THE GEOLOGICAL AND TECTONIC FRAMEWORK OF EUROPE

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Introduction

The geological record of Europe extends back in time to about 3,500 million years, approximately 1,000 million years after the Earth was formed. Europe was the birthplace of geological sciences. The first writers who have contributed something of geological significance were the ancient Greek philosophers (Adams 1954), such as Thales of Miletus (*c.*636-546 BC), Anaximander of Miletus (615-547 BC), Pythagoras of Samos (540-510 BC), Xenophanes of Colophon (540-510 BC), Herodotus of Halicarnassus (480-420? BC), Aristotle of Stagira (384-322 BC), Strabo (64 BC-23? AD) and many others. Modern geology begins with Georgius Agricola in Germany (1494-1555 AD), who was one of the most outstanding figures in the history of the geological sciences, not only of his own times, but of all time, and his rightfully called the "Forefather of Geology". Other eminent pioneering figures are Leonardo da Vinci (1452-1519 AD), Abbé Anton Lazzaro Moro (1687-1740 AD) and Antonio Vallisnieri (1661-1730 AD) in Italy, Conrad Gesner (1516-1565 AD) in Switzerland, Nicolaus Steno (1638-1686 AD) in Denmark, Abraham Gottlob Werner (1750-1817 AD) in Germany, Jöns Jacob Berzelius (1779-1848 AD) in Sweden, William Smith (1769-1839 AD), the father of English Geology, Charles Lyell (1797-1875 AD) and James Hutton (1726-1797 AD) in the United Kingdom, Georges Cuvier (1769-1832 AD) and Alexandre Brongniart (1770-1847 AD) in France, and Andreas Kordellas (1836-1909 AD) in Greece, working from the 15th to the late 19th centuries, to provide information on mineralogy, crystallography, palaeontology, stratigraphy and mineral resources. Hence, the continent's stratigraphy and structure has been studied for almost 500 years.

Initially, geology involved the examination and survey of surface rock exposures to prepare geological maps. More recently, understanding of the evolution of Europe's continental crustal structure has been greatly enhanced by the interpretation of new types of geophysical and geochemical data. The present continent of Europe stretches from its submarine continental margin in the west to the Ural mountains in the east, and from the ancient and relatively tectonically stable rocks of the Fennoscandian Shield in the north, to the young, more tectonically and volcanically active zone, of the central and eastern Mediterranean in the south.

The evolution of the continent took place as a result of lithospheric plate interactions, which are now relatively well understood. The outer region of the Earth, or lithosphere, includes the crust and the upper mantle, and is a rheologically more rigid layer lying above a more plastic layer of the upper mantle, known as the asthenosphere. The lithosphere is divided into several major tectonic plates that move relative to one another, and interact and deform, especially around their margins. Orogenesis, involving crustal thickening, deformation and metamorphism, is often followed by extensional collapse with widespread intrusion of highly evolved peraluminous granites. Plume activity is generally associated with continental break up, and there is considerable evidence of this following the splitting of the Earth's most recent supercontinent – Pangaea, beginning during the Permo-Triassic times. At present, Europe forms the western part of the Eurasian Plate. In the Mediterranean region it abuts against the African Plate to the south which, combined with the broadly SE-directed ridge-push forces of the mid-Atlantic Ridge, and the beginning of an eastward Atlantic plate compression along Iberia, give a broadly NW-SE maximum horizontal crustal compressive stress throughout much of western and central Europe.

Although the plate tectonic processes affecting Europe over the last 200 Ma period are reasonably well understood, the earlier evolution of Europe's continental lithosphere has been extremely long and complex and geological, and tectonic events are more obscure and difficult to interpret further back in time. To fully understand Europe's geology requires consideration of plate tectonic processes and the changing geometry and geography of plates operating throughout the 3,500 Ma (3.5 Ga) of the evolution of the continent.

The discussion of Europe's geological evolution that follows should be read in conjunction with Sheet 9 (Europe) of the Commission for the Geological Map of the World (CGMW) (Choubert and Faure-Muret 1976), and the recently published 1:5 million CGMW International Geological Map of Europe and Adjacent Areas (Asch 2003).

Overview of the Geological and Tectonic Structure of Europe

Like all continental landmasses, Europe presently comprises various crustal blocks, which have been assembled over geological time (Figure 1). In the extreme northwest of Scotland, there is a fragment of the late Proterozoic continent of Laurentia, initially part of a North American-Greenland landmass. Otherwise, Europe's continental basement can be divided broadly into two large and distinct regions:

- in the north and east a stable Precambrian craton known as the East European Craton (EEC), and
- in the south and west a mobile belt, comprising crustal blocks that have become successively attached to the ancient cratonic nucleus.

The boundary between these two regions is marked by the NW-SE-trending Trans-European Suture Zone (TESZ) (previously known as the Trans-European Fault, the Tornquist Line or the Tornquist-Teisseyre Line), which extends for approximately 2000 km from the North Sea to the Dobrogea region of the Black Sea. The TESZ is everywhere obscured and concealed beneath Mesozoic and Caenozoic sediments, but it has been reasonably well-defined as a broad zone of NW-SE-striking faults by subsurface geology, drilling results and geophysical methods, including deep seismic reflection data.

The East European Craton (EEC) comprises Precambrian rocks of the Baltic, Ukraine and Voronezh shields, together with the Russian or East European Platform, where the EEC is covered by relatively thin, undisturbed, Phanerozoic rock sequences. In contrast, the mobile belts to the south and west comprise Proterozoic-Palaeozoic crustal blocks (or 'microcontinents'), which originated as part of the southern Gondwana continent, tectonised by end-Precambrian Cadomian orogenesis that became attached to the south west margin of the EEC *in Palaeozoic times*. These crustal blocks, belonging to Eastern Avalonia, now form part of the basement of the English Midlands, the southern North Sea, and Armorica extending from western Iberia and Brittany eastwards through central Europe to the Bohemian Massif. The plate tectonic collision of Eastern Avalonia with the East European Craton followed closure of the Lower Palaeozoic Tornquist Sea in late Ordovician to Silurian times. Whereas, the collision of the Armorican micro-continent, with both the East European Craton and Avalonia, followed the later closure of the Rheic and Theic Oceans (Galiza-Central Massif Ocean, *e.g.*, Matte 1991, Rey *et al.* 1997) probably towards the end of middle Devonian. The southerly European Alpine orogenic belt is mostly of Caenozoic age.

In Europe, the precise locations of separate terranes, fault-bounded blocks of continental crust, usually smaller than microcontinents, related to Avalonia or Armorica are poorly exposed and concealed beneath younger rocks. Also, in places, the reworking of older rocks in later orogenies has resulted in collages of relatively small shear-zone-bounded terranes (such as the Precambrian Mona complex of North Wales, and similar complexes in the Bohemian Massif).

Hence, the crystalline basement of western and central Europe comprises a complex mosaic of crustal elements, assembled during various Precambrian orogenic cycles followed by the Phanerozoic Caledonian, Hercynian and Alpine orogenies. During this long and complex crustal evolution, earlier consolidated crustal elements were repeatedly remobilised and overprinted by later events. Thus, the basement provinces of western and central Europe are defined by the latest orogenic event affecting that portion of crust, causing widespread metamorphic reworking and, in many cases, the intrusion of calc-alkaline igneous rocks.

The oldest Precambrian basement provinces of western and central Europe, therefore, comprise the East European and Hebridean cratons, the stable Cadomian blocks of the London Platform and the East Silesian Massif, and the Caledonian, Variscan and Alpine fold belts. The boundaries between the principal structural elements of the European continental elements are in places poorly defined, partly as a result of a lack of data, and partly because they are concealed by younger rocks. Also, metamorphic overprinting of some older basement areas has occurred during later orogenic cycles. This is particularly the case with the Variscan fold belt, which in places seems to

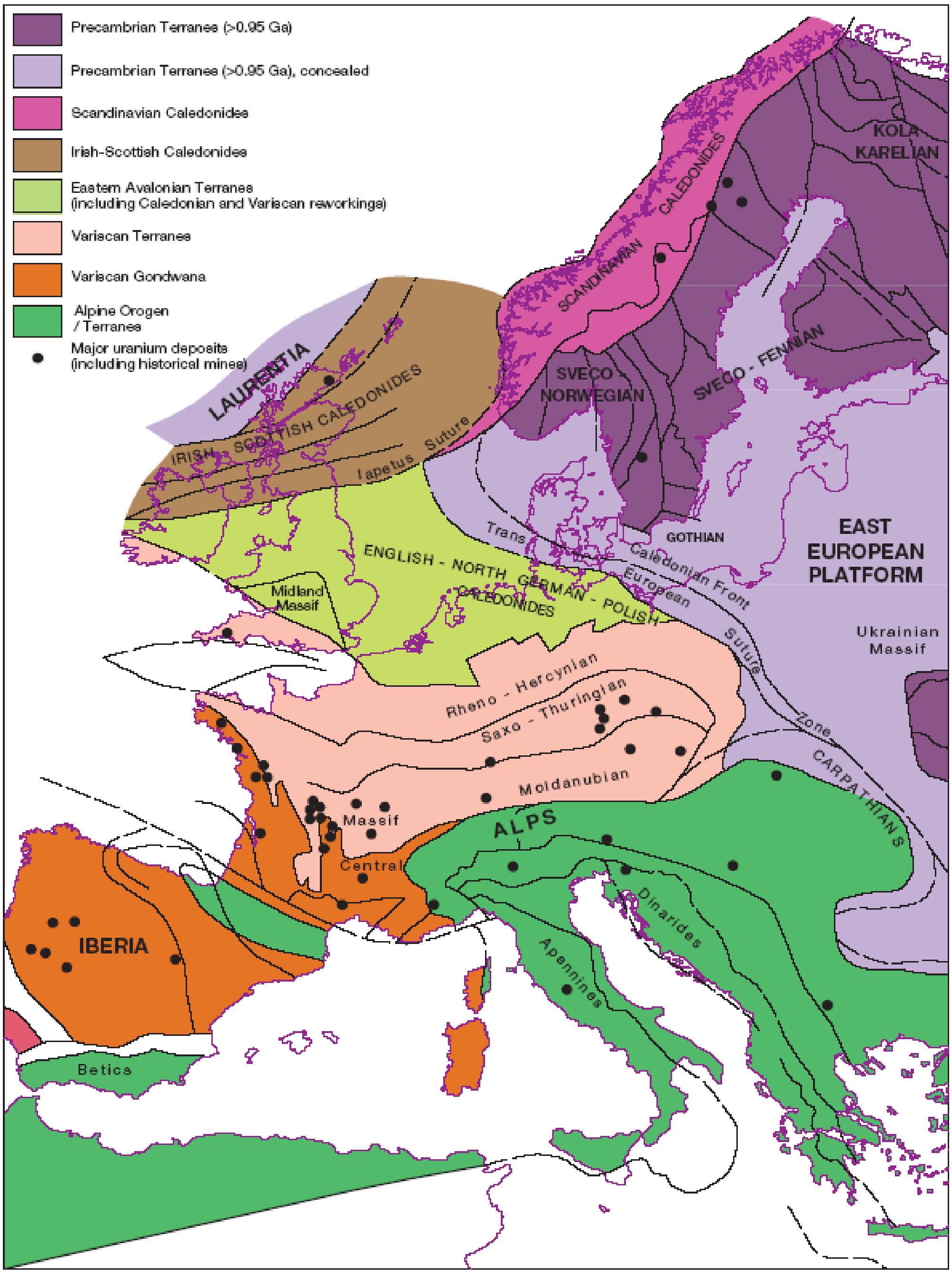

Figure 1. The ‘terrane collage’ of Precambrian and Phanerozoic Europe, a simplified sketch. Sutures and orogenic fronts are shown as bold lines, internal borders as thin or thin broken lines. Note that the size and shape of the terranes do not change significantly with time (approximate direction of younging is from north to south) (Reproduced with permission from Blundell *et al.* 1992, and Plant *et al.* 2003, Fig. 1, p. B229).

contain some Caledonian, as well as the Late Palaeozoic (Devonian-early Carboniferous) orogenic belts. Similarly, throughout the Alps of southern Europe, pre-Alpine basement rocks, including pre-Variscan basement, late-Variscan granitoids and post-Variscan volcaniclastic rocks, occur in many places.

Precambrian Europe

The Laurentian Shield

The small outcrop of Laurentian, the Lewisian Gneiss Complex of NW Scotland, has remained tectonically stable since Proterozoic times. It consists mainly of Archaean granodioritic, tonalitic and amphibolitic gneiss, formed under granulite and amphibolite facies conditions at *c.*2,700 Ma and 2,470 Ma. The protoliths of the Lewisian Gneiss Complex consist of granodioritic and tonalitic intrusions, diorite bodies, layered mafic-ultramafic bodies, mafic dykes and lenticular bodies, and minor metasedimentary rocks. Recent U-Pb zircon dating has shown that these range from 3,125 Ma to *c.*2,700 Ma. The rocks were subject to deformation at middle to lower crustal levels under granulite and upper amphibolite facies conditions during the Scourian event between *c.*2,650 Ma to 2,480 Ma. The Archaean architecture of the complex was completed by intrusion of granite sheets and pegmatites around 2,550 Ma, mainly in the Outer Hebrides. A major suite of Early Proterozoic tholeiitic dolerite and basalt dykes, the Scourie Dyke Suite, was intruded into the complex in two phases at *c.*2,400 Ma and *c.*2,000 Ma, with the former phase accompanying local shear zone formation. Arc-related metasedimentary and metavolcanic rocks were later accreted to the complex in the South Harris and Loch Maree areas at around 1,900 Ma. The terranes were then largely reworked during a Laxfordian tectonometamorphic event that peaked at *c.*1,750 Ma, and took place under amphibolite facies conditions. Only the area centred on Assynt, and small parts of the Outer Hebrides, avoided this penetrative reworking. Laxfordian granite sheets were intruded at *c.*1,855 Ma on the mainland, but considerably later at *c.*1,675 Ma in Harris and Lewis. The area was uplifted prior to 1,100-1,200 Ma ago when the older Torridonian Supergroup rocks were deposited. Some possible Grenvillian shear zone effects are recorded by uplift dates from the highly deformed Langavat meta-sedimentary belt in South Harris. Lewisianoid inliers of Laurentian affinity are also found in the Caledonian orogen as basement to the Moine Supergroup rocks of northwest Scotland.

The Fennoscandian Shield

The most extensive area of exposed Precambrian rocks in Continental Europe is in the Fennoscandian Shield, which comprises four main NW to SE trending orogenic belts with the rocks generally younging southwestwards (Figure 1).

From NE to SW these comprise:

the Kola-Karelian Orogen that consists of five Archaean terranes amalgamated by collision between 2.0-1.9 Ga;

the Svecofennian Orogen is made up of rocks younger than <2.2 Ga, which accreted and underwent collisions between 2.0-1.8 Ga, and were reworked by crustal melting between 1.8-1.54 Ga;

the Gothian Orogen, comprising rocks accreted between 1.77-1.5 Ga, is thought not to contain older rocks, and

the Sveco-Norwegian Orogen was dated at 1.05-0.9 Ga, and reworked most of the Gothian Orogen.

The Kola-Karelian Orogen

This orogenic belt has distinctive geophysical properties compared to the Svecofennian Orogen. It has an average crustal thickness of 45 km with an upper layer interpreted as mainly magnetic diorite, and an eclogite facies transition at 38 km. In the extreme NE, the **Murmansk gneiss-granulite terrane** consists predominantly of tonalitic gneiss, granodiorite, amphibolite and migmatite, and minor granulite, pyroxene gneiss and schist, with intercalated banded ironstone formation, metamorphosed in the upper amphibolite-granulite facies. The major structures are large-scale reclined folds intruded by plutons of late Archaean granitic rocks. Uranium-Pb zircon ages obtained on gneiss are 2.9-2.7 Ga.

Adjacent to this terrane, to the southwest, the composite **Sørvaranger island arc terrane** consists of:

two greenstone belts comprising amphibolite, ultramafic rocks and agglomeratic meta-volcanics and meta-psammite, pelite, banded ironstone formations and quartzite, mostly at amphibolite facies, and

amphibolite to granulite facies migmatitic alumino-silicate schist and gneiss in thrust contact with the greenstone belts. The discordant Neiden granitic pluton intruding greenstone belt rocks and the gneiss have a U-Pb and Rb-Sr age of 2.5-2.55 Ga. It has been suggested that the greenstone belts formed in arc and back-arc settings, while the gneiss is derived from turbidite, laid down in an arc-trench accretionary wedge (Windley 1992, 1995).

The **Inari gneiss terrane** consists of heterogeneous migmatitic trondhjemitic to granitic orthogneiss within which there are conformable layers and lenses of amphibolite and mica schist up to 10 km wide, associated locally with calcic gneiss, quartzite and banded ironstone formation. Uranium-Pb determination on zircon from the gneiss gives dates of 2.73-2.55 Ga.

The composite **Belomorian terrane** contains:

amphibolite-facies meta-pelitic gneiss, orthogneiss, amphibolite and granite. Uranium-Pb determinations on zircon from the tonalitic-trondhjemitic gneiss give ages of 3.11 Ga, and Nd isotopes suggest that the crustal material had separated from the mantle by 3.5 Ga. Other types of gneiss in this terrane are dated in the range 2.9-2.4 Ga, and

in Finland, the Lapponian Supergroup, which includes several greenstone belts that have a lower unit of komatiitic and tholeiitic basalt, mafic to felsic tuff (part of a plateau lava), a central unit of pillow-bearing amphibolite, arkosic quartzite and aluminous slate, and an upper unit of extensive ultramafic and basaltic komatiite, mafic lava and tuff, carbonaceous greenschist and graphitic slate. The Kittilä (island arc) greenstone belt is cut by a gabbro dated at 2.44 Ga, and in the eastern Belomorides a 2.7-2.6 Ga period of collision has been recognised.

The basement of the **Karelian composite terrane** comprises Archaean greenstone belts comparable to modern island arc assemblages, separated by gneiss and granite. More than 20 major greenstone belts up to 100-150 km long have been recognised, as well as many smaller ones, separated by belts of gneiss with different types of granite intrusions. Across eastern Finland and Karelia, there are four tectonic zones with different compositions and ages of volcanic rocks in the greenstone belts. The composition and ages of the gneiss and granite, and their degree of metamorphism and deformation also varies. Tholeiitic basalt makes up 40-70% of most greenstone belts, although some include magmatic rocks, ranging in composition from komatiite to rhyolite. The greenstone belts young westwards from 3.0-2.9 Ga in eastern and central Karelia, to 2.80-2.75 Ga in western Karelia, and 2.65 Ga in eastern Finland, consistent with the progressive westward accretion of successive island arcs, above eastward-dipping subduction zones. The gneiss and granite are less well understood than the greenstone belts. Some consist mostly of paragneiss, while others comprise mainly of orthogneiss and granite. Many show a close spatial and temporal relationship with the development of the greenstone belts. The oldest known rock in the Baltic Shield is gneiss in southeastern Karelia, which gives U-Pb zircon ages of 3.5 Ga. Amphibolite and migmatite are dated at 3.2 Ga, and tonalite spans the time range of 3.4-3.1 Ga.

The orogen was formed in the Early Proterozoic between 2.0-1.9 Ga as the Archaean terranes collided, and eventually amalgamated with Early Proterozoic (2.4-1.9 Ga) rocks. Island arcs, Andean-type magmatic arcs, sutures and remnant shelf successions were all included. The southern border of the Murmansk Terrane is marked by a northward dipping (60-80º) thrust zone several-kilometres wide, which deforms large-scale folds. The Kola suture zone is a southward-dipping thrust zone up to 40 km along which the Inari terrane is thrust over the Sorveranger terrane, while the Sirkka thrust is a major tectonic boundary along which the high-grade Belmorian terrane was thrust southwards under the low-grade Karelian terrane.

The Svecofennian Orogen

The Luleå-Kuopio suture zone separates the Kola-Karelian orogen in the NE from the Svecofennian orogen to the SW. The suture zone is displaced by 1.9-1.8 Ga north-south mega-shears, which have a strong magnetic signature, and are associated with a depression of the Mohorovicic discontinuity of about 10 km. The suture contains thrust slices of different types and origin, including two types of turbidite:

those on the Archaean craton, immediately to the NE of the suture, where autochthonous turbidite contain Archaean and Proterozoic detritus locally interbedded with tholeiitic volcanics, and

those in the suture that comprise allochthonous turbidite, deposited from debris flows and turbidity currents in submarine canyons at an accretionary margin.

The suture zone also contains serpentinite, gabbro, basaltic pillow lava, non-detrital quartzite, dolomite, Mg-rich meta-volcanics and Cu-sulphide deposits.

The Svecofennian orogen contains no Archaean terranes, and is thought to have developed by the growth and accretion of juvenile arcs dated at 2.0-1.8 Ga, and by extensive crustal melting in the period 1.8-1.55 Ga. The orogen has a mainly paramagnetic dioritic upper crustal layer, and an average crustal thickness of 48 km (maximum 54 km) and a thick lower crustal layer.

The orogen comprises several magmatic arcs with rocks and ores comparable to those of modern island arcs and intra-arc rifts. The 1.89 Ga Skellefte island arc has mature intra-arc volcanics and granodiorite-granite intrusions derived from subduction-related melts. Uranium-Pb zircon data suggest that most of the Svecofennian arc lavas were erupted between 1.92-1.87 Ga, contemporaneous with the intrusion of 1.91-1.86 Ga subduction-derived plutons and tonalitic, granodioritic and granitic batholiths. Many of the Sveco-Fennian arcs are separated by biotite-bearing granitic gneiss and schist, widely regarded as meta-greywacke and meta-pelite, which contain numerous large lenses of amphibolite, metagabbro and meta-ultramafic rocks. Nickel-Cu deposits occur in some peridotite-dunite-pyroxenite-gabbro lenses. Following arc accretion, syn- and post-collisional deformation took place. Thrusting and folding was associated with high amphibolite facies metamorphism that locally reached granulite grade, followed by the emplacement of rapakivi granite. The last event in the evolution of the Svecofennian orogen was the deposition of the Jotnian sandstone at 1.5 Ga in a large elongate basin in the Gulf of Bothnia. Locally, this extends into exposed basement as rifts, framed as a result of the extension and thinning of the Sveco-Fennian crust.

Along the SW margin of the Svecofennian orogen the 1600 km long, 150 km wide Trans-Scandinavian Batholith (1.84-1.75 Ga), which includes early arc-type monzodiorite to quartzo-monzodiorite and granite, and later leucogranite. The batholith may have developed above an eastward-dipping subduction zone on the western margin of the Sveco-Fennian orogen.

The Gothian Orogen

A small part of the Gothian orogen, which escaped Sveco-Norwegian reworking, is preserved in the extreme southeast of Sweden, and on the island of Bornholm, Denmark. There, acid meta-volcanics with a U-Pb age of 1.705 Ga, metabasite, quartzite, mica schist and gneiss with a U-Pb zircon age of 1.69 Ga, and intrusive granite are preserved. The oldest known Gothian rocks here is amphibolite dated at 1.77 Ga, associated with paragneiss deformed and metamorphosed under amphibolite conditions, and intruded by numerous calc-alkaline tonalite-granodiorite bodies. During a period of crustal extension, between 1.5-1.25 Ga rapakivi granite, gabbro and basic dykes were emplaced, bimodal volcanics were extruded, and clastic sediments were deposited in rifts in the eroded basement.

The Sveco-Norwegian Orogen

The Sveco-Norwegian orogeny was a cordilleran type collisional event that reworked the Gothian crust, and produced a north-south trending belt. It comprises meta-andesite, tuff, agglomerate, and volcanic breccia, with syn-orogenic calc-alkaline plutons and post-tectonic granite. The isotopic age of the supracrustal rocks is 1.25-1.2 Ga. The geochemical features of the earliest basalt, acid volcanics and gabbro intrusions are consistent with formation in an extensional, continental margin setting, related to the subduction processes. These culminated in the Sveco-Norwegian orogeny between 1.05-0.9 Ga, marked by deformation and associated upper amphibolite facies metamorphism.

Subsequently, the late Proterozoic East European craton drifted towards equatorial latitudes. The development of the Vättern graben system in southern Sweden reflects rifting during this time (850-700 Ma) when up to 1 km of fluviatile to marine clastic sediments were down faulted, close to the eastern border of the Sveco-Norwegian orogen, unconformably overlying the marginal shear zone.

The Cadomian Orogen

The Cadomian orogeny between 650-550 Ma (late Precambrian) was the last in the sequence of events that formed the crystalline basement rocks of Europe. The Caledonian and Hercynian basement complexes of western and central Europe, not to mention some basement inliers within the Alpine-Carpathian orogen, contain several continental crustal blocks derived during the Cadomian orogeny. These include the Irish Sea Horst, the London Platform, the Armorican and Bohemian cratons, the East Silesian block and the Malopolska Massif of south eastern Poland. Cadomian crustal elements are also recognised in the Alpine fold belt, based on their geology and radiometric age dating. Following the Cadomian orogeny, deep rifted sedimentary basins developed across Proterozoic Europe, and the wide ocean known as the Tornquist Sea opened. At the end of the Proterozoic, Europe drifted towards high southern latitudes, where the Gondwana continent was assembling [Pan African – Cadomian orogenies (650-550 Ma)]. It remained in these high latitudes during Cambrian times. However, by the Early Ordovician those parts that now constitute the Fennoscandian Shield, and the basement of the East European Platform, had broken off and drifted away as an independent tectonic plate. 'Baltica' eventually became a 'nucleus' of the future Caledonian terrain of northern Europe. Other parts of the former Proterozoic Europe, which had become attached to Gondwana, and were strongly influenced by the Cadomian orogeny, were left behind for the time being.

The Caledonian Orogen

The Caledonian orogenic cycle occurred between Late Cambrian and earliest Devonian times, and reflects the collision of the late Proterozoic continents of Baltica, Laurentia and Avalonia, a fragment of Gondwana. It marks the complex closures of the Iapetus or Proto-Atlantic Ocean. Throughout much of Europe information on the distribution and age of deformation of Caledonian fold belts is confined to outcropping Palaeozoic massifs, whereas a few radiometric age determinations are available from deep boreholes, drilled through the overlying sedimentary basins. Hence, there is uncertainty about the relationships of the concealed fold belts. The metamorphic Irish-Scottish-Scandinavian Caledonides form a NE-SW trending belt across NW Europe, interrupted by the later Irish and North Sea basins. Offshore deep borehole samples give age determinations that indicate the continuation of the Caledonides of northern Britain and Norway. In early Silurian times, a Gondwana-derived terrane, Eastern Avalonia, approached the newly-united continents of Laurentia and Baltica (Laurasia). Strike-slip and transpressional movement along the Avalonia-Laurasia suture persisted until the end of the Silurian and caused the development of the English-North German-Polish Caledonides. Thus, the Caledonian orogenic cycle eventually involved the closure of the Iapetus, the Tornquist and the Rheic oceans.

The Iapetus suture between the Laurentian tectonic unit to the NW, and a segment from the composite Gondwana-derived Irish Sea-London Platform-Brabant Massif cratonic terrane to the south-east, is marked by the Solway Line in Britain and Ireland. Deep seismic reflection data and the distribution of Ordovician faunal provinces, suggest that the position of the north-dipping Iapetus suture is located approximately along the border between England and Scotland, passes to the north of the Isle of Man, and thence crosses Ireland in a south-westerly direction where it is covered by Lower Carboniferous rocks (Figure 1).

During Cambrian and Ordovician times much of Baltica and the Laurentian crystalline block that included north-west Scotland were covered by shallow epicontinental seas. Over the East European Platform sedimentation continued with little break throughout the Palaeozoic, continuing in places into the Mesozoic. Generally, the Precambrian basement of the East European Platform now lies at a shallow depth (1-3 km) beneath relatively thin Phanerozoic cover. In the Ukrainian Massif, the basement is exposed, and in the Voronezh Massif the cover sequence is shallow enough to permit opencast mining of Archaean and Proterozoic banded ironstone formations.

Although the Iapetus suture in the British Isles is relatively well-defined, its northward continuation beneath the northern North Sea Basin is not. The Tornquist suture is thought to branch from the Iapetus suture beneath the central North Sea Basin, and strike southeastwards into north Germany and Poland, where it follows the margin of the Precambrian East European Platform. The Rheic suture is considered to be located in the mid-European Caledonides, in the Saxothuringian and Moldanubian terranes.

The Variscan Orogen

The Hercynian orogenic cycle, which took place between the Devonian and Early Permian, involved the assembly of the Earth's latest supercontinent – Pangaea. At this time, almost all of the present Continents were distributed in one approximately North to South crustal mass, with a few blocks such as those of Armorica, Iberia and Bohemia situated between it and the larger Laurentian-Baltic (Laurasia) terrain to the NW. The term Variscan refers to the European part of the Hercynian orogen or fold belt, and specifically relates to the time of late Visean–Westphalian consolidation. Variscan extension throughout western and central Europe in early Devonian times led to the development of the Rhenohercynian Basin, filled with thick Devonian and Carboniferous sediments in a double arc. These relatively undeformed Late Palaeozoic sediments can be traced in the foreland of the Variscan fold belt north of the Variscan deformation front, from southern Ireland in the west, through Britain and Belgium into northern Germany, northern Poland and then further east beneath Slovakia, some 2,500 km. The Rhenish Basin beneath the Netherlands, north Germany and much of the southern North Sea, extends northwards into the Devonian and Carboniferous rift systems of northern Britain and, then south-westwards through Ireland. It extends eastwards in the NW-SE trending Lower Silesian Basin beneath much of northern and central Poland. The Polish basins were connected laterally with the sedimentary deposits of the East European Platform and the Moscow Basin during Upper Palaeozoic times. Here, much of the Rhenohercynian Basin is buried beneath many kilometres of Permian and younger sediments, although its distribution is reasonably well known as a result of numerous boreholes drilled in the Northwest European Basin. The Rhenohercynian Basin extension to south-west Iberia, is represented by the Visean-Upper Westphalian south-western prograded flysch, in the South Portuguese Zone, located south-west of the Beja-Acebuches suture (present coordinates).

South of the Rhenohercynian Zone, the Saxothuringian zone contains the Mid-German crystalline high, which acted as an active margin. It was the site of arc magmatism during the early Carboniferous collisional phase, and the source region of the Rhenohercynian flysch. Southwards, the crystalline high has been thrust over the Palaeozoic rift sequences of the Saxothuringian Basin, which are exposed in Bavaria, Thuringia and Saxony, and the northern parts of the Black Forest and Vosges. The Iberian equivalent of that zone is the Ossa-Morena Zone, which acted as an active margin with arc magmatism, during the Westphalian collisional phase. Nevertheless, as opposed to these areas, the kinematic polarity is to the SW, compatible with the NE deep of the Beja-Acebuches suture.

The Saxothuringian rocks are in turn overthrust by nappes of virtually unmetamorphosed Palaeozoic deeper water facies and crystalline rocks, derived from the NW margin of the Moldanubian region to the south-east. The internal structure of the Moldanubian zone is complex. In places, SE-directed nappe thrusts emplace high-grade over medium grade metamorphic sequences. Similar features in the Black Forest suggest their possible occurrence in the intervening parts of southern Germany, where the Variscan basement underlies thick Mesozoic cover. To the south, the Moldanubian zone probably continues into the Variscan basement of the Alps, while to the south-west the Avalon-Meguma-South Portuguese and the Aquitaine-Cantabrian terranes collided with the Proto-Tethys-Proto-Atlantic subduction complex during the late Emsian to Givetian. This collisional event, marking the closure of the Merrimack and Massif Central oceanic basins, corresponds to the Acadian-Ligerian orogeny of North America.

In Middle and Late Devonian times, the continental masses of Laurasia and Gondwana began to converge to form Pangaea. Progressive narrowing of the Proto-Tethys Ocean allowed early contacts between Laurasia and Gondwana in the region of Iberia and NW Africa during the Fammenian Stage, thus allowing an exchange of flora and fauna between these previously distinct geographical provinces. Full collision, between

Africa and the southern margin of Fennoscandia-Baltica, happened during the late Visean, while crustal shortening in the Variscan fold belt ended during Westphalian times.

The Mesozoic Development of Europe

Following the early Permian consolidation of Pangaea, the supercontinent soon began to show signs of instability. The extensional reactivation of pre-existing faults, after the Variscan compression, and the formation of new rifts in late Permian and Triassic times, allowed the development of many large sedimentary basins. Although there was no crustal separation in Europe in Permo-Triassic times, basinal structures provided an early indication of the extent of future Jurassic, Cretaceous and early Caenozoic break-up of Pangaea in the Arctic, North and Central Atlantic and Mediterranean regions and, thus initiated a new and different reorganisation of plate boundaries that eventually led to the present day distribution of continents.

Large quantities of clastic sediments, in some cases associated with volcanic rocks, were deposited in many of the Permian basins. Many of the depocentres have trends related to pre-existing structural directions. On a European scale, one of the most important sites of basin development was along the TESZ, where geophysical data and drilling have identified deep NW-SE trending basins under thick sequences of younger cover rocks. The early Permian basins along the TESZ also influenced the development of the hypersaline late Permian Zechstein Sea in which important evaporite deposits were formed. The later halokinesis of these salt deposits to form numerous salt diapirs has played an important role in the entrapment of hydrocarbons in Europe. The two main North and South Permian basins that now underlie much of the North Sea and north Germany, were separated by the roughly E-W trending Mid-North Sea-Ringkobing-Fyn High.

Some of the important Permian depocentres continued into the Triassic, which also saw the initiation of a complex multidirectional rift system that crossed the Variscan fold belt. The Triassic rocks consist of continental to brackish marine red beds, shallow marine carbonates, sulphates and halites. An overall eustatic rise in sea level, during Triassic times, was reflected by the Triassic sediments overstepping Permian basin margins. During Late Triassic times, the clastic-evaporite regime of the Northwest European Basin was synchronous with the repeated advance of deltaic systems from the Fennoscandian High and the EEC across the northern North Sea, Denmark and the Southern Baltic sea areas.

During the Jurassic period, the break up of the supercontinent of Pangaea began along the central Atlantic axis. Middle and Late Jurassic opening of new oceanic basins also occurred in the Mediterranean area, and Gondwana became separated from Laurasia, after having formed part of Pangaea for about 100 Ma. In Europe, late Triassic-early Jurassic times commenced with a major transgression of the Tethys Sea and the establishment of a broad, open-marine shelf sea that occupied much of southern Germany, the Paris Basin, the Celtic Sea-Western Approaches region, the Irish Sea, the southern and central North Sea, Denmark and northern Germany. The open marine seas, producing mudstone, shale and minor limestone in the more westerly parts of Europe, also had a clastic input from the EEC into the Northwest European Basin. The middle and late Jurassic evolution of western and central Europe was dominated by crustal extension across the north Atlantic rift system accompanied by a changing regional stress pattern, which caused important changes to the palaeogeography. Various factors such as a changing stress regime, and the collapse of the North Sea rift dome, resulted in changes to the shape of basins and their sources of clastic detritus.

The early Cretaceous development of Europe continued to be dominated by crustal extension, associated with the north Atlantic rift system, with few changes in structural framework and on basin development. On a larger scale, tectonic activity increased at the Jurassic-Cretaceous transition.

The Alpine Orogen

Pre-Alpine basement rocks of Caledonian and Variscan and Hercynian age outcrop in scattered areas of the Alps, and are most abundant in central Europe, where high grade crystalline rocks are exposed north of the extensive uplift and erosion caused by the Alpine orogeny. The basement rocks comprise a mixture of pre-Variscan basement, Late-Variscan granitoids associated with clastic and volcaniclastic rocks, and post-Variscan volcaniclastic rocks. Data from the Alps indicate that there were at least two distinct major episodes of tectonic activity, one during the Cretaceous and a later one in the Tertiary. This second, and later phase of Tertiary convergence, results from N-S to NNE-SSW directed plate motions between Europe and Africa in the Eocene, and NW-SE directed motions in the Miocene. To the north of the Alps, a foreland basin had developed in late Eocene times, its depocentre migrating northward in response to loading and flexure of the lithosphere caused by the continental collision of Europe and Africa. To the south of the Alps, in the Po Basin of Italy, a foredeep in which syntectonic sediments accumulated was linked to the south-vergent thrusting in the southern Alps. In the western and eastern Alps, the rotating WNW motion of the Adriatic microplate was associated with transcurrent faulting. The late stages of the collision, produced spectacular large-scale backfolds in the Penninic nappes of the central Alps, movements related to a wedge of Adriatic crust, which was forced into the European crust. Shortening of the entire south Alpine fold- and thrust belt is of the order of 70-115 km. The latest movements of the collision reflect the north-westwards motion of the African plate relative to Europe, giving rise to a complex pattern of earth movement reflecting convergence.

The Alps continue to be affected by a crustal stress regime, associated with crustal thickening, although in the central Alps rising topography is already counterbalanced by the beginnings of extensional collapse tectonics. Fold belts at the Alpine northern front of the Alpine belt record the latest supracrustal trace of the Europe-vergent collisional suture, which intersects the Moho a short distance north of the Alpine south front. The latter is a south-vergent back thrust antithetic to the collision suture. In contrast, the Apennines were undergoing extension with mid-crustal and deeper detachments and metamorphic core complexes, and the formation of new oceanic crust within the main body of the orogen.

The cratonic Adriatic microplate is the foreland of both the Alpine and Apennine orogens, and has been part of the transtensional zone between Europe and Africa since Jurassic times, when the Atlantic opening reactivated the east-facing Tethyan passive margin. The microplate is now buried deep beneath the cover of Mesozoic sediments, and Neogene clastic foredeep fill, shed from the rising Alps and Apennines. South Alpine thrusting occurred during Palaeogene, Miocene, and Plio-Pleistocene events. More recently, thrust tectonics have been reflected by devastating earthquakes for example the 1,976 AD earthquake near Gerona, and possibly in 1,348 AD near Villach. Beneath the southern Alps, some of the most recent interpretations, based on deep seismic data and geology, indicate an emplaced thrust sheet involving 10 km of pre-tectonised crust intruded by arc magma, overlain by 5-7 km of Mesozoic passive margin sediments, and 3-7 km of Oligocene to Pleistocene foredeep fill. Its frontal part is a blind thrust within the Miocene section and its foreland imbrications, a zone that includes many of Italy's major oil and gas fields.

During the Neogene and Quaternary the convergence direction between Eurasia and Africa-Arabia gradually changed, and was dominated by dextral translations. This was coupled with the development of intra-Alpine shear systems, the concentration of crustal shortening to the Western Alps and the Eastern Carpathians, and the subsidence of the Pannonian Basin (Ziegler 1988, 1990). Neogene and Quaternary sediments exceed a thickness of 4 km in the deeper parts of the Pannonian Basin, and locally reach 7 km in the deepest grabens. At present, the Pannonian Basin is still seismically active and continues to subside (Sclater *et al.* 1980, Royden *et al.* 1982, Horváth *et al.* 1986, 1988).

The tensional subsidence of the Neogene Pannonian Basin, and also the Aegean back-arc basin, both of which developed during the Late Alpine orogenic cycle, was associated with major wrench deformations and important crustal shortening in the related arc systems. These deformations are, to a large extent, the expression of changes in the convergence direction between the colliding continents, and also of indent effects and ensuing "escape tectonics" (Ziegler 1988, 1990).

Caenozoic Volcanic Activity

Early Tertiary volcanics, associated with the splitting of the Atlantic Ocean, extend from east Greenland to the Hebrides, to the coast of Portugal and to Morocco. Other volcanic 'hot spots', decreasing in age from south to north and west to east, extend from the Faroe Islands to Iceland, and from Wroclaw in Poland to the Eifel Mountains in Germany respectively (Duncan *et al.* 1972, Ager 1975, 1980). Caenozoic volcanics also occur in the Central Massif of France, Catalonia, La Mancha, Almeria, Alboran and Canary Islands in Spain, the Carpatho-Pannonian region, and the volcanic provinces of Italy (Figure 3) and Greece (Figure 4).

Caenozoic volcanism in the Carpatho-Pannonian Region

Tertiary to Quaternary volcanicity is closely connected to the structural evolution of the Carpathian arc and Pannonian Basin. Subduction of the flysch basin floor in the convex front side of the Carpathian arc commenced in early Miocene in the west, and was concluded during Pliocene to Quaternary in the east. A subduction rollback was compensated by a coeval back-arc extension in the Pannonian Basin.

During late early Miocene, the Pannonian Basin began to subside under a transtensional setting on top of the Carpathians and East Alpine nappes (Royden and Horváth 1988, Ziegler 1990, Lexa and Konečný 1998). The Oligocene-earliest Miocene diastrophism was of major importance in the western Carpathians, and exceeded by far the intensity of intra-Miocene compressional movements (Brix *et al.* 1977, Kröll 1980, Wessely 1987). Following the Oligocene-early Miocene diastrophism of the northern Carpathians and the Dinarides, the area of the Pannonian Basin was uplifted, and its central and north-eastern parts became sites of extensive silicic volcanism of high-potassium calc-alkaline affinity (early to middle Miocene), giving rise to extensive dacitic to rhyolitic ignimbrite, tuff and reworked tuff, which were subsequently covered by younger sedimentary rocks (Lexa and Konečný 1998).

Middle to late Miocene intermediate volcanism of medium to high-potassium calc-alkaline affinity in the back-arc setting (central Slovakia, northern Hungary, Apuseni Mountains in Romania), produced andesitic stratovolcanoes, including differentiated rocks, subvolcanic intrusions, rare late stage rhyolite, and epithermal mineralisation. Middle Miocene to Pleistocene intermediate volcanism of the same affinity in the arc setting (eastern Carpathians) has given rise to mostly basaltic andesite, andesite stratovolcanoes, and/or small subvolcanic intrusions with rare differentiated rocks. Sporadic Pliocene to Quaternary alkaline basalt volcanism produced, in the western and northern parts of the Pannonian Basin, volcanic fields with lava flows, scoria cones, maars and diatremes (Horváth and Berkhemer 1982, Stegena and Horváth 1982, Royden and Horváth 1988, Póka 1988, Ziegler 1990, Lexa and Konečný 1998).

The change from calc-alkaline to alkaline basaltic volcanism followed the termination of crustal shortening in the northern and eastern Carpathians. Thus, it could be envisaged that steepening of the Carpathian subduction zone may have contributed towards the further development of upwelling mantle currents in the Pannonian back-area (Royden and Horváth 1988, Ziegler 1990). The Plio-Pleistocene decay of the west-dipping Carpathian subduction system was accompanied by alkaline volcanism, and only limited back-arc extension (Horváth and Royden 1981, Royden 1988, Ziegler 1990). Therefore, development of the Pannonian Basin can be directly related to changes in the convergence direction of Europe and Africa-Arabia.

Caenozoic volcanism of the European Rift System

The Tertiary to Quaternary volcanicity of the European Rift System (Massif Central and Auvergne in France, Rhine Graben and Eifel in Germany, Eger Graben in Bohemia) is characterised by mostly volcanic fields of tefrite, basanite, alkali basalt and/or hawaiite lava flows, scoria cones, maars and diatremes, in a lesser extent trachyte and phonolite extrusive domes, rare tholeiitic basalt stratovolcanoes.

Tertiary British Volcanic Province

Volcanic activity in the British Volcanic Province is related to rifting and the opening of the northern Atlantic. It consists of mostly alkaline to tholeiitic plateau basalt (icelandite, hawaiite, mugearite), and gabbro/granite subvolcanic intrusive complexes. Tertiary volcanics occur in northern Ireland and north-western Scotland, basaltic lava flows (*e.g.*, the Giant's Causeway and the northern part of the isle of Skye) are associated with northwest–southeast-trending basaltic dykes and many plutonic complexes. The dykes extend south-eastwards across northern England and continue under the North Sea.

Seismic and volcanic activity in the Eastern Mediterranean region of Italy and Greece

At the present time, tectonic activity in the eastern Mediterranean is related to the northward movement of the African and Arabian plates against the Eurasian and Anatolian plates, reflected by intense seismicity and volcanic activity in Italy and Greece (Figure 2).

Deep-focus earthquakes that originate at depths greater than 100 km coincide with the northward dipping African plate, where it is being subducted into the mantle beneath the overriding Eurasian plate. Shallow-focus earthquakes are the most destructive, in terms of loss of life and damage to human infrastructure, and are normally generated in the vicinity of divergent boundaries.

Within Greece and neighbouring countries, over two and a half thousand earthquakes with magnitudes of 5 to 8.3 M_w have occurred between 550 BC to 1999 AD. One of the most destructive earthquakes that affected the Eastern Mediterranean happened on the 21st July 365 AD on the island of Crete, and uplifted its western part by up to nine metres (Guidoboni *et al.* 1994, Drakos and Stiros 2001). Its magnitude is estimated to have been 8.5-8.7 on the Richter scale.

Caenozoic volcanism in Italy

Italian volcanism is related to the structural evolution of the Tyrrhenian Sea, which comprises

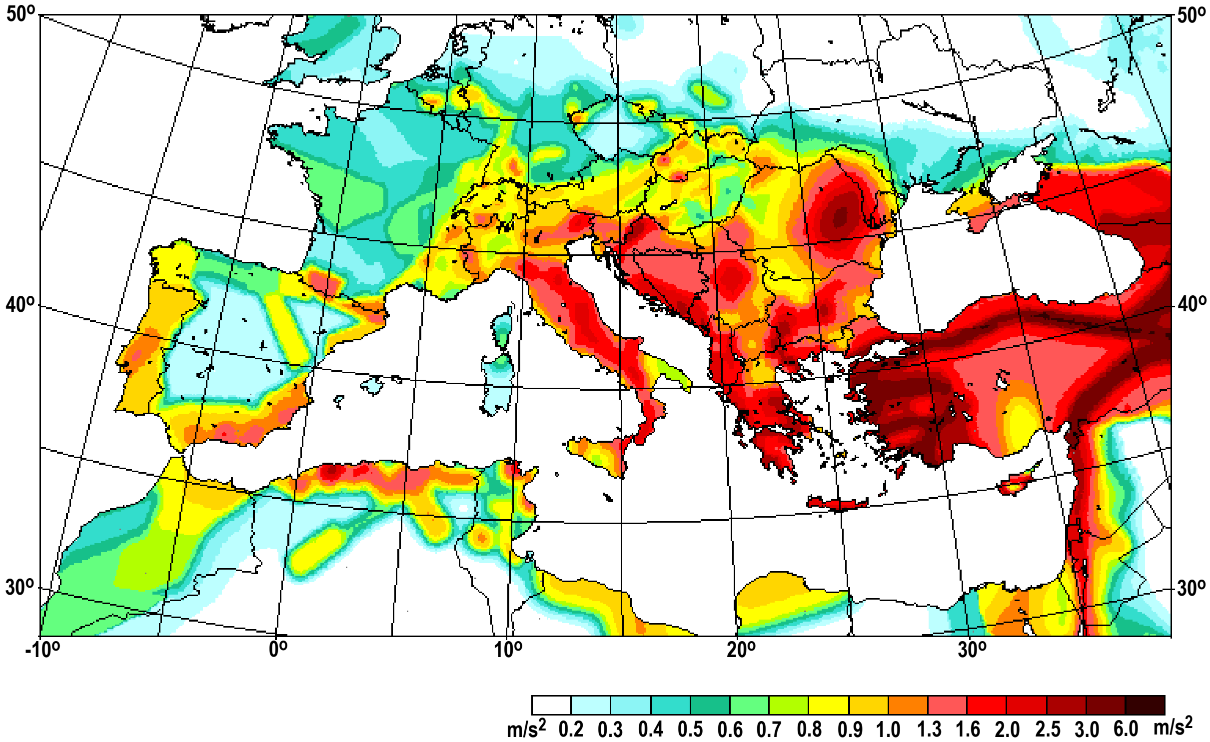

Figure 2. Horizontal Peak Ground Acceleration seismic hazard map for the Mediterranean region, representing stiff site conditions for an exceedance or occurrence rate of 10% within 50 years. Major damage occurs when ground acceleration exceeds 2 m s^{-2} (light orange to brown), which is about 20% of the acceleration of gravity (from Grünthal *et al.* 1999, Fig. 4).

two small extensional basins floored by oceanic crust. Extension began in the Late Tortonian at the Sardinia margin, and propagated eastwards reaching the Marsili basin in the Pleistocene.

Oligocene-Miocene calc-alkaline volcanism is thought to reflect the NW subduction of the leading edge of the African plate beneath the European palaeomargin, which opened the Balearic Provencal basin and rotated the Sardinia-Corsica block anti-clockwise. Volcanism, related to this subduction, migrated eastwards from the Oligocene-Early Miocene arc of Sardinia to the Aeolian Islands in the Pleistocene arc.

Pliocene-Quaternary magmatism, in central and southern Italy, generated a large variety of rock types ranging from mafic to acid, tholeiitic to calc-alkaline, Na- and K-alkaline and ultra-alkaline, in a volcanic belt that extends from Tuscany in the north, to the Southern Tyrrhenian Sea and Sicily in the south.

Recent studies indicated a complex geotectonic setting, comprising at least seven compositionally distinct magmatic provinces (Peccerillo and Panza 1999) (Figure 3).

The Tuscany province consists of both mafic and acid rocks. Acid rocks are either of crustal anatectic origin or, more commonly, reflect mixing of crustal and various mantle derived melts. Mafic rocks have lamproitic and shoshonitic-potassic-calk-alkaline affinity (Peccerillo 2003).

To the South, *The Roman province* comprises potassic and high-potassium rock series (HKS) with varying degrees of evolution.

The Umbria ultra-alkaline province comprises small centres of ultrapotassic olivine melilite, associated with carbonate-rich pyroclastic rocks, which have been suggested to represent carbonatitic magmas (Stoppa and Wolley 1997).

The Ernici-Roccamonfina province displays characteristics transitional between the Roman and Neapolitan provinces, and is characterised by the close association of potassic and high potassium magma; the former rocks display incompatible trace element contents, and Sr-Nd isotopic signatures close to those of the Neapolitan volcanoes, whereas the latter resemble Roman HKS rocks.

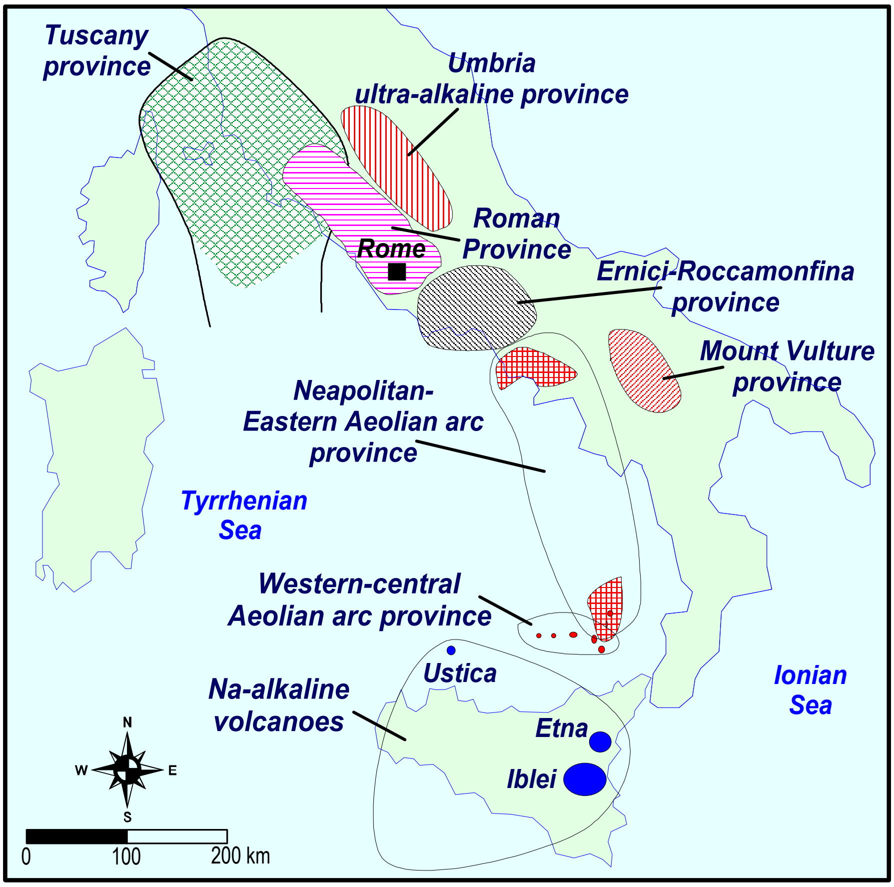

Figure 3. Caenozoic volcanic provinces in Italy.

The Neapolitan province is characterised mainly by ignimbrites and alkaline rocks of Campi Flegrei and Vesuvius (Ayuso *et al.* 1998, De Vivo *et al.* 2001). Their composition varies from potassic to high potassic, though calc-alkaline rocks. The mafic volcanic rocks have trace element ratios, and isotope trends, comparable with those of Stromboli in the eastern Aeolian arc and Vesuvius, and other Neapolitan volcanoes are thought to represent the northern extension of the Aeolian arc (Peccerillo 2001a).

The Aeolian arc province comprises the western sector, predominantly calk-alkaline, with rocks typical of island arcs and the eastern Aeolian arc, including Stromboli, comprising rocks ranging from calc-alkaline to shoshonitic and potassic composition, similar to those of the Neapolitan volcanoes (Peccerillo 2001b).

Mount Vulture lies to the east of Vesuvius, in the southern Apennines and comprises alkaline rocks enriched in Na and K. Recently erupted magmas have been interpreted as carbonatite (Stoppa and Wholley 1997).

The Na-alkaline volcanoes of Etna, Iblei, Ustica and the Sicily channel (Linosa, Pantelleria) form a distinct magmatic province, of typical

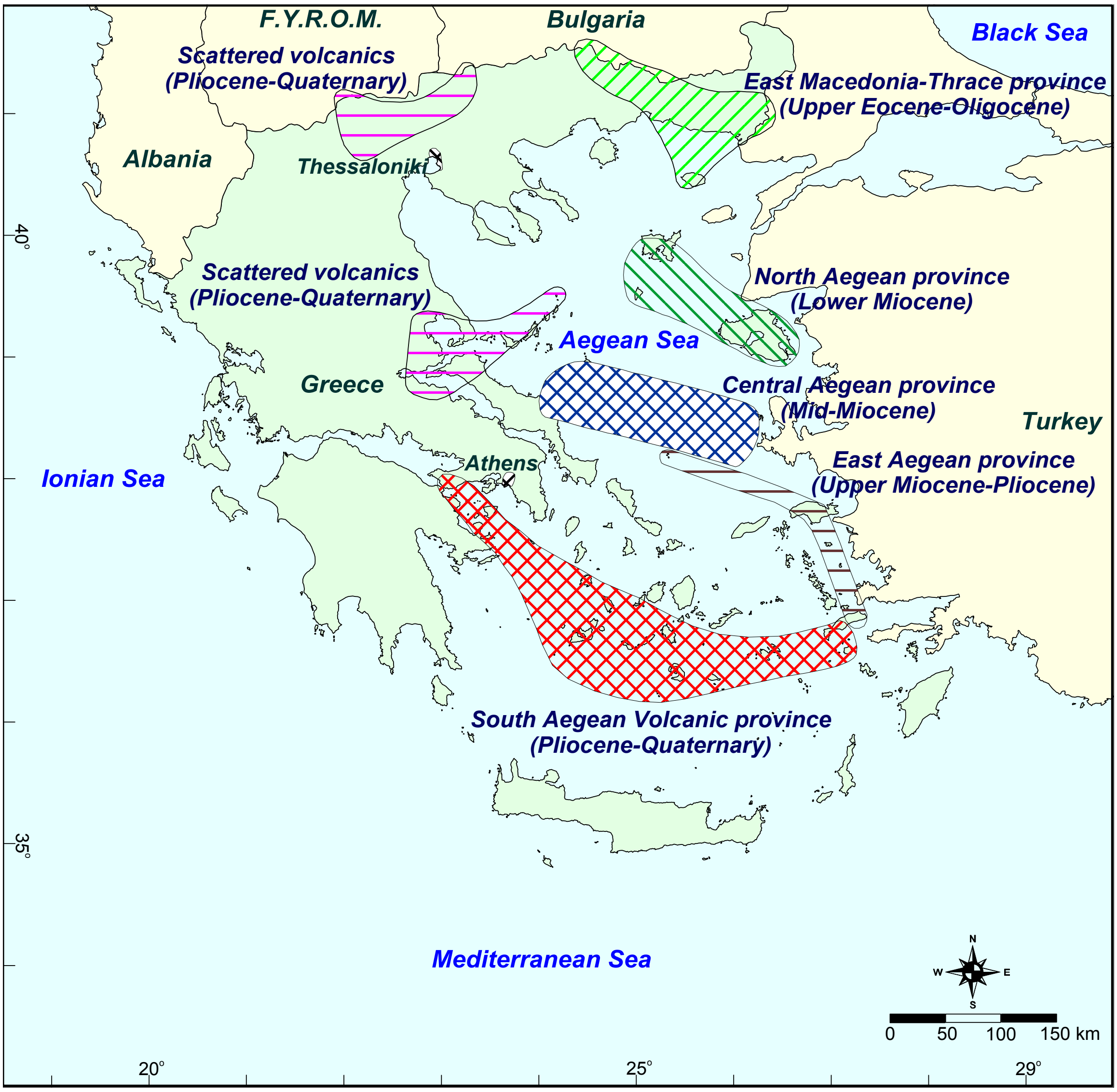

Figure 4. Caenozoic volcanic provinces in Greece. The classification is based on geotectonic setting, composition and age of volcanic rocks. NATF, North Anatolian Transform Fault (modified from Vougioukalakis 2002, Fig. 3.1, p.64).

intraplate geochemical affinity, although some arc-related signatures are recognised at Etna and Ustica (Cristofolini *et al.* 1987).

Caenozoic volcanism in Greece

In Greece, five volcanic provinces are distinguished (Pe-Piper and Piper 2002, Vougioukalakis 2002), based on age, setting and composition, as well as a scattered volcanics province (Figure 4).

The East Macedonia-Thrace province (Upper Eocene to Oligocene), comprises lava domes and flows, and extensive large ignimbrite sheets, with a trend in K_2O enrichment as the volcanicity migrated southwards. Calc-alkaline to shoshonitic volcanic rocks consist of intermediate to high-K felsic rocks, typical of the orogenic series of active continental margins. Basalt is absent, and the most mafic rock is basaltic andesite.

The North Aegean (Lower Miocene) province comprises mainly of intermediate calc-alkaline to shoshonitic volcanic rocks, typical of active continental subduction belts, except that they are overall lower in MgO.

Central Aegean (Mid-Miocene) province, comprising of high Mg-andesite, shoshonite and K-alkaline rocks occurring at small monogenic centres (lava domes), which are postulated to be associated with a divergent boundary between the Aegean microplate and the Anatolian plate.

East Aegean (Upper Miocene to Pliocene) province occupies the eastern Aegean, where the volcanic rocks range from K-Na to K- and Na-alkaline rocks. Sodic-alkaline basalt is the dominant rock type of Upper Miocene and Pliocene volcanicity. Upper Miocene trachytic rocks occur as lava flows and domes, as well as pyroclastic rocks, and range from shoshonite to rhyolite. Geochemically, they have higher total alkalis than similar rocks of the Scattered volcanics province of north-central Greece.

South Aegean (Pliocene-Quaternary) volcanic arc province extends from the Greek mainland to the islands south of Athens, through the south-central Aegean to the far eastern part of the Aegean Sea. It includes the famous volcano of Santorini, which is still active. The explosive eruption of this volcano in *c.*1500 BC is thought to have been of similar intensity to that of Krakatoa (Indonesia) in 1883 AD, with the volcanic ash found in coastal sites as far away as Israel and Anatolia. The calc-alkaline rocks are typical of island arcs, and range in composition from basalt to rhyolite.

The Scattered (Pliocene-Quaternary) volcanics are similar in age to those of the South Aegean volcanic arc province, but have a different geotectonic setting and composition, which is similar to the rocks of the Italian Roman province. They are found in northern-central Macedonia and central-eastern Greece. Their composition ranges from high potassium calc-alkaline to mafic shoshonitic rocks, with sodic alkaline basalt of Quaternary age locally. The central-eastern Greek volcanics are located on the Aegean extension of the North Anatolian Transform Fault zone.

Superficial Deposits

Geologically recent deposits, often referred to as Superficial deposits or ‘Drift’, cover most of Europe. They range from soils and weathered bedrock to sediments of fluvial, lacustrine, glacial, aeolian, coastal, estuarine and marsh origin, thought to be deposited during the last 2.4 Ma – the Quaternary Period. This is the latest period of the Caenozoic Era, and comprises two grossly unequal epochs, namely the Plio-Pleistocene (2.4 Ma to 10 ka BP) and the Holocene (10 ka BP to the present day).

The Quaternary Period was distinctively a time of frequent and marked climatic oscillations, where the colder periods exhibited mean annual air temperatures well below $0^{\circ}C$. Unfortunately, most terrestrial evidence for the majority of some 25 such glacial cycles, recognised in marine sediments, has been destroyed by subsequent events. The surviving geomorphological and stratigraphical record is usually restricted to deposits of the main *glacial* events, which each had particular geographical limits (see Figure 5). During intervening warm episodes (*interglacials*), when temperatures not unlike those of the present day prevailed, ice sheets retreated or disappeared, leaving characteristic depositional landforms and interglacial sediments.

European glacial advances generally spread outwards from the Fennoscandian shield. These were thick ice sheets, which, as they expanded, locked away large amounts of water so that global sea level fell, and land bridges appeared, linking most major land areas and present-day islands, into a single continental land mass. At the last glacial maximum, when the centre of the Weichselian ice-sheet was an estimated 2.5 km thick, sea level fell by over 120 m exposing the continental shelf (now about 90 m below sea level).

In the Fennoscandian heartland, glacial scouring cut deep valleys and laid down thick, often complex, interbedded sequences of clay, boulders, sand and gravel and wind-blown sand and dust (*loess*). In front of the advancing ice

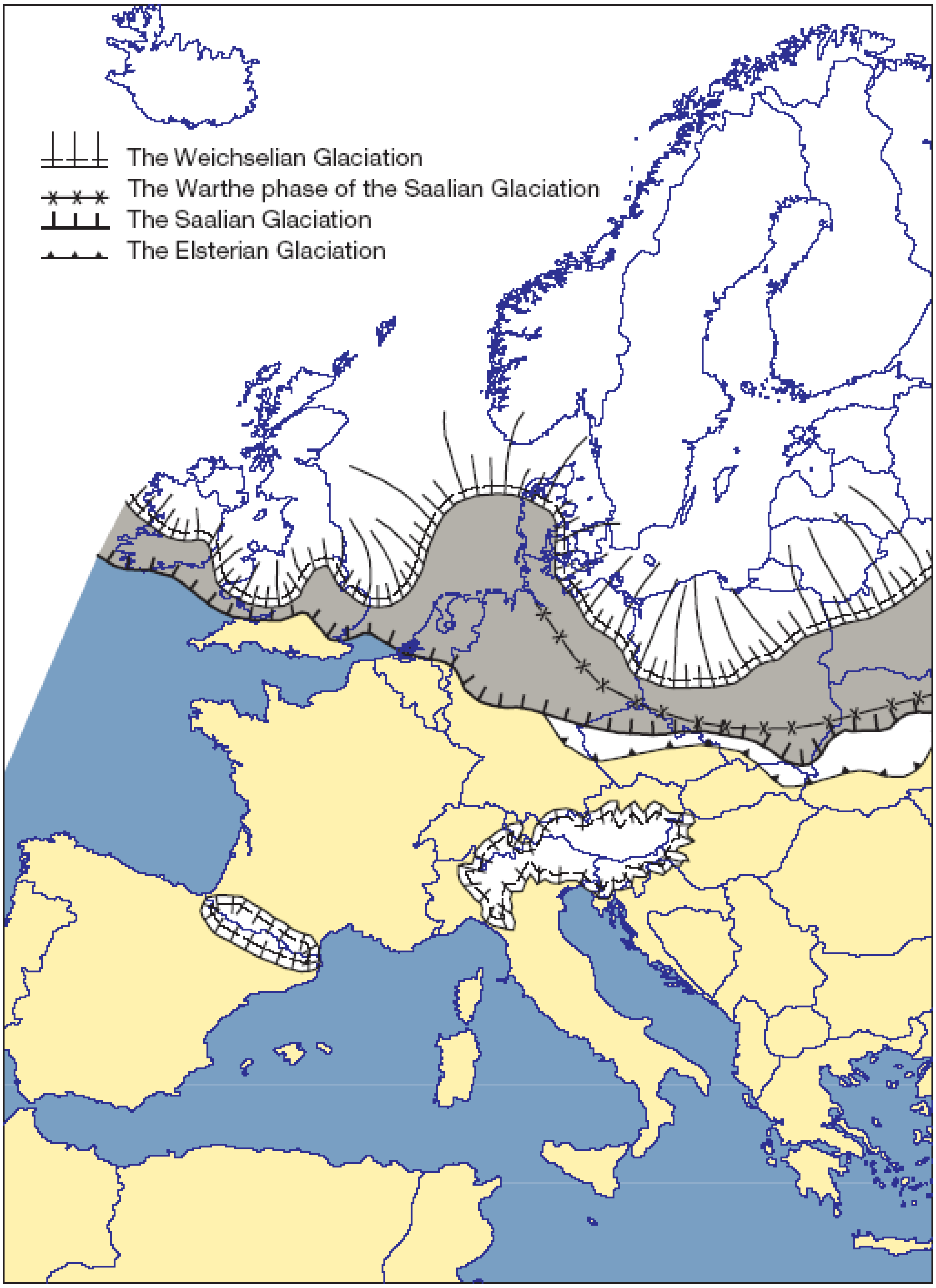

Figure 5. Maximum extent of the European ice sheets: the Weichselian Glaciation, the Warthe phase of the Saalian Glaciation, the Saalian Glaciation, and the Elsterian Glaciation (from Anderson and Borns 1997, and Plant *et al.*, 2003, Fig. 3, p.B230).

sheets, major rivers were diverted, dammed to form lakes, river terraces were cut and new drainage catchments created. Across vast distances, beyond the ice front, seasonally catastrophic melt-water floods, created extensive outwash plains (*sandbars*) of gravel, sand and silt. Over this ground, which extended to the present-day Mediterranean and beyond, periglacial conditions prevailed, in which cold, but non-glacial processes, such as loess deposition, slope debris flow (*solifluction*), karst development and soil mixing processes (*cryopedogenesis*), produced distinctive landforms and sediments.

During interglacial periods, ice melt and glacial recession led to increased river flow and aggradation, the re-establishment of forests and (after about 1 Ma BP) increased anthropogenic disturbance of the environment. Furthermore, relieved of the weight of land ice, the continental masses slowly rebounded, whilst global sea level rose with the release of water formerly locked up in ice, and marine, climate-influencing cold and warm currents, shifted direction.

These responses, after the last glacial maxima, resulted in the European coastal complex of 'drowned' fjord coastlines, raised beaches and the formation of the Irish Sea, the present North Sea and the English Channel.

After the last glacial maxima, the present day distribution of land and sea was established across Europe, with the development of the Irish and North Seas and English Channel. In some cases,

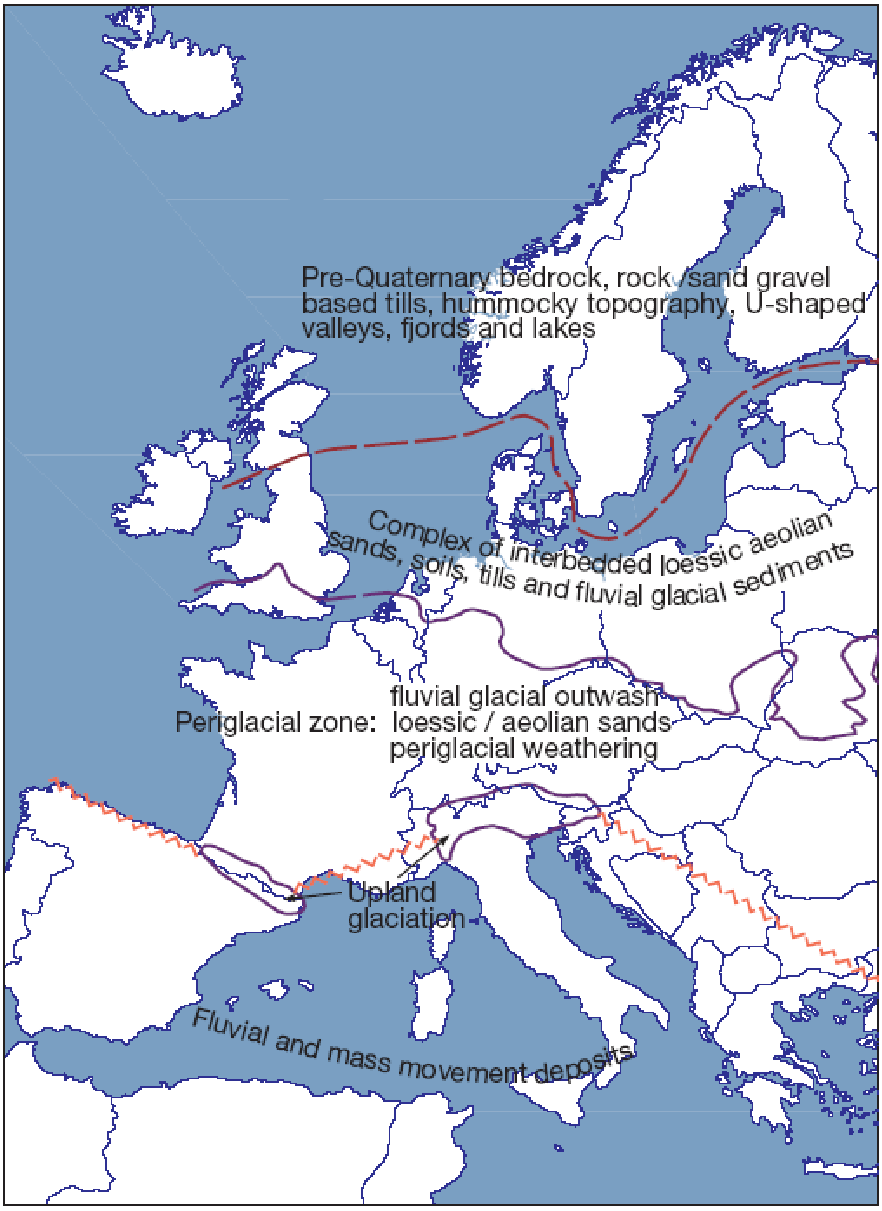

Figure 6. Quaternary domains in Europe (from Plant *et al.*, 2003, Fig. 2, p.B230).

drowned fjords and coastlines formed and elsewhere revised beaches.

At the onset of the Quaternary, the pre-glacial landscape had an existing drainage network, distributing sediments within catchments, which in north-western Europe drained into the proto North Sea basin. During ice advances, notably from the Fennoscandian region southwards, this early fluvial imprint was modified or obliterated and new drainage networks were established. These networks, together with ice transportation, redistributed pre-existing fluvial deposits and mixed them with 'northern' sourced material – the combined glacial, fluvial and Aeolian agencies, transporting this material southward. Finally, since the last glacial phase to the present-day, many of the pre-glacial river courses have been re-established, recycling the deposits yet again.

This chaotic distribution of sediments, resulting from a range of Quaternary, climate-determined processes, may be geographically delimited into four, very broad domains (Figure 6). Essentially, the Fennoscandian region underwent a net loss of material by glacial scouring, whilst much of northwest and central Europe, south to 50^{o}N, experienced a net gain of a complex suite of clays, rock rubble, sand and gravel and loess. South of this latitude, towards the present-day Mediterranean, fluvial outwash sediments and loess, blanket the underlying pre-Quaternary strata. Regionally high ground, such as the Alps, the Pyrenees and the Caucasus Bolshoy Kavkaz range, formed upland glacial centres that locally modified this European setting.

An interpretation of the geochemical data presented in this atlas should take into account two important considerations:

Firstly, Quaternary deposits cover much of 'lowland' Europe mostly obscuring bedrock geology, and that these deposits were in part created by, and certainly transported by, glacio-fluvial and aeolian processes. The consequence of this complex erosional and depositional genesis, is that material from localised mineral sources is highly likely to be dispersed in the direction of net resultant transportation, giving elongate geochemical signature anomalies that extend for considerable distances away from the source area, and potentially 'smearing' geochemical features for considerable distances away from the source area.

The second, and perhaps most important factor to consider, is human changes to the environment as humans migrated northwards across Europe as the climate improved. Subsequently, social development following the mastery of fire, the development of settled agriculture, which has become gradually industrialised, together with industrialisation and urbanisation, have increasingly polluted the environment, leaving a significant anthropogenic geochemical imprint.

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