A BRIEF SUMMARY OF THE TERTIARY-QUATERNARY LANDSCAPE EVOLUTION FOCUSING ON PALAEODRAINAGE SETTLEMENT ON THE EUROPEAN SHIELD

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Introduction

During late Cretaceous, 65 Ma ago, at the maximum transgressive phase, Europe resembled an archipelago, the Protoatlantic Ocean being largely connected with Mesogea. Several islands emerged, the Scandinavian Shield, the Ukraine area, the Rheno-Bohemian Shield, the Armorican and Central Massif in France, the Iberian and Ebro-Corso-Sardinian continent and the Taurus-Pontides chain (Pomerol 1975). More recent studies have demonstrated that marine Cretaceous calcareous sediments (50 to 200 m) covered large areas of the Armorican, Ardennes and Vosges Shields (Wyns and Guillocheau 1999, Laignel *et al.* 1998, Quesnel 1997). Their progressive denudation during the Tertiary and Quaternary led to the deposition of a thick residual weathering mantle of clay with flints. Their geochemistry and fossil content demonstrate that they are autochthonous in origin, at least for the deeper horizon (Macaire 1981, 1984, Quesnel 1997).

These continental areas were located close to the tropical boundary of a palaeoequatorial zone, located near to the southern border of Algeria (Tardy & Roquin 1998). A hot and humid climate produced a thick lateritic ferruginous weathered mantle with kaolinitic–rich saprolite over the continental areas, similar to that existing today in tropical Africa (Migon and Lidmar-Bergström 2001). Over primary aluminous rocks, secondary bauxitic ores were developed, and under erosional processes, their decomposition products (pisolite) accumulated in depressions, like karstic cavities in carbonates, as for example in the Languedoc and Provence regions in France and Parnassos area in Greece (Laville 1981, Carquet 1977, Parron and Guendon 1985, Zachos and Maratos 1973).

At the same time (65 Ma), a worldwide catastrophic event occurred, the fall of a gigantic aerolith west of Mexico peninsula. The fall produced a strong earthquake. Concurrently, ultramafic basalt was extruded at several plate boundaries (flood basalt, diabase, *etc.*) and a short, but very severe, temperature increase led probably to the disappearance of dinosaurs over the whole globe. A geochemical pathfinder of this cosmic event has been recorded worldwide in the Late Cretaceous sediments, a centimetre thick layer enriched in platinum group elements (Pt, Ir).

At the end of the Mesozoic Era, the retreat of the Upper Cretaceous sea defined the primitive river network to the east of Paris. The rivers developed on the Cretaceous marine regression surface retreating to the north. Therefore, the rivers appeared sooner in the south, and later in the north (Le Roux and Harmand 2003).

Concerning the tectonic evolution of Europe, a major change occurred at the beginning of the Caenozoic era, *i.e.*, after the opening of the Atlantic Ocean the Eurasian – North American plate has been affected by a general fragmentation. The main process is a general extensional stretching that produced numerous marginal basins and grabens (Ager 1975, Ziegler 1990).

After this era, and during Early Caenozoic, a lithospheric strain started during the Palaeogene in response to the collisional event between the North African plate moving northwards and the European plate (Wyns 2002). This event led to doming or lithospheric buckling, and near to the plate boundaries, the Alpine-Dinaride mountains were built, and the sea margin moved externally to be confined to the North Sea Graben and the southern Tethys Sea. Most of the continent emerged, and the disappearance of the sea influence induced a general cooling of the climate during the Late Tertiary and Quaternary.

The comparison of Caenozoic continental

facies, and the eustatic records, reveal a correlation between the periods of uplift, leaching and weathering, and between the periods of subsidence, carbonate sedimentation (Wyns 2002).

Central Western Europe

In the Early Tertiary, to begin with, about two thirds of the continent was emerged, and semi-arid conditions prevailed with extensive development of silcrete type covers, and oolitic Fe deposition along the palaeo-shoreline (siderolithic). In Brittany, a major uplift (300 m according to Wyns 2002) occurred between Upper Palaeocene to Middle Miocene.

At the end of the Eocene (about 30 Ma ago), following the Pyrenean compressional event, a crustal stretching occurred and various grabens were opening (Rhine, Rhône, Limagne) and infilled with detrital continental sediments. Lacustrine carbonates are a major component of these sediments.

Since the Miocene period, the sea invades most of the lowlands areas and deposition of fanglomerate in the major river estuaries was widespread (these corresponds to the so called Miocene '*faluns*' in France). In the palaeo-Rhine estuary, a natural dam was built by the fan delta sediments, and an extensive marshy area started to develop that will last until the end of Miocene, producing one of the largest lignite deposits in Europe (Brichle *et al.* 1998).

At the same time, the pre-Alps mountains are being formed with Jura overthrusts, and the rising of Massif Central. This continuous emergence led

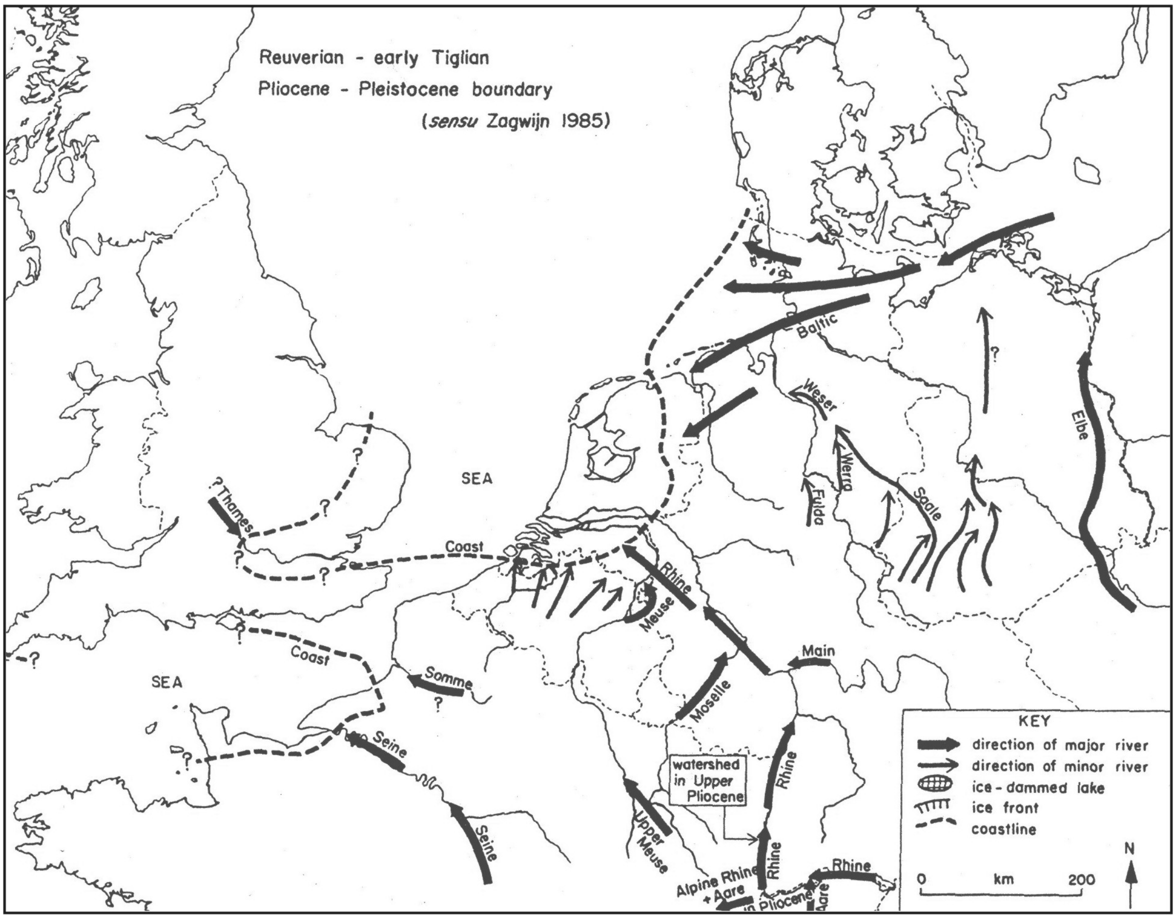

Figure 1 Schematic paleogeographical reconstruction of the major drainage lines during the late Pliocene to early Pleistocene (after Gibbard 1988).

to the development of the early drainage system over the Tertiary palaeosurface. Indeed, in the Cantal area in France, for example, the oldest basalt (11 to 9 Ma BP) filled palaeovalleys that were already incised to a depth of several metres (Dubreuil *et al.* 1995). At the same period, a younger episode of bauxitic alteration occurred in Germany and Ireland (Schwarz 1997), which may be related to a global climatic warming, due to atmospheric CO_2 increase. From 8.5 Ma BP onwards, a drainage pattern existed with a palaeo-Truyère in the west, and a palaeo-Lot to the southern Aubrac volcanic plateau. These systems functioned until the Late Pliocene when stream piracy took place (Dubreuilh *et al.* 1995).

During late Miocene (5.9-5.4 Ma BP, the Messinian period), a major retreat of the sea occurred in the Tethys Basin that could be correlated with an ice cover increase in Northern Europe, and strong evaporation produced more than 2500 m of evaporitic sediments (Orzag-Sperber 2001, Rouchy 1980).

From Pliocene (5 Ma BP), a large lithospheric bending has been observed, with extensive rising, and a concurrent downward cutting of the main valleys in Western Europe. By far, the largest Tertiary basin is the Northwest European Basin, which extends from Poland to the North Sea. These two basins accumulated a huge amount of detrital sediments, more than 3500 m thick according to Gibbard (1988). During Pleistocene, eustatic uplift of the Fennoscandian Shield to the north added detrital influx to the basin. The maximum uplift rate reached 9 m per century in the northern part of the Gulf of Bothnia. (Figure 1).

In France, during the Late Palaeocene (about 2.2 Ma) the palaeo-Loire river was initially flowing northwards, following an ancient Miocene fluvial feature. After the Helvetian period, the Loire valley shifted towards the west, in response to a southwest tilting of the Paris Basin. Regressive erosion of the Helvetian sands, after the retreat of the Falun Sea (Miocene), deepened the riverbed and, lastly, a piracy by the palaeo-Vienne river established the present river pattern (Macaire 1981, 1984). In the upstream valleys of the Loire, for example, in the Allier valley, some high level terraces have been dated as 120,000-140,000 years BP, which are synchronous with the Riss-Würm glaciation (Straffin *et al.* 1999).

Palaeo-weathering sequences, recorded in the Eocene Siderolithic of the Massif Central, show at numerous localities ferrallitic soil sequences overprinted by a later silcrete development (Thiry and Turland 1985). This indicates that after a humid tropical weathering of the Upper Cretaceous peneplain, Central Europe definitely appeared as a dry land.

In Central and Southern Britain, during the Early (1.6 Ma BP) and Middle Pleistocene, two rivers drained the country, the Bytham and the Thames (Figures 1 and 2). For most of Early

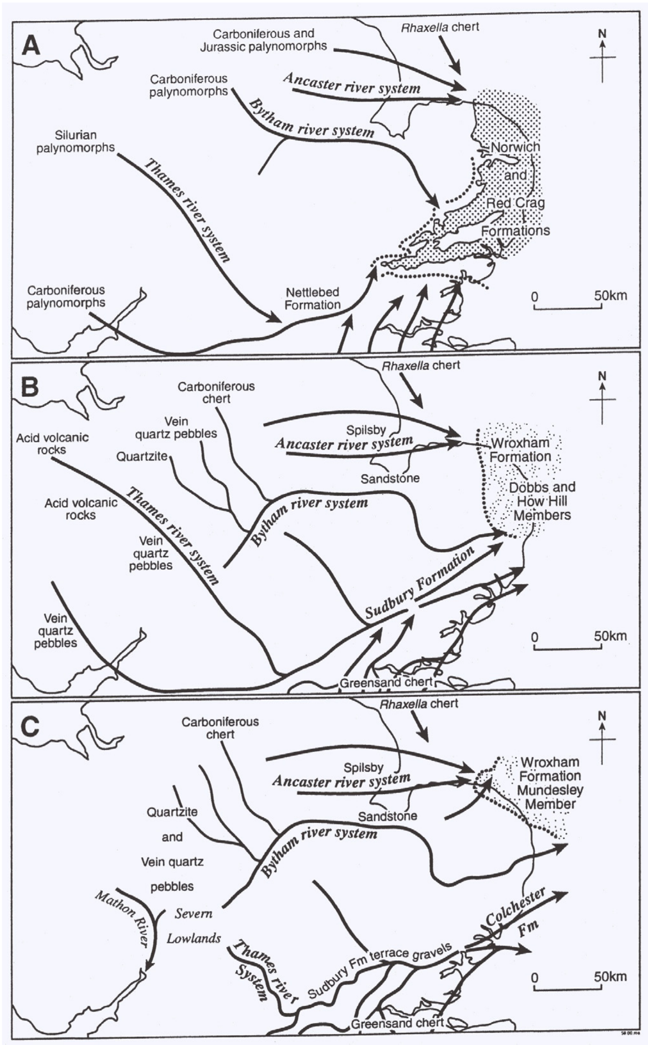

Figure 2. Early Pleistocene and early middle Pleistocene .fluvial and offshore paleogeography of midland and eastern England and the adjacent North sea basin. (After Rose *et al.* 2001).

Pleistocene, the ancestral Thames was the main river with, at its maximal extent, a catchment that extended into Wales, and across East Anglia, and

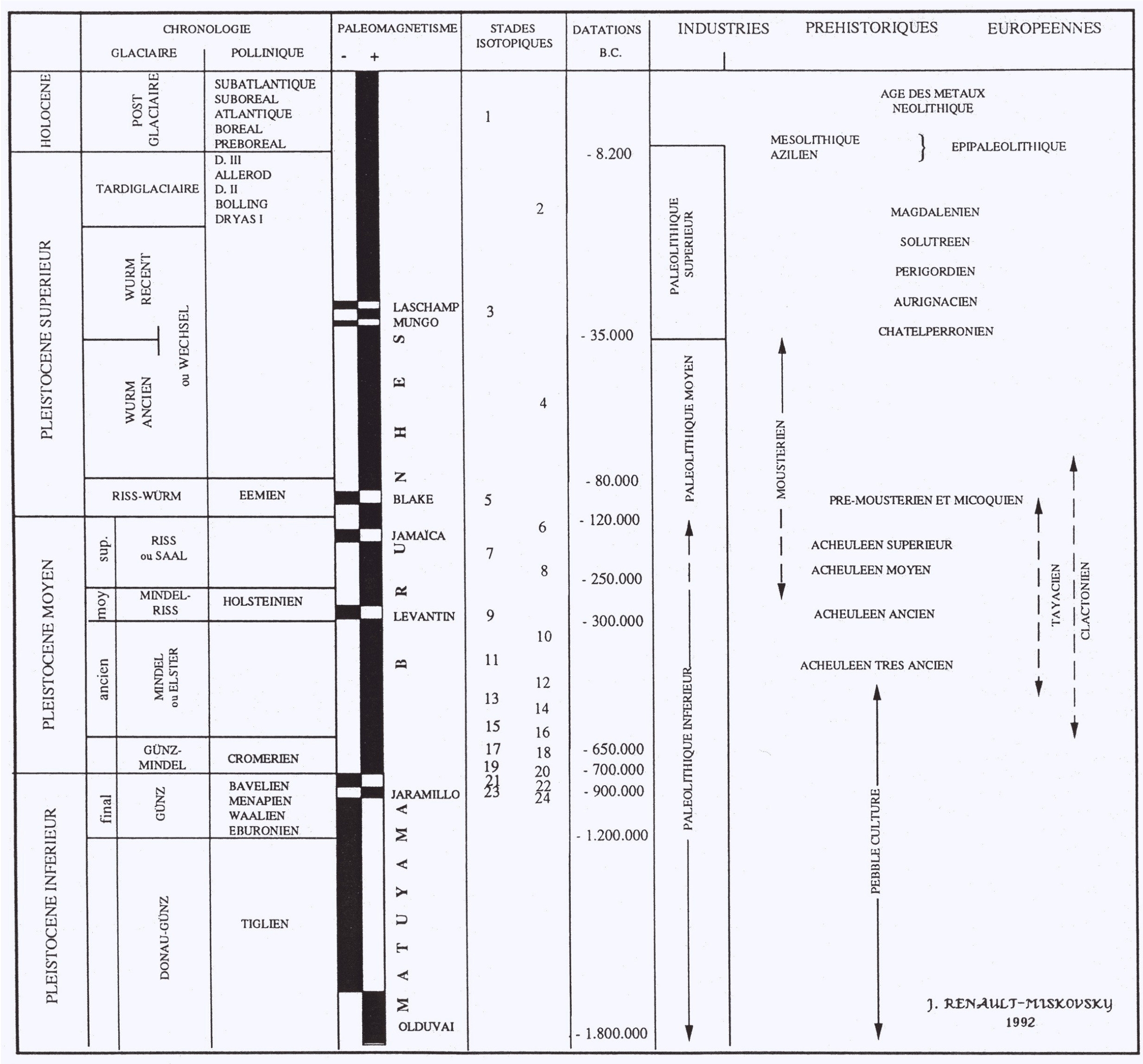

Figure 3. Comparison of various Quaternary stratigraphies: paleomagnetic reversal, isotopic stadium, absolute ages and paleoanthropology. (From Renault-Miskovsky 1982)

what is now the North Sea, to join the ancestral Rhine (Rose 1994). During this period, glaciers of the upland and peripheral mass movement supplied most of the detrital material that was redeposited along the Bytham and Thames valleys. Initially, the Bytham River was a tributary of the Thames, but progressively, extended its catchment and became the major river of Southern Britain. During the Anglian glaciation, the Bytham river disappeared, and the Thames was diverted to its present route to London (Rose 1994). (Figure 2).

According to Gibbard (1988), the river Rhine was formed in Middle Miocene. During the Pliocene, the palaeo-Rhine deposited large quantities of coarse clastic material in the Lower Rhine. In the upper Rhine Graben, the southern Vosges and southern Germany, water flowed southwards to join a pre-Alp river, aligned towards the southwest and joined the palaeo-Rhône system. Uplift of the Jura during the Middle Pliocene forced the Aure to flow to the northwest to join the Rhône tributaries, the Doubs River and a river to the southwest of Bales.

Central Eastern Europe

The Danube River was also formed at this time, its history being linked with Alpine tectonics. Together with the upheaval of the mountain ranges, the foreland depressions originated, and were subsequently infilled with marine and fluvial sediments. Reflecting the regression of the Miocene sea and differential uplift phases, the drainage pattern changed several times. The original stream still flowed west-south-westwards during the Middle Miocene. Due to the upheaval of the mountains, the primary Danube originated, drained the region to the east towards the Pannonian Basin, and further through the Iron Gate into the Black Sea.

During several subsequent development phases, the river basin changed considerably. At first the Danube lost its main-Rhine tributaries, and subsequently also a part of the Saône-Rhône system and finally the Swiss streams (except the Engadine). All these changes took place within Tertiary. Since those times, the Danube Basin remained practically without any change.

The Rhine Graben lies along the extension of the North Sea Graben. It was almost continuously

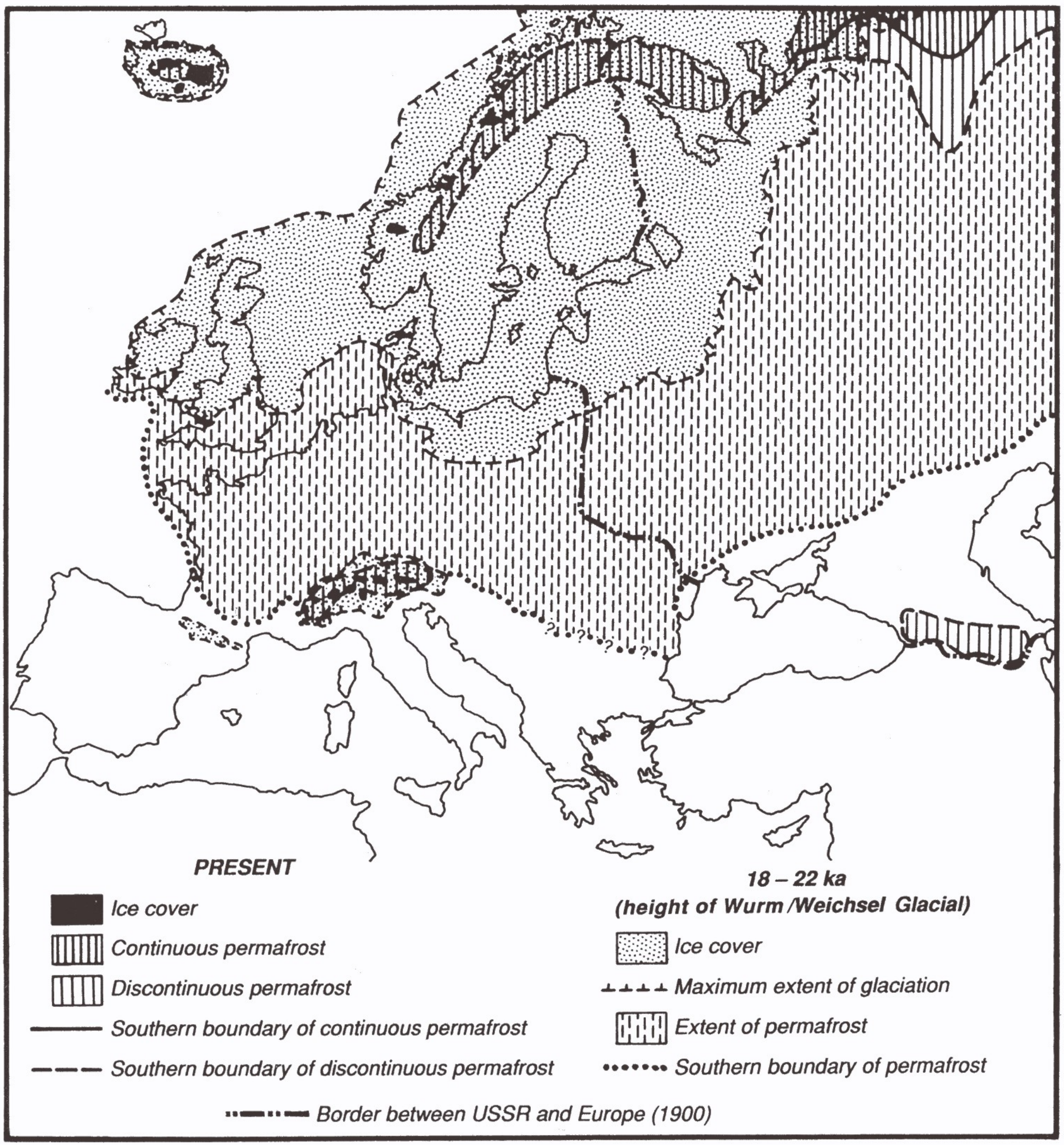

Figure 4. Ice cover and permafrost extensions during the last maximum glaciation. 18,000-22,000 years ago (after Williams *et al*. 1999).

active from Early Tertiary (Eocene) to the present (Fracassi *et al*. 2004). Alkaline volcanism in the Rhine Graben lasted episodically until Holocene. Uplift of the Vosges-Black Forest rift dome isolated the Paris Basin. These effects have a profound impact on the major river courses: to the north, the Baltic river is aligned along the axis of the Northwest European Basin, the central German rivers drain northwards towards this basin, the rivers Thames, Meuse and Rhine drain towards the North Sea Basin, and the Seine drains towards the English Channel and follows a major fracture zone (Figure 1).

During the pertinent phases of Pliocene and Pleistocene, the terrace system developed in the upper sector of the valley from the source as far as Vienna. The slowly sinking Pannonian Basin was gradually infilled with the fluvial sediments of Danube and its tributaries like Morava, Váh, Hron, Tisza, Drava, and Sava. Downstream from the Iron Gate, it was pushed by the Carpathian rivers against the Bulgarian Cretaceous plateau. From Cerna Voda the Danube River flows through the wide valley of Karasu, and the active sinking zone, into the Black Sea, and there builds up an extensive and thick delta sequence.

The rivers in Central and Eastern Europe show similar development in the course of Upper Caenozoic. After the regression of the Cretaceous sea, Central Europe definitely appeared as dry land. During the Upper Caenozoic, it represented an integral part of an extensive mainland, which extended from Central France as far as the western margin of the Russian table. In this elevated part of Central Europe, and in particular the Bohemian Massif, a quite different drainage pattern existed. The southern and eastern parts of the Bohemian Massif drained into the Alpine and Carpathian foredeep respectively. Its remaining part drained into freshwater lakes in the Cheb, Sokolov and Most Basins, where thick lignite seams developed in a marshy environment. The waters from the northern marginal uplands flowed into the German-Polish epicontinental basin.

A new modern drainage pattern developed in Late Pliocene, close to the Gauss-Matuyama (approximately 2.5 Ma BP) palaeomagnetic reversal (Tyráček 2001). Since those times until Holocene, different levels of terraces developed along the upland reaches of Weser, Labe (Elbe), Odra and Wisla rivers. Their fluvial sediments merged due north under the deposits of continental glaciation in the North European lowland (Flachland). The rivers there were forced by the Scandinavian ice-sheet to divert their courses westwards, and to follow its front towards the Atlantic Ocean. The fluvial sediments occurred mostly inside the overdeepened palaeovalleys (urstromtal), and the older drainage network is usually hidden below the younger glacial sediments. During the maximum of the Saale glaciation the meltwaters, together with Odra River, were diverted to the south, and crossed the main European water divide into the Black Sea (Tyráček 1963). The meltwaters from the Russian lobe of the Scandinavian ice sheet in the Dniepr valley (Matoshko and Chugunny 1995) were drained in the same way.

Marine sediments, within the continental sequences, are testimonies of sea ingressions into the lower reaches of the river valleys during the high sea level stands in Pleistocene interglacials.

Iberian Peninsula

In the Iberian Peninsula, a strong contrast exists between the westerly flowing rivers (Atlantic), and the others flowing towards the east or south-east into the Mediterranean Sea. The former have short, deeply incised valleys, whereas the latter have longer, wider, shallower valleys. In the Cantabric Cordillera, the tectonically induced valley pattern is considered as inherited from the alpine uplift. The steep valley gradients, and their strong erosive capacity during the Tertiary-Quaternary, have increased their southwards regressive erosion. Numerous stream captures are recorded at that time for both rivers, Ebro and Duero. These rivers are embanked for their lower part in Palaeozoic terrains, and for their upstream part, in wide Tertiary basins. Their settlement is probably pre-Tertiary, and related to reactivated block faulting. In the Tago River basin, numerous palaeo-terrace levels are known. The climatic factor seems to be the main reason for their development, with little effect from eustatic variations.

In the Mediterranean basin, mainly in the Bettic chain, the Quaternary neotectonic activity plays a major role. A rejuvenation of the Tertiary valleys has led to deep incision with the consequent destruction of the terraces. The present river pattern in this area is, thus, very young, taking into account the various upstream captures.

In the Hercynian and pre-Hercynian shield of the Iberian Peninsula (north-western and western parts), the river network was developed before the Tertiary. For example, in the north-western part of the area the rivers Sil and Mino are clearly overprinted, and transverse the shield structures, a fact indicating a pre-Tertiary settlement. The terrace distribution reflects the common Tertiary Quaternary river pattern. A study of the Veleta cirque in Sierra Nevada, where the southernmost glacier of Europe persisted during the little Ice Age, shows two glacial fluctuations during the Holocene. The morphology of Aguas and Antas valleys has been constructed by climatically induced aggradation of terraces, during the late glacial period, although the last 500 years human influence is noteworthy (Schulte 2002).

In the Late Tertiary, about 2 Ma BP, prehistoric man was living in some caves of southern France (*e.g.*, St Eble le Caput in Velay).

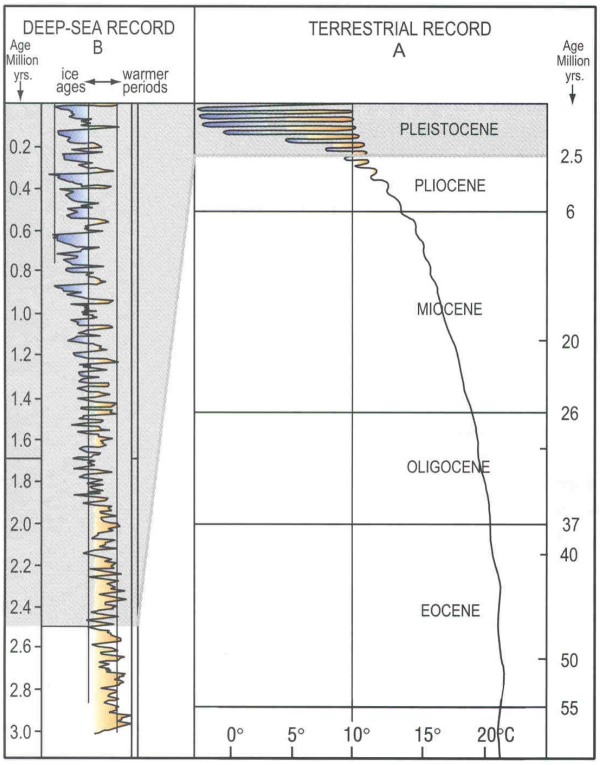

Figure. 5 Col. A: Mean annual temperatures record in central Europe during the Tertiary-Quaternary eras. Col. B: Fluctuation of the deep sea oxygen isotopes during the last 3 Ma and corresponding warm-cold alternations (after Longva and Thorsnes 1997).

During the Late Quaternary, (1.6 Ma BP) ice ages alternate with warm interglacial periods (Figures 3, 5, and 6), and in the second half with a 100,000 to 120,000 year periodicity (Conchon 1992). The events are recorded in the continental sediments, and traced by palynology and oxygen isotope studies. The first method uses the recolonisation of the cold steppe (covered mainly by *herbaceas*) by the oak forest during the interglacial periods (Petit Maire 1992).

Very early, near to the start of the Pleistocene (1.4 Ma BP) a former glacial episode (Eburonian, Figure 4) has been identified, followed one million years later by another cold episode (Menapian). During each ice age, a large volume of water is stored in both polar ice caps, leading to a general lowering of sea level, which has a strong impact on river downcutting. Their remnants are today observed below sea level in the major estuaries. In the meantime, subsidence occurred in the oceanic part, due to overloading by the ice cap (reaching locally three kilometres thickness), which was compensated by a fore-bulge of the continental margin. According to Williams *et al.* (1993), slow mantle migration increases this effect.

The occurrence of high-level river terraces in upstream areas, demonstrates the very important eustatic rising (more than 4000 m in some areas) of the European shield, in response to the strong denudation of rocks.

During the last glacial maximum (Anglian) a large lake formed by the ice dam (Figure 4), and collected the water of major western European rivers (Gibbard 1998).

Low sea levels facilitated the fauna (including man) migration, and the great mammal expansion (wholly rhinoceros, mammoth, etc.), which were well adapted to the cold climate. For example, during the late glacial episode (Würm), it was possible to walk from France to Scotland (Figure 7). At the same period, periglacial wind deposited a thick loess cover over southern England, the northern part of France, Belgium, Netherlands, Germany, and Poland. Solifluction phenomena, permafrost (Figure 4), gelifraction and seasonal flood during summer time accelerated valley down cutting. Major terrace levels along the valleys indicate momentary stops in sea level fluctuations, and lateral meandering developed when the river equilibrium curve was reached

About 100,000 years ago, the major European rivers have established their pattern. Neanderthal man was the only human species at that time. About 40,000 years ago, *Homo sapiens* appears, and progressively invades the Neanderthal habitats. The last species disappears completely approximately 27,000 years ago.

For example, in the northern part of France, the Somme River was developing a braided system (Antoine *et al.* 2000) with a major loess contribution between 18,000 and 14,670 years BP. (Dryas I). At that time, the loess deposition ended, according to a temperature increase, and the river started to meander until 10,000 years BP. An accelerated vertical cutting of the valley occurred around years 12,400 BP. Similarly, estimates of erosion rate in the upstream tributaries of the Loire show a tremendous increase at 14,000 years BP, and during the later 12,000 years (three times higher than in previous periods) due to deforestation by former human settlements (Macaire 1981, 1984). Then a normal erosional process began with erosion of colluvium from the valley walls, previously affected by the periglacial (permafrost, pergelisol) period. In the southern Netherlands, a major change occurred in

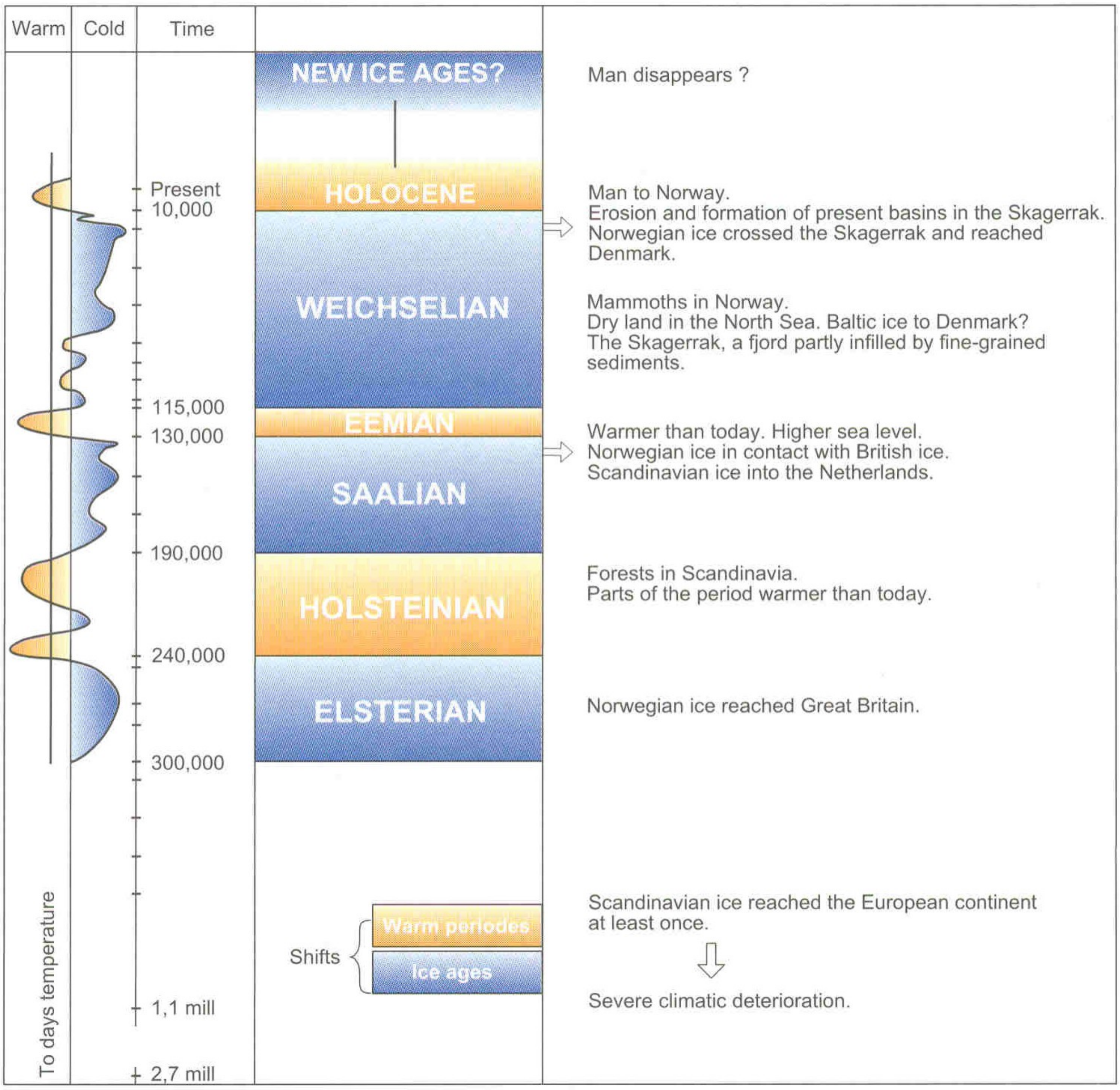

Figure 6. Stratigraphy and climatic variations during the last 2.7 Ma. in Scandinavia (after Longva and Thorsnes 1997).

the valley erosional system at 11,800 years BP (Weichselian): erosion to aggradation with aeolian sand, lacustrine and peat deposits (Starkel *et al.* 1991).

The last maximum glacial period occurred between 21,000 and 17,000 years BP in North America and Europe (Figure 6). At that time, the sea level was about 130 m below the present level! The recent discovery of a prehistoric painted Cosquer cave (dated 14,000 years BP by ^{14}C method) near Marseille (Taborin 2001), entrance of which is located 30 m below the present day level, gives a good example of the low level of the shoreline at that time.

Deglaciation started about 14,500 years ago, releasing vast quantities of water in the oceans. The deglaciation was nearly achieved by 9,500 years BP, leading to the maximum Flandrian sea transgression (Williams *et al.* 1993). After 13,000 years BP, in the Somme valley, there was a first shift in river dynamics, from a braided channel to a multiple channel, and about 10,000 years BP, a second change from a multiple to a single channel, deeply incised and with a lateral deposition of organic rich overbank sediments (Antoine *et al.* 2000).

During the last 10,000 years, a desertification process is recorded, and Saharan dust (clearly indicated in the Pb/Sc peak recorded in a Swiss peat bog (Figure 7) in Europe (Shotyk *et al.* 1998). At the same time, the majority of Alpine rivers had no ice.

About 3000 years ago, our human ancestors started to cut the forest to develop primitive agriculture and pasture, and to initiate the first metallurgy. This led to a sudden increase of the atmospheric lead (Figure 7), and a detrital sediment influx in the valleys, the starting point of another story of the earth's surface geochemistry: the man made pollution and one of its major consequences, the global climatic change!

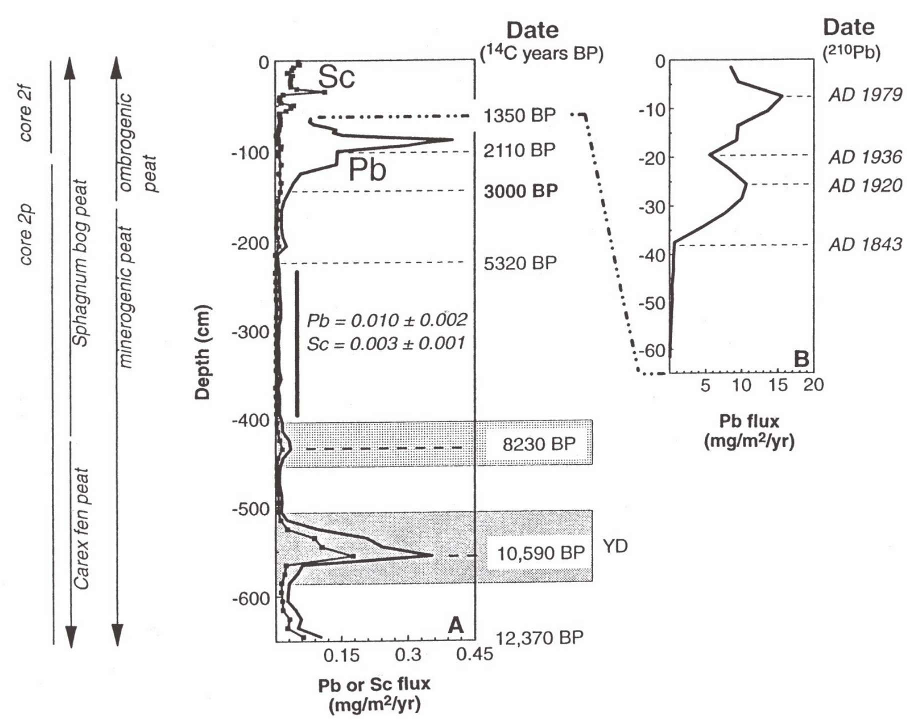

Figure. 7. Rates of athmospheric deposition of Sc and Pb in the EGR peat bog profile (after Shotyk *et al.* 1998).

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