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Some Remarks on the Geomorphological Evolution of the Eastern Alps. Constraints on Above-Surface Geometry of Tectonic Boundaries?

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Contents

Zur geomorphologischen Entwicklung der Ostalpen. Hinweise auf Geometrie tektonischer Grenzen über der heutigen Oberfläche?

Zusammenfassung

Die morphologische Form der Ostalpen wird dazu benutzt um die Geometrie fundamentaler tektonischer Grenzen in jenen Teilen des Krustenprofils einzuengen, die der direkten Beobachtung durch Erosion in die Molasse Becken längst entzogen sind. In unserem Ansatz benutzen wir

1) die enge Korrelation der Geologie der Ostalpen mit der Topographie und
2) die enge Assoziation der Entwässerungssysteme mit den geologischen Grenzen erster Ordnung.

Nachdem die derzeitige Topographie der Ostalpen etwa 20 % des gesamten Denudationsprofiles seit dem frühen Tertiär ausmacht, schlagen wir vor, daß es möglich sein sollte, diese Topographie zu verwenden, um die Form von Strukturen über der heutigen Oberfläche zu erfassen. Um solche Abschätzungen quantitativ zu erfassen benutzen wir die Diffusionsgleichung. Wir lösen diese für fixierte Randbedingungen entlang von Tälern die wir entlang einer Reihe verschieden geformter tektonischer Grenzen über der heutigen Oberfläche einschneiden lassen. Zwei weitere Variablen sind dabei wichtig zu beachten: die Denudationsgeschichte sowie die Erosivität der Gesteine. Die Denudationsgeschichte ist relativ gut durch Geobarometrie bestimmt, wobei die größte Hebung etwa im Bereich der heute größten Seehöhe erfolgte. Die Erosions und Einschneidungsraten können implizit aus den Modellberechnungen bestimmt werden. Wir bestimmen einen Wert von 0.3 km^2Ma^{-1} für die Erosionsdiffusivität der Kalkalpen sowie 7.6 km^2Ma^{-1} für die kristallinen Gesteine der Tauern. Beide Werte sind für eine Denudation von 30 Ma Dauer berechnet. Die derzeitige Form der Ostalpen kann am besten angenähert werden, wenn ursprünglich steile tektonische Grenzen zwischen Kristallin und Kalkalpen im Norden und im Süden angenommen werden. Dieses Ergebnis könnte wichtige Implikationen für die Prozesse der Deckenstapelung der Ostalpen in der Kreide haben.

Abstract

Morphological first order features of the eastern Alps are used to derive information on the geometry of fundamental tectonic boundaries in parts of the crustal profile that have long eroded into the Molasse basins. In our approach we utilise

1) the close association of the Alpine geology with the topography and
2) the association of the drainage pattern with the first order geological boundaries.

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Inasmuch as the present topography preserves about 20 % of the total denudation profile eroded since the Tertiary, we suggest that it should be possible to use this relief to infer some of the above-surface structure of the eastern Alps. In order to quantify our estimates we apply the diffusion equation and solve it with pinned boundary conditions in drainage systems that incised along a range of hypothetical shapes of the above-surface tectonic boundaries. Two other important variables control the model predictions: the exhumation history and erosion contrast between different rock types. The exhumation history is well constrained by geobarometric estimates at the present exposure level with largest amounts of denudation occurring in the area of highest present surface elevation. The erosional parameters can be determined implicitly through the model calculations. We derive best fit estimates of 0.3 km^2Ma^{-1} erosional diffusivity for the calcareous Alps and 7.6 km^2Ma^{-1} for the crystalline nappes of the central Tauern for denudation histories scaled to a 30 Ma duration. The present shape of the Alps can be best approximated with originally steeply dipping decollements between the crystalline nappes and the calcareous Alps in the north and south, respectively. The suggestion of a steep above-surface continuation of these fundamental tectonic boundaries may have important implications for Cretaceous nappe tectonics.

1. Introduction

The first order geomorphology of active mountain belts bears significant information on the tectonic evolution of the belt. Morphological parameters like its elevation, average slope and length scales of the topography can be used in combination with gravimetric, seismic and geological data to constrain the tectonic and isostatic evolution of a mountain belt. This source of information has often been neglected by geologists interpreting the structural geology of the present erosion level and it is only recently that ancient landforms, present morphology, surface geology and geophysics are used to form integrated interpretations of the history of a mountain belt (e.g. KOONS 1989; DAHLEN & BARR, 1991; STÜWE, 1991). However, one key piece of information that has found very little exploitation is the geomorphology as a direct tool to infer the above-surface geometry of geological structures in a pile with strong anisotropy with respect to its ability to erode. In many cases such information may be extremely important to support a tectonic model as, for example, interpretations of many mountain belts are based on structural data from only one horizontal slice through the middle crust (the present surface). These data are, or are not, supported by geophysical information from deeper levels but constraints on the geology from levels eroded since denudation of the belt commenced is largely lacking. Interpretations of crustal evolutions are therefore often only based on data from about half of the crustal profile subject to interpretation.

One example where it may be possible to use the geomorphology to derive information on the relative geometry of nappes in parts of the crust that have long eroded off the top of the range is the Eastern Alps. There, the present erosion level exposes pervasively rocks of greenschist and amphibolite facies grade corresponding to depths between 10 and 25 kilometres (e.g.: NIGGLI, 1976; KOLLER, 1985; MILLER, 1990; FRANK et al., 1987a) and seismic data indicate a present crustal thickness between 40 and 60 kilometres (e.g.: ARIC, 1981) and the current topography encompasses up to 3 kilometres of relief. There is therefore about 20 % of the total vertical denudation profile available for morphological interpretation of the above-surface geology.

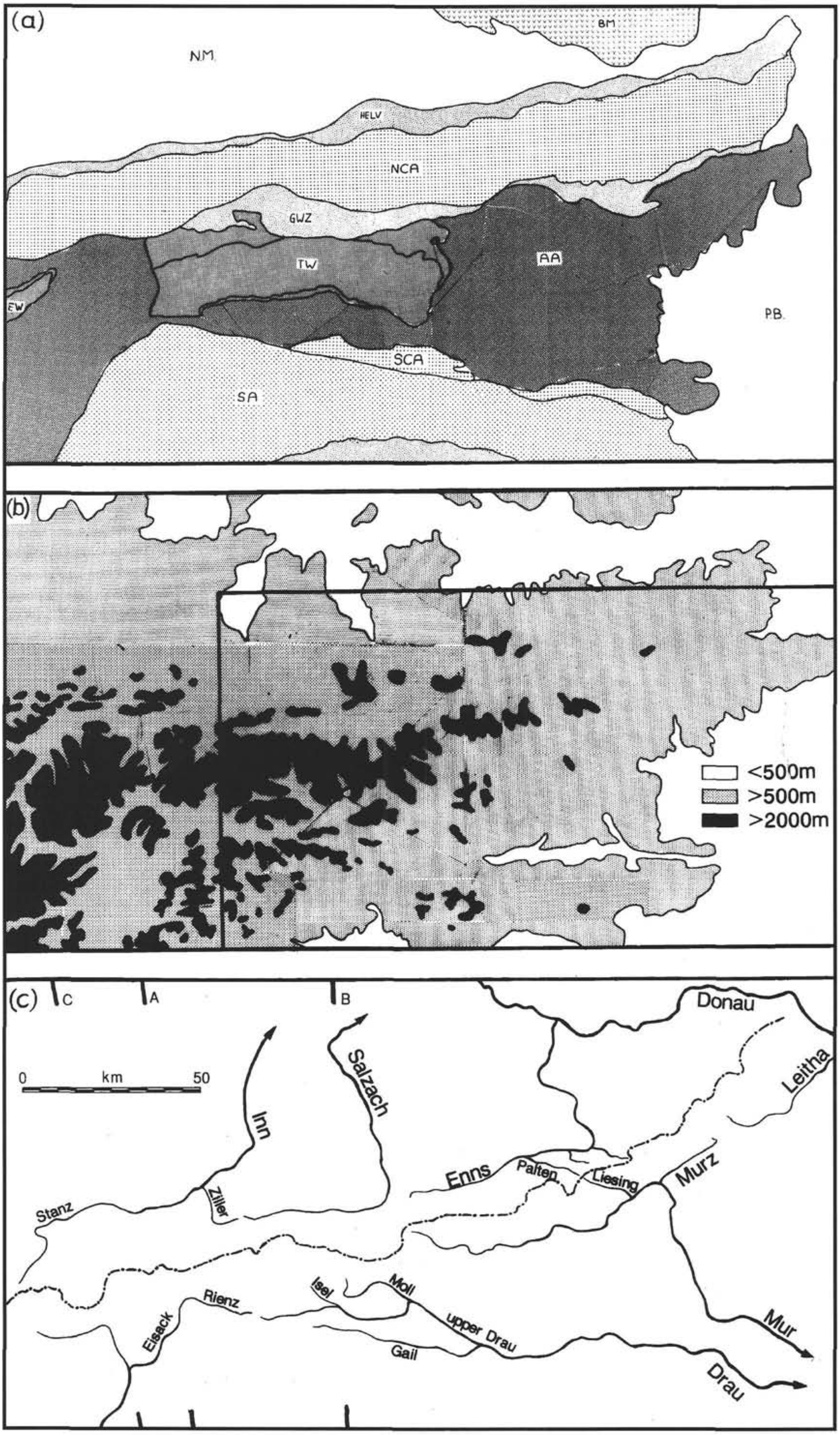
In this paper we use this available relief to place constraints on the geomorphological evolution and investigate to which extent this information can be used to infer details of the above-surface geometry of nappe juxtaposition. Our approach is handicapped by the fact that extensive carving of the topography during Alpine glaciation and Cenozoic sedimentation obscures much of the shape detail of the valley profiles subject to discussion. However, we demonstrate that the approach is, at least in principle, useful and show that information on the shape evolution of the range on the largest scale may be derived. For our estimates we utilise the fact that the majority of the drainage patterns follow fundamental tectonic boundaries which, in many cases, separate structural units with large 'erosivity' contrasts (Fig. 1). Using this fact and geobarometric constraints on the exhumation history we attempt to constrain the location of this drainage during its incision. History and thus ultimately constrain the location of tectonic boundaries. In particular we will focus on one of the boundaries of controversy in palinspastic reconstructions of the eastern Alps – the boundary between the northern calcareous Alps (NCA) and the Austroalpine and Penninic crystalline nappes. Throughout the rest of this paper we will use the term 'central Tauern' to refer to these latter parts of the eastern Alps in a morphological sense. That is, the term will be used for the geographic region south of the NCA and north of the southern calcareous Alps and southern Alps, thus encompassing the Penninic units, parts of the Austroalpine and the Graywacke Zone.

2. Constraints on the Geomorphological Evolution

If internal deformation is neglected, the shape of any landform is the consequence of the interaction of two processes:

1) the distribution of exhumation in space and time and
2) the distribution of erosion in space and time.

In discussing the interaction of these parameters we will use the word uplift to denote changes of the surface elevation with respect to a fixed reference level and denudation or exhumation to changes of the depth of rocks with respect to the surface regardless of the elevation of this surface. The terminology for the vertical motions in the lithosphere with respect to different reference levels has arisen much confusion in the last decade but has recently been clarified by ENGLAND & MOLNAR (1990) to which the interested reader is referred. We also refer to a recent study of ZHOU et al. (1994) who calibrated the rates of uplift and denudation and showed that for large exhumation rates, the uplift may be even negative (subsidence) depending on the erosion history and on the mechanical response of the lithosphere to an external driving force. It is therefore important to distinguish between those processes. We remind the reader therefore that only that constraints on exhumation may be derived from geobarometric or PT-path evidence, whilst uplift may only be constrained by sedimentological or morphological observations. In the eastern Alps the exhumation rates and its spatial distribution are reasonably well constrained by geobarometric, geochronological, and geological evidence. The distribution of uplift and erosion in space and time, on the other hand, is much less known and is only constrained by, for example, the presence of Cretaceous Gosau basins as well as the intramontane Tertiary basins. However, the logic may be reversed and it is our aim here to formulate simple assumptions about the erosion history and use those



Text-Fig. 1.
A comparison between the tectonics of the currently exposed crustal level in the Eastern Alps (Fig. 1a) with the topography of the region (Fig. 1b) and the principle drainage pattern (Fig. 1c).
The scale is the same for all three diagrams and is therefore only shown on Fig. 1c. The rectangular area on Fig. 1b indicates the approximate region which *is modelled in Figs.* 5 and 6. Location of topographic profiles of Fig. 2 are shown on Fig. 1c. NM = northern Molasse Basin; PB = Pannonian Basin; GWZ = Graywacke Zone; NCA = Northern Calcareous Alps; TW = Tauern Window; EW = Engadin Window; AA = Austroalpine rocks; HELV = Helvetic units; SCA = Southern Calcareous Alps; SA = Southern Alps; BM = Bohemian Massif. The shading corresponds to the qualitative erosivity contrast between different units: the erosional diffusivity of NM and PB is very large, TW, AA and EW is much smaller and SA and NCA is the smallest in the map area shown.

to refine our understanding of the evolution of the topography. Our assumptions are constrained by the fact that any assumptions on the nature of the erosion history must be as such as to meet the present shape of the eastern Alps at the end of the morphological evolution, for a given exhumation history.

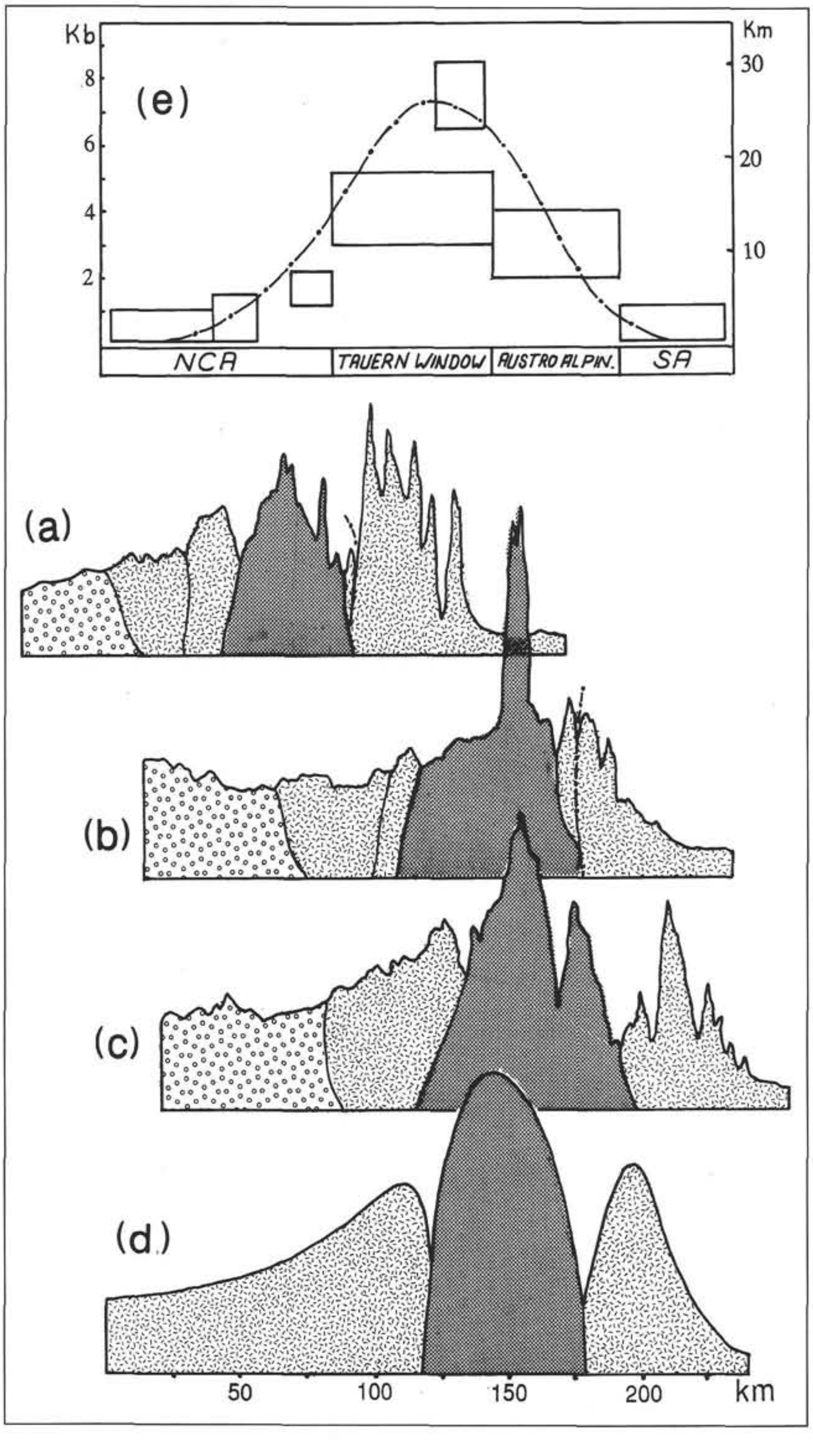
Moreover, the assumptions must correspond in distribution and nature to the large scale geology, that is, to the distribution of rock types with large differences in the erosion response, for example, limestone and crystalline schists. In this section we will discuss the principle data sets that constrain the modelling of the geomorphological evolution: the present geology and geomorphology as well as the exhumation distribution in space and time.

2.1. Geology and Geomorphology

In contrast to the western Alps, geology and geomorphology of the eastern Alps are arranged in a largely symmetric pattern about the drainage divide in the central Tauern (Fig. 1a).

The region of highest surface elevation includes peaks well above 3500 metres above sea level and is located central to the eastern Alps (Fig. 1b). It corresponds closely with the location of the Tauern Window which exposes the structurally lowest units of the Alpine nappe pile.

The rock types in this window are Penninic and include a combination of pre-alpine gneiss domes with probably large resistivity towards erosion and mostly amphibolite facies metamorphic schists with oceanic affinities and probably little erosion resistance. Outwards from the Tauern Window the average surface elevation drops to lower levels at a rate that is comparable to the rate at which structurally higher levels are attained (Fig. 1a and 1b). It is for example interesting to note that towards the west, where more Penninic rocks are exposed in the Engadin Window the drop in surface elevation is small and many peaks remain above the 3000 metre mark. In fact, the Central and Western Alps, where mostly Penninic rocks are exposed, the average surface elevation exceeds that of the Eastern Alps. The rocks covering the Penninic rocks of the Tauern Window include a narrow margin of Mesozoic schists (Schieferhülle) followed by the Paleozoic crystalline nappes of the Upper Austroalpine that constitute the majority of the the eastern Alps. The crystalline nappes of this central part of the eastern Alps are followed to the north and south by the Graywacke Zone (GWZ) by Calcareous Alps (NCA in the North and SCA in the South)



Text-Fig. 2.
Topographic profiles and interpreted geological cross-section through the Eastern Alps in the region of the Tauern Window with some peak pressure estimates.
Profiles are north-south through the Zillertaler Alpen (Fig. 2a); through the Kitzbühler Alpen (Fig. 2b) and through the Ötztaler Alpen (Fig. 2c). See also Fig. 1c for the location of the profiles. Fig. 2d is a schematisation of Fig. 2c as used for the modelling approach.
The shading indicates as follows: dark dotting = Penninic and the Austroalpine rocks with relatively large erosivity; dashes = rocks of the GWZ NCA and SA which are predominantly limestones and of small erosivity; circles = rocks of the northern Molasse basin where sediment accumulation occurs at present.
The additional line in the dashed northern region on 2a and b indicates the boundary between GWZ and NCA. Note that the fundamental drainage pattern is located between GWZ and crystalline schists on 2a and b but directly between NCA and crystalline in 2c. Fig. 2e shows a distribution of the peak pressures due to Eoalpine metamorphism after the summary of ENGLAND (1981) (boxes). The dashed line indicates the distribution of exhumation as used for the modelling.

and ultimately by Helvetic rocks and the Molasse basins around the River Danube in the North and the river Po in the South. In the South all units outside the central crystalline nappes are separated by a fundamental tectonic boundary, the Periadriatic lineament. Rocks south of this lineament are tectonically distinctively different but lithologically they are predominantly limestones in the region of interest and thus comparable to the NCA with respect to their erosivity.

The average surface elevation of the individual tectonic units drops continuously towards the north and south from the central divide with peaks still around 3000 metres in the Schieferhülle and lower parts of the Austroalpine, most high peaks in the crystalline Upper Austroalpine between 2500–3000 metres, 2000–2500 metres in the GWZ, NCA and SCA and around 2000 m in the Helvetic units. The rivers Danube and Po in the Molasse basins are located at elevations of around 500 and 100 metres, respectively. Despite this overall drop to the north and south there is a pronounced asymmetry with respect to the topography in and peripheral to the NCA and SCA (Fig. 2). Peaks in the SCA and in the Dolomites are generally somewhat higher than those in the NCA and the drop into the Molasse basins occurs rapidly and to near sea level in the south whereas in the north topography above 500 metres extends far into the German foreland.

The continuous drop of the elevation of the highest peaks and the average surface elevation of individual tectonic units is interrupted by marked discontinuities in the topography imposed by the fundamental drainage patterns (Fig. 1c). This drainage pattern is developed largely parallel to the drainage divide and follows fundamental tectonic and lithological boundaries. It is interesting to note that this is in contrast with, for example, the Himalayas, which do not have a drainage divide parallel to the region of highest surface elevation or the Kaukasus where the drainages are developed largely radial to the watershed. In the Alps, the topographic relief around these drainages is up to 3 kilometres. This relief is comparable to the thickness of some Alpine nappes and emphasizes therefore its potential for the interpretation of the above-surface structure. The boundary between the crystalline nappes of the central Tauern and the lithologically different rocks of the GWZ and NCA is unmistakably characterised by a series of W–E striking valleys namely the Klostertal, Stanzertal, and the valleys of the rivers Inn, Salzach, Enns, Liesing, Palten, Mur, Mürz and Leitha (Fig. 1c). This boundary follows with astounding persistency the contact between units of large erosion contrast and is incised to an average elevation of 500–600 metres (Fig. 1, Fig. 2). Where there is a contact between GWZ and MAA there is usually another E–W striking valley separating the GWZ from the NCA , for example the Hochfilzen and Leogang valleys or, to a certain extent, the Johnsbach and Radmer valleys in the Eisenerzer Alpen. In our discussion we will focus predominantly on sections across this set of valley where the NCA are directly opposed to the Austroalpine rocks like, for example, the Inn valley west of Innsbruck or the Enns valley near Schladming. A similar distinct drainage patterns, also at an elevation around 500 metres, has evolved in the south along Lesach, Rienz and Gail marking the Periadriatic lineament and the separation of the SCA from the crystalline rocks of the central Tauern. That the location of the drainages is rather controlled by the erosion contrast in rock types than by the location of a tectonic boundary is evidenced by the fact that in places where the SCA overlap the Periadriatic lineament to the north, drainage patterns continue to follow the line of erosivity contrast and not those of tectonic contrast, for example the valley of the upper Drau (compare Figs. 1a and c). In that respect it is noteworthy that other important tectonic boundaries are not paralleled but crosscut by drainage patterns, evidently because little contrast in the erosion properties exists between tectonically dramatically different units. For example, the upper Mur valley transects more or less randomly the contacts of Grazer Paleozoic, Gurktal nappe and the Tauern Window (Figs. 1a and 1c). On the other hand, many other tectonic boundaries that separate rocks of similar resistivity to erosion have no drainages developed along them; for example the margins of the Tauern window or the Gurktal nappe.

The shape of the west-east striking valley systems, in particular the system separating the NCA and GWZ from the central Tauern, is characterised by a marked asymmetry. The northern side is generally much steeper than the southern slopes developed in the crystalline rocks. Nevertheless, peaks on the southern side rise to generally higher elevations than in the northern calcareous Alps. This feature is particularly well developed in valley cross sections near Schladming in the Enns valley and around Innsbruck in the Inn valley. Those examples will serve us as a guide to our model estimations.

2.2. Distribution of Exhumation in Space and Time

The main crustal thickening events in the eastern Alps including the stacking of the Austroalpine nappe pile occurred in the Cretaceous at about 100–90 Ma. By the Turonian (85 Ma) the relative positions of most large tectonic units were established (TOLLMANN, 1959; FRANK, 1987). Thrusting of the Austroalpine nappe pile over the Penninic rocks exposed in tectonic windows occurred somewhat later in the Eocene. The majority of the cooling ages from outside the Tauern window record 95–70 Ma ages for both Rb/Sr and K/Ar ages indicating cooling through the 500°C isotherm from amphibolite and greenschist facies conditions (e.g.: FRANK et al., 1987b). However, it is not at all clear that these cooling ages relate to the exhumation of the rocks and we consider them as an indicator for the end of metamorphism only (e.g. EHLERS et al., 1994). Indeed, the Cretaceous deformation is likely to have been a homogeneous thickening event of the lithosphere as a whole so that no significant topography was developed at that time (STÜWE 1991; ZHOU & SANDIFORD, 1992; STÜWE & SANDIFORD, 1994). It is now well established that during continental collision the positive buoyancy of the thickened crust is largely balanced by the negative buoyancy of the thickened mantle part of the lithosphere so that little isostatic response is expected (SANDIFORD & POWELL, 1990; ENGLAND & HOUSEMAN, 1988). Other arguments for the absence of substantial topography development at this time have been discussed by ENGLAND (1981), CLIFF et al. (1985), STÜWE (1991) and STÜWE & SANDIFORD (1994) and we refer to those studies for further discussion of the possibility of substantial Cretaceous surface elevation.

The beginning of the morphological evolution of the Eastern Alps is generally accepted to coincide with the rapid onset of sedimentation in the Molasse basins in the Lattdorf (about 37 Ma; e.g.: ENGLAND, 1981; CLIFF et al., 1985). Already briefly before that, in the upper Eocene, the ocean over the Alps had receded to the Helvetikum and first development of the Molasse basins began (FUCHS, 1980a). Only in the Oligocene, however, geobarometric studies estimate the onset of rapid uplift in the central Tauern (CLIFF et al., 1985). The preservation of the Augensteinschotter

SAKAGUCHY, 1973; FUCHS, 1980b) on ancient land surfaces of the NCA in the Rupel and Eger (35–20 Ma) indicates that a substantial portion of the denudation had occurred by about 20 Ma an age that coincides with the end of the dramatically rapid Molasse sedimentation. Sedimentation in the inner Alpine basins commenced around 20 Ma in the Norische Senke, the Steirisches Becken (FUCHS, 1980b) and the preservation of these sediments indicates that the majority of exhumation has terminated by that time. The complete uplift of the present erosion surface is therefore likely to have occurred in an interval which spans no more than a 20 my period between 40 Ma and 20 Ma. The amount of denudation that must have occurred during this time is constrained by geobarometric estimates for the Eoalpine metamorphic event. In the central Tauern window rocks record 6 to 8 kbar metamorphic peak pressure (CLIFF et al., 1985; SELVERSTONE & SPEAR, 1985). Large parts of the Austroalpine east and west of the Tauern window underwent peak pressures in the range between 7 and 12 kbar (KOLLER, 1985; MILLER, 1990; FRANK et al., 1987a) and are therefore comparable with those within the Tauern window. Indeed, eclogites of up to 18 kbar pressure have been found in both, the Tauern window and the Austroalpine west and east of it along an axis parallel to the region of highest surface elevation. ENGLAND (1981) estimated an appropriate value of 3–5 kbar for the peripheral Schieferhülle from a summary survey on the available geobarometry therein (Fig. 2e). Total amounts of exhumation must therefore have been at least 15–20 kilometres in the central part of the Eastern Alps. Metamorphism in the limestone ranges is confined to minor greenschist facies metamorphism along their base (FRANK, 1987; KRALIK et al., 1987). The total amount of vertical motion of the vertical rock column in the calcareous Alps exceeds therefore not much the present surface elevation. Some of this data has been summarised by NIGGLI, (1976) and ENGLAND, (1981).

2.3. The Influence of Deformation During Exhumation

In order to use the established denudation history to model the geomorphological evolution and to constrain the shape of pre-uplift structures it is necessary to establish that internal deformation during and subsequent to the exhumation period has played no important role with respect to the shaping of surface features. We have discussed above that convergent deformation in most parts of the Austroalpine terminated with the end of the Cretaceous and that the thrusting of the nappe pile onto the Penninic units was completed in the Paleogene. The pervasive N–S deformation events terminated therefore prior to 40 Ma which we consider as the start of the morphological evolution (see above). They are therefore considered of no consequence to our considerations. Nevertheless, ongoing deformation is evidenced by, for example, the protrusion of the Helvetic nappes into the Molasse basins. However, these observations are comparably minor on the scale of the range as a whole and we will neglect their influence. On the other hand, the work of RATSCHBACHER et al. (1991), NEUBAUER & GENSER (1990), SELVERSTONE (1988) and others has shown that substantial E–W extension took place during the maximum period of exhumation in the Oligocene–Miocene. Whilst this lateral mass transfer has fundamental implications for tectonic interpretations, the present day Alpine crust is still at least 50 kilometres thick underneath the Tauern Window and the total thinning strain is thus likely to be substantially less han 1. Moreover, in our model calculations we focus predominantly on one-dimensional estimates of the geomorphology on N–S profiles across the range. This approach is justified if the lateral extent of the range is large compared to its width which is given in the eastern Alps (see Fig. 2). Therefore, it is also justified to neglect deformation events that occurred with a dominant E–W transport direction.

3. The Model Approach

We will now detail our approach in order to answer following question: to which extent is the geomorphology of the Eastern Alps a unique function of the exhumation history and the geometry of fundamental tectonic boundaries in the 10–20 kilometres of crustal profile that have been removed from our direct observation by erosion? In other words, is it possible to use the geomorphology to infer the shape evolution of the range and to which extent does this shape evolution depend on the geology above our present level of observation?

We begin with a discussion of a simple parameterisation of the erosion and the exhumation history that allows us to quantify the estimates.

In our description of the first order erosion process we utilise the diffusion equation; that is we assume that the topographic decay of the ranges of the eastern Alps can be described with a linear proportionality between erosive mass flux q [kg m^{-1}s^{-1}] and topographic gradient

$$q = k \frac{dH}{dx} \qquad (1)$$

in which k is the proportionality constant. We also assume a mass balance on local scale

$$\rho \frac{\partial H}{\partial t} = \frac{\partial q}{\partial x} + A \qquad (2)$$

in which H is the surface elevation, t is time, x is distance, ρ is density and A is mass input per time and unit area by, for example, upwards motion of rocks which we refer to here as exhumation. (1) and (2) combine to the well known relation

$$\frac{\partial H}{\partial t} = \frac{\partial^2 H}{\partial x^2} + U \qquad (3)$$

in which $\kappa = (k/\rho)$ is the erosional diffusivity in m^{2}s^{-1} and $U = (A/\rho)$ is the exhumation rate in ms^{-1}.

This relationship has found ample application in the quantitative description of the shape of individual landforms, in particular to the dating of fault scarps (e.g.: NASH, 1980; ANDREWS & HANKS, 1985; STÜWE, 1994). However, the basic assumptions underlying the diffusion equation hold equally well for the description of mountain ranges as a whole and the study of KOONS (1989) has shown that information on the evolution of drainage patterns in mountain belts may well be drawn from the diffusion equation if viewed with respect to the first order topographic features of a belt rather. We emphasize therefore that, with the approach chosen here, we will and can not model the shape of individual mountain ranges in the eastern Alps. Rather, we focus on the interpretation of the first order morphological features as schematised in Fig. 2d. We acknowledge the deficiencies of the simplification of this schematisation but do believe that it is useful inasmuch as it allows to understand features of the morphological evolution on the largest scale.

In order to solve eqn (3) for initial topography and exhumation history as discussed in the last section, a second assumption is necessary that describes the boundary conditions of integration. Here we assume that material that is eroded from the central Tauern into the principle W–E striking valleys is removed from the Eastern Alps. Erosion and incision in individual valleys that drain into one of the principle W–E striking valleys is accommodated by the model inasmuch as there is a mass balance between all material transported into and out of the drainages. We solve, therefore, eqn (3) with pinned boundary conditions along two W–E striking and incising drainages.

In the parameterisation of the exhumation and drainage incision history we assume a constant exhumation rate between the 30 Ma and the present and assume a sinusoidal exhumation distribution in north-south profiles across the range corresponding to average peak pressure estimates discussed above (Fig. 2e). Maximum exhumation of about 20–25 kilometres is assumed in the Tauern Window and Austroalpine and no more than 3 kilometres in the NCA and SCA. Local topography that developed prior to the assumed onset of pervasive exhumation is considered to be negligible on the scale of our considerations and we assume a flat initial surface. Whereas our estimates for the erosional parameters will be given in terms of exhumation rates corresponding to a choice of 30 my for the duration of exhumation, it is noted that there is a linear relationship in eqn(3) between exhumation rate U and erosion rate as expressed through the erosional diffusivity κ. Geomorphological evolutions for any multiples of κ and U will correspond to each other and could be converted according to prejudices about the total duration of the denudation period.

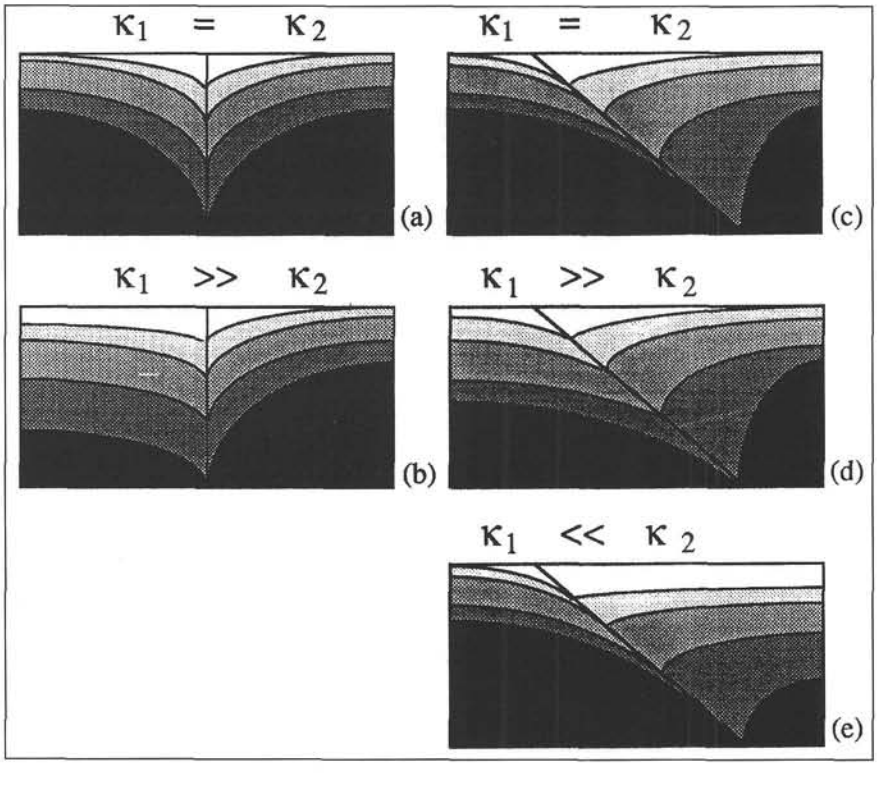
Our choice of drainage incision location relies on the actuality principle: the principle W–E striking drainages follow lithological and tectonic boundaries of strong erosion contrast and we assume that, during their evolution since the early Tertiary, they always followed this contact. Both, the drainages separating the NCA from the central Tauern and those in the south are located between 10–15 kilometres from the watershed and the two W–E striking drainage systems are therefore about 30 kilometres apart (Text-Fig. 1). The distance widens to the east and reaches near 50 kilometres width in the easternmost parts of the Alpine chain.

In summary, we use eqn (3) to infer the uplift distribution of the eastern Alps from simple assumptions about the spatial distribution of the exhumation rate as constrained by geobarometry and a range of assumptions for the geometry of the fundamental tectonic boundaries along which we assume that incision of the drainage systems has occurred. It is emphasized that both, the erosional diffusivity κ and the incision rate of the drainage systems, are uniquely defined through those assumptions and the requirement that the model evolution must match the present day topography at the end of the model run.

4. Results

Using the assumptions for the boundary conditions and the distribution of the exhumation rate in space and time as detailed above, we have solved eqn (3) in a range of model calculations for κ and H. The results of the schematic model calculations are twofold. Firstly, we are able to predict, qualitatively, the shape of valleys and mountain ranges as they may form as the consequence of the course of drainage incision and erosional diffusivity contrasts. These results are of general interest and indicate that the approach is, in principle, useful to understand the above-surface history of the incision of drainage patterns. Secondly, we have calculated simple morphological evolutions for the eastern Alps reproducing the present shape of the range and thus constraining, quantitatively, the erosion and incision rate of the drainages.

We begin with a general consideration of the evolution of valley profiles as a function of erosional diffusivity contrast and course of drainage incision. For the most simple scenario we consider a constant exhumation rate over the extent of the profile (Fig. 3). It can be seen that asymmetric valleys will develop for both, for steep and for shallow

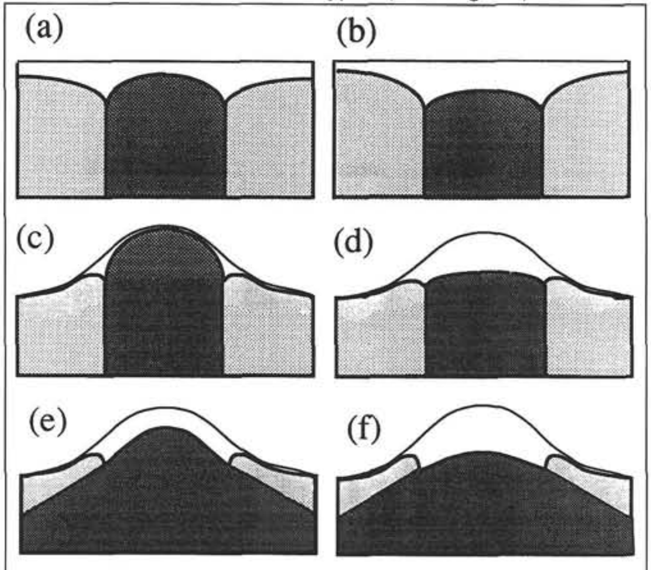


Text-Fig. 3.
Schematic sketch of predicted valley shapes that developed as the consequence of drainage incision along a steep (Figs. 3a,b) or shallow (Figs.3c,d,e) dipping fundamental tectonic boundary. It is assumed that the erosion process can be described by mass diffusion and that eroded material is removed from the system. Each diagram is drawn for four different time steps with increasingly dark shading for time steps approaching the present situation.

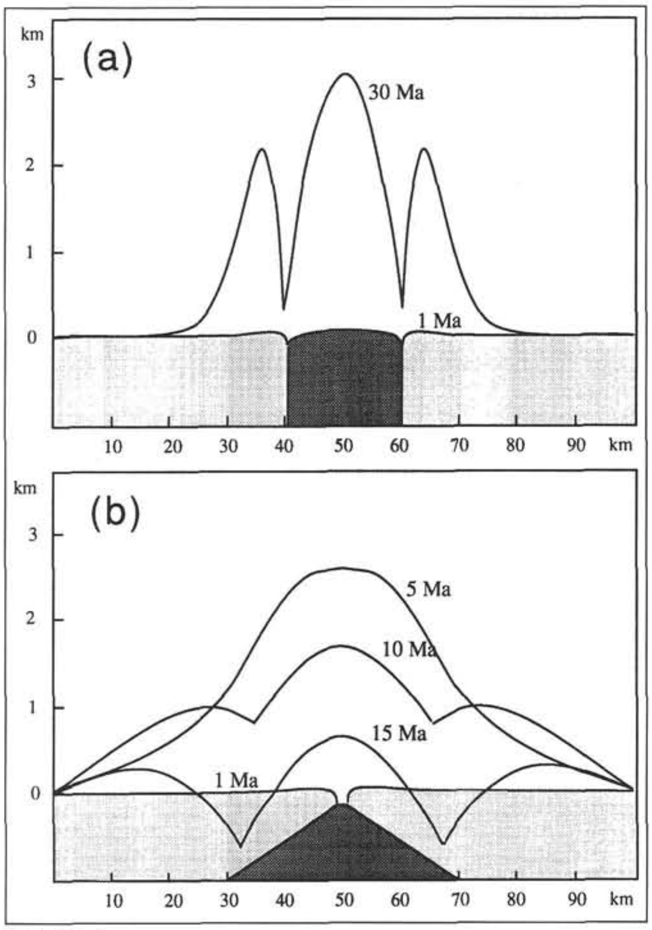
Fig. 3a shows a symmetric valley for no contrast in erosional diffusivity across a vertically incised drainage Fig. 3b shows that an asymmetric valley will develop if there is a strong erosional diffusivity contrast across the drainage Fig. 3c shows that a similar asymmetry may be found if there is little contrast in erosion rate but if drainage incision occurred along a shallow dipping tectonic boundary Fig. 3d shows that this asymmetry will be enhanced if the erosional diffusivity contrast corresponds to that of Fig. 3b but will not be so pronounced if the erosional diffusivity is larger on the hanging wall Fig. 3e. Some additional information may be drawn from the absolute elevations of the crests between drainages. However, note that the diagrams drawn here assume hillcrests at the margins of the blocks which may distort realistic relative elevations.

courses of drainage incision if there is a contrast in κ across the drainage system. Differences in the shape of the valley will lie only in the curvature of the slope profile (compare Text-Fig. 3b and Text-Fig. 3c,d,e) and in the elevation of the adjacent mountains relative to the valley floor. Interpretations of the absolute elevations from Text-Fig. 3 may be misleading as we assume a symmetry about the boundaries of the diagram and prescribe therefore one important elevation determinant: the 'ridge-stream' spacing for each mountain. Nevertheless, it can be seen that larger κ on the footwall side of the tectonic boundary will result in lower surface elevation than the opposing valley side and vice versa, for similar slope angles in both cases. One parameter that may bear some additional information on the nature of erosion contrast and the course of the drainage incision through time is the slope age. For shallow dipping tectonic and lithological boundaries along which the drainage incises slope rejuvenation will be much slower on the footwall side of the structure than on the hanging wall (compare Text-Fig. 3b and Text-Fig. 3e).

Interpretation of elevation and slopes becomes more difficult if the distribution of exhumation rate is variable over the extent of the profile and if the incision does not occur along vertical predefined strucutres. In Text-Fig. 4 we have explored, qualitatively, the expected topographies. Text-Fig. 4a and 4b show topographic profiles across a schematised N–S section through the Alps for constant exhumation rate and vertical lithological boundaries similar to Figs. 3a and 3b. It can be seen that for larger κ in the centre of the profile a lower elevation would be expected in that part of the range. In contrast, for variable *U* and largest exhumation rate in the centre of the range the elevation of all units will be proportional to the exhumation depth if the erosional diffusivities are similar in all rock types (Text-Fig. 4c). However, for larger in the centre of the range elevations are likely to be higher (Text-Fig. 4d). For shallow dipping lithological and tectonic boundaries the elevation of the ranges are a complicated function of the interplay of the magnitude of the erosivity contrast, the decollement angle and the spatial distribution of exhumation rate. Even for similar erosivities in all parts of the range elevations may be disproportional to the exhumation depth but likely to be higher in the centre (Text-Fig. 4e). For larger erosivities in the centre of the profile (Text-Fig. 4f) the elevation relationships are not predictable on a qualitative basis and have to be explored with quantitative evaluation of eqn (3).



Text-Fig. 4.
Schematic sketch of predicted topographies developed as the consequence of simultaneous exhumation and drainage incision along fundamental tectonic boundaries.
The left column is for similar erosional parameters across the range; the right column for large erosion contrasts with the central tectonic units having a larger erosional diffusivity.
Fig. 4a and 4b are for uniform denudation over the entire block. Fig. 4c and Fig. 4d are for a sinusoidally distributed exhumation rate and vertical separation between different tectonic units; Fig. 4e and Fig. 4f are drawn for sinusoidally distributed exhumation and shallow boundaries between different tectonic units.

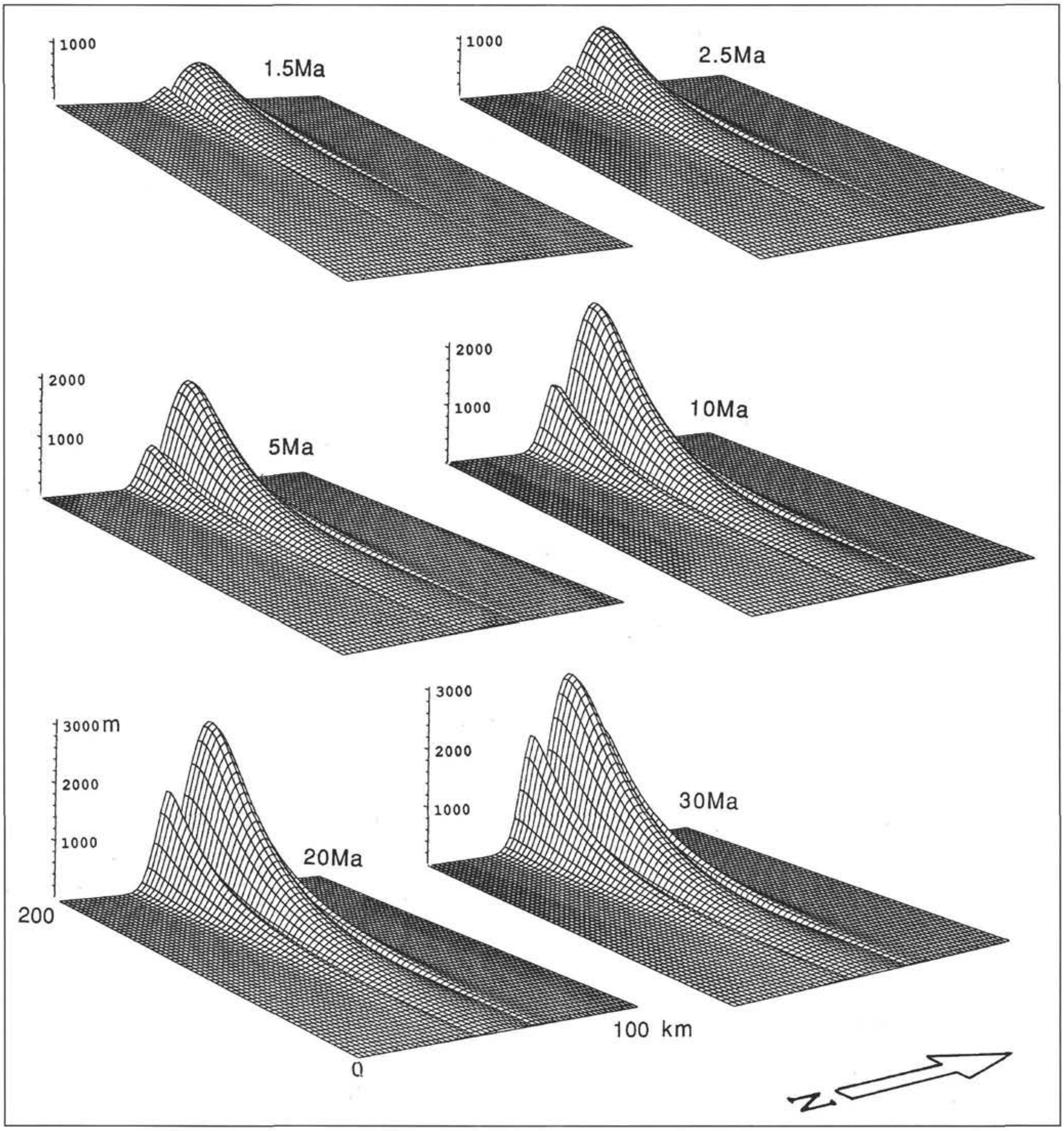


Text-Fig. 5.
Calculated topographic evolutions.
Contours are in Ma after the start of exhumation.
For these diagrams eqn (3) was solved with a CRANK-NICHOLSON finite difference scheme for flat initial conditions and sinusoidal exhumation distribution over a region 40 kilometres in width, corresponding to Fig. 2e. Fig. 5a reproduces the observed topography of the Alps reasonably well with highest elevation in the central ranges above 3000 metres and in the adjacent limestone ranges above 2000 metres. The parameters for this run are $\kappa_{limestone}$ = 0.3 km^2/ Ma and $\kappa_{crystalline}$ = 7.6 km^2/ Ma exhumation rate is 500 m/Ma and incision rate of the drainage is 320 m/Ma exhumation. Note that because of the simultaneous denudation and erosion, the line representing the present surface corresponds to initial depths according to the observed distribution of metamorphic peak pressures. Fig. 5b was calculated for shallow boundaries between rocks of low and of large κ. It can be seen that it is difficult to reproduce the observed topography. For smaller and possibly more realistic incision rates the topography becomes unrealistically long before exposing substantial regions of the softer rocks in the central Tauern. Alternatively, for the rates assumed here, the incision of the drainages reaches sea level only 15 Ma after the initial onset of denudation.

The results summarised by Figs. 3 and 4 show that both, the slope angle as well as the absolute elevations of the adjacent range may, in principle, be useful parameters to infer some details of the above-surface incision history of fundamental drainage systems.

However, in the Eastern Alps much of the detail of the slope profiles are obscured by Quaternary sedimentation and extensive topography carving during the glaciation periods. This handicap refutes the extensive use of slope features in many parts of the Eastern Alps. Nevertheless, the absolute elevations and the first order morphological features of the range may still be used.

In order to evaluate the elevation relationships for realistic geometries of the incising boundaries we have performed a series of numerical experiments using the spatial distribution of exhumation rate outlined above. In all experiments



Text-Fig. 6.
Calculated two-dimensional topographic evolution.
For these diagrams a two-dimensional form of eqn (3) was solved with an ADI-finite difference scheme for flat initial topographies and a sinusoidal exhumation rate distribution 40 kilometres in N–S extent and exponentially decaying towards the east. The choice for the distribution of the exhumation rate is based on a schematic distribution of the Alpine pressure grade recorded by the rocks (see text for discussion). It is emphasized that the sketch is purely schematic and there is a large number of local departures from this scheme (for example the relatively high pressures in the Rechnitz window (KOLLER, 1985). However, it may be used to understand some of the first order morphological features. Note that despite the constant exhumation rate over the entire 30 Ma evolution the topography of the Alps is principally established after the first 10 Ma. After this time geomorphic equilibrium is largely attained in the sense that the exhumation rate is balanced by the erosion rate and the elevation of the landforms becomes constant. This result is well supported by field evidence of, for example, SAKAGUCHY (1973).

the schematic topography of the eastern Alps (Text-Fig. 2d) was used as the required result at the end of the model evolution. We concentrated on two geometries of the lithological and tectonic boundaries between the NCA and the central Tauern:

1) Vertical boundaries as they may have existed if the limestones of the NCA have never extended further south or the sliding into their present position was largely a local movement along steep decollement structures and
2) shallow boundaries that outcrop in the centre and dip initially with about 3° to the north and south.

Such a geometry may be appropriate if the calcareous Alps once produced an extensive cover of the Austroalpine nappe pile and were transported there along shallow thrusts that are now largely removed by erosion. Text-Fig. 5 illustrates the morphology of the Alps as a function of these two different assumptions about the initial geometry. Best fit estimates for the present topography of the Alps and the exhumation rate distribution discussed above can be obtained with $\kappa_{\text{limestone}} = 0.3$ km^2/Ma and $\kappa_{\text{crystalline}} = 7.6$ km^2/ Ma and an incision rate of 239 m/Ma and maximum denudation rate in the centre of the range of 500 m/Ma (Text-Fig. 5a). No good fits, on the other hand, can be obtained if shallow continuation of the thrusts between NCA and central crystalline is assumed (Text-Fig. 5b). For such a situation and small $\kappa_{\text{limestone}}$ and small incision rates the model morphology will reach unrealistic high elevation before the softer rocks in the central Tauern are exposed. Larger incision rates and larger erosional diffusivities, on the other hand, lead to a situation illustrated in Text-Fig. 5b: the observed elevations are not reproduced in the model evolution and drainage incision to sea level occurs too early in the model evolution. Our results indicate therefore that the drainage incision in the Eastern Alps may have occurred along paths that are near vertical above the present position (as Text-Fig. 5a). Clearly, this result does not directly imply that the shape of the tectonic and lithological boundaries was also vertical but it is unlikely that the coincidence of the tectonic boundaries and the drainage system is only a characteristic feature of the present time.

In order to illustrate the morphological evolution of the Eastern Alps with the boundary conditions and parameters assumed for Text-Fig. 5a graphically, we have solved a two-dimensional form of eqn(3) and plotted a sequence of timesteps after the onset of exhumation and erosion (Text-Fig. 6). The area used for these considerations is outlined on Text-Fig. 1b. The geometric and exhumation rate parameters correspond to those of Text-Fig. 5a along the westernmost N–S slice of the plot. The assumption of the drop in exhumation rate towards the east was assumed to be exponentially decreasing to reach zero at the east margin of the map area shown in Text-Fig. 1. Whilst higher pressure rocks are exposed in small areas even at the eastern and of the Alpine chain (e.g. Rechnitz window, KOLLER, 1985) this is in the first order a reasonable approximation consistent with the Tertiary basin development in the Pannonian basin and it will serve us here as a guide. A profile through the west end of the 30 Ma timestep in Text-Fig. 6 correspond largely to the topography shown in Text-Fig. 5a. This justifies our one-dimensional approach to the previous calculations as it demonstrates that the effects of erosion in W–E direction are small. It can be seen that the model evolutions gain rapidly topography in the early stages of exhumation and that the present topography is largely established after a third of the total model run. This effect stems mainly from the nature of our assumptions about the erosion process: with elevation change being proportional to the curvature of the topography erosion is more effective in regions of large relief and less effective in regions of low relief. Therefore, exhumation outweighs erosion in the early stages of the model evolution and morphological equilibrium is reached when the erosion rate balances the exhumation rate. The result of Text-Fig. 6 is well matched by field based interpretations of the geomorphological evolution. For example SAKAGUCHY (1973) suggested on the basis of the Augensteinschotter that the present topography of the Alps was largely established in the first 20 Ma after initiation of uplift.

5. Discussion and Conclusion

In the last section we have shown that the morphology of the Eastern Alps can be best approximated with model calculations that assume vertical incision of the drainage patterns as well as an about 20 times larger erosional diffusivity of the gneisses and schists of the central Tauern than that of the adjacent limestone ranges. In our schematisation we have considered predominantly the contacts between the Austroalpine and the Northern Calcareous Alps (NCA) so that we excluded complications where the principle drainage separates the GWZ from the Austroalpine and secondary drainages separate GWZ from NCA (e.g. Salzach and Leogang valleys on the level of Zell am See). We will therefore refer in the following discussion only to locations like the Inn valley west of Innsbruck or the Enns valley east of Schladming. At these locations, our interpretations are qualitatively supported by the weak asymmetry evidenced by valley profiles across the Inn and Enns valleys (Text-Fig. 3): for shallow incision and the derived erosional diffusivity contrasts the asymmetry about these valleys would be much more pronounced.

It should also be mentioned that the result of a steep above-surface continuation of the fundamental decollement horizons is not new. It has also been arrived at from structural evidence by, for example CORNELIUS, (1940) and ANGENHEISTER & BÖGEL (1972). Nevertheless, it is tempting to use our result to speculate on its potential implication for the juxtaposition of nappes in the Austroalpine nappe pile. For example, with respect to the boundary separating the NCA from the GWZ and the Austroalpine, TOLLMANN (1959, 1977) suggested that the NCA originated from an original position closely tied with the Southern Alps along the Periadriatic lineament and were emplaced into their present position along shallow thrusts over the entire central nappe complexes of the Central Alps. The argumentation for this model is predominantly based on an interpretation of low grade alpine metamorphism as the consequence of at least transient burial by the NCA and other parts of the upper Austroalpine units, and the fact that these parts lie in a tectonically higher position than the crystalline nappes of the central Tauern. FRANK (1983,1987), on the other hand, suggested that the present relative arrangement of the units is similar to the original one and is, in part, supported by more recent studies that discovered that much of the transport of the Cretaceous nappes is actually from S–E to N–W rather than from S to N (RATSCHBACHER, 1986, 1987; NEUBAUER, 1987; NEUBAUER & GENSER, 1990). Here, it is possible to state that the latter interpretation is supported on the basis of geomorphological grounds. On the other hand, it is important to note that our interpretations are based on a large erosivity contrast across that tectonic boundary. It is therefore still possible that the boundary of large erosivity contrast, that is the lithological boundary between NCA and central Tauern, is correctly interpreted to be steeply extending above the surface but that the tectonic boundary separating the units continued shallow above the roof of the central Tauern. Finally it is important to note that many of the drainage systems discussed here are located along tectonic boundaries that coincide in their present position with steeply dipping strike-slip fault zones. It could therefore be argued that the steep incision history suggested here is a mere artifact of the steeply dipping fault zones and is unrelated to the tectonic boundary which may have been shallow. However, such a scenario is highly unlikely as it would imply that the coincidence of the fault zones and the decollements at the present erosion level is merely coincidental.

In summary, following conclusions may be drawn from this study:

❶ Simple assumptions about the nature of the erosion process can be used together with a simplified scheme of the distribution of exhumation rate in the Eastern Alps to produce model evolutions that approximate first order features of the observed morphology of the range. These model calculations can be used to derive the erosional diffusivity and the incision rates of the drainages for the range. They can also be used but also to make simplified predictions about the nature of the nappe geometry in parts of the metamorphic pile that has been removed from direct observation by erosion.

❷ The incision of the fundamental drainage patterns of the eastern Alps is likely to have occurred along steep paths extending vertically above the present north-south position of the drainages.

❸ For realistic assumptions about the spatial distribution of exhumation rate, the shape of the eastern Alps can be best fitted with a diffusion model if the erosional diffusivities are assumed with $\kappa_{\text{limestone}} = 0.3$ km^2/Ma and $\kappa_{\text{crystalline}} = 7.6$ km^2/Ma as well as an incision rate of about 240 m/ Ma and maximum exhumation rate in the centre of the range of 500 m/Ma.

❹ The interpretation of steep incision implies a steep continuation of the boundary of strong erosivity contrast between limestone and crystalline rocks above the present contact. If this interpretation is correct is may have important implications for the interpretation of alpine tectonics.

❺ We have shown that geomorphological information may be used as a constraint on questions traditionally only tackled by hard rock geologists. Much of the uncertainties of the interpretations presented in this study are due to the incompleteness of our morphological data set. We suggest that detailed geomorphological information in combination with Palaeontological evidence may be an important tool for future, more detailed interpretation of above-surface geological features.

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