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Modelling Sequential Biosphere Systems under Climate Change for Radioactive Waste Disposal

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Deliverable D2:

Consolidation of Needs of the European Waste Management Agencies and the Regulator of the Consortium

Work package 1: Site-specific and palaeo environmental data

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Foreword

The BIOCLIM project (Modelling Sequential BIOsphere systems under CLIMate change for Radioactive Waste Disposal) is part of the EURATOM fifth European framework programme. The project was launched in October 2000 for a three-year period. The project aims to provide a scientific basis and practical methodology for assessing the possible long-term implications of climate and environmental change on the safety of radioactive waste repositories in deep geological formations. Five work packages have been identified to fulfil the project objectives:

Work package 1 consolidates the needs of the European agencies belonging to the consortium and summarises how environmental change is currently treated in performance assessment.

Work packages 2 and 3 are concerned with the development of two innovative and complementary strategies for representing time series of long term climate change, based on (a) a detailed mechanistic analysis of the regional implications of specific 'snapshots' of projected global climate conditions at selected times (the hierarchical strategy) and (b) empirical downscaling of continuous projections of global climate change over the next glacial-interglacial cycle and beyond (the integrated strategy).

Work package 4 explores and evaluates the potential effects of projected climate change on the nature of biosphere systems associated with identified regions in Europe, taking into account their possible implications for the long-term safety performance of hypothetical radioactive waste disposal systems.

Work package 5 is concerned with the final dissemination of the results obtained from the three-year project among the international community.

The project brings together representatives from European agencies with national responsibilities for the safe management and disposal of radioactive waste, either as waste management agencies or regulators, together with a number of highly experienced climate research teams. The participating organisations and their representatives are listed below.

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- Commissariat à l'Energie Atomique/ Laboratoire des Sciences du Climat et de l'Environnement (CEA/LSCE) France - **N. de Noblet, D. Paillard**
- United Kingdom Nirex Limited (NIREX), UK - **P. Degnan**
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For this deliverable the main contributors are the waste management agencies (Andra, Nirex, GRS, ENRESA, NRI), the regulator (EA) and the consultant company (Enviros QuantiSci). Note that M. C. Thorne and Associates Limited and V. Cilek (Institute of Geology, Czech Republic) also contributed to this document as subcontractors to Nirex and NRI, respectively.

Contents List

Summary

The nature of long-lived radioactive wastes is that they present a radiological hazard over a period of time that is extremely long compared with the timescale over which the engineered protection systems and institutional management of a disposal, or long-term storage, facility can be guaranteed. Safety assessments for potential deep repositories need to be able to provide indicators of safety performance over time periods of hundreds of thousands of years. On such timescales, it is generally assumed that radionuclides may be slowly released from the containment system, migrating via geosphere pathways until they reach the accessible environment. Hence, there is a need to study the evolution of the environment external to the disposal system and the ways in which this might impact on its long-term radiological safety performance, for example in terms of influences on the migration and accumulation of radionuclides.

One method that can contribute to understanding of how the biosphere might change in the future is to develop an awareness of how the characteristics of the region of interest have changed up to the present day as a result of the influences of past climate and environmental changes. It may then be possible to justify the use of environmental conditions that have occurred in the past as indicators of characteristics in the future, according to scientific understanding of the main influences on projected future change over the timescales relevant to the assessment. An important part of the basic understanding that underpins long-term radiological safety assessments is therefore information collected from site characterisation surveys; such data, coupled with palaeoclimate and palaeo-ecological records at regional and global scales, can then be used to reconstruct the progression of past environmental change over periods of time comparable with those of interest to the assessment.

This report summarises work undertaken by national agencies from four European countries (France, Spain, United Kingdom and Czech Republic) to develop site and region-specific descriptions of environmental change during the Quaternary period, with particular emphasis on the last glacial cycle. The data and information collated in this report for three of these countries (France, Spain and the United Kingdom) will be used within BIOCLIM to guide the development of downscaling rules for regional climate characteristics and thereby to provide a basis for linking climate model output to system descriptions required for the purposes long-term safety assessment.

In each case, the description begins with a summary of the present-day characteristics of the regions/sites of interest, categorised under the following headings:

- site location and the geology of the region;
- human communities and land use;
- topography;
- climate;
- lithostratigraphy;
- surface water bodies; and
- biota

These site descriptions are then followed by a detailed presentation of the information base that has enabled palaeo-reconstructions of environmental change to be made within each country. The intention is that, by correlating these reconstructions with the global climate record, it will be possible to develop downscaling procedures that allow the projected effects of future global climate change to be reflected in assumptions about biosphere conditions relevant to long-term radiological safety assessments.

Key outputs from the palaeoenvironmental analysis for each selected region include:

- a narrative description of the sequence of climate change at a regional scale, expressed in terms of simple climate parameters, such as the estimated mean annual temperature, associated with defined time periods.
- associated descriptions of environmental change, taking into account the effects on hydrology, soils and vegetation.
- identification of key environmental properties associated with a range of 'typical' conditions that have prevailed in different regions of Europe during the last glacial-interglacial cycle.

Additionnal information for the Czech Republic has also been summarised for interest and comparison.

Because the information described here has been derived from national programmes in different countries, different approaches have been adopted to the collection of palaeodata and the interpretation of application of such data to long-term safety assessments. One reason for such differences is that fact that national programmes across Europe are at different stages in the implementation of strategic approaches to the identification, investigation and development of suitable candidate sites for deep geological waste repositories. In addition, differences in the palaeohistories of regions across Europe (e.g. whether or not they have been subjected to glaciation) mean that the types of evidence that is available for constructing narratives of environmental evolution up to the present day are not the same. Nevertheless, the information provides a valuable resource to guide understanding of the type, magnitude and rate of environmental change in different regions of Europe over a period of 100 000 years or more.

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1. Introduction

1.1. - Background and Objectives

In many countries throughout the European Union (EU) there are national projects to provide for the safe management of long-lived radioactive wastes. One of the fundamental principles of radioactive waste management is that future generations should be afforded the same protection as those alive today. Containment and isolation are key strategies in ensuring that such standards of protection are achieved; hence, waste management agencies and regulatory bodies are considering the possibility of disposing of high-level and long-lived intermediate-level radioactive wastes, possibly preceded by long-term retrievable storage, in deep geological formations. Such a strategy is intended to protect humans and their environment by isolating the wastes from direct contact and exposure and by minimising the release of radionuclides to the environment.

However, the nature of these wastes is such that they present a radiological hazard over a period of time that is extremely long compared with the timescale over which the engineered protection systems and institutional management of a disposal, or long-term storage, facility can be guaranteed. Safety assessments for potential deep repositories need to be able to provide indicators of safety performance over time periods of hundreds of thousands of years. On such timescales, it is generally assumed that radionuclides may be slowly released from the containment system, migrating via geosphere pathways until they reach the accessible environment. Hence, there is a need to study the evolution of the environment external to the disposal system and the ways in which this might impact on its long-term radiological safety performance, for example in terms of influences on the migration and accumulation and radionuclides.

Although long-term radiological safety assessment should provide for a comprehensive appraisal of all potentially relevant factors, there are limits to the extent that assessment models can be expected to simulate explicitly the various Features, Events and Processes (FEPs) associated with the long-term behaviour of complex environmental systems. One method that can contribute to understanding of how the biosphere might change in the future is to develop an awareness of how the characteristics of the region of interest have changed up to the present day as a result of the influences of past climate and environmental changes. It may then be possible to justify the use of environmental conditions that have occurred in the past as indicators of characteristics in the future, according to scientific understanding of the main influences on projected future change over the timescales relevant to the assessment. An important part of the basic understanding that underpins long-term radiological safety assessments is therefore information collected from site characterisation surveys; such data, coupled with palaeoclimate and palaeo-ecological records at regional and global scales, can then be used to reconstruct the progression of past environmental change over periods of time comparable with those of interest to the assessment.

The objective of this second BIOCLIM report is to provide narrative descriptions of past changes within the biosphere, based on an interpretation of palaeodata relevant to different regions of Europe that are of interest to project participants. The main focus of the study is on three regions, located in eastern France, central/southern Spain and central England. The data and information collated in this report will be used as an input to other Work Packages, including Work Package 3 (e.g. some of the data will be used to guide development of downscaling rules for regional climate characterstics) and Work Package 4 (e.g. linking climate model output to system descriptions required for the purposes long-term safety assessment).

The overall theme of the work described in this report can be illustrated by the link between vegetation patterns and climate. A general scheme for representing vegetation categories at a global scale (based on work described in [Ref. 1]) is illustrated for the two most recent climatic extremes, the Holocene thermal optimum (6 000 ± 1 000 y Before Present) and the last Glacial Maximum (20 000 ± 2 000 y Before Present) in Figure 1-1 and Figure 1-2, respectively.

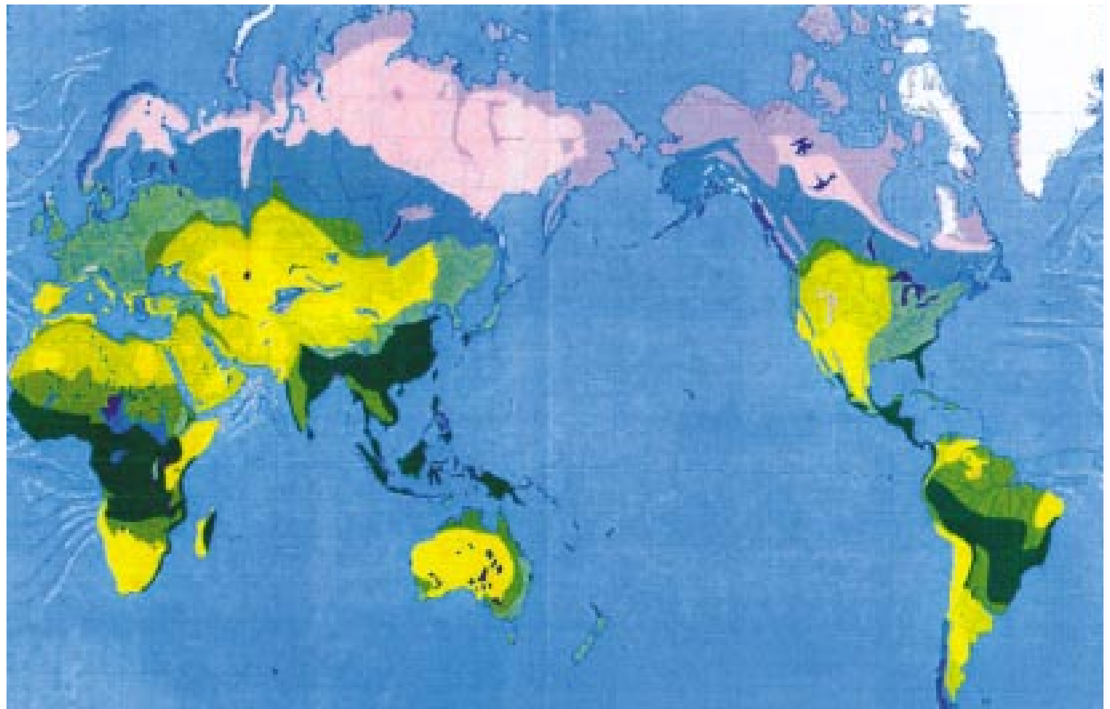

***Figure 1-1**: World vegetation patterns at the Holocene thermal optimum [Ref. 1]*

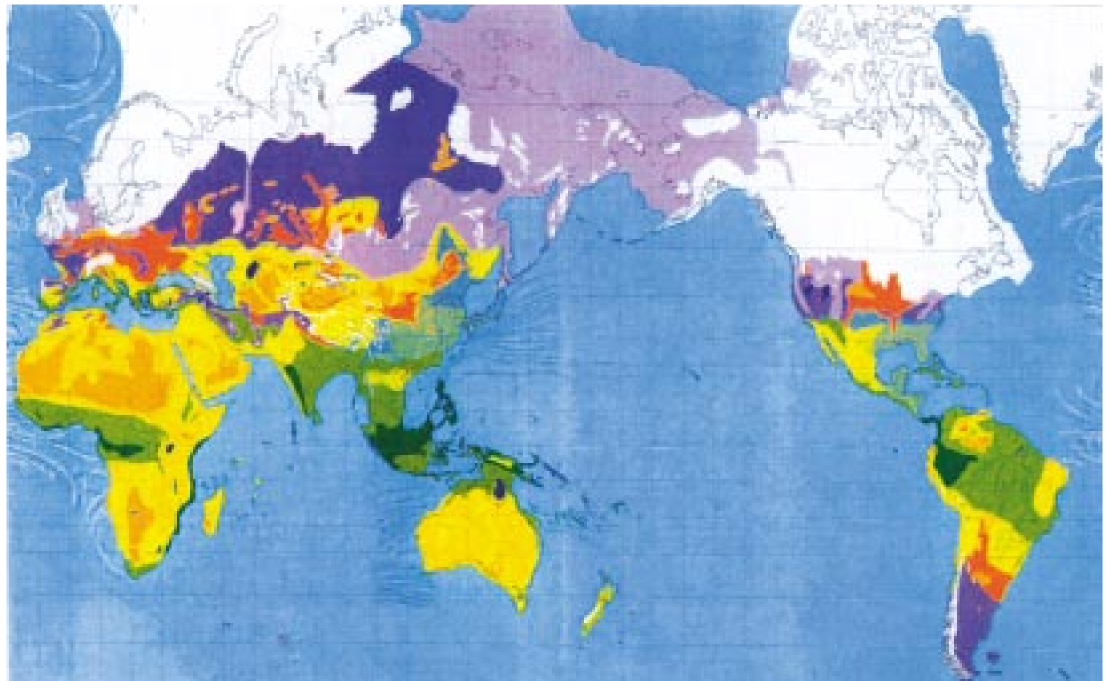

***Figure 1-2**: World vegetation at the Last Glacial Maximum [Ref. 1]*

The legend for these world vegetation maps is shown in Figure 1-3. Although the information is presented somewhat coarsely at a global scale, it is evident that the pattern of variation of vegetation across Europe at the time of the Last Glacial Maximum was substantially different from that at the Holecene thermal optimum. The trends of environmental change in the future are also expected to be different for different sites and regions across Europe.

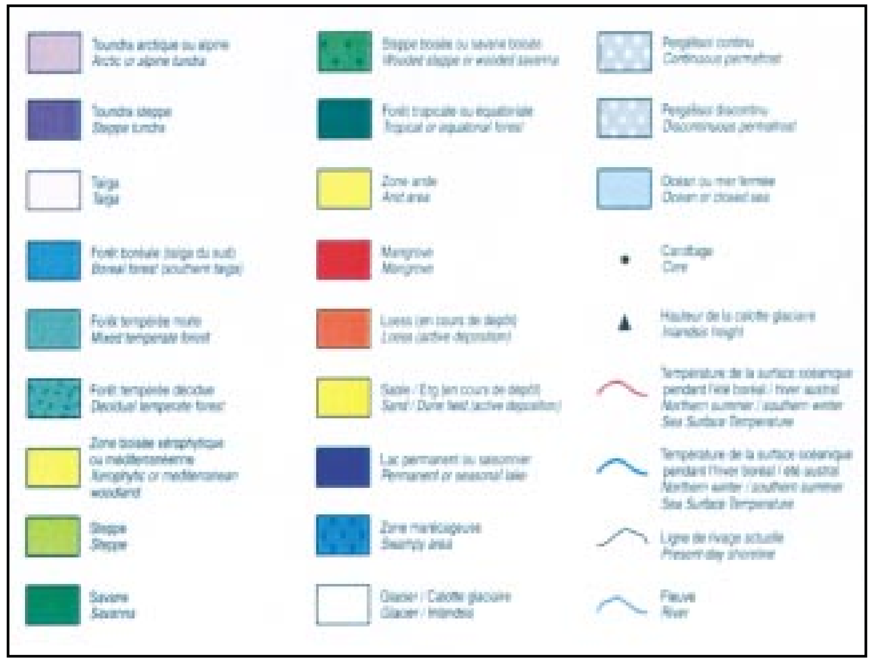

***Figure 1-3**: Legend for Figures 1-1 and 1-2 [Ref. 1]*

1.2. - Approach

The information described in this report has been derived from national programmes in different countries, which have until now adopted different approaches to the collection of palaeodata and the interpretation of such data for long-term safety assessments. One reason for such differences is that national programmes across Europe are at different stages in the implementation of strategic approaches to the identification, investigation and development of suitable candidate sites for deep geological waste repositories. In addition, differences in the palaeohistories of regions across Europe (e.g. whether or not they have been subjected to glaciation) mean that the types of evidence that are available for constructing narratives of environmental evolution up to the present day are not the same.

A variety of different sources of palaeodata has therefore been used as input to this report, and these data have necessarily been interpreted in different ways according to the requirements of particular national programmes. Features of the main contributions to this report (from France, Spain and the United Kingdom), which are to be used in later stages of the BIOCLIM project, include the following:

- France

  The Andra programme for development of a deep geological repository for long-lived radioactive wastes is currently focused on the construction of an underground research laboratory at a specific location, the Meuse/Haute-Marne site, in eastern

France. Consequently, the emphasis in providing site characterisation information has been on using a range of different sources of palaeodata to reconstruct the environmental evolution of a well-defined region. Not all of these data sources correspond directly to the particular location of interest, so interpretation is necessary to translate information obtained from other locations within France, or on a larger spatial scale, into narratives of past change, and projected future evolution, at the Meuse/Haute-Marne site.

- Spain

The ENRESA deep geological repository programme is currently at the stage of conducting generic studies of disposal concepts, with no particular focus on candidate sites, or regions, within the Spanish territory. Nevertheless, in order to test its capability for undertaking long-term radiological safety assessments, ENRESA is conducting investigations into environmental change. Palaeodata have therefore been collected at specific locations in the south and centre of Spain that are believed to be sufficiently representative of wider regional environmental characteristics that they provide a valid basis for the current programme of assessments. Although there is no expectation that these should be considered as candidate repository locations, they are being used within the BIOCLIM project as test cases for development and application of the methodology for describing projections of future biosphere change.

- United Kingdom

The situation in the United Kingdom radioactive waste management programme is similar to that in Spain, in so far as there is no current activity concerned with site selection or investigation in connection with the development of a deep geological repository for long-lived wastes. Unlike both Spain and France, however, the palaeo-environmental record in much of the United Kingdom is strongly affected by the presence of ice sheets during glacial episodes. In the absence of a specific site, reconstruction of environmental change for the purpose of BIOCLIM is being considered on a regional scale. This is based on a range of environmental indicators, but draws specifically on a reconstruction of seasonal temperatures in Central England over the last 22,000 years, developed from information collected at a variety of sites across the British Isles.

The information reported in this document begins (Section 2) with a description of the present-day characteristics of the regions/sites of interest in France, Spain and the United Kingdom, categorised under the following headings:

- site location and the geology of the region;
- human communities and land use;
- topography;
- climate;
- lithostratigraphy;
- surface water bodies; and
- biota

These site descriptions are then followed (Sections 3 to 5) by a detailed presentation of the information basis that has allowed palaeo-reconstructions of environmental change to be made for each country. The intention is that, by correlating these reconstructions with the global climate record, it will be possible to develop downscaling procedures that allow the projected effects of future global climate change to be reflected in assumptions about biosphere conditions relevant to long-term radiological safety assessments.

The strategies to be developed within BIOCLIM for identifiying and representing projected future environmental change at specific locations are being tested initially only for France, Spain and the United Kingdom. However, participation in the BIOCLIM project by representatives from NRI has enabled the collation of information describing evidence for environmental change in central Europe, with a particular focus on the Czech Republic. This information is summarised in Appendix A, for interest and comparison with the western European data sets.

1.3. - Calibration of Timeframes

A fundamental consideration in the reconstruction and comparison of environmental evolution narratives for different European regions is the variety of nomenclature used by scientists to describe palaeological timeframes. The assignment of climate conditions and other palaeodata to named stages of the Quaternary is often specific to a given country, or even to a particular study site. In the reports that follow, contributors have used the terminology that is most appropriate to their own countries to characterise regional climate and environmental conditions associated with particular stages in the record.

A common denominator for all such schemes is provided by the various stages in the oxygen isotope record, which have been tied to particular calendar ages before present (BP). However, it is not always clear how a particular named stage should be correlated with named stages identified elsewhere or with the Oxygen Isotope Stage (OIS) classification used in relation to deep-sea sediment cores. To support correlations between the various regions studied in BIOCLIM, a brief account is provided here of the OIS classification and its relation to calendar age. This provides the context for a presentation of the nomenclature generally used in Britain, France and Spain to describe Quaternary deposits and a discussion of the degree of confidence with which those deposits can be assigned to a specific OIS and associated with a specific calendar age.

For the purposes of climatic reconstruction, it is useful to consider the range of climatic conditions that has been exhibited over the whole of the Quaternary. Indeed, in continental Europe, there are continuous, or near-continuous sedimentary records that can be used for palaeoclimatic reconstruction over much of that period. However, in the British Isles no long, continuous records have been identified and almost all the climatic reconstructions that have been undertaken have related to the last glacial-interglacial cycle, i.e. from OIS 5e to the present day. Even within this period, the emphasis has been on climate change since the Last Glacial Maximum (OIS 2). For these reasons, the account of Quaternary Stages given here is more detailed for the last glacial-interglacial cycle than it is for the earlier part of the Quaternary.

The correlation and dating of Quaternary deposits remains an active research area. Interpretations of the various formations are subject to revision on an on-going basis. For this reason, the correlations and dates provided here should be regarded as the best currently available. In particular, when climatological histories are constructed and compared, it should be remembered that inconsistencies within and between such reconstructions may arise because of errors in the dates attributed to individual formations or groups of correlated formations.

The base of the Quaternary, as defined by the International Union of Geological Sciences (IUGS) occurs just below the top of the Olduvai magneto-subchron at Vrica in Italy. Its age on an astronomically tuned timescale is estimated at 1.905 Ma. However, a wide range of evidence suggests that the IUGS boundary was placed at an inappropriate horizon and that of the base of the Quaternary should be more appropriately dated at 2.5 Ma BP. The Stratigraphy Commission of the International Union for Quaternary Research (INQUA) has been seeking a suitably defined boundary stratotype [Ref. 3]. In this section, the broader definition of the Quaternary, beginning at about 2.5 Ma Before Present (BP), is adopted.

Hemispheric and global correlations in the Quaternary may be made using magnetostratigraphy on longer timescales, or geochronology on shorter ones. However, the standard means of effecting such correlations is by making correlations with the oxygen isotope stratigraphic scale derived from deep-ocean sediments [Ref. 3]. In broad terms, the even-numbered stages correspond to global cold (or 'glacial') periods, whereas the odd-numbered stages correspond to global warm (or 'interglacial') periods. However, it should be realised that these stages are identified by inspection of a complex _180 signal and that two successive stages do not necessarily represent a full glacial-interglacial cycle similar to that which occurred between about 120 ka BP and the present day.

Calendar ages for the oxygen isotope stratigraphic scale are obtained by orbital tuning and by correlation with reversals of magnetic polarity, notably the Matuyama-Brunhes boundary at approximately 780 ka BP. Approximate dates for the mid-points of odd numbered stages back to around 1.2 Ma BP are given in the following table, derived by inspection of Figure 1 of [Ref. 3]..

OIS	Calendar Age (ka)	OIS	Calendar Age (ka)
1	5	19	790
3	50	21	850
5	100	23	910
7	210	25	960
9	320	27	990
11	400	29	1030
13	500	31	1080
15	600	33	1120
17	700	35	1180

It is emphasised that the distinctions between stages in the early part of the record are not always clear, e.g. OIS 27 to 29 are not readily distinguished.

Table 1-1 provides an initial basis for cross-referencing between different conventions for describing the Quaternary stratigraphy that have been adopted in different countries. The different schemes include:

- The NW European stage nomenclature, with sub-stages for the Holocene and Weichselian identified in the Elsevier Geological Time Tables, which is commonly used in detailed palaeoclimate surveys and reconstructions for the Quaternary;
- The Alpine nomenclature, which, although not strongly correlated with global climate stages, has been historically used in France because of its correlation to events in the geological record;
- The French nomenclature associated with global climatic stages and events.
- The nomenclature adopted in UK studies reported here, which is again closely tied to the Quaternary geological record, but also follows more general OIS-stage naming conventions.

The calendar ages of the boundaries between Oxygen Isotope Stages (OIS) in **Table 1.1** have been taken from the work of Bradley [Ref. 3], and confirmed by direct inspection of the orbitally-tuned $\delta^{18}O$ records. More detailed discussion of the local terminology and strategraphy used in each country is provided in discussion of the palaeo-reconstructions for each region/site of interest.

Quaternary Stratigraphic Nomeclature

Approximate Calendar Age (ka BP)	OIS	NW Europe Stage	NW Europe Substage	Alpine System	French naming convention for global climate stages	UK naming convention (in this study)
0 – 5	1	Holocene	Sub-atlantic	Holocène	*Also known as Flandrian*	Recent Holocene
5 – 7	1		Sub-boreal Atlantic Boreal			Holocene Thermal Optimum
7 – 10	1		Pre-boreal			Early Holocene
10 – 10,5	1	Weichselian	Late Glacial	Würm récent	Younger Dryas	Late Younger Dryas
10,5 – 11	1					Early Younger Dryas
11 – 13	1 or 2				Late Glacial Interstadial *also known as Bølling-Allerød*	Windermere Interstadial
13 – 18	2		Pleniglacial		Oldest Dryas (13-15 ka BP)	Late Glacial
18 – 22	2					Late Devensian
22 – 38	2 or 3				Maxiglacial (15-26 ka BP) Interstadial (26-32 ka BP)	*Unclassified (period of Late Devensian Ice Sheet Development)*
38 – 41	3			Würm ancien	Cold Glacial (36-51 ka BP)	Middle Weichselian
41 – 77	3 or 4		Early Glacial		Temperate Glacial (51-70 ka BP) Early Glacial (70-76 ka BP)	Unclassified *(often described as mid-Devensian, including the Upton Warren interstadial)*
77 – 91	*5a*		Old Glacial	Interglacial Riss - Würm	*St Germain II (76-85 ka BP)*	Odderade Interstadial
91 – 97	5b				*Mélisey II (85-91 ka BP)*	Rederstall Stadial
97 – 104	5c				*St Germain I (91-100 ka BP)*	Brørup Interstadial
104 – 116	5d				*Mélisey I (101-106 ka BP)*	Herning Stadial
116 – 131	5e	Eemian			*Eemian (106-126 ka BP)*	Eemian
131 – 250	6 or 7	Saalian		Riss recent (RI)		
250 – 300	8	Hosteinian		RI / RII		
300 – 650	9 – 15	Elsterian		Riss ancien (RII/ RIII) Mindel		
650 – 700	16	Cromerian		Interglacial Mindel – Günz		
>700	17	Menapian Waalian Eburonian Tiglian Praetiglian		Günz (Donau) (Biner)		
>2 400	17	Reuverian Brunssumian		(Villafranchien)		

***Table 1-1**: Simple Correlation of Stratigraphic Nomenclatures in Databases providing Input to this Study*

2. Present-day characteristics of selected regions/sites

2.1. - France

The Meuse/Haute-Marne site is located in the Meuse department in the eastern part of the Paris basin, within 250 m of the border with the Haute-Marne department (Figure 2-1). This site was chosen in August 1999 by the French government for the establishment of an underground research laboratory in a clay formation.

Figure 2-1: Location of the Meuse/Haute-Marne site

Information relating to the present-day characteristics of the site is provided in a series of Andra reports (see, for example [Ref. 4; Ref. 5; Ref. 6; Ref. 7]). This information, summarised below, is used to establish the context for evaluating future environmental changes that could occur.

2.1.1 - Site Location and Geology

The latitude of the site, and its moderate continentality within the European mainland, are relevant factors in evaluating the potential effects of global climate change over the time frames of interest for radiological assessment. Studies of the major biomes that have existed in France during the Quaternary period have considered these location-related influences in characterising climatic parameters [Ref. 8].

Below the ground surface in the region, there is a succession of Cretaceous, Jurassic and Triassic sediments originally deposited between 245 and 96 million years before present. These are in excess of 1000 m in depth, and dip at an angle of 1° - 1.5° to the northwest [Ref. 7]. Sediments include limestones, marls and clays (Figure 2-2; Figure 2-3).

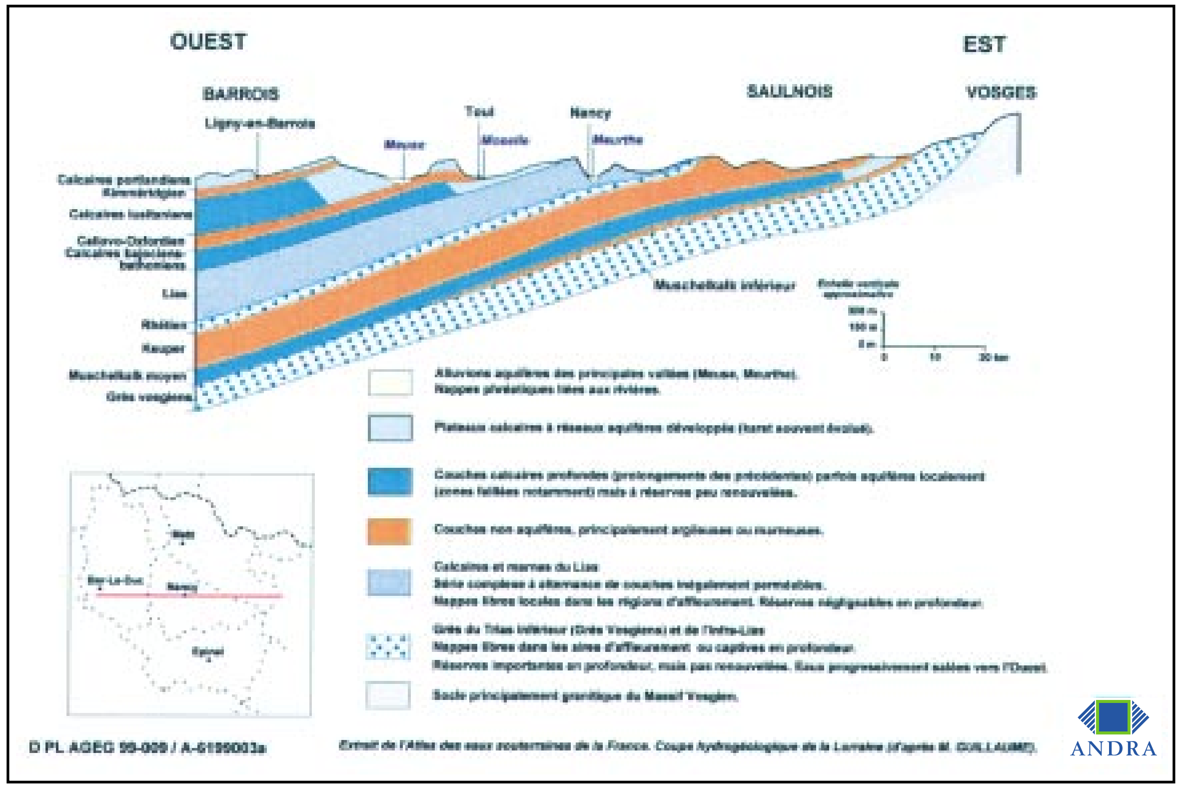

Figure 2-2: Schematic hydrogeological section of the eastern Paris basin

The geological environment is considered very stable (seismic zone 0) and likely to remain so over the next million years [Ref. 7]. There are no significant natural resources in the vicinity of the site, with neither the Dogger limestone nor the Oxfordian limestone currently being used as aquifers. The uppermost (Tithonian) limestone formation is used as a source of domestic, agricultural and industrial water. Compared with the importance of climate, features and processes of geological origin are considered unlikely to have a predominant influence on future biosphere systems at the site over the timeframe of interest.

2.1.2 - Human Communities and Land Use

Present-day land use in the region around the site of the underground research laboratory is primarily agricultural, with some agricultural service industries. Mixed farming is practised, with the production of crops (e.g. cereals and oil producing crops) and rearing of cattle [Ref. 5; Ref. 9]. Within a 2.5 km radius of the site, there are four villages/hamlets; the closest habitation (a farm called 'du Cité') is 300 m to the east of the site. The possibility of future changes in land use over the timescale of the assessment, and their impact on potential radiological exposure pathways, are a primary consideration in the description and modelling of assessment biosphere systems.

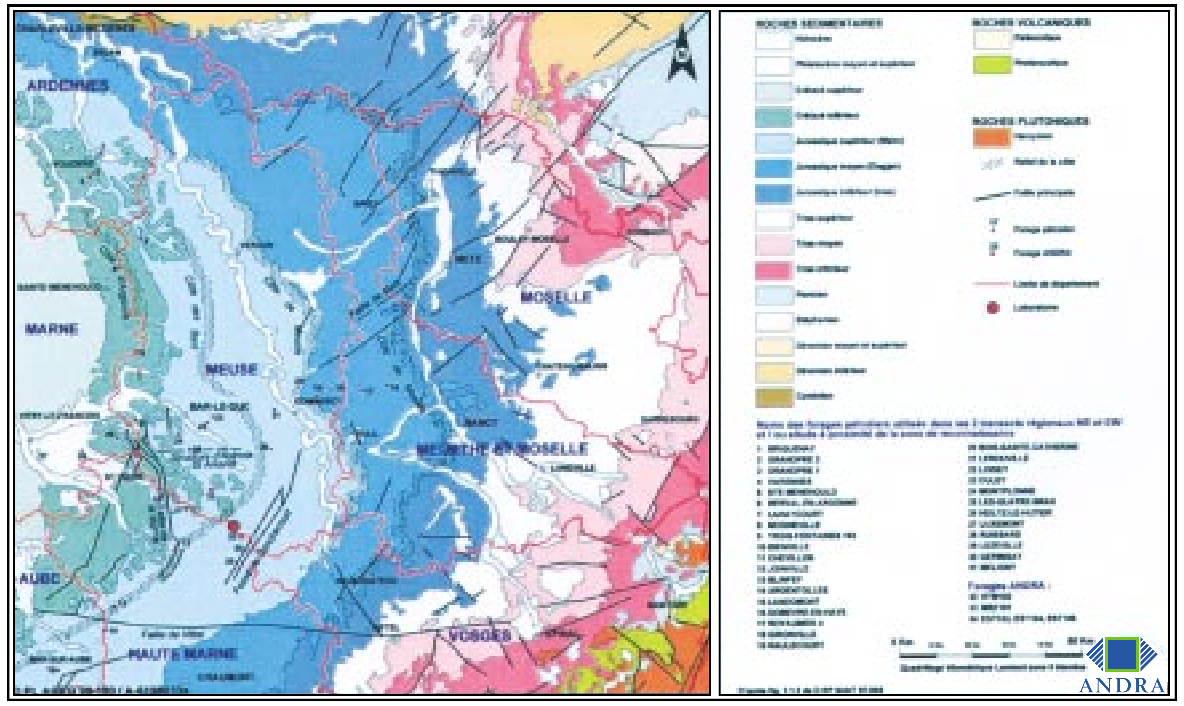

Figure 2-3: Geology and geomorphology of north eastern of the Paris basin

2.1.3 - Topography

The Meuse/Haute-Marne site has an average elevation of 370 m above sea level [Ref. 5]. The ground surface at the specific location of the underground research laboratory falls towards the northeast, with elevation ranging from 360 m to 376 m. On a more regional scale, the site is situated on a limestone plateau that ranges in elevation from 300 m to 400 m [Ref. 5].

2.1.4 - Climate

The present-day climate in the region is strongly influenced by its latitude and moderate continentality. It is characterised as a 'temperate oceanic' climate with slight continental influence, having an annual average temperature of about 10°C and precipitation in the range 0.7 m y^{-1} to 1 m y^{-1} [Ref. 5]. The prevailing wind is from the southwest.

During the Quaternary, the region has experienced the effects of global climate change associated with glacial-interglacial cycling and, although there is no evidence of ice sheet cover, it is believed to have experienced periglacial conditions with annual average temperatures some 15°C lower than the present-day value [Ref. 6]. During periglacial conditions, permafrost extended to a depth of approximately 100 m (see Section 3.3).

2.1.5 - Lithostratigraphy

The soil in the region is primarily chalky and can have a high content of stones and pebbles, although there are areas of finer-grained soils [Ref. 5]. The typical soil porosity is 0.6, with a dry bulk density of 1000 kg m^{-3}. For some crops currently grown in the region, the irrigation requirement is 0.15 m y^{-1} [Ref. 10], but future requirements will depend on the agricultural practices at the time. Soil development is influenced by weathering of the near-surface Tithonian limestone formation, which exhibits karst properties and is used in the region (although not currently within 4 km of the site of the underground research laboratory) as a source of domestic, agricultural and industrial water. Other influences on local soil properties include the effects on physical characteristics, chemistry and humic content associated with agricultural land use.

With a generally subdued topography and stable geological environment, the near-surface lithostratigraphy is considered to be similarly stable. An average erosion rate of 10 m per 100 000 years has been estimated [Ref. 5]. However, the soils in the region are exposed to amendment by human action and the consequences of climate change, the effects of which need to be taken into account in characterising assessment biosphere systems.

2.1.6 - Surface Water Bodies

The region of interest incorporates the catchment areas of the rivers Saulx and Ormançon, which are tributaries of the Marne. Drainage in the region is primarily from south to north [Ref. 6]. The site of the proposed underground research laboratory is drained by a stream (la Bureau); this, in turn, discharges into an upper part of the local river (l'Orge), which has a catchment area of 99 km^2, and hence to the river Saulx. Smaller rivers, such as l'Orge, are fed by springs in the Tithonian limestone, but also serve as sources of groundwater recharge over segments of their length. The course of la Bureau is dry for a large part of the year, but fishing is possible in the larger water courses of the region [Ref. 7].

2.1.7 - Biota

Terrestrial and aquatic plant and animal life associated with the present-day biosphere system are consistent with the climate conditions, soil quality and land use. Despite the predominance of agriculture, there are diverse micro-habitats representative of semi-natural ecosystems. Wooded areas and lakes, in particular, support a diversity of native plants and animals organised in moderately complex foodwebs [Ref. 7].

2.2. - Spain

The sites where detailed characterisation and palaeo-environmental activities have been undertaken by ENRESA are not being considered as candidates for the development of a deep geological repository. However, they are being used to provide information to guide generic radiological safety assessment studies. The work encompasses three different locations:

- Cúllar-Baza Basin,
- Padul peat bog,
- Toledo area.

The first two of these are located in the south of Spain, the latter is in the centre of the country.

2.2.1 - Cúllar-Baza Basin

2.2.1.1 Site Location and Geology

The Cúllar-Baza Basin (Figure 2-4) is located in the central part of the Betic mountain range, which occupies a large area (aproximately 4,500 km²) in northeast extreme of the Granada Province of Andalucia in southeastern Spain. The sediments that fill this basin are of Pliocene and Pleistocene ages and have a continental origin. It is one of the few zones of Europe where almost continuous sedimentation took place during nearly the whole of the Quaternary period, when most of the Cenozoic basins were eroded, downcut and cast out and fluvial terraces were developed.

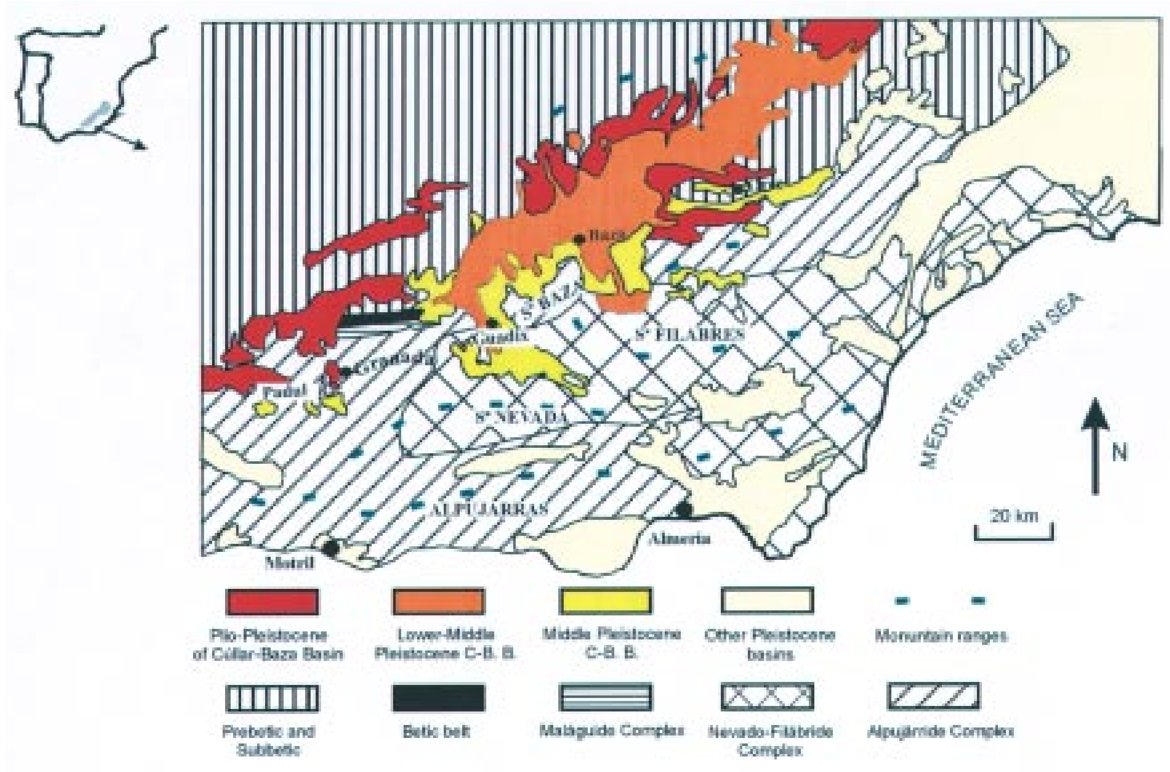

Figure 2-4: Cúllar-Baza Basin and Padul peat bog geological setting

The bedrock is mainly constituted of Mesozoic limestones, dolostones, marls and gypsum. Overlying these materials, Neogene sediments of marine origin are found. In the Upper Tortonian or at the Tortonian-Messinian boundary [Ref. 11; Ref. 12; Ref. 13; Ref. 14; Ref. 15; Ref. 16] the sedimentation changed into a continental pattern and the deposition of fluvial and lacustrine materials began.

Previous to the deposition of the oldest continental materials, the Miocene marine sediments suffered alpine tectonics; a compressive phase of intra-Tortonian age resulted in the Cúllar-Baza Basin becoming a marine corridor connecting the Atlantic Ocean and the Mediterranean Sea. Later, a regression during Upper Tortonian time [Ref. 17] occurred.

Pliocene and Quaternary sediments include conglomerates and sands linked to the mountain ranges, lutites and sands and, in central parts of the basin, carbonated and gypsiferous lutites, carbonated beds and gypsum levels, arranged according to a centripetal deposition model (Section 2.2.1.3).

2.2.1.2 Topography

The Cúllar-Baza Basin is an irregular-shaped old plateau with its major axis oriented in a SW-NE direction at 900-1000 meters above sea level. The elevations range from 650 m, in the river beds, to 1050 m in the highest plateaus. The morphology is characterised as 'bad-lands'.

2.2.1.3 Lithostratigraphy

The Cúllar-Baza Basin can be described, sedimentologically, by a centripetal deposition model [Ref. 18; Ref. 19]. According to such a model, it is assumed that alluvial fans at the foot of the mountain ranges gradually passed to a system of alluvial fan linked channels that flowed out to a central system of small saline lakes, arranged in a mosaic pattern with sedimentation of gypsiferous lutites, gypsiferous sands and gypsum (Figure 2-5). In the central part of the basin it is possible to find centimetrical to decimetrical lutite beds with intrasedimentary gypsum crystals containing ostracodes and insect cuticules. The facies sequence is: gravels (sheet flow or channel infill linked), lens-shaped channel fill sands, mud flat playa deposits (red lutites), lacustrine sands with abundant ostracode valves and sometimes mollusc remains, grey lacustrine gypsiferous lutites and sands, carbonate and gypsum beds.

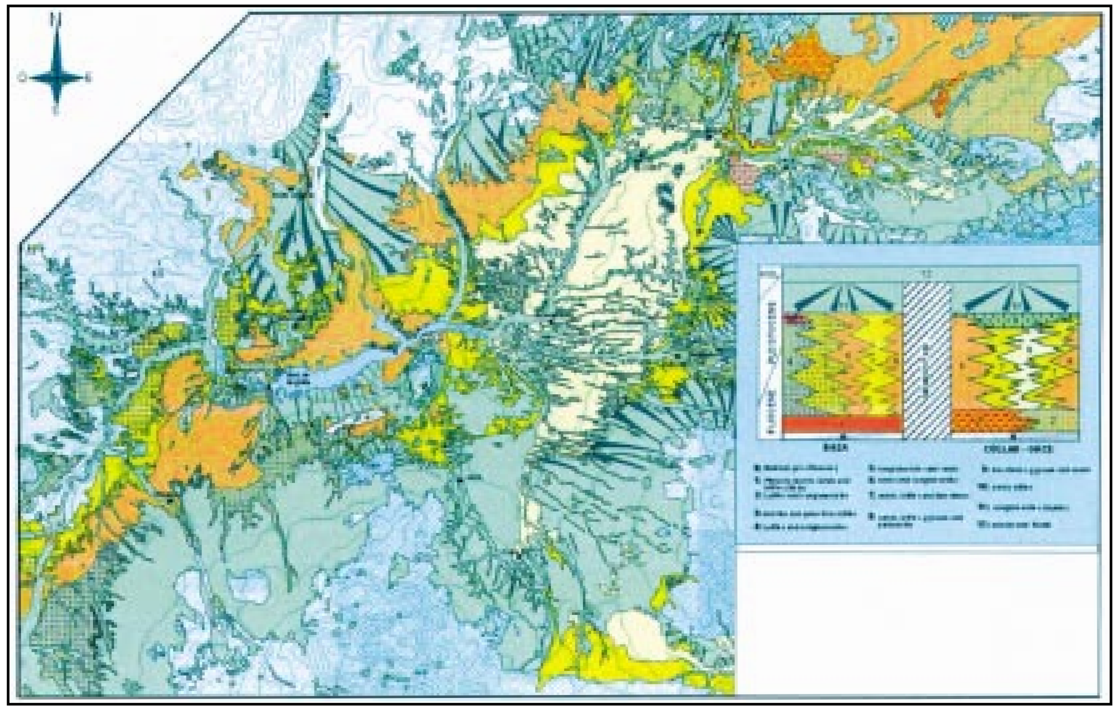

***Figure 2-5**: Stratigraphy of Cúllar-Baza Basin*

Lacustrine deposits were not very laterally continuous, highlighting the existence of a "microenvironmental mosaic" with independent ephemeral and shallow water bodies, separated by sediments, that would be connected during "high" pluvial stages. Some of these would be fed directly by alluvial fan distributary channels, whereas others could be linked to saline or brackish springs.

This sedimentation pattern, with a distinctive lacustrine expansion event, continued until the upper part of the Middle Pleistocene. At this point the basin was covered by both breccias and carbonate-cemented conglomerates with a clay and sandy matrix, transported by coalescent aluvial fan systems that had eroded the uppermost Middle Pleistocene lacustrine deposits. Subsequently, fluvial downcutting took place into the sedimentary deposits.

2.2.1.4 Climate

The climate in the region of the Cúllar-Baza Basin is Mediterranean with a strong continental influence: winters are cold and dry whereas summers are extremely hot, with maximum temperatures of over 40ºC. The mean annual temperature is between 10 and 12.5ºC and the annual average rainfall is in the range 300 to 350 mm y^{-1}.

This semi-arid climate has favoured the development of a 'bad-lands' landscape, mainly covered by steppe plants; major trees are found only along the scarce rivers that run through the basin.

2.2.1.5 Surface Water Bodies

The region of interest incorporates the catchment areas of the rivers Castril, Guardal and Fardes, tributaries of the Guadalquivir river. Drainage in the region is primarily from northeast to southwest. Along the basin there are some springs characterised by their brackish waters with mainly either carbonated or sulfated ions. In the basin, ephemeral water courses and surficial runoff are common.

This pattern was determined at the end of Middle Pleistocene times, when halokinetic movements (linked to Keuper saline deposits) and local tilting processes took place and the basin incision and further erosion began. These processes served to establish the current fluvial system, producing the typical creek and bad-lands landscape that can be observed today. Likewise, the basin drainage was slightly modified and the transportation of eroded materials began towards the Atlantic Ocean via the Guadalquivir river.

2.2.1.6 Biota

Terrestrial plants and animal life associated with the present-day biosphere system are consistent with the climate conditions. Steppe plants are dominant (but scarce) and major trees can be found only along the few rivers that run through the basin.

2.2.2 - Padul Peat Bog

2.2.2.1 Site Location and Geology

The Padul peat bog is located 20 km south of the city of Granada (Andalucia, southern Spain), at latitude 37ºN and longitude 3º40´ (Figure 2-4). It consists of very shallow endorreic basin, surrounded by mountains, which is permanently covered by water. The site is located close to the Betic mountain range, at the point of contact between the Betic Zone (Alpujarridean Complex) and the Granada Continental Basin.

The peat bog is bounded to the north by a fault N125ºE dipping 70º to 80º SW. This fault, and underlying mechanisms, resulted in the slippage of the southern block; the rate of subsidence has been almost always in equilibrium with the rate of sedimentation.

Thus, the Padul peat bog is located in a subsiding tectonic basin (Figure 2-6) developed on Alpujarride Complex rocks, mainly limestones and dolomites, and infilled by detritic materials, sometimes carbonate cemented. Alternating beds of peat occur in the upper part of the basin. On its non-disturbed boundaries, the peat interfingers with the thick clastic sediments of the alluvial fans (Figure 2-7).

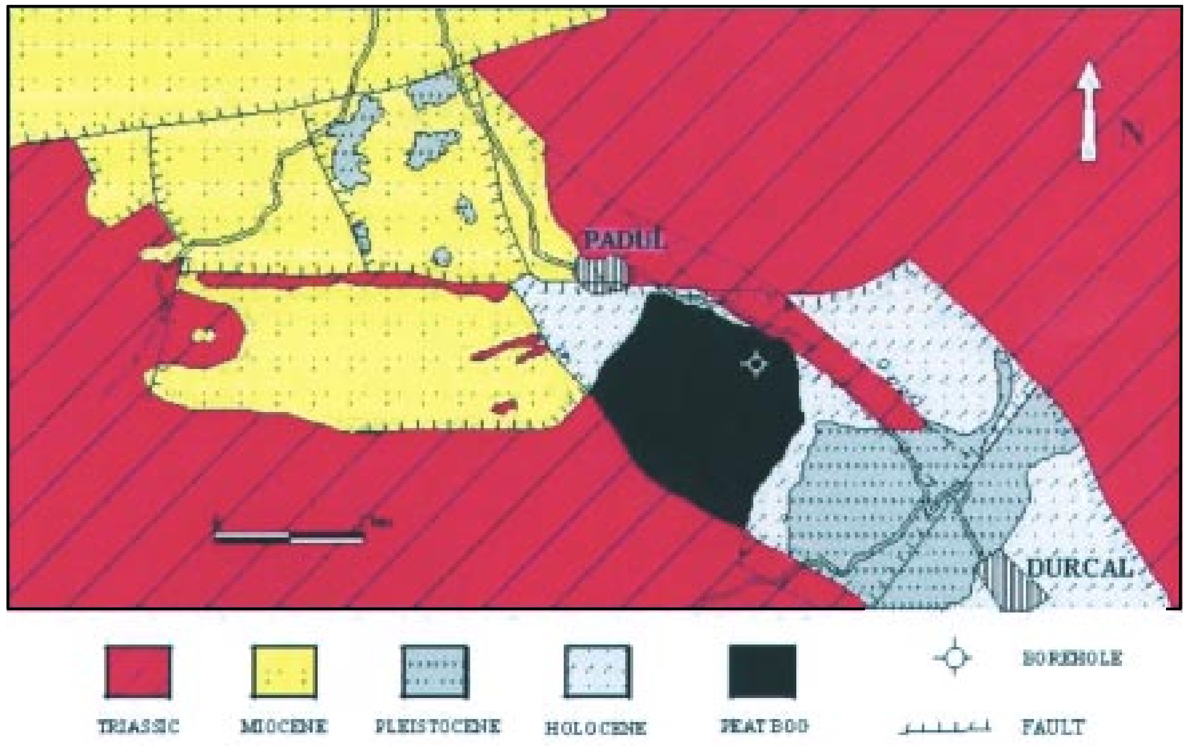

Figure 2-6: *Geological setting of Padul peat bog*

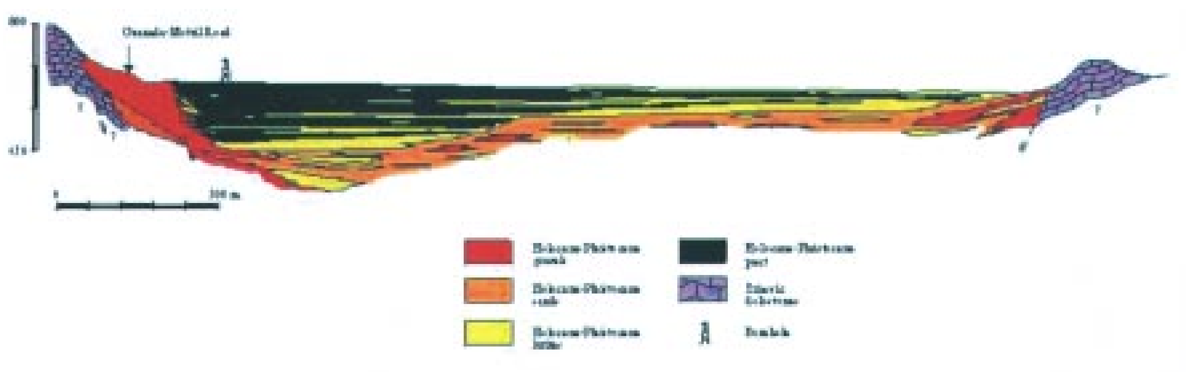

Figure 2-7: *Padul stratigraphic section*

2.2.2.2 Human Communities and Land Use

The peat bog is located 200 m south of Padul town. Present day land-use of the peat bog is industrial: the peat is being extracted for agricultural use.

2.2.2.3 Topography

The Padul Peat Bog is a flattened depression 720 meters above sea level. It has a surface area of 4 km^2 with a NW-SE oriented longitudinal axis. The peat achieves a maximum depth of 100m. In the southeast part, it is surrounded by Sierra del Manar mountains (part of the Sierra Nevada mountain range), with a maximum altitude of 1,520 meters above sea level. At the western margin, there is the Sierra Albuñuelas range whereas to the south, the Valdesa and Cijancos peaks protect the Padul peat bog from erosion by the Dúrcal river.

2.2.2.4 Climate

Padul has a Mediterranean climate with a strong continental influence: this is the cool semiarid stage according to the modern climatogram of Emberger [Ref. 20] exhibiting cold and dry features according to Walter's climatogram [Ref. 21]. The climatic parameters for the Granada area, where Padul is located, are: annual total precipitation 453 mm, average maximum daily temperature of the hottest month 31.2°C, and mean temperature of the coldest month 2.7°C.

2.2.2.5 Lithostratigraphy

A new 103 m-long borehole was drilled in this peat bog in 1997 in order to study not only the pollen assemblages but also the biomarkers of the sediments to reconstruct the palaeoenvironmental evolution of the area. The drilling was carried out in the central-east part of the basin because this is where it has its maximum depth. However, because peat had been extracted from the bog, the top of the core was approximately 8 meters below the top of the uppermost peat level. A 7.7 m-thick stratigraphic section, named CEX, whose uppermost 4.4 m could be correlated with the upper part of the borehole, was therefore exposed in an 8m-deep trench excavated at one of the extremes of the peat bog.

The most abundant material at the site is peat, although there are also lutites that are rich in organic matter as well as some marls. Figure 2-8 illustrates the observed lithology of the core (100 m depth) and the stratigraphic section (CEX). From the bottom to the top, this consists of:

- 7.0 m Heterometric and angular dolomitic gravels.
- 16.0 m Grey lutites with three interbedded well-preserved peat layers.
- 11.0 m Marls, marls with gravels with an important peat bed in the uppermost part.
- 19.0 m Peaty lutites and peat with two interbeddings, one of lutites and the other of marls.
- 14.0 m Massive peat with variable lutitic content.
- 5.5 m Grey and black marls, black sands and peat.
- 25.0 m Massive peat with with variable lutitic content.
- 2.2 m Marls and sandy marls.

This whole section covers a time span from 4,450±60 y BP (^{14}C) [Ref. 22] at the top and 883,000 ± 49,000 y BP at 97.10 meters (amino acid racemization dating method).

Lithology

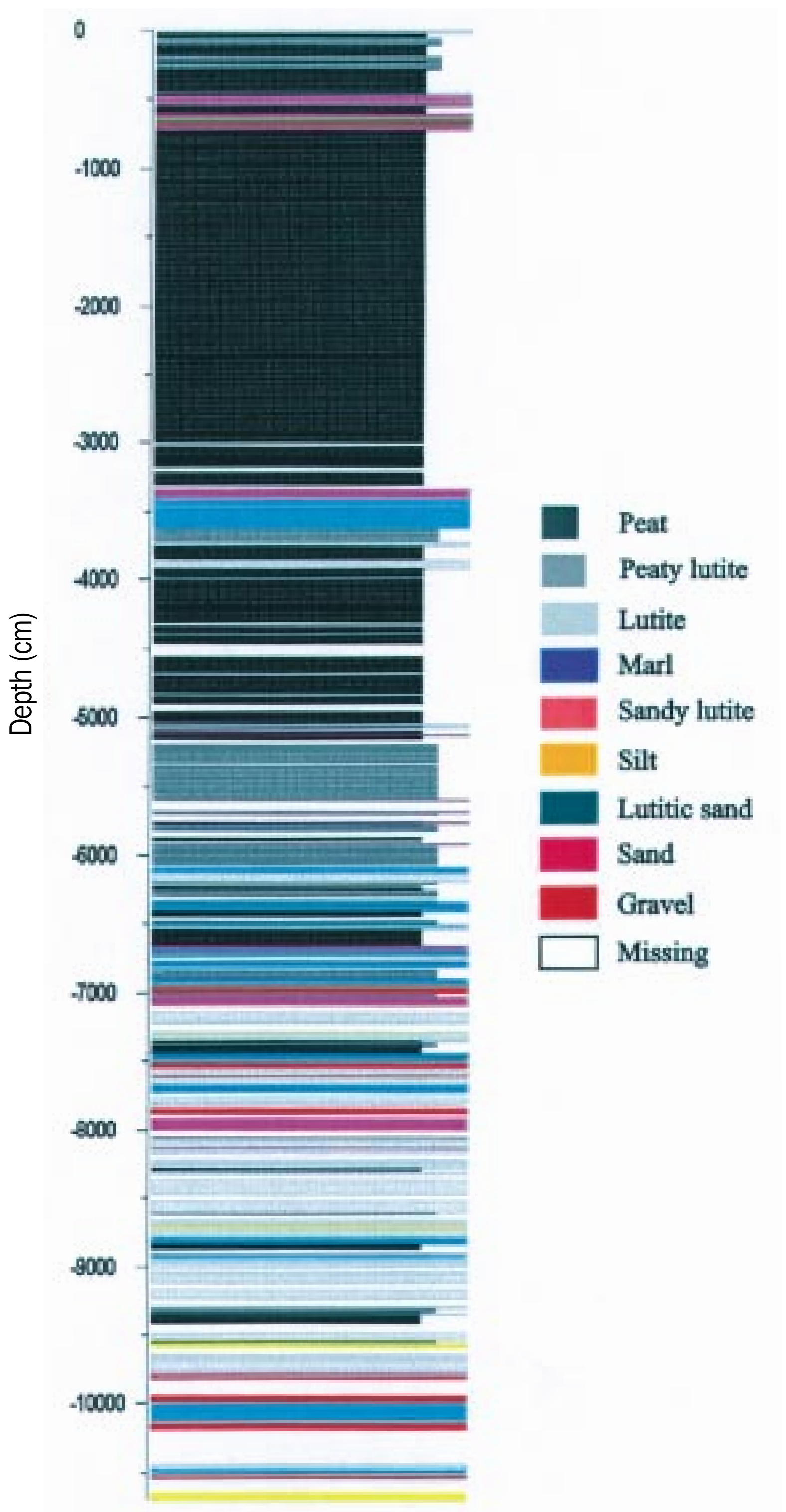

Figure 2-8: Padul section of lithology

2.2.2.6 Surface Water Bodies

Surface water bodies are not important in the Padul endorreic basin. Only alluvial fans at the foot of the mountain are found.

The Padul basin is a discharge area for groundwater flow from the surrounding aquifers (with the exception of the one constituted by Alpujarride limestones and dolostones at the southern edge). Groundwater flow directions change from sub-horizontal, within the Mesozoic aquifers adjacent to the basin, to an essentially vertical upward discharge within the peat-filled half-graben. The most important contribution to overall groundwater discharge occurs at the northern boundary of the Quaternary infill.

Present rainfall in the area is considered to be a minor factor in the water balance within the peat deposit. Taking into account evapotranspiration and run-off, input from precipitation is estimated to contribute only about 2% of the total throughput of water. Hence, fluctuations in the water table within the peat have been effectively controlled by infiltration from the surrounding catchment areas; an important contribution to this is the accumulation and melting of ice and snow.

Groundwater discharge, coupled with the characteristic of the peat as a heat-generator owing to the exothermal process of organic decomposition, gives the bog a considerable inertia to climate change.

2.2.2.7 Biota

Present day plants of Padul peat bog are mainly aquatic. Typha, Chara and Poeacea are abundant.

2.2.3 - Toledo Area

2.2.3.1 Site location and Geology

The Tagus depression, also known as the southern Submeseta, is the second largest in extent of the interior basins of the Iberian Meseta. It is an intracratonic Tertiary basin that originated after the alpine compressive movements that took place during the upper Cretaceous period. The most recent Tertiary sediments are of Villafrancian age, and represent the end of the silting-up process and the beginning of new morphogenetic processes that occurred between 2.0 and 2.5 million years BP, leading to the present configuration of the basin.

At the end of the Miocene, a new phase began with the formation of La Raña piedmont and the first river terraces. These are the most typical sedimentary deposits of the Tajo River Depression. Other characteristic formations are alluvial fans, glacis, aeolian accumulations of sand and clay, travertines and tuffs, and volcanic rocks in the El Campo de Calatrava area. Crustings and limestone crusts are also commonly represented in the Depression [Ref. 23].

The evolutionary patterns of these fluvial landforms have been governed by climate as well as by the inherited topography, the lithology of the substrate and the regional tectonics.

The Montes de Toledo, the peneplain of Extremadura and the Guadiana River Depression constitute a morpho-structural region with its head at the Montes de Toledo. This exhibits a non-uniform distribution of Quaternary sediments related to the drainage system of its two main collecting rivers, namely the Tajo River and the Guadiana River.

The La Raña formation, conventionally located at the Neogene-Quaternary transition, is the sedimentary formation with the greatest areal extent and regional significance. It is located on a piedmont rim surounding the eastern mountainous zones and as discontinuous patches that extend throughout the peneplain of Cáceres and the Guadiana River Depression. There is controversy over the genesis of this formation of extensive nappes of thin quartz conglomerates, which are of a fluvial nature with peculiar edaphic characteristics. In addition, there are differences of opinion relating to its palaeo-environmental meaning.

Hill slope deposits are also very extensive. These consist of colluvions within a matrix, linking the mountain sides with the La Raña formation, or areas with boulders including quartzitic composition and loose pebbles that arose through the action of gelifraction processes during cold Pleistocene periods.

In the Montes de Toledo area, there is a superposition of alluvial fans of different generations whose lithofacies are similar to those of the La Raña formation, joining together the latter with the river terraces and current river alluviums. The Guadiana River has developed a very broad river valley on the Tertiary sediments of Extremadura. In the southern part of the Montes de Toledo, fluvial terraces constitute extensive platforms of quartzitic pebbles, sand and clayey silts, but of very small thickness. For instance, in the valley of the Bullarque river it is possible to identify up to three such levels as steps in a 20m altitudinal range above the current valley bottom. There are also other strata with lithologies similar that of the La Raña formation at higher topographic levels [Ref. 24].

2.2.3.2 Topography

The southern Submeseta is a wide interior depression of the Iberian Meseta with an average altitude of 600-700 m above sea level, which is limited in extent by with mountain ranges both to the NE and NW (Cordillera Ibérica and Sistema Central) and to the S. and SE (Montes de Toledo and Sierra Morena). For its part, the peneplain of Extremadura has an altitude of 400 m. The Guadiana River flows to the south with an average slope of 0.6 ‰.

2.2.3.3 Lithostratigraphy

Lithologically, the Tajo river Submeseta is quite monotonous, being composed of Miocene continental deposits: clayey deposits and marls. It is gypsiferous in its central part (south of Madrid), with limestones at the top of the hills (the so-called “caliza del páramo”, which is an Upper Miocene formation). From the southern part of the Guadarrama and Gredos mountain ranges the plain is covered by Pliocene alluvial fans (i.e. La Raña).

The western area of the Iberian Peninsula, from the south of the Sistema Central range to the Campos de Calatrava area, is dominated by Lower Palaeozoic formations, mainly shales and sandstones, profoundly eroded to the point of constituting a peneplain, and limestones to the south of Badajoz. Also, intrusive granitic formations are common.

2.2.3.4 Climate

In central Spain, the climate is Mediterranean with an arid-semiarid signature. The annual average temperature ranges from 15.5 °C in Extremadura to 13.9 °C in La Mancha region. Summer temperatures are much higher, above 25 °C, with absolute extreme temperatures of 46 °C. Annual average precipitation is in the 300-400 mm range, unevenly distributed through the year, with a minimum during July-August and a maximum during the autumn (within the northern part of the Submeseta) or the spring (within the southern part, which incorporates the Tagus depression).

2.2.3.5 Surface Water Bodies

The Tajo river has an average annual flow of about 480-500 m^3/s. The river exhibits a pluvio-nival regime in the upper part of the catchment, at more than 1800 m above sea level, becoming pluvial as the river flows through the basin. By contrast, the Guadiana river regime is pluvial thoughout its length, with an annual average stream flow of only 79 m^3/s.

Some large reservoirs are located on these rivers. La Serena reservoir, on the Guadiana river, impounds 3.22 km^3, while the Cíjara reservoir, on the same river, occupies a volume of 1.5 km^3. On the Tajo river, the Buendia reservoir has 1.64 km^3 capacity and the Valdecañas reservoir, 1.44 km^3.

2.2.3.6 Biota

The climax vegetation is represented by Quercetum ilicis but this has been extensively eliminated by human action. Nowadays it has been substituted by bush and steppe vegetation (Stipa tenacissima, Lygeum starpum, Cistus ladaniferus, Juniperus communis). In higher altitude areas (1200 to 1400 m above sea level), the arboreal vegetation is composed of Q. pyrenaica, and Pinus sylvestris.

2.3. - United Kingdom

2.3.1 - Location, Geology, Topography and Quaternary Lithostratigraphy

For the purposes of BIOCLIM, ‘central England’ is taken to lie within the area encompassed by the sites used by Atkinson et al. [Ref. 25] to reconstruct seasonal temperatures over the last 22,000 years from information on beetle (coleoptera) associations. The overall area in which these sites are located extends from the Solway Firth in the north to Cornwall in the south. The main cluster of sites is situated in the west Midlands of England, with the two most easterly being in London and Cambridge, and the two most westerly being in Ireland. The study area has been further constrained in order to exclude the uplands of central northern and northwest England. Figure 2-9 is a location map showing the area that has been adopted for the purposes of the study.

Even within this more constrained region, a wide range of environmental contexts is present. For a summary of the geology of Britain, the definitive reference would be the ‘Geology of England and Wales’ [Ref. 26] and its companion ‘Geology of Scotland’ [Ref. 27]. However, for a succinct overview it is difficult to improve upon the introduction to the classic monograph ‘Britain’s Structure and Scenery’, first published in 1946 [Ref. 28]. This considers the geology, geomorphology and topography of Britain and emphasises that, if one draws a line from approximately the mouth of the river Tees to the mouth of the river Exe, the main hill masses and mountains lie to the north and west, whereas the main stretches of plain and lowland lie to the south and east. This is the basis for the often-made distinction between Highland Britain and Lowland Britain. Central England, as defined for the purpose of this study, lies almost entirely within Lowland Britain.

Lowland Britain is best described as an undulating lowland, where lines of low hills are separated by broad open valleys and where ‘islands’ of upland break the monotony of the more level areas. Even the highest of the hills scarcely ever exceed 300 m above sea level, though many of the ridges reach about 200 m [Ref. 28]. The soils tend to be deep and rich, there are few steep slopes to interrupt cultivation and plough lands are to be found right to the tops of the hills. Consequently there is little to hinder man’s use of the environment: human settlement is essentially continuous and the cultivated land of one parish merges into that of the next. Villages and towns are closely and evenly scattered, although their siting has sometimes been dictated by convenience of a water supply or by situation on a natural routeway. It follows that the greater part of Lowland Britain is occupied by farmland, which includes both cultivated land for agriculture and grass land for grazing livestock, and that such moorlands, heaths, ‘wastes’ and other unimproved lands as occur do so as remnants of previously more widespread environments interrupting the otherwise continuous farmland and coinciding with patches of poorer soils [Ref. 28].

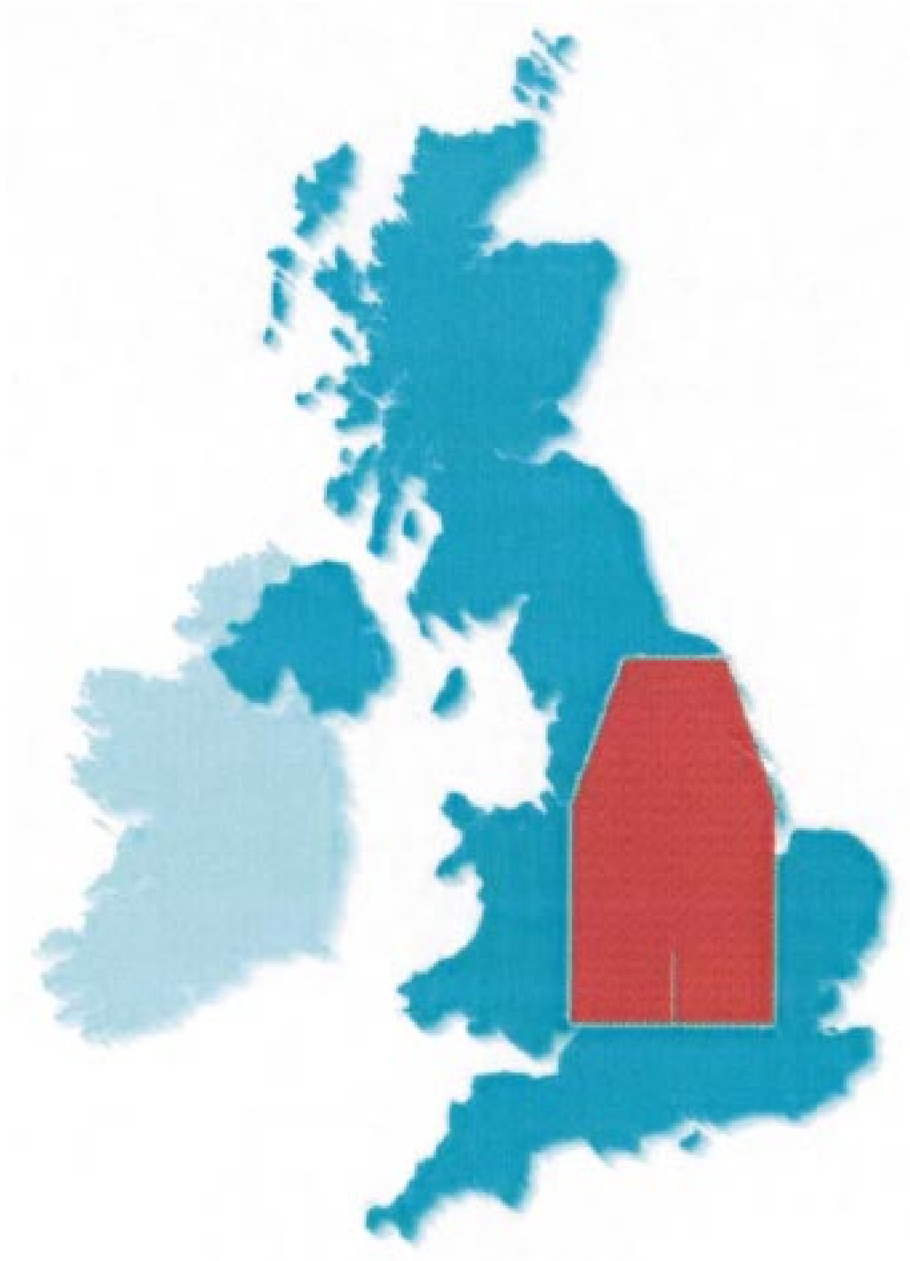

Figure 2-9: Location of Central England

Speaking very generally, in geological terms, the oldest lithologies exposed in Britain are present in the north-west and the rocks become steadily younger as one goes to the south and east, so that the major stretches of Tertiary rocks are to be found in the London and Hampshire basins. The Midlands of England are characterised by Triassic deposits and inliers of older rocks. Moving south and east, one encounters the successive belts of scarplands that sweep across England from the north-east to the south-west. These comprise the Liassic clays, Oolite sequence, lower Cretaceous rocks, and Chalk. In the south-east, this orderly sequence is disturbed, both structurally and due to local non-deposition, as a result of the far-field effects of Alpine orogeny [Ref. 28].

Overlying the solid geology of much of Britain are unconsolidated Quaternary deposits. In Britain, those sediments that formed as a result of glacially related processes are often referred to as the Drift. Central England lies entirely within the area covered by the South Sheet of the Geological Survey Ten Mile Map, First Edition (Quaternary) 1977 [Ref. 29]. This shows the great extent of the Boulder Clay and Morainic Drift, which originated during the Anglian glaciation, stretching as far south as North London. A detailed account of this glaciation in the British Isles has been provided by Clayton [Ref. 30] and the following comments are based on his review.

The Anglian glaciation formed the most extensive ice sheet in the British Isles, and increasingly most of the pre-Devensian tills and related outwash deposits are related to this stage. The southern limit reached Finchley in North London, almost reached the Thames west of the Goring Gap, and covered all of South Wales and southern Ireland. It probably lay close to (and at times reached) the present north coast of Devon and Cornwall and probably reached the Scilly Isles.

The dating of this major glaciation remains a matter of some dispute. In stratigraphic terms, it predates the Hoxnian interglacial, and this is commonly attributed to Oxygen Isotope Stage 9 (OIS 9). Thus, the Anglian could be OIS 10 (about 350 000 years BP). However, Bowen and Sykes [Ref. 31], using amino acid ratios, attribute part of the Swanscombe deposits (which also follow the Anglian glaciation) to OIS 11. This contrasts with the usual attribution of the Swanscombe (Boyn Hill) terrace deposits to the Hoxnian. If the views of Bowen and Sykes are accepted, this places the Anglian at OIS 12 and about 440 000 years BP; however, Clayton [Ref. 30] warns that no great reliance should be placed on amino acid dating. Some additional support for attributing the Anglian glaciation to OIS 12 comes from the work of Atkinson and Rowe [Ref. 32], who correlate an overlying interglacial tufa from West Stow, Suffolk to OIS 11. However, this is based on a U-series age for the tufa that is subject to considerable uncertainty. The Anglian glaciation certainly post-dates the Cromerian, which Bowen and Sykes [Ref. 31] correlated with OIS 13. However, there seems to be a hiatus in the British sequence between the lowermost part of the Beestonian and the Cromerian of the East Anglian coast, and it is not clear with which of the several Dutch Cromerian interglacials the East Anglian deposits correlate. Overall, notwithstanding these uncertainties, Clayton [Ref. 30] considers that there is a growing consensus that the Anglian is OIS 12.

The various lithological types of till found in East Anglia give a useful impression of the types of deposit formed by the Anglian glaciation. Perrin et al. [Ref. 33] distinguished tills associated with the North Sea Drift Ice from those associated with the Lowestoft Till. The Lowestoft Till is the main deposit in East Anglia and is the source of the Chalky Boulder Clay that covers most of the area. This Chalky Boulder Clay was formed by glacial erosion of the Fen Basin and Chalk escarpment to the east.

2.3.2 - Land Use, Soils and Biota

As already mentioned, Lowland Britain is given over largely to agriculture. Detailed information on agricultural activities is provided in a variety of surveys undertaken by the Ministry of Agriculture, Fisheries and Food (MAFF)[1]. The various types of survey data that are available are summarised in **Table 2-1**.

[1] MAFF has recently been repositioned as part of the Department of Food, Environment and Rural Affairs within the revised UK Government Structure. However, as most of the information of interest was collected prior to the General Election of 7 June 2001, the old nomenclature has been retained in this report.

Title of survey	Geographical coverage	Frequency (timing within year)	Sample Size	Description
December Agricultural Survey	England	Annual (December)	29,636	Livestock numbers and crop areas collected.
Agricultural and Horticultural Census-June	England	Annual (June)	119,605	To provide a complete annual picture of agriculture and horticulture. This annual census is the only means by which MAFF and the industry obtain a regular and comprehensive picture.
Grain Fed to Livestock	England & Wales	Monthly (subject to review)	10,601	Records the quantity of grain (bought in and grown on own farm) fed to livestock on the farm.
Cereals Stocks Survey	England & Wales	Quarterly (March, June, September, and December)	3,274	Measures the quantity of cereals stocks remaining on farm as the crop year unfolds.
Cereals Production Survey	England & Wales	Twice per year (August and April)	9,931	Provides an accurate, timely and independent estimate of the cereals harvest. The August estimate is produced soon after harvest. The April survey records the level of production once most of the cereals have been sold off farm.
Pea and Bean Production (Dried)	England	Annual (November)	1,100	Provides an estimate of pea and bean harvest on farm.
Oilseed Rape Production	England	Annual (August)	880	Provides an estimate of Oilseed Rape harvest.
Annual Survey of Tenanted Land (Main Survey & Pilot)	England & Wales	Annual (October)	5,000	Collects information on the level agricultural land rents paid by farmers.
Earnings and Hours of Agricultural and Horticultural Workers	England & Wales	Annual (September)	2,400	Collects details of the hours worked and earning of hired farm workers.
Orchard Fruit Survey	England & Wales	Annual (June)	2,317	Records details of the top fruit sector (apples, plums, raspberries etc.).
Glasshouse Survey	England & Wales	Annual (January)	3,598	Collects information on glasshouse area and horticultural crops grown in glasshouses.
Vegetables and Flowers Survey	England & Wales	Annual (January)	5,994	Records planted area of vegetables and flowers grown on farms.
Press of Home-Grown Apples & Pears	England & Wales	Annual (September - provisional figures/ February - final figures)	9	Estimates the volume and value of cider apples and perry pears produced.
Mushroom Census	Great Britain	Annual (March)	348	Collects information on the volume and value of mushroom production.
Production & Marketing of Hatching Chicks & Eggs	England & Wales	Monthly	69	Records details of the number of hatching chicks and eggs produced by hatcheries which are then sold on to other farms to rear for poultry meat or as egg laying birds. Statistics provide a leading indicator of trends in the sector.
Farm Business Survey	England (similar Surveys in other UK countries)	Annual (predominantly Spring/ Summer depending on farmers accounting year).	2,354	Collects detailed farm accounts data (on value of outputs, cost of inputs and income) to provide analysis by farm type.
Aggregate Agricultural Account	United Kingdom	Annual		Provides estimate of agriculture's Gross Output, Gross Input and Total Income from Farming. It is only available at the aggregate level but is published 1 month after the end of the year.

***Table 2-1**: UK Land Use Survey Data*

Land use throughout Britain is also classified through a Land Use Classification Scheme developed by the Institute of Terrestrial Ecology (ITE) [Ref. 34].

The ITE land-classification scheme comprises 32 categories, each of which reflects a characteristically different type of land, as summarised in **Table 2-2**. The Countryside Information System (CIS) provides a GIS for displaying and analysing the ITE classification geographically, together with a range of associated datasets based on information gathered during the 1990 Countryside Survey. A major new audit of the countryside began in 2000 (http://www.cs2000.org.uk/). This involves extensive ecological studies at selected field sites combined with land cover imaging from space.

1.	Undulating country, varied agriculture, mainly grassland
2.	Open, gentle slopes, often lowland, varied agriculture
3.	Flat arable land, mainly cereals, little native vegetation
4.	Flat, intensive agriculture, otherwise mainly built-up
5.	Lowland, somewhat enclosed land, varied agriculture and vegetation
6.	Gently rolling enclosed country, mainly fertile pastures
7.	Coastal with variable morphology and vegetation
8.	Coastal, often estuarine, mainly pasture, otherwise built-up
9.	Fairly flat, open intensive agriculture, often built-up
10.	Flat plains with intensive farming, often arable/grass mixtures
11.	Rich alluvial plains, mainly open with arable or pasture
12.	Very fertile coastal plains with very productive crop.
13.	Somewhat variable land forms, mainly flat, heterogeneous land use
14.	Level coastal plains with arable, otherwise often urbanised
15.	Valley bottoms with mixed agriculture, predominantly pastoral
16.	Undulating lowlands, variable agriculture and native vegetation
17.	Rounded intermediate slopes, mainly improvable permanent pasture
18.	Rounded hills, some steep slopes, varied moorlands
19.	Smooth hills, mainly heather moors, often afforested
20.	Mid-valley slopes, wide range of vegetation types
21.	Upper valley slopes, mainly covered with bogs
22.	Margins of high mountains, moorlands, often afforested
23.	High mountain summits, with well-drained moorlands
24.	Upper, steep, mountain slopes, usually bog-covered
25.	Lowlands with variable land use, mainly arable
26.	Fertile lowlands with intensive agriculture
27.	Fertile lowland margins with mixed agriculture
28.	Varied lowland margins with heterogeneous land use
29.	Sheltered coasts with varied land use, often crofting
30.	Open coasts with low hills dominated by bogs
31.	Cold exposed coasts with variable land use and crofting
32.	Bleak undulating surfaces mainly covered with bogs

***Table 2-2**: Land Use Classes for the UK [Ref. 34]*

The CIS currently stores and displays the land class information on a 1 km^2 grid covering the whole of the UK. Within the program, each ITE class is correlated to a range of environmental variables, such as topography, soil type, linear features (hedgerows), and densities of natural and cultivated vegetation.

The ITE has also provided a synthesis of land-use data for Great Britain based on satellite observations. The following table lists the Landsat-derived cover types used in the current Land Cover Map of Great Britain. This map is currently being revised, as part of Countryside Survey 2000. The resolution of the ITE map extends down to about 1 hectare and it distinguishes between arable or tilled land and pasture, and a range of other land types.

	Land Cover Type
A	SEA / ESTUARY
B	INLAND WATER
C	COASTAL BARE GROUND (BEACH / MUDFLATS / CLIFFS)
D	SALTMARSH
E	ROUGH PASTURE / DUNE GRASS / GRASS MOOR
F	PASTURE / MEADOW / AMENITY GRASS
G	MARSH / ROUGH GRASS
H	GRASS / SHRUB HEATH
I	SHRUB HEATH
J	BRACKEN
K	DECIDUOUS / MIXED WOOD
L	CONIFEROUS / EVERGREEN WOODLAND
M	BOG (HERBACEOUS)
N	TILLED LAND (ARABLE CROPS)
O	SUBURBAN / RURAL DEVELOPMENT
P	URBAN DEVELOPMENT
Q	INLAND BARE GROUND
U	UNCLASSIFIED

***Table 2-3**: Land Cover Classes for the Satellite Observations of the UK*

The grading of agricultural land is also described by MAFF [Ref. 35]. Useful descriptions of natural and semi-natural environments in Lowland Britain are also available in a popular account [Ref. 36].

The soils of England and Wales are shown on a series of 1:250 000 scale maps available from the Soil Survey of England and Wales. Central England is covered by Sheets 3, 4 and 6 in this series, which relate to Midland and Western England, Eastern England and South East England, respectively. The soil classification system is described by Avery [Ref. 37], which provides approximate correlations at the Major Soil Group and Soil Group levels with USDA and UN FAO soil classification systems.

The biota of Lowland Britain are described in a wide variety of field guides and a useful overview is provided by [Ref. 36].

2.3.3 - Climate

The present-day climate of Britain has recently been characterised by Hulme [Ref. 38], based on a gridded, 10 km resolution climatology for the period 1961 to 1990. The average annual temperature over land of the British Isles is about 8.6°C. The warmest years in the 340-year Central England Temperature (CET) record were 1990 and 1999, both 1.2°C above the 1961-90 average. The coldest year was 1740, 2.7°C below this average.

Maps of seasonal temperature and precipitation for the British Isles are shown in Figure 2-10 and Figure 2-11, respectively.

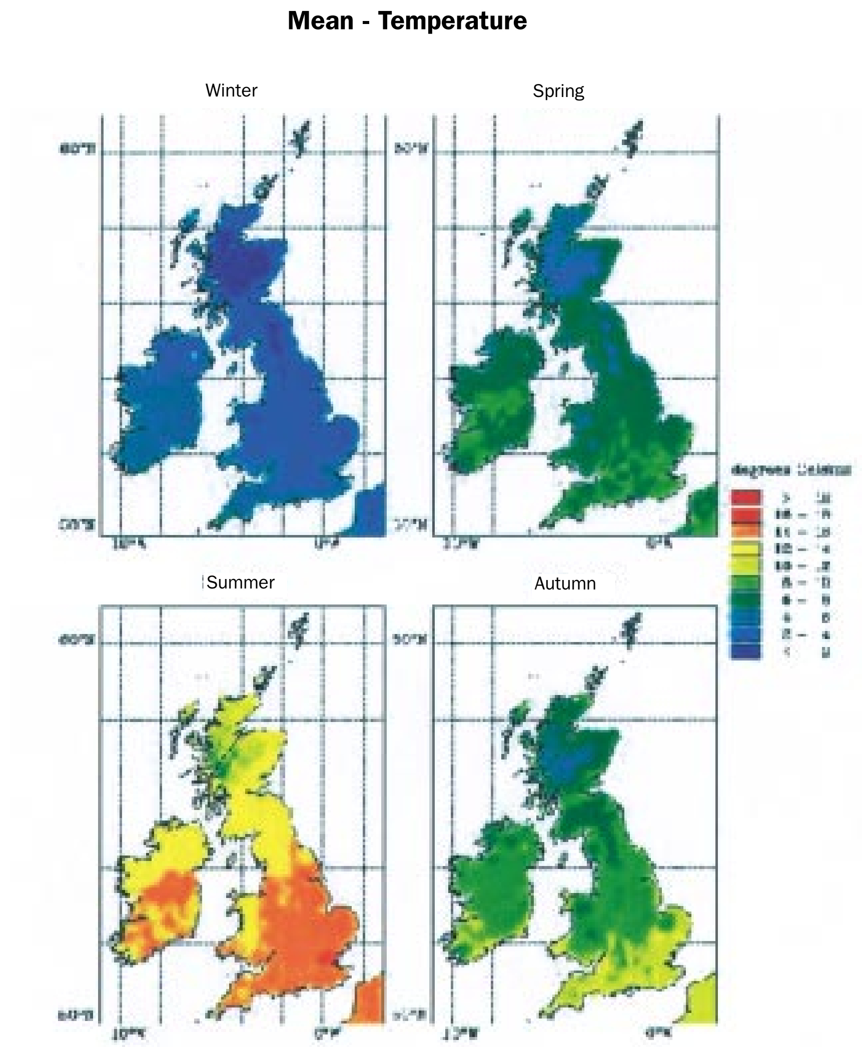

***Figure 2-10:** Seasonal mean temperature (°C) 1961 to 1990 period [Ref. 38].*

(Here, and in Figure 2.11, the data shown are for the average (modal) elevation in each 10 km grid cell and winter=DJF, spring=MAM, summer=JJA, autumn=SON)

Latitude and elevation have a strong, but seasonally dependent, influence on temperatures in the British Isles. Summer mean temperature is more closely related to latitude than to elevation and falls from 17°C in the south of England to around 11-12°C in northern Scotland. Elevation can reduce summer temperatures locally by as much as 3°C. It should be noted that these influences are reported in [Ref. 38] on a 10 km grid; elevation effects on point temperatures can be much larger.

In winter, latitude has a much weaker influence on mean temperatures and, at sea level, the north of Scotland is almost as mild as the south of England (c.4.5°C). This is largely because of the ameliorating effects of the Gulf Stream.

Longitude has only a secondary influence on temperature. In summer, mean temperatures fall by about 3°C from the east of England to the west of Ireland. In winter, there is an increase of temperature of about 1°C from the east of England to the west of Ireland.

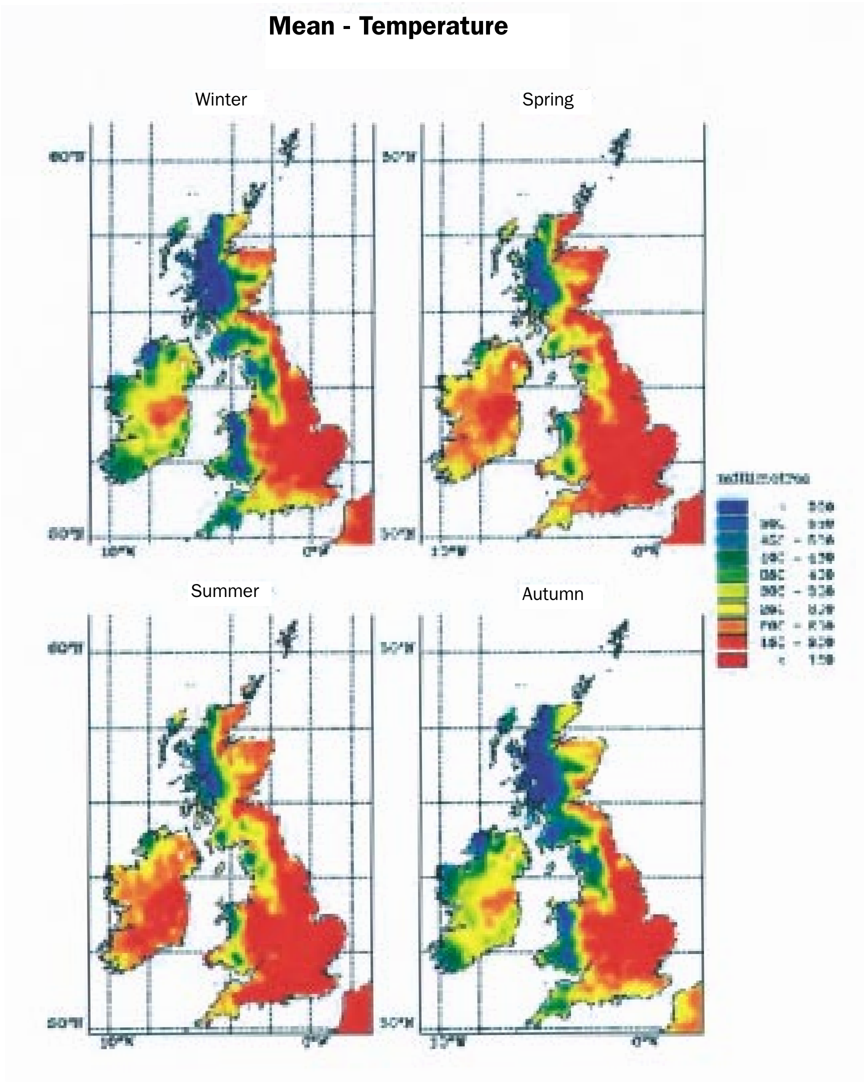

Figure 2-11: Seasonal mean precipitation (mm) 1961 to 1990 period [Ref. 38].

The annual average precipitation over the land area of the British Isles for 1961 to 1990 was 1106 mm. Year-to-year variations can be as large as about ±350 mm. The wettest year in the 230-year precipitation record for England and Wales was 1872 (40% above the 1961-90 average) and the driest year was 1788 (33% below the same average).

Latitude exerts an influence on precipitation in the British Isles, with the influence being greater in winter than summer. Over southern England, summer and winter precipitation totals are comparable (between 150 and 200 mm), but the effect of elevation on winter precipitation in the upland areas of the Pennines and Scottish Highlands is about twice that on summer totals. Winter precipitation reaches 600 mm in the north of Scotland, but summer precipitation only just reaches 400 mm. Larger elevational influences would be measured if a finer-resolution gridded climatology were to be used.

The influence of elevation on precipitation is very marked over the hills and mountains of southern Ireland, south-western England, north and south Wales, the Lake District and the Highlands of Scotland, giving a strong west-east contrast in precipitation. In winter, seasonal precipitation totals over the highest areas of Wales are nearly 600 mm, compared with about 150 mm in eastern rain-shadow areas. In summer, seasonal precipitation totals in the east are similar to those in winter, but in western areas they are only half their winter values.

2.3.4 - Surface and Near-surface Hydrology

For lowland catchments, it is convenient to base the hydrological classification of soils on the standard scheme developed by the Institute of Hydrology [Ref. 39]. This scheme has been used as a basis for recent assessment studies undertaken by Nirex. Four broad classes of soils were considered:

- well-drained soils with the water table at depth greater than 2m;
- well-drained soils with the water table at depth less than 2m;
- surface-water gley soils;
- groundwater gley soils.

Waterlogged (usually peat) soils, which are also included in the scheme, were not considered. This is because they tend not to be cultivated (unless artificially drained), as excessive water can retard the downward development of, or asphyxiate, plant roots.

In the case of surface waterlogging, the soils have only limited connectivity with underlying groundwater. They are also of limited interest in lowland areas of Central England.

Within each of these broad classes a more detailed characterisation was adopted. Thus, for example, well-drained soils with the water table at depth greater than 2m were differentiated as shown in **Table 2-4**. Similarly, well-drained soils with the water table at depth less than 2m were differentiated as shown in **Table 2-5**.

Other aspects of the surface and near-surface hydrology of Central England are covered in various other synthesis reports and databases (e.g. [Ref. 39]; [Ref. 40]) and archives such as the National Environmental Research Council National Groundwater Archive (http://www.nwl.ac.uk/ih/nrfa).

A	Flow Mechanism	Substrate Hydrology
1	Weakly consolidated, microporous by-pass flow uncommon (Chalk)	Chalk, chalk rubble Clay with flints plateau drift Chalky drift
2	Weakly consolidated, microporous, by-pass flow uncommon (Limestone)	Soft Magnesian, brashy or Oolitic limestone and ironstone
3	Weakly consolidated, macroporous, by-pass flow uncommon	Soft sandstone, weakly consolidated sand
4	Strongly consolidated, non or slightly porous, by-pass flow common.	Weathered/fissured intrusive/metamorphic rock Hard fissured limestone Hard (fissured) sandstone
5	Unconsolidated, macroporous, by-pass flow very uncommon	Blown sand, Gravel, Sand
6	Unconsolidated, microporous, by-pass flow common	Colluvium, Coverloam, Loamy drift

***Table 2-4**: Differentiation of well-drained soils with water table at depth greater than 2m*

E	Flow Mechanism	Substrate Hydrology
7	Unconsolidated, macroporous, by-pass flow very uncommon	Blown Sand, Gravel, Sand
8	Unconsolidated, microporous, by-pass flow common	Hard but deeply shattered rocks River alluvium, Marine alluvium, Cover loam, Loamy Drift, Chalky Drift

***Table 2-5**: Differentiation of well-drained soils with water table at depth less than 2m*

3. Paleodata for France

3.1. - Background and Objectives

3.1.1 - Reference Data

3.1.1.1 Glacial advances

The uppermost moraines of the last glacial cycle extend over Wales, the North Sea, and Denmark, before describing a major lobe in northern Germany. At their closest, the land-based Fennoscandian and UK ice sheets were some 500 km to the north of the Meuse/Haute Marne site in eastern France, while the principal mountain glaciers remained about 150 km to the southeast (Alps, Massif central and Jura).

Fossil periglacial structures [Ref. 41] show that, during these cold periods, the region was subjected to a periglacial type of climate, cold and dry, with the development of deeper and more continuous permafrost than elsewhere in France, owing its relatively northerly and continental position.

The nearest glaciers were located on the Vosges mountains, 80 km east-south-east of the site. Their exposure to westerly winds, and a maximum altitude of approximately 1400 m, permitted the accumulation of considerable volumes of snow. The Vosges range has therefore been covered several times by ice caps during the Quaternary period. In the last glaciation, the thickness of this cap was an estimated 500 to 600m [Ref. 42]. It sent distributary glaciers into the peripheral valleys (Moselle, Moselotte, Onion) to around 800m altitude.

The number and age of the Vosges glacier advances and retreats during the Quaternary are uncertain. However, it appears that the maximum glacial ice development of the last cycle did not coincide with the maximum extension of the Fennoscandian ice sheet (at around 20 000 years BP). Glaciation appears to have oocurred earlier, possibly at around 40 000 BP (OIS3), which seems to be the general rule for other French mountain ranges (Massif central, Alps etc.) [Ref. 43]. This could be explained by the dryness of the regional climate during the later part of the glacial cycle.

3.1.1.2 Climatic records

a) <u>Reference climatic record: Grande Pile sequence</u>

Situated 120 km southeast of the Meuse/Haute-Marne site and at about 330m altitude, the 'Grande Pile' peat bog in the Vosges developed behind an earlier moraine. The bog is some 17m thick, and its palynological analysis by Geneviève Woillard [Ref. 44; Ref. 45] helped to reconstruct the evolution of regional vegetation and climate for he last 140 000 years. This provides the primary reference for Meuse/Haute-Marne site palaeoclimatic reconstruction.

The Grande Pile sequence, which begins with the end of the second last (Saalien or Riss) glaciation, covers the second last interglacial (Eemian or Riss/Würm) and the last (Weichselian or Würm) glaciation, up to the present interglacial. The celebrity of this section stems from the fact that it was one of the first to be correlated with the isotopic curves obtained from the North Atlantic boreholes. This reputation also made it ideal for use in the reconstruction of temperatures of the earlier part of the last cycle by a transfer function approach [Ref. 46; Ref. 47].

However, the Grande Pile cannot serve as an absolute analogue for the Meuse/Haute-Marne site, for two main reasons. First, being located close to the Vosges ice cap, this sequence is situated in a mountainous context, in the shelter of an entrenched valley. Second, the climatic reconstructions of Guiot et al. [Ref. 47] are based on flora developed on an acid granitic substrate resulting in transfer functions that produce notoriously excessive palaeotemperatures. In the view of certain specialists, these estimated temperatures are so high as to preclude the formation of icecaps.

By contrast, the Meuse/Haute-Marne site is in a topographic situation of limestone hills and plateaux. The climatic context is therefore more continental than at Grande Pile. In order to translate palaeo-environmental indicators to the Meuse/Haute-Marne site, it is therefore necessary to calibrate the thermal curves using other regional markers, such as periglacial casts and deposits.

b) Other records used to take into account spatial variability in climate

- The Achenheim loess. Not far from Strasbourg, the Achenheim loess beds reveal a thick eolian periglacial cover, representing several climatic cycles. The last cycle (Eemian, Weichselian) is represented by deposits up to 17m thick and is particularly rich in molluscs. This sequence has given rise to several multidisciplinary studies, with reconstruction of the climatic evolution [Ref. 48].

  Due to its geographic position, this site is an important marker for comparisons with Northwest and Central Europe. It also helps to rank the major features of the evolution of the last cycle and to match them against the major global events. These loess deposits are located in the Alsace trench, in other words, in a very specific regional context, yet they reveal the major climatic trends identified in the other long-sequences such as that of Grande Pile, with the possible exception of the Pleniglacial interstades. This would tend to demonstrate the low intensity of these episodes and helps attribute them to changes in humidity, rather than in temperature.
- The 'breeding grounds' of the Hautes Fagnes. Some 150 km northeast of the Meuse/Haute-Marne site, in the Belgian Ardennes, lie several dozen decametric circular depressions, interpreted as of periglacial origin and dated to the Younger Dryas (11 000 years BP). Like their equivalents in the Netherlands, Wales and Ireland, they are bordered by a small rampart, and are hence conventionally described as scars of fossil pingos. However, a specialist in the field [Ref. 49] sees them rather as mineral palsen, although the difference between the two forms does not appear to be very clear. The distinction is important, however, because pingos require continuous permafrost, whereas palsen can be formed in discontinuous permafrost.
- The 'fish ponds' of the Paris Basin. Abundant small circular depressions also exist in the Paris Basin and its margins. Often called 'fish ponds', such features abound in Brie, Sologne, Lorraine, etc. [Ref. 50; Ref. 51; Ref. 52; Ref. 53]. These numerous depressions are often interpreted as being of periglacial origin [Ref. 50; Ref. 52; Ref. 53; Ref. 54], although the absence of a border rampart has discounted the hypothesis that they are scars of fossil pingos. Certain forms could nonetheless correspond to the past existence of permafrost [Ref. 55].

  Whilst these very numerous depressions attracted the attention of researchers in the Fifties and Sixties, the certainty of their formation being associated with periglacial conditions still remains to be demonstrated. The Lorraine structures appear to be explicable by karstic drawdown [Ref. 51], which does not seem to apply to several Sologne sites recently discovered during geological map surveys. This question was developed and discussed at the SGF, during the "Journées à la mémoire d'André Cailleux" conference in January 1997. Some trenches intersecting these structures could help pinpoint their origin and undoubtedly advance the knowledge of the French permafrost.

3.1.1.2 Climatic records

Maps of environments during last climatic extremes in France (8000 ± 1000 years BP and 18 000 ± 2000 years BP) (see Figure 3-1 and Figure 3-2) summarize all the available knowledge, particularly with respect to vegetation and permafrost [Ref. 56]. World maps for the same dates [Ref. 1] (shown in Section 1) provide a general context.

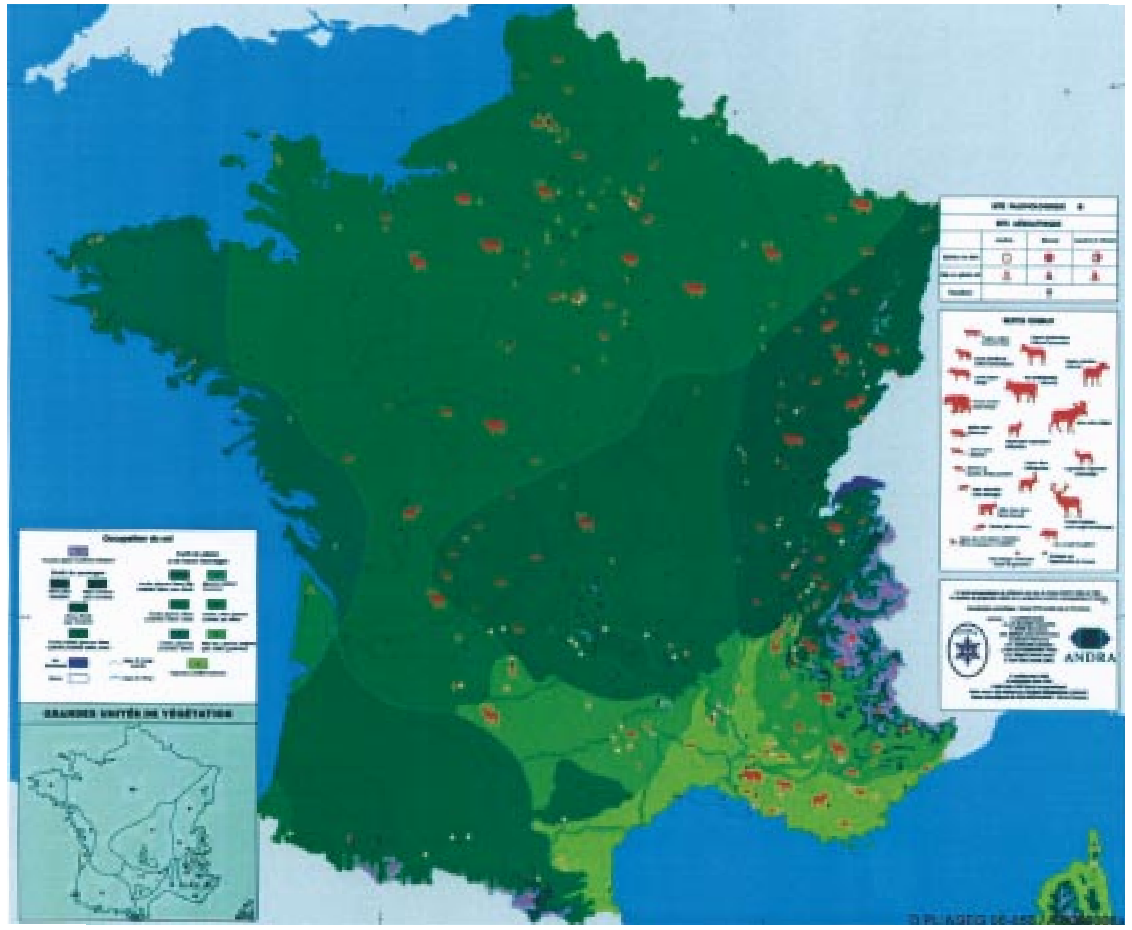

Figure 3-1: France at the Holocene climatic optimum (8 000 ± 1 000 y BP)

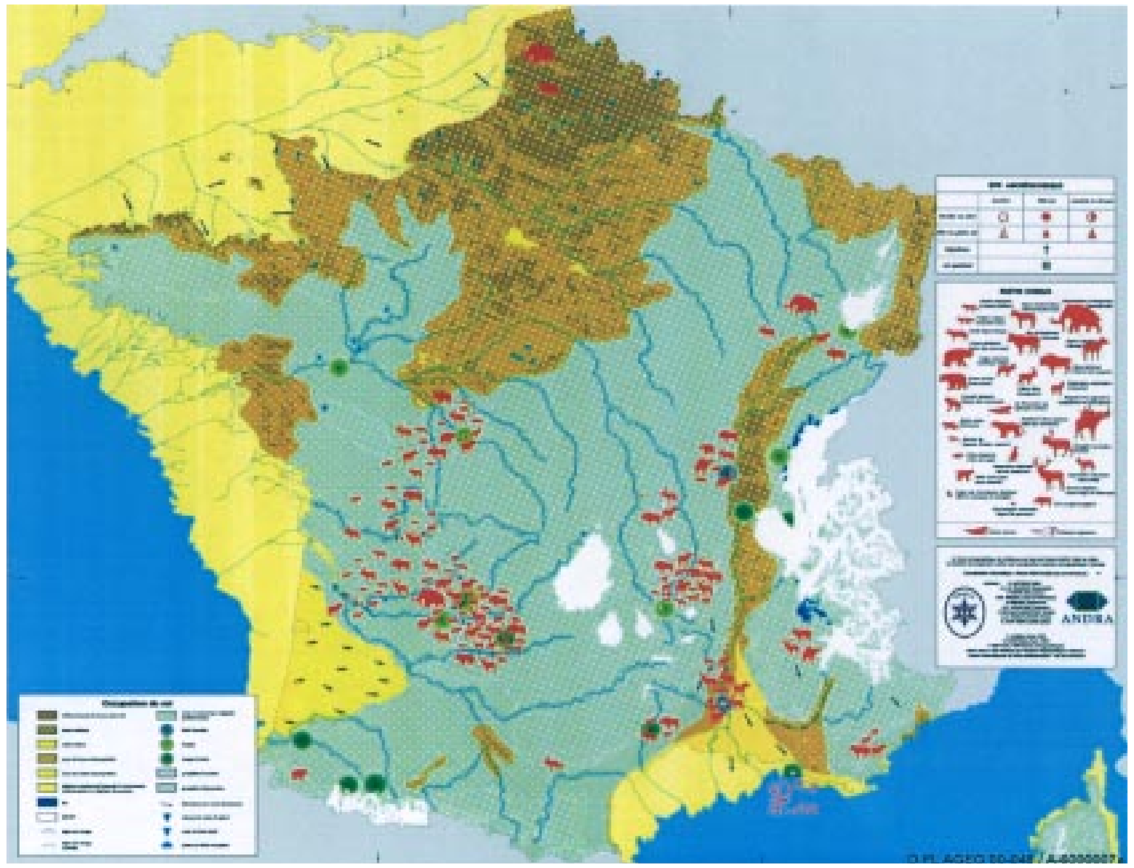

Figure 3-2: France at the Last Glacial Maximum (18 000 ± 2 000 y BP)

3.1.2 - Environmental Change during the Last Climatic Cycle

A Quaternary climatic cycle is defined as the time interval between two climatic optima. It begins with an interglacial and contains the progress of a glaciation. At present, in a continental environment, only the last cycle is well known, explaining its selection as a basis for scenario development.

For the needs of this project, a simplified climatic scenario is proposed, reduced to the succession of main climatic events characterised by annual averages. The selected events in this simplified scenario are numbered 1 to 13.

Reconstruction of the values of climatic parameters for the site itself from the set of data listed above needs to take into account the differences associated with the various methods employed (i.e. pollen spectra and insects; periglacial structures) and those arising from spatial variability of climate according to geographic criteria. This has been achieved using published transport functions for the different types of palaeoclimatic data, as described in: [Ref. 46; Ref. 57; Ref. 58; Ref. 59; Ref. 60; Ref. 61; Ref. 62; Ref. 63; Ref. 64; Ref. 65]. All these data were discussed and adapted to the Meuse/Haute-Marne study zone (taking account of latitude, continentality, altitude, topography, substrate, fossil traces, proximity of ice-covered zones, etc). To consolidate this exercise, various studies and climatic maps concerning the Present, as well as the mean annual temperatures, or the annual number of frost days, were used.

In order to account for the contribution of interpretation to each method of analysis and the cumulative uncertainties associated with palaeodata, two scenarios have been developed:

- A "cold" scenario. This corresponds to the information supplied by the fossil periglacial phenomena known in the field and reflects more strongly information concerning the minimum temperature experienced by the soil.
- A "warm" (or more precisely "less cold" or "temperate") scenario. This is based on vegetation reconstructions carried out by palynology, reflecting more strongly the interpretation of air temperature.

It is recognised that soil and air temperatures are different entities and cannot therefore be directly compared; moreover, soil temperature records tend to be winter-weighted, whereas air temperature (palynological) reconstructions are more likely to be summer-weighted. Nevertheless, together they provide a mechanism for incorporating all the available sources of palaedata in establishing an overall confidence interval for the environmental change scenario.

The proposed sequence of change, designed for the needs of assessment modelling, is very schematic (static, smoothed to remove high-frequency fluctuations and transitional phases). It is limited to a series of mean annual values for each of the selected steps (events) in the climatic evolution during the last cycle (OIS 5 to 1), as distinguished for eastern France. The durations are arbitrarily measured in thousands of years; the shortest step that has been distinguished is the cold peak of the Younger Dryas, which lasted less than 1 000 years, extended to a basic duration of 1 000 years for this schematisation.

- The Eemian: The last climatic cycle begins with an interglacial: the Eemian of the Nordic scale, or Riss-Würm of the Alpine nomenclature.

The Eemian starts at around 126 000 years BP and ends around 116 000 years BP, or around 75 000 years BP, depending on whether or not the first preglacial cold waves are included.

- The first part of the Eemian (OIS 5e) is hot: probably 1 to 2°C warmer than the present interglacial. This is **event No. 1** of the environmental change scenario.

- The second part is marked by two intense coolings (OIS 5d and 5b = Mélisey I and II), which sometimes tend to qualify it as Preglacial or Pre-Würm.
These are **events Nos. 2 and 4** of the scenario. We have assigned them a duration of five thousand years each. They are probably synchronous with advances of Alpine glaciers and correspond to two palaeosoils of the Burgundian association (Vanney series). The more recent (OIS 5b) is the colder of the two.
The palaeo-vegetation record indicates an environment approximately identical to the present southern Scandinavia or the Moscow area.
- **Events Nos. 3 and 5** (Saint-Germain I and II) correspond to more temperate conditions, which (together with OIS5e) frame the cold waves.

- The Lower Pleniglacial: This corresponds to OIS 4, which announces the Würm (Alpine scale) or the Weichselian (nordic scale) and begins around 75 000 years BP. It is identified as **event No. 6** within the scenario, and has been assigned a duration of 6 000 years including transition periods. It was very wet, corresponding to local glacial developments in nothern mountains (Scandinavia, Ulster) and also probably in the Vosges range.

- The Middle Pleniglacial: Between 70 000 years BP and 30 000 years BP (OIS 3), is a period of stationary cold conditions (a "cruising" periglacial) interrupted by a number of still poorly defined interstades. The has been simplified for the purposes of environmental change reconstruction by dividing this period into two equal units designed to test the effects of the cold over long durations (**events Nos. 7 and 8**)

- The Recent Pleniglacial: After a mild interstadial phase (**event No. 9**), lasting 5 000 years without transitional periods, the last glaciation, between 25 000 years BP and 15 000 years BP, was the coldest interval of the last 130 000 years (**event No. 10**).

The glacial maximum is dated 18 000 BP and the environments for France at this time (shown in Figure 3-2) have been reconstructed from 14C dated records [Ref. 56]. During this maximum cold period the mean annual temperature is estimated to have been 15°C lower than that of today. Averaged over the entire duration of event No. 10, which includes shorter, less cold episods, the mean temperatures are estimated to have been around twelve degrees lower than today.

During event No. 10, North-European inland ice sheets achieve their maximum extent. It is also in this period that the periglacial ambiance was the most drastic in Meuse/Haute-Marne (as everywhere in continental Europe), with an attendant maximum development of the permafrost and windy conditions.

- The Deglaciation: The climate warmed rapidly between 15 000 years BP and 10 000 years BP, (OIS 2) (**event No. 11**), before reaching the Holocene interglacial regime (OIS 1).

At around 11 000 years BP, this warming was interrupted by an intense cold spell known as the Younger Dryas (**event No. 12**), which lasted at for approximately a millennium, during which glacial and periglacial conditions were re-established.

- The Present Interglacial or Holocene: The Thermal Optimum (**event No. 13**) is estimated to have occurred approximately 8 000 years BP. The palaeoenvironments in France during this period have been synthesised by mapping (Figure 3-1) [Ref. 56]. The mean annual temperature on the site at this maximum is not particularly well characterised (either 2-3 °C or only 1°C higher than today).

The present day mean temperature close to the Meuse/Haute-Marne site is +9.8°C. Although the present interglacial (OIS 1) witnessed a thermal optimum, the mean annual regional temperatures averaged over the entire duration of event No. 13 have been smoothed to this present-day value.

The (smoothed) climatic history of the last 126 000 years has been reconstructed by chaining together these thirteen events in a sequence representing the assumed climate evolution over the last climatic cycle.

Table 3-1 below summarizes the succession of events of the last climatic cycle at the Meuse/Haute-Marne site. It show the timing, duration and the mean annual temperatures adopted for the two scenarios .

Climatic evolution			Calendar Age (ka BP) including transition durations	Estimated Duration (ka)	Temperature (°C) annual thermal value	
OIS	N° *	*SELECTED EVENTS* Name			"Warm" Scenario	"Cold" Scenario
1	13	Holocene	0 – 10	10	+10°	+ 10°
2	12	Younger Dryas	10 – 11	1	- 1°	- 3°
	11	Late glacial	11 – 15	4	+ 4°	+ 2°
3	10	Maxi glacial	15 – 26	11	- 6°	- 12,5°
	9	Interstade	26 – 32	6	+ 2°	+ 1°
	8	Cold glacial	32 – 51	19	- 5°	- 10°
	7	Temperate glacial	51 – 70	19	0°	- 2°
4	6	Early glacial	70 – 76	6	- 4°	- 8°
5	5	St Germain II	76 – 85	9	+ 5°	+ 2°
	4	Melisey II	85 – 91	6	- 3°	- 5°
	3	St Germain I	91 – 100	9	+ 6°	+ 3°
	2	Melisey I	100 – 106	6	0°	- 2°
	1	Eemian	106 – 126	20	+ 11°	+ 11°

* these thirteen climatic events (stages) are arbitrarily numbered in their natural succession, from the oldest to the most recent.

***Table 3-1**: Situations and Parameters selected for the Climatic Scenario at the Meuse/Haute-Marne site during last glacial cycle.*

As indicated in **Table 3-2**, below, there are several uncertainties regarding the assignment of calendar ages and identification of stratigraphic cut-offs to constrain the climatic reconstruction. This table also indicates the uncertainties associated with the proposed climatic scenario that arise from the different interpretations of Grande Pile sequence [Ref. 43; Ref. 44; Ref. 45; Ref. 66] and gives information about assumed changes in precipitation rate during the climatic cycle.

Grande-Pile stratigraphy (1)		Ois	T (°C) (estimated)		Proposed Climatic Scenario (2)			Grande-Pile climatic reconstruction (pollen & beetles) (3)		
Age (ka PB)	Local name		Summer	Winter	Stage	Age (ka PB)	Name	Name	Age (ka BP)	T°C(r)
0 – 10,2	Holocene	1			13	0 – 10	Holocene	Holocene	0 – 11	10
10,2 – 10.7	Recent Dryas	2			12	10 – 11	Recent Dryas	Recent Dryas	11 – 13.5	3
10.7 – 29	Lanterne III				11	11 – 15	Late glacial	Late glacial	13.5 – 18.5	5
		3			10	15 – 26	Maxi glacial	Maxi glacial	18.5 – 29	0
					9	26 – 32	Interstade	Glacial	29 – 73	2
29 – 70	Lanterne II				8	32 – 51	Cold glacial			
		4			7	51 – 70	Temperate glacial			
70 – 75	Ognon				6	70 – 76	Early glacial			
	Lanterne I									
75 – 85	St Germain	5a	15.5	-1	5	76 – 85	St Germain II	St Germain II	73 – 88	9
85 – 95	Melisey II	5b			4	85 – 91	Melisey II	Melisey II	88 – 94	4
95 – 105	St Germain I	5c	15.5	-1	3	91 – 100	St Germain I	St Germain I	94 – 103	8
105 – 115	Melisey I	5d			2	100 – 106	Melisey I	Melisey I	103 – 109	3
115 – 127	Eemian	5e	15.5	-1	1	106 – 120	Eemian	Pre Melisey	109 – 116	5
								Eemian	116 – 129	9

(1) from [Ref.66] - (2) from Table 3-1 - (3) from [Ref.67]

***Table 3-2**: Climatic Parameter Values and Time Uncertainties from the Grande Pile Analysis*

3.1.3 - *Periglacial Phenomena occuring during Cold Stages*

Numerous periglacial phenomena affect both the formations belonging to the substrata and the fluviatile formations [Ref. 68; Ref. 69; Ref. 70; Ref. 71; Ref. 72; Ref. 73; Ref. 74; Ref. 75; Ref. 76]. Among these many phenomena, we can mention:

- Ice wedges and polygonal patterned ground reaching 1.8m in diameter. They are developed on alluvial terraces, but also in the carbonates heavily weathered on the surface. Ice perturbations (corrugations, injections) are recorded both in the Albo-Aptian clays and on the surface of the Jurassic limestones. The largest reach up to 2m in height.
- Cryoclastic hillside slope deposits, including shingles (or scree) bedded to varying degrees, carpeting the foot of the reliefs (~3.5m). These materials undergo solifluction and cryoreptation on the slopes and can be taken up as alluvia.
- Intense fracturing of the Jurassic limestones on the Barrois hillsides, which are "completely dismantled" over a thickness of 2 to 3m by congelifraction and congeliturbation.
- Large vertical diaclases in the Oxfordian limestones, reaching up to 6.6m in depth with a 1.6m opening at the top. These diaclases are filled with red silt mixed with congelifracted scree. An identical filling mode of cryoclastic scree mixed with red clay plugs the numerous karstic depressions.
- Plateaux silts (1 to 3m) on the surface, with a large component of "round-dull" grains implying strong eolization of periglacial origin;
- Dry valleys with asymmetric slopes whereof the slopes and the filling of their beds have been shaped largely by the action of periglacial processes.

The scale and distribution of these periglacial events follow an altitude and orientation gradient. In particular, they mainly disturb the slopes exposed to the north and east, and exceptionally, to the southeast.

3.2. - Vegetation Reconstruction for the French Site

3.2.1 - *Literature Data (from 400 000 years BP)*

The approach followed by the Paleoecology laboratory of the University of Marseilles makes use of new and unpublished data concerning the Grande Pile (Vosges) sequence. In addition, it takes account of an inventory of all the available data that served or could serve for reconstructions of the palaeoenvironments and palaeoclimates during the last four climatic cycles, at distances that permit reasonable extrapolation to the Meuse/Haute-Marne site.

This approach is required because the Quaternary in the region of the site is very poorly represented and, in any case, has not been the subject of any study permitting a retrospective evaluation of the climatic conditions that might be experienced in the coming millennia.

It is also justified because it permits a range of different palaeoenvironmental markers to be taken into account (physical signals such as those provided by geomorphology, pedology and geochemistry, and biological signals such as pollens, macro-remains, molluscs, insects and diatoms). It also helps to account for certain divergences in interpretations stemming from different perceptions or processing of the data.

3.2.1.1 - Recent data from the Grande Pile (Vosges)

- Presentation of the site

The Grande Pile peat bog (47°44' N, 6° 30' 14'' E, 330 m) located in the commune of Saint Germain, Haute -Saône, belongs to the Ognon basin. The site is famous because it corresponds to one of the very few wetlands of Middle Europe in which a sedimentation of lacustrine and then palustrine deposits could have taken place continuously since the end of the penultimate major glaciation, thereby covering about 140 000 years BP. It is located only 200 km from the Meuse/Haute-Marne site and, since its discovery by Woillard and Seret, has been the subject of numerous studies, including one of the very first correlations between European continental records and Atlantic oceanic sequences covering the last climatic cycle [Ref. 76] and the first quantitative climatic reconstruction from pollen data [Ref. 77].

At present, the wetland, with an area of 25 hectares (60 acres) receives water only from small local streams. The peat has been extracted for a long time and the bog has been drained, so that it has been invaded by a forest of birches (Betula pubescens), willows and alders, with Calluna undergrowth and, on the margins, by oaks from the peripheral forest consisting of mixed woodland of common oaks and yoke-elms.

- Research history

The site, discovered by G. Seret [Ref. 78], was then the subject of intensive palaeoecological research: pollen analyses by G. Woillard including the work which made the site famous [Ref. 79; Ref. 80; Ref. 81; Ref. 82; Ref. 83; Ref. 84; Ref. 85; Ref. 86] and by de Beaulieu and Reille [Ref. 87]. The diatoms were closely investigated [Ref. 88; Ref. 89; Ref. 90; Ref. 91; Ref. 92] and these data provided a basis for quantitative climatic reconstructions [Ref. 47; Ref. 77; Ref. 93; Ref. 94]. The year 1990 saw the initiation of a project to refine these climatic reconstructions by the use of insect fossils, which provide an excellent basis for characterising palaeo-environments and the palaeoclimates. Two series of adjacent cores were obtained for this purpose: the first (eight boreholes) in the central part of the swamp, the location of the reference pollen sequence GP10, was completely worked to find insects [Ref. 47]; the second, about 300 m further south (five boreholes) in a marginal situation, revealed a fairly thick sedimentary deposit. The results are currently being processed.

- Pollen diagram : description and brief interpretation

The recent GP 11 diagram was subdivided into thirty-one pollen zones (ZP):

- Riss Glaciation (ZP 1)

This zone is characterized by very low pollen concentrations and extremely sparse spectra of tree pollens. The co-dominant taxons are poaceae, cyparaceae and various steppe plants. This unit indicates a tundra to steppe tundra landscape, and is the equivalent of ZP1 of sequence GP 20 [see Figure 3-3 from Ref. 87] and corresponds to the end of the penultimate glaciation to which G.Seret gave the local name of the Lure glaciation.

- Eemian Interglacial (ZP 2 to 13)

Local zones 2 to 13 overlie the dynamics of the last interglacial period and fairly accurately reproduce the succession of zones 2a to 21 of GP 20, but with some differences in detail in the pollen frequencies. The progressive forest dynamics involves the replacement of pre-steppe pioneer plants by juniper and boreal woodlands, comprising birches and pines (taiga: “cold mixed” biome), followed by formations including both pines and leafy species, before finally reaching a stage dominated by mixed deciduous forests (predominating oaks and hazelnut trees, succeed by a mix of hornbeams and oaks: deciduous temperate biome), which corresponds to the climatic optimum. We then enter a phase of temperature regression, called catathermic: the mixed woods of alders are enriched in firs (“cool mixed” biome) preceding the development of a forest dominated by fir and spruce, and all the temperate taxons are finally supplanted by probably open boreal forests, dominated by pines and spruce with relatively abundant birches, and then by pines.

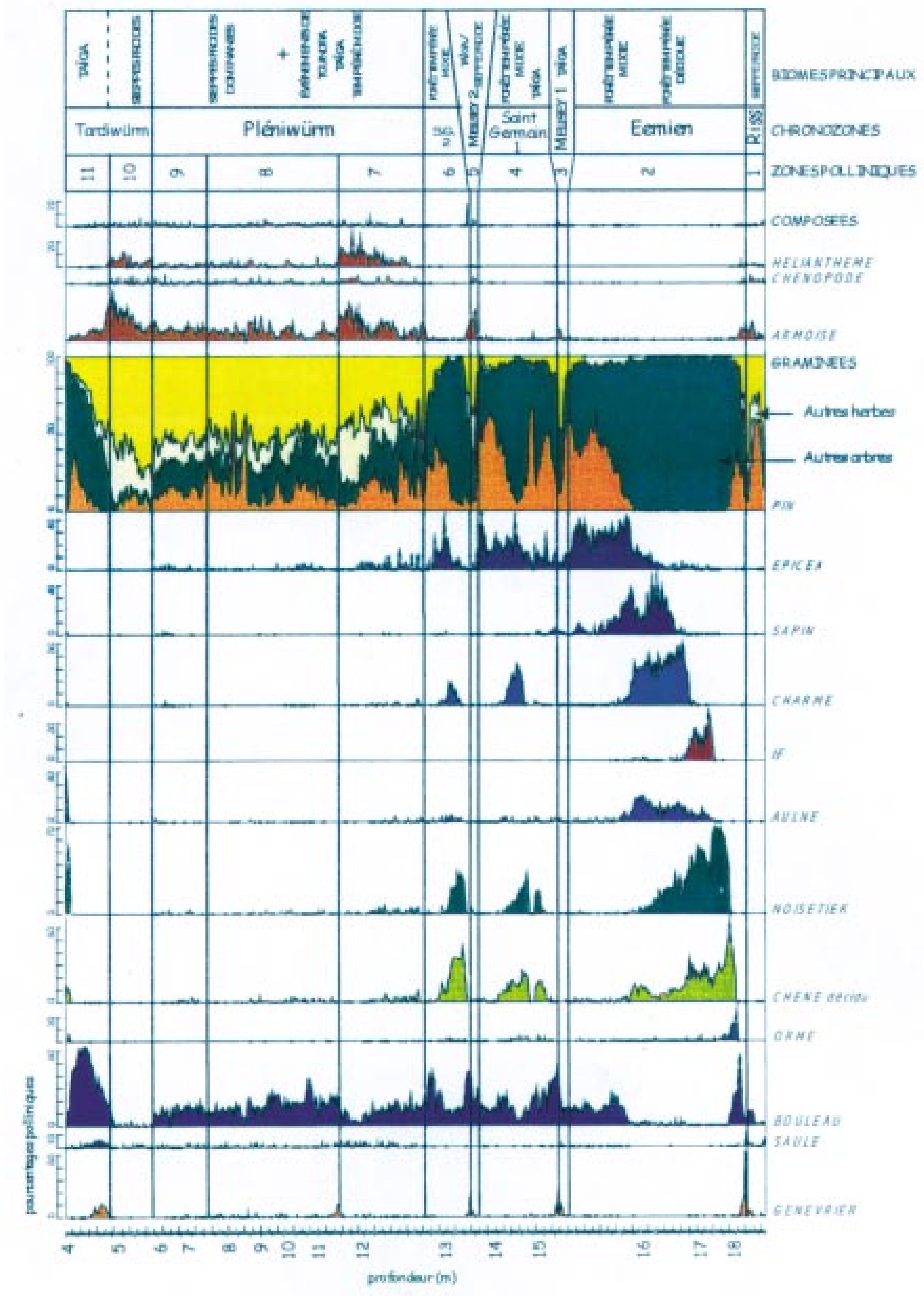

Figure 3-3: *Simplified pollen diagram of Grande Pile 20 [Ref. 77]*

3.2.1.2 - The Velay Sequence

The only sequence continuously covering the last four climatic cycles in western Europe is the Velay sequence, which although 500 km distant from the Meuse/Haute-Marne site, remains an unavoidable reference. The great similarity between the evolution of the vegetation during the last interglacial at Grande Pile and in Velay has been demonstrated [Ref. 87]: the relatively high altitude of Velay (1200 m) appears to be offset by its comparatively low latitude. Hence this shows that it is not foolhardy to seek references very far south. A correlation between the long Velay sequence and the German stratotypes has also been proposed [Ref. 95].

This exceptional sequence is presented in a simplified view in Figure 3-4. It sheds a new light on the climatic variability of western Europe, demonstrating the global (transhemispheric) characteristics of the great climatic cycles: evident similarities emerge between the pollen curves showing the variations in temperate to boreal biomes and the curves of the climatic markers of the Vostok Antarctic ice core. Nevertheless, the dynamic of ecosystems represented at Velay display pronounced regional features.

Figure 3-4 shows the variations in the pollen frequencies of the main forest taxons during the interglacials initiating the four cycles. In all cases, following a phase of pioneering colonization by pine (Pinus) and birch (Betula), a variable length phase of expansion of the suite of oak (Quercus) and hazel (Corylus) follows, which corresponds to the thermal optimum.

This is followed by the invasion of deciduous and coniferous varieties that are less thermophilic and/or with a slower dispersion, and finally the development of boreal forest. Except for the final step, which has not yet been reached, the same general dynamic is found in the course of the Holocene, albeit with many differences in detail. For example, at the beginning of the Holocene, the expansion of Quercus was preceded by that of Corylus, which could be explained by the aptitude of the latter taxon to play a pioneering role. However, this interpretation is unlikely since in all the preceding interglacials, the oak forest is established before the hazel optimum.

In three cases, hemlock (Taxus) experiences a phase of prosperity marking the beginning of the regression of the mixed oak grove. Locally it has no success during the Holocene, but it exists in highly localized areas where a Holocene optimum has been recorded after the maximum of the mixed oaks. In three cases, this regression favors the yoke-elm (Carpinus), which nonetheless plays no role during the Praclaux interglacial and the Holocene.

The mountain taxons, fir (Abies), beech (Fagus) and spruce (Picea) experience various degrees of success : the Praclaux interglacial is characterized by the premature extension and the long success of Abies, combined with Picea and then with Fagus (this is also the only occasion when a taxon that has disappeared from western Europe is observed, Pterocarya) ; during the Landos interglacial, Abies and Fagus simultaneously take over from Carpinus; during Bouchet 1, none of the mountain taxons experiences any expansion, the dynamic of the end of the interglacial seems to be interrupted by a cold wave directly favorable to the boreal pine forests. During the last interglacial, Abies and especially Picea experience phases of vigorous expansion while Fagus is absent, as in most of the European sequences of the same age. This feature contrasts it with the Holocene, during which beech plays a major role whereas spruce is absent.

The differences between the forest successions of these interglacials are no doubt chiefly due to internal causes: the refuges during the previous glacials did not have the same locations and created different migratory routes at each reconquest, with different competitive conditions. However, they were also controlled by orbital factors, which vary from one interglacial period to the next. Although each early interglacial clearly coincides with an insolation maximum in the northern latitudes, the amplitude of this insolation and its variations during the interglacial, the seasonality parameters, have not

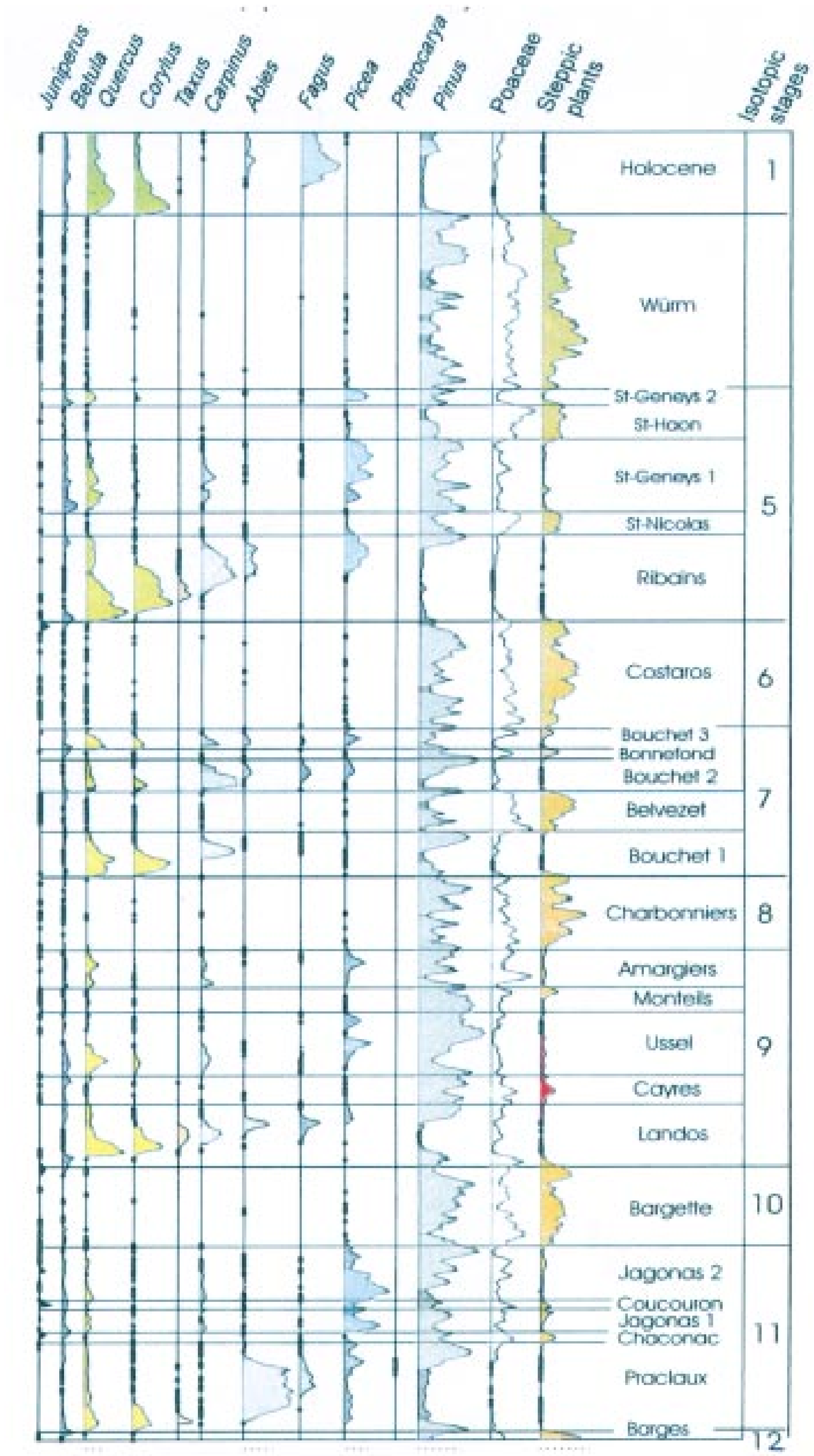

Figure 3-4: Pollen diagram of the Maars du Velay, Massif Central

been identical and have favoured one particular dynamic rather than another. Ecologists and climatologists still need to combine their effors, because an exhaustive explanatory model is far from having been constructed.

3.2.1.3 - Pollen data near the site during the last glacial cycle

- Late glacial and Holocene

The Holocene was closely investigated in a recent study [Ref. 56] using data taken from the literature by a group of regional experts, coordinated by Andra. Figure 3-1 shows the distribution of vegetation in France at 8 000 years BP. This period is characterized in Middle Europe and in a large portion of France by the strong dominance of hazel, in association with mixed oak. This unit is associated with the deciduous temperate biome.

- Last glacial (75 000 BP to 15.000 BP) (14C ages)

If we set aside the Grande Pile record, the lacustrine and palustrine peaty sequences of the last glacial constitute brief entities intercalated in minerogenic deposits. They have been the subjects of pollen analyses, which usually attest to the same type of environment: tundra to shrubby birches. In fact, it is mainly through the study of macrofossils of aquatic plants and by reference to their present ecology that the climatic variations can be inferred [Ref. 96].
It is in the Netherlands that the now classic subdivision of the last Pleniglacial has been established:

- Ancient Pleniglacial between about 75 000 years BP and about 55 000 years BP (desert to desert-steppe landscape);
- Middle Pleniglacial (between 55 000 and 29 000 years BP), less severe and marked by the alternation in the region concerned of three periods characterized by polar deserts to Arctic tundra (however, few palaeobotanic are data available) and three more temperate intervals which are the interstades of Moershoofd (between 50 000 and 43 000 years BP), Hengelo (between 39 000 and 37 000 years BP) and Denekamp (between 32 000 and 29 000 years BP);
- Recent Pleniglacial (between 29 000 and 16 000 BP).

This chronology, established by van Huisteden [Ref. 97] and Ran [Ref. 98] in their twin theses, has been revised today in the light of marine and ice sequences. Estimates of the precise ages and duration of the interstades vary between authors, but without putting the original scheme completely into question.

These data obtained in the Netherlands and Belgium conform fairly closely to those obtained at Grande Pile and suggest similar climatic conditions in the sector of the site. The limestone substrate undoubtedly favors the development of cold steppe on the slopes in periods of plant cover.

In Belgium in the 1960s, Bastin attempted to extract pollen from loess sediments [Ref. 99]. The results obtained so often appear aberrant that it was preferred not to take them into account in reconstructions of palaeoclimates for the Meuse/Haute-Marne site.

The Recent Pleniglacial is illustrated by the map of France (see Figure 3-2), charted as part of a scientific joint project, coordinated by Andra.

- Eemian interglacial and early glacial (128 000-75 000 years BP)

This grouping of entities is justified because this unit, dominated by temperate episodes, corresponds to OIS 5. On the continent, these intervals, which are fairly well chararacterised by many pollen sequences, nonetheless raise a number of questions that are not fully resolved concerning the climatic parameters.

Firstly, long before the discovery of Grande Pile, the interstades of Amersfoort/Brørup and Oddrade had been described in the Netherlands, Northern Germany and Denmark. Their correspondence with the Saint-Germain temperate episodes Ia, Ic and II of Grande Pile is clearly established. However, during the optimum of these interstades, when Grande Pile was occupied by deciduous temperate vegetation, territories that bordered the North Sea were covered by boreal forests. This pattern clashes completely with those of the Eemian and the Holocene during which the ecotone between temperate deciduous forests and boreal forests advanced far to the north of Stockholm. This difference cannot be explained by the migration time of the temperate taxons from their refuges, because these interstades are quite as long as the first half of the Holocene, a time when the oaks easily reached Sweden, and also because the Mélisey 1 stage did not last long enough to eradicate the thermophylic refuges not far from Grande Pile. In fact, the latter was recolonized by mesophilic leafy varieties at the very beginning of Saint Germain 1.

The following attempts have been made to explain this strange situation:

- The Gulf Stream was diminished during the Saint-Germain temperate episodes and did not penetrate the North Sea : however, this situation is not clearly confirmed by marine data;
- An ice dome began to grow at the end of the Eemian and during Mélisey 1 on the Scandinavian shield and conditioned the descent of the cold fronts towards middle Europe.

Regardless of the cause of this phenomenon, considerable doubt remains: we cannot clearly define the position of the ecotone between the deciduous or mixed forests and the boreal forests. We are therefore unable to state precisely which vegetation dominated at the time in the neighborhood of the site. Yet the pollen analyses of a stalagmitic floor of the Sclandia Cave near Namur by Bastin et al. [Ref. 100] appears to associate this sector to the domain of mixed forests with temperate leafy varieties (hazel, lime tree, yoke-elms and pines). Thus, the site probably belonged more to the mixed woods domain and the track of the ecotone would have followed a NW-SE direction rather than an east-west orientation.

As to the Eemian, discussions are ongoing regarding the duration and stability or climatic instability of this interglacial, which cannot be discussed here. Note however that numerous efforts have been made to synthesize the changes in vegetation and climate during this interglacial at the scale of the European continent [Ref. 101].

- The Upper Middle Pleistocene

Data are scarce for this interval. Reference is made in other work by Andra to the discontinuous sequences of the Rhine valley, the debated Karlich sequence near Bonn, the Belvedere sequence near Maastricht and the Herzeele sequence in northern France, a very likely equivalent to the Holsteinian.

3.2.2 - Regional Data (from 16 000 years BP)

The chrono-ecology department of the University of Besançon was asked to analyze original data from four sequences, located in the Meuse/Haute-Marne site region [Ref. 102].

- Sites selected

Pollen analyses were performed in the natural wetlands suitable for the proper preservation of pollen and fossil spores. Although the low altitude areas suffer from a lack of potential sites such as peat bogs or lakes, they nonetheless offer environments such as lowland swamps, dead arms of rivers, and even wetland prairies, which supply reliable pollen results.

Although most of the fillings analyzed in these zones begin in the Preboreal or the Boreal, two sites on the Lorraine plateau and in the Moselle valley nonetheless provided pollen recordings contemporary with the Late Glacial.

- Geographic and geomorpholigical situation

At 226 m altitude, the Ham-sous-Varsberg acid peat bog is located on Vosgian sandstones, which mark the edge of the Lorraine plateau to the northeast. A 2.5 m borehole displays alternating levels of organic sands and peat.

The Marly site, a palaeochannel in the Seille valley, was subjected to archeological digs and therefore allowed sampling on a section. More or less organic clay levels are intercalated between peat levels to a depth of 3.20 m.

The Waville site, on the bank of a tributory of the Rupt-de-Mad, is located in an entrenched valley at 188 m altitude in the Côtes de Moselle ; the sequence sampled is stepped over 4.5 m with a succession of levels of peat and organic reworked limestone tufa.
A final site on the Lorraine plateau, Francaltroff, is a wet prairie on the edge of a stream at 298 m altitude. This site offers a sequence of peat and stepped organic reworked limestone tufa over 7.7 m; at the base of the borehole (786-790 cm), a level of constructed limestone tufa (diameter > 0.5 cm) is observed.

- Pollen data

In the absence of strictly local pollen references, the zoning of the four diagrams (see Figure 3-5) is based on the main features of the evolution of the extra-regional plant cover. Data are available for the Ardennes département, for Belgium and Luxembourg, for the Paris Basin, for the Vosges and for the Jura.

Zones polliniques locales				Zones		Végétation	Dates
Francaltroff	Waville	Marly	Ham/Varsberg				
13				SUBATLANTIQUE	HOLOCÈNE	apparition du noyer	
12	11					augmentation des herbacées	
11	10						
10	9					apparition du charme	2700 BP
9	8			SUBBORÉAL		développement du hêtre et de l'aulne	
	7						4700 BP
8	6			ATLANTIQUE RÉCENT		Régression progressive de la chênaie mixte	
7							
6						Apparition de l'aulne	6000 BP
5	5			ATLANTIQUE ANCIEN		Plein essor de la chênaie mixte (chêne, orme, tilleul, frêne et érable)	
	4						8000 BP
4	3	9		BORÉAL		1ères essences mésothermophiles	
3	2					Dominance du noisetier	9000 BP
2	1			PREBORÉAL		plein essor du pin	10000 BP
1		8	6	DRYAS RÉCENT	TARDIGLACIAIRE	Ouverture des fôrets de pins et retour de la steppe	11000 BP
		7	5	ALLERØD		Migration du pin	
		6	4				
		5	3				12000 BP
		4		BØLLING		Augmentation du bouleau	
		3	2				
		2				Expension du genèvrier et du saule	12600 BP
		1	1	DRYAS ANCIEN		steppe peu boisée	15000 BP

Figure 3-5: *Synthesis of the history of the plant cover compiled from the four sites analyzed*

- Late Glacial Vegetation

The ancient Dryas is characterized by a very thinly wooded steppe where Cyperaceae and Poaceae predominate. The steppe-like element is represented by Artemisia (sage brush), Helianthemum, Thalictrum and Potentilla (cinquefoil). In these plain zones, Salix (willow) and Betula (birch) make up small clumps of trees; the presence of pollens of Pinus (pine) is certainly justified by the distant inputs. The very low pollen concentrations confirm the extent of the steppes.

The Bølling-Allerød interstade begins with the Bølling which is characterized by an extension of the shrubs (Juniperus, Salix) and Betula. In fact, the climatic upheaval engendered by a rise in temperature that took place at the time permitted all these pioneering shrubs to colonize the steppe of the Ancient Dryas rapidly causing a sharp increase in the pollen content of the sediment. However, there is also a predominance of Cyperaceae and Poaceae in the herbaceous strata, as well as the presence of the steppelike varieties, primarily represented by Artemisia. Salix displays very high percentages (15 to 20%), implying a substantial cover of this shrub on the margin of the two sites investigated. The Allerød is distinguished by the full development of Pinus and Betula pollens, revealing the development of open forests of the boreal type.

During the cooling phase of the Ancient Dryas, the herbaceous varieties again progressed. The fractions of NAP (non-arboreal pollens) reached 50%; the Cyperaceae, Poaceae and steppe-like taxons again predominate in the pollen spectra. The development of a more open landscape is marked by a drop in pollen concentrations.

- Holocene Vegetation

In these low altitude areas of Lorraine, the Holocene begins with a Preboreal, dominated by Pinus and Betula, and from this time, a rapid increase in pollen concentrations is observed in the valley locations. The Boreal is conventionally marked by high values of Corylus whose predominance in the spectra is observed up to the Recent Atlantic. During the Ancient Atlantic, forest vegetation dominated the Lorraine territory; the mixed oak grove (essentially Quercus : oak, Ulmus : elm and Tilia : lime) is the dominant population, with a high content of Corylus (hazel) (between 30 and 40%). Fraxinus (ash) develops more clearly at the end of the period. Hedera (ivy) and shrubs sich as Viburnum (viorne), Sambucus (elder), Frangula (alder buckthorn) are also abundant. The herbaceous vegetation is dominated by Poaceae and Cyperacea, with proportions often close to 30%.

The development of Alnus begins in the early Recent Atlantic; this change in the vegetation is also marked by the decrease of the mixed oak grove and particularly of the proportion of Ulmus. On the Francaltroff and Waville sites, the Tilia values increase at this time. High proportions of Alnus, accompanied by Fagus, characterize the Subboreal. The Subatlantic is marked by the development of a more open plant landscape, largely as a result of anthropic action. A dominance of NAP (80-90%) is accordingly observed.

3.3. - Landform Change

3.3.1 - Development of Permafrost

This section takes account of the data obtained in the GDRE polar program of the CNRS from 1992 to 1996, in the areas bordering the North Atlantic (cooling zone) and the stratigraphic data obtained in Belgium and in Northern France at low altitude [Ref. 64; Ref. 65; Ref. 75; Ref. 103].

The periglacial structures observed at the surface indicate that a relatively thick permafrost developed in France during cold stages, particularly in the eastern part of the Paris Basin where the Meuse/Haute-Marne site is located [Ref. 41; Ref. 104].

The existence of this permafrost, its thickness and its continuity, have direct implications for the surface environment and the type of biosphere (modifications of hydrogeological flows and water resources, seasonal phenomena connected with the dynamics of the active layer and erosion processes). However, the characteristics of this permafrost, in terms of effective thickness and dynamics of development, are not directly accessible by observation. Geological evidence from the cold periods concerns only superficial phenomena, such as ice wedges and polygonal soils, as congelifraction broke up the frost-cracked rocks (bedded scree). Accordingly, interpretations of the depth of this permafrost remain variable depending on the indicators employed. Synthesis of the land records made to produce palaeoclimatic maps of France during the last glacial maximum [Ref. 56], together with the latest publications that accompanied them [Ref. 104; Ref. 105], allow the hypothesis to be advanced of a widespread and thick permafrost in France, particularly in the region where the study site is located.

The extent of permafrost development has been evaluated by means of numerical simulations: modelling the penetration of the 0°C isotherm from the ground surface by applying values of local climatic, petrophysical and geothermal parameters and assumed surface conditions of the soil (in particular, the presence of snow cover). Figure 3-6 summarizes the results of these calculations for the climatic scenarios of the last climatic cycle (**Table 3-1**).

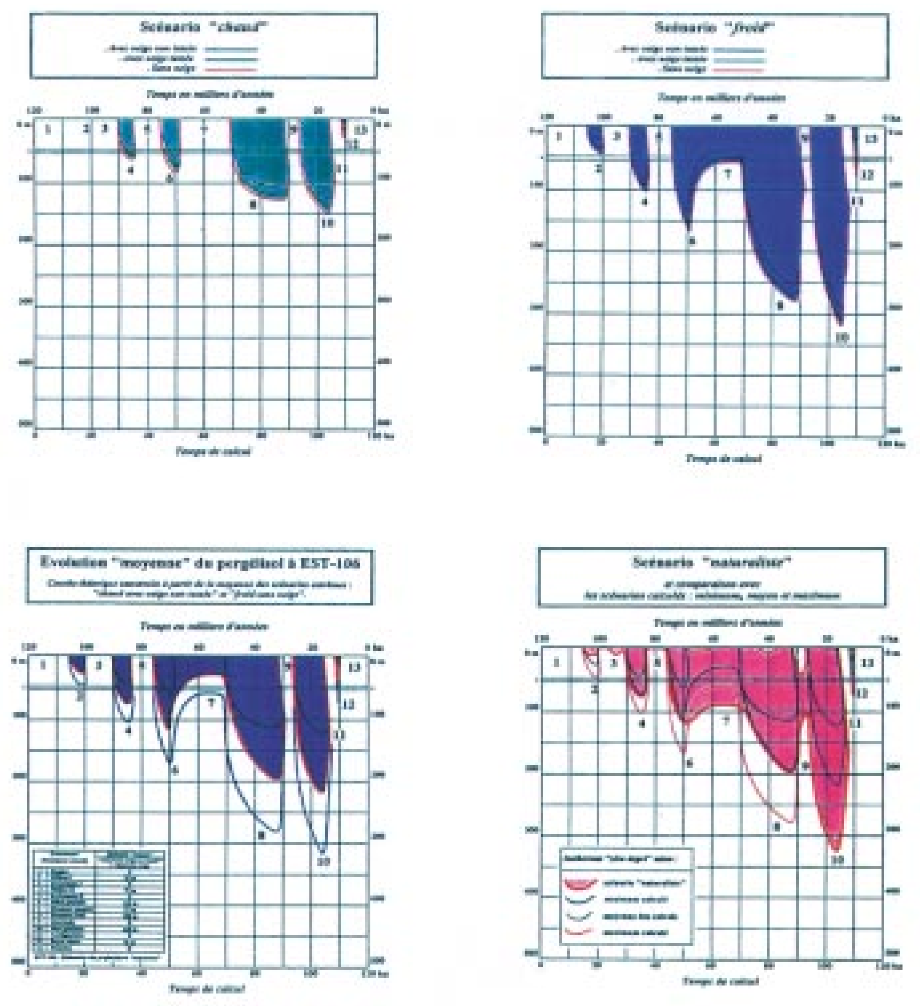

Figure 3-6: *Permafrost depth modelling for the last 120 000 y BP*

The results obtained indicate a rapid and deeper penetration of freezing temperatures on the Meuse/Haute-Marne site during the cold stages, associated in particular with the petrophysical characteristics of the layers and the absence of an aquifer at the surface. These simulations indicate in particular that the presence of continuous permafrost, in other words, at least 50 meters deep, may have been a frequent situation (40 to 50% of the time during this climatic cycle). The maximum penetration of the 0°C isotherm on the site could have reached a considerable depth during the Glacial Maximum (125 to 315 m depending on the scenario). According to these calculations, permafrost could have developed at the site even during the short and moderately cold episodes of the cycle (i.e. Mélisey I and II).

Analysis of speleothems sampled in the karstic caves of the Meuse/Haute-Marne area and of southern France (accurate datings of growth anomalies and isotopic analyses, at lamina scale) contributes further information on this point [Ref. 106]. The growth periods of these speleothems, compared with the curve of the 180 variations observed in marine sediment cores (SPECMAP) and with the palaeotemperature and palaeoprecipitation curves reconstructed from the pollen sequences of the Grande Pile and Echets climatic reconstructions, indicate an absence of groundwater flows during these cold episodes, particulary Mélisey I, which was relatively wet.

3.3.2 - Landscape and Soil Evolution during a Climatic Cycle

The Meuse/Haute-Marne area is affected by a generalised erosional process that started a few million years ago, during the Pliocene epoch: valley incisions, retreats of the line of cuestas and plateaux erosion. There is a potential for significant surface environment and soil modification to occur during a climatic cycle. Such changes are highlighted in **Table 3-3**.

The main changes occurred in valley areas. During a glacial period, the alluvial plains are eroded and rivers incise the substratum (10-12 meters for the Marne valley during the last glacial period). The alluvial plains of the valleys (field areas) therefore disappear at the begining of cold periods. They are then re-constructed (and exist only) during the interglacial periods.

Regional climate state	Meuse/Haute-Marne site, France				
	Vegetation	**Pedogenesis & soil character**	**Hydrology**	**Erosion & Deposition**	**Hydrogeology**
Temperate	Similar to present day. Dominated by woodland with changing composition.	Development of red soils from limestone dissolution (and older grey soils) on plateaux. Development of alluvial plain soils in valleys.	As at the present day. Small meadering rivers in valleys; dry small valleys on plateaux. Active cave circulation, karstic actions.	Floodplain silty formations deposit in valleys. Karstic actions: dissolution of limestone formations and basal erosion of cover formations.	Flooding of all aquifers and dynamic evolution of hydraulic gradients. Local karstic by-pass between valleys
Boreal	Dominated by coniferous species (pine), birch, poplar and alder. Expansion of trees if post periglacial; retreat of trees if after temperate.	Discontinuous permafrost. Gravels and some peat formation in valleys Thin grey soil on plateaux	Large braided rivers in valleys. Flooding and run-off during spring and summer. Karst actions If post periglacial (with relict permafrost at depth) rivers flood in small 'dry' valleys on plateau.	Alluvial deposits in valleys If post temperate or before periglacial conditions: - Fluvial incision of valleys in bedrock (total: 10m incised per climatic cycle for the main valleys) - Karstic erosion If post periglacial conditions: - Fluvial transport of debris slides previously accumulated in valleys - Seasonal intermittent karst activity	Occurring after a periglacial period: remaining local permafrost layer at depth. Change in water circulation with modifications of springs and recharge areas
Periglacial	Meadows of grass with scare trees located in sheltered valleys	Extensive continuous permafrost with a deep seasonal active zone. Generalised wind deflation. Almost no soil formations: gravels in valleys and pebbles on slopes.	Dry conditions and permafrost with seasonal surface water / active zone. Intermittent summer braided river networks in valleys	No karst actions in limestone formations Physical erosion: - Mass movement down slopes for marly formation outcrops - Active fracturing of limestone formations: plateau valleys form, valleys widen and cuestas retreat / debris slide accumulation - Wind action. No loess deposit in the studied area	Reduced heads, lowered water levels, reduced infiltration and changed fluid pathways. Interuption of aquifer circulation, even at deep levels; regionally frozen at outcrop; changes in static hydraulic gradients. (Salt exclusion from ice in frozen aquifers)

Table 3-3: Regional Climate States and Associated Environmental Changes at the French Site.

3.4. - Summary of Meuse/Haute-Marne Site Palaeoenvironmental Records

Nature of record	Technique	Source	Timeframe for the reconstruction (years)	Continuous / not Associated time periods (years)	Scales	How information is used	References
CLIMATOLOGY							
Pollen/ Sedimentary deposits	Palinology	Literature	10^5	Continuous Step: $<10^2$ Sequence duration: 10^4	Regional France	Air temperature Precipitation	Review of litterature
Periglacial records	Natural analogues	Literature	10^6	Discontinuous Step: $<10^4$	Regional France	Soil temperature	-Map CNF-INQUA/ANDRA
Speleothems	Precise dating of growth anomalies/ isotope ratios	Experiments	10^5	Discontinuous Step:$<10^2$	Local	Evolution of infiltration (precipitation)	ANDRA references
VEGETATION							
Pollen/ Sedimentary deposits	Palinology	Literature	10^6	Continuous Step: $<10^2$-10^3 Sequence duration: 10^4	Local Regional	Nature and evolution of vegetation Spatial variability	ANDRA references
			18 000 & 8 000 BP	Discontinuous	France		-Map CNF-INQUA/ANDRA
Charcoal/ archeologic sites	Anthracology	Literature	Last Glacial Maximum 18 000 BP	Discontinuous	France	Shrub vegetation	-Map CNF-INQUA/ANDRA
SOIL							
Erosion surface & superficial deposits	Geomorphology	Experiments	10^6	Discontinuous Step: $<10^3$ to 10^4 Duration: 10^6	Regional	Soil modification (aeolian deposits /deflation; alteration)	ANDRA references
	Erosion dynamics	Experiments	10^6	Discontinuous Step: $<10^3$ to 10^4 Duration: 10^6	Local Regional	Modifications to: Topography Substratum/ nature of soil Water resources (surface aquifer)	ANDRA references
Soil	Pedology	Literature		Discontinuous	Local	Present day soil (initial soil)	

4. Paleodata for Spain

4.1 - Cúllar-Baza Basin

The $\delta^{18}O$ signal analyzed in continental ostracode valves belonging to Cyprideis torosa (Jones) from a 323.7 m-long section recovered in Cúllar-Baza Basin, reflects, mainly, both global climatic variations and local temperature oscillations expressed through changes of the evaporation/infiltration ratio in water bodies and in the rain over a time scale ranging from the Plio-Pleistocene boundary to the upper part of Middle Pleistocene (380±73 ky BP) [Ref. 18; Ref. 19].

The centripetal deposition model of the basin that consists of alluvial fans at the borders that flow out into a lacustrine system comprising a mosaic of small and shallow lakes. Rainwater was directly introduced into surface water bodies through surface runoff and the alluvial fan channels. This water is characterised by the isotopic composition of the arriving precipitation.

Periods with high $\delta^{13}C$ and $\delta^{18}O$ values have been associated with warm and arid palaeoenvironmental conditions, whereas low d13C and $\delta^{18}O$ values have been correlated with cold and humid episodes. According to this interpretation, four Cold and Humid Great Periods (low $\delta^{18}O$) alternated with four Warm and Arid Great Periods (high $\delta^{18}O$) as established from the smoothed $\delta^{18}O$ curve (Figure 4-1).

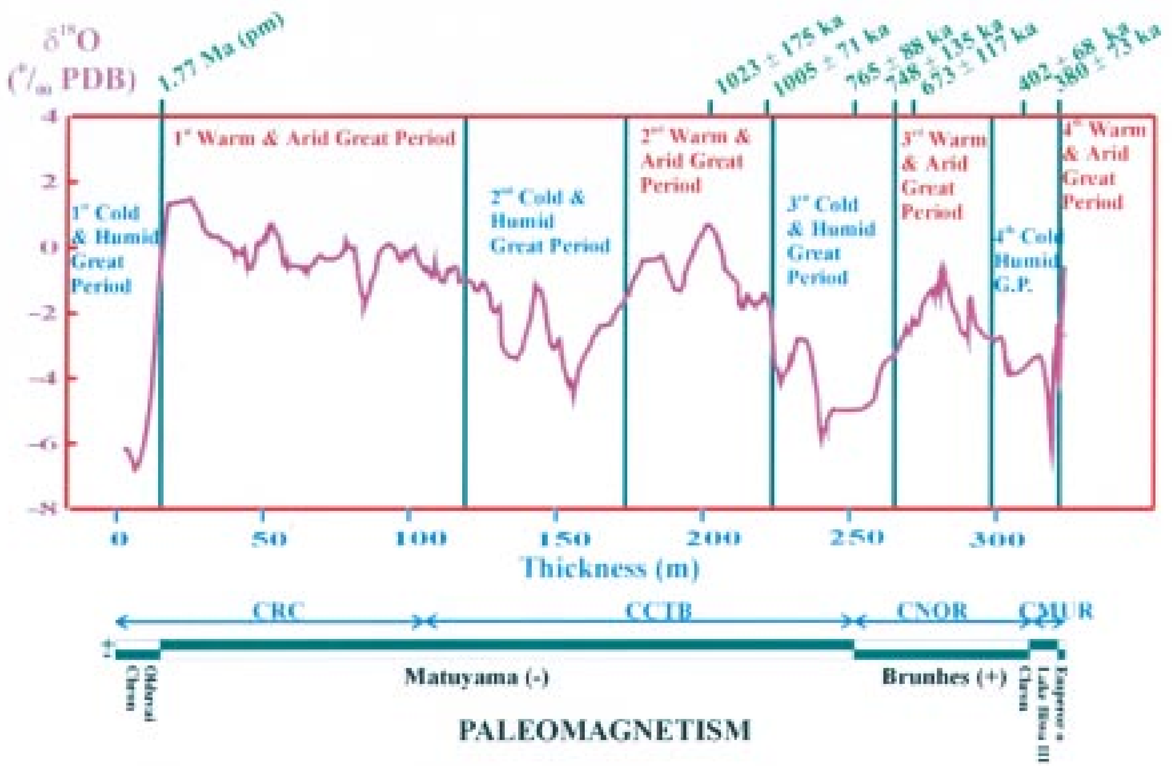

Figure 4-1: Palaeoenvironmental evolution of Cúllar-Baza Basin inferred from the d180 signal analyzed in ostracodes

This interpretation has been reinforced by the presence of intrasedimentary gypsum crystals, which are developed under high salinity and arid stages, during both the 2nd Warm and Arid Great Period and the δ180 relative maximum of the 2nd Cold and Humid Great Period.

The δ180 signal has been compared with the palaeosalinities measured in the fluid inclusions of the intrasedimentary gypsum crystals, verifing that salinity was greater during the warm and arid periods and decreased during the cold and humid ones.

Apart from global oscillations, an assortment of pieces of evidence for changes in regional and local climate characteristics, along with changes in the behaviour of water bodies, has also been identified. These include variations in the hydrogeochemical characteristics and faunal assemblages, which are recorded as minor variations in the δ180 curve.

A summary of the available palaeodata is given below for the Cúllar-Baza Basin (**Table 4-1**) and for the Cúllar-Baza Basin and Padul site (**Table 4-2**).

Activities	Observations
Geological synthesis	4,500 km^2
Detailed cartography	4,500 km^2
Sampling	1312 samples 42 stratigraphic sections 2020 meters
Amino acid racemization	623 samples
Palinology	29 samples
Carbon and Oxygen Isotopes	311 samples
Trace element analysis	326 samples
Palaeomagnetism	408 samples
Fluid inclusions (palaeothermometry)	25 samples
Fluid inclusions (laser ablation)	6 samples

***Table 4-1**: Synthesis of palaeodata for Cúllar-Baza Basin*

Nature of record	Technique	Source	Timeframe for the reconstruction	Continuous / not Associated time periods	Scales	How information is used	References
CLIMATOLOGY							
Ostracodes Pollen Biomarkers Fluid Inclusions	Palaeontology Geochemistry Palinology Palaeothermometry	Experimental	10^6 years 10^5 years 10^4 years	Continuous	Regional National Global	Deduce ecology and salinity. Deduce palaeoenvironmental evolution. Deduce vegetation. Extrapolate beyond the area of investigation.	Ref. 18 Ref. 19 Ref. 22
VEGETATION							
Pollen Biomarkers	Geochemistry Palinology	Experimental	10^6 years 10^5 years 10^4 years	Continuous	Regional National	Deduce vegetation	Ref. 19 Ref. 22
HYDROLOGY							
Fluid Inclusions Sediments	Palaethermometry	Experimental	10^6 years 10^5 years	Continuous	Regional	Deduce palaeosalinities, recharge, run-off.	Ref. 18 Ref. 19 Ref. 22
GEOLOGY							
Sediments	sedimentology	Experimental Literature (synthesis)	10^6 years 10^5 years 10^4 years	Continuous	Local Regional	Deduce geological evolution, stratigraphy and climate.	Ref. 18 Ref. 19 Ref. 22

__Table 4-2__: Nature of palaeodata for Padul and Cúllar-Baza Basin

4.2 - Padul Peat Bog

In the Padul Peat Bog sample section, only the first 25 meters have been studied in detail (**Table 4-3**). The Eemian interglacial, Würm and Postglacial episodes can be distinguished. The begining of Würm episode is characterized, in particular, by very low arboreal pollen percentages. The middle part of this Last Glacial shows climatic fluctuations that are poorly defined. At the end of Würm, the climatic change that occurred promoted the expansion of non-arboreal local vegetation. After this time (approximately 13,000 years BP), a succession of climatic phases occurred, which is quite similar to the classic one established in central Europe, but with notable peculiarities, e.g. the expansion of semi-arid vegetation took place.

Activities	Observations
Borehole drilling	103 meters 8 metres CEX trench
Amino acid racemization dating	32 borehole samples 28 CEX trench samples
Organic characterisation	98 borehole samples 76 CEX trench samples
Isotope analysis (sediment)	409 borehole samples 152 CEX trench samples
Isotope analysis (fossils)	99 borehole samples 62 CEX trench samples
Dating (14C)	16 CEX trench samples
Dating (U/Th)	4 borehole samples
Palynology	289 borehole samples 54 CEX trench samples

__Table 4-3__: Synthesis of palaeodata for the Padul peat bog

4.3 - Toledo area

The nature of the available palaeodata is summarised in **Table 4-4**.

Nature of record	Technique	Source	Timeframe for the reconstruction	Continuous/not Associated time periods	Scales	How information is used	References
CLIMATOLOGY							
Pollen	Palynology	Experimental	Middle-Upper Peistocene	Discontinuous	Regional and local (alluvial fans)	Regional climate interpretation	Ref. 107 Ref. 108 Ref. 109
δ13C and δ18O	Isotopic analyses	Experimental	From OIS 7 to OIS 3	Discontinuous	Regional and local (speleotherms)	Regional climatic interpretation	
Eolian and lucustrine deposits	Sedimentology	Experimental	Middle-Upper Peistocene	Discontinuous	Regional (winds)	To deduce persistent wind dierctions (atmospheric high pressure areas)	
VEGETATION							
Pollen	Palynology	Experimental	From OIS 7 to OIS 3	Discontinuous	Local and regional	To interpret vegetation succession and floral asssociations	Ref. 107 Ref. 109
Toposequences of soils	Edaphology and Sedimentology	Experimental	From Pliocene to Upper Peistocene	Discontinuous	Regional	Regional long-term environmental conditions	
HYDROLOGY							
Fluvial travertines	Sedimentology	Experimental	From OIS 7 to OIS 3	Discontinuous	Local	Chronosequences of the evolution of fluvial systems	Ref. 107 Ref. 108
GEOLOGY							
Fluvial terraces and glacis	Photo interpretation Field work (mapping and sampling)	Experimental	From Lower Pleistocene to present	Discontinuous	Regional	Fluvial dynamics at a regional scale Neotectonic events and processes	Ref. 107 Ref. 108 Ref. 109
Weathering sequences on profiles	Geochemistry Mineralogy Sedimentology Edaphology	Experimental	From Lower Pleistocene period	Continuous	Regional	Long-term climatic conditions	
Speleothems and travertines	Stable isotopic analyses	Experimental	From OIS 7 to OIS 3	Discontinuous	Local	Warm and humid climatic period characterisation	
$\delta^{12}C$ and $\delta^{18}O$ from speleothems and travertines	Thermoluminiscene Palaeomagnetism Palaeontology (vertebrates and invertebrates) Archeological studies	Experimental	From OIS 7 to	Discontinuous	Local	Landscape evolution (trees vs. herbaceous plants)	
Dating of Quaternary deposits (continental carbonate deposit and fluvial terraces and glacis)	Amino Acid Racemization	Experimental	From Pliocene-Pleistocene conventional boundary (1.6 Ma BP)	Continuous	Regional	Geomorphological evolution of the central part of the Iberian Peninsula from Pliocene times	

Table 4-4: Nature of palaeodata for the Toledo area

4.4 - Quaternary Climate Stage for the South of Spain

4.4.1 - Introduction

During the Quaternary cold periods in the Iberian Peninsula, glaciers settled down and periglacial conditions occurred over extensive areas. However, these areas had a marginal character compared with those associated with other European glaciers, because of the peninsular latitude and altitude, and were confined to mountainous zones. In the Lower and Middle Pleistocene, during the glacial cycles Günz (900-700 ka BP), Mindel (650-300 ka BP) and Riss (200 ka BP), the Iberian climate could be relatively temperate and less rigorous than in the rest of Europe. However, these glacial periods were associated with an increase of aridity, whereas the corresponding interglacial stages were characterised by an increase in temperature and, mainly, of humidity, reflected in an alternation of mediterranean steppe and deciduous temperate forests or mediterranean ones, with which some thermophilous and exotic species (*Carya, Liquidambar,* etc.) could be associated.

In the Upper Pleistocene, the Eemian (OIS 5e) was characterized by temperate and warm conditions. However, the Prewürm period exhibited alternation of brief cold and arid stadials (OIS 5b and 5d), with expansion of steppic formations of *Poaceae* and *Artemisia*, separated by interstadials (OIS 5a and 5c) in which arboreal Mediterranean vegetation prevailed. In the Pleniwürm period (70-15 ka BP) the climate would have been a very continental one, relatively cold and quite arid but not similar to that of the remainder of western Europe, and much more severe in the northern and central peninsular regions. At the end of Pleistocene, during the Late Glacial, a clear bioclimatic and biogeographic distinction is observed between Eurosiberian and Mediterranean zones, whose current limit is in the southern slopes of the Cantabrian and Pyrenean mountains, to the north, and between the most continental oceanic and southern zones of Galicia and the north of Portugal, to the west. Thus, in regions such as Andalucia and Levante, the stadial climatic crises have produced more aridity and warmer conditions, with prevalence of *Artemisia* and *Ephedra* steppes as well as black pine formations next to other more thermophilous species *(Pinus halepensis and Pinus pinea).* The Holocene climatic amelioration also presents peculiarities in the Iberian Peninsula. During the Atlantic period the Eurosiberian region is more temperate and humid that the Mediterranean one, with an increase of *Quercetum-mixtum* forests and a corresponding reduction in the extent of the characteristic pine formations of the Würm glaciation. In the Mediterranean region, species prevail (such as *Quercus faginea, Quercus ilex* or *Quercus suber*) that reveal a seasonal rhythm of precipitation and more thermophilous conditions.

A palaeoclimatic reconstruction for the south of Spain has been synthesized for the Quaternary, with greatest detail for the last 104 ka, based on palaeoenvironmental results obtained from the Padul peat bog and Cúllar-Baza basin, both of which are situated within Granada province.

In Padul, with sedimentary records from the Upper Pleistocene and Holocene, palynologic studies have been carried out [Ref. 22]. Two boreholes were made in a very shallow and permanently water-covered peat bog. The site, at 785 m altitude, has undergone sedimentation processes since the Tertiary, which implies stratigraphic lagoons in the deposits. These studies are supported by ^{14}C dating, allowing descriptions to be developed of the vegetation and the climatic evolution of the most southerly region of Europe, from the early Würm. For the great European Prewürm interstadials, original equivalents are found. This relatively temperate episode concludes in a clearly arid, but not thermically extreme, period, which is equivalent to the marine OIS 4. The middle part of the

Last Glacial shows climatic fluctuations that are poorly characterized, as is frequently the case in European palaeodata for this period, while during the whole of the Last Glacial period there was no climatic amelioration.

Toward 15 ka BP a great expansion of a regional steppe cover took place. This event marks the beginning of the Oldest Dryas, often referred to in the SE of France. The climatic amelioration toward 13 ka BP is more pronounced here that anywhere else in Europe, whereas that of 10 ka BP (the conventional beginning of the Holocen) is not so clearly defined, maybe because Padul is located far to the south yet adjacent to periglacial areas. During the Late Glacial and in the Holocene a new vegetational period appears, characterized by the early appearance and prevalence of southern *Quercus ilex* forests and by the early occurrence of *Quercus suber* and *Olea*, pointing to a complete postglacial reforestation history in a region with a current semiarid mediterranean climate. Palaeoclimatically, this indicates a warm and humid climatic optimum just before 8 ka BP, as well as suggesting that the climatic fluctuations of the Holocene were of limited significance.

The Cúllar-Baza basin covers a large area, aproximately 4500 km^2, with an altitude between 650 and 1050 m, and provides a sedimentary record from the Plio-Pleistocene limit until the Middle Pleistocene. The deposits are continental according to a centripetal model, from marginal alluvial fans to a lacustrine central system. Dating has been undertaken through palaeomagnetism and amino acid racemization, indicating that the age of the deposits is between 1.852 Ma and 380 ka BP approximately [Ref. 18]. The ostracodes *Cyprideis torosa* (Jones) of each level underwent carbon and oxygen isotopic analyses as well as trace element analyses. The $\delta^{18}O$ and $\delta^{13}C$ curves give information about global palaeoclimatic evolution [Ref. 18]. They also allowed the general conclusion to be drawn that the palaeoenvironmental characteristics in Cúllar-Baza basin during the Lower and Middle Pleistocene comprised four cold and humid periods alternating with four warm and arid ones, which can be extrapolated to the whole of the south of the Iberian Peninsula [Ref. 18]. These periods may be correlated with the glacial and interglacial cycles of the central European chronology.

4.4.2 - Palaeoclimatic Reconstruction from Padul Data

The data from the Padul boreholes P3 (Middle Würm/ Holocene), with a reasonable series of datings, and P3 (St Germain Ia/ Middle Würm), with only three datings, provide a notable contribution to the reconstruction of palaeoclimatic conditions in the south of the Iberian Peninsula for the last glacial cycle. The climatic evolution of Padul has been followed back to 104 ka BP (i.e. to OIS 5c).

- St. Germain I to St. Germain II (104->63.5 ka BP)

Oxygen Isotopic Stage 5, which is not totally covered by borehole P2, is subdivided in five substages, the oldest of which (5e) is identified with the Eemian interglacial, dated 125-120 ka BP. This represents the thermal maximum within the Upper Pleistocene and Holocene. A short colder phase (5d) follows the Eeemian interglacial and, then, another two warm phases (5c and 5a) separated by OIS 5b, which is colder than 5d. Guiot et al. [Ref. 77] identify the two warmer phases following the Eemian, respectively, as the St Germain I and St Germain II interestadials, and the colder phases 5d and 5b with the Mélisey I and Mélisey II stadials. Borehole P2 does not extend to times before the St Germain I period; that is to say, the Eemian thermal maximum is not reached and is not possible to continue the Padul climatic evolution beyond 104 ka BP.

Substage OIS 5c (104-96 ka BP) begins with a dominant thermophilous vegetation (*Pistacia, Olea, Helianthemum halimifolium* and *even Juniperus*) but not an arid one, as demonstrated by the low percentages of steppe vegetation and sustained values of *Erica arborea*. It corresponds to a thermomediterranean thermoclime (17-19 ºC) and dry ombroclime (350-650 mm). Later on, the St Germain Ia stage begins with a slight climatic deterioration, reflected in a minor presence of thermophilous species and *Erica arborea* as well as by greater abundance of steppe species and *Pinus*. The corresponding average annual temperature is 8-13 °C and the average annual precipitation from 200 to 250 mm. The next phase, known as the St Germain Ib, is marked almost exclusively by the substitution of *Erica arborea* by *Quercus ilex*, with a clear increase of *Juniperus*. The average annual temperature would have been between 13 and 17 °C, with the average annual precipitation between 650 and 1000 mm. The St Germain Ic period reveals a predominant mesohydrophillus vegetation, with sustained values of deciduous *Quercus* and *Erica arborea*, low and stationary frequencies of *Quercus ilex*, and slight increases of *Alnus* and *Betula*. The presence of *Linum* and *Liliaceae* are also verified. The high percentages of *Erica arborea* indicates a near population, so that their decrease emphasizes the regional steppe species and *Quercus* transport. The average annual temperature would be comprised between 13 and 17 °C, while the precipitation would be in the range 650-1000 mm.

OIS 5b (96-84 ka BP), is correlated with the Mélisey II stage and represents an episode of dry ombroclime (average annual precipitation between 350 and 600 mm) becoming semiarid (200-350 mm) as well as a supramediterranean thermoclime (mean annual temperature between 8 and 13 °C). Arboreal species, except *Pinus*, lose their representation, being replaced by steppe (*Poaceae*) and semidesert species (*Artemisia*, Chenopodiaceae and *Ephedra*).

During OIS 5a (84->63.5 ka BP), correlated with the St Germain II stage, a thermal recovery relative to the Mélisey II stadial took place. This recovery is shown by the succession of deciduous *Quercus*, *Quercus ilex*, *Juniperus* and *Erica arborea* as well as by *Artemisia* and Chenopodiaceae decreases. The first phase was dominated by deciduous *Quercus* and *Juniperus*, which need an annual precipitation greater than 600 mm, more than a third of which should fall in summer time. In the second phase, *Quercus ilex* prevailed, deciduous *Quercus* diminished and *Juniperus* disappeared, with an increase of both Poaceae and *Olea*, both of which tolerate drier ombroclimes (precipitation less than 600 mm/year). In a third phase, the recovery of deciduous *Quercus* took place, as well as a minor presence of *Quercus ilex* and the appearance of *Erica arborea*, which require greater humidity. The thermoclime would be mesomediterranean (13-17 °C) basically, with a dry to subhumid ombroclime (average annual precipitations from 650-1000 mm). The later part of OIS 5a is marked by an increased presence of steppe species and the practical disappearance of *Quercus ilex* and deciduous *Quercus*. This heralds the onset of the the colder and much more arid OIS 4 period.

- Eowürm (<63.5 ka BP onward)

Oxygen Isotopic Stage 4 (OIS 4) corresponds to the Eowürm. It is characterized by cold and extremely arid conditions, only comparable with those from late pleniglacial or final Würm. It is quite distinct from the overlying series (Middle Würm), with semidesertic vegetation or steppe poor in trees, and the underlying series (St Germain II interestadial), with vegetation rich in arboreal species except *Pinus* and *Juniperus*. The predominant vegetation of the Eowürm indicates very arid or xeric conditions with an arid ombroclime (mean annual precipitation <200 mm) and oromediterranean thermoclime (mean annual temperature between 4 and 8 °C). The climate change at the beginning of this episode brought about important botanical consequences, which indicate a marked cooling. So, thermophilous species *(Olea, Helianthemum halimifolium, Pistacia)* disappeared and did not reappear until the later Postglacial period.

- Middle Würm (60-24 ka BP)

OIS 3 extends from 60 to 24 ka BP. In Padul, Middle Würm climatic episodes have a poorly defined character, lacking 'stadial' and 'interstadial' definitions. This supports the concept of the Middle Würm as an ‘interphase’; a long period with not very wide climatic fluctuations. During the Middle Würm, vegetation was moderately arid, becoming more so later in the period.

Thus, deciduous *Quercus* and *Juniperus* disappeared completely at the end of this period, being replaced by *Pinus* as well as steppe species and Poaceae. The thermal conditions approach those of supra-mediterranean (mean annual temperature 8 to 13 °C) although possibly an oromediterranean thermoclime (4-8 °C) may have prevailed, evolving the ombroclimatic conditions from semiarid (mean annual precipitation between 200 and 350 mm) to dry (350-600 mm). The climatic environment would be compatible with steppe vegetation and steppe with trees, under semiarid conditions and semidesertic vegetation (scattered bush plants), in arid conditions. Although there is no borehole chronology between 38 and 63.5 ka BP, palynology indicates a very arid vegetation with scarce arboreal pollen, except *Pinus*, with total disappearance of deciduous *Quercus* and *Quercus ilex*, before 38 ka BP.

- Final Würm to Holocene Transition (24-11 ka BP)

The period 24 to 11 ka BP (OIS 2) corresponds to the Final Würm to Holocene transition. The Last Glacial Maximum occurred in the first half of this period, achieving its greatest intensity at approximately 18 ka BP. In a general way, the period between 23.6 and 19.8 ka BP (Middle-Final Würm) is characterized by the presence of *Artemisia* and *Pinus*, and by the almost total absence of other arboreal species except deciduous *Quercus*, and a low proportion of Poaceae. Cold and arid climate conditions are therefore considered to have occurred, with a semidesert character that is more marked over a brief interval at around 19.8 ka BP, with an important decrease of *Pinus* and increase of *Artemisia* and steppe species. Thermal conditions would be near to the oromediterranean (mean annual temperature 4-8 °C) and even cryoromediterranean values (mean annual temperature < 4 °C and average minimum temperature of the coldest month below -7 °C), with a semiarid (mean annual precipitation between 200 and 350 mm) or arid (precipitation< 200 mm) ombroclime.

Between 19.8 and 15.2 ka BP (Final Würm), steppe and semidesert conditions alternated, indicated by the prevalence of *Pinus* and deciduous *Quercus, Erica arborea, Quercus ilex* and *Juniperus*, with Poaceae prevailing over *Artemisia* but both in decline. In the last epoch of OIS 2, 15.2-11 ka BP, both the transition to the Bølling-Allerød late-glacial interstadial and the brief cold episode known as Younger Dryas took place. We have followed the Pons [Ref. 22] chronology, viz:

- Older Dryas (15 to 13.3 or 12.8 ka BP),
- Bølling-Allerød late-glacial interestadial (13.3 or 12 ka BP to 11 or 10.7 ka BP) and
- Younger Dryas (11 or 10.7 to 10.3 or 10.0 ka BP).

The Older Dryas stadial is characterized by a decrease of *Pinus* as well as by the relative increase of Poaceae over *Artemisia*, *Juniperus* and steppe species. As this period progresses Chenopodiaceae, *Artemisia* and *Ephedra* increase, but *Quercus ilex* and deciduous *Quercus* disappear, and *Juniperus* (resistant to drought and cold conditions) increases. During the Older Dryas, the thermoclime could have evolved from oromediterranean (4-8 °C), at the beginning, to supramediterranean (8-13 °C), under a dry (350-600 mm) to semiarid (200-350 mm) ombroclime and under semidesert bioclime with *Artemisia* predominant. In Padul, at the end of this period a specific climate amelioration was experienced at about 13 ka BP. This amelioration seems to have reached the rest of Europe towards 10 ka BP. Pons and Reille [Ref. 22] explain this time difference by noting that the zone is located so far south and close to zones of tree refuge during the Pleniglacial. This will have favoured the rapid recovery of thermophilous vegetation, especially *Quercus ilex* (a climatic amelioration indicator), that form sclerophilous oak forests and deciduous *Quercus*. Both dominate the arboreal stratum within the whole Holocene. An abrupt decrease of *Pinus* is verified.

During the Bølling-Allerød late-glacial interstadial (13.3 or 12 to 11 or 10.7 ka BP) the sclerophilous oak forest development is succeeded by supramediterranean deciduous plain leaf forests. The thermoclime evolves from supramediterranean (8-13 °C) with semiarid or dry ombroclime (200-600 mm) to mesomediterranean (13-17°C) under subhumid ombroclime (600-1000 mm). The most characteristic feature of the Younger Dryas (11 or 10.7 to 10.3 or 10.0 ka BP) is aridity but not cool conditions. In this episode, *Quercus ilex* is replaced by *Artemisia*, Chenopodiaceae and *Ephedra*, and the regionally distributed species (e.g. *Pinus, Juniperus* and deciduous *Quercus*) decrease. The thermoclime was oromediterranean (4-8°C) under arid to semiarid ombroclimatic conditions (mean annual precipitation between < 200 and 350 mm).

- Holocene or Postglacial (11 ka BP to the present)

Oxygen Isotopic Stage 1 (OIS 1), from 11 ka BP to the present time, extends over the whole Holocene or postglacial period. Pons and Reille [Ref. 22] locate the beginning of the Holocene in Padul toward 10 ka BP, when *Quercus ilex* (arboreal stratum) and *Pistacia* (shrub stratum), both characteristic species of the sclerophilous mediterranean forests, are identified. A Poaceae and *Juniperus* association and its persistence, which signifies an open forest vegetation, are typical of the transition zone between semidesert and the sclerophilous zone (a region with winter rains, typical of the mediterranean coasts).

Towards 9.3 ka BP, the establishment of thermophilous vegetation, typical of sclerophilous mediterranean forest, is accentuated, suffering a setback at the early Megathermal period (9-5.3 ka BP) with the highest temperatures in the Iberian Peninsula during the Holocene. This was a warm and relatively stable period, comprising the Boreal and Atlantic phases. The Holocene Thermal Optimum is located within this epoch. In the Boreal phase, at the beginning of the Megathermal, a deterioration of climatic conditions takes place. A decrease of arboreal pollen occurs and a notable reduction in *Quercus ilex*, deciduous *Quercus* and Poaceae, but with all of them recovering at around 8.2 ka BP. Quercus suber is continuously present until the present time. From 10.3 to 8.2 ka BP, for the Preboreal and a part of Boreal periods, a mesomediterranean (13-17°C) thermocline is accepted from 8.2-7.9 ka BP, because *Quercus suber* was abundant and persistent; however, a thermo-mediterranean (17-19°C) thermocline may have occurred. The ombroclime could have oscillated from dry (350-600 mm) in the Preboreal to subhumid (600-1000 mm) in the Boreal period. From later Boreal and during the Atlantic period (7.9-5.3 ka BP) there was a continuous presence of *Olea* and the maximum of deciduous *Quercus*, as well as the maintenance of *Quercus suber* and a initial slight decrease of *Quercus* ilex, which recovered to reach its maximum abundance in the final part of this period. The maxima for deciduous *Quercus* values occur between 7.8 and 6.3 ka BP, whereas the maximum of *Quercus ilex* was around 5.9 ka BP. The 'Thermal Optimum' in Padul corresponds to the interval 6.3-5.4 ka BP, with thermomediterranean thermoclime (17 to 19ºC) and subhumid ombroclime (mean annual precipitation between 600 and1000 mm).

Starting from 5.0 ka BP, within the Subboreal period (5.0 to 2.8 ka BP), a slight worsening of the climatic conditions took place. This is shown by a slight reduction in arboreal pollen, although the general conditions are not notably modified in the pollen diagram, concluding at 4.4 ka BP. Subsequent to 5.4 ka BP, zonal vegetation characteristics correspond to a mesomediterranean (13-17 ºC) or high thermo-mediterranean thermoclime under a drier ombroclime than at the Climate Optimal (mean annual precipitation < 600-1000 mm).

4.4.3 - Palaeoclimatic Reconstruction from the Cúllar-Baza Basin Data

The most recent palaeo-environmental records from the Cúllar-Baza basin are dated at 380 ka BP. Hence there are no available regional data to characterise conditions in Padul and Cúllar-Baza between 104 and 380 ka BP. According to the $\delta^{18}O$ and $\delta^{13}C$ results, four great cold and humid periods as well as four alternating great arid and warm episodes took place (see Figure 4-1). Cold and humid periods can be tentatively identified with three glaciations from the Central European chronology, one of which is divided in two episodes: Donau, Günz 1 and Günz 2, and Mindel. On the other hand, arid and warm episodes are correlated with the interglacial periods: Donau-Günz, the climate amelioration between Günz 1 and 2, Cromerian and early Holstein [Ref. 18]. Although it is not easy to establish an exact correlation between oxygen episodes of the marine record and those detected in Cúllar-Baza deposits, some have been identified from the $\delta^{18}O$ curve [Ref. 18].

The great climatic periods of Cúllar-Baza basin (Figure 4-1), with their calendar ages and Oxygen Isotope Stages, are:

- 1st Great cold and humid period: earlier than 1770 ka BP. Donau glaciation. OIS>60.
- 1st Great warm and arid period: 1770-1305 ka BP. Donau-Günz interglacial. OIS 43 to OIS 59.
- 2nd Great cold and humid period. From 1305 to 1055 ka BP. Episode 1 of the Günz glaciation. OIS 32-42.
- 2nd Great warm and arid period: 1055-1005 ka BP. Interstadial episode of improvement within the Günz glaciation. OIS 25 to OIS 31.
- 3rd Great cold and humid period. From 1005 to 748 ka BP. Episode 2 of the Günz glaciation. OIS 22-24.
- 3rd Great warm and arid period: 748-591 ka BP. Cromerian interglacial. OIS 17-20.
- 4th Great cold and humid period: 591-380 ka BP. Mindel glaciation. OIS 16-14.
- 4th Great warm and arid period. Starting from 380 ka BP. Beginning of the Holstein interglacial. OIS 11, 10, 9.

4.4.4 - Reconstruction of Sequences of Change during the Last Climatic Cycle

A climate reconstruction for southern Spain during the last glacial-interglacial cycle, based on both palaeoclimate data and on orbital forcing modelling results, is summarised in **Table 4-5**. Mean annual temperature and precipitation data for every identified climate stage have been deduced from palaeobotanical analyses of two pollen sequences from the two peat bog borehole samples take from Padul by Pons and Reille in 1988 [Ref. 22]. This pollen record from the Upper Pleistocene (St. German I interstadial) to the Holocene has also been correlated with the KET 8003 Tyrrhenian core pollen and oxygen isotope records, and with temperature and precipitation data from La Grande Pile and Les Echets (France) [Ref. 77].

The tentative climatic reconstruction is calibrated on ^{14}C dates extending back to 31,000 ± 1300 y BP in the Padul record and by reference to the insolation variation curve for the month of July at 60º latitude N from 150 ka BP to 100 ka AP.

Continental stage names for the Late Quaternary commonly accepted in both Spain and France and their corresponding Oxygen Isotope Stages (OIS) have been used. Correlations among palaeobotanical and, when possible, radiometric data from Padul sequences and from core KET8003 have been compared with those from Les Echets and La Grade Pile, although that comparison has been of little value as no Mediterranean element has been found either at Les Echets or at La Grande Pile.

The ages of the boundaries between the OIS have been taken from the work of Guiot et al. [Ref. 77], as follows:

OIS	Age (Ka BP)
1	0-11
2	11-24
3	24-60
4	60-72
5a	72-84
5b	84-92
5c	92-104
5d	104-112
5e	112-128

At the bottom of the sequence, two interstadial episodes (attributed to St. Germain I, whose basis is absent, and to St. Germain II), separated by a well-marked stadial (Mélisey II), are identified. This part corresponds to most of the Prewürm (104-72 ka BP, dated by reference to Les Echets and the SPECMAP smoothed oxygen isotope curve [Ref. 77]).

A very arid episode follows that corresponds to OIS 4 of the marine isotopic stratigraphy. This episode whose main characteristic was dryness is characterized throughout Europe as a cold stadial episode at the beginning of the Würm. On top of this cold stadial a likely hiatus exists giving way to a long interphase comprising both the Middle-Würm and the late Pleniglacial or Final Würm up to the global climatic amelioration recorded at about 13,000 y BP. This climatic ameliortiation is very clear at Padul and far more pronounced than anywhere else in Europe, and represents a distinctive characteristic of Padul sequence in relation to other European palynological records.

Both the Oldest Dryas and Younger Dryas are identified by respective climatic shifts towards dryness, the first dated at around 15 000 years BP and the second dated between 9 930 (±130) and 12 080 (±180) years BP. The stadial vegetation attributable to the Younger Dryas is associated with a lithological change, which is in turn affected by a hiatus that could explain this two thousand years interval between those dates [Ref. 22].

Mean annual temperature and mean annual precipitation for each of the climate stages identified in the palynological record have been deduced from modern vegetation characteristics based on Rivas-Martinez bioclimatic analysis of vegetation series for the Iberian Peninsula [Ref. 110].

Calendar Age (ka BP)	OIS	Local Name for southern Spain reconstruction	Mean Annual Temperature (°C)	Mean Annual Precipitation (mm)	Climate Class			Comments
					Köppen-Trewartha	Walter	Rivas Martinez	
0 – 0.54	1	Subboreal	13-17 to 17-19	<600-1000	Cs	ZB IV	Mesomediterranean to thermomediterranean, dry to subhumid	More uncertainty and climate variability, with marked pluvial fluctuations and dried tendency. Slight deterioration of climatic conditions
5.4 – 6.3	1	Atlantic	17-19	600-1000	Aw	ZB II	Thermomediterranean subhumid	Thermal Optimum
6.3 – 7.9	1	Atlantic/Boreal	-	-	Cs	ZB IV	Mesomediterranean subhumid	Maximum of deciduous *Quercus* curve
7.9 – 8.2	1	Boreal	17-19	600-1000	Cs	ZB IV	Thermomediterranean subhumid	-
8.2 – 10.3	1	Preboreal/ Boreal	13-17	350-600	Cs	ZB IV	Mesomediterranean, dry	-
10.3/10.0 – 11/10.7	1	Younger Dryas	4-8	200-350	BSk	ZB III/IV	Oromediterranean, arid to semiarid	Rapid climatic deterioration. Arid but as cold as the Oldest Dryas, or even the Final Würm / Middle Würm.
11.0/10.7 – 13.3/12	2	Bølling-Allerød Late Glacial Interstadial	8-13 to 13-17	200-600 to 600-1000	Cf	ZB VI	Supramediterranean mesomediterranean, semiarid or dry to subhumid	Specific climatic amelioration toward 13 Ka BP (at 10 ka BP for the rest of Europe). Vegetation recovery, especially oak forests, *Quercus ilex* and deciduous *Quercus*. Both then dominate the arboreal stratum to the present time.
13.3/12.8 – 15.8	2	Oldest Dryas	4-8 to 8-13	350-650 to 200-350	BSk	ZB III/IV	Oromediterranean to supramediterranean, dry to semiarid	-
15.2 – 19.8	2	Final Würm	<4	<200-350	EC-FT	ZB VIII/IX	Cryomediterranean, dry	Last Glacial Maximum toward 18 Ka BP. Steppe and semidesert conditions alternate.
19.8 – 23.6	2	Final Würm/ Middle Würm	4-8 or <4	<200-350	EO-EC	ZB VIII	Oromediterranean or cryomediterranean, arid	Cold and arid, semidesert. Minimum average temperature of coldest month below –7ºC. Around 19.8 ka BP more becomes more like semidesert.
24 – 38	3	Middle Würm	8-13 to 4-8	200-350 to 350-600	DCa-DCb	ZB VI/VIII	Supramediterranean to oromediterranean, semiarid to dry	Slightly arid environmental conditions. Poorly marked climatic episodes due to varied climatic gradations. Little climatic fluctuation.
>38	3		-	-	-	-	-	No data at Padul for this period. Palynology indicates very arid vegetation.
<63.5	4	Eowürm	4-8	<200	BSk	ZB III/IV	Oromediterranean, arid	Cold and extremely arid episode.
>63.5 – 84	5a	St. Germain II	13-17	>200 to 650-1000	Cs	ZB IV	Mesomediterranean	General thermal recovery, although it includes the early part of the regression to the colder and arid OIS 4 period.
84 – 96	5b	Mélisey II	8-13	350-600 to 200-350	BSk	ZB III/IV	Supramediterranean, dry to semiarid	-
96 – 104	5c	St. Germain Ic	13-17	650-1000	DO	ZBVI	Mesomediterranean, subhumid	-
	5c	St. Germain Ib	13-17	600-1000	DO	ZBVI	Mesomediterranean, subhumid	-
	5c	St. Germain Ia	8-13	200-350	DO - DC	ZBVI	Supramediterranean, semiarid	Slight climatic deterioration.
	5c	-	17-19	350-650	Cs	ZBIV	Thermomediterranean, dry	-

***Table 4-5**: Characterisation of Climate States Sequences for Southern Spain during the last Climatic Cycle*

4.5 - Palaeoenvironmental Reconstructions for the Toledo Area

4.5.1 - Quaternary Climatology

The environmental peculiarities of the Iberian Peninsula with respect to other regions of Europe are a result of its southern latitude, between the Atlantic and the Mediterranean seas, the morphology of its continental shelf and its orography. As a result of these peculiarities, there is an important regional aspect to the climates that have existed throughout the Quaternary, with the Mediterranean type prevailing over most of the Iberian Peninsula with varying degrees of aridness. During glacial periods the temperatures dropped considerably, but not to the extent that there was any generalized permafrost. This phenomenon occurred only in specific areas and at great altitude. These periods did cause an important increase in aridness in the peninsular environmental conditions, although the degree of continentalization induced by the glacial-eustatic fluctuations throughout the Quaternary was relatively slight [Ref. 108].

Sixteen fluvial terraces have been identified and their chronological sequence established in the Tajo River Basin [Ref. 107]. Sedimentological, palaeontological, palynological, edaphological and geoarcheological analyses carried out in the terraces and associated deposits have made it possible to determine the evolution of the Quaternary climate for the central zone of Spain, at a latitude of 40ºN. It has also been possible to quantify Quaternary palaeotemperatures and palaeorainfall on the basis of Climatic Analogue Modelling of pollen from the fluvial deposits. Comparing palynological data and the stable isotope ratios in a continuous travertine sequence of the Upper Pleistocene-Holocene has corroborated the validity of $\delta^{13}C$ as a palaeoclimatic and palaeoenvironmental indicator in continental carbonate deposits [Ref. 109]. However, the use of $\delta^{18}O$ as a palaeoclimatic indicator in continental carbonate deposits poses many uncertainties as a result of the isotopic fractionation that may occur during the formation of the deposits, uncertainty that is greater in travertines than in speleothems because speleothems present a lower number of variables affecting their isotopic ratios due to their non-biological origin.

Travertines and speleothems provide biased palaeoclimatic indications because their very existence is an indication of warm and moist climatic conditions. In general, both their presence and absence are climatic indicators. Thus, during dry periods there is no speleothem deposition, whereas during cold and moist periods they are dissolved due to the aggresive nature of the water. Under dry conditions, travertinic platforms are incised and terraced. Therefore, the information obtained on the palaeoclimatic evolution of the Iberian Peninsula during the Pleistocene, by this kind of analysis, is biased, as for example the data derived from the Reguerillo site. The reconstruction of palaeoenvironmental and palaeoclimatic evolution by examination of carbonate deposits has been possible by using a multidisciplinary method that is based on geomorphology, topostratigraphy, petrography, sedimentology, palaeontology, palynology, C and O stable isotope analyses and absolute dating. It has been possible to date the travertines and terraces in fluvial systems by the amino acid racemization technique [Ref. 109]. This technique, together with geomorphological and sedimentological analysis have made it possible to reconstruct the evolution of the fluvial network chronologically, and the information could be used for estimating the fluvial incision rates during the Quaternary.

Between the palaeoenvironmental and palaeoclimatic evolution deduced from independent studies carried out in the terraces of the Tajo river valley and the continental carbonate deposits of the Central region of the Iberian Peninsula a very good corrrelation has been established. During the Quaternary, the climate in the

Tajo valley areas under study was temperate with variations in humidity. Thus, towards the end of the Pliocene and Lower Pleistocene the climate in this zone was moister and warmer than at the present time, as indicated by the soils of the Talavera de la Reina chronosequence. In the same way, towards the limit of the Lower-Middle Pleistocene there was a sudden change leading to a general process of aridification, resulting from a dryer period with relative deficits of water and with intermediate episodes of climatic amelioration. On the other hand, the faunistic and floristic associations of the Middle and Upper Pleistocene indicate climatic conditions clearly Mediterranean, both during the aggradation and incision of the terraces. The conditions were fairly similar to these of the present time, although there was some variability of temperature and rainfall rates between deposition and fluvial incision periods. The genesis of alluvial fans overlying these terraces indicates a tendency towards aridity during the periods of incision. Thus, two important factors driving environmental changes in the Iberian Peninsula during the Quaternary are the variations on rainfall, which had more control than did thermal variations and imply variations in the availability of water in the geosphere-lithosphere system, and the dynamics of incision-sedimentation processes in the fluvial systems that were present.

In a general way, when in the Iberian Peninsula the Upper Pleistocene began with the Riss-Würm Interglacial (120 ka BP), the climatic conditions were warmer and more humid than in the north and centre of Europe. In this time period, the temperature was slightly lower than during the interglacial periods of the Lower and Middle Pleistocene. The prevailing characteristic of the Iberian Peninsula climate during the Würm glaciation episode was aridness; during the Pleniwürm, thermophilous species disappeared as steppe species began to prevail. During the Late Glacial (15 to 10 ka BP) the climate was generally cold and xeric, albeit less severe and arid than in the Pleniglacial. During the Pleniglacial period, well-defined biogeographical differences between the Eurosiberian and Mediterranean regions of the Iberian Peninsula appear to have existed. The Late Glacial began with a cold period and ended with another cold period but more humid than the former one. Although the temperatures were cooler than today, the interstadial periods of the Late Glacial show evidence of a climate similar to or slightly more humid than that of the present. From the beginning of the Holocene, at about 10 ka BP, there was an ongoing climatic amelioration until the current climate of the Iberian Peninsula was reached.

4.5.2 *- Geology and Hydrology*

The Tajo river basin is interesting as regards the evolutionary similarity between this valley and other major valleys in Spain. Practically all the Quaternary deposits in Spain are continental, with a predominance of fluvial, glacis, piedmont and alluvial fan deposits. The Quaternary began with the deposition of piedmont deposits, followed by fluvial dissection that created a complex system of terraces, glacis and alluvial fans in the major river valleys. The clastic piedmont of La Raña and the limestone plateau known as the Páramo are the Pliocene geomorphological and chronological indicators of subsequent Quaternary evolution. This evolution has been subject to processes more of erosion (initiated during the Upper Neogene) than of accumulation. These processes of erosion have structured the landscape as a system of surfaces, with or without deposits, during the Pliocene, Pleistocene and Holocene. These systems are relatively well known (in terms of geomorphology, geometry, lithology, soils and spatial and temporal geometric relationships), but important gaps still exist in our knowledge of their origins and associated deposits, chronology and palaeoenvironmental significance [Ref. 108]. It is not known if all or some forms correspond to certain climates or other geodynamic processes, such as tectonic processes.

Three areas close to the Toledo zone, in the Tajo river valley (Talavera de la Reina, Toledo and Fuentidueña de Tajo), were studied in detail [Ref. 107]. These zones present advantages for interpretation because of the presence of: long sequences of terraces constructed in the valley extending downwards from the piedmont of La Raña; toposequences of soils with different degrees of evolution that may be valid as palaeoclimatic indicators; thick terraces along with thick associated deposits of lateral origin; varied lithological and sedimentary environments (eolian and lacustrine deposits included. There is the possibility of establishing pollen diagrams for certain levels of the terraces, and determining vertebrate and invertebrate fauna from the Middle and Lower Pleistocene. On the other hand, speleothems and travertines in a karstic zone in Madrid (Reguerillo) and fluvial travertines at Priego (Cuenca) were also studied [Ref. 109] in the central region of Spain.

Due to the coarse detritic nature of the terrace deposits, the establishment of absolute chronologies is almost impossible to achieve in the valleys of the interior of the Iberian Peninsula. However, luminiscence techniques were used for dating sediments, and their application has given very good results in the Tajo valley for deposits of less than 130 ka age. On the other hand an edapho-geomorphological chronosequence analysis has been performed in the area of Talavera de la Reina, with 14 alluvial surfaces from the piedmont of La Raña to the level of the alluvial plain. The possible climatic evolution was evaluated on the basis of soil classification, development of the edaphic profile, position of the upper limit of the carbonate accumulations, distribution and development of carbonate accumulations, correspondence between the current moisture front and the carbonate accumulations, weathering rate, and the sequence of genetic horizons. Terrace overbank facies and alluvial fan deposits superimposed on the terraces were sampled for palynological analysis of the Toledo area. In the same way, studies of the micromammals (vertebrates) and gasteropods (invertebrates) in the Toledo and Fuentidueña regions were undertaken.

- Fluvial terraces and glacis

The most complete sequence of terraces was found in the Talavera de la Reina area. The piedmont of La Raña is located at an elevation of more than +200 m with respect to the average water level of the Tajo river. In this zone, the valley is strongly asymmetric and is made up of 13 alluvial levels located between +185m and +3.5m above the current alluvial plain. In the Toledo area, the valley is asymmetric too, this asymmetry being controlled by structural processes. In the Fuentidueña de Tajo area the main characteristic is a stepped sequence of 12 terraces.

- Weathering sequences on soil profiles

The soils existing at all the surfaces of the Talavera de la Reina alluvial sequence are Alfisols, except those from the Holocene alluvial plain, and the most recent argillic horizon surface in this area is from the Upper Pleistocene. The most evolved soil in the sequence is the Ultic Paleoxeralf of La Raña formation. Carbonate crusts are found in certain soils corresponding to the Lower Pleistocene, and there was a generalised calcification and a redistribution of carbonates during the Middle Pleistocene and the Upper Pleistocene, but not during the Holocene [Ref. 107]. Conversely, the intense illuviation of clay minerals during the Pliocene and Lower Pleistocene indicates a warmer and more humid climate than at present.

The speleothems and travertines in a karstic zone in Madrid (Reguerillo) and fluvial travertines at Priego (Cuenca) were also studied using quantitative dating methods such as U/Th, Electron Spin Resonance (ESR) and AminoAcid Racemization (AAR) techniques. Palaeoenvironmental analyses were based on field sedimentology and petrography of solid and detrital rocks, palynology, granulometry and facies analysis, x-ray diffraction (to characterize diagenetic processes), x-ray fluorescence (to correlate trace element contents), and direct palaeoenvironmental studies such as analyses of stable isotopes in speleothemes, travertines and vertebrate remains.

Chronosequences of the evolution of the fluvial system on the basis of geomorphological and sedimentological analysis and of absolute dating techniques in some of the zones under study were reconstructed. Thus, for the last 750 ka, in the Priego area, the evolution of the fluvial systems of the Guadiela, Trabaque and Escabas rivers has been determined. In the karstic zone of the Cueva del Reguerillo, the evolution of the fluvial system of the Lozoya and Jarama rivers from the end of the Pliocene was also reconstructed. On the other hand, other classes of analysis, such as petrography, palaeontology, isotopic oxygen and carbon ratios, palaeomagnetism and absolute dating, have made it possible to interpret the palaeoclimatic and palaeoenvironmental evolution of the Cueva del Reguerillo karstic zone from the end of the Pliocene. For the Lozoya river, incision rates since the Neogene have been obtained for different periods of the Quaternary.

4.5.3 - Vegetation

Ihe Toledo area five pollen analyses were performed, corresponding to Middle and Upper Pleistocene levels. This pollen was sampled in distal or medial-distal sequences of alluvial fans superimposed on the alluvial deposits of certain terraces, with the exception of one of them, which was obtained from overbank deposits. Climatic modelling analyses performed with these pollen diagrams allow a few generalizations to be made about the Middle and Upper Pleistocene climate for the Toledo area and for the the Tajo river basin. Limited regional influence occurred, with arboreal pollen *(Juniperus, Quercus spp, Olea*) very similar in all deposits. Transitions included periods of rapid deforestation, colonization by herbaceous plants and the installation of trees, development of taxa indicating local humidity. A regional influence that was detected was the occasional existence of temperate forests (*Castanea, Betula* and *Corylus*), which are possible only under environmental conditions of greater humidity, and their expansion to surrounding areas.

The Eastern Upper Buenavista terrace, at +60m above current Tajo River level, and dated ca. 780 ka [Ref. 107] exhibits a flora with *Juniperus, Olea, Quercus spp., Juglans, Castanea* and *Corylus*. The first stages are colonization with *Juniperus, Olea, Juglans* and Chenopodiaceae and are poor in arboreal pollen, reflecting open vegetation landscapes where *Olea* is being replaced by *Quercus spp.* and *Pinus* at regional level, but with neither of these two being very abundant. The accompaning vegetation is constituted by Chenopodiaceae, Asteriodae, Cichoroidae, Rosaceae and Poaceae. The climate was warm, with a savanna-type landscape.

At the beginning of the Middle Pleistocene, the Lower Buenavista terrace, +40m above current river water level, presents a very similar vegetation to that of the Upper Buenavista terrace, but it also shows the presence of micromammals, mainly rodents, and of macromammals *(Hippopotamus amphibrous, Dolichodoriceros savini, Mammuthus trongontherii* and *Equus caballus ssp.*). Climate could have evolved to a Mediterranean type with periods of higher humidity.

Evolution to more arid conditions is observed in the Eastern Upper Salchicha terrace, which is more or less contemporary with the Eastern Upper Buenavista terrace. Here, after an initial stage of colonisation, characterised by a steppe of Chenopodiaceae, a stage dominated by *Quercus spp.* follows. *Olea* progressively disappears and *Artemisia* arrives at the same time that the total absence of *Olea* occurs. This might reflect a general deterioration of climate conditions, with the loss of specific local elements and impoverishment of the local vegetation.

By the end of the Middle Pleistocene, in the Pinedo formation, at +30m above the current level of the Tajo River, a progressive loss of *Juniperus* is detected as well as *Olea*; the amounts of *Pinus* decrease as do those of *Betula, Corylus* and *Castanea*, taxa that were better represented in the Eastern Lower Salchicha formation, a somewhat more modern terrace than the Eastern Upper Salchicha, where more humid conditions would have prevailed.

In the Valdelobos terrace, +4m above the Tajo River level, and dating frmo the Upper Pleistocene, *Juniperus* seems to dominate the local vegetation pattern, together with Chenopodiaceae, *Artemisia*, Lamiaceae, Papaveraceae, Rosaceae and *Rumex*, defining a very open warm-steppe vegetal landscape.

This might reflect that, as a whole, Mediterranean climatic conditions would have prevailed in the Toledo area during both the Middle and Upper Pleistocene, with some phases of greater humidity favouring greater development of temperate taxa at a regional level, but with a progressive increase in aridity towards the top of the formation.

4.6 - Characterisation of Palaeoenvironments in Spain

Ihe main climatic states encountered in the southern part of the Iberian Peninsula during the Quaternary have been deduced from the palynological analysis of P2 and P3 peat bog cores from the site of Padul, Granada, [Ref. 22], on the one hand, and from the $\delta^{18}O$ and $\delta^{13}C$ curves analysed in continental ostracode valves from the Cúllar-Baza Basin [Ref. 18], on the other hand.

The latter study reflects both global climatic variations and local temperature oscillations over a time scale ranging from the Plio-Pleistocene boundary (1.77 Ma BP) to the upper part of Middle Pleistocene (380 ± 73 Ka BP) [Ref. 18; Ref. 19], whereas the former enables a description of the vegetational and climatic history of the Padul area from the Upper Pleistocene to the Holocene (ca. 4450 ± 60 a BP) to be developed [Ref. 22].

The smoothed $\delta^{18}O$ curve from the Cúllar-Baza Basin points towards the establishment of four cold and humid Great Periods, alternating with four warm and arid Great Periods. However, for the purposes of describing the broad climatic states encountered in the Iberian Peninsula during the Quaternary, only the information provided by the two borings made at Padul can allow us both a climatic classification according the Köppen-Trewartha scheme (or that of Walter) (see Table 5-4) and biome descriptions for the climate types.

The Köppen-Trewartha system has been developed with the primary aim of dividing climates according to a set of temperature-based criteria meaningful in terms of the natural vegetation [Ref. 154]. In the Iberian Peninsula, the development of patterns of vegetation characteristics of the Quaternary began in the Upper Pliocene, as a warm and humid climate of subtropical type started to deterioirate at around 2.4 Ma BP. This brought about an increase in aridity and the subsequent expansion of Mediterranean species. The first glacial-interglacial cycles in the Iberian peninsula were characterised by an increase in aridity during the glacial episodes and an increase in humidity during the interglacial stages. From the Middle Pleistocene, the rhythm of the climate oscillations became faster, pleniglacial stages being more rigorous and the interglacial ones less humid [Ref. 111].

Nevertheless, at the beginning of the last glacial-interglacial cycle, between around 118 000 and

75 000 years BP, the climate was warm and humid. During the Middle-Late Würm (75 ka to 15 ka BP), steppe formations are common all around the Iberian Peninsula, being quickly substituted by the extremely dynamic Tardiglacial vegetation: sclerophylic forest formations in the Mediterranean bioclimatic region, and deciduous forest formations in the Eurosiberian bioclimatic region [Ref. 111]. So, aridity is and has also been a main component of the Iberian peninsula landscape. The vegetational and environmental evolution reflected by the succession of the pollen sequences at Padul were first analysed according to the Rivas-Martinez [Ref. 110] bioclimatic classification scheme [Ref. 22; Ref. 112] that takes into account both tempeature-based bioclimatic stages and precipitation-based ombroclimatic units. For every bioclimatic stage, as a function of average annual precipitation, several ombroclimatic units can be identified that correspond quite approximately with characteristic vegetation types. For the climate scenarios and associated vegetation types, the Walter [Ref. 113] zonobiome classification has been followed. Zonobiomes largely correspond, with a few exceptions, to soil type and zonal vegetation, and each zonobiome is clearly defined by a particular type of climate diagram [Ref. 113].

In order to describe discrete climate classes, the continuous record provided by the palynological description of the Padul sequence was broken up on the basis of thresholds defined on the ACLIN1 index curve [Ref. 114] by Garcin and Godefroy [Ref. 115]. Four major climate classes have been identified: Interglacial (ACLIN1 index > 4.3), Interstadial (ACLIN1 index between 3.5 and 4.3), Stadial (ACLIN1 index between 2.5 and 3.5) and Glacial, with ACLIN1 index less than 2.5. ACLIN1 is an index of climatic change due to variations in the Earth's orbital characteristics according to the Milankovitch theory although it only incorporates some of the natural and man-driven processes that influence climate.

A climate classification scheme based solely on an index such as this may lead to a rather limited perception of the climatic evolution experienced by the area of interest. A set of climate scenarios of a transient nature was therefore specified in order to depict the climatic evolution of the Padul area from the St. Germain I interstadial to 4.4 ka BP [Ref. 112].

The individual zonobiomes on the Iberian Peninsula comprise two main zonobiomes as defined by Walter [Ref. 113]:

- **ZB IV** – Winter rain and summer drought, arid-humid, with Mediterranean brown earths as the zonal soil type and sclerophylous woody plants as zonal vegetation, and

- **ZB V** – Warm-temperate (maritime), humid with yellow or red podsols as the zonal soil type and temperate evergreen forests as zonal vegetation.

Also, three small transitional zones known as *zonoecotones* [Ref. 113] can be identified. In the southeast of Spain, zonoecotone IV-III, which is the driest part of Europe; in central Ebro River Basin, zonoecotone IV-VII, and zonoecotone IV-V on the northwestern coast of Portugal. Moreover, in the mountainous areas of the Mediterranean, a distinction must be made between the humid altitudinal belts where the evergreen sclerophyllous forest is succeded by a sub-Mediterranean deciduous forest (the Pyrenees), and the arid altitudinal belts with a summer drought, where there is no deciduous forest (Sierra de Guadarrama, S. de Gredos) [Ref. 113]. The larger zonobiomes can be further subdivided into *subzonobiomes* (sZB) on the basis of climatic deviations

Zonobiomes IV and V correspond, respectively, to the present Interglacial climate class, for the Mediterranean and Eurosiberian bioclimatic regions of the Iberian Peninsula. The limit between these bioclimatic regions shifts southward as the global climatic conditions evolve towards a full glacial situation. For correlation with climate states classified using the Köppen-Trewartha scheme, the following relationships are proposed for the Mediterranean Bioclimatic region:

Interglacial:

ZB IV – Winter Rain with an Arid-Humid Climate and Sclerophylic Woodlands.

Cs — Subtropical dry summer (Köppen-Trewartha) Thermo/Mesomediterranean, dry/subhumid (Rivas-Martinez).

ZB VII – Arid-Temperate Climate

BSh — Tropical/subtropical semiarid (Köppen-Trewartha) Thermomediterranean, semiarid/dry (Rivas-Martinez).

BWh — Tropical/subtropical arid (Köppen-Trewartha) Thermomediterranean, arid (Rivas-Martinez).

ZB II – Humid-Arid Tropical Summer Rain Region with Deciduous Forests

Aw — Tropical wet-dry (Köppen-Trewartha) Inframediterranean, subhumid/ humid (Rivas-Martinez).

Interstadial:

ZB VI – Temperate-Nemoral Clim

Cf — Humid subtropical (Köppen-Trewartha) Suprameditерranean, subhumid/humid (Rivas-Martinez).

ZB VI – Temperate-Nemoral Climate

Do — Temperate oceanic (Köppen-Trewartha) Supramediterranean, humid (Rivas-Martinez)

ZE VI/VIII – Boreonemoral zone

Dca — Temperate continental, warm summer (Köppen-Trewartha) Supramediterranean, dry (Rivas-Martinez)

Dcb — Temperate continental cool summer (Köppen-Trewartha) Oromediterranean, dry (Rivas-Martinez)

Stadial:

ZE III/IV – Semidesert

BSk — Temperate semiarid (Köppen-Trewartha) Oromediterranean, semiarid (Rivas-Martinez)

ZE III/IV – Semidesert

BWk — Temperate arid (Köppen-Trewartha) Mesomediterranean, arid/semiarid (Rivas-Martinez)

Glacial:

ZB VIII – Cold-Temperate Boreal Climate

Eo — Subarctic oceanic (Köppen-Trewartha) Cryomediterranean, subhumid/humid (Rivas-Martinez)

ZE VIII/IX – Forest Tundra

EC — Subarctic continental (Köppen-Trewartha) Cryomediterranean, arid/semiarid (Rivas-Martinez)

OB VIII – Mountain Tundra

FT — Tundra climate (Köppen-Trewartha) Cryoromediterranean, arid (Rivas-Martinez)

Table 4-6 provides a brief description of the environmental characteristics associated with the broad climate states encountered in southern Spain during the Quaternary period.

CLIMATE	Southern Spain Region				
	VEGETATION	PEDOGENESIS & SOIL CHARATER	HYDROLOGY	EROSION & DEPOSITION	HYDROGEOLOGY
Interglacial	Similar to present day. Dominated by sclerophyllous vegetation in the Mediterranean bioclimatic region, and by deciduous forests in the Eurosiberian bioclimatic region.	Xeralfs, an Alfisol subgroup associated with the moist winter, dry summer pattern of the Mediterranean climate. The soil profile is similar to that of Chernozem soils but with less humus content. Also Mollisols typical of semiarid climates are common.	At least 70 % of annual precipitation occurs during the winter months. Low river flows in summer due to summer water-balance deficit.	High soil erosion rates due to intense precipitation, high topography and scarce vegetation cover.	Water levels closely related to water recharge pattern. Higher water levels in winter months, very low ones in summer.
Interstadial	Dominated by mesohygrophilous vegetation with some thermophilous species. Coniferous and mixed coniferous-deciduous forest.	Ultisols rich in oxides of both iron and aluminum for the moister, warmer episodes, and Alfisols rich in humus and moderately leached for more humid continental climates.	Less contrasted precipitation patterns than in the Interglacial climate state, but still lower river flows in summer.	Characteristic meandering regime for fluvial erosion/ deposition patterns.	
Stadial	Very arid vegetation although not a very cold adapted type, except during cold stadial episodes. Shrubs or sparse grasses and short grass prairie (steppe and semidesert).	Calcification is the dominant pedogenic process. Molisols (steppe lands) and Aridisols (semidesert shrub). Very small humus content.	Aridity of hydric origin, not of thermic origin. Very low year round river flows. No permanent streams, as evaporation exceeds precipitation.	Intermitent fluvial erosion linked to sporadic downpours.	Very small infiltration rates. Few exploitable aquifers. Recharge mainly limited to river thalweg. Groundwater movement mainly restricted to deep aquifers, but very low because of limited recharge.
Glacial	Boreal coniferous forest and tundra vegetation. Needleleaf forest (boreal forest) and open lichen woodland (taïga).	Inceptisols and organic Histosols, light grey soils wet, strongly leached and acidic. Beneath the topsoil layer, a layer of humus is found.	Small amount of precipitation concentrated in the few warmer months. Permafrost prevails under large areas. Water in the soil melts in summer, enhancing freeze-thaw erosion. Braided rivers with periglacial or glaciofluvial regimes.	Little or no chemical alteration, but intense mechanical break up of the parent rock. Specific geomorphic processes resulting in distinctive landforms.	

***Table 4-6**: Regional Climate States and Associated Environmental Changes in Southern Spain*

5. Paleodata for central England

5.1 - Cúllar-Baza Basin

Although much detailed work has been undertaken subsequently (see [Ref. 2]), the broad classification of British Quaternary Stages proposed in 1973 [Ref. 116] has been found to be useful by many workers in the field and is often used as a basis for description. This scheme is set out in **Table 5-1** below, augmented by supplementary information from [Ref. 2].

Stage	Substage or Important	Age (ka BP)	OIS	Comments
Flandrian		10-0	1	Also known as the Holocene
Devensian	Late	26-10	2	All ages are ^{14}C values. The Middle Devensian includes the Upton Warren interstadial complex where as the Chelford interstadial is located in the Early Devensian at about 60 ka BP
	Middle	50-26	3	
	Early	Before 50	5d-3	
Ipswichian		124	5e	Central estimate of age. Duration estimated at 10 to 15 ka
Wolstonian	Ridgacre Fotmation Kidderminster Member	160	6	Overall period covered is from 270 to 130 ka BP, estimated from graphical information. Note that the Wolstonian type location is now considered to be pre-Hoxnian and has been correlated with the Lowestoft Formation. The only lithostratigraphical evidence adduced to support a post-Hoxnian, but pre-Ipswichian, glaciation of East Anglia comes from the Nar Valley in Norfolk. Evidence includes gravels interpreted as outwash deposits, but no tills.
	Strensham Court Bed	~200	7	
	Bushley Green Member		8	
Hoxnian	Hoxne Formation	319	9	See notes relating to the Anglian below.
	Spring Hill Member		10	Also, note that some authors extend the Wolsonian to cover OIS 10 to 6, but still allow the Hoxnian to relate to OIS 11 to 9.
	Swanscombe Member	~400 or 471	11	
Anglian	Lowestoft Formation	440	12	The dating of this major glaciation remains a matter of some dispute. See discussion in Section 2.3.1.
Cromerian		880-460	21-13	Age range estimated from graphical information.
Beestonian		Before 880	21+	Included for completeness. These early stages are not discussed in this part of BIOCLIM.
Pastonian				
Baventian				
Antian				
Thurnian				
Ludhamian				
Waltonian				

***Table 5-1**: Quaternary Stratigraphy of the British Isles*

5.2 - Climate Characterisation

It is emphasised that it is not within the scope of this report to provide a comprehensive compilation of the palaeodata available that are relevant to central England. A large number of sites have been studied in the British Isles and northwest Europe, and analyses of substantial numbers of samples at each of these sites have been undertaken for pollen, coleoptera and plant macrofossils. The papers cited herein are themselves recent syntheses or reviews of the primary literature. Thus, for a full appreciation of the literature, there is a need to scrutinise not only these papers, but also the large number of primary sources to which they refer. For climate characterisation, the emphasis here is on quantitative, rather than qualitative, reconstructions.

Because of the effects of Late Devensian (Weichselian) ice sheets in eroding sedimentary deposits of earlier date, climate reconstructions for Britain and the northwest European mainland have concentrated on the period since the Last Glacial Maximum (the Late Weichselian Pleniglacial). These reconstructions extend from the Late Glacial through the Younger Dryas and into the Holocene. Only limited data are available for earlier periods, though multi-proxy climate reconstructions for the Eemian and Early Weichselian have been undertaken by Aalbersberg and Litt [Ref. 117] for northwest Europe, and Huijzer and Isarin [Ref. 118] have performed a multi-proxy analysis for the Middle Weichselian Pleniglacial[1] of northwest Europe at 41-38 ka BP (41,000 to 38,000 years Before Present). In this summary, climatic reconstructions for these earlier periods are described first, before discussing the Late Glacial to Holocene transition in greater detail. Some remarks are then made on climate at the Holocene thermal optimum, before finally describing the climate of the area at the present day.

Although the emphasis of the review is on Britain and more specifically on central England, several of the studies reviewed have adopted a wider geographical basis. It has been considered useful to retain the wider geographical bases where available, as these allow changes in British climate to be seen in a wider context and facilitate evaluation of the consistency of the available reconstructions. It is noted that the studies reported relate to three distinct periods at around 120 ka BP, around 40 ka BP and more recently than 22 ka BP. These three periods provide useful information on a transition from interglacial to glacial conditions, a cold episode during a long period of cooling leading up to an extensive northern hemisphere glaciation, and a transition from glacial to interglacial conditions. However, for a continuous record of glacial-interglacial cycling use has to be made of records from further south in Europe. Interpretation of these long records is not addressed herein, as they are discussed in the French and Spanish contributions to the project (Sections III and IV).

5.2.1 - The Eemian and Early Weichselian (c. 120 ka BP onward)

Aalbersberg and Litt [Ref. 117] studied palaeobotanical, coleopteran and periglacial data from 106 sites across northwest Europe in order to reconstruct palaeoclimatic conditions during the Eemian and Early Weichselian. Because the period of interest falls outside the range of ^{14}C detection and interpretation, absolute chronometric dating is difficult and the number of sites in the area with reliable dates is small. Indeed, as noted above, most of the sites in Europe with established long chronologies, e.g. Grande Pile [Ref. 45], lie south of the region of interest. Because of the lack of absolute chronometric dating, botanical biozones were used to correlate from site to site. To avoid latitudinal variations in climate as much as possible, an east-west transect across Europe between 50°N and 60°N was chosen. This transect includes Ireland in the west, and Poland and the Baltic States in the east. The transect was not extended further east, because literature from this region was difficult to access.

Aalbersberg and Litt [Ref. 117] comment that, because of apparent uniform vegetational development in the Eemian over the transect, it was possible to use biostratigraphical zones as time slices, but that it would have been preferable to use absolute dates to avoid problems with plant immigration and local differences in ecology. There is an element of circularity in this argument, as without absolute dating it is difficult to be sure that vegetational changes at the various sites have occurred in synchrony. For this reason, the seven time slices are probably best viewed as diachronous stages of succession, with a detailed timing that depends on location.

The seven time slices studied are characterised in the following table[2] (**Table 5-2**)

Time Slice	Period	Description
1	Eemian	*Pinus-Quercetum mixtum-Corylus* phase
2	Eemian	*Carpinus-Picea* phase
3	Eemian	*Pinus-Picea-Abies* phase
4	Early Weichselian	Herning Stadial
5	Early Weichselian	Brørup Interstadial
6	Early Weichselian	Rederstall Stadial
7	Early Weichselian	Oddrade Interstadial

***Table 5-2**: Time slices from the Eemian and early Weichselian*

Brief descriptions of each of these time slices are given below (**Table 5-3**). Where available, the range (not including error bars) of minimum mean January and July temperatures and temperature amplitudes for British sites is provided in the following table. Note that the temperature amplitudes appear to have been constructed separately and do not correspond exactly to the difference in mimimum mean temperatures for July and January.

Time Slice	Number of sites	Range of British Values (°C)		
		Minimum Mean January Temperature	Minimum Mean July Temperature	Temperature Amplitude
1	4/5	-3 to 0	16 to 22	18 to 20.5
2	2	-1 to 0	16 to 17.5	18 to 18.5
3	2	0	15 to 17.5	17 to 17.5
4	1	-23.5	9.5	33
5	2-4	-5/-6 or -10	10 to 16.5	17.5 or 21.5
6	0	No data	No data	No data
7	0	No data	No data	No data

***Table 5-3**: Range of British values for each time slice*

1) This is the authors' nomenclature. The Middle Weichselian Stadial is an alternative, and probably better, description. The whole of the Weichselian can be broadly described as corresponding to the Würm glaciation.

2) The descriptions in this table are taken from the original paper. *Quercus mixtum* is taken to mean *Quercus spp.* During the latter part of the Eemian a pine-oak-hazel woodland is replaced by a hornbeam-spruce phase and this, in turn, is replaced by a pine-spruce-fir phase as the climate deteriorates.

The first time slice is considered by the authors to be the period in which the climate had reached its most temperate character. Evidence from coleoptera supports the view that this was the thermal maximum of the Eemian Interglacial, with many species that today have central and southern European geographical ranges present as far north as the British Isles. In the second time slice, the climate has changed from continental to oceanic. Although summer temperatures were probably lower than in the first time slice, the climate in general was milder, especially during the winter. The third time slice represents a transition from temperate to boreal climate. Most of the temperate trees have disappeared, to be replaced by spruce, pine and fir (*Picea, Pinus* and *Abies*), and tree birch (*Betula*) reappears. High levels of *Ericales* pollen occur, indicating the presence of heathlands, often accompanied by high *Sphagnum* percentages, indicating the presence of bogs.

The Herning Stadial (Time Slice 4) is a very cold episode characterised by an absence of forest. The temperatures cited may underestimate the harshness of this episode, as they probably reflect, in part, the transition to the subsequent Brørup Interstadial. During the Brørup Interstadial (Time Slice 5), the available data suggest a rather continental temperate climate in most of northwest Europe. However, in Britain, somewhat warmer winters, i.e. a more oceanic climate, are indicated. The presence of heather (*Calluna*) and larch (*Larix*) in most of the region indicates that annual precipitation was somewhere between 400 and 600 mm.

In the Rederstall Stadial (Time Slice 6), the absence of forest means that mean summer temperatures were not much more than 10°C. Although the evidence is limited, mean January temperatures of around –10°C are indicated. Finally, during the Odderade Interstadial (Time Slice 7) conditions were similar to those during the Brørup Interstadial.

5.2.2 - The Middle Weichselian Pleniglacial (41-38 ka BP)

The Middle Weichselian Pleniglacial episode at around 41 to 38 ka BP corresponds to the period immediately after that associated with the Upton Warren Interstadial Complex in Britain. It corresponds to a short period of very cold conditions and has been studied in detail by Huijzer and Isarin [Ref. 118]. Many of the relevant data originate from The Netherlands, but there are also a number of informative sites from central England. At these latter sites, the temperature of the warmest month is estimated at 7 to 11°C. The annual average temperature is estimated at around –9°C and the authors suggest that almost all of England would have been characterised as a zone of discontinuous permafrost. The temperature of the coldest month is estimated as –27 to –26°C for the English sites. As a consequence, the annual amplitude ranges from 33 to 38°C, indicating that a high degree of continentality prevailed in England at this time.

In addition to the reconstruction of the thermal regime, there is some evidence for aeolian activity, which suggests overall aridity at this time. Palaeobotanical evidence also supports low precipitation over this interval. Fluvial incision at the end of the interval suggests an increase in river discharge at that time. However, it is not clear whether this implies an increase in precipitation or mainly a change in the thermal regime.

5.2.3 - The Late Glacial (Late Weichselian) to Holocene Transition (22 – 9 ka BP)

The Last Glacial Maximum occurred in northwest Europe at around 22 to 19 ka BP. Thereafter, there was a relatively rapid amelioration of climate, albeit with fluctuations, through to the early Holocene at around 9 ka BP. The Holocene thermal optimum occurred at around 6 ka BP. It is this glacial to interglacial transition that is described in more detail below.

The climate of Europe for an area north of the Pyrenees-Alps line to central France at 18 ka BP has been reconstructed from pollen data by Peyron et al. [Ref. 119][1]. In that region, the reconstructed temperature of the coldest month was -30±10°C and the reconstructed annual-mean temperature was -12±3°C. For comparison, Atkinson et al. [Ref. 25] comments that during the Late Devensian Pleniglacial (22 to 18 ka BP) in southern Britain, summer temperatures were below 10°C and the coldest winter month was around –16°C or below. Inspection of the figure provided in their paper indicates that the warmest month had a mean temperature in the range 6 to 13°C and that the coldest month had a mean temperature between –11 and –33°C. These two results indicate a mean annual temperature of around –10°C. There is no evidence from Atkinson et al. [Ref. 25] of any substantial warming from 22 to 18 ka BP. Overall, the reconstructions of Peyron et al. [Ref. 119] and Atkinson *et al.* [Ref. 25] appear reasonably consistent. Independently, Williams [Ref. 120] and Lockwood [Ref. 121] suggested c. 250 mm y^{1} precipitation for the early and later parts of the Late Devensian Pleniglacial in central England.

Climatic reconstructions for the period between 18 ka BP and 14 ka BP are sparse. However, the data presented by Atkinson *et al.* [Ref. 25] suggest that no substantial warming of southern England occurred over this period, notwithstanding the substantial retreat of the margins of the British ice sheet that characterised this interval [Ref. 122; Ref. 124].

A useful overview of climatic changes in Europe in the period 14 to 9 ka BP has been provided by Lowe *et al.* [Ref. 125]. This provides a synthesis of data from 12 areas, including northwest Europe and southwest Europe. Within the northwest Europe region, separate reconstructions are provided for Ireland, England and Wales with southern Scotland, the Highlands and Islands of Scotland, north Belgium, The Netherlands, northwest Germany, and Switzerland. These reconstructions take into account the work of Atkinson *et al.* [Ref. 25]. Details of the geomorphological, soil and vegetational histories for northwest Europe over this period are provided in a companion paper by Walker *et al.* [Ref. 126] and a more detailed paper relating specifically to Europe that makes use of both terrestrial and marine data has been published by Walker [Ref. 127].

All the northwest European records agree that a marked climatic warming occurred at 13 ka BP, with an increase in mean July temperature of between 6 and 8°C occurring over a time interval of no more than about 100 years. Thereafter, there is some distinction between the records. Those from the British Isles and The Netherlands show a relatively uniform decrease in mean July temperature until the beginning of the Younger Dryas at 11 ka BP. However, the north Belgian record, which is described as schematic, shows high mean July temperatures being maintained until about 11.3 ka BP, with a rapid decrease to conditions characteristic of the Younger Dryas immediately thereafter.

The Younger Dryas is the interval between 11 and 10 ka BP during which the lowest temperatures of the Late Glacial episode (14 to 9 ka BP) were recorded. In southern Sweden, Denmark and western Norway, mean July temperatures fell by 4-5°C from the preceding Interstadial thermal maximum. However, in the British Isles and The Netherlands, the overall decline was 7-8°C. This resulted in mean July air

1) Throughout, ages are ^{14}C ages, unless specified otherwise.

temperatures for central England of about 10° C [Ref. 25] and mean January air temperatures of about -20°C.

Lowe *et al.* [Ref. 125] commented that recent research suggests significant changes in humidity during the Younger Dryas. The coldest and most arid part of this period seems to have been during the interval 10.5 to 10.0 ka BP in mainland Britain, Belgium, The Netherlands and parts of southwest Europe. There are also indications of a marked dry period in southwest Europe during the early Holocene. It appears, therefore, that a change to a drier regime began during the Younger Dryas and continued in some regions into the early Holocene.

The transition from the Younger Dryas to the Holocene is reflected in the proxy records from all the regions around the North Atlantic by an abrupt and significant climatic warming [Ref. 125]. It is still debated whether the Younger Dryas was a regional or a global episode, but there is increasing evidence for this episode from regions other than the North Atlantic margins, including some from the Southern Hemisphere [Ref. 128].

At the end of the Younger Dryas, increases in mean July temperatures of about 6°C are recorded for western Norway and around 8°C for the British Isles [Ref. 125]. The warming appears in the records as a more or less synchronous event at about 10 ka BP. However, this synchrony could be an artefact because of the occurrence of a plateau of constant ^{14}C age at around this time. Lowe et al. [Ref. 125] commented that climate change at the Younger Dryas-Holocene boundary does not appear to have been unidirectional. Minor climatic oscillations have been recorded on both sides of the Atlantic and significant glacier readvances occurred in Iceland, Norway, Switzerland and in the Labrador-Baffin area. However, in Britain and Ireland the climate amelioration appears to have been essentially unidirectional [Ref. 127].

Overall, Lowe *et al.* [Ref. 125] conclude that the inferred history of climatic changes during the last glacial-interglacial transition derived from terrestrial sequences from the North Atlantic seaboard fit closely, although not perfectly, with the Ruddiman and McIntyre [Ref. 129] model of oceanic surface temperature changes. Variations in surface ocean temperatures are, therefore, considered to be a major factor governing terrestrial climates, although their influence was less pronounced in areas close to the Laurentide and Fennoscandian ice sheets.

More recently, Coope *et al.* [Ref. 130] have reconstructed temperature gradients in northern Europe during the last glacial to Holocene transition using the mutual climatic range method based on fossil coleopteran assemblages from 77 sites. These sites range from Ireland in the west to Poland and Finland in the east. Results are plotted on 16 maps each representative of a time slice from 14.5 ka BP to 9.0 ka BP. Eight of the maps provide estimates of the mean temperature of the warmest month derived from each site where data are available, whereas the other eight show isotherms interpolated through these values. Thirty-eight of the sites studied are within the British Isles. Coope *et al.* [Ref. 130] comment specifically on late-glacial climate fluctuations as they are interpreted from coleopteran assemblages for the British Isles. Firstly, there is a sudden and intense climatic warming at about 13 ka BP, which involved a rise in the mean temperature of the warmest month of about 7°C. The thermal maximum occurred early in the period widely referred to as the 'Late-glacial Interstadial' or 'Bølling-Allerod Interstadial' and can be dated to between 13 and 12.5 ka BP. This was followed by a sudden deterioration in the thermal climate, after which temperatures did not reach values as high as those attained during the thermal maximum. Several minor thermal oscillations occurred during the second half of the Late–glacial Interstadial. The Younger Dryas Stadial is marked by a sudden incoming of many obligate northern, cold-adapted species of beetle into lowland Britain, indicating further climatic cooling. Shortly after 10 ka BP, there was another sudden and intense climatic warming of the order of 7°C, so that by 9.6 ka BP temperatures in Britain were as warm as, or even warmer, than those at the present day.

The Younger Dryas has provided an interesting episode to simulate using Atmospheric General Circulation Models (AGCMs), as detailed reconstructions based on palaeoindicator data are available for comparative purposes. For example, Renssen and Isarin [Ref. 131] compared results for temperatures in northwest Europe obtained using the ECHAM model with reconstructions based on geological and palaeoecological records. Isarin and Renssen [Ref. 132] described in detail the types of records used. Maps for mean winter, summer and annual temperatures were produced and compared. This demonstrated that simulated winters were about 10°C too warm in Ireland and England and that simulated summers were too warm in continental Europe. Isarin et al. [Ref. 133] also compared AGCM results with palaeoreconstructions of the wind climate during the Younger Dryas. The palaeodata used in the reconstructions were for aeolian landforms in the Netherlands and Poland.

Isarin and Renssen [Ref. 132] provide detailed maps for mean July, mean January and mean annual temperatures for the Younger Dryas based on periglacial, beetle and botanical evidence. Reconstructed mean July temperatures for Britain ranged from 13°C on the south coast of England to about 10°C in central Scotland. Reconstructed mean January temperatures were between –15 and -20°C for most of England. Mean annual temperatures ranged from about –1°C on the south coast of England to below -8°C in much of Scotland.

A more detailed climatic reconstruction of two distinct phases of the Younger Dryas based on botanical data was undertaken by Isarin and Bohncke [Ref. 134], who compared their results with beetle and glaciological data. The botanical reconstruction was based on 140 pollen and plant macrofossil diagrams.

The first part of the Younger Dryas is characterised as the phase of maximum cold and is dated from about 10,950 to 10,550 a BP. It is for this phase that minimum mean July isotherms range from 13°C on the south coast of England to about 10°C in central Scotland. Subsequent to this, a phase of warming is indicated from 10,550 to 10,150 a BP. Overall, there is a northward shift of the 13°C isotherm of about 2° latitude compared with the previous phase. This suggests a summer warming of 1 to 2°C in Britain.

Comparison of the results obtained for the cold phase of the Younger Dryas with beetle data indicated that the two approaches were consistent. However, reconstructions based on fluctuations in equilibrium-line altitudes of glaciers in the British Isles and southwest Norway revealed some discrepancies, with the glaciological data indicating lower temperatures than had been inferred from the biological information. One possibility is that the glaciological reconstructions are biased because of inappropriate assumptions about amounts and patterns of precipitation during the Younger Dryas. However, bias in the botanically based results cannot be ruled out, as Birks[1] has shown that, for two sites in western Norway, Alleröd temperatures reconstructed from fossil pollen evidence alone were 2 to 6°C higher than those based on plant macrofossils.

Comparisons of the last-glacial to Holocene transition in Britain have been made against data from the GRIP and GISP-2 ice cores from Greenland. Lowe *et al.* [Ref. 135] obtained a palaeotemperature record based on fossil coleopteran evidence from a site in Gransmoor in eastern England. Calibration of the radiocarbon dates associated with this record enabled a direct comparison to be made with the palaeotemperature curve and snow accumulation record from the GISP-2 ice core. The similarity between the two data sets was striking. The overall shapes of the curves matched well. Also, although the inflections in the British temperature curve generally precede those in ice accumulation, in each case the discrepancy is less than 150 years. This is within the error range of both the radiocarbon and ice-core dating. The evidence presented is used to infer a measure of synchrony between atmospheric changes over Greenland and parts of northwest Europe during the last glacial-interglacial transition, which, in turn, supports the suggestion that major warming episodes in the North Atlantic region were characterised by marked storm track displacement northward towards Greenland.

1) Birks (1993) is given as the citation in Isarin and Bohncke [Ref. 134], but this is not listed in the reference list, so it has not been possible to check the validity of this interpretation.

In a more recent study, Mayle *et al.* [Ref. 136] compared age-calibrated (cal) data[1] from four sequences in Britain that span the last glacial-Holocene transition. The four sequences are from Llanilid (south Wales), Gransmoor (eastern England), Whitrig Bog (southern Scotland) and Borrobol (northern Scotland). The data from these sites were also compared with data from the GRIP ice-core record. A detailed synthesis of the work is provided in Figure 6 of the published paper. The authors consider that there is a degree of compatibility between the British and GRIP palaeoclimatic records.

Also, overall, the British records show:

- a thermal peak between 15.0 and 14.5 cal ka BP;
- climate cooling commencing at 14.5 cal ka BP;
- a period of marked climatic instability from 14.4 to 12.7 cal ka BP, the regional effects of which are difficult to resolve using the evidence presently available;
- further climatic cooling, which commenced at around 13 cal ka BP, after which the lake biota, catchment soils and vegetation, at least in some parts of Britain, did not recover until the onset of the Holocene;
- continued climatic cooling, with the most severe impact on lake ecosystems occurring during the period c. 12.6 to 11.5 cal ka BP.

Correlation of British records and the development of a detailed event stratigraphy for the Late Glacial-Holocene transition are described in detail by Lowe et al. [Ref. 137]. This paper also includes a high-resolution estimate, based on beetle data, of the mean temperature of the warmest month for lowland Britain from 15 ka to 11.3 ka BP. This temperature falls relatively smoothly from about 19°C at 15 ka BP to 12°C at 13 ka BP. It then remains constant at that value until 11.4 ka BP before rising rapidly to 20°C.

5.2.4 - *The Holocene Thermal Optimum (6 ka BP)*

Biomes of European vegetation at 6 ka BP (the Holocene thermal optimum) have been reconstructed by Prentice *et al.* [Ref. 138]. Overall conclusions from that study were that:

- Temperate deciduous forests extended further north and up to higher elevations than today, occupying areas now covered by cool mixed forest and cool conifer forest in northern Europe and in the mountains of central and southern Europe;
- Taiga and tundra were not present at any of the sampling sites in Fennoscandia at 6 ka BP. The western boundary of the taiga lay far to the east in Russia and even cool conifer forest was largely confined east of the Baltic. The south-to-north zonation in Sweden and Norway at 6 ka BP proceeds directly from temperate deciduous forest through cold mixed forest to cold deciduous forest, which extends to the Arctic coast. These cold forest biomes are confined to small areas of relatively maritime climates in present-day Europe, but at 6 ka BP they occupied much larger areas of northern Europe.

In the Mediterranean region, xerophytic woods/scrub and steppe were absent from the sampling sites. Instead, broad-leaved, evergreen/warm mixed forests, and even temperate deciduous forests, were widespread throughout southern Europe and the Near East.

Overall, these conclusions were interpreted to imply an increase in summer temperatures of about 2oC above present-day values across much of Europe and a more maritime climate in northern Europe. The replacement of today's xerophytic vegetation in the Mediterranean region implies a combination of winters colder than those of the present day and wetter than present conditions during the growing season.

A more detailed analysis of climate anomalies at 6 ka BP relative to the present day is provided by Cheddadi *et al.* [Ref. 140]. In that study, the climate variables reconstructed were the mean temperature of the coldest month, growing degree days above 5°C, and moisture availability expressed as precipitation minus evapotranspiration and as a moisture availability index. Comparisons of pollen-based reconstructions with PMIP (Palaeoclimate Modelling Intercomparison Project) simulations for 6 000 years BP have been reported by Masson *et al.* [Ref. 141]. Various model-data disagreements are identified and these are tentatively attributed to local influences of the surrounding oceans that were not taken into account in the first PMIP simulations.

5.2.5 - *Summary of the Sequence of Late Quaternary Climate Stages in Central England*

Detailed climatic data for the British Isles, supplemented by information for northwest Europe, are summarised in **Table 5-4**. In order to construct this table, it has been necessary to relate British and continental stage names for the Late Quaternary to Oxygen Isotope Stages (OIS) and to calendar ages. A brief account of this correlation is given below (see also Section 1.3 for a more general discussion of timeframe correlations).

It is generally agreed that the Eemian interglacial, known for the onshore deposits in Britain as the Ipswichian corresponds to OIS 5e. Although there is some uncertainty as to dates, the most recent guide to British Quaternary lithostratigraphy provides a central date for the Ipswichian of 124 ka BP [Ref. 2]. This is in accord with the orbitally-tuned $\delta^{18}O$ data of Shackleton, which indicate global sea level above, or no more than 4 m below, its present-day value between 129 and 118 ka BP. It should be noted that some authors have adopted the convention of assigning the name Eemian to the whole of OIS 5. As this convention is unusual and there are well-known stage names for OIS 5d to 5a, this convention has not been used herein.

In France, OIS 5d to 5a are known as Mélisey I, St Germain I, Mélisey II and St Germain II, respectively. However, the climatic data for these stages for Britain are taken from the work of Aalbersberg and Litt [Ref. 117]. These authors adopt a long chronology for the Weichselian (or Würm) glaciation that comprises OIS 5d to 2 inclusive. Other authors consider the Weichselian to comprise only OIS 4 to 2 inclusive. To avoid confusion, the term Weichselian is here reserved for OIS 4 to 2. The special names adopted by Aalbersberg and Litt for OIS 5d to 5a are unambiguous and are used here. These are the Herning stadial, the Brørup interstadial, the Rederstall stadial and the Oddrade interstadial, respectively.

In Britain, the 1973 classification of Quaternary stages would place the Chelford interstadial younger than OIS 5a. At that time, it was dated to around 60 ka BP, which places it close to the boundary between OIS 3 and 4 [Ref. 116]. However, more recent work [Ref. 2] makes it clear that the Chelford formation is a composite body. The lower part of this formation probably pre-dates the Eemian interglacial (OIS 5e). The key member of the upper part of the formation is the Farm Wood Member. This was originally assigned a ^{14}C age of around 60 ka BP [Ref. 116]. However, this is now regarded as a minimum age and a U-series age of 86 +26/-21 ka BP suggests a tentative association of the Chelford interstadial with OIS 5a [Ref. 2]. The later Upton Warren interstadial has been associated with ^{14}C ages of around 41 ka BP [Ref. 116]. However, the amino acid racemization data indicate an age of about 57 ka BP [Ref. 116], around the boundary of OIS 3 and 4.

1) The age-calibration gives 14C ages before present based on CALIB 3.0 of Stuiver and Reimer [Ref. 139].

Huijzer and Isarin [Ref. 118] studied a period that they termed the Middle Weichselian Pleniglacial episode. This was dated to 41 to 38 ka BP and was described as the period immediately following the Upton Warren interstadial. However, this attribution was based on the original Upton Warren ^{14}C ages. Nevertheless, the period studied was identified and dated on the basis of a variety of ^{14}C and amino acid racemization age estimates, so the dates of 41 to 38 ka BP are thought to be secure. However, there is no necessary implication that this time slice immediately followed the Upton Warren interstadial in Britain.

After the Middle Weichselian pleniglacial, climatic data for Britain become scarce during development of the Late Devensian ice sheet that represents the culmination of the Weichselian glacial episode. This development occurs during the latter part of OIS 3 and the early part of OIS 2. The Last Glacial Maximum (LGM), known as the Late Devensian in Britain, is centred around 20 ka BP and climatic reconstructions become available from the work of Atkinson *et al.* [Ref. 25] from 22 ka BP to the present day. Over this period, it is convenient to distinguish the Late Glacial period of deglaciation from 18 ka BP to 13 ka BP, the Windermere interstadial from 13 ka BP to 11 ka BP, the Younger Dryas from 11 to 10 ka BP and the Holocene (Flandrian) from 10 ka BP to the present day. These dates are taken from Atkinson *et al.* [Ref. 25], where they are described as ^{14}C ages. Within the Younger Dryas (identified with the Loch Lomond glacial readvance in Britain), a climatic distinction between the early and later parts is recognised. Also, in the Holocene, there is some merit in distinguishing the thermal optimum at around 6 ka BP, as this has been the subject of a number of palaeoclimatic reconstructions.

It is interesting to compare the temperature estimates summarised in **Table 5-4** with those adopted in scenarios for modelling permafrost development at the French site (**Table 3-1**). The records are in generally good agreement. The main differences are that the Melisey I episode seems to have been more extreme in Britain than in France, whereas the converse is the case for Melisey II, and that a late glacial warming occurred in France, which is not observed in the British record.

Calendar Age (ka BP)	OIS	Local Name for Central England reconstruction	Description	Mean Annual Temperature (°C)		Köppen-Trewartha Climate Class	Basis	Refs.
				Best Estimate	Uncertainty			
0 – 5	1	Recent Holocene	Within range of current UK climate, as characterised by the instrumental record and confirmed by longer-term palaeodata. Vegetational characteristics similar to those at the present day.	+10	±2	DO	Direct observation	[Ref. 38] [Ref. 123]
5 – 7	1	Holocenel Thermal Optimum		+12	±2	DO	Increase in temperature of about 2°C across much of Europe.	[Ref. 138]
7 – 10	1	Early Holocene		+10	±3	DO	By 9.6 ka BP temperatures in the British Isles were as warm, or even warmer than, at the present day	[Ref. 130]
10 – 10.5	1	Late Younger Dryas	A period of intense cold a associated with the formation of corrie glaciers in the British uplands	-8	±6	EC	Ensures that the rapid temperature fall at the the beginning of the Younger Dryas is in accord with observations from Britain and the Netherlands and that both periods are consistent with Atkinson et al. Climate classification recognises warm summers and extremely cold winters.	[Ref. 118]
10.5 – 11	1	Early Younger Dryas		+0	±6	EC		[Ref. 125]
11 – 13	1 or 2	Windermere interstadial		+8	±3	DC	Coldest month a little below 0oC and warmest around 16°C, based on individual fauna.	[Ref. 118]
13 – 18	2	Late Glacial		-10	-14 to + 2	FT	No indication of significant warming during ice retreat	[Ref. 118]
18 – 22	2	Last Glacial	Ice-sheets covered most of Northern Britain. Southern Britain was periglacial in character.	-10	-14 to + 2	FT	Coleopteran reconstruction from Atkinson *et al* suggests a mean annual temperature of –4°C, but the results for individual fauna reported in their paper suggest a lower value, more in accord with the work of Peyron *et al*. The upper bound of the uncertainty range is supported by Atkinson *et al.*, but not by Peyron *et al*. The lower bound is consistent in both reports.	[Ref. 118] [Ref. 119]
22 – 38	2 or 3		Not characterised.	-	-	-	-	-
38 – 41	3	Middle Weichselian pleniglacial	Brief period of exceptionally cold conditions	-9	±2	FT, possibly EC	Sites from Central England. Uncertainty is based on variability between these sites	[Ref. 118]
41 – 77	3 or 4		Generally cooling relative to the Oddrade interstadial	-	-	-	-	-
77 – 91	5a	Oddrade Interstadial	For vegetational associations and a general description of conditions, see the main text.	+3	±3	EO	ilar in northwest Europe to the Brørup interstadial	[Ref. 117]
91 – 97	5b	Rederstall stadial		0	±3	EC or EO	Based on general northwest European data, but no specific British data. Difficult to select EC or EO, as coldest month was around –10°C.	[Ref. 117]
97 – 104	5c	Brørup interstadial		+3	±3	EO	Based on time slice 5 of Aalbersberg and Litt. Small temperature amplitude indicates oceanic climate.	[Ref. 117]
104 – 116	5d	Herning stadial		-7	±3	EC	Based on time slice 4 of Aalbersberg and Litt, but for only one British site; uncertainty based on time slice 5	[Ref. 117]
116 – 131	5e	Eemian		+10	±2	DO	Based on time slices 1 to 3 of Aalbersberg and Litt	[Ref. 117]

***Table 5-4**: Characterisation of Climate States Sequences for Central England during the last Climatic Cycle*

5.3 - Vegetational Characteristics

The climate reconstructions discussed above are often based on palaeobotanical evidence. For this reason, there is little merit in discussing vegetational characteristics separately in great detail. Instead reference should be made to the numerous citations included in the references relating to climate reconstruction. However, it is probably useful to provide a brief account of the overall pattern of post-glacial evolution of soils and vegetation in northwest Europe and to illustrate this by detailed information for west Cumbria that has been reviewed in the context of the Nirex programme [Ref. 124].

A model of climate, soil, vegetation and floristic evolution for an interglacial cycle in northwest Europe was proposed by Iverson [Ref. 142; Ref. 143], based on empirical evidence from Denmark. Four stages were proposed: Cryocratic, Procratic, Mesocratic and Telocratic.

The Cryocratic stage is characterised by immature, unstable, base-rich soils on which is developed an open herb and dwarf shrub vegetation with arctic-alpine flora. This stage occurred prior to about 10 ka BP.

The succeeding Protocratic stage, in general, was a period of rising temperatures and increasing shade as tree taxa immigrated to northwest Europe, shading out plants of arctic-alpine meadows. Soil maturation occurred over this period. The plant communities comprised herb-rich meadows with juniper (*Juniperus*) scrub and successively tree birches (*Betula spp.*) and Pine (*Pinus*). Poplar or aspen (*Populus tremula*) and willow (*Salix*) were also elements of the evolving forest. At the beginning of the Protocratic stage, it is likely that the stature of tree birches did not exceed 4 m, but with increasing warmth their stature increased and the composition of the forest changed. Pedogenesis was slow during the early part of the Protocratic stage, because low temperatures inhibited both chemical and biological processes, but increased as temperatures and humidity increased. As soil development may take up to 5,000 years, even at the end of the stage there were extensive areas in northwest Europe, especially uplands and coastlands, with immature soils susceptible to further development because of both climatic and vegetational change. By the end of the stage, the forests of birch, hazel and pine already contained elements of the mixed oak forest that was to characterise the Mesocratic stage.

This mixed oak forest was dominated by the Sessile Oak (*Quercus petraea*), with co-dominants of elm (*Ulmus*), alder (*Alnus*), lime (*Tilia*) and ash (*Fraxinus*). The forest was rich in shrubs, some attaining the stature of small trees, such as holly (*Ilex*), hazel (*Corylus*) and yew (*Taxus*); herbs, such as wood rushes, wood anemone and wood sorrel; and climbers such as honeysuckle and ivy, particularly in the more oceanic parts of northwest Europe. The soils associated with this Mesocratic forest were base-rich and characteristically had the horizon of mull humus associated with brown forest soils. Although, leaching of bases and sesquioxides could have led to incipient podzols, in general the soils would have been well mixed due to the activities of soil fauna.

Declining temperatures, decreased shading, due to the opening of the forest canopy, and increasing precipitation characterised the Telocratic stage. Retrogressive plant succession occurred. Late emigrating trees, such as beech (*Fagus*) and hornbeam (*Carpinus*) replaced the dominants and co-dominants of the mixed oak forest, conifers such as pine reappeared, heathlands of *Ericales* (especially *Calluna*, *Erica* and *Empetrum*) were of some significance. Raised and blanket bogs, dominated by *Sphagnum*, developed at both high and low altitudes.

It should be noted that Iverson's model though useful as a general description does not accommodate the great variety of parent materials present in northwest Europe. Also, it does not include any representation of the impacts of man on soils and vegetation over the last few thousand years [Ref. 124].

A general pattern of vegetation change during the Holocene in Europe has been published by Huntley and his co-workers using 44 taxa from 500 sites where pollen diagrams have been published [Ref. 144; Ref. 145; Ref. 146; Ref. 147]. Illustrative figures based on this work showing vegetational patterns across Europe from 13 ka BP to the present at 1 ka intervals are presented by Thorne et al. [Ref. 124].

To illustrate a vegetational history characteristic of one area of England, reference is made to the post-glacial vegetational history of west Cumbria outlined by Thorne *et al.* [Ref. 124]. It illustrates the density of palaeobotanical information available in the UK, being based on data from 22 sites. Various classification schemes have been used and between six and eight chronozones are used to characterise the period from 10 ka BP to recent times when human influences have become dominant.

Immediately after the end of interstadial conditions, open vegetation, solifluction, erosion and the inwash of coarse sediments to lake basins gave way to light woodland vegetation, slope stabilisation and soil development. Juniper was an early coloniser, but was soon superseded by birch, which shaded out the juniper. However, locally, juniper persisted until about 8.8 ka BP. In the northern part of the area, extensive crowberry (*Empetrum nigrum*) heaths existed until 9 ka BP. This probably indicates an oceanic climate, high precipitation and leaching of nutrients from fluvio-glacial sandy soils.

The period from 9 to 5 ka BP witnessed a great expansion of hazel (*Corylus avellana*) and the arrival of elm (*Ulmus*) and oak (*Quercus*). Ivy (*Hedera helix*) is recorded from 8.3 ka BP and oak, notably Quercus petraea, became increasingly important. At around 7 ka BP, there was a great expansion of Alder (*Alnus glutinosa*), replacing birch on poor, waterlogged soils and invading forests on drier, richer soils.

From about 5 ka BP, human influences dominated, with the disappearance of elm, due to coppicing and clearance for agriculture. Abandoned clearings were colonised by birch, which also responded to an extended area of podzols. Ash (*Fraxinus*) arrived in west Cumbria during this period and flourished on clearance sites. In the coastal lowlands, raised bogs of *Sphagnum* developed extensively.

The above account illustrates that although the main features of post-glacial vegetational succession are well-understood for England and conform relatively closely to the Iverson scheme, there are substantial local variations and anomalies, e.g. the presence of *Empetrum* heaths in west Cumbria in the early Holocene. The low frequencies of pine, the pre-eminence of oak over elm, the absence of lime and the late arrival of ash in the woodlands of west Cumbria all emphasise the distinctiveness of the vegetation and its evolution in that area. Similar degrees of local variation can be anticipated for other regions in Britain.

5.4 - Geology and Hydrogeology

5.4.1 - Valley Incision and Erosion Rates

Although Quaternary glaciations are mainly characteristic of the northwest (upland) part of Britain, ice sheets have in the past extended into the area characterised in this study as Central England. In particular, the Anglian glaciation (OIS 12) extended over the lowlands of eastern England and East Anglia [Ref. 148]. It was this glaciation that laid down the extensive till deposits that cover much of the region. The more recent Late Devensian glaciation (OIS 2) did not extend so far south, but it did create an extensive till sheet in the lowlands of Northumbria and it is of interest to compare the degree of post-glacial erosion associated with these two till sheets.

There are two main lines of evidence about landform changes brought about by glaciation, the erosional features of the uplands (and in places of the lowlands) and river diversions (both major and minor). In respect of the effects of glacial erosion on Lowland Britain, a consensus has developed that The Wash and The Fens are the result of erosion during the Anglian advance, and similar arguments have been advanced for the Vale of Belvoir. The low elevation of the crest of the Chalk outcrop east of The Fens and the absence of anything like a normal escarpment is also regarded as the work of ice [Ref. 30]. More quantitatively, Clayton [Ref. 149] estimated the volume of 'chalky boulder clay' of eastern England as about 300 km^3, of which about 200 km^3 came from the lowering and setting back of the Chalk escarpment and the remainder came from the Jurassic outcrop in The Fens. However, it was not known how much material had been lost in solution, or from outwash, so these volumes may be underestimates. For comparison, reconstruction of the pre-Anglian 'Ingham River' that flowed across The Fens from west to east [Ref. 150] gives a minimum figure for the depth of excavation by Anglian ice in The Fen basin of about 25 m. Based on this, Clayton [Ref. 30] has estimated the excavated volume of Jurassic mudrocks as 276 km^3, to which he adds a figure for the lowering and setting back of the Chalk escarpment of at least 183 km^3. Thus, the total excavated volume is at least 460 km^3, which can be compared with a matching reconstructed till volume of 390 km^3.

The Anglian till is associated with a large number of buried (tunnel) valleys [Ref. 151]. Quite a number of these are below the valleys of modern rivers, suggesting that a sagging of the till surface above these deep fills brought about a coincidence of alignment [Ref. 30].

The Anglian ice also interacted with the River Thames and eventually diverted it into its current course [Ref. 30].

Based on a detailed review of the available evidence, Clayton [Ref. 30] has developed an overall quantitative estimate of the erosive effectiveness of glaciation in Britain. In general terms, each glaciation has contributed an average thickness of 27 m of deposits, derived from the erosion of some 20 m of solid rock. This erosion has been widespread and by no means confined to the uplands, though it is only there that it has left an immediately obvious record in classic glacial landform assemblages. Between glacial episodes, about one third of the deposits left behind by the previous glaciation are removed by the processes of slope denudation and river erosion. The remaining two thirds of the deposits are swept away by the next glacial advance.

It is emphasised that considerable spatial variations in rates of glacial erosion have occurred. There is some evidence that the average amount of glacial erosion in lowland areas has been somewhat greater than in upland areas [Ref. 148]. However, the major distinctions are at a more local scale. Landform and offshore evidence reveals many locations where glacial troughs, meltwater gorges and subglacial channels imply far greater rates [Ref. 30].

Subsequent to a glacial episode, the resultant till is subject to a continuing process of erosion. Clayton [Ref. 30] has investigated the degree of erosion that occurs. The approach relies on reconstruction of the original form of the till surface, so that a map of the depth of subsequent surface lowering can be constructed from the contours of the land surface today. The palaeosurface is constructed as a smooth fit to the current interfluves. As this neglects any lowering of the interfluves, it means that the degree of surface lowering and the volume of eroded material are necessarily underestimated. However, the magnitude of this surface lowering was thought to be no more than 1 to 2 m, corresponding to an underestimation of the volume of material removed of less than 15%. Conversely, slumping over subglacial valleys would have resulted in surface lowering without the erosional removal of material. The magnitude of this effect was again estimated as no more than 15%. Overall, Clayton [Ref. 30] considered that he was slightly underestimating erosion, but probably by no more than 10%.

Clayton [Ref. 30] applied this approach to the two principal till sheets of Lowland England, the Anglian of East Anglia and the Late Devensian between the Southern Uplands and the sea north of the River Tyne in Northumberland.

In the case of the Anglian till, deposited some 440 ka BP, maximum depths of valley cutting have not exceeded 60 m. The average depth of erosion across the whole area was 16.91 m and the modal depth of erosion was 10.46 m. The average depth of erosion corresponds to a rate of 38 mm ka^{-1}.

Whereas the Anglian till fully covers the area investigated by Clayton [Ref. 30], the Northumberland till does not fully clothe the solid rocks. Also, whereas the rivers of the Anglian till originate within the study domain, those of the Northumbrian till rise beyond the till sheet to cross it to the sea. For the whole of the Northumbrian till, the maximum depth of incision is 47.1 m, the average depth of incision is 11.85 m and the modal depth of incision is 7.46 m. As this till was deposited about 15 ka BP, the average rate of erosion is 790 mm ka^{-1}. Study of a sub-area selected to eliminate, as far as possible, the effects of rivers rising outside the till gave a maximum depth of incision of 18.4 m, an average depth of 4.7 m and a modal depth of 1.2 m. The average depth corresponded to an erosion rate of 313 mm ka^{-1}.

Graphs of the distribution of denudation depths for the Anglian and Northumbrian tills are very similar in shape and support the view that the data from both areas are a true representation of dissection below an original sloping surface with sub-parallel rivers [Ref. 30]. The higher rate of incision of the Northumbrian till indicates that downcutting of rivers is relatively rapid in the immediate post-glacial period and then slows as the long profile of these rivers comes into equilibrium. It should be recognised that this equilibrium is also affected by post-glacial sea-level rise, as this affects the base level to which the long profile is graded.

5.4.2 - Soil Development and Hydrogeology

The lowland parts of central England are characterised by a wide variety of different types of solid geology. However, this underlying variety is of only limited relevance in the context of BIOCLIM, as it is overlain over most of the area by unconsolidated Quaternary deposits that were formed during glacial episodes. In the north of the area of interest, these deposits date mainly from the Late Devensian at around 20 ka BP. However, in the south of the area, deposits of Anglian age (c. 440 ka BP) remain beyond the limits of Late Devensian ice-sheet advance [Ref. 30]. These Quaternary deposits comprise various tills together with outwash sands and gravels. In the more recent deposits, many sharp depositional features such as drumlins, eskers and kames can be observed [Ref. 124].

The Quaternary deposits found in central England are typically around 20 m thick and have become incised by fluvial erosion. They exhibit considerable structure on scales ranging from less than one metre to many kilometres. The soils that overlie them have properties that are determined more by the nature of the Quaternary deposits than by the underlying solid geology. It is these soils and their immediately underlying substrates that are of primary interest in the context of the biosphere system descriptions to be developed in BIOCLIM.

These soils and their associated subsoils can be distinguished in classes using the Hydrology of Soil Types (HOST) Scheme [Ref. 152]. This distinguishes soils and their underlying substrates into a wide variety of hydrological classes. For safety assessment purposes, a simplified classification has been used [Ref. 153]. This distinguishes:

- well-drained soils with groundwater at a depth of more than 2 m;
- well-drained soils with groundwater at a depth of less than 2 m;

- surface-water gleys with deep groundwater at a depth of more than 2 m;
- groundwater gleys with shallow groundwater at a depth of less than 2 m.

Each of these classes can be further subdivided, as required. This is illustrated in the following table (**Table 5-5**) for the well-drained soils with groundwater at a depth of more than 2 m.

A	Flow Mechanism	Representative Substrate
1	Weakly consolidated, microporous by-pass flow uncommon	Chalk, chalk rubble Clay with flints plateau drift Chalky drift
2	Weakly consolidated, microporous, by-pass flow uncommon	Soft Magnesian, brashy or Oolitic limestone and ironstone
3	Weakly consolidated, macroporous, by-pass flow uncommon	Soft sandstone, weakly consolidated sand
4	Strongly consolidated, non or slightly porous, by-pass flow common.	Weathered/fissured intrusive/metamorphic rock Hard fissured limestone Hard (fissured) sandstone
5	Unconsolidated, macroporous, by-pass flow very uncommon	Blown sand Gravel Sand
6	Unconsolidated, microporous, by-pass flow common	Colluvium Coverloam Loamy drift

***Table 5-5**: Flow mechanisms and representative substrate*

5.5 - Conclusions

Extensive data are available to provide quantitative palaeoclimatic reconstructions for northwest Europe for the period subsequent to the Last Glacial Maximum of the Late Devensian/Weichselian. Furthermore, many of the sites upon which these reconstructions are based are located in Britain, so the construction of detailed palaeoclimatic histories for central England over that period is relatively straightforward. Palaeoclimatic reconstructions for earlier periods are more fragmentary. It is possible to undertake reconstructions for the Eemian and Early Weichselian, but there is some doubt as to whether the time slices that have been developed are synchronous. Some reconstructions for the period around 40 ka BP are also possible. Most reconstructions have been for temperature, but some have also included consideration of variations in precipitation, water balance and aeolian effects.

The palaeoclimatic reconstructions that have been undertaken have been based on geomorphological, botanical and coleopteran (beetle) data. The botanical data that are available are very extensive, so it is straightforward to associate the palaeoclimatic data with vegetational histories. Although the general pattern of post-glacial vegetation development is clear and Iverson's scheme provides a useful context for description for central England, the detailed data for west Cumbria illustrate the degree to which this general pattern can be modified by local influences. However, it seems unlikely that such local variations will be of much relevance in the context of BIOCLIM.

Deep hydrogeology is of only limited relevance to BIOCLIM. Therefore, the main emphasis needs to be placed on the hydrological characterisation of soils and subsoils in a way that is appropriate to assessment studies. A hydrologically based approach has been devised for this purpose. This is related directly to a standard scheme for the hydrological classification of soils that is in use in the UK.

Table 5-6 (based on work described in [Ref. 154]) provides a brief description of the broad climate states encountered in Britain during the Late Quaternary. The descriptions for the Boreal and Periglacial states refer to stages of the slow cooling trend towards a full glacial epoch. In the post-glacial phase, the warming is sufficiently rapid that these states are expressed only transiently. This means that their full characteristics, as set out in the table, are never expressed. The immediately post-glacial period is better thought of as transitional between the glacial and temperate states than as one or more intermediate states.

For correlation with climate states classified using the Köppen-Trewartha scheme, the following relationships are proposed:

- Temperate would normally be DO, but could also be DC;
- Boreal is EO;
- Periglacial is EC and the less extreme part of FT;
- Glacial is FT.

CLIMATE	Central England Region				
	VEGETATION	PEDOGENESIS & SOIL CHARATER	HYDROLOGY	EROSION & DEPOSITION	HYDROGEOLOGY
Temperate	Similar to present day. Dominated by deciduous woodland species and grasses.	Alfisols - Increase in organic material available for incorporation into soil. Distinct soil horizon development. Clayey to loamy particle sizes. Peat formation common under wet conditions. Decalcification and leaching of acidic soils.	Possibly increased annual rainfall during warmer periods (winter storms). Lower river flows in summer. Generally, year round river flows.	Chemical and mechanical (water aided) weathering prevalent. Transport and deposition in rivers and off-shore.	Stress relief and weathering enhance near-surface permeability. Isostatic rebound effects gradually modify gradients. Generally high water levels, especially in winter months.
Boreal	Dominated by coniferous species (pine, birch and spruce).	Spodosols - Gleyed (reduced) and podzolised (acidic) soil development common. Extensive peat bogs.	Flooding and run off at spring thaw. Reduced summer rainfall compared to present day, but increased autumn and winter precipitation.		
Periglacial	Juniper shrub, dwarf willow, grasses, sedges and small herbaceous plants.	Gelisols - Extensive discontinuous permafrost; nvolutions, ice wedge casts, heaved and patterned ground. Fragipan horizons inhibit growth.	Generally drier than boreal, but increased run off after annual spring thaw. Extensive outwash plains. New knick points due to lowered sea levels.	Enhanced freeze-thaw erosion resulting in enhanced regolith. Relatively little chemical erosion. Mass movement away from slopes restricted to intermittent rivers.	Reduced heads, lowered water levels, reduced infiltration. Movement mainly confined to deeper levels and near-surface seasonal flow in active zone only. Salt exclusion from ice.
Glacial	Moss, lichen and minor shrubs on bare rock surfaces.	Extensive till and minor loess on retreat of ice sheets.	Ice dammed proglacial lakes and braided river networks (extensive and shallow). Permafrost conditions ahead of ice sheets.	Localised sub-glacial erosion exagerates pre-existing topography. On average, 20 m bedrock erosion per glaciation, but much more in incised areas. Probably >90% of onshore Quaternary deposits laid down during ice sheet retreat.	Possibly significant changes in hydraulic gradient (magnitude and directions). Ice-sheet loading affects stress patterns and fluid pathways.

***Table 5-6**: Regional Climate States and Associated Environmental Changes in Central England*

6. References

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Appendix A: Narrative description and paleodata for the czech republic (central Europe)

List of Contents:

A.1. - Introduction

The current approved strategy for the back-end of nuclear fuel cycle in the Czech Republic is based on direct disposal of spent nuclear fuel in granitic host rock. The basic scheme of a Czech nuclear waste repository consists of vertical shafts and a system of horizontal galleries with large diameter bore holes used for disposal of containers with spent nuclear fuel and other types of radioactive wastes. Bentonitic materials will be used as buffer, backfill and sealing materials. Although such a repository can be considered safe on the timescales of decades or centuries, its behaviour on the time scales of millenia or longer must be carefully considered from different points of view:

1. retardation and dilution properties of the host rock,
2. recrystallisation or degradation of the buffer and backfill materials based on clay minerals, especially montmorillonite,
3. climate change.

The basic requirements for the host rock of repositories are defined in the Czech legislative documents and are consequential on the research reports. The most important required features can be defined as follows:

- sufficient area (tens of square km) and thickness (1000 m at least),
- lithological homogeneity with minimal hydrothermal alterations and rock veins,
- tectonic fractures and displacement as low as possible,
- without presence of deposits and indications of mineral resources,
- groundwater permeability as low as possible,
- seismic and geodynamic stability of the region.

The selection of a suitable geological unit for deep a geological repository is substantially limited by the small area of the Czech Republic and by its complicated geological structure. The Bohemian Massif, which represents the easternmost known part of the European Variscides, forms the majority of territory of the Czech Republic. The West Carpathians units, which belong to the Alpine-Carpathian orogenetic belt, are present in the eastern part of the republic.

The Bohemian Massif consists of three main groups:

- Precambrian (Cadomian) basement,
- Crystalline and Paleozoic rocks affected by the Hercynian orogeny,
- Post-Hercynian platforms (Permo-Carboniferous, Mesozoic and Tertiary sediments).

The occurrence of the extensive Hercynian plutonism is a characteristic feature of the Bohemia Massif. The Hercynian plutonites are exclusively granitoids. The two largest bodies, the Moldanubian Pluton with the area of 8000 km^2 and the Central Bohemian Plutonic Complex with the area of 3200 km^2 as well as many smaller bodies, belong among them (Fig. A10). According to geochronological data, the age of the majority of the above mentioned granitoids is between 350 and 300 Ma and their development is connected to the late tectonic phase of Hercynian metamorphism.

The siting process for a deep geological repository started with an area survey stage at the beginning of 1990s. In total, 27 suitable regions were selected in various rock formations (magmatic, sedimentary and metamorphic) on the basis of existing regional geological information by the Czech Geological Survey. The siting process continued with detailed evaluation of geological information in 13 regions (the areas of the regions are from 120 to 20 km^2) situated exclusively in granitic rocks. For geological investigations 8 sites in 5 regions are proposed (the areas of sites are from 16 to 56 km^2).

This appendix concentrates primarily on the issue of climate change and its influence on the safety of nuclear waste repositories from the point of view of the last one million years and the next one million years (one million years = 1 Ma). It is clear that while there exists a substantial and coherent body of data on Quaternary palaeoclimates there is a dispute about the future climate development, especially when the considered climate perspective is as long as 1 Ma.

Two basic approaches are possible to address the issue of future climate development:
1) modelling,
2) long-term palaeoclimate studies.

This document concentrates on the second approach for the reasons as follows:

- It is believed that it is highly improbable that the climate of the next 1 Ma will lie outside the limits of Mesozoic and Cenozoic climates. The climates of the last 100 Ma can be considered as an appropriate climatic background for estimation of future climates. The 100 Ma arena provides a reliable context for developing different climate scenarios.
- Many climate models (especially 2D or 3D ocean-land coupled models) cover large parts of the Europe or the Northern Hemisphere including Central-European area where Czech Republic is situated. Such models are probably more accurate than local models simulated on less sophisticated computers. However, the Czech Republic is rather a small area (some 250 km in N-S direction, and 400 km in W-E direction) when compared to the grid of large-scale climate models (typically 200 x 200 km).

A.2. - State of the palaeoclimatological art for the area of the Czech Republic

The area of the Czech Republic has belonged to the classical European mining regions since the medieval period – e.g. a depth of 500 m was for the first time reached in Kutna Hora during the 14th century, whereas a depth of 1000 m was for the first time reached in Pribram in the 19th century. These mining activities helped to establish a long, continuous tradition of geological studies. The Variscan Bohemian Massif became during the second half of the 19th century, one of the classical European geological terrains. Many detailed palaeontological and geological studies resulted in reasonable knowledge in depth of the rock distribution, amplitude of tectonic movements, basin geology and other geological aspects of this area, including palaeoenvironmental studies.

Quaternary studies developed gradually before World War II and were mostly concerned with archaeological excavations. However, in the early 1960s, a new school of Quaternary geology led by G.J. Kukla and V. Lo_ek started research on the thick loess series with multiple fossil soils that are present and later initiated Holocene studies. The palaeoclimate research is now mostly associated with PAGES activities and the best reviews of local activities can be found as the proceedings of PAGES meetings (Ruzicková, Zeman and Mirecki eds. 1993, Ruzicková and Zeman eds. 1995, Kadlec ed. 2000).

The area of the Czech Republic has a very dense network of Quaternary sites that have been studied by palaeobiological and palaeoenvironmental methods (malacozoology, vertebrate palaeontology, pollen analysis), but very few sites where isotopic research and dating have been performed. The general features of climate oscillations are well known from numerous, now mostly non-existant due to subsequent exploitation (mainly brick-fields), sites for the Middle-Upper Pleistocene and Holocene, but the area lacks really detailed geological profiles such as lake varves. The result is a well established, but rather general, synthesis of Pleistocene climates as deduced from about 60 sites (loess series, cave sediments, speleothems) and a more detailed understanding of Holocene environments established on more than 150 studied sites (mostly karst sediments, peat bogs, tufa deposits – Figures A5 and A6). It provides a good background for the understanding not only of past climates but regional differences as well. Some of the basic articles are listed in the bibliography.

A.3. - Methods

This study represents a compilation of the available data on palaeoclimatic and palaeoenvironmental changes over the area of Czech Republic including some recent, as yet unpublished, results. The common and useful approach is to divide the studied changes into several hierarchical levels as follows:

1. Mesozoic and Tertiary prelude
2. Pleistocene climates
3. Last ice age fluctuations
4. Holocene climate and environment
5. Last one thousand years of climatic variability

The climate is not the only important factor, among the characteristics of the geological environment, that may influence the safety of nuclear waste repositories. In fact most of the earth processes are interconnected – e.g. the microfracturing of the rock massif caused by glaciation or neovolcanic activity may lead to the enhanced circulation of fluids and thus more intensive weathering of the sealing agents of a repository. The factor of time can be diminished or enhanced by the intensity of geological processes. Therefore, some attention is paid not only to external climate forcing but also to internal geological forces such as uplift of Bohemian Massif, neovolcanic activity and tectonism.

A.4. - Pleistocene climate and environment

A.4.1. - Introduction

We observe throughout geological history several factors that are required for the occurrence of ice ages:

- Continent or islands must be at the right place or high enough to initiate and build up the masses.
- The equator-pole climate gradients should be high, to efficiently transfer the water vapour evaporated in the tropical zone to the polar regions. Glaciations are not only the result of low temperatures but of humidity transfer to the low temperature areas.
- The global pattern of sea currents should be organised in such way to bring moisture poleward but not to melt the ice sheets.
- The concentration of greenhouse gasses, mainly CO^2, should be low.

The climate system has, from 3.2 to 2.4 Ma BP evolved through a cooling stage ending in abrupt cooling and ice expansion at 2.7 to 2.5 Ma BP. Global rapid tectonic movements possibly triggered these changes. The Central American Isthmus closed and poleward heat and humidity transport increased. The Greenland-Scotland ridge sank down more than 1000 m and the warm near-surface Atlantic currents were able to reach the Greenland-Norwegian regions, while the cold bottom currents could spread over the Atlantic. Himalayan uplift may have caused a change of the upper troposphere winds. Northern Hemisphere glaciation probably represented the switching mechanism for global ice age onset because the Antarctic ice sheet was isolated by mid-ocean ridges. The combined effect of several causes is thought to have influenced this switch, but continuing discussion and a number of uncertainties make any final judgement premature.

A.4.2. - Pleistocene ice ages

We live in the Quaternary period which has been assigned a conventional beginning at 1.8 Ma BP whereas other scientists have proposed a "long" Pleistocene starting at approx. 2.7 Ma BP. The Earth's climate has undergone periodic glaciations and cyclic environmental changes during this time. These have been accompanied by changes in the geochemical fluxes of many atmospheric elements, biosphere productivity and oceanic and atmospheric circulation patterns. Deep-sea sediments show that, during Pleistocene, the climatic changes have been dominated by orbital forcing - the changing distance and inclination between the Sun and Earth. Temperature and ice volume were mainly controlled by so called Milankovitch orbital cycles – changes in precession (19 and 23 ka), obliquity (41 ka) and eccentricity (100 ka). Several other cycles (1 Ma, 400 ka and 60 ka) do sometimes appear in the fossil record.

Although the astronomical theory of Quaternary climate changes is generally accepted, one should be aware that the global climate state is not a simple function of the incoming solar energy. The Earth modulates the insolation by changes in surface reflectivity, heat retention in the oceans and heat redistribution by sea currents. The process of climate modulation also includes complex biological feedbacks and biogeochemical cycling of atmospheric elements.

The Pleistocene epoch can be divided into series of ice ages or glacials and warm periods or interglacials. The term "ice ages" should be restricted only to the polar and temperate areas covered by continental ice sheets, because the tropical and subtropical zones cooled some 4 to 7°C, but mild tropical weather prevailed even during "ice ages". The more exact terms such as "cryomere" or "Pleistocene cool mode" have been proposed but they are not widely used.

During glacial episodes, the Antarctic ice sheet was not significantly larger than now because dry conditions and partial isolation did not allow the build-up of more extensive ice sheet. The most drastic changes in glaciated area (shifts from 10% to 29% in the global extent of ice covered land) occurred in the Northern Hemisphere. The Laurentide ice sheet covered the northern part of the U.S. reaching as far south as New York. Iceland and Greenland were almost entirely ice-covered. The Scandinavian ice sheet extended south to Kiev, Warsaw and Berlin. Much of Siberia was overspread by a Siberian ice sheet. High mountains on all continents carried (even in Japan and Hawaii) glaciers of varying dimensions.

We can distinguish several Pleistocene phases in the area of the Czech Republic:

- Lower Pleistocene glacials were probably (according to the characteristics of loess development) warmer and more humid than later glacials of the last 1 Ma. The bright red to red deeply weathered interglacial soils are characteristic of the period prior to Brunhes-Matuyama palaeomagnetic boundary (Beroun highway outcrop). The fossil content of Lower Pleistocene sediments reflects the presence of thermophilic elements (e.g. outcrops of so called red breccia in Slovak Karst, Eastern Slovakia, see Horacek and Lo_ek 1982, Lo_ek 1982). The evidence is scarce and limited to a few sites. However the general course of the Lower Pleistocene was of mild glacials, warmer and, in some phases, even more arid, interglacials. The frequency of climatic changes was probably higher and the differences between glacial and interglacial conditions, less than during the Middle-Late Pleistocene.
- Middle and Late Pleistocene strata of the Brunhes palaeomagnetic period as recorded in loess series and calcareous sediments display an alternating sequence of well-defined glacial and interglacial sediments. The mean annual temperatures can be estimated in range - 2 to 3 °C during pleniglacials, some 10 0C colder than in interglacial conditions. The glacials were drier – it is estimated some 300 - 400 mm of mean annual rainfall in areas below 400 m a.s.l. The glacial ecosystems can be characterised as cold steppe or grassland, but forest refugia (spruce, birch, juniper) were present as "islands". Pollen analyses and even some macrofossils indicate a rather enigmatic presence of more demanding tree species such as elm and oak during warm phases of the last glacial. The malacofauna is represented for most of the glacials by a monotonous assemblage of several species such as Pupilla. Although the glacials of the last 1 Ma seem to have a similar character, the interglacials are more individual as evidenced by fossil fauna (Horacek and Lo_ek 1982). This may have been caused by random migration from either a western Atlantic direction or along the Donau river from the south-east, or even along the outer limits of the Carpathian range from the area of present-day Poland. The soils in the loess series can be correlated by thermoluminiscence dating and amino-acid racemisation to common marine oxygen isotope stages (Frechen et al. 2000).

A.4.3. - Cyclicity

The effects of glacial climate and continental ice sheet development included fall in global sea level by up to 120 m, because the water cumulated in the ice sheets. The cyclicity of glacial and interglacial modes remains puzzling for the early Pleistocene. The 40 ka cycle seems to be dominant at that time whereas some 0.9 Ma BP the 100 ka cycle began to dominate. The early Pleistocene ice ages were shorter, less severe and the interglacial climates were warmer and possibly (as evidenced by red soils in loess sequences) more arid. The 40 ka orbital cycle is, in respect to solar insolation, stronger than the 100 ka cycle. This raises the question as to why climate over the last million years has been driven by this cycle? A possible explanation is the extent of the ice sheets. They grew so large about 1 Ma BP that, due to thermal inertia, longer cycles prevailed. The climatic change during glacials is most severe in the polar and temperate zone where annual average temperatures dropped by about 10 °C and the total precipitation decreased by about 50%. The equatorial zone witnessed less pronounced change. The glacial seasonality of the temperate zone can be compared to present Siberia – short hot summer alternated with long dry windy winters.

A.4.4. - Abrupt climatic changes

The last million years is marked in the temperate zone by 9 large ice ages lasting about 100 ka and 9 interglacials lasting about 20 ka. We have no reasons to conclude – in spite of the present warming – that the interglacial period we live in will not change into another glacial. The orbital parameters suggest significant cooling 5 ka after present. The last ice age was interrupted by abrupt climatic changes. These are well documented in deep-sea sediments during the last ice age but very probably they will be found in the other glacial intervals. They are known as follows:

Dansgaard-Oeschger oscillation is a rapid, relatively short warm and cold oscillation that punctuates the last glaciation and lasts up to three thousand years. The mean annual temperature may rise within a few decades by up to 10 °C and then fall abruptly back into glacial conditions.

Heinrich event is a period of massive iceberg discharge into the North Atlantic, which occurred several times during the last ice age and probably many times throughout the Pleistocene. The meltwater blocked the upwelling sea currents, so reducing the thermohaline circulation and thus poleward heat transfer. One of the most surprising and alarming climate findings of recent years holds that the thermohaline conveyor belt represented by a complex of sea currents can be switched off and on within a few years. The result is a drastic global climatic change. However, changes in the thermohaline circulation during interglacials seems to be less extreme and less sudden.

The terrestrial record has other characteristic features than those exhibited by marine sediments. The presence of ice-rafted detritus characteristic for Heinrich events cannot be observed there, but recorded changes of magnetic susceptibility and the presence of different wind-blown sediments (known as marker-loess) indicate the existence of abrupt climatic changes in the continental fossil record. The provenance of heavy minerals in loess strata of the last ice age indicates the prevailing westerlies and wind patterns that can be compared with the North Atlantic Oscillation.

A.4.5. - Pleistocene palaeometeorology

The fact that loess-transporting winds came from NW, W and SW directions was established decades ago on the basis of loess dune orientation and the presence of particles from neighbouring rocks (many authors listed in Demek and Kukla, 1969). The same wind direction appear to have been characteristic in the case of most Central European loess deposits although some authors (Vasicek, 1951) have observed evidence of episodes with dominant easterly winds. Such a wind field corresponds to the contemporary North Atlantic Oscillation pattern (Hurrell 1995). Even more important, observations of general sedimentation features of loess deposits point to at least two different modes of loess deposition, as follows:

- Series of individual loess laminae some 2 - 5 cm thick can be observed as episodic strata occurring throughout the last glacial cycle (Dolni Vestonice, Zemechy). The relatively coarse sandy grains in the lowermost part of the laminae and gradual decline in particle size indicate a regime with repeated dust storms with each storm corresponding to one lamina. As a consequence, very variable rates of dust sedimentation especially in small deposits and dunes in the lee of hills and within the valleys are to be expected. Whereas the plateau loess of China and other Asian occurrences may represent a “continuous” long term fossil record, many Central European loess deposits more likely represent detailed “floating” fragments of fossil record to which has been added an enhanced local meteorological signal.
- Relatively homogenous, massive loess without visible stratification probably corresponds to a steady, uniform westerlies regime. The palaeoclimatic data for the last glacial cycle (Tziperman, 1997) demonstrates unstable changes of wind direction and a general variability in the climatic oscillations which is more clearly demonstrated by the macroscopic features of loess sedimentation than by, for example, magnetic susceptibility (Horacek and Bucha, unpublished results of palomagnetic studies of loess deposits in Czech Republic).

The basic loess textural division between laminar and massive types should not cause several mechanisms of laminar texture origin to be overlooked, as following examples make clear:

1. Dust storms may produce laminae where grain size gradually diminishes as the wind velocity decreases (Zemechy in Central Bohemia, abundant exposures of the lower part of pre-Eemian cycle). However, the silty layers (3 - 20 cm thick) are quite often intercalated with narrow (1 - 3 mm) clayey, usually grey or rusty horizons. These horizons may represent the loess surfaces exposed for a longer period of time (days, weeks) to gradual sedimentation of predominantly clay particles (sometimes associated with mica) after storms or during periods of weak wind activity. The lamination cannot normally be observed on freshly cleaned profiles, but it is often seen in the weathered part of the loess profile.

2. The lamination caused by sheet erosion and deposition, snowmelt or by any overland water flow is frequently observed in contemporary brickyards, but it is rarely recognisable in the fossil record unless it contains an admixture of fluviatile materials such as rounded quartz gravel. The special example of erosional lamination is often represented by pellet sands. The contemporary formation of pellet sands can be observed when torrential or stormy rain falls during hot summers on dry soil, so that small soil “pellets” (polyhedrons comprising 1 - 3 mm in diameter bodies limited by desiccation cracks and coated by oriented clay skins) are washed out. The pellets are usually formed by chernozem or brown soils, so that they represent a contrasting layer within the loess series. When the pellet sand is formed by yellow loess and embedded in yellow loess of different age, such as the upper part of pellet sand strata in Sedlec-Kutna Hora above the Eemian soil), it is virtually impossible to distinguish the differences between autochtonous soil and transported soil sediments. The consequences for climatic interpretation are obvious.

3. The lamination caused by frost creep, solifluction and gelifluction is often associated with weak glacial soils, especially PK I soil (22 - 29 ka BP, Dolni Vestonice and elsewhere). Typically the lamination looks like a series of 30 - 100 varves some 1 - 10 mm thick, where brown or rusty laminae are mixed with yellow loess laminae. The rusty colour is of epigenetic origin and represents an originally more calcareous layer partly replaced by Fe-hydroxides coming from a more acidic environment within the surface layer. The calcium content is increased at the freeze-thaw interface due to the freezing of water with dissolved calcium bicarbonate. Gelifluction lamination is usually quite striking. It can be recognised by a change from almost parallel texture to low waves or even complex rollsand turnovers. We consider the following observations to be most important from a Pleistocene palaeometeorological point of view:

- There were at least some periods when the wind pattern during ice ages corresponded to the Holocene pattern of the North Atlantic Oscillation (NAO).
- The wind velocity seems to have oscillated between two basic regimes – I) steady low velocity NW, W and WE winds; II) stormy, high velocity windy episodes that were many times repeated.

A.4.6. - The extent of continental glaciations

The problem of the study of continental glaciation in terrestrial conditions is that new glaciations nearly wipe out the evidence of past glaciations (exceptions are palaeosols that can be preserved in incised channels). The extent of past glaciations can be estimated from geomorphological studies. It is indicated by glacial landforms such as morraines, glacial features – drumlins, eskers, roche moutonneé, striations and sediments such as tills or tillites.

Such glacial landforms can be found only as small and rare forms in Krkonose (Giant Mts.), Sumava and Hruby Jesenik Mts. (Silezia) at heights aproximately 700 m a.s.l. or higher. We therefore suppose the existence of several small (1.5 km or less) mountain glaciers during the Pleistocene. No glacial bedrock striation caused by thick continental glaciers was ever reported from the area of the Czech Republic.

Glacial sediments including erratics of Scandinavian red granites (rapakivi), rare amber and other Nordic rocks including abundant Cretaceous flintstone can be found in two areas of the Czech Republic:

- Silesia (a region close to Poland) where the flat terrain enabled the advance of at least two ice sheets (Elster and Saale glaciations, OIS 12/14 and 7, respectively) some 20 km into the Czech Republic (see Figs. A1 - A4).
- The Liberec region where the continental ice sheet transported abundant erratics and fine grained sediments several km into the Bohemian interior.

In both cases, it is not certain whether the continental glacier crossed the boundaries of the Czech Republic or if the sediments represent out-wash material from a nearby ice sheet. The absence of morraines (not present as geomorphological features), but the presence of erratic boulders (especially in the Silesia region) provide support for each of the proposed solutions.

A.4.7. - Permafrost distribution

Various periglacial phenomena are reported from the area of the Czech Republic – sorted soils, stone glaciers, nivation cirques, solifluction tongues etc. The issue of permafrost has been discussed, mostly at a theoretical level, by many authors (see Czudek 1997) without arriving at any definite conclusions. The deepest level of permafrost as evidenced by microfracturing and plastic deformation is reported from Blahutovice borehole (Moravia, Fig. A4) – 220 m. However, the site is located near the limits of a continental ice sheet and developed in medium soft shales. The maximal estimate for permafrost thickness is given by Demek (1976) – 300 m. Because very few of these estimates are established from field observations and because they are mostly concerned with locations close to the limits of the ice, we expect that permafrost in the interior of Bohemia could develop as a discontinuous layer some 50 to 100 m thick (or less). Not only the crystalline complexes of the Variscan Bohemian Massif but also even the Upper Cretaceous sandstones do not display any enhanced microfracturing that can be attributed to the permafrost action. Microgelivation can be observed in some sandstone areas to cause the formation of rockshelters, small caves and 1 - 2 m thick vertical fissures filled with loose sand.

A.5. - The Holocene climate and environment

A.5.1. - Introduction

The Holocene Epoch, also referred as Recent, is the latest interglacial interval of the Quaternary Period. It is unique because it is coincident with the development of post-Palaeolithic human civilisation. New studies show that the major climatic changes during the Holocene have been simultaneous over the majority of the globe, but smaller or short-lived climatic changes are often restricted to small areas. For example, Holocene climate fluctuations of the last few centuries in the Rhine catchment are slightly different to and not synchronous with those in the Elbe area. Similarly, minor climatic oscillations in Switzerland do not correspond to the oscillations recorded in Greece or Poland. The smaller and shorter climatic fluctuations are, the more they tend to be restricted to specific landscapes and regions.

The Holocene has been considered as a being remarkably stable epoch, with major coolings limited to 1.2 to 1.8 °C range and a major warming some 2 to 3 °C higher than present (annual average global values). However, precipitation varied considerably, by at least -50% to +100% on decadal, centennial and millennial time scales. There is growing evidence of at least three crises when Holocene climate deteriorated abruptly, only to return to its previous stage within a few centuries. These are recorded in abrupt falls of many of Africa's lakes and are dated to 12 000, 8200 and 5200 years BP (calendar years). Other droughts took place during the end of Late Chalcolithic period some 4500 to 3900 years BP, the Early Iron Age at 2800 to 3300 years BP and possibly on many other occasions. These aridity waves were often associated with human ethnic and cultural migrations and societal changes. The droughts, not the temperature, have always represented the principle obstacle to biome or civilisation development during the Holocene (Fig. A7).

The main causes of Holocene climate change are not well understood, but the most frequent explanations are as follows:

- The first half of the Holocene was generally warmer in the Northern Hemisphere, because this part of the Earth received during summer months, some 8% more of the solar radiation than it does at present. The elevated temperatures and humidity led to a so-called thermal optimum (9000 to 5500 years BP). As the vegetation cover diversified under warm and more humid conditions, the so-called forest optimum was reached in the Temperate Zone some 6000 years ago. Subhumid forest dominated Europe and temperate Asia during this interval.
- The climates in the tropical and subtropical zones were largely controlled by the position of Intertropical Zone of Convergence (ITCZ) and its associated rains. The ITCZ several times moved to the north and back again bringing and withdrawing rains in a very climate-sensitive semi-arid belt of Asia and Africa. It very probably affected the monsoon regime of the Indian Ocean, which was stronger in the early Holocene.
- The periodical switching off the North Atlantic Oscillation (periodicity: 7 - 30 years) and El Nino Southern Oscillation (periodicity: 4 - 6 years) and the complex interplay among these large oceanic and atmospheric circulation systems led to abrupt short-lived temperature and humidity fluctuations.
- The human role in nature was far from being passive. Mesolithic forest clearing, Neolithic agriculture, pastoralism and changes in the land-use and thus surface reflectivity, massive recent emissions of greenhouse gasses, nitrous oxides, aerosols, industrial dust and many other factors are either contributing to the natural climatic "cycles" or in some cases counterbalancing them.

A.5.2. - The humidity and temperature course of the Mid-European Holocene

Detailed research on the Holocene deposits – mostly calcareous slope sediments, tufa bodies and soil sequences – conducted during the last few decades on numerous profiles has led to the collection of a large set of climatic and environmental proxies. The most useful summary of such studies seems to be precipitation and temperature curves constructed for the whole Holocene and regionally based on a network of about one hundred sites scattered over the region of the Czech and Slovak republics (Lozek and Cilek, 1995; Fig. A7).

The curves have been constructed by the combination of two principal sources of evidence from the fossil record:

- palaeoenvironmental and palaeoclimatic malacostratigraphic evidence; and
- a sedimentological approach expressed mainly as calcium-carbonate metabolism i.e. the rate of carbonate leaching or precipitation in soil profiles, karst sediments and spring limestones.

Independent lines of evidence such as palynological data (Firbas, 1935; Krippel, 1986) and archaeological finds (Bouzek, 1993) were also taken into account.

The dating of the curves represents a special problem since only a limited number of radiocarbon dates are available for the studied area. Especially, the exact timing of dry phases during the Epiatlantic indicated by soil horizons in tufa bodies has been estimated from sedimentation rates (Fig. A7). The ages expressed in calendar years were mostly based on archaeological finds correlated with the established chronologies. We consider that minor absolute dating shifts may take place but that the relative chronology is reliably established.

The sensitivity and time resolution varies according to the kind of fossil record. Whereas the karst sediments and slope series provide long continuous records from the Late Glacial to Recent, they can seldom serve to distinguish periods shorter than several centuries. The tufas and other spring limestones yield a more detailed resolution since the total thickness of freshwater limestones deposited during several thousands of years may exceed 10 m. On the other hand, the tufas are usually limited to either Late Glacial to Boreal, or Atlantic-Subatlantic periods, with deposition terminated by intensive down cutting during the Late Boreal or Subatlantic.

The growing impact of man on the landscape over the last several thousand years causes a deterioration of the climatic signal in natural indicators. Therefore, other proxies such as the abundance of dated prehistoric grain-pits along riverbanks, settlement density, and the development of lacustrine sites (Pfahlbauten) must be taken into consideration. Further development in this area are difficult to forecast, since any palaeoclimatic curve is subject to further modifications and the adding of new details according to new evidence from previously unknown sources.

A.5.3. - Permafrost distribution

The conventional view of the last millennium climate is encapsulated in the simple sequence of the Medieval Warm Epoch, Little Ice Age and Industrial Warming. Until recently,[7] no evidence for synchronous climate changes on the global level had been found, but many regional anomalies happen on decadal time scales. The most significant environmental risks are not associated with mean temperatures, but with changes of circulation patterns resulting in seasonality shifts and prolonged drought periods. The other important criterion of the climate change is the frequency of extreme states - e.g. the Medieval Warm Epoch (9th to early 15th century) represents an interval of abundant anomalies in ocean circulation patterns. Some of these may have led to anomalous warmth in some (but not all) regions.

The Little Ice Age (conventionally 1550 -1850) is one of the coldest intervals in the entire Holocene. It displays wide temperature variations unevenly distributed in different regions. Some areas were warm at times when others were cold and vice versa. Solar variations and volcanic eruptions can be correlated with climate oscillations of the last milenium. However to find such correlations for the last century is more difficult. Over this period, humans seem to be reaching a point of becoming one of the prime factors determining short-term climate change.

There are three principal databases in the Czech Republic concerning the development of climate during the last one thousand years:

- Temperature series of Prague - Klementinum since 1771. The set is influenced by the urban heat island and the location at the top of a Baroque astronomical tower, but it represents one of the longest European temperature series (Manley 1659, Berlin 1719, Saint Peterburg 1753 etc.).
- Chronicle records as published by R. Brazdil and O. Kotyza in four volumes (see references).
- Chronicle records (about 40 thousand recorded events) in an unpublished monograph of Vasku, Cilek and Svoboda (500 pages). The record in incomplete for the years prior to 1400 (and especially 1200) because of the lack of reliable sources.

Some other studies (speleothems, incomplete dendrometrical sets) throw some extra light on climate development for specific regions and periods. In general, climate variability of the last 1 ka is small in respect to the safety of nuclear waste repositories. The range of mean annual temperatures falls within –1.5 °C and aproximately +1.2 °C in comparison with contemporary values. Basic irregular periodicities of 5 to 7 years and 20 to 40 years can be observed and probably attributed to the North Atlantic Oscillation. The relatively stable climatic period was at certain times (notably 1590 - 1610, 1635 - 1665, 1705 - 1715) interrupted by more humid and cold phases. These periods were closely linked to the increased frequency of famine and harvest deterioration. Some climatic phenomena are depicted in Figs. A8 and A9.

[7] A recent report by Jones (2001) contains relevant information.

A.5.4. - Permafrost distribution

Environmental changes of the Mid-European Holocene have often been described in detail (Lo_ek 1973). There exists a set of Holocene sites in the Czech Republic where complex biostratigraphic research has been carried out, mostly on the basis of malacostratigraphy (Lozek, many articles) or pollen analysis. The basic disadvantage of the majority of the studied sites (about 150) is the lack of radiocarbon dates, with indirect datings established on base of fossil assemblages and archaeological finds, and with low resolution of the fossil record (centuries). However, the regional patterns of Holocene sedimentation, together with detailed palaeontology and sedimentology of some sites enables a reliable general picture of Holocene development to be obtained, including erosional phases (aprox. 6000 years BP, 2000 years BP, 14th century), soil formation, gradual environmental decalcification, forest-grassland changes and some other aspects.

From the point of view of this study, the humidity changes and thus groundwater circulation seem to be more important than e.g. beech forest formation during the Atlantic phase in the place of former oak forest. Some of the basic changes of the environment are summarised in Fig. A7.

A.5.5. - Permafrost distribution

Several regions of the Czech Republic can be distinguished according to their environmental and climatic Holocene history, as follows:

- The region east of the line Vienna-Kromeriz displays affinity to the more continental and less geologically stable Western Carpathians. The species assemblages, soil cover and neotectonic activity represent a major European ecosystem.
- The roughly E-W boundary intersecting Prague between Thermofyticum and Mesofyticum divides Bohemia into two parts – the northern Thermofyticum belongs mostly to chernozem area on sedimentary substrates, whereas the southern, colder region with crystalline substrates is covered mostly by brown soils. Agricultural production is concentrated in Thermofyticum, whereas for Mesofyticum mixed agriculture and forestry is more common.
- The deciduous, mostly oak forest is characteristic of altitudes below 350 to 400 m a.s.l. The 350 m boundary is sometimes called the “magic” divide because the low lying areas have a different evolution – the light, fertile soils developed mostly on loess, which is rarely and insignificantly found at higher altitudes, led to early (often Neolithic) land use associated with prehistoric deforestration, species exchange and migration. The more cold and humid areas above 400 m were occupied much later, during the Urnfield, Hallstat and La Téne cultures of the Late Bronze and Iron Ages or even during the Central and Late Medieval periods of 1100 - 1400 AD.
- The natural beech forest developed within the 400 - 800 m range and the area above 800 m was covered mostly by spruce forests.

A.6. - Geomorphological changes during the last 1 Ma

A.6.1. - Neo-volcanic activity

The younger volcanic rocks of the Bohemian Massif are associated with the formation of the Eger rift, a SW-NE graben structure formed during Palaeogene-Neogene tectonic unrest when deformations of the Earth's crust reached such depths that molten masses penetrated to the surface. All younger volcanic activity is associated with this tectonic event, as in the Rhine graben. The complex history of the volcanic mountain range Ceske Stredohori (Bohemian Middle Mountains) can be reduced here to several most important episodes as follows (Cajz 2000):

- The main volcanic phase and the opening of Eger Rift took place over – 28 to –22 Ma. It was associated with formation of large composite volcanoes, long lava flows, shallow lake sedimentation, lahars and related phenomena.
- Erosion and very limited volcanic activity revealed some of the deeper structures and led also to local explosive volcanism from -12 to - 5 Ma (e.g. Slanska a Vinaricka hora in Kladno region).
- There are several small Quaternary volcanoes in the area of the Czech republic. All of them have been known since the 18th - 19th century and have been intensively studied (e.g. Komorni hurka was studied by J.W. Goethe to solve the problem of neptunism). The age of the two youngest volcanoes is 170 - 400 ka for Zelezna hurka (Eisenbühl) and 450 - 900 ka for Komorni hurka (Kammerbühl).

Young volcanism is restricted to two areas – Jeseniky Mts. in Northern Moravia and the Silesia and Eger area (Chebsko). The first region is located close to the limits of Pleistocene glaciations and the other area is well known for its small but numerous earthquakes.

A.6.2. - Neotectonic activity

The Bohemian Massif reacts to tectonic movements in the Alpine and Carpathians belts in a very irregular way, because sometimes it is firmly connected with southern and eastern regions whereas at other periods it stands as a separate geological unit. The most intensive neotectonic movements have been associated with the following periods:

1. The most intensive neotectonic phase associated with mosaic uplift and inclination of "megablocks" took place during the Palaeogene-Neogene transition and it corresponds to the main neovolcanic phase.
2. The tectonic history of the Pliocene is not well understood, but it is assumed that uplift happened along the mountain boundary zone. The amplitude of movements was probably several hundred meters at the boundaries of the mountain belt but only several tens of meters in the interior. The basal plane of Upper Cretaceous sandstones is almost undisturbed in Central Bohemia.
3. The gradual upwelling of the central part of Bohemian Massif took place after the Brunhes-Matuyama palaeomagnetic reversal (approx. -780 ka). This is known because we find calcareous marsh marls (Unetice, Prezletice) as sediments of the former Vltava river some 70 to 80 m above the present course of the river. The deep canyon of the Vltava valley was formed during approximately the last 800 ka. The incision of major rivers was associated with downcutting of their smaller tributaries. The uplift of the marginal parts of the Massif, e.g. Otava in Southern Bohemia was considerably less – about 15 - 25 m.

Within the area of the Czech Republic, two basic types of relief and its history can be distinguished:

- Upper Mesozoic-Palaeogene planation relief. The majority of the relief of Czech Republic can be described as a peneplain or etchplain. Some very ancient features of the relief can be observed. They prove very limited tectogenesis and erosion since the end of the Mesozoic.
- The mountain slopes, some active fault systems and river valleys display marked Quaternary morphogenesis associated with upwelling of the centre of Bohemian Massif in the last 0.7 Ma.

The elementary distinction between these two kinds of relief is clearly visible in the field.

A.6.3. - Glacioisostasy

There is no evidence of glacioisostatic movements reported from the Bohemian area. However, the early Quaternary Elbe River valleys are known to be incised to 300 to 450 m in the neighbouring Dresden area (Saxony). Such valleys were probably pushed down by the continental ice sheet, but during ice ablation, the area was filled with fluviatile sediments so the weight of the ice was replaced by the weight of sediments. We have to expect some tectonic response to the advance of ice sheets, but the evidence is inconclusive. Some seemingly modern features of the relief, such as the existence of debris formed by side erosion in the Elbe Sandstone area may represent a key for the understanding of possibly large uplift (200 m or more, as Cretaceous sandstones are located almost 600 m higher in Decinsky Sneznik area than in the basin) of the northern mountains.

A.6.4. - Erosion and rock denudation

The rate of rock erosion and denudation varies considerably for both types of relief as mentioned in the context of neotectonic activity. We have not only rock denudation but also the opposite mechanism of aeolian aggradation during glacial episodes. The downcutting and denudation along major river valleys can be reliably estimated to have been some 80 to 120 m or less during the last 1 Ma. Rock denudation in peneplain areas depends on sheet erosion and possibly even more on gelifluction processes. Very few Early Pleistocene sites are known from the area of the Czech Republic, so it is considered that some important erosional event happened before the Middle Pleistocene. The loess deposits of the last two cycles are common so the erosion during the last 250 ka is small or even negligible over the peneplain but could be substantially larger in incised valleys.

The rock denudation of the last 1 Ma is uneven, but in the Variscan crystalline complexes and over the peneplain we consider that it was less than 100 m and very probably less than 20 m. Due to aggradation, the denudation may even be negative in some locations.

A.6.5. - Catastrophic events (earthquakes, high floods)

The distribution of earthquakes and the historical earthquake database were compiled in the last few decades by several teams. The problem is far too complex for a short summary and especially for forecasting the next 1 Ma. It should be noted, however, that the risk factors such as neotectonic and neovolcanic activity, high uneven rate of rock denudation, enhanced fluid circulation and the existence of a periglacial zone close the margins of an advancing glacier are often grouped together. The stable cratons of Variscan crystalline complexes represent on the other hand the most appropriate regions for repository location.

Landslides are common in the Western Carpathians and the neovolcanic region of Ceske Stredohori, but they are rare in other regions. High floods can reach above + 6 m for the 100 year high flood and about + 11 m can be estimated for the 1000 year high flood. The accumulation of river bottom sediments has been some 6 to 12 m during the Holocene. The accumulation and high flood levels are considerably less in peneplain areas (2 to 6 m).

A.7. - Conclusions

1. General: The safety of nuclear waste repositories depends on several interconnected environmental and geological factors. The most important are as follows:

1) retardation and dilution properties of host rock,
2) recrystallisation or degradation of the buffer and backfill materials based on clay minerals, especially montmorillonite,
3) climate forcing.

2. Extent of Pleistocene glaciations and the depth of permafrost: Maximum limits of former glaciations are shown in Figs. A1 – A4. Only northern parts of the Czech Republic (Ostrava region, Decin-Liberec region) were directly or indirectly influenced by continental glaciation and probably enhanced permafrost formation. No evidence of permafrost formation has ever been observed deeper than 20 – 30 m in the interior of Bohemia. This does not mean the permafrost could not occur there, but it did not leave any visible traces in the rock structures. However, periglacial phenomena are more abundant above the level of aproximately 700 m a.s.l.

The 700 m a.s.l. level should be taken as an uppermost general safety limit for the construction of nuclear waste repository for these reasons:

1) Higher regions are more influenced by periglacial phenomena including slope processes, landsliding, formation of solifluctional ("cryoplanation") terraces.
2) Higher regions are always more humid (550 - 650 mm of mean annual rainfall for theinterior, but 700 - 1000 mm or more for the mountains).

3. Holocene changes: All the intricate changes of Holocene landscape have only a limited impact on the safety of nuclear waste repositories. The level to some 6 m below the ground represents the uppermost part of lithosphere that is affected by seasonality changes. We find there the mean annual temperature (7-9 °C) and below this limit the temperature starts to rise some 1 °C per 30 to 50 m. The mean annual temperature range for the whole Mid-European Holocene (with the exception of Preboreal beginning) can be estimated to be some 3 to 4 °C, but for the majority of Holocene it was restricted to 1 to 2 °C (Fig. A6 and A7). Precipitation changes were far more decisive because they influenced or governed the forest-grassland transition, prehistorical ethnic migrations and groundwater regimes. Many of the temperature and precipitation changes were associated with continentality shifts (hot summers, harsh, dry winters) and caused by the interplay between Siberian high and Azores low pressure systems, especially in the cold part of the year.

The precipitation of calcium carbonate and the presence of demanding forest species of small mammals and molluscs in present-day steppe environments indicates that, especially during the Middle Holocene, the annual precipitation was, for several thousand years, almost doubled at 800 to 1500 mm. Therefore, hydrological "greenhouse" models have to take into account the possibility of a 4 to 6 thousand year interval of enhanced precipitation.

4. Relief, tectonics and rock denudation: The risk factors such as neotectonic and neovolcanic activity, high uneven rate of rock denudation, enhanced fluid circulation, the existence of a periglacial zone close the margins of an advancing ice sheet are often grouped together. The stable cratons of Variscan crystalline complexes represent, on the other hand, the most appropriate regions for repository location.

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List of Figures

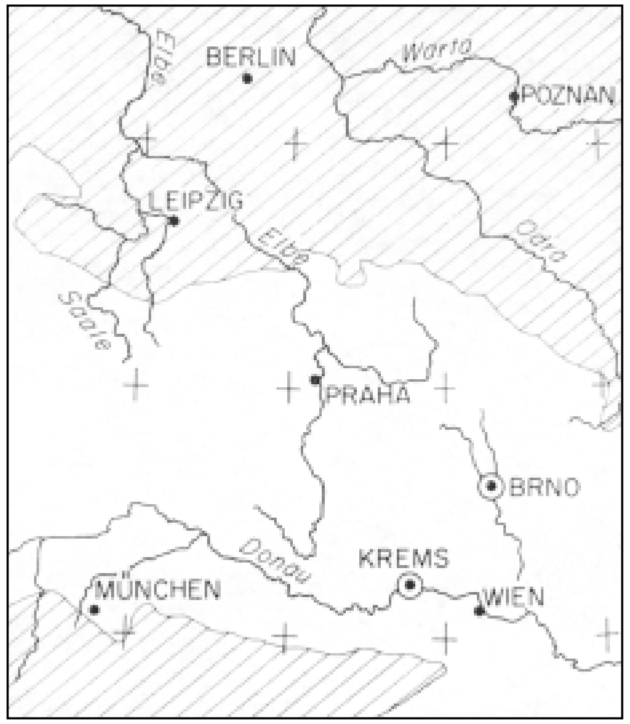


Figure A1: *The extent of the maximal Pleistocene glaciation of central Europe (Fink and Kukla, 1977)*

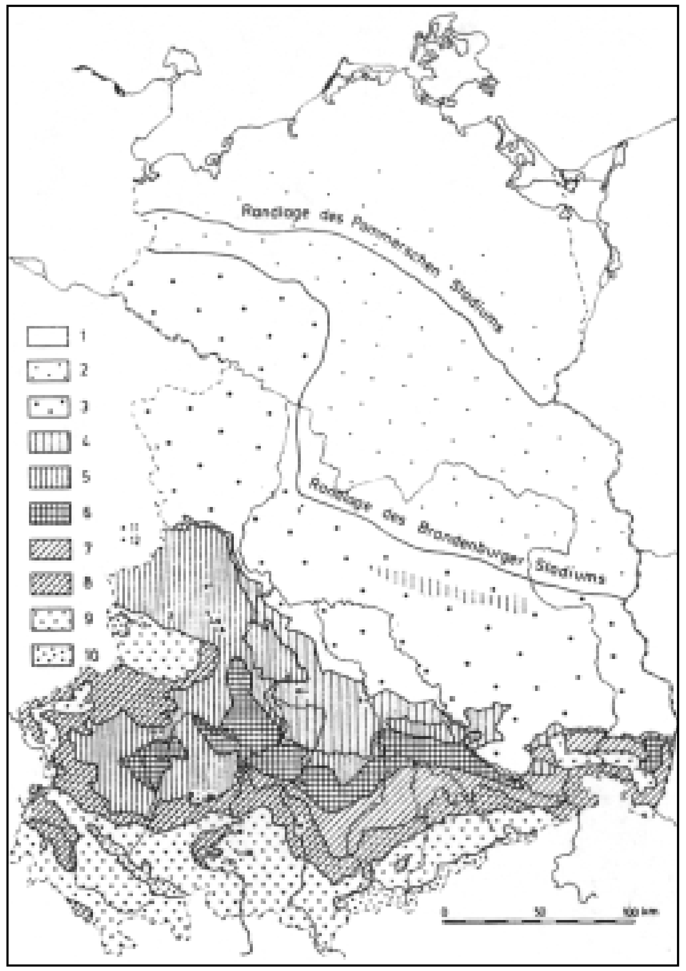


Figure A2: *The terminal morraines of the Pommerania and Brandenburg Pleistocene stages in Eastern Germany (Richter et al., 1970). The most intensive glaciation (Saale) stopped close to the boundary of the Czech Republic. The last glaciation – Weichsel – reached the line approximately between Berlin-Warsaw. The symbols 1-10 represent different kinds of Quaternary sediments.*

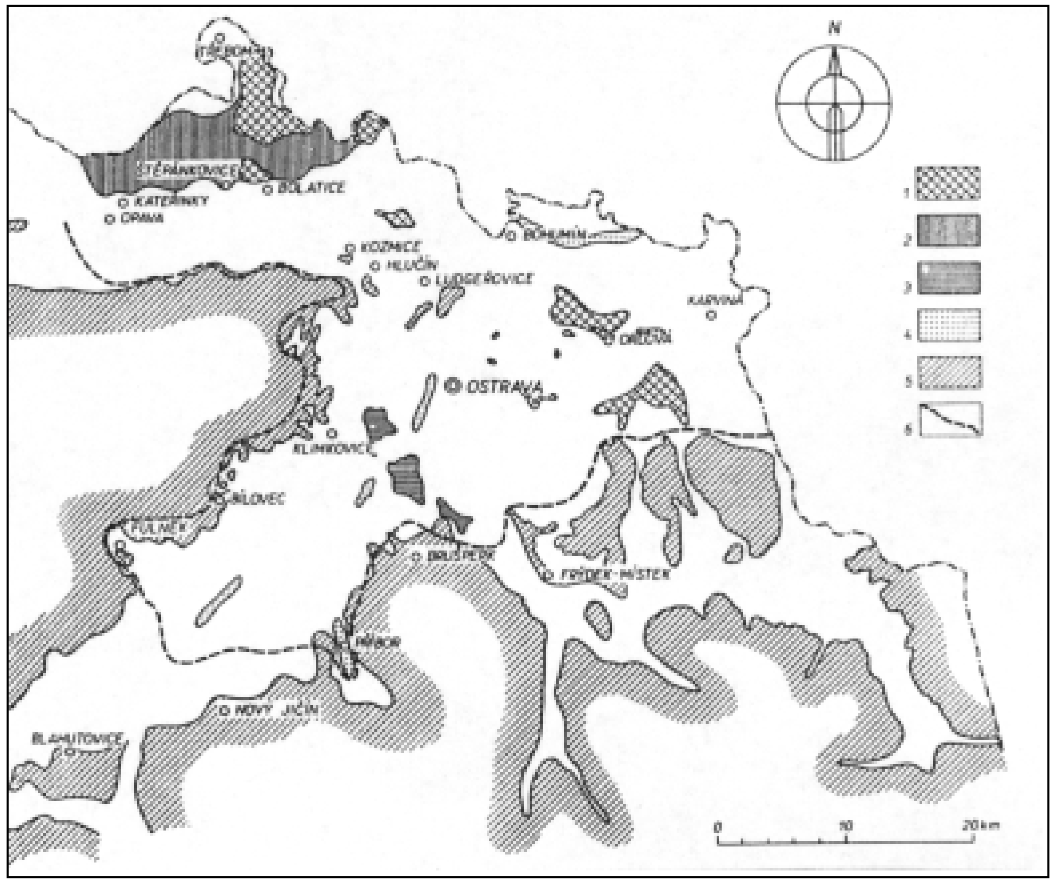
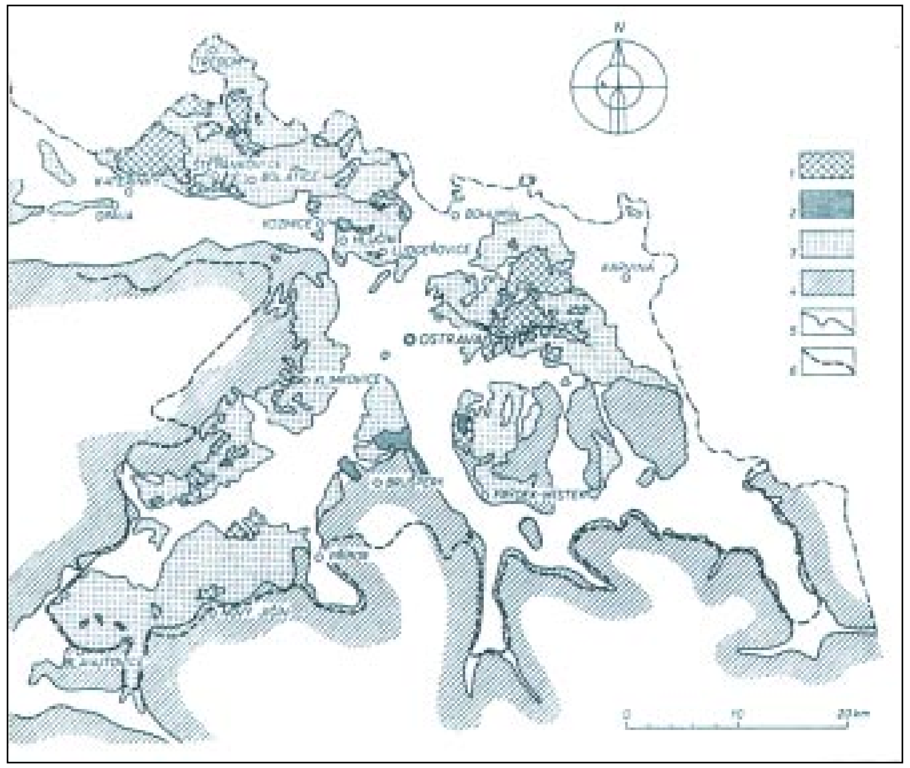


Figure A3: *The extent (6) of the Elster glaciation in the Ostrava (Silesia) region (Macoun et al., 1965). Symbols 1-5 correspond to different Quaternary sediments.*

Figure A4: *The most extensive Saale glaciation reached some 40 km in the interior of Silesia (6) but only several km into the interior of Bohemia. The site Blahutovice where the nuclear power plant was proposed two decades ago at the southernmost part of the former glacier is known for the development of permafrost at depths of 220 m (Macoun et al., 1965; Czudek, 1977). Symbols 1-5 correspond to different Quanternary sediments.*



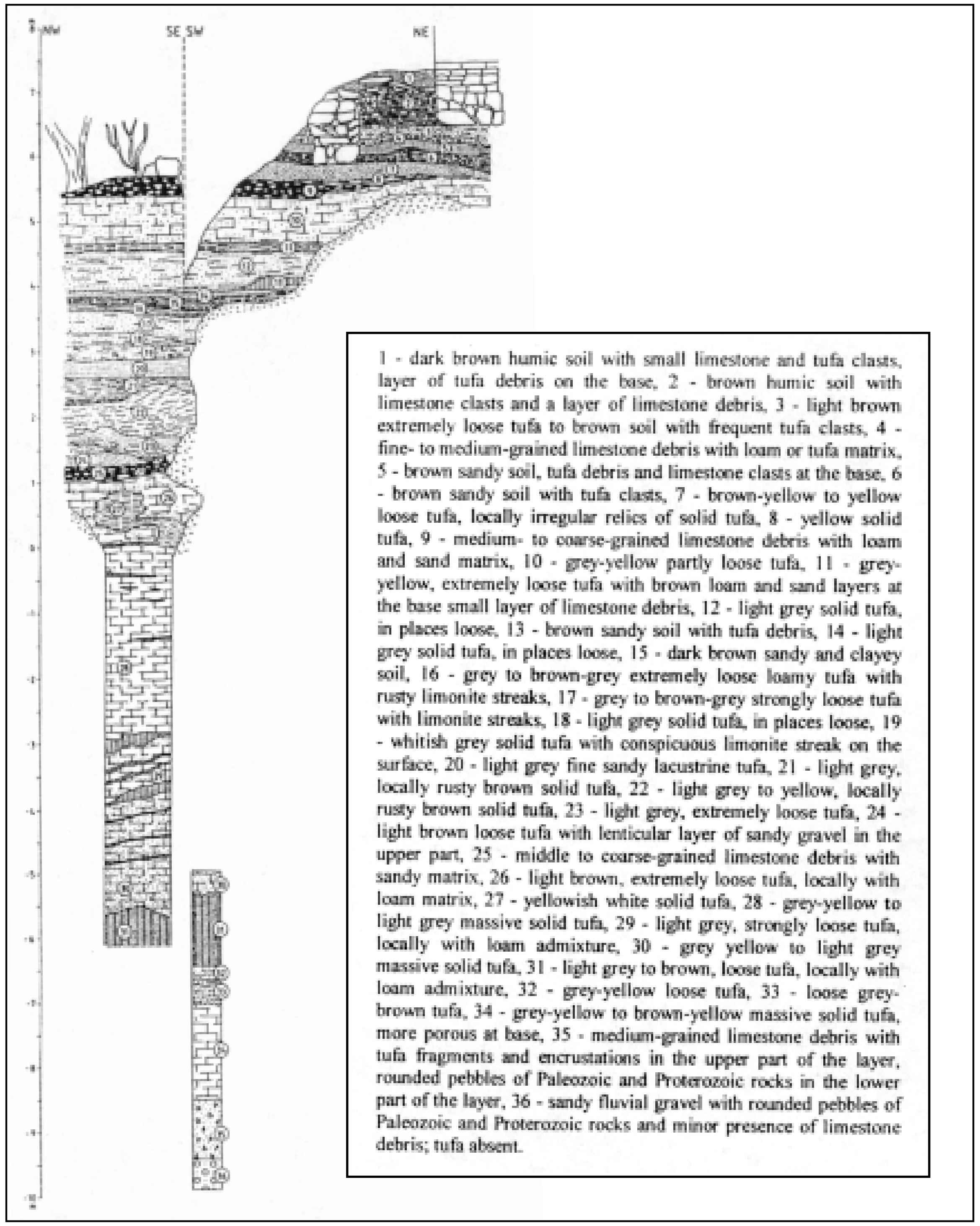


Figure A5: *The Mid-European Holocene is frequently studied in tufa bodies. The 17 m thick Holocene accumulation of carbonates in Bohemian Karst close to Praha helped to distinguish dry and wet climatic phases (see next figure) (Zák et al., 2001, monograph in print).*

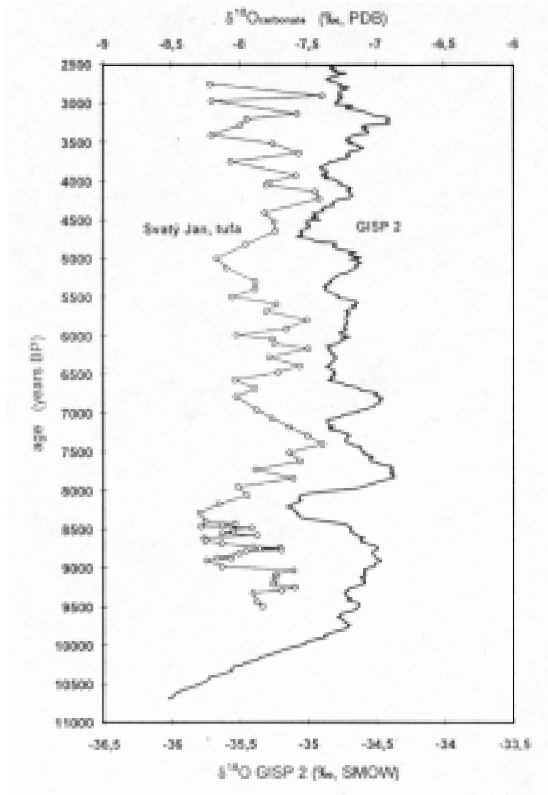


Figure A6: *Variations in oxygen isotope composition from calcareous tufa body in Bohemian Karst and from the GISP 2 ice core (Zák et al., monograph in print 2001).*

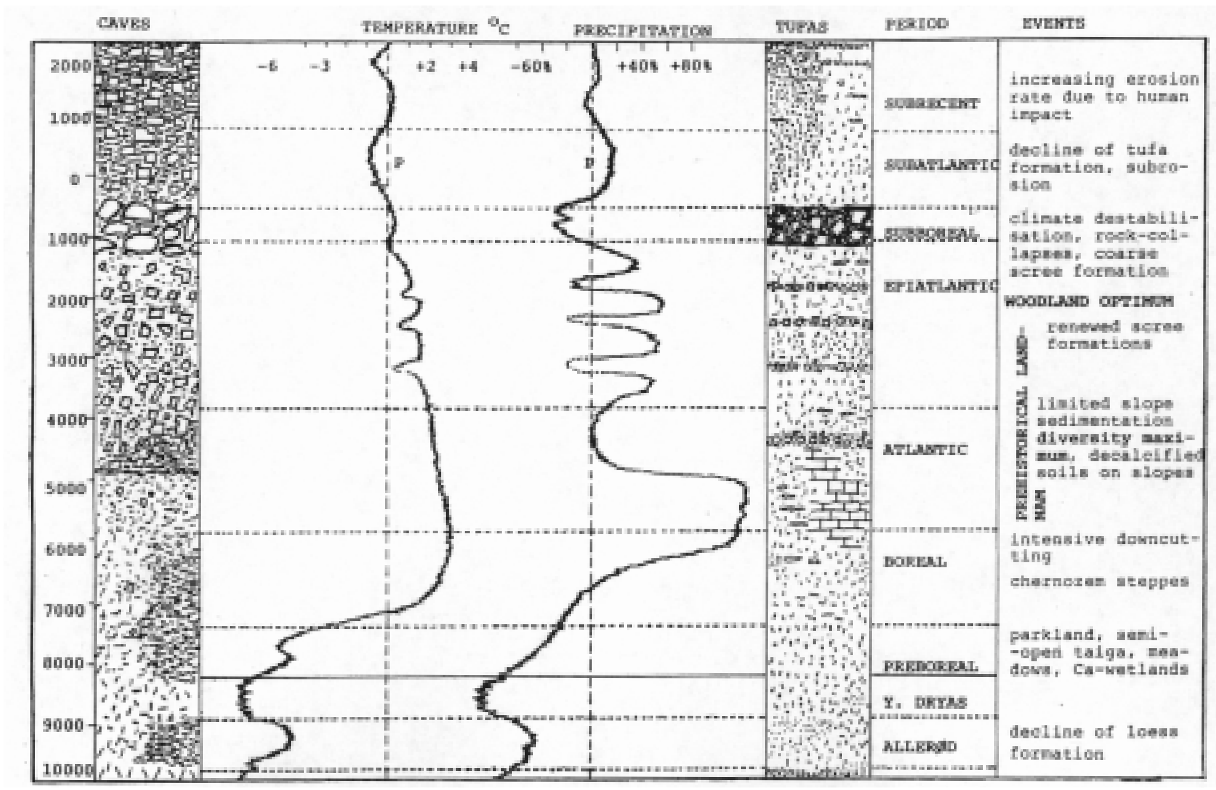


Figure A7: *Precipitation, temperature and other main events of the Bohemian Holocene (Lo_ek and Cílek, 1995).Time in radiocarbon years. The model of precipitation and temperature is established on mollusc assemblages, soil development and carbonate precipitation (a synthesis of nearly 100 Holocene profiles in the Czech Republic).*

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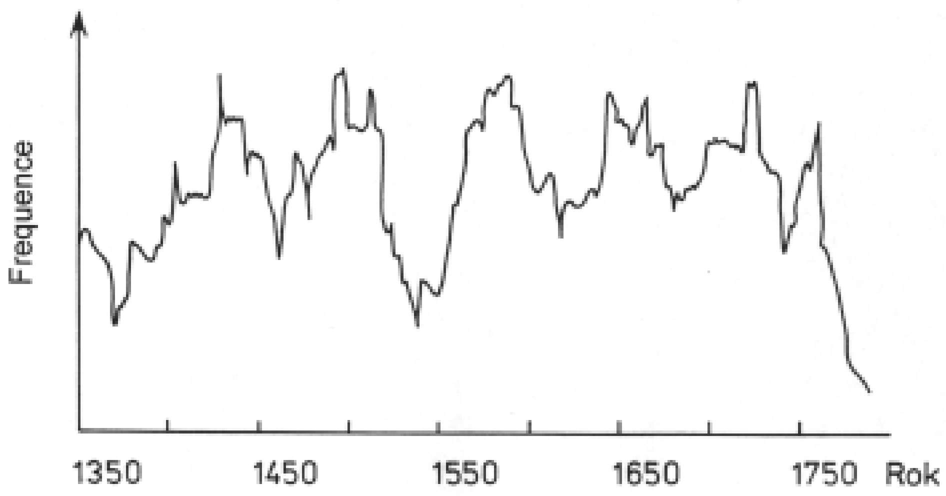

Figure A8: Summer high floods in Bohemia between 1350 and 1850 (Vasku et al., monograph in print) An irregular 20-40 years periodicity can be observed.

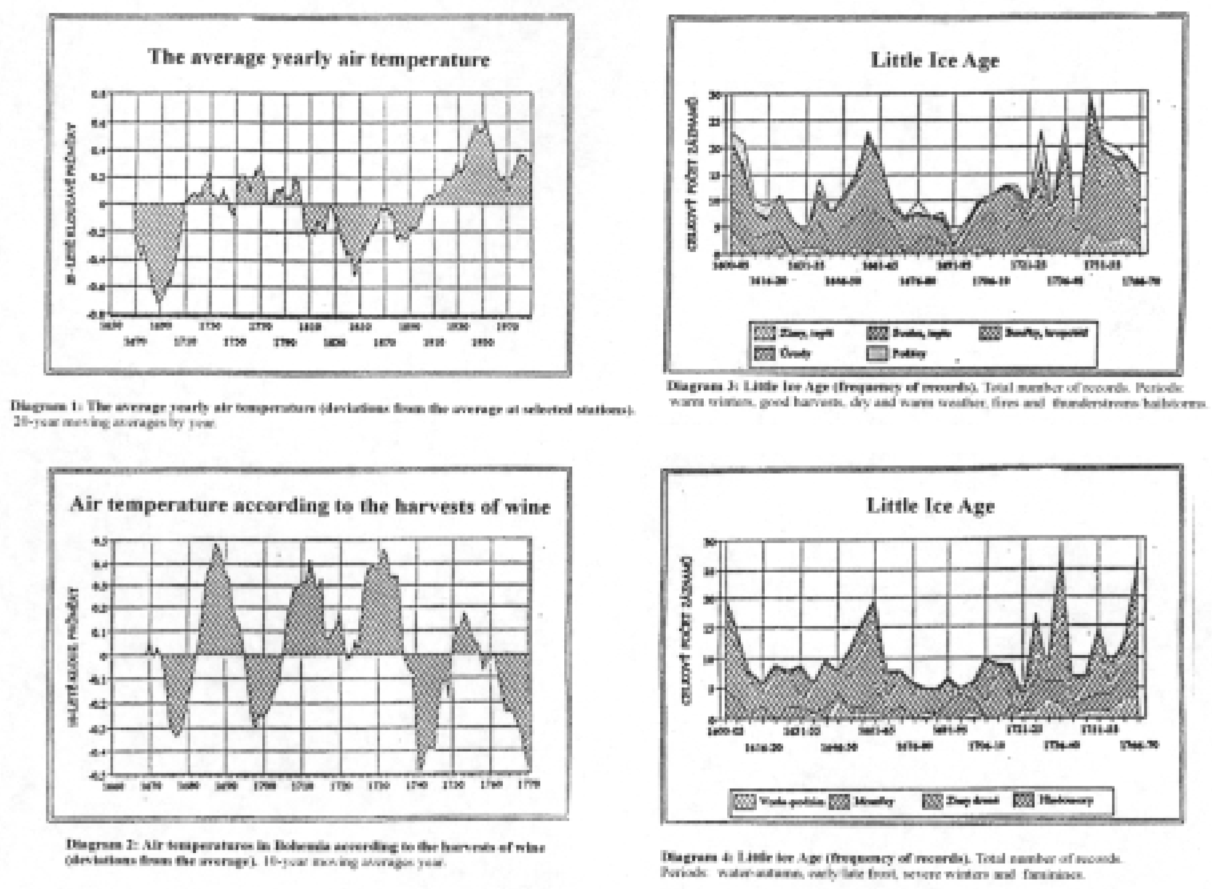

Figure A9: Examples of the documentation of climatic changes of the last thousand years (Vasku et al., monograph in print).

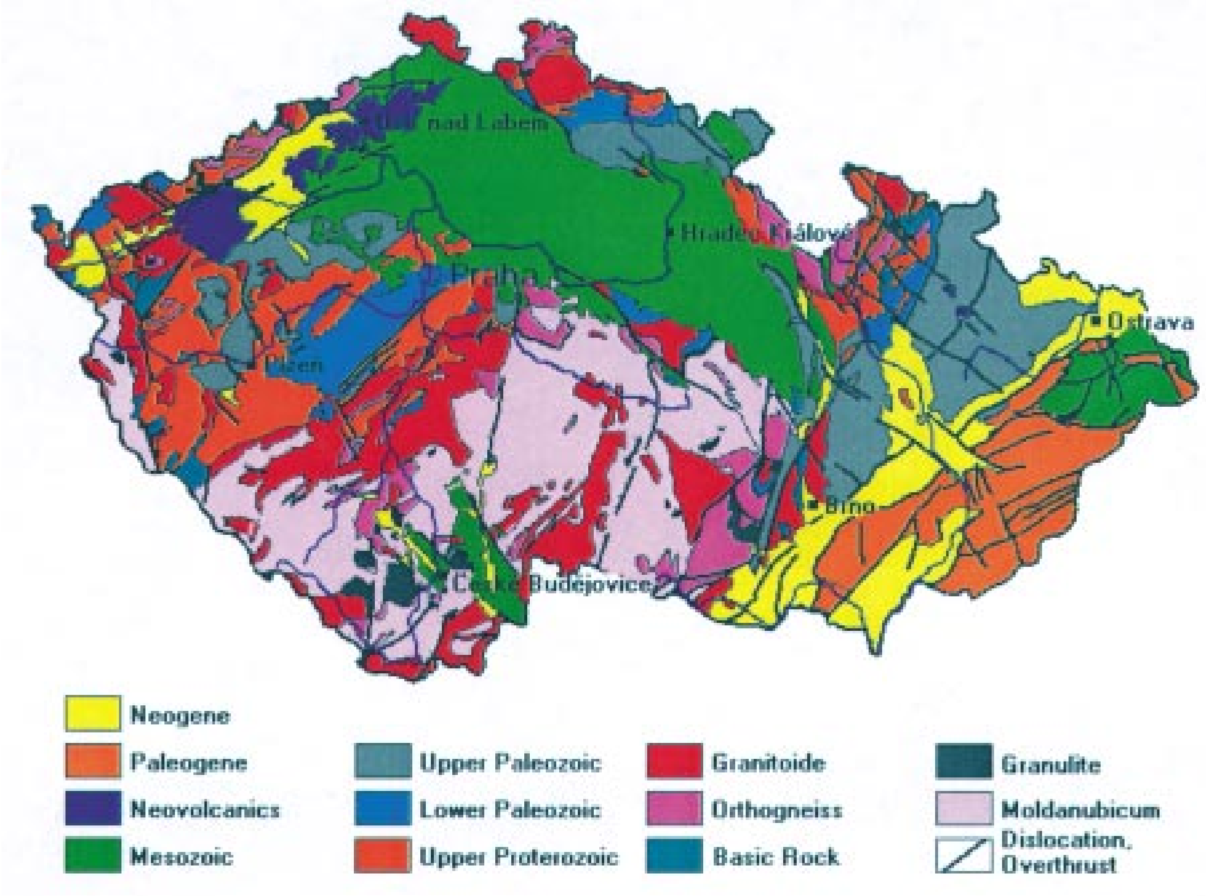

Figure A10: Simplified geological map of the Czech Republic. The eight sites selected for geological investigations are exclusively situated in granitoid rocks.

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