GEOLOGY OF EUROPE

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Contents

Summary

The European continent is part of the Eurasian continent and is separated from Asia by

the late Paleozoic Uralian orogen. The European continent comprises two major sectors, Fennosarmatia in Eastern Europe with an Archean/Early Proterozoic basement and a Middle Proterozoic to Tertiary cover, and Central/Western/Southern Europe with Paleozoic orogens, which accreted since Silurian towards Fennosarmatia. Both sectors are separated by the Caledonian thrust front and the Tornquist-Teisseyre fault (Trans-European suture zone), the later representing a wide zone of superposed fault-suture-type structures. Southern Europe and the Mediterranean Sea represent a geodynamically active area including microcontinents and domains with ocean floor. This area also comprises a strong seismicity and seismic hazards due to present-day activity of subduction zones, transform faults, thrust systems and normal faults.

The European continent formed by several major steps of evolution. Archean nuclei have been created and amalgamated by the formation of Late Archean and Early Proterozoic greenstone belts and granulite-gneiss terrains. Three major microcontinents amalgamated during a ca. 1.8 Ga old orogeny to Fennosarmatia (Eastern Europe), a craton which represents the stable craton since that time and which unified with North America to Laurussia during the Caledonian orogeny (ca. 400 Ma). Proterozoic rift systems developed within Fennosarmatia and platform sediments were deposited on it since Middle Proterozoic times. The stepwise accretion of orogenic belts occurred along margins, including the Timan (ca. 600 Ma), Caledonian (ca. 450-400 Ma) and Variscan-Scythian orogens (ca. 360-310 Ma). In contrast, the Precambrian basement is subordinate and mainly of Late Proterozoic age in Central/Western/Southern Europe. There, crust formation reflects the stepwise accretion of progressively younger orogenic belts. These include Cadomian (ca. 670 – 520 Ma), Caledonian (ca. 500 – 400 Ma), Variscan (380-300 Ma), Cimmerian (ca. 210-180 Ma) and Alpine (120-0 Ma) orogenic belts. The formation of sedimentary basins postdating each of these orogens is partly related to rifting and the opening history of the Tethyan and Atlantic oceans. These sedimentary basins include the North and South German, Paris, Aquitan and North Sea basins as well as the Moesian platform.

During the Quaternary, glacial processes due to the formation of a large inland ice shield largely influenced the landscape of Northern and Central Europe.

1. Introduction

Europe is part of the Eurasian continent and comprises as a geological entity the continental units extending from the Urals and Caucasus mountain ranges as limiting boundaries against Asia to the passive continental margins of the Atlantic Ocean in the west and the Mediterranean and Black Seas in the south, and the Barents Sea in the north.

The geological structure of the European continent is highly diverse and reflects the stepwise growth from an Archean nucleus in northeastern Europe to the recent accretion of units in the south, along margins of the Mediterranean Sea. Many classical concepts of geology have been developed in Europe, based on observations of European geology. This review intends to present a short and concise overview of the geological and geophysical structure of Europe. The main intention is to show how the geological structure developed through earth history and how it influences human life including their development during pre-historical and historical evolution as both topography and the distribution of geological resources control human activity. Consequently, some attention is paid to the geologically interesting cultural heritage of ancient mines as this is also within the present focus of activity of the United Nations.

2. Geological and Geophysical Overview

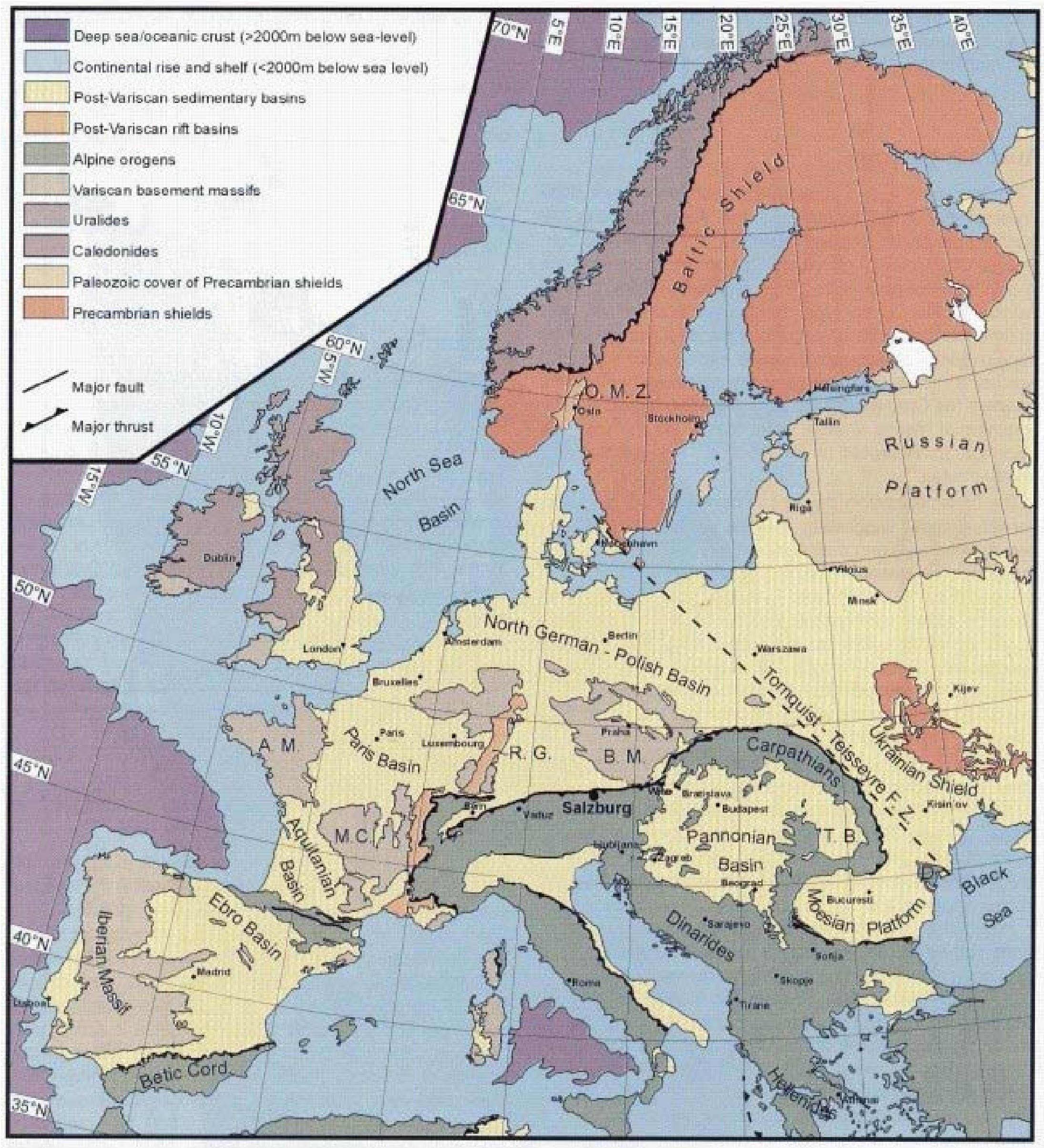

Figure 1. Simplified geological map of Europe showing the main orogenic systems. A.M. - Armorican massif, B.M. – Bohemian massif, F.Z. – fault zone, M.C. French Massif Central, O.M.Z. – Oslo-Mjösen Zone, R.G. – Rhine graben, T.B. – Transylvanian basin

Europe is divided into a number of major tectonic units that represent a sequence of continental growth towards the southwest since Late Archaean times (Fig. 1). These units largely differ in the present-day geophysical properties and topography as well (Figs. 1, 2). Large portions of Eastern/Central and Western/Southern Europe are covered by flat-lying Permian to Neogene platform sediments. They overlie a pre-Late Carboniferous plutono-metamorphic basement. The distribution of the basement structures is shown in Figure 1, and 4 -5. The structural units of Europe include (Figure 1):

1. *Fennosarmatia* is the old continental nucleus, which mainly formed during Archaean and Early Proterozoic times. The cratonic basement is exposed in the Baltic and Ukrainic (or Podolic) shields whereas other portions are covered by Late Proterozoic to Quaternary sediments of the East European Platform and the North Caspian Trough.
2. Small remnants of *Laurentia* with Early Proterozoic age are exposed in northwestern Scotland and the Hebrides.
3. The Caledonian belt (also Caledonides or Paleo-Europe) overrides the Baltic Shield on its northwestern margins and the Laurentian cratonic units on its southeastern margin. The Caledonian belt trends northeast-southwest and comprises mainly Early Paleozoic island arc, ophiolite and passive continental margin sequences which finally collided during the Late Silurian (Caledonian) orogeny. A further unit is the largely hidden *Avalonian microcontinent* which forms an east-west trending belt and which has been accreted to Fennosarmatia during the Late Silurian, too.
4. The Variscan orogenic belt (also Variscides or Meso-Europe) was formed during the Carboniferous. The belt extends from the Iberian Peninsula through Western and Central Europe to the Tornquist-Teisseyre Zone (which is recently also coined as Trans-European Suture Zone) at the south-western margin of Fennosarmatia. The present southern limit of the Variscan belt is the Alpine (orogenic) front. But it has to be noted that the basement within the Alpides of Neo-Europe has been formed as part of the Variscides, too.
5. Skythides represents the extension of the Variscides along the southern margin of Fennsarmatia and is mostly included in Alpine orogenic belts.
6. Small remnants of a Cimmerian orogen are preserved in southeastern Europe forming a belt extending from Dobrudja via the southern Crimea peninsula to the Caucasus.
7. The highly arcuate Alpine belt (also Alpides or Neo-Europe) comprises the Cretaceous to Cenozoic mountain ranges which formed through accretion of Gondwana-derived continental microplates to stable Europe. The Alpides extend from the Betic Cordillera on the Iberian Peninsula through Sicily, the Apennines, Alps, Dinarides, Carpathians to Balkan and Hellenides and can be traced further towards the east as part of the “Alpine-Himalayan orogenic system”. The structural complexities of the Alpine belt arise from the motion of a number of microplates, the active subduction of oceanic crust and the opening of back arc basins with the formation of new oceanic crust. The Alpidic orogeny is not completed; active tectonic processes are still ongoing, as the Mediterranean Sea is not closed.
8. The Mediterranean Sea is a complex system of continental microplates like the Adriatic (Apulian) microplate, the Corso-Sardinic and Balearic blocks, which are separated by Oligocene-Neogene back arc basins in the western Mediterranean and Neotethyan, Mesozoic oceanic crust forming the Eastern Mediterranean Sea which is presently subducting beneath the Hellenic arc.

9. Variscan Europe is partly covered by a number of Late Paleozoic to Cenozoic extensional and rift basins of variable ages. The basins include the Oslo-Mjösen Zone, a Permian rift with exclusively volcanic rocks, Late Paleozoic-Mesozoic North-German, the Mesozoic North Sea, South German and Paris basins, and the Cretaceous to Cenozoic Aquitan and Ebro basins. The Rhone-Rhine and Rhine rifts are of mainly Oligocene-Miocene age and formed in response to Alpine orogeny.
10. The Moesian platform is a further, independent little microplate that formed during the Late Cretaceous opening of the Black Sea. It likely split off from the southern Fennosarmatian margin and comprises a Late Proterozoic basement.
11. The Black Sea is located at the interface between the Alpine and Cimmerian orogenic belts. The western Black Sea is underlain by oceanic crust of supposed Late Cretaceous to Paleogene age. In contrast, the eastern Black Sea comprises orogenic crust which has been shortened by Cenozoic tectonic processes.
12. Late Mesozoic and Cenozoic anorogenic intraplate volcanism is widespread in northwestern and western Europe. Volcanism and shallow plutons of Late Cretaceous and Early Tertiary age formed in response to initial stages of the opening of North Atlantic sectors of the Atlantic Ocean. Hot-spot related volcanism is widespread in Ireland, Scotland, the French Central Massif, the Rhenic Shield and the northwestern Bohemian Massif.
13. Finally, a passive continental margin and slope is facing towards the Atlantic Ocean and Barents Sea. The passive continental margin was formed at different times during rifting and subsequent break-up between Middle-Late Cretaceous along Iberian sectors of the Atlantic margin, and during Late Cretaceous to Paleogene in northern sectors of the Atlantic margin.

In terms of geophysics various properties of the European crust are well investigated, e.g. Moho depths and heat flow. The Moho is at 35-55 km depth beneath Fennosarmatia, except beneath Phanerozoic aulacogens which incised into the East European platform. The Moho beneath the Caledonides and Variscides is at an intermediate level (ca. 32-35 km). In areas with Mesozoic-Tertiary rifting the crust is thinned with mostly linear features monitoring the surface geological structure. There, the Moho depth is as shallow as 22-25 km beneath the surface. In contrast, the Moho is at a depth of ca. 50-60 km beneath the Alpine mountain ranges indicating pronounced, still-existing mountain roots. The Urals are interpreted as preserving the Late Paleozoic mountain root. In contrast, back arc basins like the Aegean Sea and Pannonian basin or extensional collapse basins have a much shallower Moho, reaching a shallow level, e.g., 23 km beneath the Pannonian basin.

Fennosarmatia shows a low geothermal gradient (ca. 8 °C/km), low heat flow (30-50 $Wm^{-2}sec^{-1}$) and partly no asthenosphere beneath it (Figure 2). In general, the lithospheric base is at a level of 200 kilometers, in contrast to Paleo- and Meso-Europe where the lithosphere is ca. 100-120 kilometers thick. The lithosphere is also thinned beneath rifts and back arc basins.

The topography of Europe reflects Late Paleozoic to Quaternary tectonic processes. The Fennosarmatian topography is interpreted as recording intense peneplanation active since Late Proterozoic times. The present uplift of the Baltic Shield and Caledonides is caused by isostatic unloading due to melting of the ice shield formed during the last inland ice glaciation. The Variscides show a rugged topography with peneplained and uplifted basement massifs and smooth hilly basin areas in between. Together, these features are interpreted as recording young, Late Neogene to Quaternary uplift in the order of several hundred meters due to compressional stresses induced by the Alpine orogeny.

Mountain ranges of Neo-Europe are as high as ca. 4000 meters, the Caucasus near 6000 meters, and reflect Cenozoic, still ongoing tectonic processes. In addition, an overall uplift still of enigmatic origin in the order of several hundred meters is observed in these belts and adjacent basins including the margins of the Mediterranean Sea.

In the following, various structures are described from the oldest to youngest units. Maps with pre-Late Carboniferous basement are shown in Figures 1 and 4-7. The sequence also gives a model of the tectonic evolution of Europe, which shows the stepwise growth during the history. Note that evolutionary models have some significant uncertainties going back in time. Note furthermore that some new models mainly for the Precambrian evolution have just been developed, which are not the result of convergence of ideas.

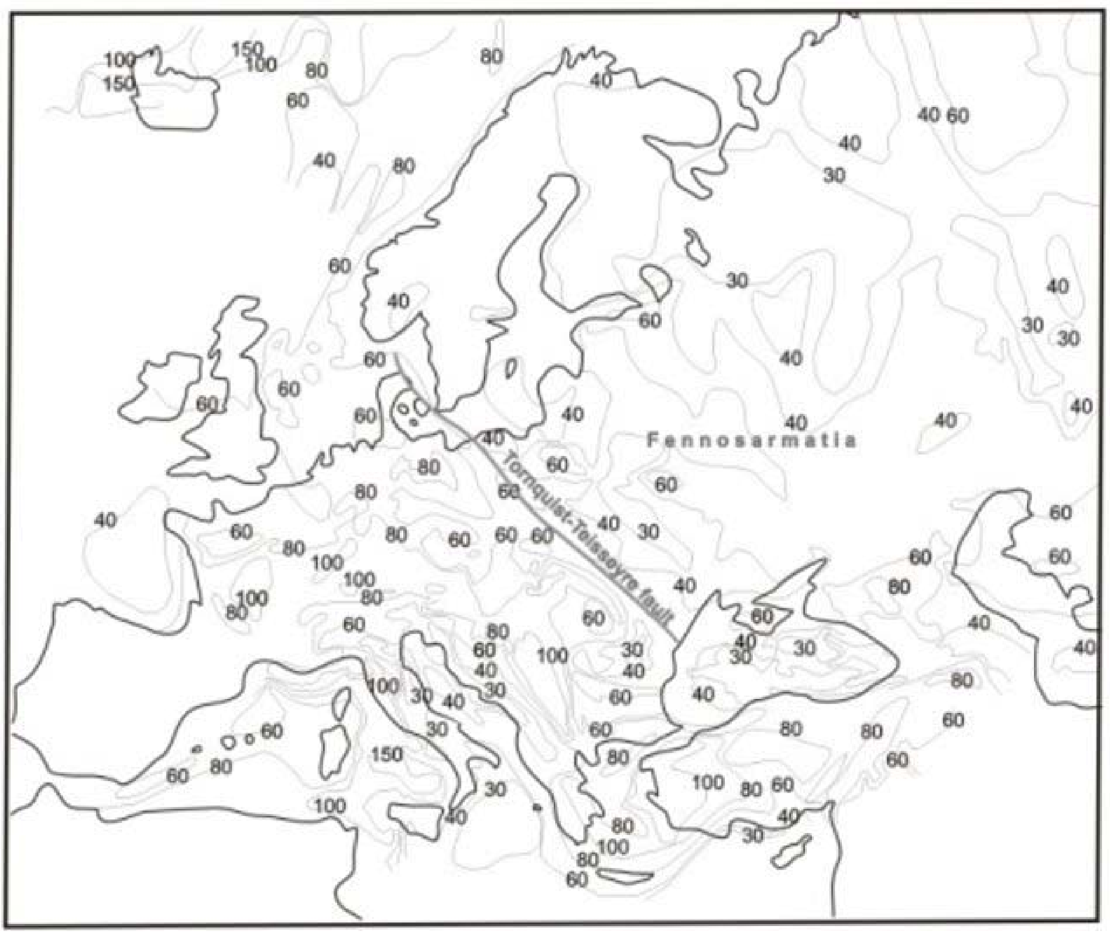

Figure 2. Heat flow map of the European continent. Distribution displays a pronounced difference between the old, cratonic Fennosarmatia with a low heat flow, and Phanerozoic orogenic belts of Central, Western and Southern Europe

3. Laurentian Basement

Small remnants of North American basement rocks collectively referred to as Laurentian basement are exposed in northwestern Scotland. These include mainly Early Proterozoic Scourian and Dalradian gneisses, which are overlain by Late Proterozoic red beds ("Oldest Red"). These were overthrusted along the ductile Moine thrust by the Caledonian orogenic wedge during the Late Silurian.

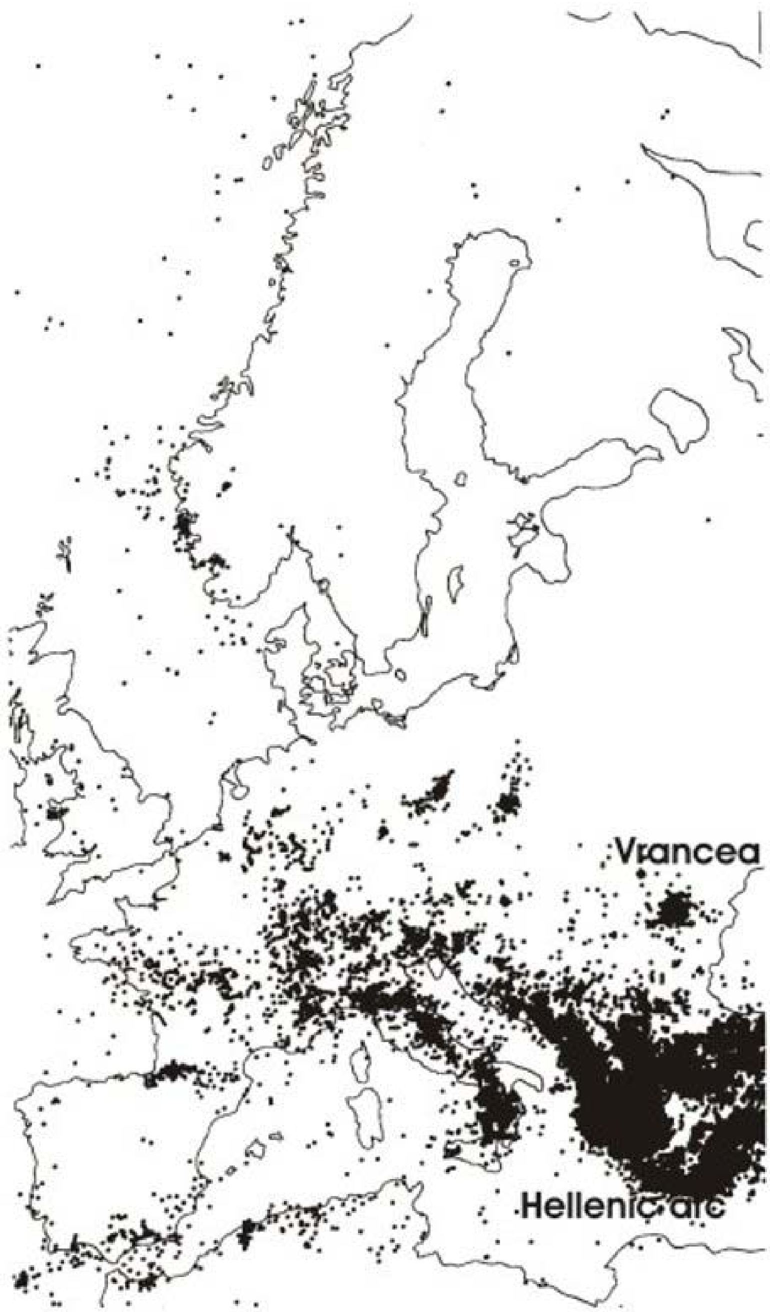

Figure 3. Map showing distribution of recent earthquakes. Note the tectonically active Mediterranean Sea and surrounding mountain belts. (Modified after Blundell et al., 1992).

4. Fennosarmatia And The East European Platform

4.1. Overview

Eastern and Northern Europe comprises a Precambrian basement of mainly Late Archaean to Early Proterozoic age with some subordinate, Late Proterozoic (Sveko-Norwegian) portions at its westernmost surface exposure within the Baltic Shield (Figs. 1, 4, 5). The Precambrian basement is exposed in two shields, the Baltic and the Podolian/Ukrainian Shields. The Precambrian basement of Eastern and Northern Europe is involved along its northwestern and southwestern margins in Phanerozoic orogens, specifically in the Caledonides.

Numerous boreholes penetrate the basement of the East European platform so that lithologies and zonation are reasonably well known. Geophysical signatures allow the tracing of major structures over large distances. The Fennosarmatian basement as a whole is divided into three major blocks which were accreted to each other during Late Paleoproterozoic tectonic processes. Fennosarmatia comprises *Fennoscandia* with an Archaean core and a number of Proterozoic orogens in the southwest, *Sarmatia* with a large Archaean core (mainly amphibolite- and granulite facies rocks of an age of 3.7 to 3.0 Ga) and a NE-striking Paleoproterozoic orogen along its northern margin which is intruded by the Osnitsk-Mikashevichi Igneous Belt (with ca. 2.0-1.95 Ma old plutons) and the *Volgo-Uralia block* with mainly Archaean rocks, too. Fennoscandia is exposed in the Baltic Shield, Sarmatia in the Podolic Shield. The Kursk magnetic anomaly is an extremely large area with Early Proterozoic banded iron formations belonging to Sarmatia. The Volgo-Uralia block is completely covered by younger sedimentary successions.

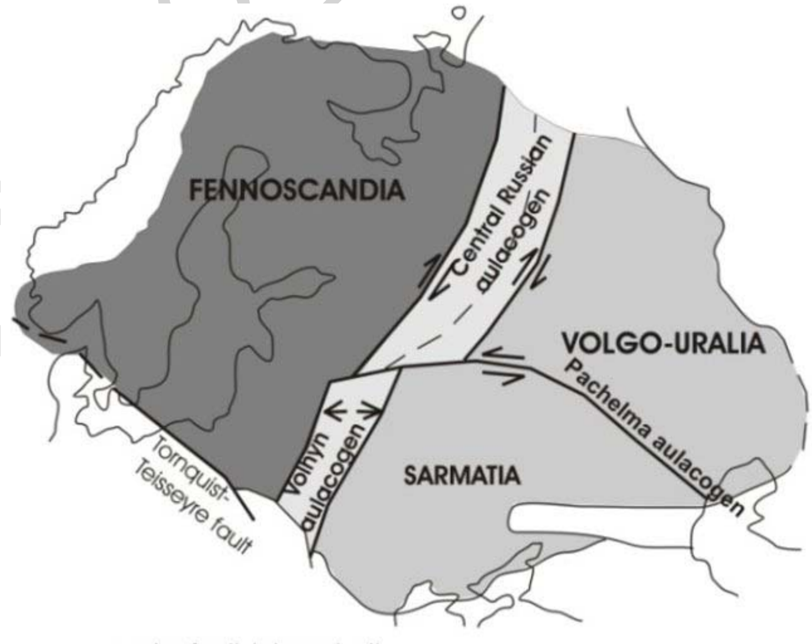

Figure 4. Map displaying the principal basement terranes of Fennosarmatia. (Modified after Bogdanova et al., 1996).

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Biographical Sketch

Fanz Neubauer was educated at the University of Graz and is now a professor of geology at the University of Salzburg in Austria. He has an international reputation for the regional geology of the eastern Alps. However he has also worked extensively in other European regions, in particular the Carpathians. More recently, he has also worked in the Caribbean and in Tibet.