) is subducted along the Sunda trench. Subduction is perpendicular to the arc in Java and oblique to the arc in Sumatra. The eastern lobe of the huge Bengal Fan deposited more than 1 km of sediment on the subducting plate along Sumatra (Hamilton 1979) | (a) A subduction system has been continuous along the northern front of the Adriatic microplate from at least Campanian to Palaeogene time (Fig. 10b). The turbidite sequence of the Rhenodanubian and Magura flysch, receiving clastic material from multiple sources (Trautwein 2000), covered the ocean floor |
| (b) NE of the trench a thick accretionary wedge marks the front of the overriding plate and culminates in a forearc ridge forming an island chain (Mentawai Islands). The emergence of islands in the forearc in front of Sumatra, in contrast to Java where the forearc ridge is completely under water, is due to the high amount of sediments scraped off the Bengal Fan in the Sumatra sector (Moore *et al.*1980; Malod & Kemal 1996) | (b) The Rhenodanubian flysch is a preserved remnant of the accretionary wedge: erosion dominated the regime instead of accretion (Trautwein 2000) |
| (c) The forearc ridge, as exposed on Nias Island, consists of a stack of tectonic slices of upper-plate basement with crystalline rocks, ophiolite slivers derived from upper-plate oceanic crust, and accreted sediments (Hamilton 1988; Samuel *et al.*1997). Nias also hosts an active carbonate platform (Pubellier *et al.*1992) | (c) The Priabonian Eisenrichterstein reef near Salzburg in the Eastern Alps (Darga 1990) is an equivalent of the Nias carbonate platform. The ophiolitic detritus supplied from the north into the Šambron–Kamenica zone of the Western Carpathians is evidence for an accretionary wedge in the Carpathians: mafic clasts were eroded from a forearc ridge island |
| (d) Continental crust of the Sumatra forearc basin remained under shallow water or above sea level during the Palaeogene subsiding to neritic to bathyal depth in the Neogene (Izart *et al.*1994). These features were partly controlled by subduction erosion (van der Werff 1996). Terrestrial heat flow is low in the Sumatra forearc basin (41 mW m$^{-2}$: Subono & Siswoyo 1995) | (d) The forearc basin (200 km wide and 700 km long) on the continental crust of the Eastern Alps and the Western Carpathians is represented by Paleogene basins. It contained up to 1.5 km thick sediment near the volcanic arc in the Bakony and an up to 4 km thick succession near the forearc ridge in the Levoča Basin |
| | Maximum horizontal stress directions calculated from fault-plane analysis trend NW–SE in present-day coordinates, enclosing an angle of about 45° with the margin of the overriding plate (Peresson & Decker 1997; Fodor *et al.*1995). This direction is probably close to the subduction direction below the Eastern Alpine–Western Carpathian active margin and is conspicuously perpendicular to the facies boundaries as illustrated in Figs 9–11 |
| | A high level of diagenesis that occurred under low-temperature conditions (Hurai *et al.*1995) in the Central Carpathian Palaeogene Basin indicates low heat flow |
| (e) There is a continuous active magmatic arc along the Sunda sector (Westerveld 1952) | (e) On the overriding plate there was a magmatic arc in the Palaeogene (Kázmér & Józsa 1989; von Blanckenburg & Davies 1995) |
| (f) There is perpendicular subduction below Java and oblique subduction below Sumatra | (f) We assume that oblique subduction (as recognized by Wagreich (1995) for the Late Cretaceous) continued into the Palaeogene along the external margin of the ALCAPA unit. Supportive arguments are compression oblique to the margin of the overriding plate, but perpendicular to the boundaries of the shifting basins (Peresson & Decker 1997; Fodor 1995) |
| (g) Oblique subduction produced the 1650 km long arc-parallel strike-slip fault in Sumatra (Malod *et al.*1995). Dextral shear since mid-Tertiary time produced at least 150 km total offset (McCarthy & Elders 1997) | (g) We suggest that oblique subduction triggered the formation of the >700 km long Periadriatic Lineament as an arc-parallel strike-slip fault, an equivalent of the Sumatra Fault. Palaeogene right-lateral offset is more than 150 km (Kázmér & Kovács 1985; Tari 1996*a*) |

## From accretion to erosion (Fig. 11)

Subduction of the European plate below the Adriatic plate was continuous throughout the Campanian–Miocene interval. Intervals of accretion of sediments are documented by thermal data during this process (Trautwein *et al*. 2001*a*, *b*).

The eastward progress of basin subsidence on the overriding plate proceeded at a rate of about 8 mm a$^{-1}$ during an interval of *c*. 55 Ma, covering a distance of about 400 km (Fig. 9). For this calculation we considered the similar migration of Gosau basins in the Northern Calcareous Alps during Cretaceous time (Wagreich 1995).

Most of the ALCAPA terrane behaved uniformly during the Palaeogene. However, a 20–50 km wide marginal sector on the trenchward side displays higher mobility (earlier subsidence than the rest, uplift in the time of subsidence of the internal sectors, folding, etc.): this forms the Northern Calcareous Alps and the Šambron Zone (Soták *et al*. 2001). This higher mobility is probably due to an extremely thin crust at the advancing edge of the overriding plate, easily affected by the growth or erosion of the accretionary wedge.

Basin subsidence isochrons are more or less parallel (Fig. 9), and perpendicular to the maximum horizontal stress in the Palaeogene (Fig. 10b). In line with the theory of Wagreich (1995), we suggest that the major cause of migration of the Palaeogene basins was subduction erosion. Seismic observations in Costa Rica (Flueh *et al*. 2000) prove that there are slivers of detached upper-plate crust attached to the subducting plate (Meschede *et al*. 1999*a*, *b*); a similar situation is suggested for the Eastern Alpine–Western Carpathian active margin.

The brittle upper crust of the Adriatic plate was cross-cut by normal faults (e.g. Mindszenty *et al*. 1988). The brittle–ductile boundary was in a lower position near the subduction zone (as a result of the cooling effect of the subducting plate and sediments), although it had been at an elevated position near the magmatic arc, owing to heating by the mantle and by magmatism. The outward slope of the brittle–ductile boundary and lack of support for the brittle crust at the trench resulted in extension and thinning of the forearc along normal faults flattening into the ductile lower crust. Ductile flow of the lower crust contributed to the extension (Fig. 11).

The leading edge of the Adriatic plate has undergone subduc-

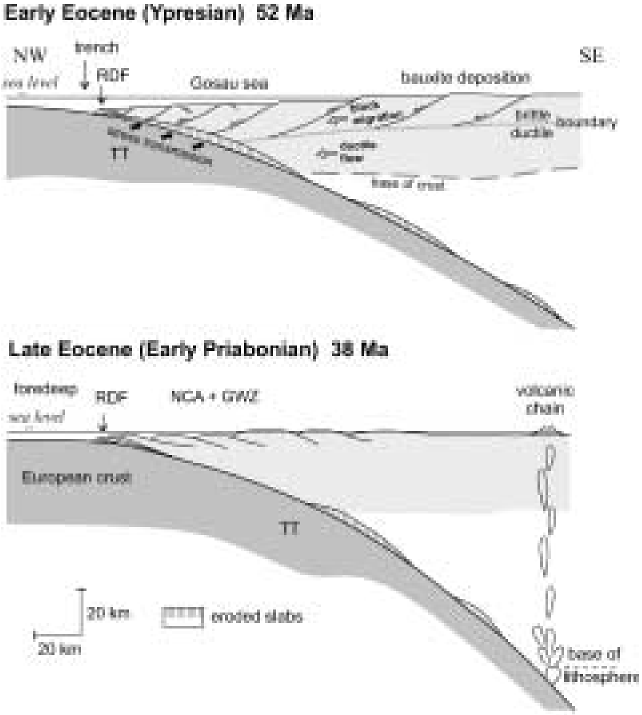


**Fig. 11.** Subduction erosion in the Eastern Alps and West Carpathians (inspired by Meschede *et al.* 1999*a*, *b*). The overriding plate is reduced both in thickness and in width by the subducting plate. Either subduction or slab-breakoff magmatism produced the marked volcanic chain. RDF, Rhenodanubian Flysch; TT, Tauern Terrane; NCA, Northern Calcareous Alps; GWZ, Greywacke Zone.

tion erosion (by an oceanic ridge (Wagreich 1995), by the Tauern terrane (Kurz *et al*. 2001b) or by marginal portions of the Austroalpine plate (Liu *et al*. 2001)). The Tauern terrane subducted to a depth equivalent to >20 MPa, undergoing eclogite-facies metamorphism (Kurz *et al*. 2001*b*). The removal of material along the leading edge and from below the frontal part (from a zone of a few tens of kilometres width) further weakened lateral support and caused an added subsidence and crustal thinning of the marginal 40–60 km wide zone (Gosau zone in the Eastern Alps and Šambron–Kamenica zone in the Western Carpathians).

Crustal stretching was countered by Late Eocene thrusting in the Gosau zone (Tollmann 1976), which produced repeated emergence, erosion and subsidence in the Northern Calcareous Alps. The subducted lithosphere reached the melting zone and produced arc magmatism (Kagami *et al*. 1991). Alternatively, von Blanckenburg & Davies (1995) and von Blanckenburg *et al*. (1998) suggested that breakoff of the subducting slab at the boundary of continental and oceanic crust produced melting in the lithospheric mantle.

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