World Geomorphological Landscapes

Monique Fort
Marie-Françoise André
Editors

Landscapes and Landforms of France

Springer

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Series Editor:

Piotr Migoń

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Series Editor Preface

Landforms and landscapes vary enormously across the Earth, from high mountains to endless plains. At a smaller scale, nature often surprises us, creating shapes which look improbable. Many physical landscapes are so immensely beautiful that they received the highest possible recognition – they hold the status of World Heritage properties. Apart from often being immensely scenic, landscapes tell stories which not uncommonly can be traced back in time for tens of million years and include unique events. In addition, many landscapes owe their appearance and harmony not solely to the natural forces. Since centuries, or even millennia, they have been shaped by humans who modified hillslopes, river courses, and coastlines, and erected structures which often blend with the natural landforms to form inseparable entities.

These landscapes are studied by geomorphology – 'the science of scenery' – a part of Earth sciences that focuses on landforms, their assemblages, and surface and subsurface processes that moulded them in the past and that change them today. Shapes of landforms and regularities of their spatial distribution, their origin, evolution, and ages are the subject of research. Geomorphology is also a science of considerable practical importance since many geomorphic processes occur so suddenly and unexpectedly, and with such a force, that they pose significant hazards to human populations and not uncommonly result in considerable damage or even casualties.

With this book focused on France, we launch a new book series *World Geomorphological Landscapes*. It aims to be a scientific library of monographs that present and explain physical landscapes across the globe, focusing on both representative and uniquely spectacular examples. Each book will contain details on geomorphology of a particular country or a geographically coherent region. The core of each book is a succinct presentation of key geomorphological localities (landscapes), representative for the geomorphic diversity of each country. Written in easy-to-read language, the landform evolution stories presented in each volume give together an overview of what each particular country has to offer. But they can also serve as a guidance for holidaymaking geoscientists as to where to go to enjoy the best of geomorphology.

The series is thus a unique reference source not only for geomorphologists, but all Earth scientists, geographers, and conservationists. It complements the existing reference books in geomorphology which focus on specific themes rather than regions or localities and fills a growing gap between poorly accessible regional studies, often in national languages, and papers in international journals which put major emphasis on understanding processes rather than particular landscapes.

The World Geomorphological Landscapes series is produced under the scientific patronage of the International Association of Geomorphologists – a society that brings together geomorphologists from all around the world. The IAG was established in 1989 and is an independent scientific association affiliated at the International Geographical Union and the International Union of Geological Sciences. Among its main aims are to promote geomorphology and to foster dissemination of geomorphological knowledge. I believe that this lavishly illustrated series, which however sticks to the scientific rigour, is a most appropriate means to fulfil these aims and to serve the geoscientific community.

Series Editor Piotr Migoń

Foreword

France presents a wide variety of landscapes, both natural and cultural, making this country the most visited in the world (Chap. 1). If we consider physical aspects of the landscape, this variety can be explained by a series of factors: (1) the topographical contrasts, from the highest summit of Europe down to the ocean; (2) a comprehensive collection of rock types (Fig. 1) and their related morphostructural units (sedimentary basins, basement uplands, active orogens, faulted systems with volcanism, coastal plains, deltas and marshes); (3) the long geological history and the succession of bioclimatic environments from tropical to glacial and periglacial environments, which left their imprint in the landscape; and (4) the large present-day bioclimatic diversity, at the junction of the Atlantic, Continental, and Mediterranean influences, which gives the geomorphological landscapes different atmospheres and lights (e.g. Brittany compared with French Riviera).

Prehistoric and historical (including Roman) legacies are also an integral part of French landscapes and landforms, often requiring a geoarcheological approach to better appreciate the role of early cultural groups in modelling their environment, exploiting their resources, and understanding the advantages of specific sites beyond their potential constraints or hazards. In that respect, two major characteristics should be highlighted. First, the abundance of limestone plateaus in the south of France explains both the number of beautifully ornamented caves and the wall paintings left by prehistoric humans as they sought sheltered sites during the last glaciation. Second, the combination of suitable soils and well-exposed slopes made France the country of viticultural 'terroirs', often developed on south- or southeast-facing scarps ensuring a good drainage and a sunny atmosphere whatever their structural origin: fault steps of Alsace, Burgundy, or Rhone Valley, cuesta of Champagne or thrust front of the western Jura.

This book is intended to provide the reader with an overview of French landscapes and landforms, reflecting as far as possible their diversity. To date, France is a country endowed with 34 sites inscribed as cultural heritage sites on the UNESCO World Heritage list, often backed by exceptional natural sites (e.g. Mont St-Michel (Chap. 5) or Paris and the banks of the Seine River (Chap. 2)). On the other hand, only three sites have been inscribed as natural heritage sites, including Corsican granitic landscapes (Chap. 23) and La Reunion volcanic landforms (Chap. 25), whereas the mixed 'Cultural and Natural Heritage' label is recognised in one site only (Gavarnie in the Pyrenees (Chap. 12)). Many chapters of this book deal with World Heritage Sites (WHS), either already listed by UNESCO or currently under consideration for UNESCO label recognition (e.g. Mont Blanc Massif, Chaîne des Puys volcanoes, Chauvet Cave – Pont d'Arc, and Camargue). Others have already received the label of 'Grands Sites de France': this is the case of Aven d'Orgnac (Chap. 19), Massif du Canigou (Chap. 13), and Cirque de Navacelles (Chap. 11). These UNESCO WHS and 'Grands Sites de France' are shown in Fig. 2.

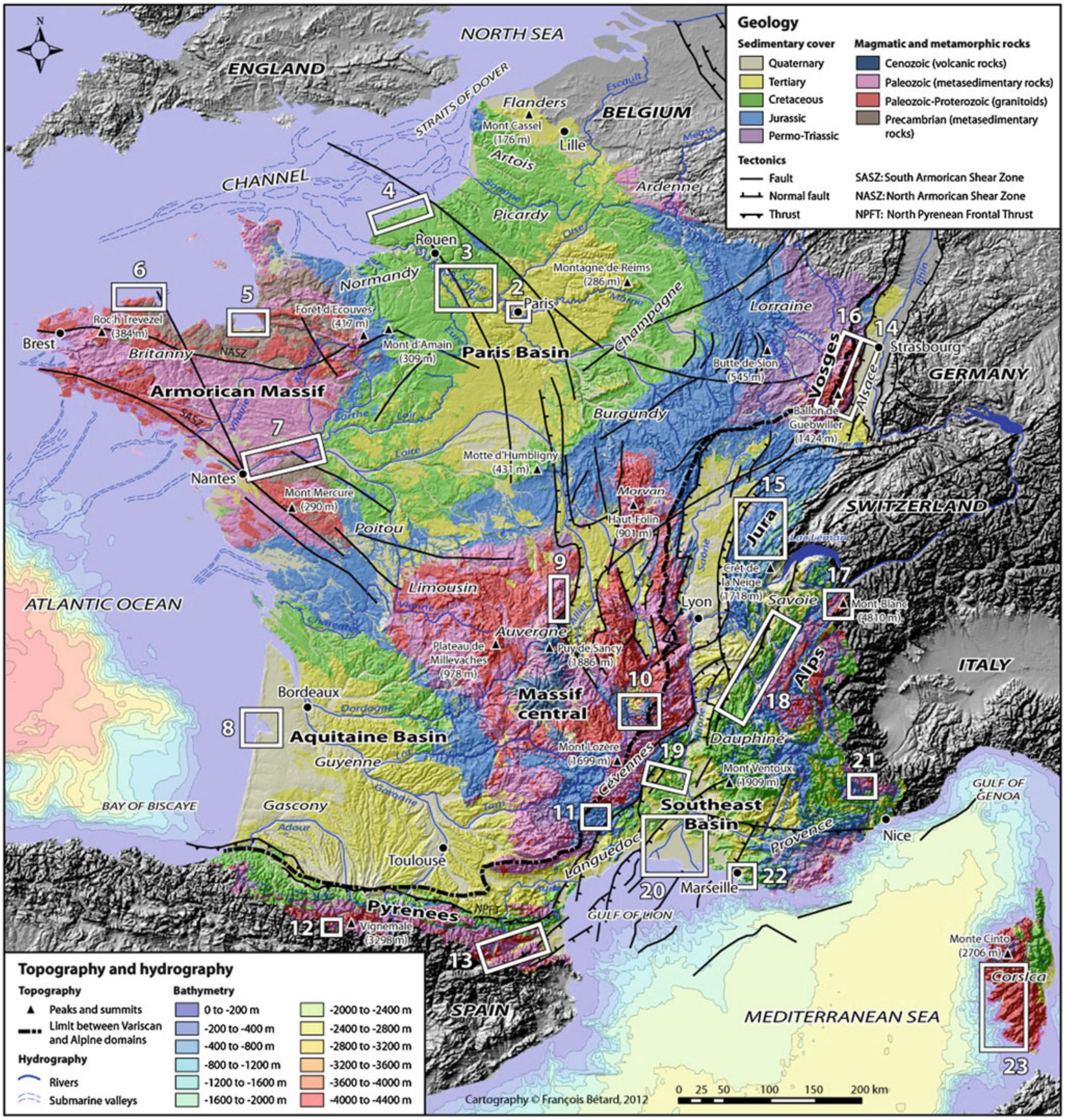

Fig. 1 Main geological frame of the different areas described in this book, with numbers refering to chapters (Drawing F. Bétard)

The book is organised in a sequence of chapters according to the following itinerary. Starting from Paris (Chap. 2), founded by the Romans, it is shown how in its early development the capital city benefited from links along the Seine River that favoured fluvial trade and from its substrate that offers abundant resource for building stones. Chapter 3 describes the famous entrenched meanders of the Seine River Valley downstream of Paris, developed under the alternation of glacial/interglacial periods: rich in mediaeval castles built on the chalk cliffs, the valley later attracted many Impressionist painters (Fig. 2).

The high Normandy coast and cliffs (Chap. 4), with their imposing verticality, their whiteness varying in tone with the ever-changing light and tide, and their ghostly shapes, also exerted a powerful attraction to painters and novelists. The instability of the cliffs has become a real concern for policymakers. Quite different is the Mont Saint-Michel bay (Chap. 5), characterised by its exceptional tidal range and the immensity of its tidal flat, overlooked by the Abbey perched on an island of which integrity is endangered by the progress of sedimentation. In contrast, the celebrated Pink Granite coast of northern Brittany (Chap. 6) illustrates both the influence of selective weathering under terrestrial conditions and the stripping of the saprolite by marine processes.

The Loire River Valley (Chap. 7), famous for its vineyards and royal châteaux, is much wider than the Seine Valley, and in its lower part it consists of a patchwork of geomorphic compartments (islands, separated by multiple branches of the river) that are remodelled under the influence of floods originating from the Massif Central highlands. Arcachon Bay (Chap. 8) is already part of southern France: bordered by the largest coastal dune belt in Europe, it is a typical semi-sheltered lagoon located on the Atlantic coast of France, facing the wave-dominated coast of the Bay of Biscay. It has become a famous oyster cultivation area and hosts various recreational activities (sport-fishing, sailing, and ecotourism) all year around.

The volcanic *Chaîne des Puys* range (Chap. 9) displays a wide spectrum of potentially active volcano types, very attractive for scientists, students, and visitors. Used for grazing as far back as the Neolithic period, and more intensively since the Roman Empire, volcanic slopes have been heavily deforested and eroded. With its status of French Regional Nature Park acquired in 1977, the *Chaîne des Puys* has been protected ever since. To the south, the Velay and its Vivarais rim (Chap. 10) combine many historical aspects of the Massif Central, from its Hercynian basement to the Tertiary tectonic and volcanic reactivations following the Pyrenean and Alpine orogenies, and from the Mesozoic and Tertiary planations to the Plio-Quaternary excavation of valleys. With the Cirque de Navacelles (Chap. 11), we have a perfect example of a meander incised by the Vis River in its gorge across the Causse du Larzac (limestone plateau), downstream from the metamorphic and granitic Cévennes Mountains. Yet it is much more complex than a simple bend in a watercourse, as karstic influence contributed to its evolution. Overlooked by panoramic viewpoints, it is listed on the 'Grand sites de France'.

The Cirque de Gavarnie (Chap. 12), a 1,500-m-high limestone theatre, is an exceptional landscape recognised in 1997 as a UNESCO World Heritage site for both its natural and cultural values. It results from a long evolution, including the formation of the Pyrenean range, the combination of both karstic and glacial influences, and a long history of human occupation and exchanges across the French-Spanish border. In the Eastern Pyrenees (Chap. 13), where the Mediterranean and Atlantic biomes meet, the Têt river catchment displays a spectacular suite of tectonic, glacial, periglacial, fluvial, and hillslope forms. Famous for its prominent fragments of smooth, pre-Quaternary Paleic relief remnants where glacial erosion has not serrated the interfluves, this Mediterranean part of the Pyrenees also preserves good records of post-orogenic landscape evolution and base-level changes since the early Neogene.

The Vosgian-Alsatian side of the Rhine Graben (Chap. 14) developed in response to Alpine orogeny: it is a unique, tectonically controlled landscape, famous for its vineyards and its traditional well-preserved architecture and culture. Nearby, the Jura Massif (Chap. 15) displays in its external part an original fold-and-thrust belt overriding the Bresse graben and bearing famous vineyards, in addition to scenic blind valleys, exsurgence springs and glacially formed lakes with Neolithic pile-dwelling settlements. The Vosges Mountains (Chap. 16) formed in uplifted Hercynian basement, affected by Quaternary glaciation. Upon its bald, rounded summit ridges, heathland and meadows with specific vegetal communities result from deforestation

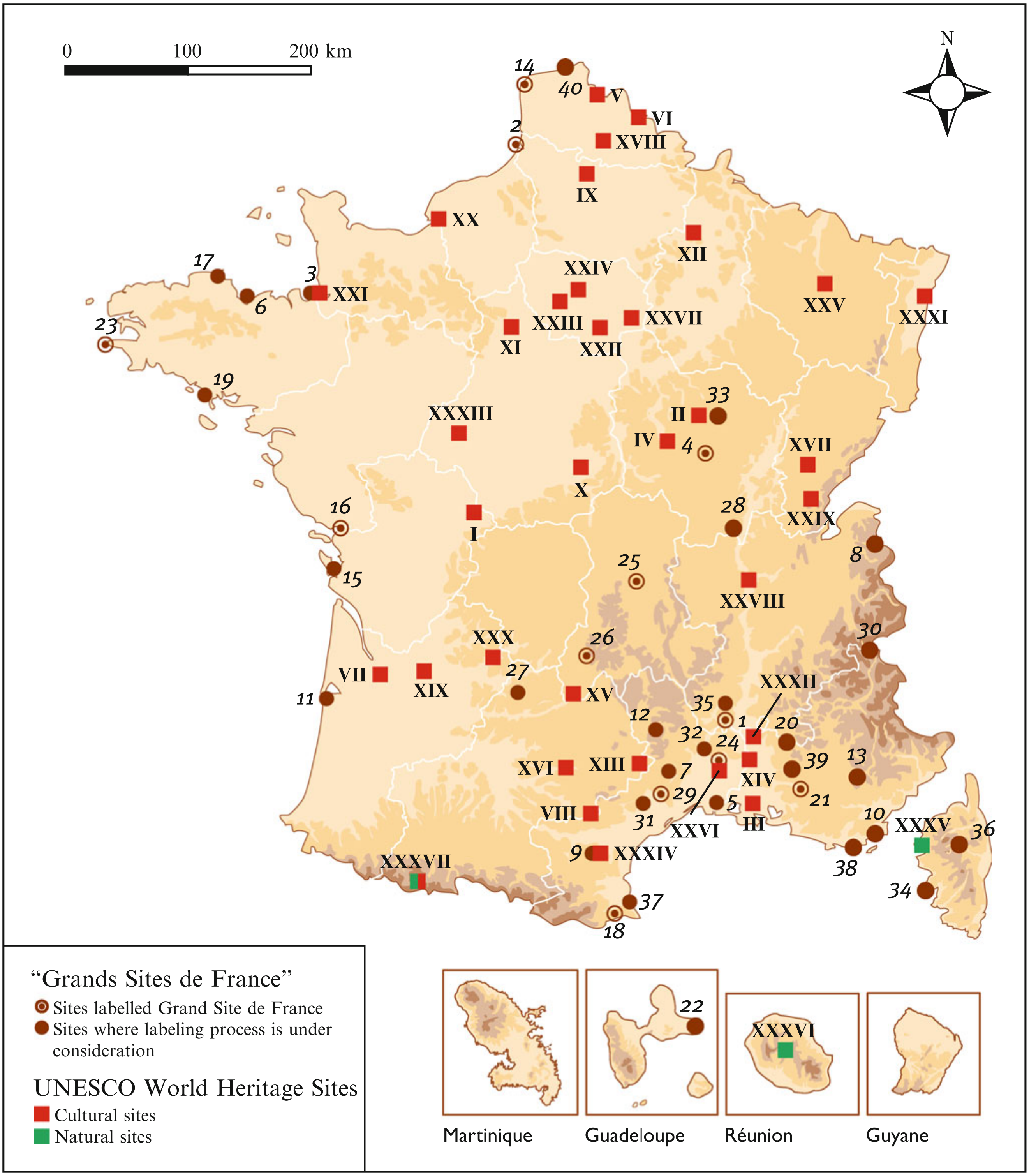

Fig. 2 Sites with Grands Sites de France Label (in arabic numbers). *1*: Aven d'Orgnac; *2*: Baie de Somme; *3*: Baie du Mont-Saint-Michel *; *4*: Bibracte-Mont Beuvray; *5*: Camargue gardoise; *6*: Caps d'Erquy-Fréhel; *7*: Cirque de Navacelles ***; *8*: Cirque de Sixt Fer à Cheval; *9*: Cité de Carcassonne *; *10*: Domaine du Rayol, Le Jardin des Méditerranées; *11*: Dune du Pilat; *12*: Gorges du Tarn et de la Jonte ***; *13*: Gorges du Verdon; *14*: Les Deux Caps Blanc-Nez, Gris-Nez; *15*: Marais et Place Forte de Brouage; *16*: Marais Poitevin; *17*: Abbaye de Beauport; *18*: Massif du Canigó; *19*: Massif dunaire de Gâvres-Quiberon; *20*: Mont Ventoux; *21*: Sainte-Victoire; *22*: Pointe des Châteaux; *23*: Pointe du Raz en Cap Sizun;

since the Bronze Age period. The protection and management of this natural heritage is ensured by a Nature Park and four Nature Reserves.

The Mont Blanc Massif (Chap. 17), the highest of the external crystalline massifs of the Western Alps, deserves a special place. Renowned for its extensive glacier cover, steep granite rockwalls and vertiginous peaks, the massif has attracted both tourists and scientists over several centuries. Accelerating glacier retreat and permafrost degradation both represent major threat to this emblematic landscape. Nearby, the French Prealpine geomorphological landscapes (Chap. 18) are excellent examples of sedimentary folded relief, and they host the four French members of the European and Global Geoparks Network including the Bauges Regional Nature Park, famous for its perched synclines and karstified relief. Great limestone cliffs overlying marly bedrock favour dramatic collapses like that of Mont Granier in 1248 AD.

Continuing southwards, Mediterranean influences become predominant. In the Lower Ardèche region (Chap. 19), the Messinian Salinity Crisis was the primary cause of the incision of the Ardèche Canyon and of the reorganisation of the Rhône River catchment. The end of this crisis contributed to the development of a specific karst system, including the Orgnac aven and the Chauvet cave, famous for its outstanding prehistoric wall paintings (the oldest in the world to date). The Lower Rhône River valley and its Delta (Chap. 20) have been a major axis of communication linking the Mediterranean to northern Europe since antiquity. Numerous archaeological excavations demonstrate human-environment interactions, emphasising the strong constraint of fluvial-deltaic environments, and how human societies, since the Greeks and the Romans, found some solutions to mitigate the fluvial risk. The landforms are now subject to different changes related to human activities, and the protection of the natural component has become a real challenge. The region of Mount Bego (Chap. 21) in the Southern French Alps, is an interesting place to observe scenic inherited landforms as well as cultural remains left by the ancient societies who lived there. The glacial imprint is widespread, and

Fig. 2 (continued) *24*: Pont du Gard *; *25*: Puy de Dôme; *26*: Puy Mary – Volcan du Cantal; *27*: Rocamadour **; *28*: Roches de Solutré-Pouilly-Vergisson; *29*: Saint-Guilhem le Désert et Gorges de l'Hérault **; *30*: Vallée de la Clarée et Vallée Étroite; *31*: Vallée du Salagou; *32*: Gorges du Gardon; *33*: Alésia; *34*: Iles Sanguinaires – Pointe de la Parata; *35*: Gorges de l'Ardèche; *36*: Vallée de la Restonica; 37: Anse de Paulilles; *38*: Presqu'île de Giens, Salins d'Hyères; *39*: Massif des Ocres; *40*: Dunes de Flandre. * *World Heritage UNESCO site;*** *World Heritage UNESCO site on grounds of Saint-Jacques de Compostelle trails*; *** *World Heritage UNESCO site on grounds of Causses and Cévennes, Cultural Landscape of Mediterranean agropastoralism*. Note that this label 'Grand Site de France' is decerned by the French State to the Grand Site Manager for a period of 6 years. This label acknowledges the manager's action agrees well with sustainable development principles.

French World Heritage Sites (in Roman numbers). *I*: Abbey Church of Saint-Savin-sur-Gartempe; *II*: Cistercian Abbey of Fontenay; *III*: Arles, Roman and Romanesque Monuments; *IV*: Vézelay, Church and Hill; *V*: Belfries of Belgium and France; *VI*: Nord-Pas de Calais Mining Basin; *VII*: Bordeaux, Port of the Moon; *VIII*: Canal du Midi; *IX*: Amiens Cathedral; *X*: Bourges Cathedral; *XI*: Chartres Cathedral; *XII*: Cathedral of Notre-Dame, Abbey of Saint-Remi, & Palace of Tau, Reims; *XIII*: The Causses and Cévennes; *XIV*: Historical center of Avignon: Papal Palace & Avignon Bridge; *XV*: Routes of Santiago de Compostela in France; *XVI*: Episcopal City of Albi; *XVII*: Royal Saltworks of Arc-et-Senans; *XVIII*: Fortifications of Vauban; *XIX*: Jurisdiction of Saint-Émilion; *XX*: Le Havre, the City rebuilt by Auguste Perret; *XXI*: Mont Saint-Michel and its Bay; *XXII*: Palace and Park of Fontainebleau; *XXIII*: Palace and Park of Versailles; *XXIV*: Paris, Banks of the Seine; *XXV*: Place Stanislas, Place de la Carrière, and Place d'Alliance in Nancy; *XXVI*: Pont du Gard, Roman Aqueduc; *XXVII*: Provins, Town of Medieval Fairs; *XXVIII*: Historic Old Town center of Lyon; *XXIX*: Prehistoric pile dwellings around the Alps; *XXX*: Prehistoric Sites and Decorated Caves of the Vézère Valley; *XXXI*: Strasbourg – Grande Île; *XXXII*: Roman Theatre and its Surroundings and the "Triumphal Arch" of Orange; *XXXIII*: The Loire Valley between Sully-sur-Loire and Chalonnes-sur-Loire; *XXXIV*: Cité de Carcassonne – historic Fortified City of Carcassonne; *XXXV*: Gulf of Porto: Calanche of Piana, Gulf of Girolata, Scandola Reserve, Corsica; *XXXVI*: The Pitons, Cirques and Remparts of La Réunion; *XXXVII*: Pyrénées: Gavarnie-Mont Perdu (Drawing F. Bétard) the first human traces date back to the Neolithic, three millennia before Protohistoric societies left the outstanding petroglyphs of the so-called Vallée des Merveilles (Valley of Wonders). The Cosquer cave (Chap. 22) with its famous prehistoric paintings is located along a karstic coast submerged after the Last Glacial Maximum. Both lithology and tectonics explain the coexistence in the same area of terrestrial and submerged karst features that developed since the Neogene period.

The book concludes with three chapters about islands. First Corsica (Chap. 23) is like a granitic mountain in the sea, offering a large set of mesoscale forms and rock slopes carved by differential surface weathering, with contrasting landforms between the upper areas that were glaciated and the coastal landforms influenced by the sea. At local scales granite slabs and castellated tors, and at microscales, gnammas, and tafoni, are emblematic landforms that attracted early societies. The coral reefs and lagoons of French Polynesia islands (Chap. 24) illustrate well the pioneering theory of Darwin, revised by plate tectonics. These islands also offer an interesting example of combined volcanic geomorphology and karst development on an uplifted coral reef, affected both by high-energy events, and the generation of microforms by reef bioerosion. Finally, La Réunion (Chap. 25) is a volcanic island dating back at least 3 million years. It is celebrated as a Natural UNESCO Heritage site, thanks to its dormant volcano Piton des Neiges and its very active Piton de la Fournaise. Outstanding landforms include the steep *Remparts*, deep gorges, and waterfalls that favoured the development of endemic species that are now protected.

This book could not have been completed without the help and assistance of various individuals. We would like first to warmly thank Piotr Migoń, the director of the Landscapes and Landfoms Book series, who encouraged us to prepare this book in coordination with the Paris 8th International Conference of Geomorphology. Working with Elodie Tronche (Springer) was also a pleasure and we are most grateful to her for her involvement in the making of the book. Warm thanks also go to our French colleagues who agreed to prepare their contributions in a limited time period despite their many other commitments, and to additional partners who helped with the illustration, either by adapting existing figures or by kindly giving their permission for reproduction. Last, special thanks are due to Ian Evans, from Durham University, who greatly helped us in the final stage of English editing, and to François Bétard who provided the final general maps attached to this foreword and to Chap. 1. To all, we express our sincere gratitude.

Monique Fort
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Contents

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Introduction: Landscapes and Landforms of France, A Large Diversity

1

Jean-Pierre Peulvast

The extraordinary diversity of landscapes observed in France is widely related to the geological and geodynamic characteristics of its territory, although it also represents the marks of past and present bioclimatic conditions and the results of the labor of hundreds of human generations. Among the physical conditions, geomorphic factors control, for example, the features of many urban sites and create strong constraints on the territorial organization or the rural activities, since they influence other characteristics of the environment (soils, local climates, hydrogeology, distribution of morphogenetic processes, etc.) and of the economic or everyday life (terrestrial or fluvial communications, hazards and risks, natural heritage, etc.). Among these controlling factors, one can find the stream patterns and the way they are inset into regional structures and landforms (e.g., sites of wind or water gap through folded ridges); the configuration of hill slopes, related or not with stepped systems of surfaces and structural asymmetries; or the contrasts in morpho-pedological and hydrological aptitudes between a karstic plateau and the surrounding depressions shaped into impermeable clay or marl.

At regional and continental scales, the distribution and characteristics of the large-scale geomorphic units are very influent. According to the classical works of E. Reclus, P. Vidal de la Blache, E. de Martonne, A. Demangeon, J. Brunhes, and R. Dion, the progressive construction of the French territory cannot be understood without taking into account the articulations between the large physiographic domains, directly controlled by the geology. For example, such articulations and contacts, including more or less practicable passageways between the main units, could be historically valorized as trade routes and commerce centers, as well as ways for invasions. Although the notion of determinism has been strongly criticized by human geographers in the last decades, this observation remains true nowadays. Indeed, it often refers to historical times in which technology could not provide to the societies the same degree of freedom as today with regard to the biophysical elements of their environment. But it appears that modern societies, even the most developed, do not escape from constraints and risks related to natural factors.

Therefore, among other environmental conditions, geomorphic factors are as influent as historical, political, or economic factors in the settlement of cities, in the development of an exchange route or another, or in the territorial management. What could be understood on the geography of France and of its regions without the classical reference to the "seuils" or thresholds between sedimentary basins and the "corridors" such as the rift system elongated from the Rhine graben to the Mediterranean Sea? What would be a regional or touristic geography which would neglect the characteristics of its mountains and systems of plains and low plateaus? The original landforms of some of these regions, folded, volcanic, or karstic, for example, are parts of the landscape heritage as well of the environment and are more and more frequently protected as such. In particular, this is the vocation of the programs of definition and inventory of geosites and geomorphosites.

The presence and distribution of these sites largely depend on the relief itself, more or less contrasted or vigorous, which is the result of combined and antagonist actions of internal geodynamics (emplacement of geological structures, uplift, stability or subsidence trend, neotectonics, volcanism, etc.) and of erosion *s.l.* (weathering, waste removal and transport, sedimentation). Understanding the landforms constructed this way, often over long geological periods, only appears through a morphostructural analysis, which considers the combination of these different factors. This knowledge is useful at continental scale as well as that of much smaller units such as the cuesta systems of Lorraine (Fig. 2, page x). This idea is well illustrated by the geomorphic maps of France at 1:2,500,000 and 1:1,000,000. At these scales, most of the master lines of the relief appear mainly controlled by the geological structure (Battiau-Queney 1993). This is the case of the mountain ranges, of tectonic

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origin, as well as of ridges and scarps shaped by selective erosion in the Armorican Massif and the Paris Basin (see Fig. between the Foreword and this Chapter). At medium scales, those of units of tens of kilometers represented on 1:50,000 and 1:100,000 maps, the structural control on space organization is still more evident, including in areas with moderate energy of relief.

Small-scale landforms and superficial regolith or soil mantles are influent as well. Mostly corresponding to the last stages of the morphological history and to the current dynamics, they give their mark to the landscapes and contribute to confer to them the potentials and constraints which weigh on land use and organization. The corresponding landscape diversity is exceptional. Owing to the situation of France at midlatitudes, the country underwent, during the last millions of years, tens of alternating periods of warm or cool temperate conditions and of cold climates, with repeated formation of continuous or discontinuous permafrost and of glaciers on the main mountains. Therefore, the territory displays an exceptional collection of active landforms and heritages of past morphoclimatic conditions. Good illustrations are given by features such as contrasted coastal landscapes, mountain glacial landscapes, or large fluvial valleys in regions of plains and low plateaus, the slopes and surroundings of which keep the strong imprint of the Quaternary periglacial dynamics.

The narrowing of the French "isthmus" (de Martonne 1942) increases the concentration in a relatively small territory of this large diversity of landscapes and geomorphic types, sometimes presented as a summary of the European landforms which only would be deprived of the Fennoscandian lakes and fjords (Mottet 1993). Two main types of landform systems may be distinguished, on the basis of the nature, number, and distribution of remarkable geomorphological landscapes and sites. To the north of the Pyrenees and northwest of a sinuous line which extends from the Montagne Noire to the crest of the Vosges massif through the crest lines of the Espinouse, Cévennes, Vivarais, Lyonnais, Beaujolais and Charolais mounts, and then the Côte d'Or, Langres and Upper Saône plateaus lies the France of plains, plateaus, and modest basement uplands. Except in the more elevated and partly mountainous massifs of Auvergne and Forez, it gently slopes toward the northwestern epicontinental seas (North Sea, English Channel) and the wide continental shelf, fringed by generally low coasts where abrupt cliffs (Pays de Caux, Bretagne) alternate with sand beaches. Only cut by a few passes or "seuils" (Langres, Charolais, Jarez), the master line coincides with the water divide between Atlantic and Mediterranean catchments and is also punctuated by most of the highest points of this part of the territory, between 500 and 1,700 m. The only exceptions are a few crystalline horsts (Forez: 1,640 m) and the highest volcanic mountains (Cantal, Puy de Sancy: 1,851 et 1,885 m), within the Massif Central.

To the east and southeast, the elevated rim of these highlands overlooks by a few hundreds of meters to 1,000 m a long corridor of plains and narrow plateaus which, from the Alsace plain to the Lower Rhône valley and the Bas-Languedoc through the Bresse plain and the Rhône corridor, belongs to the Alpine foreland. Similarly, the south of the Aquitaine Basin corresponds to the Pyrenean foreland. In the alpine domain (Alpes-Jura, Pyrénées-Provence, Corse, Pyrénées), the recent, mainly Cenozoic orogenic, processes formed very high mountains, with strong topographic contrasts, often over smaller areas. The distribution, altitudes (up to 4,810 m in the Alps, 3,300 m in the Pyrenees, 2,780 m in Corsica), and style of the landforms depend on these deformations and of the complex geodynamic history of the ranges which multiplicated structural orientations, divisions, and contrasts, between high alpine mountains, also represented in Corsica, narrow plateaus, highlands presenting jagged landforms in spite of modest altitudes (Corbières, Provence), small basins, wide coastal plains, and abrupt sea cliffs deeply scalloped by coves and "calanques." The drainage was progressively organized and reorganized toward the Mediterranean Sea (Rhône), the North Sea (Rhine), and also toward the Atlantic Ocean (rivers of the central and western Pyrenees), influenced by late deformations in the alpine foreland basins. Partly controlled by ample eustatic variations of the Plio-Quaternary times, they were more strongly marked, in the southeast, by the Messinian salinity crisis during which the Mediterranean Sea was temporarily reduced to a deep and dry enclosed basin, 5.4 million years ago. The depression of the base level down to −2,000 m triggered the fast incision of narrow canyons later fossilized during the Pliocene transgression (Rhône), as well as the formation of deep karstic systems, later drowned (Fontaine de Vaucluse).

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Paris and the Seine River: Antic Sites, Underground Resources and Risks

2

Monique Fort, Christine Chaussé, Nathalie Vanara, and Gilles Thomas

Abstract

Paris City has developed on both sides of the Seine River. People began living there in the Mesolithic Age, as shown by the knowledge recently gained on early settlements and fluctuations of the river course thanks to excavations carried out with urban renewal projects. The very city (Lutetia) was founded by the Romans at the beginning of the Christian Era. The city benefited from its links with the river that favoured fluvial trade and from its substrate that offers abundant resource for building stones. This wealth explains an exceptional architectural heritage well preserved in the city. Yet, both the river and the old underground quarries are now a factor of potential risks that are carefully surveyed and managed. This chapter aims at reconstructing the different facets of unknown Paris, hidden resources and assets, as a complement to what is usually written on and praised for the City of Light.

Keywords

Palaeogeography • Underground Paris • Catacombs • Subsidence risk • Flood risk

2.1 Introduction

Paris is a magic place, attracting tourists from all over the world. Famous for the Notre Dame Cathedral, for its elegant, iron-made Eiffel Tower, Paris City has developed on both sides of the Seine River (Fig. 2.1). People began living there in the Mesolithic Age, but the very city – Lutetia – was founded by the Romans early in the Christian Era. This was a convenient site where the river could easily be crossed over by a ford and which favoured fluvial trade with the surrounding regions, as expressed by the Paris logo and maxim "Fluctuat nec mergitur". Paris is also surrounded by hills (*Montmartre, Passy*, *Montagne Sainte-Geneviève*), formed during the Quaternary by the Seine River incision through the Tertiary substrate (see also Chap. 3). The latter offers abundant resource for building stones that explain the exceptional architectural heritage still alive. Indeed, from the Mediaeval Age the population of Paris was the highest of any city of Europe, at the crossroads of trade routes between Spain and Flanders. This wealth favoured the development of significant religious edifices such as the abbeys of *Saint Germain-des-Prés*, *Saint Victor* and *Saint Martin-des-Champs* and the *Sorbonne*, one of the oldest universities in France.

During the following centuries, urban development involved spatial growth on the surrounding parishes and demolition of older buildings. Large renovation of the city beginning from 1853 was carried by Baron Haussmann who set a new grid of wide streets (like *Avenue de l'Opera*) to erase

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Fig. 2.1 Ile de la Cité and Notre Dame. Around AD, the Seine channel was occupied by a series of mounds and small islands that formed natural bridge piles and determined what has become the very heart of Paris (Photo credit: Monique Fort)

insalubrious districts and make space for traffic and more residential buildings. Many old houses were pulled down.

Paris is now the centre of a very large agglomeration extending over more than 105 km^2, vulnerable to natural hazards like floods or indirect man-made hazards like cavity collapses. The city management has to adjust to these hazards; meanwhile, urban renovations provide exceptional opportunities to decipher the ancient traces of early settlements and environments. This chapter aims at reconstructing these earliest traces, highlighting both the Seine River and underground assets, resources and potential threats, often forgotten as Paris is so much considered as the City of Light.

2.2 An Ancient Site and History

Regaining the human history along the Seine in Paris is not an easy thing. The capital city, Paris, is also a city of art, and its heritage is protected by the *Conventions Culturelles* of 1954 and 1985, supplemented in 1991 by the inclusion of both riverbanks in World Heritage of UNESCO. If this regulatory framework ensures the protection of buildings, it also limits the renovation. Access to subsoil where archaeological remains are buried is therefore exceptional. However, this legal framework requires protective measures during the renewal of neighbourhoods. Excavations are then engaged when the remains discovered are of scientific interest.

Bounded on both sides of the *Île de la Cité*, the ancient and mediaeval city is now fairly well known thanks to its rediscovery during the renovation of the city in the nineteenth century. Outside this time and spatial slot, excavations have been few, and those illustrating the link between people and the river have been even less. However, over the past 20 years, the data were renewed thanks to new archaeological research illustrating both the more ancient past of the city and its river and the outskirts of the ancient Lutetia. These observations have been made on a few sites scattered along the river (Fig. 2.2a).

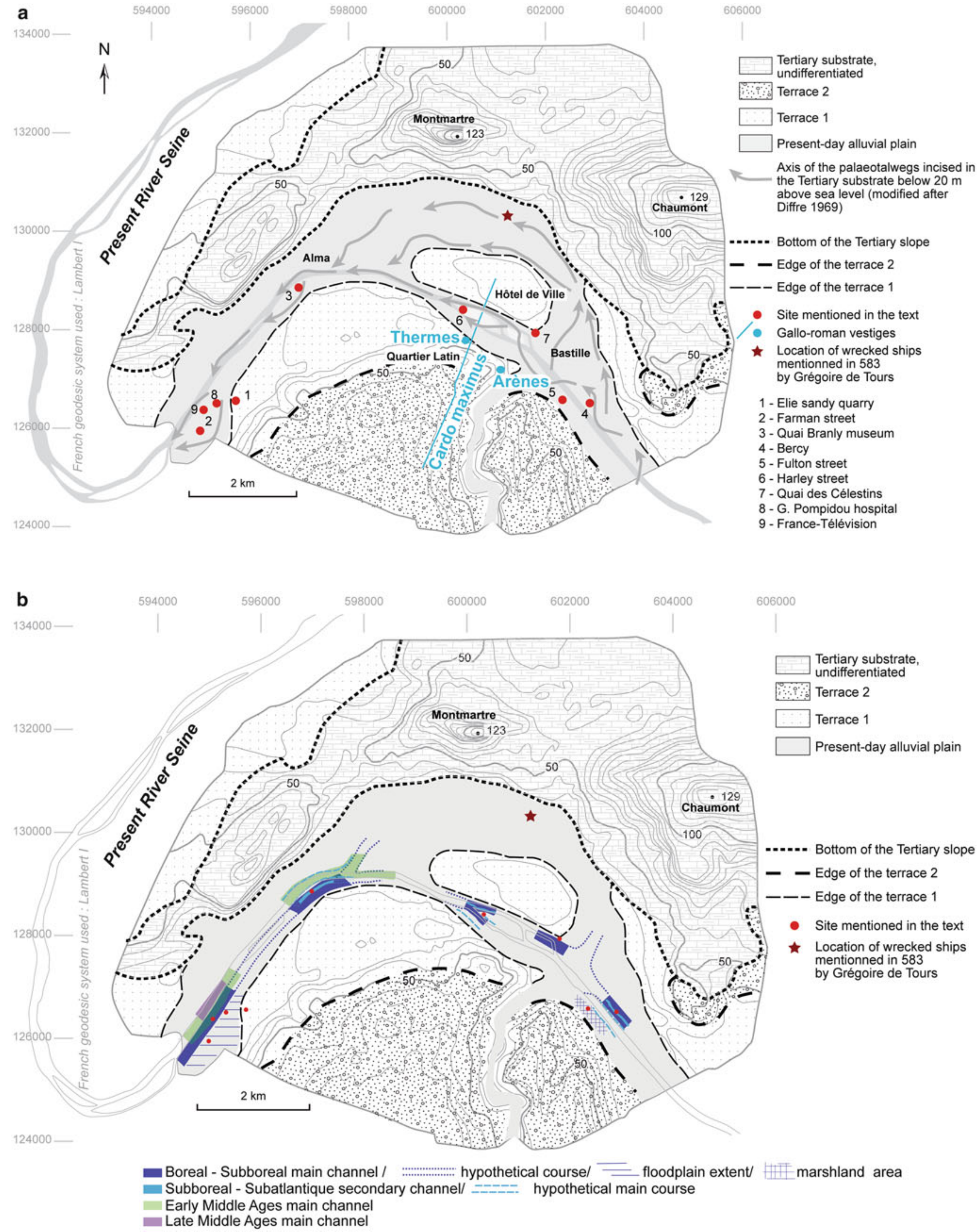

Fig. 2.2 (**a**) Simplified bedrock geology map of Paris and location of the excavations. (**b**) Schematic reconstitution of the course of the Seine River during the Holocene

2.2.1 The Parisian Space Prior to the Holocene

The Seine in Paris describes a wide meander, the first in a series that extends about 50 miles downstream. Its present bed is located in a floodplain (±30 m asl), 2 km wide at best that divides the city (Fig. 2.2a). On the right bank, it is connected to the marly limestone slope dominated by Chaumont and Montmartre buttes (>120 m asl). On the left bank, it is cut into a system of alluvial terraces (terraces 1 and 2), which outcrop between 35 and 65 m asl.

No data document these ancient fluvial formations, whose ages are currently ignored. However, compared with the more recognised system of terraces upstream of Paris (Chaussé et al. 2004), the formation of the terrace 1 could have occurred between the end of the Middle Pleniglacial (30 ky BP) and Weichselian Glacial Maximum (20–18 ky BP). In the nineteenth century, its sediments have yielded a set of lithic and faunal remains discovered in the sandpit Elie located southwest of the city (site 1, Fig. 2.2a). Artefacts would consist of handaxes and "*Mousterian flint*". The assemblage of large mammals combines taxa evolving both in cold and temperate environments (*Elephas primigenius, Cervus tarandus, Elephas antiquus, Rhinoceros mercki, Hippopotamus major*, etc.). Amongst these unstratigraphically located remains, human bones were discovered (Billy 1955). The site Elie could be the first evidence of prehistoric occupation in Paris dating back at best to Upper or Middle Pleistocene (>120 ky BP).

The setting up of the floodplain dates back to the Upper Pleistocene, i.e. last Weichselian cold stage (>30 ky BP) based on data collected from the upstream part of the Seine catchment (Chaussé et al. 2004). The plain is built upon coarse, 7–8 m thick fluvial deposits. These sediments can reach 12–13 m thick along palaeo-thalwegs incised into the Tertiary basement (Fig. 2.2a) (Diffre 1969). Their courses diverge at the Bastille area before joining again in Alma area. To the north, several palaeo-thalwegs flow in a wide loop along the foot of the Tertiary slopes, while in the south it cuts across the terrace 1 and prefigures the present bed course of the river. No archaeological remain has been found in these formations.

2.2.2 The Postglacial

The early Holocene history of the Seine River and that of its neighbours is a little better known. The first evidences date back to the Boreal (9,000–8,000 BP) and are located southwest of the city, in street Farman (site 2, Fig. 2.2a) where a Mesolithic site was recently found (Souffi et al. in press, 2012). The settlement located in the flood plain was bordered to the northwest by a channel (Fig. 2.2b). Although undated, this more or less deep channel could be linked to that identified at the Quai Branly museum (site 3, Fig. 2.2a), which was active between the Boreal and early Subboreal (±4,100 BP) (Chaussé et al. 2008). Posts associated with some ceramic shards represent the remains of a diffuse Neolithic settlement located on the lower bank of the channel. Such a channel was also found in Bercy (site 4, Fig. 2.2a, b) where its left bank supports a Neolithic village whose last occupants abandoned their dugouts (Fig. 2.3a) (Lanchon 1998). The Bercy channel was probably connected to a swamp as recognised at Fulton Street, developed in an old oxbow. The Neolithic groups then began to clear the area to allow growing crops (Leroyer 2006).

The next period begins just before the Subboreal and lasts until sub-Atlantic (2,700 BP). The river incised its bed, and the process was accompanied by a stronger hydrodynamic activity probably responsible for bank erosion as evidenced by the data collected in Harley Street, Quai Branly and Quai des Célestins (Fig. 2.2a). Along the Quai Branly and at Bercy, the channel shrunk gradually, hence was converted into a secondary channel being clogged (Lanchon 1998; Chaussé et al. 2008) (Fig. 2.2b). This process signs the migration of the main river bed to its current position. The banks of the palaeochannel were diffusely occupied by protohistoric populations. It was the same for the *Île de la Cité* which was until recently regarded as the cradle of the Gallic city. Recent excavations carried further downstream would instead locate in Nanterre the original Lutetia of the Parisii, a Gallic tribe mentioned by Julius Caesar (Viand 2008).

2.2.3 The Upper Holocene

The second part of sub-Atlantic beginning around 2,000 BP coincides with the appearance and development of Lutetia. It extended from the left bank to the right bank between the *Quartier Latin*, the *Île de la Cité* and *Hôtel de Ville neighbourhood*. The Gallo-Roman city was organised along a SSW-NNE axis represented by the *cardo maximus*, marked today by St. Jacques, Cité and St. Martin streets (Fig. 2.2a). Its creation dates back to the first century AD (Busson 2001; http://www.paris.culture.fr/en/). Later on, the mediaeval city grew from the first core. The configuration of the river at this time is not known due to lack of archaeological and geomorphological data. Only the work by Vacquer (Dupuy 1900) carried at the end of the nineteenth century proposes a reconstitution of the centre of Paris (Fig. 2.4), which since has hardly been improved.

It is rather on the outskirts of the ancient city that more recent data were collected. At G. Pompidou Hospital

Fig. 2.3 (**a**) Neolithic dugout discovered in the Bercy excavation (Photo credit: Carlos Valero, Inrap). (**b**) Mediaeval wattle discovered in the Quai Branly excavation (Photo credit: Patrick Pion, Université Paris X Nanterre)

and France Télévision building (sites 8, 9, Fig. 2.2a), southwest of Paris, investigations helped to identify the river course around the fourth to fifth centuries. It is a more than 7-m-deep main channel, extending over a width of about 70 m into which a second shallower (5 m) channel is cut and fill. It was fixed up in the Middle Ages and backfilled in the fourteenth century (Jugie 2011) (Fig. 2.2b). At Quai Branly (site 3, Fig. 2.2a, b), the main channel of the beginning of the Christian Era joined the present course of the river. But a secondary course was abandoned, transformed in fishery during the fourth and fifth centuries, as evidenced by post alignments and wattle discovery (Fig. 2.3b) (Pion et al. 2005).

The more recent history of the river and its riverside populations is not documented by archaeology. Written sources are taking over, and become abundant when the river expands over the city. The first written mention of the damages in Paris by a flood dates from February 583. *Gregory of Tours* tells when ship wrecks occurred in the north of Paris (Dupuy 1900). Obviously, the northern palaeo-thalweg along the Tertiary hill sides (Fig. 2.2a) remained active throughout the Holocene. Yet, no recent excavations have documented it to date.

2.3 The Dark Side of the City of Light: Quarries and Catacombs of Paris

Paris was founded and built upon its quarries and hundreds of kilometres of tunnels run under Paris, almost all of which are of artificial origin (Clément and Thomas 2001). The sedimentary, Tertiary substrate provided different types of rocks that were easily accessible and enabled the building of the city as we see it now in all its architectural glory. Yet, the abandonment of these underground galleries caused serious subsidence problems that had to be identified, consolidated and monitored. Now, the underground galleries of the capital have become an attraction.

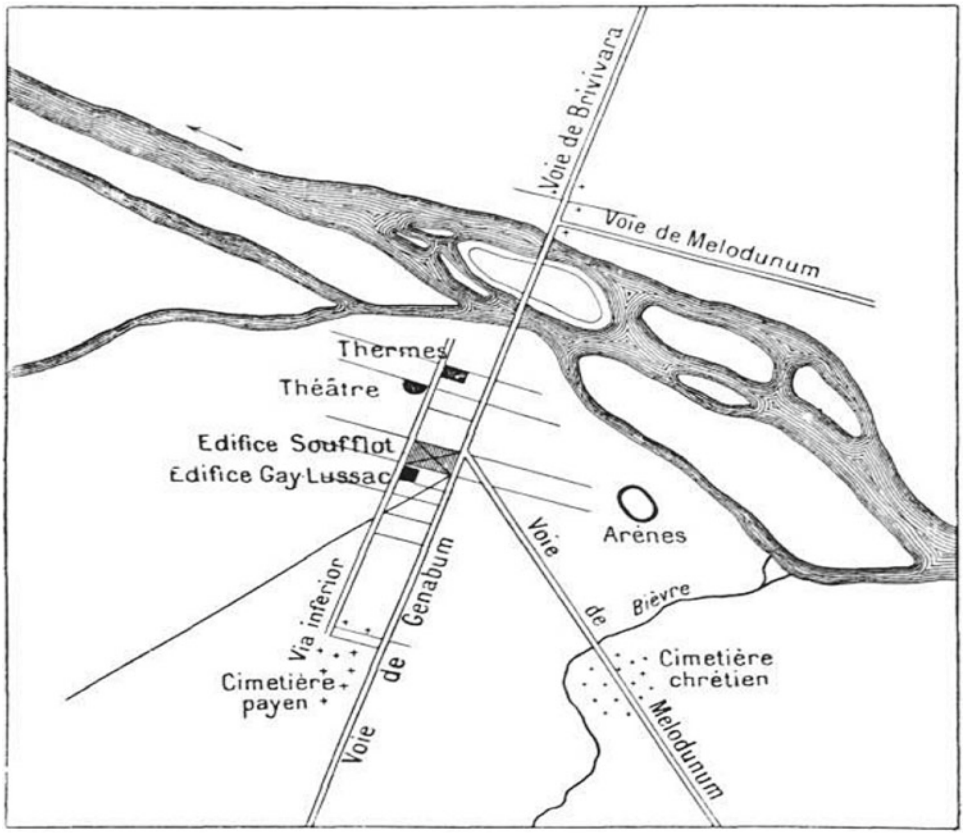

Fig. 2.4 Planche Vacquer: Palaeochannel network of the River Seine surrounding "Île de la Cité" during Gallo-Roman period, as distinguished by T. Vacquer, according to Dupuy (1900)

2.3.1 Paris Founded and Built Upon Its Quarries

Open sky quarries were exploited from Antiquity while underground quarries were exploited as from the end of the twelfth century only. In 1813, Imperial decrees forbade the opening of new quarries, and the last Parisian quarries ceased operating in 1910. This interdiction was extended to the entire Seine department on 9 May 1962. Today, it is estimated that one twelfth of Paris is undermined by ancient quarries and in the Île-de-France Region, 3,000 ha of land spread over 70 municipalities are affected by the presence of old quarries (Fig. 2.5).

Lutetian (=from Lutetia, Paris' Roman name) limestone or "*Banc Royal*" provided the building stone and was also used for delicate sculptures such as those of the porch of Notre Dame Cathedral due to its fine, regular grain (Fig. 2.6). Underground mining extended over 2,350 ha in Paris and the adjacent areas of Haut de Seine and Val de Marne departments. The digging of horizontal quarry entrances on hillsides gave access to galleries overlapping more or less at right angles. At intersections, pillars were left in place so that the rock overlying the mine remained stable. From the fifteenth century, shafts were dug to access valuable strata, which were hollowed out by longwall face advance. The voids were backfilled by mining waste or by imported surface earth. These were contained behind dry stone walls reinforced by stacked pillars (Fig. 2.7b).

Plaster of Paris made from Barthonien gypsum heated at 120 °C was exported worldwide through the multiplication of quarries from the seventeenth century: 800 ha were exploited, amongst which is the well-known quarry of Butte Chaumont. The rock cohesion required the use of explosives for its extraction. Underground galleries of ogival or trapezoidal shapes intersect at right angles, with abandoned pillars in place to ensure the strength of the whole structure.

Senonian chalk was used for the manufacture of lime and whitewash (*Blanc de Meudon*). It was extracted southwest of Paris (35 ha; Fig. 2.5). The quarries were first exploited by the method of irregularly abandoned pillars, with several tiered levels, which resulted in frequent collapses. Hence, a new operating technique was adopted in 1868 and imposed the use of regularly abandoned pillars. Once extraction was completed, the galleries were reshaped into regular arches for increased stability.

Ypresian plastic clay, used for bricks and tiles, was exploited in the 16th district of the city by shafts and radiating galleries.

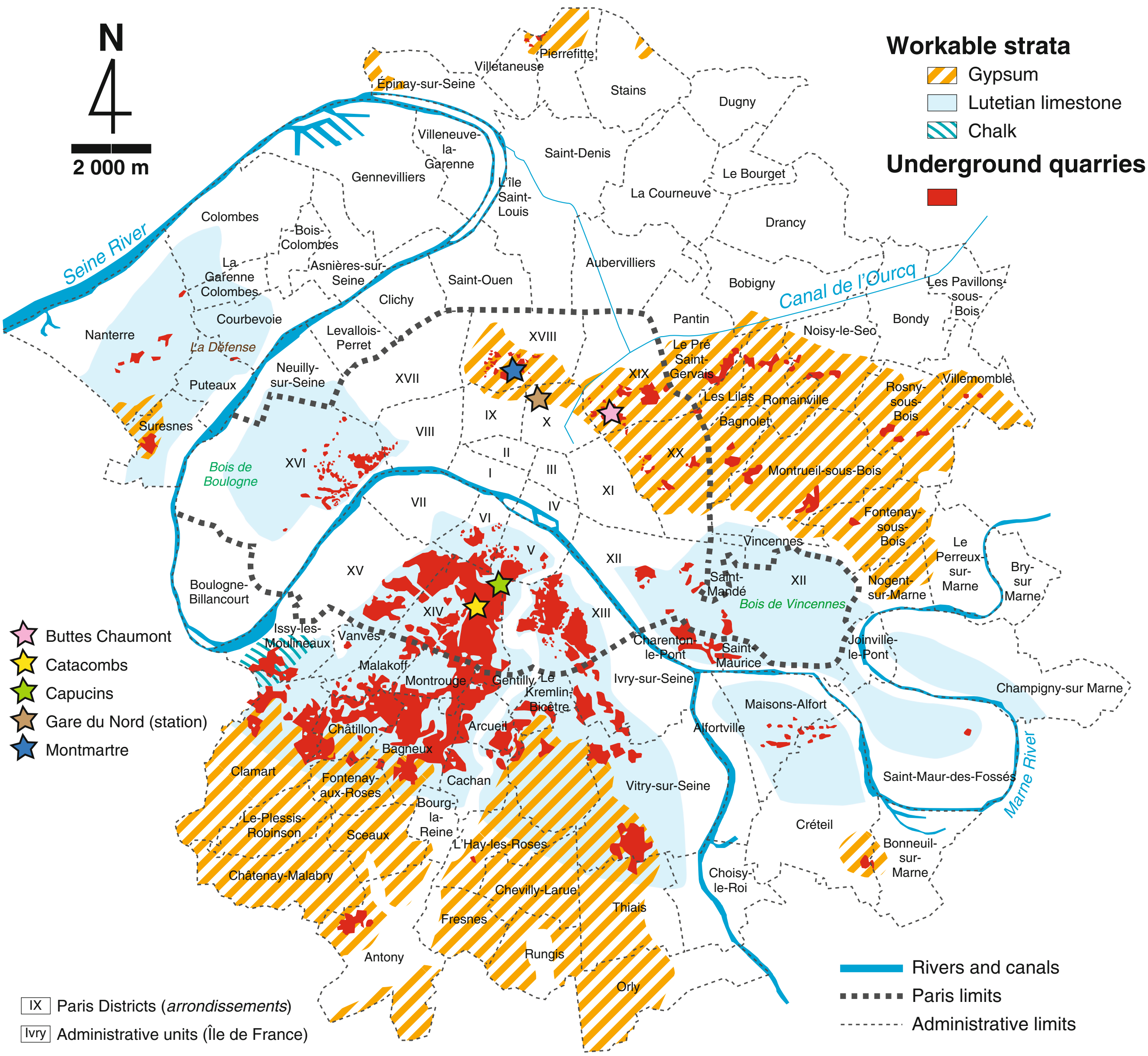

Fig. 2.5 Map of old quarries in the former Dept of Seine (Modified from the "Old Quarries Map", Ecole des Mines de Paris, and redrawn by N. Vanara)

Underground mining of supra-gypsum marls (upper Barthonien) and lignites (Ypresian false clays) are mentioned respectively in the 19th and 14th districts (Gerards 1908).

2.3.2 A City Under Surveillance: Subsidence, Collapses and Sinkholes

Paris lies on undermined bedrock (Caron et al. 1986). The fate of all abandoned cavities is to progressively subside with time. This slow and insidious work was revealed when sudden collapses of buildings occurred. Following several dramatic collapses, a Quarries Inspection Office was created in 1777; it carried out an efficient survey and reinforcement work of cavities. Surface hazards caused by underground disorders can be classified into three categories: (1) Subsidence was frequent in areas where quarries had been dynamited or backfilled (Buttes Montmartre and Chaumont). (2) Collapses are more dangerous. The most recent, largest and deadliest collapse occurred on 1 June 1961, between Clamart and Issy-les-Moulineaux where the roof fall of an old chalk mine wiped 23 buildings off the map. It was therefore decided in 1981 to carry out an early treatment consisting of almost systematic grout injection of residual cavities. (3) The origin of the subsidence is not always due to quarrying. In gypsum, groundwater can create pockets of dissolution evolving in sinkholes. The most important sinkhole was discovered in 1975 below the Gare du Nord train station, and its stabilisation has necessitated 7,300 m^3 of grouting.