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The hydrogeology of Western Europe: a basic framework

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Abstract

The principal hydrogeological provinces are identified and briefly described. The main aquifers are in the Mesozoic and Cenozoic cover which overlies the Hercynian basement. North of the Hercynian Front, an older cover of Devonian and Carboniferous rocks, resting on Caledonian basement, contains aquifers of secondary importance. Groundwater is a very essential component of freshwater supplies in Western Europe.

Keywords: aquifers, groundwater provinces, hydrogeological maps, water resources

Introduction

The purpose of this paper is to identify the principal hydrogeological provinces of Western Europe (Figs 1 & 2) and summarize the main features that control the hydrogeology. Necessarily it over-simplifies a complicated picture but the prime objective is to emphasize the more important aspects and provide a basic framework so that regional studies can be placed more readily in an overall context.

The very diverse geology of Western Europe, comprising rocks of Precambrian to Quaternary ages, is reflected in the hydrogeology of a region divided into two unequal parts by the Pyrenees and the Alps. To the south lie the Iberian and the Italian peninsulas of quite unrelated basic structure; the former is dominated by the central Hercynian massif of the Meseta, and the latter by the Po Basin in the north and the central spine of the Apennine Mountain Chain, both the result of the Alpine orogeny. North of the Pyrenees and the Alps, extensive lowland plains, formed by Mesozoic and Cenozoic sediments, overlie the Hercynian basement which is exposed in isolated massifs across the entire area from Ireland to eastern Germany (Fig. 2). Along the northern margin of the plain the hydrogeology has been much influenced by the Pleistocene glaciations and particularly the resultant glacio-fluvial deposits (Embleton 1984).

The Mesozoic and Cenozoic rocks in the north are up to many kilometres thick, disposed in and around several major sedimentary basins—the Anglo-Paris, the Aquitaine and the London basins, and the North Sea Tertiary basin. Other important hydrogeological features (Fig. 2) are the various molasse basins north and south of the Pyrenees and the Alps, the Triassic basins of central, northwest and eastern England, the Triassic and Jurassic aquifers of southern Germany and eastern Spain, the Tertiary and Quaternary deposits infilling the troughs and valleys in the mountains and uplands of Switzerland, Germany, Spain and Italy, the Rhine–Rhône rift valley system, and the Atlantic volcanic archipelagos.

The Pyrenees and Alps also define a major climatic boundary. The region to the north experiences a maritime climate but with a continental type intruding in the east and at times exerting an influence much further west. The average annual rainfall is generally less than 1000 mm and evaporation is of the order of 400 to 550 mm/a. South of the Alps and the Pyrenees and in southern France, hot dry summers and mild wet winters prevail around the Mediterranean Sea. Recharge of groundwater resources from rainfall occurs essentially in the winter and typical values on the lower ground are 50–100 mm/a. Along the east coast of Spain, rainfall occurs in the spring and autumn and the winter is dry. Northwest Spain has a maritime climate and the Meseta plateau, the Ebro (or Ebre) basin and the Plain of Lombardy approach a continental climate, sub-arid in Spain but more humid in Italy. Recharge in the Spanish Meseta is about 30–50 mm/a but along the Apennines it exceeds 200 mm/a, although about 50–100 mm/a are more typical on the lower ground and in coastal areas (da Cunha 1989).

The principal aquifers of Western Europe are in the Mesozoic and Cenozoic sequences and include Triassic sandstones and carbonates, Jurassic carbonates, Lower Cretaceous sandstones, the Cretaceous and Lower Tertiary chalks, Tertiary sandstones and limestones, and Quaternary sands and gravels. This paper is principally concerned with the regional distribution of these aquifers in the various hydrogeological provinces. Quaternary fluvial and glacio-fluvial deposits occur in many parts of the region and provide many local sources of groundwater but, in the following text, only the main sources are referred to.

Groundwater is a very important source of water in Western Europe, providing over 90% of public (drinking) water supplies in Denmark and Italy, 70% or more in Germany, Belgium and Luxembourg, and equally high proportions in many parts of the remaining countries. The total use exceeds $40 \times 10^9\ m^3/a$. In

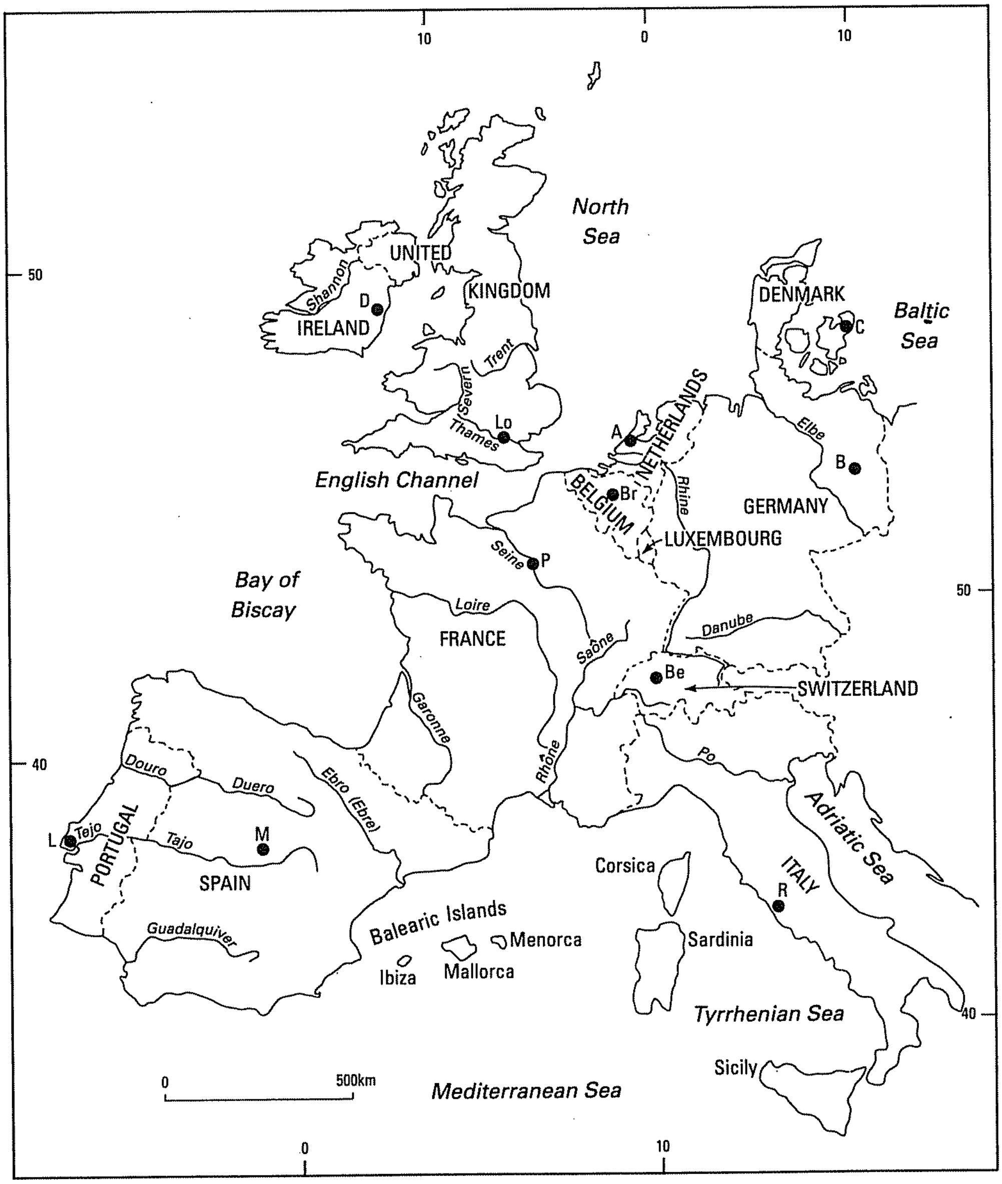

FIG. 1. Western Europe—national boundaries. A, Amsterdam; B, Berlin; Be, Berne; Br, Brussels; C, Copenhagen; D, Dublin; L, Lisbon; Lo, London; M, Madrid; P, Paris; R, Rome.

southern Europe, and especially in Spain, a large proportion of the groundwater abstracted is used for irrigation. Groundwater in the deeper parts of the sedimentary basins and in areas of high heat flow is used for geothermal energy, particularly in France and Italy (Haenel & Staroste 1988; Hurtig *et al.* 1992). Groundwater at low temperatures is also actively developed as an energy source, with the assistance of heat pumps, in France, Germany and Switzerland.

The hydrogeology of each country in western Europe has been reviewed by the United Nations (Anon 1991) and further details are given in the Explanatory Notes that accompany the individual maps forming the International Hydrogeological Map of Europe, published (from 1974) by the Bundesanstalt für Geowissenschaften und Rohstoffe and UNESCO. These publications contain comprehensive references to the literature.

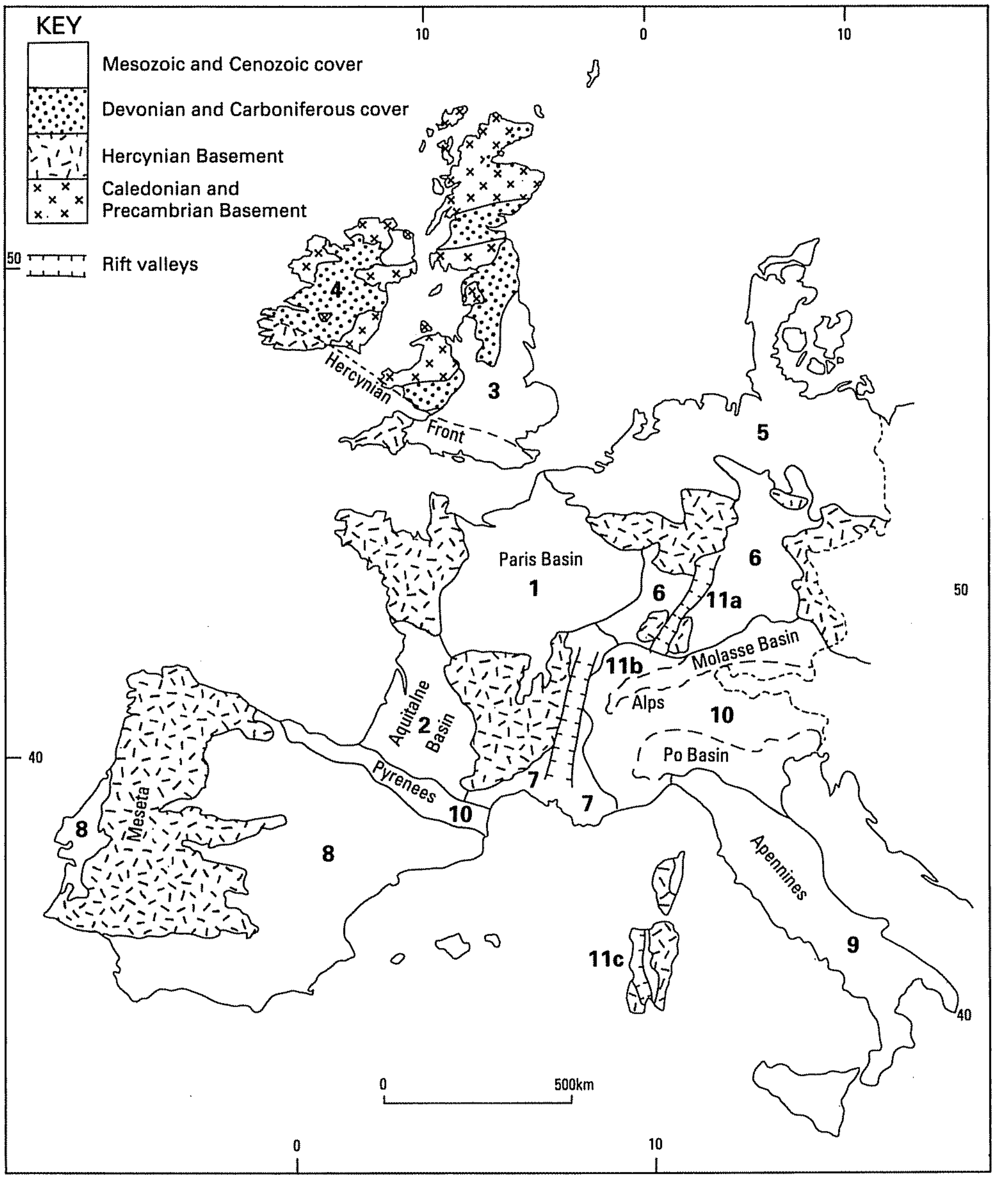

FIG. 2. Hydrogeological provinces of Western Europe. 1, Paris Basin; 2, Aquitaine Basin; 3, British Province; 4, Irish Province; 5, North Sea and Baltic Lowlands; 6, Uplands of eastern France, and central and southern Germany; 7, Sub-Alpine Basin and Grands Causses; 8, Iberian Peninsula and Balearic Islands; 9, Apennines and coastal areas; 10, Alpine fold mountains and marginal areas; 11, Rift valleys: (a) Upper Rhine Graben, (b) Rhône–Saône Graben, (c) Campidano Rift.

The basement

Over much of Europe the basement consists of Precambrian and Palaeozoic rocks that have been extensively folded and faulted by the Caledonian and Hercynian orogenies giving rise to the very complex structures seen, for example, in the Hercynian massifs (Fig. 2) exposed across the north European lowlands and the Iberian peninsula, as well as in the cores of the Pyrenees and the Alps; the islands of Corsica and Sardinia consist almost entirely of crystalline rocks. The sequences include igneous and metamorphic rocks representing the roots of the Hercynian mountains but in some massifs, for example the Massif Central, volcanic rocks of Tertiary and Quaternary ages are also incorporated. Essentially these rocks are hard and compact. The permeability tends to be low and water movement is invariably in fissures which are generally most frequent in the upper 100 m. Springs are usually small but relatively common, often draining independent, disconnected fracture systems. Aquifers are of local significance although the Carboniferous Limestone is an important aquifer in northeast France and Belgium. There the outcrop of this karstic Visean limestone is some 53 km^2. Rain contributes only 60% of the recharge since a very important proportion is derived from leakage from the overlying Chalk. Because of over-exploitation, groundwater levels are declining by 1.5 to 2 m per year in this aquifer.

In Britain and Ireland, north of the Hercynian Front (Fig. 2), the Upper Palaeozoic sequences are relatively undeformed and include many sandstones and limestones which are secondary aquifers. For example, the Old Red Sandstone facies of the Devonian, an ancient molasse deposit, includes thick aquifers of secondary value. Consequently, north of the Hercynian Front, the basement is represented by the Precambrian and Lower Palaeozoic rocks that form the Caledonian orogenic belt (Fig. 2). As with the Hercynian basement, significant groundwater flow in these compact rocks is almost entirely limited to fractures in the top 100 m of the sequence, although slow groundwater flow does occur at much greater depths and the basement rocks are by no means impermeable at depth.

TABLE 1. *Use of groundwater in Western Europe*

	Total use ($\times 10^6 m^3/a$)	Drinking water provided by groundwater (%)
Belgium	622	71
Denmark	1150	98
France	7020	62
Germany	8770	75
Ireland	96	15
Italy	12162	93
Luxembourg	26	70
Netherlands	1353	64
Portugal	2000	49
Spain	5410	30
United Kingdom:		
England & Wales	2280	31
Scotland	33	4
Northern Ireland	28	11

Sources: Anon (1982), Margat (1989).

Hydrogeological provinces

Paris Basin

The Paris Basin (Fig. 3) began to develop at the end of the Triassic Period. Since then a variable sequence of more than 3 km of Jurassic to Tertiary sediments has accumulated. A dominant feature of northern France, it is of considerable importance hydrogeologically. Although apparently truncated by the English Channel, it actually extends beyond this boundary to form with the Wessex Basin of southern England, the comprehensive structure referred to as the Anglo-Paris Basin.

Carbonate rocks of Jurassic, Cretaceous and Tertiary ages form the main aquifers of the Paris Basin although sandstones in the Cretaceous and Tertiary are also important. In the present context, the eastern boundary of the basin is taken at the base of the Jurassic. The formations in the various sequences display considerable lateral facies changes throughout the basin. The Jurassic limestones are fractured and very karstified. They form an important aquifer particularly on the eastern, southern and, to a lesser extent, the western rim of the basin. In the east, three calcareous aquifers—The Dogger, the Oxfordian and the Portlandian—are separated by clays. The Dogger, 100 to 150 m thick and covering an area of 3300 km^2, is very fractured particularly because of subsidence caused by underlying ironstone mining. The Oxfordian is 150 to 200 m thick and covers 1500 km^2 while the Portlandian is 120 to 140 m thick. All these aquifers are very karstified giving rise to large springs. A karstic system south of Toul is 24 km long and the flow velocity is as much as 1 km per hour at times of high water levels.

Towards the south the interbedded clays die out and the three limestones unite as a single aquifer which forms a wide plateau (Seuil de Bourgogne) between the Paris Basin and the Rhône–Saône Rift and between the northeast of the Massif Central and the southwestern part of the Vosges. Similarly, the Jurassic limestones form extensive plateaux at the southwestern margin of the basin (Seuil du Poitou) extending into the Aquitaine Basin. They are very faulted (mainly along NW–SE lines) and karstified especially in the Poiters area where they are 100 to 200 m thick.

In the centre of the Paris Basin, the Jurassic limestones, particularly the Dogger which lies at a depth of 1600 to 2000 m, have been a source of low-enthalpy geothermal energy since 1969, yielding water at a maximum temperature of 85°C. Within a radius of 50 km of the centre of Paris there are, at present, 40 geothermal doublets comprising an abstraction and an injection well; each system abstracts 150 to 300 m^3/hour at an average temperature of 70 to 75°C. The water is used to heat 150 000 apartments before being reinjected into the aquifer at 40 to 45°C. This use of geothermal energy is equivalent to 140 to 150 × 10^3 tonnes of oil per year.

The Lower Cretaceous Albian Green Sand is an important aquifer. It comprises three sandy layers, 30 to 200 m thick, with a porosity of 5 to 20% and a transmissivity ranging from 10^{-4} to 4×10^{-3} m^2/s. Formerly artesian at Puits de Grenelle, in Paris, it supplied

Karstic systems are developed locally, particularly in Normandy in the northwest, and Senonais in the southeast, some being as much as 27 km long with flow velocities of up to 540 m/hour.

Towards the centre of the Paris Basin, Cenozoic aquifers include the Ypresian sands, the Lutetian limestone, the lacustrine limestone of Brie, the Oligocene sand of Fontainbleau and the lacustrine limestone of Beauce; each is up to 50 to 60 m thick. They all pass downgradient into confined or semi-confined zones.

Aquitaine Basin

The Aquitaine Basin occurs in southwest France between the Massif Central and the Pyrenees. It is an asymmetrical structure because of the tectonic movement associated with the development of the Pyrenees that began in Cretaceous times. The basin contains a sequence ranging from the Jurassic to the Cretaceous but the Mesozoic rocks lie at considerable depths in the north Pyrenees foredeep. They are overlain by a thick unconsolidated Cenozoic sequence. The maximum thickness of the sedimentary pile is some 10 km.

Middle and Upper Jurassic limestones (Bajocian to Oxfordian), up to more than 300 m thick, are significant aquifers mainly on the northern and eastern margins of the basin but especially near the Massif Central where they form the Causses du Quercy, a very karstified plateau. They are overlain by Cenomanian sands and 300 to 350 m of Senonian porous and fractured, chalky limestones, locally karstified, which crop out on the north of the basin.

Palaeogene deposits form a complex multi-layered confined aquifer of limestones, clays and molassic sands. In the northwest the facies is marine and is more calcareous and argillaceous, passing laterally towards the southeast into a sandy continental (molasse) facies. This sequence is overlain by Miocene molasse deposits containing bioclastic shelly limestones in the west and centre of the basin but becoming continental towards the east. In the west of the basin, in the Landes, permeable Plio-Quaternary sands have a thickness of 10 to 150 m.

British Province

The Hercynian Front crosses southern Britain from Kent to South Wales (Fig. 2). To the north the Precambrian and Lower Palaeozoic rocks of the Caledonian orogenic belt represent the basement. The overlying Upper Palaeozoic sequences form uplands in Wales and northern England and occur in the Central Graben of Scotland and in northeast Scotland. They are only gently folded and the Devonian (Old Red Sandstone facies) and Carboniferous limestones and sandstones are aquifers but generally yields from wells and springs are small and they are of only secondary importance.

In eastern and southern England the Palaeozoic older cover is overlain by the younger cover of post-Carboniferous rocks and this sequence forms the English lowlands and contains the major aquifers: the Permo-Triassic sandstones, the Jurassic limestones and the Cretaceous Chalk (Fig. 4).

The Permo-Triassic sandstones occur in a series of deep basins in western, central, northwestern and eastern England. At the margins of these basins they are valuable aquifers with well yields exceeding 50 to 100 l/s. The maximum thicknesses exceed 1000 m. The specific yield can be between 20 and 25% and the overall high transmissivity of $2 \times 10^{-2}\,m^2/s$ is due mainly to the fissured nature of the sandstones.

The Jurassic limestones form important aquifers in three areas: the Great and Inferior Oolites of the Cotswold Hills in southwest England, the Lincolnshire Limestone in eastern England, and the Corallian limestones of northeast England (Fig. 4). These limestones are very fissured, although not karstified, and the transmissivity is commonly in excess of $10^{-2}\,m^2/s$. The Lincolnshire Limestone, where it is confined to the east of the southern part of its outcrop, is particularly prolific with yields from individual wells as high as 350 l/s.

The Chalk is the prime aquifer in England. As in France and other parts of northern Europe (Downing *et al.* 1993), it is a very porous, fissured limestone composed of the calcareous skeletal fragments of planktonic algae. The permeability pattern is closely related to the form of the valley systems and in the valleys the transmissivity can exceed $2 \times 10^{-2}\,m^2/s$ giving yields of 50 to 100 l/s. Although the Chalk is up to 400 m thick, the main water-bearing horizons are generally in the more fissured upper 50 to 60 m. Karstic solution features are developed to a limited extent at the margins of overlying Tertiary deposits and boulder clay.

The Chalk is extensively developed in the London and Hampshire basins and in eastern England. It is exploited below Tertiary cover especially in the London Basin, where water levels are currently some 50 m below sea level, and below glacial tills over much of the region north of the Thames.

Lower Cretaceous sandstones represent a less important aquifer around the rim of the Chalk outcrop in eastern and southern England and west of London where they are a confined aquifer.

Palaeocene sands, immediately above the Chalk, are water-bearing in the London Basin but they are usually exploited by developing the Chalk which induces downward flow into the fissures of the lower aquifer. In the Hampshire Basin, Palaeogene sands provide small yields.

Lower Pleistocene sands in eastern England, referred to as the Crag, give useful supplies especially where the underlying Chalk is too deep. Locally sand layers in the

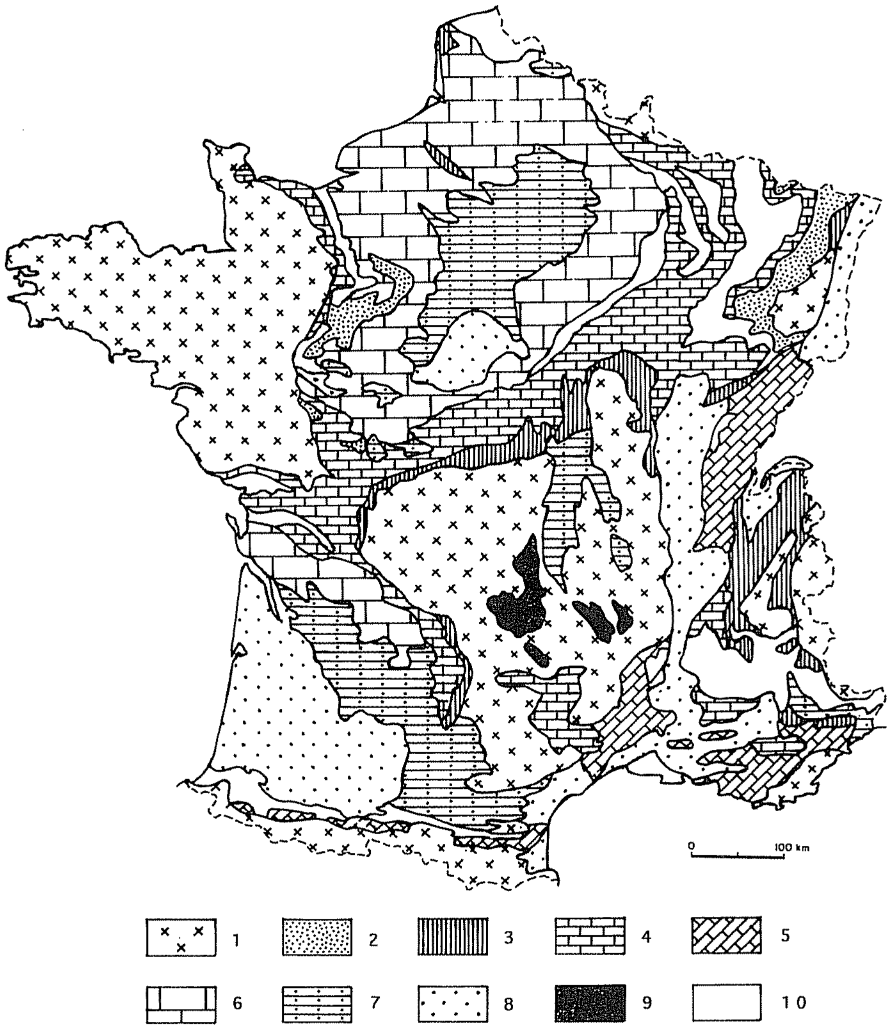

FIG. 3. Hydrogeology of France. (1) Crystalline and/or Palaeozoic rocks: discontinuous aquifers, some of local significance in folded and karstified limestones. (2) Mesozoic arenaceous, porous aquifers: Lower Triassic sandstones (in the east) and Cenomanian sands (in the west). (3) Local aquifers or formations of low permeability, mainly Mesozoic. (4) Calcareous aquifers in tabular, fractured and partly karstified Mesozoic limestones. (5) Calcareous aquifers in folded, fractured and partly karstified Mesozoic limestones. (6) Upper Cretaceous Chalk (Paris Basin) or porous chalky limestones (Aquitaine Basin). (7) Palaeogene aquifers, generally multi-layered. (8) Neogene and Quaternary deposits, very permeable in the Rhine Rift, the Paris and Aquitaine basins, and the Mediterranean area, but much less so in the Rhône–Saône Rift (except near Lyon). (9) Heterogeneous and local aquifers, porous or fissured, in recent volcanic formations. (10) No significant aquifers.

the city for many years. By 1936 exploitation was at a rate of 34 million m^3/a, well in excess of the natural recharge of 25 million m^3. Now only 20% of the abstraction is still from flowing wells. At the base of the Cenomanian, a sand 30 to 90 m thick, is a secondary, but nevertheless, a regionally important aquifer in the southwest of the basin.

The Cretaceous Chalk is indisputably the dominant aquifer of the Paris Basin cropping out over some 70 000 km^2, forming a rim around the central Tertiary outcrop. It is a classic dual-porosity aquifer comprising a soft, white, microporous limestone, 100 to 600 m thick, with a porosity of 30 to 40%. The high permeability is due to extensive interconnecting fissures which derive water from microfissures in the fine-grained matrix. The specific yield is generally only about 1 to 2%, although up to 9% below valleys; well yields are typically 100 l/s. The average annual recharge amounts to 10×10^9 m^3.

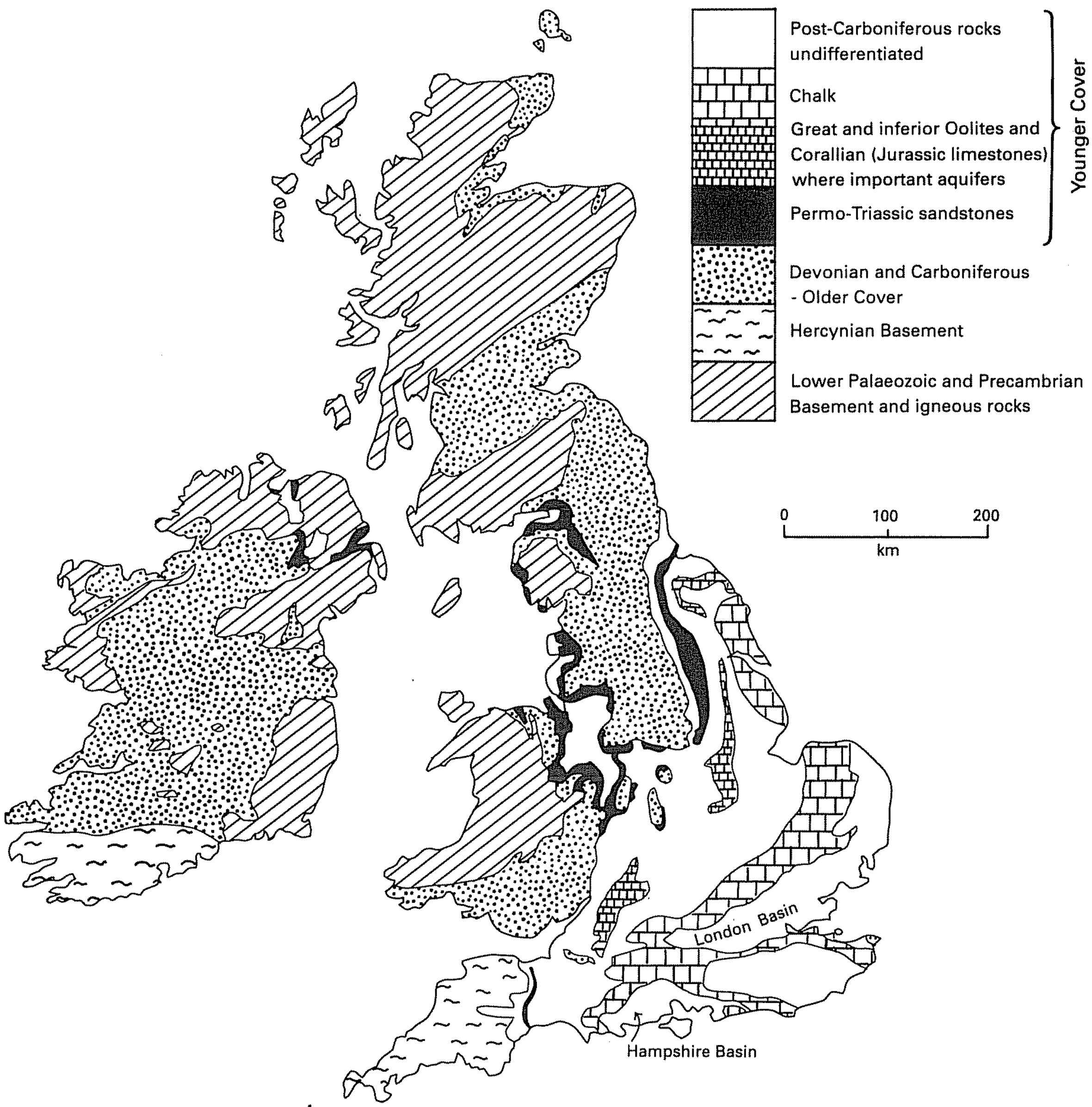

FIG. 4. Hydrogeology of the British Isles.

overlying glacial deposits are also of some significance. Alluvial deposits are not usually important aquifers in England because of limited thicknesses and a tendency to contain quite a high proportion of clay.

Irish Province

South of the Hercynian Front, which extends from Dungarven to Dingle, the Upper Palaeozoic basement is intensely folded (Fig. 2). But north of the boundary, as in England and Wales, the Devonian and Carboniferous rocks of the foreland are only gently folded and contain aquifers. However, in this northern region the Lower Palaeozoic and Precambrian basement is exposed over extensive areas (Fig. 4). Nevertheless, much of central Ireland is underlain by the Carboniferous Limestone and the best aquifers are in this formation in fissured karstified limestones in the Munster synclines, the Barrow valley and in the midlands of Ireland. In

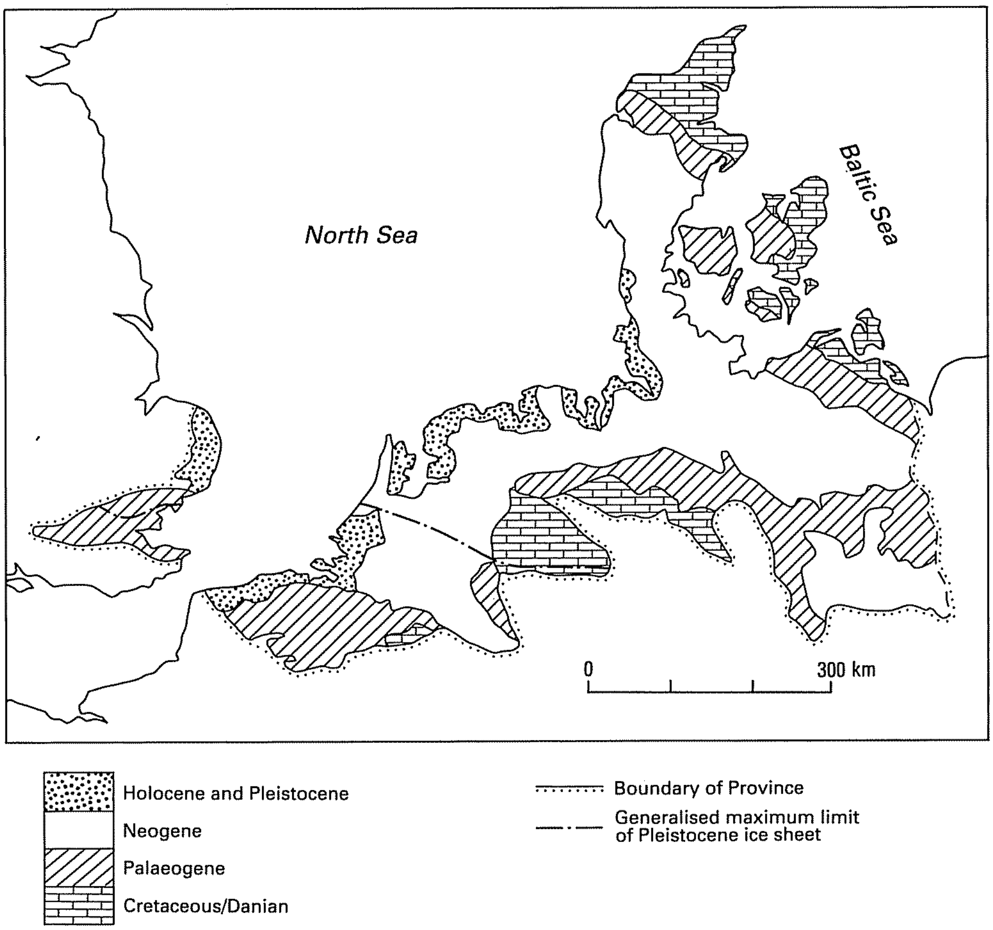

FIG. 5. Hydrogeology of the North Sea and Baltic Lowlands. (The extensive cover of glacial deposits over most of the region is not shown.)

Northern Ireland, Permo-Triassic sandstones are valuable aquifers at the margin of a deep Mesozoic basin. The Mesozoic sequence, including the Chalk, is almost entirely obscured by Tertiary basalts up to 800 m thick. Joints and fractures give the basalts limited permeability. Quaternary deposits are widespread in Ireland and local supplies are obtained from glacio-fluvial and alluvial sediments.

The North Sea and Baltic Lowlands

The North European Plain, north of the Hercynian massifs of the Ardennes, Harz and Bohemia, is underlain by Tertiary sediments and largely covered by glacial till, moraines and glacio-fluvial deposits. Strictly speaking the Tertiary outcrops in Eastern England form part of this region (Fig. 5). At the margin of the Tertiary deposits the Chalk crops out and is developed for water supply in Belgium, the Netherlands and Denmark. Over the remainder of the region it is too deep to be exploited and the water it contains is saline.

Cretaceous rocks including some chalks are also developed for water supply in the Munster Basin of north Germany, and Cretaceous sandstones and limestones are important aquifers near the margin of the Quaternary cover.

Tertiary aquifers are significant in Denmark and Belgium, where marine and continental sequences of sands occur; in Denmark limestones are also exploited for supply. In the Netherlands, at the margin of the Quaternary, Tertiary sands form aquifers as in north Germany.

Miocene and Upper Oligocene sequences in Germany also contain aquifers. They are protected from upward migration of saline waters by underlying clays of the Middle Oligocene. However, in many areas the Tertiary deposits are not important aquifers because they lie below thick Quaternary deposits.

The Quaternary cover forms a coastal belt of sand dunes and marshes in Belgium, the Netherlands and Germany which pass inland into a belt of glacial sands. These sands are all important aquifers in sequences that have an average thickness of 50 to 100 m but they are particularly prominent in the Netherlands.

The Netherlands lies within the major delta of the Rhine, Meuse and Scheldt rivers and some 25% of the country is below sea level. Much of the country is underlain by a thick unconsolidated aquifer system of Quaternary deposits overlying Tertiary clays which form an impermeable base. The original high water table has been lowered by an artificial drainage system of ditches, canals and polders and, as brackish water underlies a large part of the country, care has to be taken to avoid upconing and lateral movement of saline water. The coastal sand dunes, which are up to 30 m above sea level, contain a fresh water lens. The natural equilibrium was disturbed about 100 years ago as increasing amounts of groundwater were abstracted. Since 1957 saline intrusion has been controlled by artificial recharge.

Glacio-fluvial sands and gravels are very important aquifers in Denmark, providing 50% of the water supply. Aquifers are represented by outwash plains and valley fill, and as sand and gravel layers in morainic till. Similar deposits are prominent sources of groundwater in north Germany; coarse-grained sediments in sub-glacial erosion channels provide good aquifers. Cities such as Hamburg, Hannover and Bremen are partly supplied from glacio-fluvial sands. In the lower parts of the Quaternary sequence, saline waters occur, derived from diapiric salt domes, and saline intrusion can be a problem in coastal areas. Coarse alluvial deposits in the Rhine and Elbe valleys are exploited by bank infiltration and some resources are replenished by artificial recharge.

Uplands of eastern France, and central and southern Germany

This region is bounded in the west by the eastern margin of the Paris Basin, in the south by the molasse trough of the Alps, and in the east by the Bohemian massif. The western part is dissected by the Rhine Graben and the Hercynian massifs of the Vosges, the Black Forest and the Odenwald (Fig. 2). Much of the area is covered by Triassic rocks with Jurassic sediments forming a prominent semi-circular outcrop around them in the south and southeast in Germany.

As a result of uplift and folding during the Alpine orogeny, central Germany is a complex area consisting of a series of Hercynian massifs separated by uplands and depressions containing faulted and folded sediments mainly of Triassic age (Fig. 6). Prominent features are the Hesse Depression and the Thuringian Basin which lie between the Rheinisches Schiefergebirge, the Harz and the Bohemian massifs.

Southern Germany is characterized by scarp and vale topography formed by Triassic and Jurassic strata up to 1500 m thick, the Middle Jurassic carbonates, the Triassic sandstone, and the Muschelkalk being responsible for the main scarps. The sequence represents a multi-layered aquifer system with the permeability largely related to fractures and joints. Individual aquifers can be interconnected by facies changes and faults.

The principal aquifer is the Triassic Buntsandstein, a clastic formation 500 to 1000 m thick in Germany but decreasing to the west and southwest to less than 500 m in France. Groundwater flow is mainly in joints and fractures except in the middle section in Germany where intergranular flow is important. The porosity ranges from less than 1% to 10 to 15% where it crops out and is fissured. The average hydraulic conductivity is 10^{-5} to 2×10^{-5} m/s and the transmissivity varies with saturated thickness, being less at outcrop but of the order of 10^{-2} to 2×10^{-2} m^2/s where 500 m thick. Yields from wells range up to 150 l/s. In France most of the formation actually dips steeply towards the centre of the Paris Basin and topographically it is part of that basin.

The Muschelkalk comprises an upper and lower calcareous unit separated by mudstones and evaporites. The thickness of each calcareous unit ranges from 60 to 100 m in France and the total thickness in Germany is 100 to 250 m. The limestones have relatively high permeabilities partly because of karstic features. Groundwater that has been in contact with the Middle Muschelkalk can be mineralized but in parts of southern Germany the evaporites have been leached out entirely and well yields of fresh water range up to 150 l/s.

The Upper Jurassic limestones, 200 to 600 m thick, represent an important extensively karstified, regional aquifer in southern Germany. Their semi-circular outcrop north of the Danube forms the Swabian Alb and the Franconian Alb (Fig. 6).

Sub-Alpine Basin and Grands Causses

Between the southeastern limit of the Massif Central, the southwestern Alps and the Mediterranean, the Sub-Alpine Basin covers some 25 000 km^2 and contains a Mesozoic and Cenozoic sequence up to 9 km thick.

The main aquifers are Upper Jurassic limestones which are folded and faulted in the Causses du Languedoc (at the southeast margin of the Massif Central) and in the Alpes de Haute-Provence, to the north of a line from Marseille to Nice. Calcareous formations in the sequence are at least 250 m thick, fractured and often karstified, but they do not have extensive outcrops because of the folded nature of the sequence. Towards the north, in the area known as the

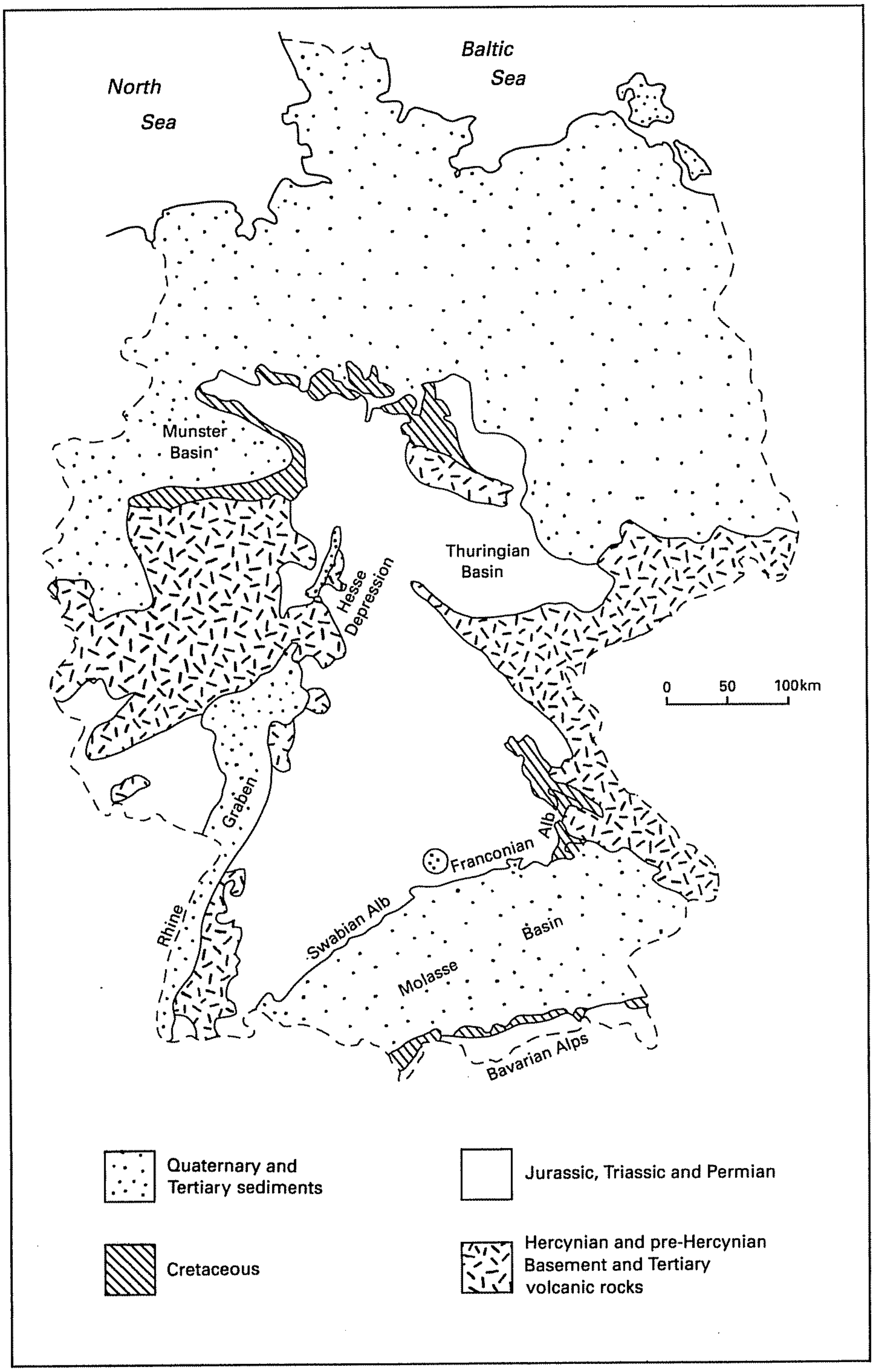

FIG. 6. Hydrogeology of Germany (after Anon 1991).

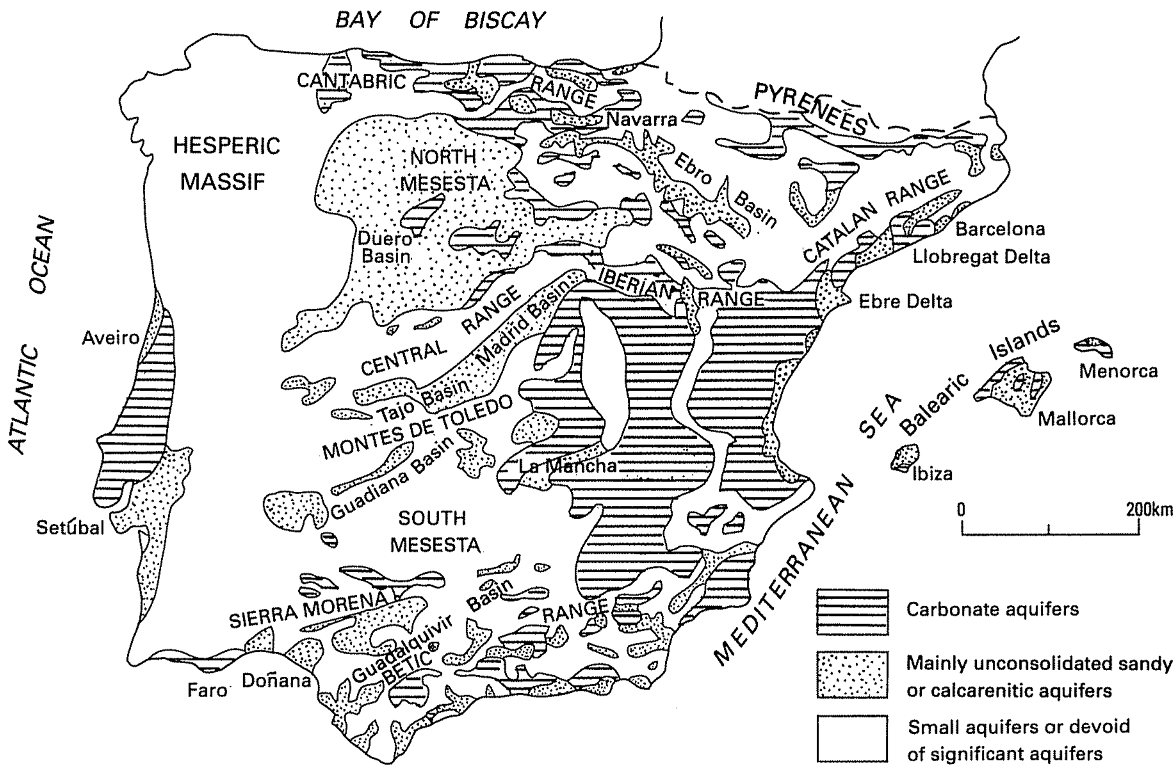

FIG. 7. Hydrogeology of the Iberian Peninsula and Balearic Islands.

Dauphinoise, south of Grenoble, the Lower Cretaceous Urgonian Limestone, 200 to 400 m thick, forms extensive and very karstic aquifers in Vercors and the Plateau de Vaucluse, near Avignon. The transmissivity ranges from 10^{-2} to $10^{-1}\,m^2/s$. The Fontaine de Vaucluse, a famous and typical karstic resurgence, has been traced for 46 km and has flow rates of up to $150\,m^3/s$.

Pliocene-Quaternary and Quaternary alluvial deposits form significant aquifers in several parts of the Sub-Alpine Basin, for example the Plain of Crau, where 70% of a total use of 40 million m^3 is provided for irrigation.

The Grand Causses consists of tabular Jurassic limestones and dolomites deposited in a deep trough in the crystalline and Palaeozoic basement of the southern part of the Massif Central; the trough contains a Jurassic sequence of more than 1500 m.

The Iberian Peninsula and the Balearic Islands

The foundation of the Iberian Peninsula, which embraces Spain and Portugal, comprises folded and partly metamorphosed Hercynian basement that forms the central highlands or the Mesetas (Fig. 7). Thick Mesozoic sediments, predominantly carbonates and marls, but including sands and sandstones on the Atlantic margin, were deposited around the basement rocks. Thick halokinetic sequences of anhydrite and even halite are commonly found near the base. The Mesozoic formations were covered by early Cenozoic sediments that contain a large proportion of carbonates along the Mediterranean coast. Mountain ranges, reactivated during the Alpine orogeny, are found at the margins and across the interior (Fig. 7), with extensive folding and thrusting of pre-Miocene sediments. Within the Mesetas, large grabens have been filled with thick continental, playa-like sediments. Sediments deposited in gulfs with restricted circulations, and which include thick evaporites in the central areas, infill the largely unfolded basins of the Duero (or Douro), Tajo (or Tejo) and Guadiana in the high plains, and at lower elevations, the Ebro (or Ebre) and Guadalquivir basins. The major La Mancha carbonate aquifer occurs in the central and southwestern Meseta in the upper Guadiana Basin and in the headwaters of some of the smaller Mediterranean river catchments. The Balearic Islands are part of the carbonate region of the Mediterranean basin separated from the Iberian

Peninsula by a large graben below the sea. Except for Menorca, they are an extension of the Betic Range in the southeast of the Peninsula.

In broad terms the Iberian Peninsula can be divided into a western and northwestern hard-rock domain, a central domain dominated by clastic, often fine-grained and clay-rich sediments, and a northern and Mediterranean domain, including the Balearic Islands, with extensive thick carbonate formations and karstic features. Restricted, but thick and well developed Quaternary deposits along the major rivers systems and the delta plains are also important hydrogeologically.

Groundwater is developed only to a limited extent in the wet northwest but water supplies for villages have been developed from granites, as in northern Portugal. Along the wet, narrow, coastal strip bordering the Bay of Biscay and along the Pyrenees, large karstic springs are tapped for supplies in the more densely inhabited areas although there is no intensive development by means of wells.

Along the drier Mediterranean coast and the Balearic Islands, there are very productive carbonate and alluvial aquifers, but the recharge is limited. Groundwater demands for towns and industry, including the tourist industry, is very high but by far the greatest demand is for agriculture. Wells more than 300 m deep are not uncommon. Large falls of groundwater levels (up to several metres per year) and saline intrusion, both from the sea and deep-seated formations, occur in some areas. Some sustained declines in groundwater levels are actually long-term transient situations during which reserves are being used. Many springs and rivers have become dry. Development of the central grabens has had similar results, especially in the carbonate aquifers of La Mancha, where a groundwater-fed major wetland (Tablas de Daimiel) has dried out. Similar conflicts over the use of groundwater occur in the central Duero basin and the lower Guadalquivir marshes and wetlands of Doñana.

Many of the aquifers constitute valuable reserves of good quality water for drinking water supplies, as in the Aveiro area, the Peninsula of Setúbal and the northern Madrid basin within the Tajo basin. Some alluvial aquifers, with fast turnover times of storage, constitute important emergency water reserves near the coast, as in the aquifer system of the Llobregat delta, near Barcelona. In Mallorca some intensively used karstified carbonate aquifer units are virtually drained in summer and replenished in winter.

Salinity is a major problem in some formations. For example in the central Ebro (Ebre) basin, irrigation with imported water of former dry lands, comprising evaporitic-rich sediments, produces saline return flows that pollute downstream aquifers. Influent rivers are common along the Mediterranean coast and this leads to similar problems. Saline pollution in the Llobregat river due to the mining of potash salts in the central basins is a serious case of groundwater contamination, because of recharge by the river of the Lower Llobregat aquifer system, a vital water resource in the Barcelona area.

The aquifers are very variable because of the complex geological setting. Consequently it is difficult to give characteristic values for thicknesses and hydraulic properties. The thickness of the Mesozoic carbonate formations may exceed 1000 m in the Mediterranean basin, but wells do not generally penetrate more than 500 m. Permeable zones occur in intercalated palaeokarsts, which were formed during regressions of the sea, and by dissolution of carbonate by coastal processes, and from extensive fracturing. Transmissivities range up to $0.3\,m^2/s$, with wells yielding over 200 l/s. The late Cenozoic calcarenites of the Mediterranean coast and the Balearic Islands, which may be up to 150 m thick, can yield more than 150 l/s from individual wells. In La Mancha, the two-layered flat-lying limestones are less than 200 m thick and the transmissivity varies between 5×10^{-4} and $0.2\,m^2/s$.

Sandstones, up to 300 m thick with transmissivities varying between 10^{-3} and $10^{-2}\,m^2/s$, occur in Aveiro and they increase in thickness towards the south. In the Setúbal Peninsula there are more than 1000 m of sediments, but wells only penetrate the upper 300 m.

Cenozoic sediments, up to 3000 m thick, infill the large grabens as for example near Madrid. They are generally of low permeability but large freshwater reserves do occur in areas where the sequence does not include evaporites. Early attempts to exploit the Madrid basin were a failure because of poor well technology at the time. This strongly influenced government water policies in Spain. Recently, by applying modern drilling techniques, wells up to 500 m deep yield up to 200 l/s when suitable facies are drilled. In the Duero basin, wells penetrating up to 200 m typically yield 10 to 30 l/s from aquifers with transmissivities between 10^{-3} and $3 \times 10^{-3}\,m^2/s$.

Quaternary formations of the Guadalquivir delta and Doñana area are up to 200 m thick. They are mainly fine to medium-grained sands with coarse layers at depth that give a total transmissivity of between 3×10^{-3} and $5 \times 10^{-2}\,m^2/s$ and provide well yields of up to 100 l/s. The permeability of 5 to 30 m of saturated alluvium in the central Ebro basin is about 10^{-3} m/s; typical well yields are 10 to 30 l/s. In the lower Llobregat system efficient wells generally yield more than 50 l/s, and up to 400 l/s in some areas.

Apennines and coastal areas

The Apennine mountain chain forms the backbone of Italy, extending from the Po valley to Calabria and into Sicily (Fig. 8). It displays a very varied relief with upland areas interspersed with valleys and depressions and bounded on the east and west by coastal plains.

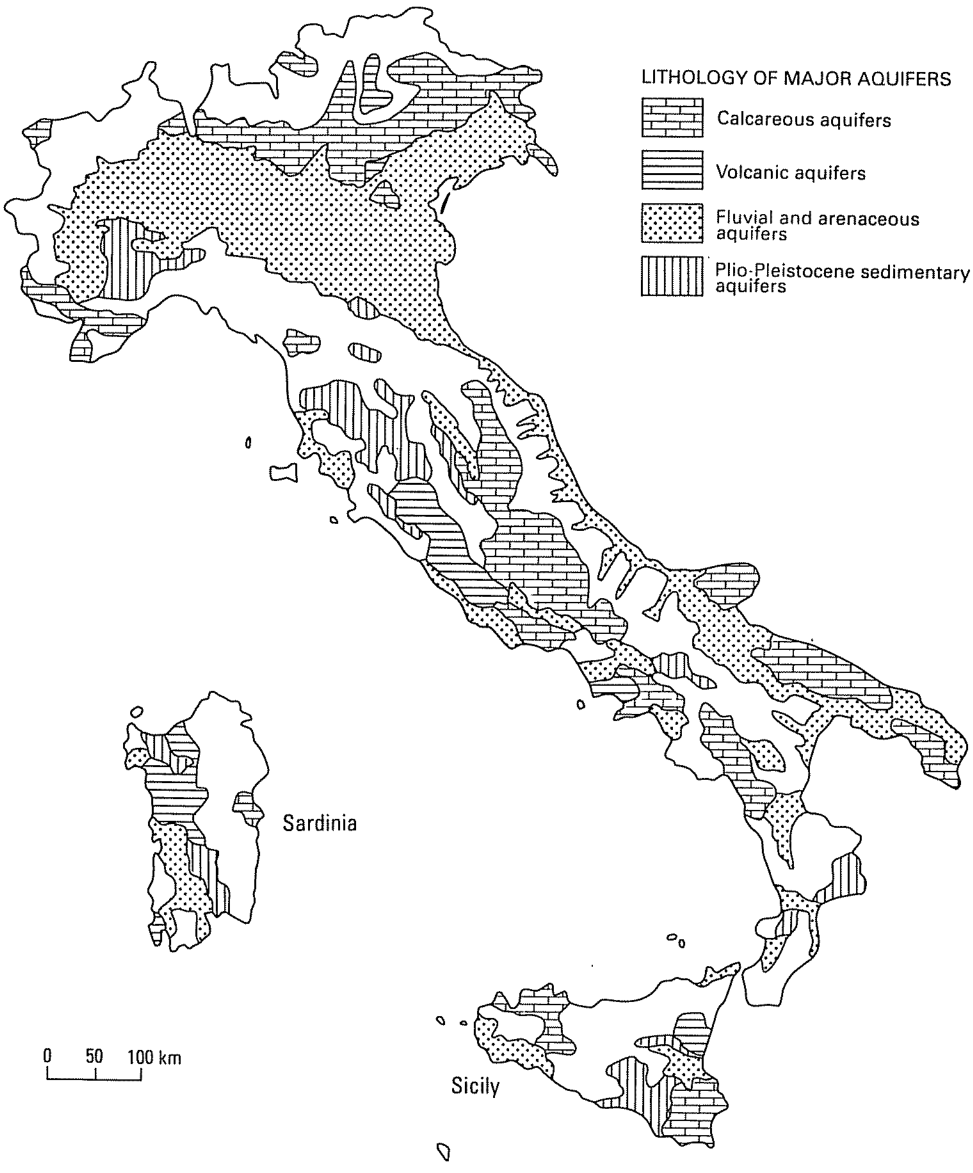

FIG. 8. Hydrogeology of Italy (after Anon 1991).

Carbonate rocks dating from Triassic to Miocene periods are a prominent feature and form important aquifers in central and southern Italy (Fig. 8). These rocks are well replenished by rainfall, have extensive karstic features and supply high-capacity springs used by many villages and urban areas, including Rome.

A series of volcanic aquifers extend along the west side of the Apennines (Fig. 8). Their permeability varies according to the extent of weathering, both in recent times and between phases of eruption. These volcanic rocks feed many large springs. The only volcanic activity on the peninsula in recent times has been around Naples, in the Phlegrean Fields and from Vesuvius. Although the Phlegrean Fields do not contain significant aquifers, the rocks forming Vesuvius are very permeable and water infiltrating the volcano flows into underlying sedimentary aquifers providing supplies for many wells.

High-enthalpy geothermal fields exist in Tuscany, southwest and south of Florence. The major field is at Larderello where over 600 MW of electrical energy are produced from a dry steam field. The main reservoir is a very permeable Triassic to Jurassic carbonate and

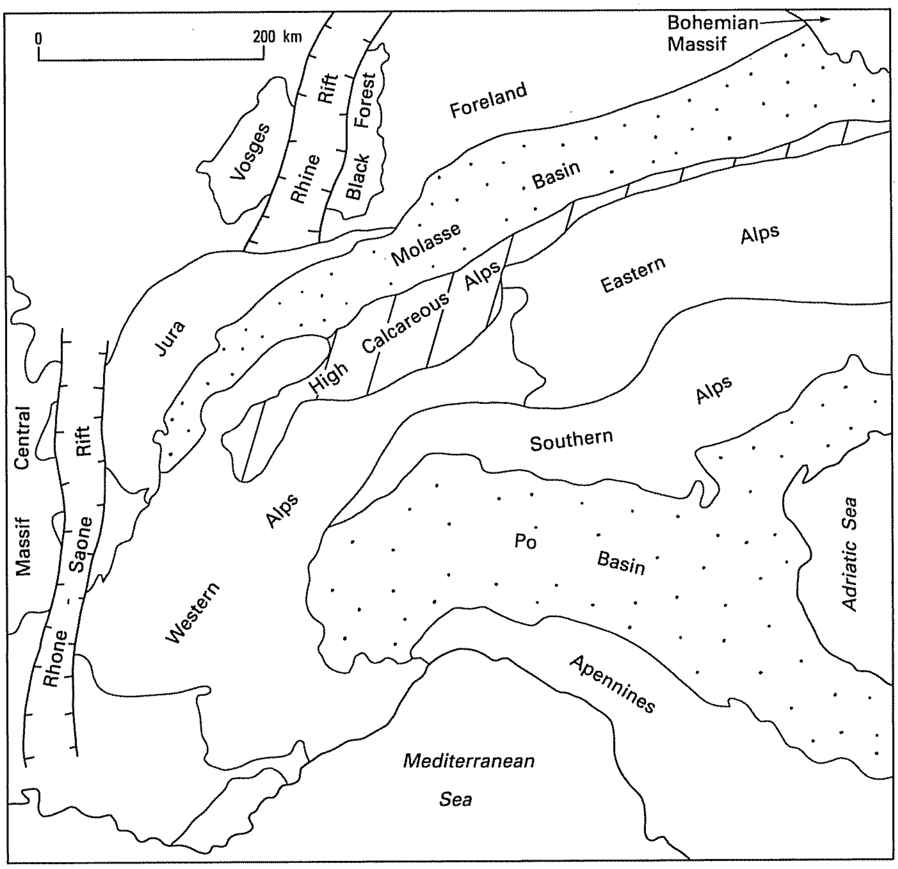

FIG. 9. Hydrogeology of the Alps and marginal areas.

anhydrite sequence but a second deeper reservoir occurs at 3 to 4 km (Haenel & Staroste 1988).

Deep depressions infilled with thick coarse-grained Quaternary deposits occur along the coastal margins and extend deep into the mountains. These multi-layered aquifers are very permeable and are extensively exploited for water supply.

On Sicily the Quaternary volcanic rocks of the large active volcano, Etna, represent the island's most important aquifers. Lava and pyroclastic deposits cover over 1300 km^2 and rest on sediments with low permeability. Many springs issue from the volcanic rocks but most of the discharge is from drainage galleries, some over 2 km long. Average yields from the longer galleries range from 100 to 1000 l/s. In the southeast of the island, horizontal calcareous rocks form the Iblei tableland. Carbonates are also important in the northwest of the island. Large springs discharge from limestones and some of the groundwater flows into overlying Pleistocene deposits in valleys.

Alpine fold mountains and marginal areas

The principal Alpine fold mountains are the Alps, the Pyrenees and the Apennines but also the various ranges of the Iberian Peninsula, in particular the Betic range in southern Spain. The Apennines and the Iberian mountain range have been discussed and therefore this section is restricted to the Alps and the Pyrenees and their marginal areas.

The Alps is an arc-shaped mountain range extending from southeast France through northern Italy, Switzerland, southern Germany and into Austria (Fig. 9). Basically, it comprises the western and northern arc of the Calcareous Alps, an inner belt of the Crystalline Alps of interstratified Palaeozoic and Triassic rocks, and the Southern Alps with extensive Permo-Triassic sequences, particularly the Triassic limestones of the Dolomites. The crystalline metamorphic rocks are not very permeable except where fractures have been created by tectonism.

The intermontane deep valleys are of particular interest to hydrogeologists as well as the widespread karst, a feature of the Calcareous Alps and Southern Alps. The rocks are not usually exploited directly for water supply because of the terrain but the many large springs that issue from very extensive fracture and solution flow systems are developed to advantage.

The geology of the Alps is extremely complicated. It comprises major recumbent folds, nappes and thrusts that are extensively faulted and fractured. Groundwater probably played an important role in their formation. The buoyancy effects of high fluid pressures in saturated rocks, which at depth can approach the lithostatic pressure (Hubbert & Rubey 1959), can explain the large-scale rock movements that have occurred in the Alps, including gravity sliding over extensive distances.

To the north of the Alps there is a deep Molasse Basin which began to infill in the Oliogene with alluvial fan and deltaic sediments, initially derived from the Bohemian massif but later, and mainly, with erosional material from the Alps as their uplift began. The molasse, which now forms the Swiss and Bavarian plateaux, is several kilometres thick and contains a number of aquifers; the upper part is a significant aquifer in Germany, providing yields of up to 100 l/s. The basin also contains three important deep aquifers: Cretaceous and Jurassic karstic limestones, the dolomitic Muschelkalk, and the Lower Buntsandstein (Triassic). These yield mineral and thermal waters in Switzerland although their configuration is not well known.

The molasse is overlain by thick, coarse-grained glacial deposits derived from the Alps, and Alpine rivers have cut deep, wide valleys into the molasse sediments. The Quaternary deposits include major aquifers, as for example near Munich, where they are one of the major groundwater sources in Germany. Throughout the Alps and the marginal areas, deep valleys and depressions formed by glacial action are infilled by thick sands and gravels that form extensive aquifers. Important examples are the Rhine, Rhône, and Emme valleys (the last rises north of Interlaken and crosses the Molasse Basin).

On the northwest margin of the Molasse Basin, folded Mesozoic sediments form the Jura Mountains. This is an arc-shaped range extending for more than 30 km from Lyon to beyond Basle, across eastern France, northern Switzerland and southern Germany. The Mesozoic cover, comprising mainly Jurassic rocks in the outer zone and Jurassic with some Cretaceous in the inner, has slumped over Keuper (Triassic) formations and even been overthrust over the Rhône–Saône Rift by up to 25 to 30 km. The range consists of successive zones of folds and plateaux. The Middle and Upper Jurassic and the Lower Cretaceous are mainly limestones with a few interbedded clay layers; the calcareous sequences can be thicker than 1500 m. Separate aquifer basins are formed by folds, faulted folds, overthrusts and transverse faults. Karstic systems are particularly well developed in the Jura, and give rise to significant springs. It is an area of upland karst where snow melt represents an important part of the recharge to the karstic systems.

The Po Basin lies to the south of the Alps between the Alps and the Apennines. It developed in late Miocene and Lower Pliocene times concurrently with the uplift of the two mountain ranges. Subsidence and infilling has continued to the present day. The sediments, which are over 1 km thick in many areas, are represented by glacio-fluvial, fluvial and deltaic deposits. They become coarser and hence more permeable towards the top. The entire sequence actually forms a single aquifer complex but at depth the groundwater is saline. The transmissivity is of the order of 10^{-3} to 10^{-1} m^2/s. In the past excessive abstraction has caused significant ground settlement as well as saline intrusion in the coastal zone. These problems and particularly the risk to Venice, led to a very positive management programme for groundwater development which has alleviated the worst effects.

The Pyrenees extend from the Bay of Biscay to the Mediterranean. The tectonic movements that led to their creation began in Cretaceous times but developed particularly in Eocene times. The Ebro Basin is a foredeep of the Pyrenees infilled by thick continental deposits. Basically, the mountains comprise an inner axis of Palaeozoic rocks and large batholiths, two Internal Zones, to the north and south, of Mesozoic and Cenozoic rocks with ancient cores, and then two External Zones, or marginal zones, of thick late Mesozoic and Cenozoic sediments which are less intensely folded (Ager 1980). The Jurassic and Cretaceous rocks are principally carbonates although Cretaceous sandstones are prominent on the Spanish side. Karstic features are well developed and the Pyrenees include many deep and extensive limestone conduits. Glacial and fluvial deposits provide small but nevertheless important aquifers in these mountains.

Major rift valleys

The dominant rift system in western Europe is the Rhine–Rhône–Campidano Rift or Graben extending from north Germany through France and into Sardinia (Fig. 2). The Upper Rhine Graben splits near Frankfurt into the Hesse Depression and the Lower Rhine Graben which runs north-west below Tertiary cover to link with the Central North Sea fracture system. From the southern end of the Upper Rhine Graben the structure sidesteps to the southwest, possibly because of a transform fault, into the Rhône–Saône Trough which appears to continue as the Campidano Rift in Sardinia (Ager 1980). This extensive rift system is of considerable significance hydrogeologically.

The Rhine Graben is 300 km long and 30 to 50 km wide. As a result of faulting that began in Eocene times,

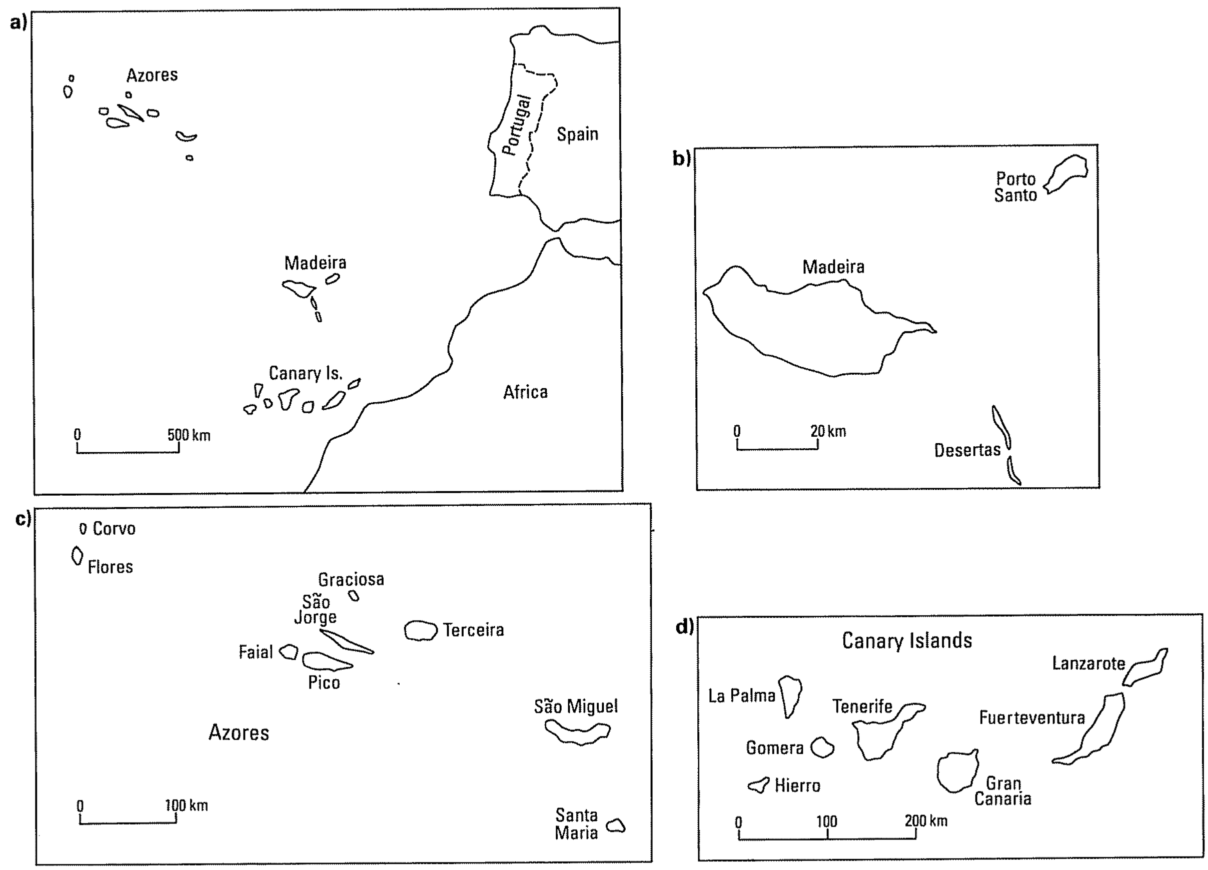

FIG. 10. Atlantic volcanic archipelagos: (a) general location, (b) Madeira and adjacent islands, (c) Azores, (d) Canary Islands.

the Hercynian basement is now covered by 1 to 3.4 km of sediments, including Oligocene evaporites up to 2000 m thick which provide for the potash mines of Alsace. The upper part of the sequence is represented by Quaternary fluviatile gravels and sands up to 250 m thick which have transmissivities as high as 0.1 to 0.5 m^2/s and represent an important aquifer.

The Rhône–Saône Rift is a structural depression, 30 to 60 km wide, between the Massif Central, the Jura and the Alps. Although it is of Tertiary origin it contains a complex sequence of Mesozoic to Quaternary rocks. In the Bresse Plain, to the north of Lyon, water-bearing formations are only found in Miocene sands, 80 m thick, overlain by thick lacustrine Pliocene clays. South of Lyon, the Miocene is a molasse deposit up to 600 m thick developed at the margin of the Alpine zone. It is overlain by a thick Pliocene clay deposited in a gulf between Lyon and the present coastline. The Quaternary alluvial deposits represent significant aquifers at only a few locations, as near Lyon. Between Valence and the coast the Rhône Rift intersects the wide sedimentary Sub-Alpine Basin.

In Sardinia the Rhine–Rhône Rift is considered to continue as the Campidano Rift which is infilled with early Tertiary to Quaternary sediments that provide an aquifer some 200 m thick.

On the northern side of the Massif Central the basement is faulted down to depths of up to 2000 m in the two Limagnes rifts. They are infilled with detrital and lacustrine sands, arkoses, marls and limestones mainly of Oligocene age. This multi-layered aquifer is known particularly for providing mineral water and the natural discharge of carbon dioxide.

Groundwater in the Atlantic volcanic archipelagos

The Atlantic volcanic archipelagos of the Canaries, Madeira, the Azores and the Salvagems—the uninhabited islets between the Canaries and Madeira—are high volcanic cones, either isolated or in groups, rising from the deep ocean floor (Fig. 10). The only exceptions are Fuerteventura and Lanzarote, the easternmost Canary

Islands, which rest near the African continental shelf, at a relatively short distance from the coast. The Canaries are the largest and most populated islands of the archipelagos and also those receiving the least precipitation because of their proximity to the high atmospheric pressure area of the Sahara. Fuerteventura and Lanzarote receive less than 150 mm/a, and less than 100 mm/a in some areas. Some of the islands are very high, as for example Tenerife, which attains 3700 m above sea level from a submarine base more than 3000 m deep. Slopes may be as steep as 0.5 which explains the large landslides produced over geological time. The high islands cause an intense orographic effect on the NNE trade winds and as a consequence the northern slopes receive a higher rainfall (up to 1000 mm/a) than the southern coastal areas (less than 200 mm/a in the Canaries). The orographic effect is not evident when the altitude is less than 800 m, as in Lanzarote and Porto Santo.

All the islands are entirely of volcanic origin except for some alluvium and raised coastal deposits, in which volcanic rocks predominate, and minor, occasional calcarenites. The volcanism is mid-Miocene to Recent in age with historical eruptions in some islands. In the 18th century, Lanzarote had the largest, documented, single volcanic eruption in historical times, in terms of both the volume of tephra and lavas and the duration of the eruption, although the eruption was relatively quiescent. Some islands rest on an old complex of submarine and metamorphosed volcanic rocks but others are entirely formed above sea level by recent volcanic formations. On São Miguel, in the Azores, 3 MW of electrical energy are produced by a power station using geothermal energy.

The hydrogeological characteristics of these volcanic rocks vary over a very wide range. Young brecciated lavas are very permeable but are often dry since they generally occur at high elevations except near the coast where they contain sea water, that is sometimes used to supply clean, saline water for desalting plants. The permeability may be greater than 10^{-2} m/s and some wells yield 500 l/s for only small drawdowns. The older the material, the lower the permeability, especially in the case of brecciated lavas, pyroclasts and ashes. Old (Miocene) formations are commonly aquitards but they may contain permeable features linked to dykes and the associated fissures, as well as consolidation fractures, and distorted lava joints. Dykes behave as barriers to flow or act as preferred flow paths depending on the circumstances. Overall the mean permeability is typically between 10^{-7} and 10^{-5} m/s. Metamorphosed old volcanic rocks and exhumed, old magmatic chambers are practically impervious and are able to support the high dams that retain water reservoirs, as in Gran Canaria.

Generally there is a high dome of groundwater, with a low turnover time, in the old volcanic rocks that form the cores of the islands. Often this water is a high sodium-bicarbonate type due to the alteration of the rocks by CO_2 derived from the slow degassing of magmatic chambers. Recharge mostly flows through the cover of younger volcanic rocks and appears as springs and seepages where the cover thins out, or discharges at the coast if the permeable cover is thick. When the volcanic rocks are young and lacking a significant old core, a freshwater body floats on the saline groundwater. The salinity of airborne moisture particles has a significant effect on groundwater salinity. In areas of high rainfall, the chloride content of recharge is 15 to 50 mg/l, but where the climate is dry and recharge is small (less than 10 mm/a) the groundwater is saline (more than 1 g/l and up to 5 g/l).

In many of the islands, groundwater exploitation is limited to the development of springs, supplemented by wells, rain-fed cisterns and, in some cases, reservoirs that collect surface runoff. In other islands springs are rare or too small where the young volcanic cover is thick enough to carry the recharge to the coast (for example on El Heiro, one of the smaller Canary Islands, and some of the islands of the Azores) or recharge is small due to aridity (Fuerteventura and in the south of Gran Canaria). In these situations wells have been drilled but with variable success because of low yields, or the production of brackish or saline water, or because they are not deep enough.

In most of Gran Canaria and in Tenerife the situation is quite different. Intensive agricultural development over the last 100 years has led to extensive groundwater exploitation, commonly by traditional deep, large diameter wells in Gran Canaria and 1 to 6 km long galleries (water mines) in Tenerife, which penetrate into the low permeability island cores, in some cases up to 1000 m below the ground surface. Because of the high elevation of many of the wells and galleries, they preferentially tap the groundwater storage. As a consequence most of the springs and small rivers have disappeared. Although abstraction does not exceed the recharge the drawdown of the water table is up to 10 m/a in some areas and the total decline is up to 400 m. This is due to long-term hydraulic drainage. Generally, at least some permeability exists in the upper 100 m of the sequence and at some locations at even greater depths. The permeability depends on the age, the degree of internal weathering and the type and nature of the rock. Yields from wells and galleries vary over a wide range, from almost nil (a fraction of a litre per second for 300 m penetration with maximum drawdown) to 450 l/s from a gallery in Tenerife. Typical large diameter wells, with long horizontal drains at the base, yield 1 to 20 l/s. Deep machine-drilled wells yield 0.5 to 10 l/s and water galleries produce 0.5 to 50 l/s. Such yields are commonly transient and their maintenance requires periodic redrilling in areas away from the coast. Obviously there is a limit to this process.

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