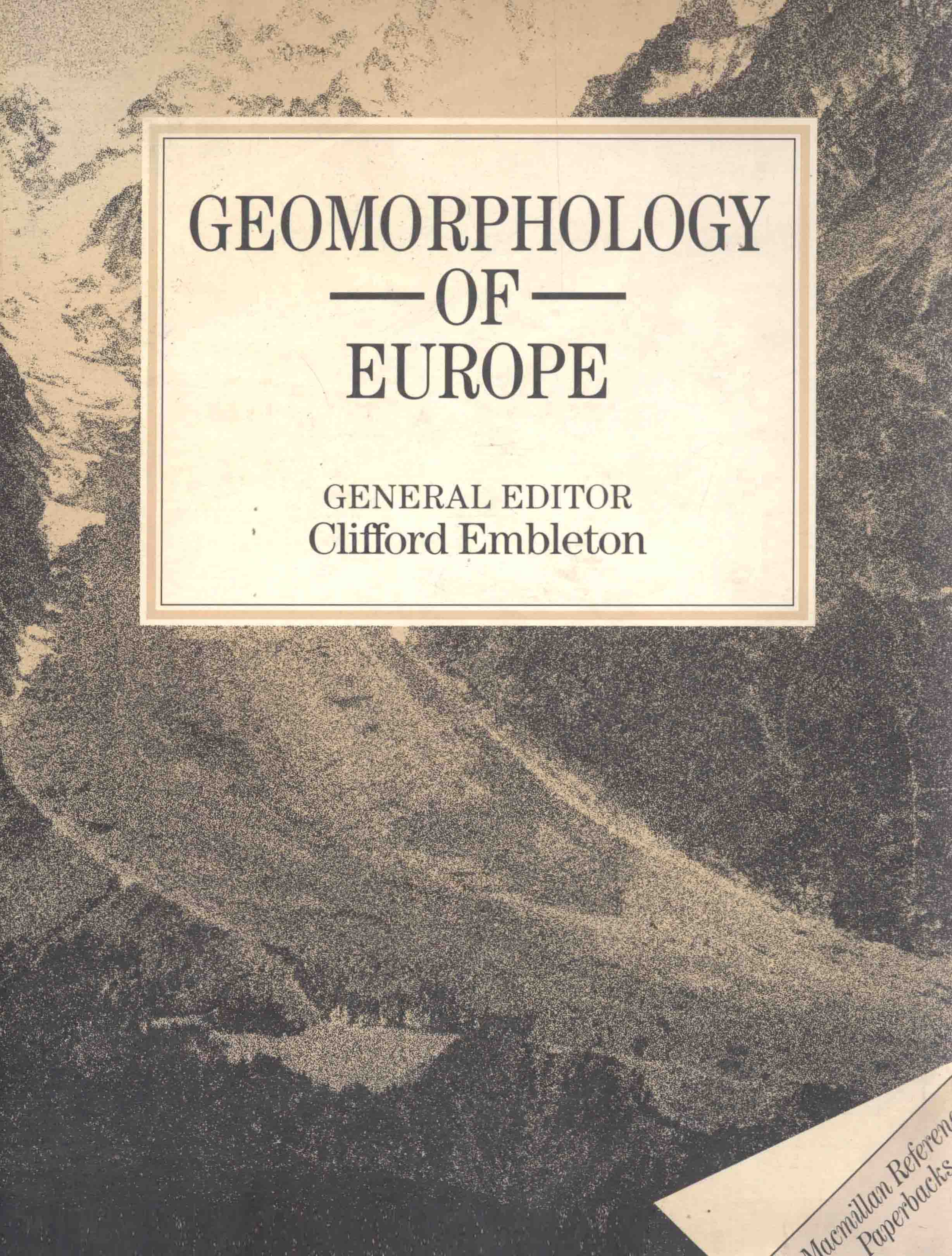

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GENERAL EDITOR
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General Editor: Clifford Embleton

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Preface

This book has been compiled and written by members of the Commission on Geomorphological Survey and Mapping of the International Geographical Union. Originally proposed in 1976 as a text to accompany and explain the *International Geomorphological Map of Europe* (1 : 2.5 million), the outline of the book was prepared by the Commission at a meeting in Nové Mesto, Czechoslovakia, in 1977. Since then, there has been a considerable delay in publishing the *International Map*; meanwhile, work on this book progressed and has overtaken the schedule for printing the Map. At the same time, the book has been enlarged and its aims have changed to some extent: it is no longer envisaged simply as an explanation of the Map but as a work in its own right, providing the first comprehensive survey of the geomorphology of Europe.

The editor is well aware of shortcomings in the work and of unevenness of treatment. The original contributions were in many cases written in languages other than English; the sections on the USSR were translated from the Russian by J. Demek, that on eastern Austria was translated from the German by B. Bauer, and those on France were translated by the editor himself. Translation of technical works causes many problems, for literal conversion into English usually produces a meaningless result unless the translator is closely conversant with the subject matter. Even then, obscurities often remain and are impossible to remove wholly unless direct contact between author, translator and editor can be achieved. Unfortunately this is not only very time-consuming, but has not always been possible. There have also been considerable problems of postal communication, especially between eastern and western Europe. I should like at this point to pay tribute to Dr J. Demek of the University of Brno, without whose assistance and guidance this book would never have been completed. His knowledge of eastern European languages other than his own, and of German and English has been of immense value, and the editor has had invaluable discussions with him on numerous visits to Brno to clear up various difficulties. Other areas that have presented problems have been in the standardization of place names (whose spelling is far from consistent even in the major atlases), on how far to preserve feature names in the original language (e.g., Giant Mountains or Krkonose?), in obtaining a representative selection of photographs and in deciding how many references to list.

The regional division of Europe employed in this book is based mainly on structure and to a less extent on relief. It should be recognized that it is an arbitrary division in many instances, and that the dividing lines are not hard and fast. For example, the separation of the Scandinavian mountains from the Fennoscandian Shield is in many ways quite unrealistic and arbitrary, yet there are major morphological differences between these two units. The divisions cut strongly across national frontiers, which has caused problems of continuity of treatment and of correlation.

The level of detail varies considerably from one region to another, and the lengths of individual sections are not in proportion to the area covered. This is inevitable, for far more is known about the geomorphology of some areas than of others, and some areas present a much greater variety of landform or of geomorphological history than others. No attempt has been made to standardize the contributions from different authors, although each author has been asked as far as possible and where appropriate to deal with certain basic topics such as relief, geology, structure, Tertiary and Quaternary landscape evolution, Pleistocene glaciation, coastal forms, etc. The several contributions reveal interesting differences of geomorphological thought and approach; in some the emphasis is on tectonics and tectonic history, in others on climatic geomorphology, while in others on the Quaternary. Some authors pay great attention to present-day processes of erosion; others feel that older events and structures are more significant in the present landscape.

This book, then, represents both an amalgamation and a compromise. It represents a considerable effort of international cooperation, and shows above all how much remains to be achieved in understanding the geomorphology of what is probably the world's most complex continent.

C. Embleton
Pedras da Rainha
Good Friday, 1983

Acknowledgements

First, I want to thank all the contributors to the book, who have dealt patiently with my queries and requests for information, but especially Jaromir Demek without whose help this book would never have been completed. Many other people have helped in the various stages of preparation of the material: I am particularly grateful to Mrs V. Dittrichová for help in translation at an early stage; to Roma Beaumont, Kathy Hopkirk and Gordon Reynell for the redrawing of all the maps and diagrams, including some of immense complexity; and to Clare Baynes, Helena Gardberg, Anne Rogers and Celia Vangen for typing the manuscript, sometimes in several successive versions and often from very difficult originals. Finally, I want to thank Dr. A. Ralph for her care and patience in seeing the book through the press.

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(The authors of chapters or sections are shown in italics)

Chapter 1
Structural and Tectonic Framework of the Continent of Europe

1.1 Introduction

The various chapters that comprise Part I are concerned with broad aspects of the relief and structural patterns, the evolution of these patterns through time and the formative processes controlling their evolution. At the outset, it should be noted that, while it is intended to be used as an independent guide to the geomorphology of Europe, this book also aims to complement and explain the *International Geomorphological Map of Europe*, published in 16 sheets on a scale of 1: 2.5 million. Reference to individual sheets of the Map is made in this book; an understanding of the features depicted on the Map will be facilitated by consulting the relevant sections.

For the purposes of both the Book and the Map, Europe (*see* Fig. 1.1) is taken to extend from Iceland in the west to the Ural Mountains in the east. The southern limit is provided by the Mediterranean Sea. Turkey, other than the small part lying west of the Bosporus, is excluded. Covering a land area of roughly 10^7 km^2, the continent includes a great diversity of relief and structural forms (*see* Fig. 1.2), including vast plains, plateaus and high mountain ranges. Elevations of the land range from over 4500 m (e.g., Mont Blanc, 4810 m) to a few metres below sea level in the Netherlands. The ages of the rocks exposed at the surface vary from the most recent sediments of the present-day to Precambrian rocks more than 2600 Ma old (*see* Fig. 1.3). Further contrasts in the landform arise from the diversity of climate: from Arctic to Mediterranean, from semiarid to humid; the shifting climatic patterns of the Cenozoic have powerfully influenced landform evolution, especially in connection with the repeated glaciation of the northern half of the continent in the Pleistocene. A separate chapter (*see* Chapter 2) is devoted to the submarine forms around Europe, which also display considerable variety, but about which less is known.

The authors of the three chapters in Part I are all Russian. Their viewpoint differs frequently from that of geologists and geomorphologists in western Europe: for example, in respect of the theory of plate tectonics and the importance of the structural control of landform. No attempt is made (nor would it be possible) to present any unified theory, acceptable to both eastern and western European countries, of the structural evolution of Europe. In Part I and elsewhere, considerable attention is devoted to morphostructure. This term, introduced by Gerasimov (1946), refers to a structural unit expressed in the relief, modelled by denudation and/or sedimentation. The degree of modelling depends on the tectonic activity of the area and on its climate. A hierarchical system of morphostructures is recognized, ranging from the largest 'megamorphostructures', such as the Fennoscandian Shield and Russian platform, to micromorphostructures, such as a fault-controlled valley perhaps only a few tens or hundreds of metres in size. The *International Geomorphological Map of Europe* incorporates three major elements in its conceptual framework: (1) the differentiation of relief classes according to relief amplitude, (2) the differentiation of relief according to morphostructural type and (3) the differentiation of so-called 'special relief forms' of mainly exogenic origin.

1.2 Structural Evolution in Europe

At the outset, it should be noted that there are differences of opinion on two fundamental questions. One concerns the interpretation of the Precambrian record in which there are many uncertainties, owing partly to inadequate data on absolute age determinations. The second relates to the particular hypothesis of global tectonics that is adopted.

The earliest stage in the geological history of Europe can be seen from Fig. 1.4. The distribution of Archaean and Proterozoic rocks (Lower–Middle Precambrian, Middle Precambrian and Upper Precambrian) shown in this diagram suggests that there are cores of Archaean rocks around the peripheries of which younger fold zones have been accreted. The Archaean cores can be recognized in the crystalline basement rocks of the northwestern Scottish Highlands and Outer Hebrides, the Bohemian massif, the Balkans, the southern Carpathians and the Fennoscandian Shield – both in Scandinavia and the Kola Peninsula. As is seen from Fig. 1.4, the early Precambrian rocks also comprise separate portions of the basement of the eastern European platform buried under a sedimentary cover. It is assumed that in the Massif Central of France, and the Armorican and certain other massifs, late Precambrian rocks are found overlying the early Precambrian varieties. Similar assumptions, although without convincing evidence, are made from some other areas where the Precambrian rocks are common [see Matveevskaya (1975)]. Following numerous periods of folding in the Precambrian, the Archaean cores became joined together. All of these Precambrian complexes of different ages formed the basement complex of the western and eastern European platforms 2500–3000 Ma ago. Thus, by the beginning of the Phanerozoic, the basement of the European continent already existed. One school of thought believes that the early Precambrian formations originated on oceanic crust. This was a lengthy process for

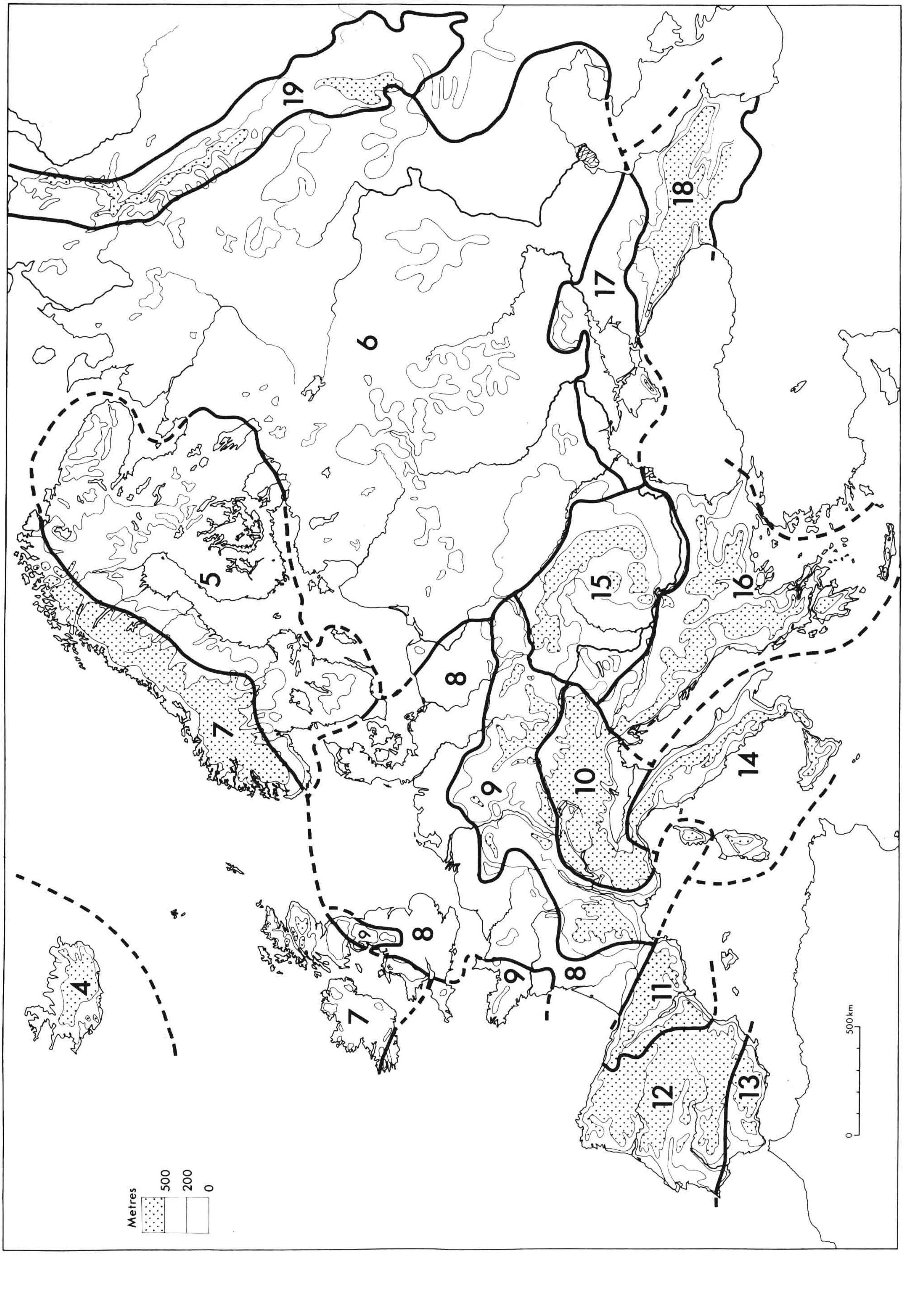

Fig. 1.1. Geomorphological regions of Europe. The numbers correspond to the chapters in this book.

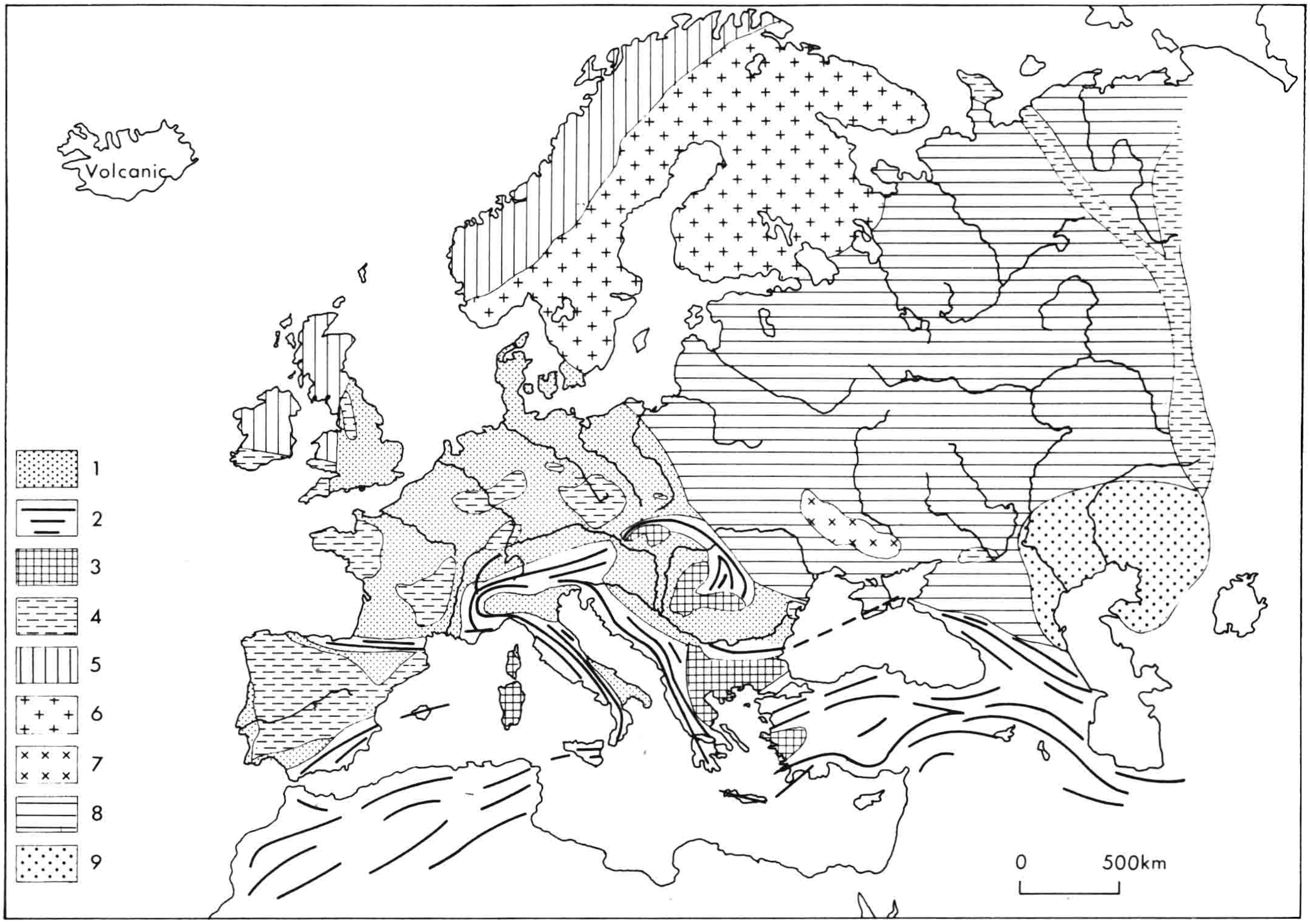

Fig. 1.2 The major morphostructural divisions of Europe: (1) lowlands and scarplands composed of Mesozoic and Tertiary sediments; (2) Alpine fold mountain belts; (3) Hercynian massifs involved in Alpine folding; (4) Hercynian massifs and fold belts; (5) Caledonian fold mountain belts; (6) Fennoscandian (Baltic) Shield; (7) Ukrainian Shield; (8) Russian platform; (9) Caspian lowlands.

the duration of the Precambrian era, three to four times greater than that of Phanerozoic. A similar picture may also be observed in some other ancient platform areas, such as North America and central Siberia. Characterizing the Kola and Pre-Dnepr megablocks of the eastern European platform as being the most ancient, Khain indicates that they '... are remnants of the most ancient continental crust which ... evolved as a result of granitization of basic volcanic sequences, that is of the primary crust of the oceanic type' [see Khain (1977a) p.50].

The Precambrian history of the European subcontinent was not only marked by the accretion of younger fold zones around ancient cores (*see* Fig. 1.5) but also by the repeated fracturing of various Precambrian rock masses along deep-seated faults into large blocks (i.e. megablocks). Some of these megablocks were uplifted while others subsided, the subsiding blocks often becoming covered by the sea. Evidence of such subsidence is manifested locally in the form of horizontal or subhorizontal marine and metamorphosed marine sediments (e.g., the rocks of the middle Proterozoic mantle of Karelia). Within the megablocks, the direction of tectonic movement changed frequently over the course of the many millions of years of Precambrian history. Therefore, the megablocks carved out of the Archaean and early Proterozoic rocks do not coincide with the ancient fold zones. By the end of the Upper Precambrian (Riphaean), however, some of the present-day structural outlines of Europe were becoming apparent.

The Ural geosyncline bounding the continent on the east was initiated in the Riphaean on the residual oceanic crust of the present-day western Siberian platform. Following an inherited but irregular pattern, the geosynclines of central Europe began to develop from the late Precambrian to the Palaeozoic. At the very end of the Riphaean (more precisely, at the boundary between the Riphaean and Cambrian: some 800 Ma ago) the Caledonian geosyncline of Scandinavia was formed. Finally, approximately the same age is attributed to the initiation of folding in the vast geosynclinal belt of the Tethys Ocean. Initiation of the present-day Alpine mountain system of Europe and north Africa also took place at that distant time. Many large platform structural forms (megablocks), such as graben–syneclises and syneclises, horst–anteclises and anteclises, were also formed then. These are expressed in the present-day relief both directly, as in the case of the

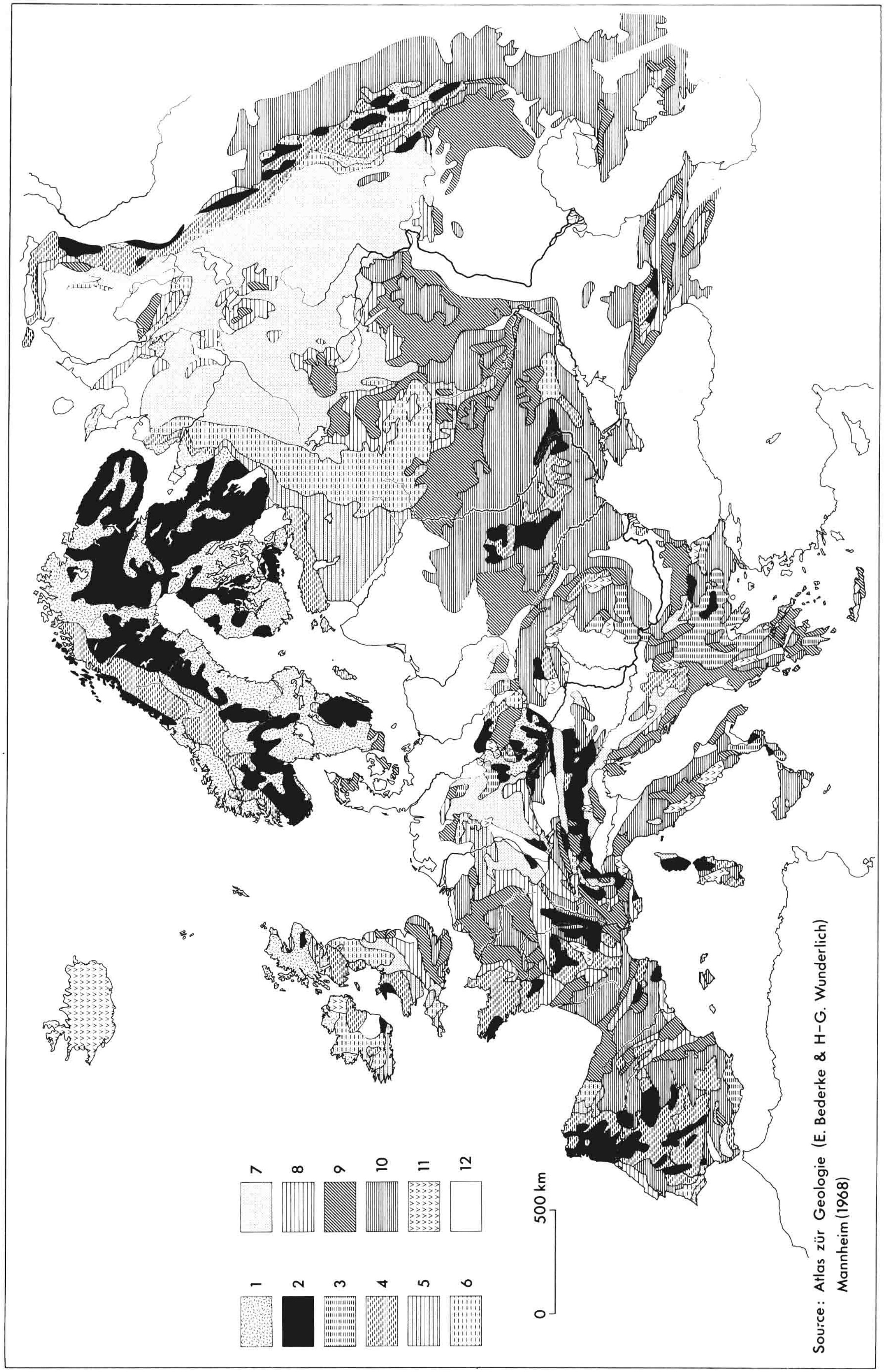

Fig. 1.3 The geology of Europe [from *Atlas zür Geologie* (1968)]: (1) Archaean crystalline; (2) later Precambrian and Cambrian; (3) undifferentiated Lower Palaeozoic; (4) Ordovician and Silurian; (5) Devonian; (6) Carboniferous; (7) Triassic; (8) Jurassic; (9) Cretaceous; (10) Tertiary; (11) Neovolcanic; (12) Quaternary.

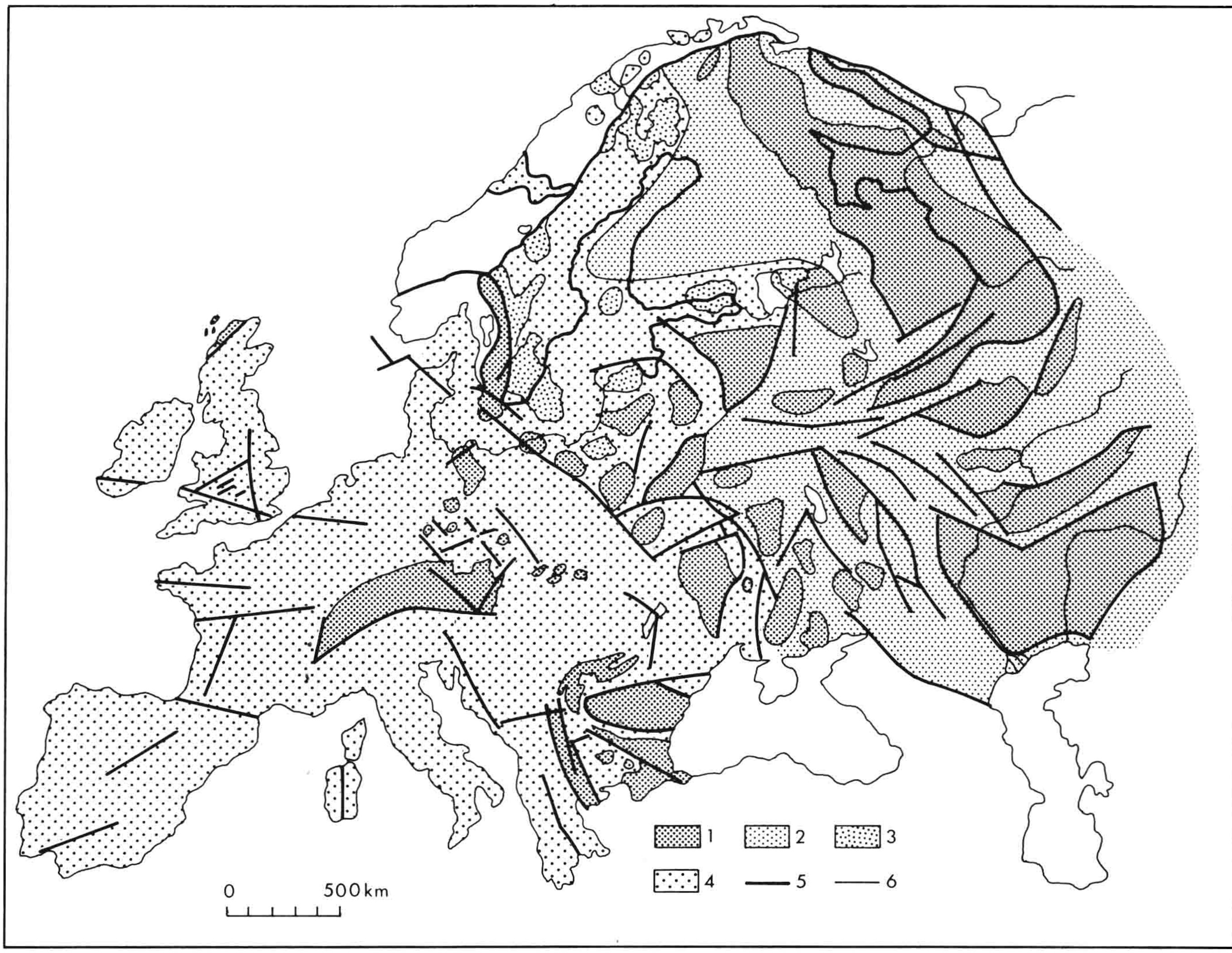

Fig. 1.4 Structure of the Precambrian basement [after Matveevskaya (1975)]: (1) crustal blocks consolidated in the Archaean (early Precambrian); (2) Karelides (middle Precambrian); (3) Rapakivi-type granites and granitoids of various ages; (4) Gotian–Dalslandian fold systems (late Precambrian); (5) boundaries of ancient blocks marked by major fractures; (6) other boundaries.

complex Baltic graben–syneclise, the Caspian syneclise and others, and in the form of inverted relief, such as the complex horst–anteclise of the central Russian elevated plain and the Volyn'–Podolsk plateau.

The Precambrian period was characterized by many orogenic episodes accompanied by metamorphism and complex magmatic processes (basic and acid magmatism), by the uplift and subsidence of megablocks and by frequent regional changes from marine regimes to continental. All these events led to the formation of the basement of the European subcontinent.

Despite the fact that the Phanerozoic covers a time interval three to four times less than that of the Precambrian, it has played an important role in the formation of the European subcontinent and its relief. The Phanerozoic history was at least as complex as the Precambrian, if not more so. This is not only because the Phanerozoic is a younger stage whose geological and geomorphological record is more fully and precisely documented, but also for the following reasons. It now seems likely that in the early Precambrian (i.e. 3000–3500 Ma ago) at the outset of the formation of continental crust, the relief was less complex than it is today with a relatively low amplitude (including the ocean floors). This is evidenced by the rocks formed at that time and by the absence of deep-sea facies. Depressions were initiated in the oceanic crust (the Earth's primary crust) along the ancient faults as isometric, irregularly shaped and ring-shaped features. Fine detrital material that accumulated in these depressions gave rise to greywacke formations. Study of this detrital material has shown that it was derived from erosion of fissure lavas (i.e. from the primary basaltic crust). Apart from the depressions, there also existed rounded or irregular uplifts. Then there were uplifts in which the greywackes and basic lavas had already been granitized. Evidently, granitization was one of the first causes of the progressive differentiation of the relief: the density decrease of the crustal rocks caused the granitized portions to be uplifted. In other words, granitization disturbed the isostatic equilibrium of the Earth's crust, while subsequent uplifts

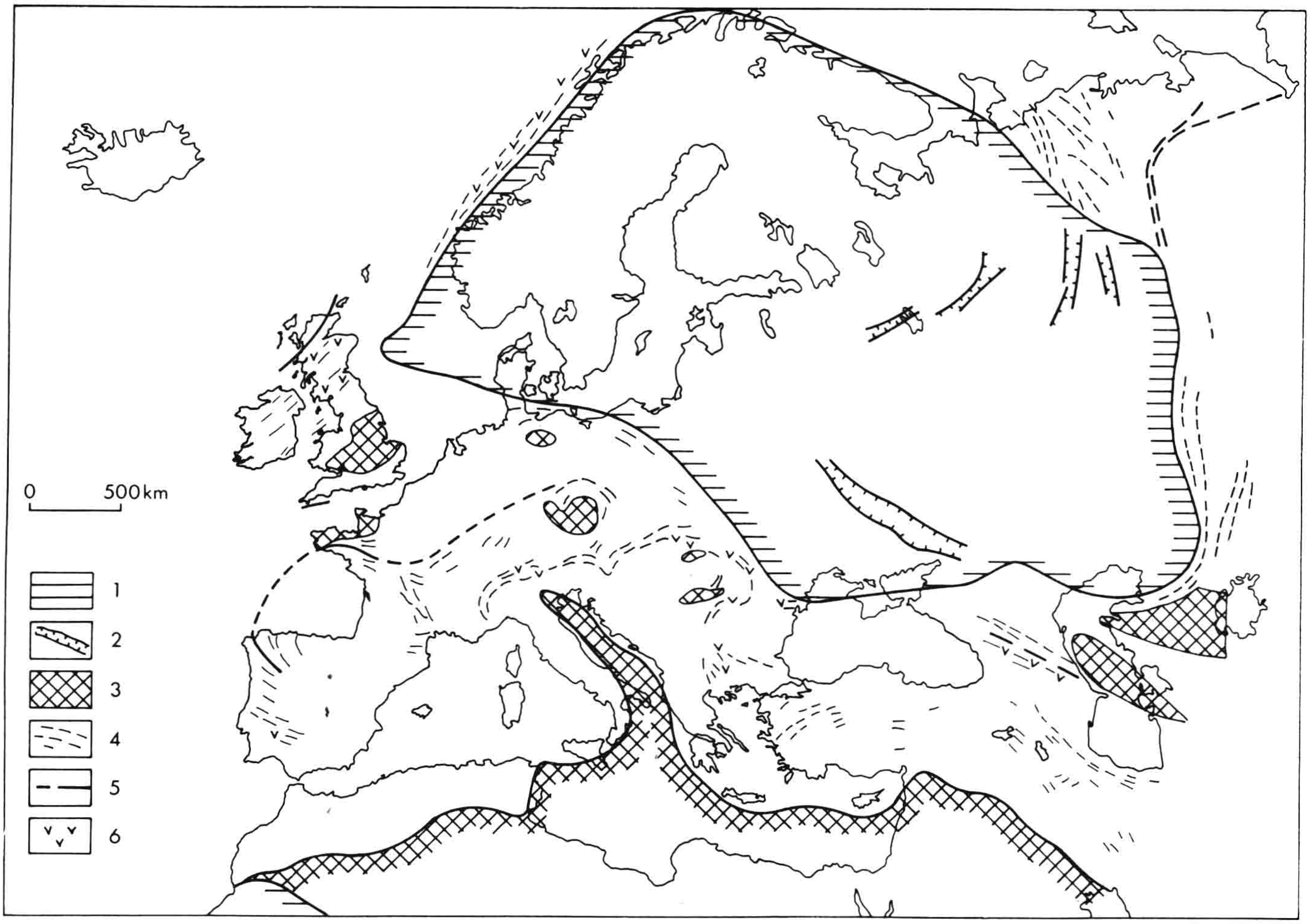

Fig. 1.5 Cratons and Precambrian folded complexes in Europe [after Khain (1977b)]: (1) ancient craton; (2) rifts (aulacogens) within craton; (3) reworked ancient massif; (4) Baikalian folded complexes; (5) ophiolite belt; (6) spilitic rocks.

restored it.

Apart from the rounded and isometric structures, linear structural forms began to develop in the newly evolving depressions. So-called protogeosynclines were formed, in which accumulated the products of erosion—not only of basic rocks but also of acidic varieties. Evidence for this is provided by the arkose sandstones found in these sequences. Acid volcanics are also observed in the depressions (Krivoy Rog, Saxonides, etc.). The rocks infilling these ancient depressions are crumpled into simple linear folds, often with gentle dips. The predominance of acid rocks and erosion products from crustal materials less dense than the basaltic crust accounted for the subsequent isostatic uplift of the folded structures. This stage of the Earth's development ended approximately 1700–2000 Ma ago but, like the previous stages, did not end everywhere simultaneously. In other words, its lower boundary is time-transgressive, varying in different areas over an interval of 300 Ma. The ancient cores of the shields in every continent are composed of Archaean folded zones that are restricted to the protogeosynclines and even to older depressions mentioned previously. All these zones should be thought of as being associated with deep-seated fault zones—a term introduced by Peive (1956a, b, 1960) and by Rukhin (1959). The concept of a global framework of faults is one that has been developed in various countries [e.g., see Hobbs (1911), Sonder (1956), Belousov (1976)]. It is suggested that, at the earlier stages of the Earth's history, the faults were not so deep and their pattern was less distinct, the fault zone being confined to the thinner, more easily broken basaltic crust. The relief contrasts, as has been mentioned already, were negligible.

After the late Precambrian (i.e. Proterozoic, Riphaean) another stage of geological, tectonic and geomorphological development began—the next megachron—which continued throughout the entire Phanerozoic [see Yanshin (1966)]. This megachron was termed by Stille the 'Neogeikum', during which the same tectonic style was maintained. Faults penetrated to greater depths and the associated geosynclines became deeper, more extended and linear. This is borne out by the great thicknesses and the facies composition of the Riphaean and later geosynclinal formations. The continental crust continued to form in the geosynclines. Relief amplitude appeared to be increasing up to the present-day maximum. This increase has been caused by the very process of the formation of the continental crust and its increase in thickness and is intimately associated with maintaining the figure of the

Earth in dynamic equilibrium [see Bashenina (1967)].

Analysis of the present-day relief, crustal thickness and geological history of Europe shows that the longer the period of geosynclinal development (covering more than one tectonic cycle) and the more intense the postorogenic activation the greater is the thickness of the crust. The general elevation of the relief is and, probably was, directly associated, from a global point of view, with the crustal thickness.

Geosynclines of the new megachron began to develop at the outset on the oceanic crust along the peripheries of Europe. Thus, the former tendency—accretion by younger structural formations around ancient cores—was preserved during the new megachron. Development of the European geosynclines was extremely varied and intricate in space, history and time of completion. In the north-west of Scandinavia, geosynclinal development was restricted to the Lower Palaeozoic. In the Urals, the central European Hercynian blocks and central Spain (e.g., Sierra Guadarrama, etc.) this development continued up to the end of the Palaeozoic and the beginning of the Mesozoic. In the major part of Cantabria and Iberia, geosynclines developed even during the Mesozoic. In all the mountainous zones of the former Tethys Ocean (i.e. around the Mediterranean Sea, the Carpathians, Pontides, Taurus, Caucasus and Elbrus) geosynclinal development started in the Riphaean and ended only in the Cenozoic, locally even in the Holocene; the rocks infilling the marginal and intramontane basins appear to be deformed into folds, even locally forming the slopes of the mountains.

All the Tethyan mountain systems are extremely complex, which is likely to be due to the duration of their construction: for example, the Great Caucasus underwent a final inversion of relief as far back as the pre-Jurassic. Southwards and eastwards, the rocks and folded structures composing this mountain system become younger. No less complex is the history of other Alpine mountain belts with their fold–block and fold–block–thrust structural patterns and their great diversity of relief forms. The basement complex of the continent was subjected to frequent, although nonsynchronous, fracturing along reactivated faults and accompanied by differential subsidence. Subsidence was followed by marine transgressions and accumulation of marine sediments. These events led to the development of the thick sedimentary cover that rests on the basement over a major part of the continent. Because of the intricate arrangement of the zones of uplift and subsidence, and the frequent changes in the direction of movements, the sedimentary blanket is of varying thickness, age and composition. Many graben–syneclises and syneclises, horst–anteclises and anteclises were subjected to inversion. Some of them, however, retained a tendency towards uplift or subsidence over the entire megachron, giving rise to uplifted denudation plateaus and plains or to depositional lowland plains.

Another characteristic aspect of geosynclinal development in Europe was the inclusion of fragments of the basement complex in the geosynclines at various stages of their development. The geosynclines were initiated on the oceanic crust along the continental margins; fracturing of the continental crust allowed the separation of basement blocks which became incorporated in the orogenic zone. In the young mountain belts (i.e. the Alps, Caucasus and Pyrenees), these crystalline blocks occur up to the highest altitudes.

It can be seen then that the continent of Europe is still very active tectonically. Fracturing and complex differential movements occur even at the present time, not only in the mountainous areas but also in the lowlands. This is indicated—particularly in western Europe, which is more mobile—by active magmatism, by high seismicity and even by the fact that the Anglo–Parisian Basin was probably divided only during the Quaternary.

1.3 Endogenic Processes

1.3.1 General Relationships of Structure, Tectonics and Relief

At present, the structural–tectonic base is represented by the following major elements: (1) shields (e.g., Fennoscandian, Ukrainian); (2) platforms consisting of graben–syneclises and horst–anteclises, syneclises and anteclises of different ages which, from time to time, developed on the Precambrian basement; (3) Caledonian, Hercynian and Mesozoic orogenic zones; and (4) young Alpine forms. From this it follows that the chronological boundaries between the principal tectonic cycles, and within those cycles, are not always distinct.

Belousov (1976) suggested that these boundaries are roughly synchronous, basing his conclusion on the evidence of orogenic zones of different ages in different continents. It is hardly probable, however, that the structural history of Europe should be considered as one of alternating periods of tectonic activity and relative inactivity, followed by widespread denudation and levelling. Such a supposition is totally at variance with geological and geophysical data. It is true that throughout the tectonic history of the earth there have been regional 'relaxations' or 'intensifications' of tectonic activity, but there is no indication that tectonism is steadily diminishing or dying.

Although the platform and shield areas of Europe are, at present, less active tectonically than some of the younger orogenic zones, their low-lying character or their low amplitude of relief is not simply the result of prolonged denudation following cessation of tectonic activity. For example, the Russian platform—the largest in Europe—is believed to be a plain not just because it has been subjected to repeated phases of erosion but also because of the operation of isostatic compensation, along with other global megamorphostructures. The extensive western Siberian lowland is also a result of isostatic compensation, which caused the major part of the lowland to subside during the Mesozoic–Cenozoic era. The principle of isostatic compensation is a very important one in the morphostructural development of western Europe and especially the platform areas. The elevation of erosional plains is balanced by the subsidence of other areas where

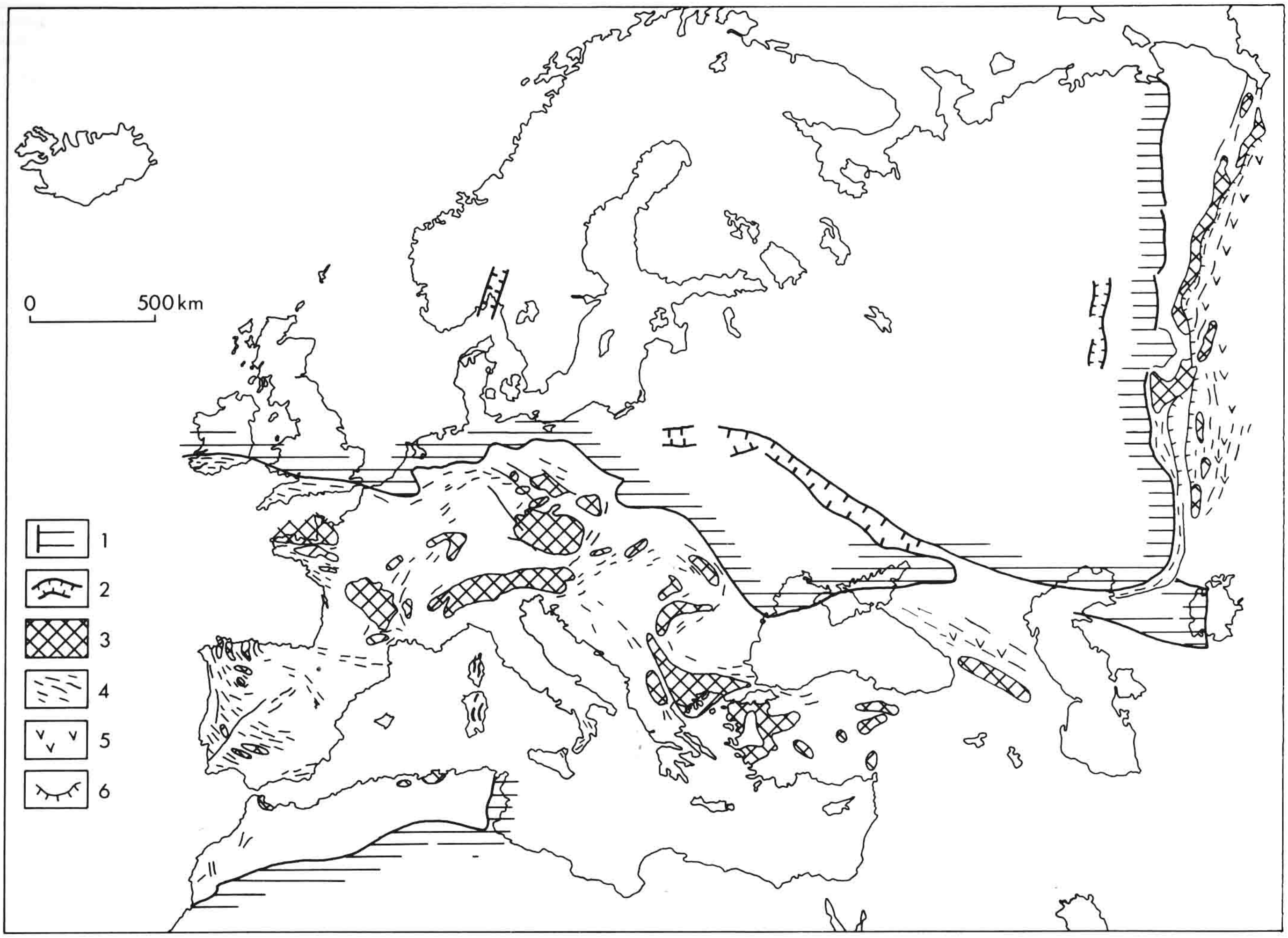

Fig. 1.6 Major Hercynian structures of Europe [after Khain (1977b)]: (1) pre-Hercynian platform; (2) Hercynian rifts (aulacogens); (3) pre-Hercynian reworked massifs; (4) Hercynian folded complexes; (5) basic volcanics; (6) thrusts and major faults.

sediments accumulate. Similar considerations apply to the behaviour of horst–anteclises or graben–syneclises throughout the entire Phanerozoic and also govern the formation of morphostructures in orogenic zones (e.g., the compensatory links between mountain systems and their marginal and intermontane depressions).

Geosynclinal development varied considerably between the orogenic zones. There was no further geosynclinal development in north-west Britain and Scandinavia after the Caledonian Epoch, nor was there any in central Europe or the Urals after the Hercynian. The Hercynides, however, require a special explanation (*see* Fig. 1.6). The Hercynian orogenic zones of the Urals, occurring under thick Mesozoic–Cenozoic sequences in western Siberia, extend as far as their eastern portion where the basement is older (Baikalian). If the younger geosynclines in every mountainous area are assumed to be initiated on the oceanic crust (i.e. from the ocean side) the idea of the accretion of the Hercynides of the Urals by younger geosynclines should be abandoned, since no oceanic crust existed at that time within the limits of western Siberia. The same also applies to the western European Hercynides.

1.3.2 Role of Faulting in the Formation of the Relief of Europe

All the major relief features of the Earth have been created by processes operating in the crust or mantle layers. These processes account for the irregularities of the Earth's relief and consist of folding, various disjunctive dislocations, vertical movements (i.e. uplift and subsidence) and various volcanic and seismic events at different depths. During the last decade, however, it has been established that, among the endogenic relief-forming factors, deep-seated faults of various orders (i.e. different extent, width and depth of origin) play a unique, major role throughout the geological history of the Earth. This was first shown by Karpinsky in 1887. Later many other scientists [e.g., Hobbs (1911), Cloos (1939), Stille (1924, 1936), Sonder (1956), Machatchek (1955), Peive (1956a, 1960), Khain (1964), Vardanyanz (1932), Dobrynin (1948), Borisov (1966)] recognized the importance of these faults.

It is only during the last 15 years, however, that geomorphologists, as well as structural geologists, have begun to emphasize the importance of faults as primary crustal features. They have also shown that the transition regions between oceans and continents are marked by deep-seated fracture zones which correspond to geosynclines [see Rukhin, (1959)]. The faults of the Canadian Shield are traceable in its relief and in its pattern of great rivers, such as the Saskatchewan, through a sedimentary cover 3 km thick or more. Geomorphological maps of Czechoslovakia by Demek and others, of France by Joly and Paskoff and of Italy by Sauro and others show the expression of deep-seated faults and other smaller tectonic dislocations in the relief. Soviet geomorphologists [e.g., Simonov and Bashenina] have prepared two sets of maps; one of neostructural forms and the other of geomorphology which show clear relationships. Specialized studies have been made by Bashenina (1967, 1973), Piotrovskiy (1972) and others of the role of faults and associated block tectonics in the evolution of the relief. These studies were undertaken mainly by geomorphologists working on mountain areas using aerial photographs and later using satellite imagery. As a result of these investigations, it has become evident that the major relief features of Europe, as of other continents, are determined to some degree by faults of different orders.

1.3.2.1 Zones of deep-seated faults and other subordinate tectonic dislocations

Fault zones are differentiated with respect to the depth of initiation, extent, width, manifestation of different tectonic processes operating in them and according to the role they play in the evolution of the relief [see Khain (1964), Bashenina (1973, 1977)]. The Soviet tectonists—Borisov, Khain and others—believe that the term 'deep-seated fault' is not strictly correct. These faults are weak zones penetrating to different depths in the Earth's crust and mantle. They '... are not a result of complication of structures, but represent primary features of the Earth's crustal structure, with respect to which many other features, as for example geosynclines, are secondary, derivative elements' [see Khain (1964) p.251].

Deep-seated faults are frequently associated with the Benioff zones. They dip at angles of up to 60° and are exposed at the Earth's surface in the areas of island arcs and deep-sea trenches. These faults are associated with earthquake foci concentrated at depths of a few kilometres to 100–200 km, more rarely being located at depths of 300–900 km (i.e. deep-focus earthquakes). The widths of the fault zones may be 200 km or more. Melting of the mantle and crustal material takes place in these fault zones. Magma and gas are extruded up associated vertical fractures of a lower order that intersect the oblique faults and give rise to the surface vulcanism of island arcs. The concept of oblique faults in the transition zone between continents and oceans was first introduced by Zavaritsky and Benioff, and was then further developed by a number of other geologists and seismologists. The major deep-seated faults were termed Benioff–Zavaritsky zones, probably without associating this term with Benioff's general concept. Since the latter is in dispute, it seems preferable to use the term deep-seated fault zone when associated with active geosynclinal zones.

Apart from the faults of transition zones, other large global faults of deep origin and great extent are known. Many such faults that cross the Atlantic and Pacific Oceans have their own names in the published literature. Ocean faults extend to all continents. Their topographical expression on these continents is rather complex. They fail to maintain one and the same trend: their intersection with other faults, mostly perpendicular, causes them to shift somewhat and to change their direction. The same phenomenon may apply to the faults they intersect.

The faults of the Atlantic Ocean are clearly expressed in the relief of Europe, such as the Gibbs fault running from Newfoundland through the Porcupine Bank and the southern parts of Ireland and Great Britain, being distinctly represented in the relief of the latter, and the Gloria fault extending into Spain from the Azores, passing into the graben of the Guadalquivir River. There are also other large faults of a transcontinental type. For example, the major Ural fault running through the Aral Sea, Iranian highlands, and the north-western part of the Indian Ocean is traceable in Oman; transverse Transcaucasian faults are identified in the Arabian peninsula. Large mountainous massifs, complex grabens and young volcanoes (e.g., Elbrus, Kazbek, Italian volcanoes, the volcanic areas of the Massif Central, etc.) are associated with the intersection of faults of various trends. The largest mineral deposits are commonly localized at these intersections.

These major faults, together with others of lower orders, form a global network which divides the Earth's crust and mantle into blocks of various orders—from global megablocks to minor crustal blocks several kilometres in size. Many fault zones are long-standing features that have maintained their activity during several tectonic cycles: some Riphaean faults are still active.

1.3.2.2 Fault-induced tectonic processes

Tectonic processes operating during the entire period of the Earth's geological history are known to penetrate to the Earth's surface along the deep-seated fault zones. Folding, various magmatic events, secondary dislocations along lower-order faults, negative and positive vertical movements, horizontal movements and earthquakes took place in the geosynclines related to these faults. The deep-seated faults appear to act as conductors for all known deep processes.

The deep-seated faults account for the formation of a system of oceanic and continental rift zones (*see* Fig. 1.7). There is a lot of contradictory data on the problems of riftogenesis. Rift valleys expressed in the present-day relief are located mainly in fault zones not more than 70 km deep. Minor rift valleys, such as those of the southern Urals and the Ohže river valley, are restricted to crustal faults of lesser depths. The rift-forming process is commonly associated with a fault zone accompanied by some horizontal tension. Rift zones are recognized traditionally as consisting of one or more longitudinal, almost parallel depressions—narrow linear grabens showing a displacement *en échelon* along transverse faults. The sides of the troughs are represented by horst ranges and massifs which have also been formed as a result of tension. The latter is accompanied by the squeezing of a system of horsts to different heights [see Bashenina (1977)]. It is supposed