



# The Development of Landscapes in Germany

# 1.1

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## Abstract

The landscapes of Germany cover a wide range of diverse landform assemblages which evolved due to differences in environmental and geological boundary conditions and Quaternary glacial and periglacial processes. These are listed from north to south in: (I and II) The Northern Lowlands with its young and old glacial landforms and coastal areas, (III) The Central Uplands, (IV) The Rhine Rift Valley and the South German Scarplands, and (V and VI) The area of the Alpine Foreland and the Alps. The Northern Lowlands are built of Quaternary deposits including Pleistocene glacial and fluvial-glacial deposits, aeolian sands and loess deposits and Holocene alluvial and colluvial deposits, mires and marshes, barrier islands and the tidal flats of the wadden sea. The landforms of the Central Uplands have developed in a complex lithological and structural setting, which results from different phases of sedimentation and tectonic deformation from the early Palaeozoic to the Quaternary. In the southwest, the Mesozoic rocks of the Central Uplands dip below the Cenozoic rocks of the Alpine Foreland which is covered by Cenozoic sediments ranging in age from the Paleogene to the Quaternary. The Quaternary is characterized mostly by glacial and fluvio-glacial deposits. In this area the contact of the horizontal and the upfolded Cenozoic Molasse sediments marks the tectonic transition to the Alps. The southernmost part of Germany includes the Northern Calcareous Alps. Examples from all regions are given in the following chapters of this book.

## Keywords

Landscapes of Germany · Geomorphology of Germany · Late Pleistocene landscapes of Germany

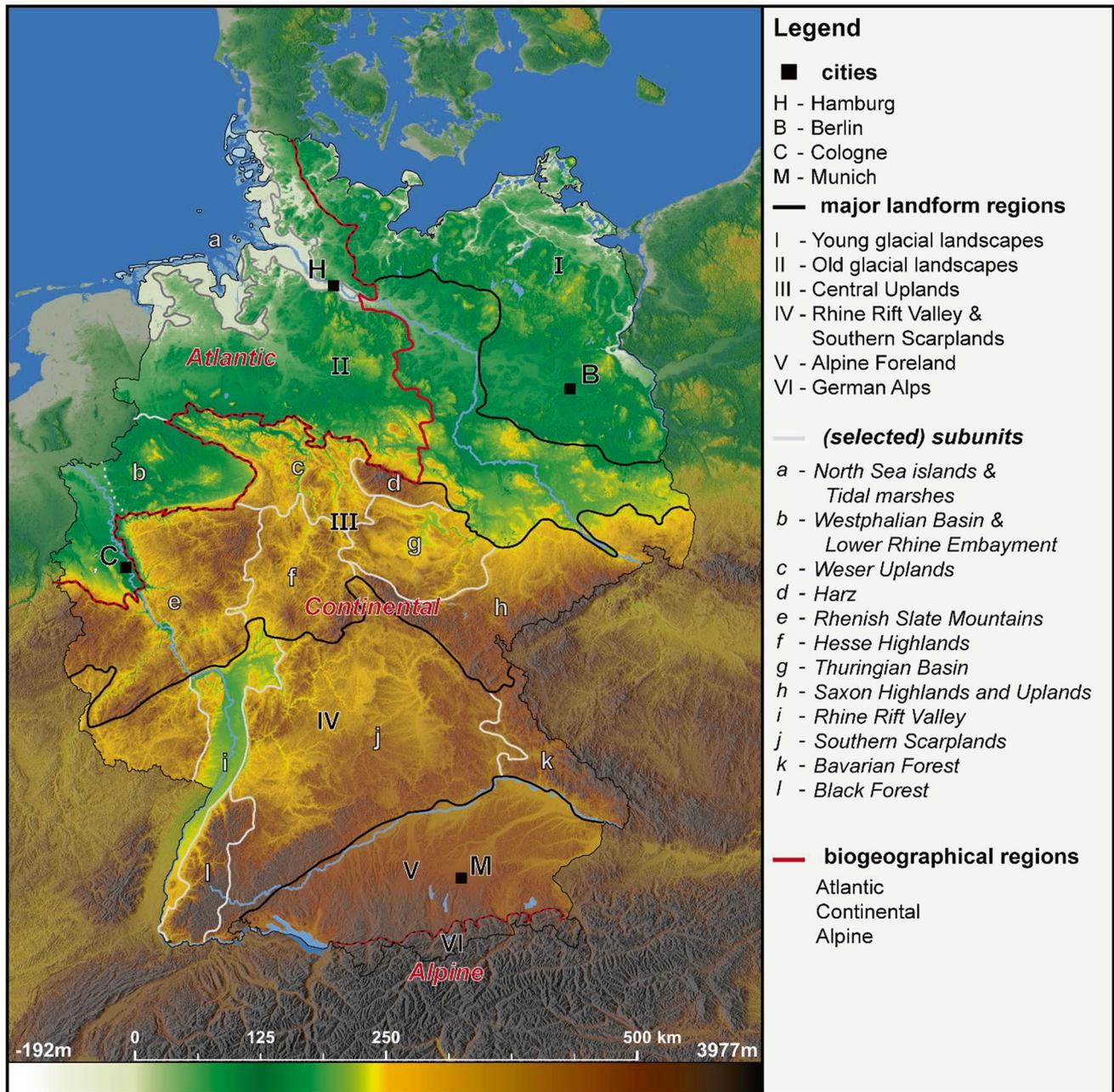
## 1.1.1 Introduction and General Approach

Landscape development, the processes, and physical geography of Germany were presented by Liedtke and Marcinek (2002) and, subsequently, in two volumes describing the northern (Böse et al. 2022) and southern (Eberle et al. 2023) parts of Germany. Additional summaries and an overview were provided by Glaser et al. (2007) and Zöller (2017). The first book on landscapes and landforms in Germany was edited by Frank Ahnert in 1989 as Catena supplement on the occasion of the 2nd International Conference on Geomorphology in Frankfurt (Ahnert 1989). As that work was done before the reunification of Germany, only contributions from Western Germany were included.

## 1.1.2 Geology and Regional Classification of Natural Landscapes

The geology especially the Quaternary geology of Germany is diverse and responsible for different landscapes in Germany. The geomorphology of Germany exhibits a roughly sixfold division of major landscape types. These are arranged from north to south in the Northern Lowlands with their young and old glacial landforms and coastal areas (see Figs. 1.1 and 1.2; Part II), the Central Uplands (Part III), the Rhine Rift Valley and the South German Scarplands (Part IV), and the area of the Alpine Foreland and the Alps (Part V and VI) (Ahnert 1989; Fischer 2002; Habbe 2002). The Northern Lowlands are built of Quaternary deposits including Pleistocene glacial and fluvial-glacial deposits,

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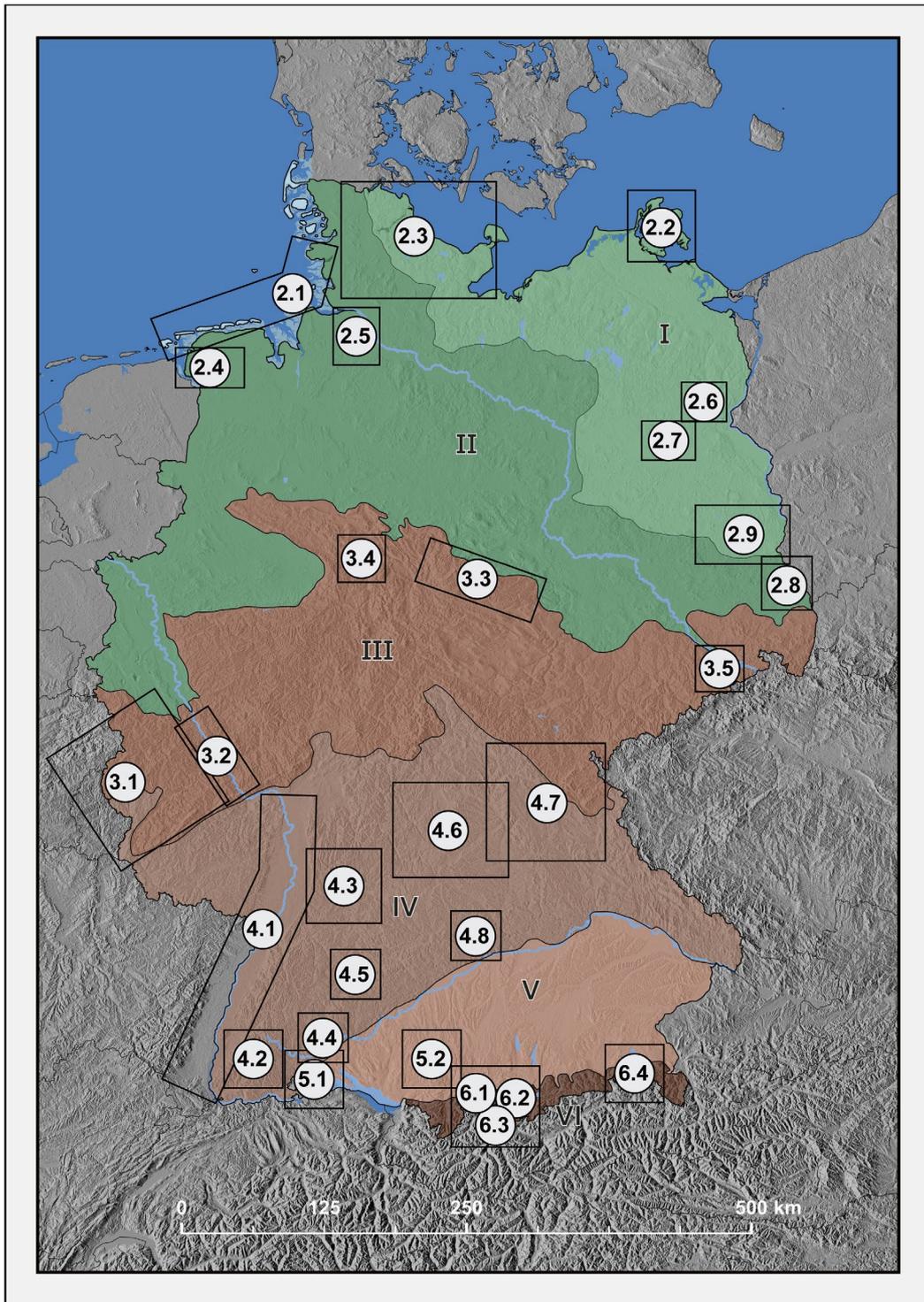


**Fig. 1.1** Relief based on SRTM data. Data source CGIAR-CSI (2018), Eurostat (2021), EEA (2023). The three main biogeographical regions based on BFN (2011) and Ssymank (1994)

aeolian sands and loess deposits and Holocene alluvial and colluvial deposits, mires and marshes, and the tidal flats of the Wadden Sea and islands. In the Central Uplands which are located roughly between Düsseldorf and Hanover in the west, Halle and Görlitz in the east, and the Danube valley in the south, landforms have developed in a complex lithological and structural setting, which itself is the outcome of different phases of sedimentation and tectonic deformation since the early Palaeozoic to the Quaternary (Ahnert 1989; Henningsen and Katzung 2002). In the southwest, the Mesozoic rocks of the Central Uplands dip under the

Cenozoic rocks of the Alpine Foreland which is covered by Tertiary sediments and Quaternary glacial and fluvio-glacial deposits. Here the contact of the horizontal and the upfolded Tertiary Molasse marks the tectonic transition to the Alps. The southernmost part of Germany includes the Northern Calcareous Alps (Nördliche Kalkalpen).

The geological setting of Germany owes its complex structure to three major orogenic phases encompassing the Caledonian, Variscan, and Alpine orogenesis (Figs. 1.3 and 1.4) (Meschede 2018). The oldest rocks in the deeper underground of the Northern Lowlands are metamorphic

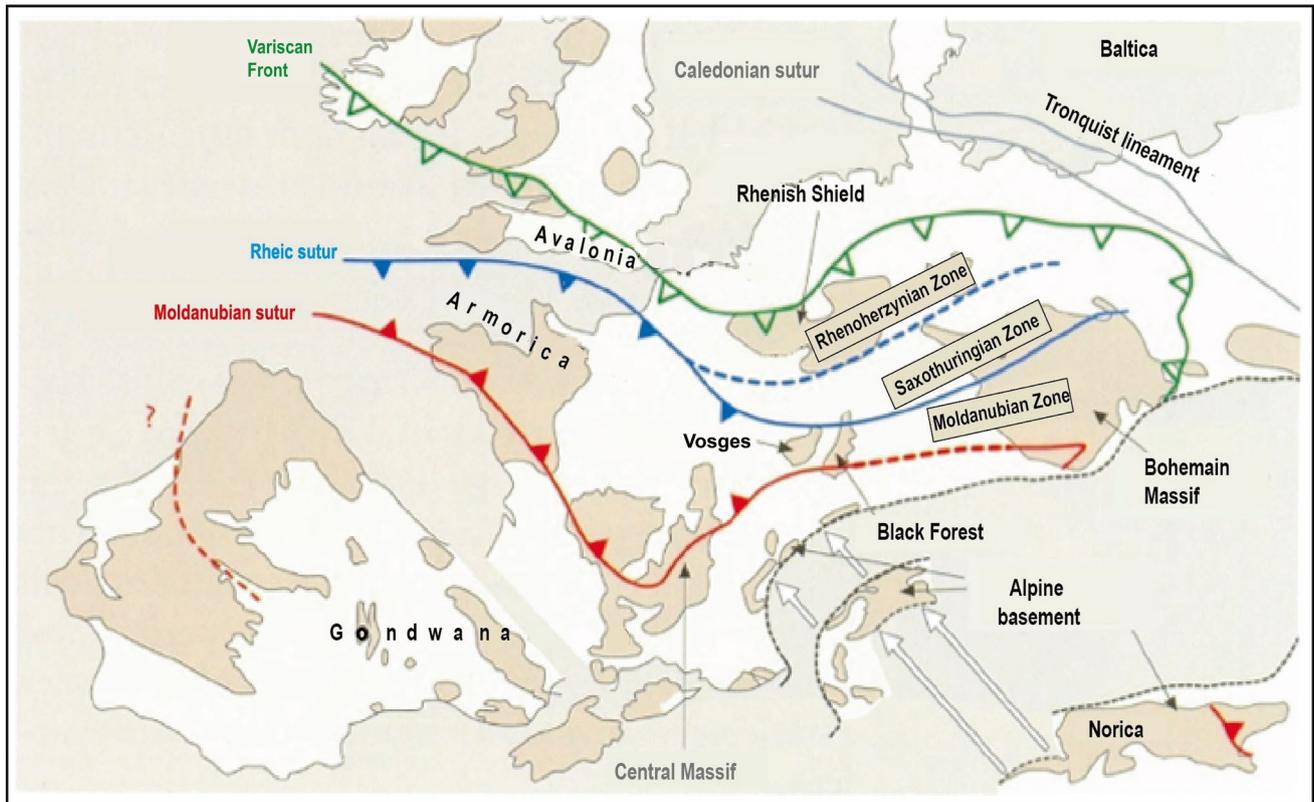


**Fig. 1.2** The major landform regions of Germany. I, II: The North German Lowland (I: Young glacial landforms; II: Older glacial landforms); III: The Central Uplands; IV: The Rhine Rift Valley and

Southern Scarplands; V: The Alpine Foreland; VI: The German Alps. Data source Glaser et al. (2007), BFN (2011), CGIAR-CSI (2018). Numbers indicate the detailed regions published in this book

(gneisses, schists, and slates), formed from sedimentary, volcanic, and plutonic rocks. These rocks range in age from the Precambrian to the early Palaeozoic and were part

of the terrain Avalonia which accreted with Baltica during the Caledonian orogenesis (Fig. 1.3) (Meschede 2018). Exposures of these rocks are only found in the Hohe Venn



**Fig. 1.3** Plate tectonic reconstruction of the European basement (modified according to Frisch and Meschede 2021)

of the Eifel/Ardennes (Walter et al. 1992). The second major orogenesis was Variscan which occurred in the late Palaeozoic time and involved large parts of Armorica, a terrain complex consisting of different tectonic units (Meschede 2018). During this orogeny Gondwana and Laurussia (Old Red Continent) accreted, forming thereby the supercontinent of Pangea. The accretion resulted in a broad chain of folded mountain ranges which extended in Europe from the Sudetes in Poland through Germany, Belgium, Luxembourg, France, to Spain and southwestern England and Ireland. In Germany, the Variscan mountain chain was worn down from the uppermost Carboniferous to Permian (Ahnert 1989; Walter et al. 1992). Denudation created a landscape with subdued relief, which in the geological record is often represented by an erosional unconformity. The fossil denudation surface is also an important structural boundary. This boundary separates the highly deformed Variscan basement from a less deformed cover of Mesozoic rocks (Ahnert 1989). During the Permian time, downfaulted graben structures, troughs, and valleys were filled with sediments. Important deposits are among others the Upper Permian (Zechstein) salt series (Reinhold and Hammer 2016). Figure 1.5 shows the distribution of the major geological units.

Relatively little is known about the landscapes in the early and middle Mesozoic. In some areas the rocks of the

Variscan basement were covered with several hundreds to thousands of metres of Mesozoic rocks (e.g., in Harz), while in other areas the basement rocks remained exposed, presumably forming a low-elevation landscape with subdued relief and a thick weathering cover (e.g., Rhenish Slate Mountains). However, in the late Cretaceous plate tectonic movements in the area of the Alps produced a new stress field in Central Europe. The transmitted stresses resulted in uplift and subsidence of some areas and were associated with warping, faulting, and folding of the Mesozoic rocks and reactivation of older faults and zones of weakness, as well as with tilting along new and old faults of the old, more rigid Variscan basement (Meschede 2018; Rothe 2005) (Fig. 1.6).

During the Cenozoic time, the collision between the African plate and the Eurasian plate created a fold mountain range with intense nappe tectonics. Several nappes of the Alps moved from the root zone towards the north and produced a complex nappe pile. In Germany, the Northern Calcareous Alps, which consist to a great share of Permo-Mesozoic limestones and dolomites, are part of the East Alpine nappe pile. The northward movement of the nappes of the Alps caused also some deformation of Cenozoic sediments that were deposited in the north of the uplifted mountain range (Rothe 2005). Tectonic stresses resulted in

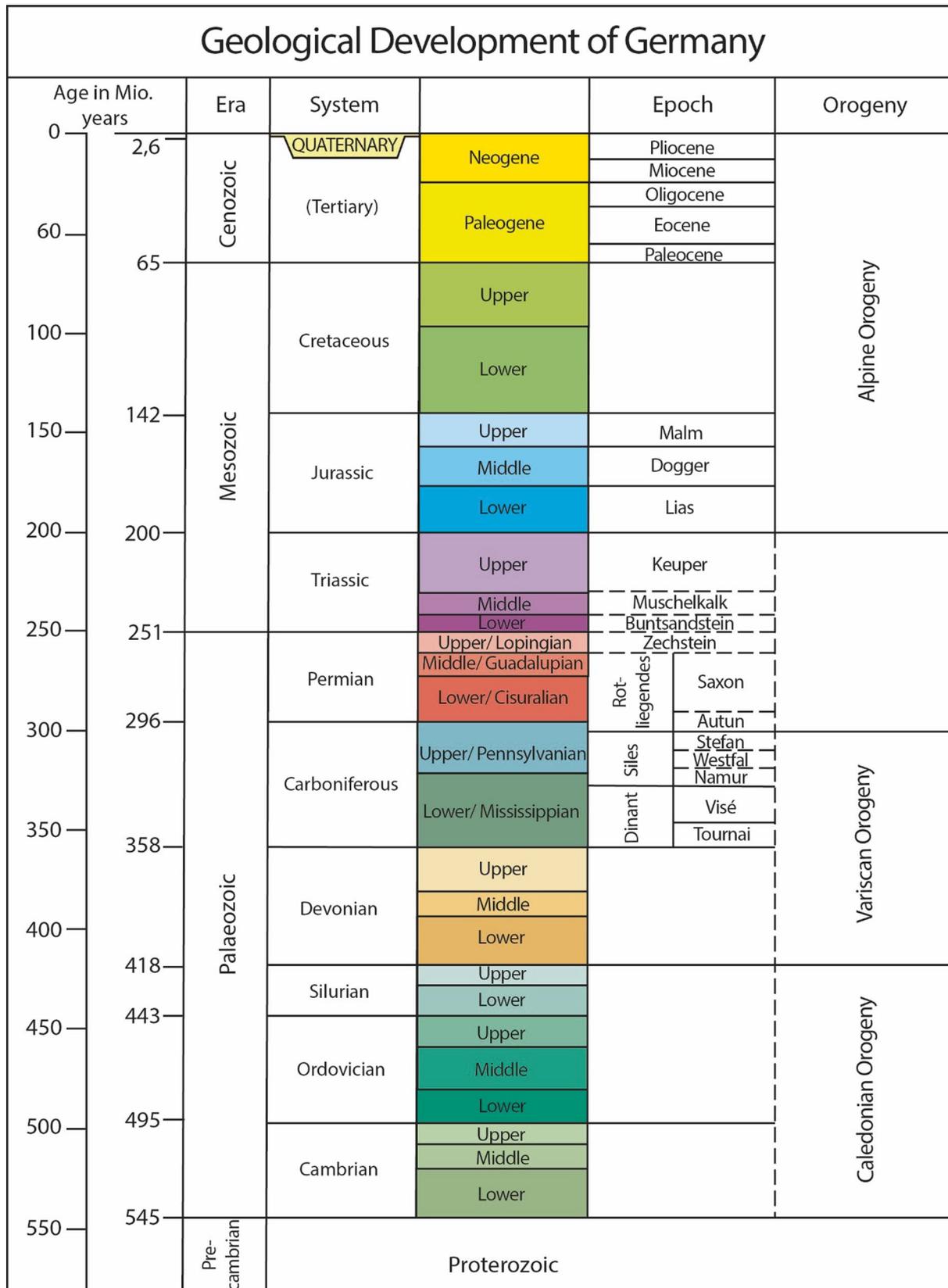
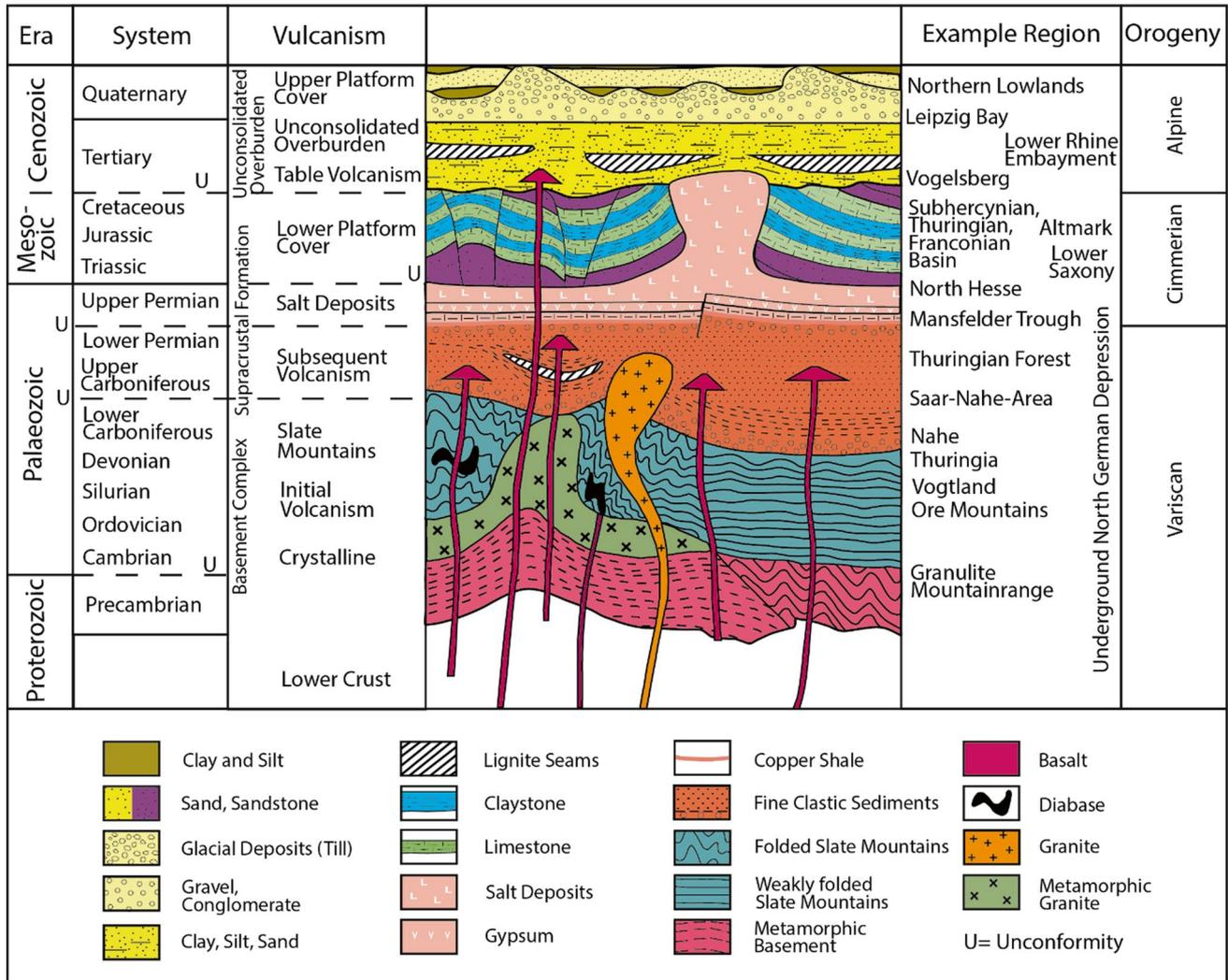


Fig. 1.4 Stratigraphic timetable (modified after International Commission on Stratigraphy 2023)

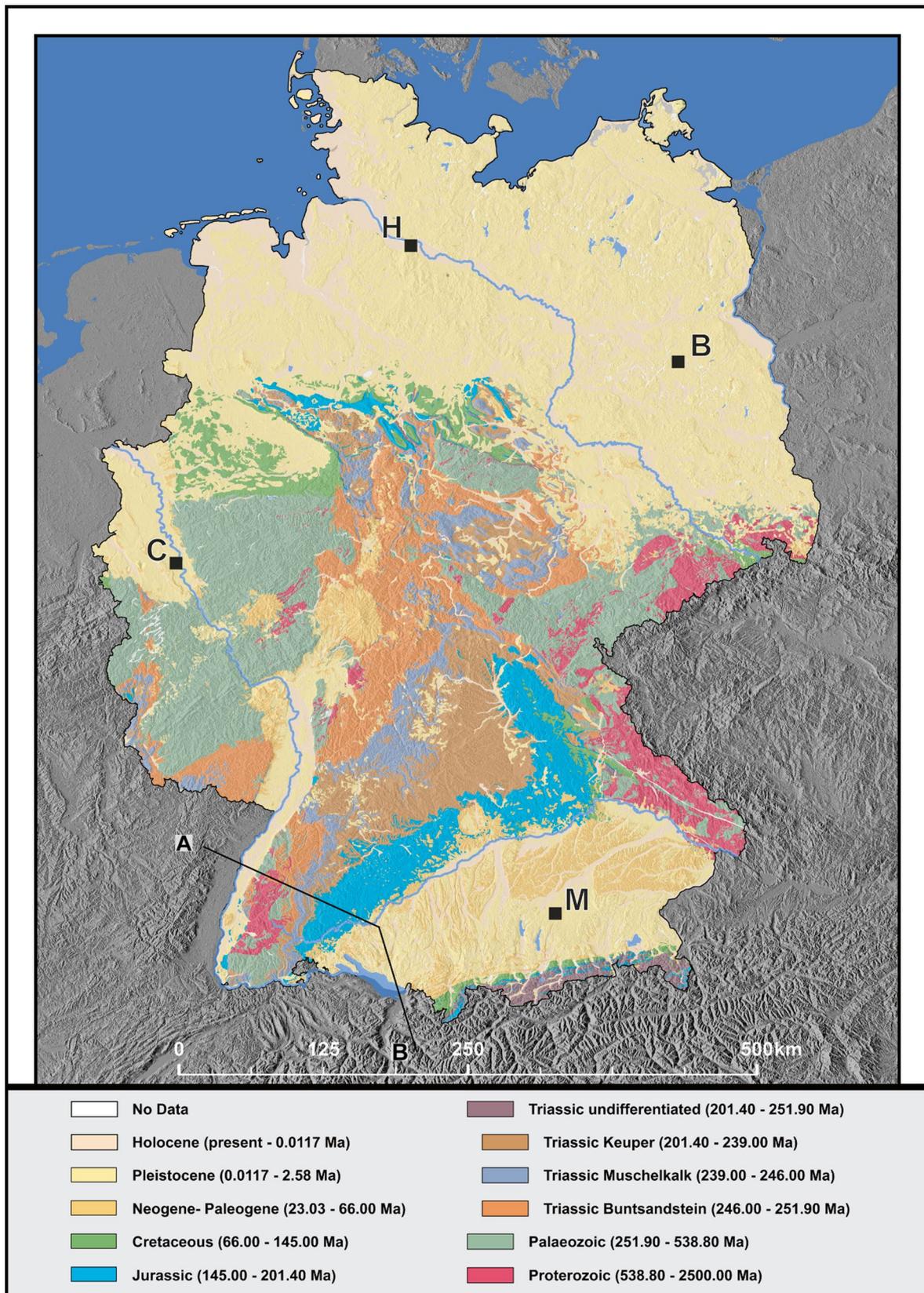


**Fig. 1.5** General geological scheme of the German lithostratigraphy and major orogenesis. Modified according to Böse et al. (2022)

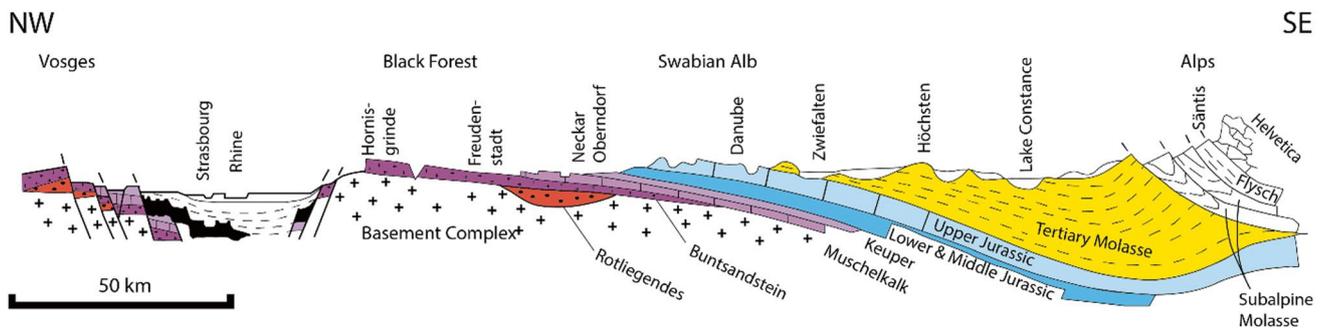
further uplift of old mountain blocks such as the Rhenish Slate Mountains and the Harz, and in the development of Paleogene and Neogene volcanic fields. In addition, they contributed to the development of large graben and rift structures such as the Upper Rhine Graben (Meschede 2018; see Fuchs 2025, Chap. 4.1). The latter is part of the European tectonic graben system starting in the Rhone graben in the south and continuing north of the Upper Rhine Graben in two branches in a Y-structure with the largest volcano of Germany, the Vogelsberg in Hesse, just in the centre (Fig. 1.10). While the western branch of this tectonic system continues in the Lower Rhine Embayment and the North Sea, the eastern branch follows the graben and depression structures in Hesse and Lower Saxony (the Hesse depression and the Leine Valley Graben). This structure ends in Norway with the Oslo-Mjøsen Zone. In Southern Germany, these movements caused an east-tilting of the Mesozoic strata and uplift of mountain blocks

along marginal faults of the Rhine graben such as the Black Forest, Odenwald, and Spessart. This resulted in the development of the South German Scarplands (Part IV). Figure 1.7 represents a profile from the western shoulder of the Upper Rhine Graben (Vosges) to the cuesta landscape in the southeast, and further on to the Danube, the Alpine (Molasse) foreland, and Northern Calcareous Alps in the southernmost part. Jurassic limestones of the Franconian Alb and Swabian Alb form the most prominent cuestas in Southern Germany.

Neogene sea-level changes which were associated with regional marine transgressions left thick deposits particularly in the northern parts of Germany. Regressions were repeatedly associated with the development of coastal forests, the material for later lignite (Walter et al. 1992). Thus, the Tertiary represents the time of the development of several important structural outlines of the German landscapes. Gerwin et al. (2023) provide a summary and overview on



**Fig. 1.6** Geology of Germany. The cross-section A–B is shown in Fig. 1.7. B = Berlin, C = Cologne, H = Hamburg, M = Munich. *Data source* BGR (2003), CGIAR-CSI (2018)



**Fig. 1.7** Geological cross-section from the Vosges (A) to the Alps (B). For the location (A–B see Fig. 1.6). Modified from Geyer and Gwinner (1991)

the ongoing lignite mining in the Lower Rhine Embayment and Lusatia (Lausitz). An example of the transformation of an old morainic landscape by numerous opencast lignite mines into the present-day anthropogenic lakelands is given by Böse and Hardt (2025, Chap. 2.9).

In the Quaternary, tectonic movements resulting from the ongoing uplift of the Alps, and marked alternations of climatic conditions caused significant changes in landscape dynamics. Important geomorphological changes were associated with the advance of ice sheets during the Mid- and Late Pleistocene. In the Northern Lowlands of Germany, the ice sheets of the Elsterian glaciation advanced with ice lobes reaching to as far as Erfurt-Weimar and the Lusatian Mountains, while the Saalian ice lobes advanced in Western Germany as far south as Düsseldorf. During the last glacial cycle in the Late Pleistocene, the ice sheets (the Weichselian glaciation) reached only to Brandenburg and Schleswig–Holstein (Ehlers 2020). The glaciations transformed most of the Northern Lowlands and left behind glacial and fluvio-glacial deposits, basins filled with lakes, ice-marginal valleys, aeolian sands (Chaps. 2.3, 2.6, 2.7 and 2.8; Stolz 2025; Lüthgens 2025; Hardt 2025; Kupetz 2025), and - along the northern margin of the Central Upland - loess deposits (Lehmkuhl et al. 2016, 2018). Non-glaciated regions became subject to periglacial conditions (Marcinek et al. 2002). In Southern Germany, alpine glaciations caused the development of glacial landforms such as trough valleys, arêtes and horns, cirques, and roche moutonnées in the central parts of the Alps, while in the foreland glacial erosion resulted in the development of proglacial lakes (Fischer 2002; Habbe 2002). Depositional features include glacial and fluvio-glacial deposits and aeolian sands and loess. The Central Uplands remained mostly unglaciated. A few exceptions with local glaciers and ice caps are the Black Forest (Hofmann 2025, Chap. 4.2), Bavarian Forest (Mentlík et al. 2013; Raab and Völkel 2003), and the Harz Mountains (Klinge 2025, Chap. 3.3). Climate change and regional uplift during the Pleistocene also resulted in the development of several river terraces along the major rivers.

A prominent example is the terrace staircase in the middle Rhine valley (Böse et al. 2022; Fischer et al. 2025, Chap. 3.2). During the Pleistocene, volcanic activity started again in the Eifel and in the Eger Graben. The youngest phase of volcanic activity is characterized particularly by maar volcanoes and in the Eifel by maar volcanoes and scoria cones (Hofbauer 2016). The Eifel has more than 98 maars and maar-like volcanoes. Most of these are filled with aeolian and fluvial deposits and are termed dry maars. The youngest volcanic eruption is represented by the Ulmener Maar which appears to have been formed in the last 11,000 years (Hofbauer 2016) (see Zöller and Lehmkuhl 2025, Chap. 3.1).

Among the youngest landform complexes in Germany are the coasts (e.g., Chaps. 2.1, 2.2 and 2.5; Hadler et al. 2025, Gehrmann and Hoffmann 2025; Grube 2025). At the North Sea, these include marsh lands and barrier islands. Their development started at the end of the Pleistocene and extended into the Holocene. The coast of the Baltic Sea has been mainly shaped in glacially remoulded deposits and, partly, in Cretaceous chalk. During the Holocene marine erosion contributed to the development of steep cliffs while glacially formed embayments became transformed by nearshore currents. Longshore currents transporting eroded material from cliffs and beaches formed spits and bars, which are still very active. In many places, they connect higher elevated glacial deposits such as in the Bodden coastal area of northeastern Germany (see Gehrmann and Hoffmann 2025, Chap. 2.2).

### 1.1.3 Quaternary Climate Change: Glaciations and Periglacial Landscape Transformation

The six main landscape regions (Fig. 1.3) were strongly shaped during the Quaternary due to the lowering of the temperature and the onset of cryogenic (periglacial and glacial) processes. Ice advances since the Mid Pleistocene

covered huge areas in Northern and Southern Germany. Regions I and II in Northern Germany are composed mostly of glacial and fluvioglacial deposits which originated in the southwestern sector of the Scandinavian Ice Sheet (SIS). They reached the margins of several areas of the Central Uplands (Region III) during the Mid-Pleistocene (Fig. 1.8). For example, the inland ice of Elsterian and Saalian periods extended into the Weser Uplands (Weserbergland; cf. Fig. 3.4.9, indicated by glaciogenic sands in the north of Freden) (Römer 2025, Chap. 3.4). It also advanced to the northern margin of the Rhenish Slate Mountains and overrode the lower parts of the Harz Mountains (Fig. 1.8). In some areas, such as in the Leipzig Bay or in the Westphalian Basin (or Münsterland Embayment), vast proglacial and ice-dammed lakes were formed. Meinsen et al. (2011) provided evidence for a large outburst flood towards the North Sea during the collapse of the Saalian ice sheet. Deep glaciotectonic disturbances, involving also Neogene deposits, formed outstanding end-moraine ridges like the Muskau Arch (Muskauer Faltenbogen) (Kupetz 2025, Chap. 2.8).

Between 32 and 20 ka, the SIS in Northern Germany reached its maximum extent during the last glacial cycle (Böse et al. 2022; Lüthgens et al. 2010; Lüthgens and Böse, 2012). The ice advanced towards the central parts of Schleswig–Holstein (see Stolz 2025, Chap. 2.3), reaching almost the Elbe River thereby covering the northern parts of Hamburg and the Berlin city (Hardt 2025, Chap. 2.7; see Fig. 1.7). A prominent boulder-rich end-moraine of the Pomeranian phase of the Weichselian glaciation and the related fluvioglacial morphology is described by Lüthgens 2025 (Chap. 2.6). In Eastern Germany, the southward advance of glaciers towards the more elevated areas resulted in a reorientation of the south-to-north flowing rivers. Rivers which formerly drained into the Baltic Sea were diverted towards the northwest and drained into the North Sea. The redirection of rivers was associated with the development of wide fluvial systems (ice-marginal valley or glacial spillway=Urstromtal; see Fig. 1.8). The extent of the ice margins differed markedly. Since the Mid-Pleistocene, several of these river systems received vast amounts of meltwater from the ice sheets in the north and were also fed by rivers originating in the uplands, developing huge glacial spillways running more or less parallel to the front of the ice margins. In Northern Germany, these glacial spillways are trending southeast-northwest and were draining towards the North Sea basin. Since the late Glacial time, another reorganization of the river networks in the central and eastern parts of Germany has occurred. Only some sections of the ice-marginal valleys are now used by small rivers and the river Oder is again flowing to the Baltic Sea.

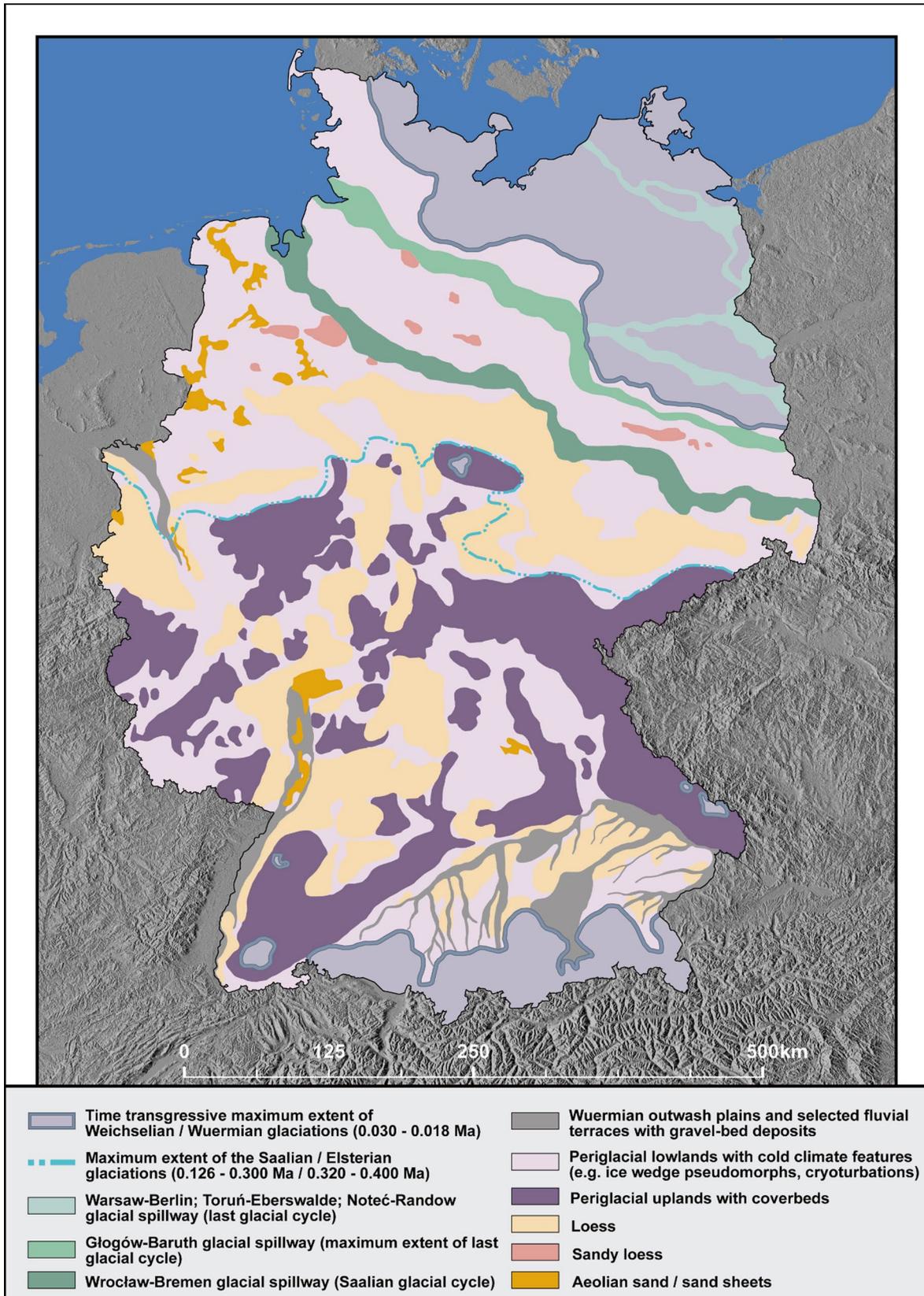
In addition, aeolian deposits appeared with the onset of the ice age. Silt and sand-sized particles were produced

mostly by glacial grinding and periglacial weathering. They were transported and deflated from wide braided river systems and exposed shelf areas. Especially the wind-blown dust was accumulated as loess deposits in several regions of Germany. Regarding its geography, the loess distribution in Germany follows a specific pattern (Lehmkuhl et al. 2018) which includes (1) The northern Central European loess belt in the north of the German Uplands (e.g., the Rhenish Slate Mountains, Harz Mountains, Ore Mountains); (2) The Upper Rhine Graben (see Fuchs 2025, Chap. 4.1; Mächtle and Bubbenzer 2025, Chap. 4.3); (3) The basins of the German Uplands in central and southwestern Germany including several subregions (see for example in the Nördlinger Ries, Seybold and Hölzl 2025, Chap. 4.8), and the Kraichgau area; (4) Along the German stretches of the Danube River, mainly in the southern part of Bavaria. The distribution of these loess-landscapes in Germany is summarized in the mapping approach of Lehmkuhl et al. (2018) and (2021). The elevation of the loess cover increases from north to south from approximately 200 to 300 m a.s.l. up to about 600 m a.s.l. Orography is a controlling factor of temperature, and especially orographic barriers are controlling the precipitation patterns, which were influencing the distribution of loess and periglacial features. The distribution of sandy loess in Northern Germany displays a characteristic elevation below 200 m a.s.l.

The distribution of aeolian sand is displayed in Fig. 1.8. Large sand sheets including dune fields are covering vast areas of the Northern Lowlands, especially in the area of the older glacial landforms (Region II in Figs. 1.1 and 1.2). Smaller sand areas occur along large rivers, for example on the east side of the Rhine River (e.g., Upper Rhine Graben, Lehmkuhl et al. 2018, 2021; Fuchs 2025, Chap. 4.1). Periglacial sand dunes in the young glacial landscape are mainly located on terraces of the ice-marginal valleys and adjacent areas.

The mountainous Regions III and IV were strongly affected by periglacial processes during the glacial cycles. Periglacial morphogenesis included the development of periglacial debris and cover beds. In addition, asymmetric valleys formed due to different weathering intensities on west- and east-facing slopes. Small local valley glaciers, ice caps, and cirque glaciers developed in the highest parts of the Harz, the Black Forest, and the Bavarian Forest (cf. Klinge 2025, Chap. 3.3; Hofmann 2025, Chap. 4.2). In lowland regions, which were not covered by ice, cryogenic features affected and transformed the sediments. Examples are cryoturbations, ice wedge pseudomorphs, and patterned ground. These features provide information about the distribution of permafrost in Germany during the coldest periods of the Pleistocene.

Landscapes in the Central Uplands and in the South German Scarplands display a polygenetic development,

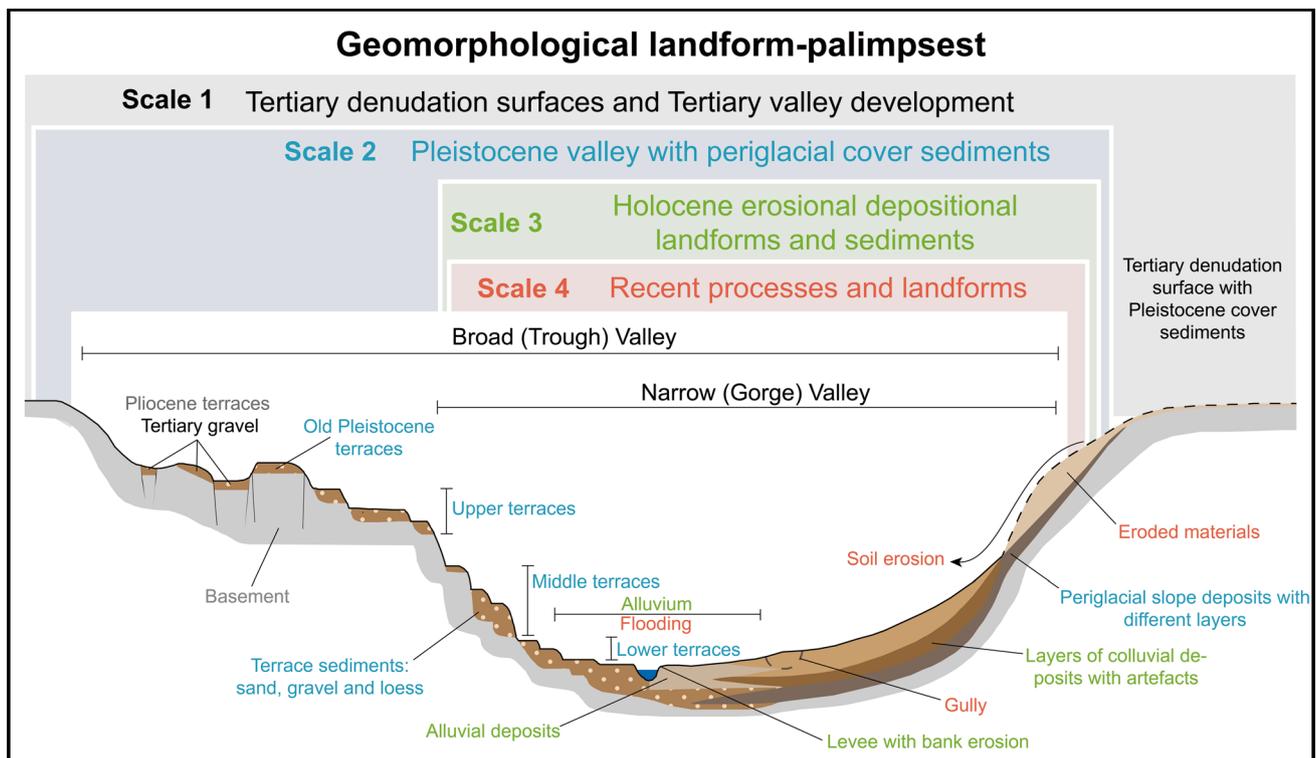


**Fig. 1.8** Landscapes of Germany during the last glacial cycle. *Data source* Liedtke (2003), Van Husen and Reitner (2011), CGIAR-CSI (2018), Lehmkuhl et al. (2018, 2021)

which has resulted in a nested hierarchy of landforms which have evolved at different times under different tectonic and environmental conditions and remained in the landscape due to their different sensitivity to change and recovery (Chorley et al. 1984; Easterbrook 1999). The nested hierarchy of landforms is interpreted as ‘relief generations’, which form a typical landscape palimpsest (Chorley et al. 1984). Ancient, large-scale landforms which were formed in the past are superimposed by younger or recent landforms evolved under different environmental conditions (e.g., Knight 2012; Dikau et al. 2020). In Germany it is possible to distinguish four polyhierarchical landforms as relief generations (Fig. 1.9): **Stage (1):** The development of Tertiary denudation surfaces cutting the different bedrocks, especially of the Variscan mountain areas (e.g., Rhenish Shield, Harz: Chaps. 3.1, 3.2, and 3.3, Zöller and Lehmkuhl 2025; Fischer et al. 2025; Klinge 2025). The development of these surfaces was associated with a long period (phase) of intense Late Mesozoic to Tertiary weathering (Mesozoic-Tertiary weathering mantles = Mesozoisch-Tertiäre Verwitterungsdecken, MTVs) and denudation of the Palaeozoic bedrock, e.g., in the slates and sandstones of the Rhenish Shield (e.g., Felix-Henningsen 1994; Semmel 1996). Weathering and denudation acted on a low-lying

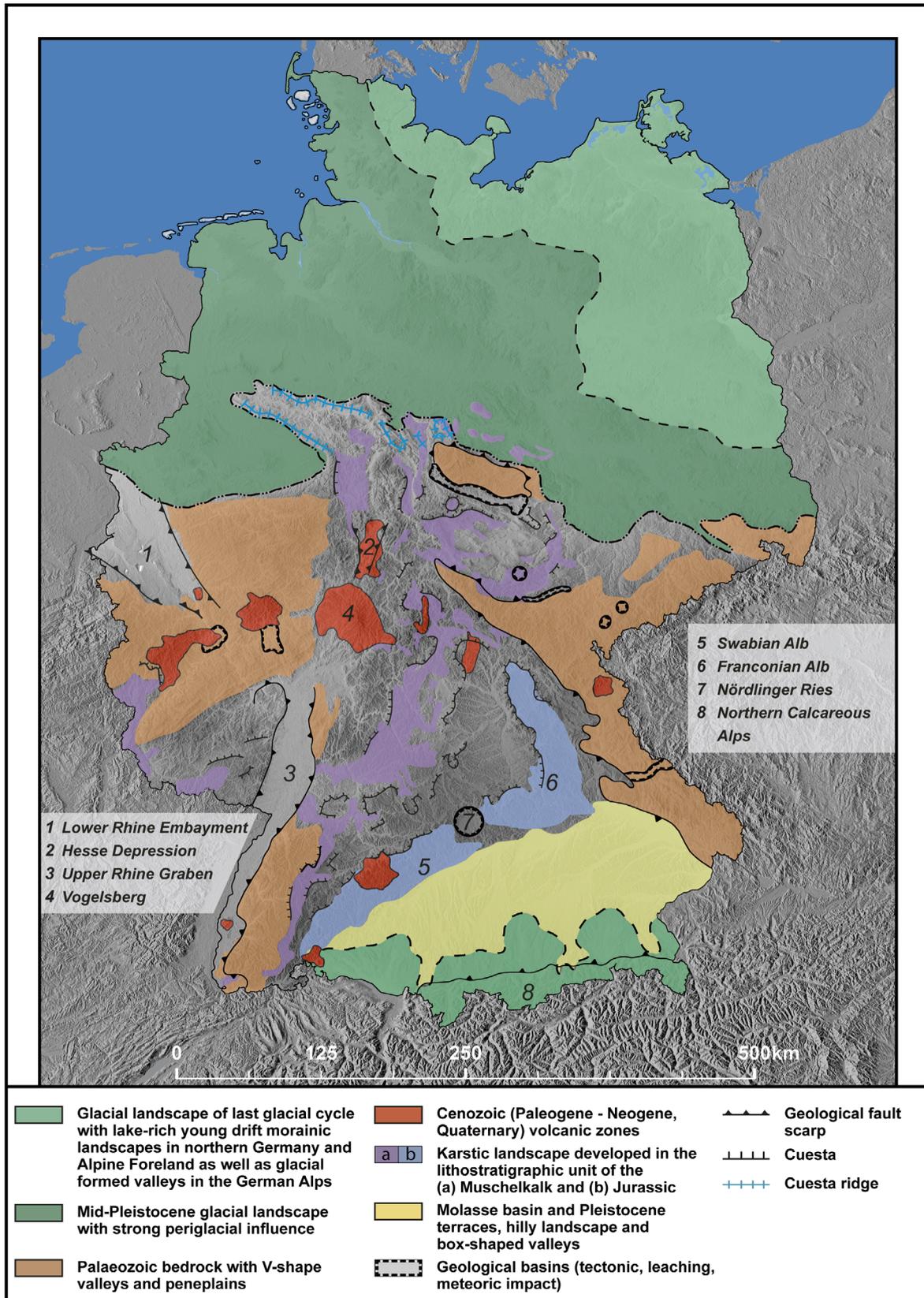
continental area under relatively stable tectonic conditions, which were presumably interspersed by only minor vertical crustal movements (Demoulin and Hallot 2009). **Stage (2):** The incision of broad valleys into the older denudation surfaces, triggered by modest tectonic uplift. **Stage (3):** Increased uplift and accelerated river incision resulted in the origin of narrow valleys concomitant with the development of the Pleistocene staircase of terraces under periglacial dynamics. **Stage (4):** Holocene and recent landforms and geomorphic processes, including the origin of floodplain and colluvial deposits and forms and materials associated with human intervention (right side of Fig. 1.9). The left side of the diagram in Fig. 1.9 represents the Middle Rhine Valley and is presented by Fischer et al. in Chap. 3.2, Fig. 3.2.2).

Regions V and VI (Fig. 1.2) were affected by the Pleistocene glaciations of the European Alps. Valley glaciers moved towards the alpine foreland creating vast foreland glaciers of Malaspina-type. Whereas in the west large outflow glaciers created the basin of Lake Constance, which drained towards the Rhine and upper Danube (Kamleitner et al. 2023), the meltwaters of the outflow glaciers in the east were drained by south-to-north directed rivers, towards the Danube. Glacio-fluvial meltwaters



**Fig. 1.9** Conceptual cross-section of the polyhierarchical, nested taxonomy of landforms as ‘relief generations’. The old Tertiary peniplains, including preserved remnants of the Mesozoic-Tertiary weathering mantles (MTVs, Stage 1), were dissected during the Pleistocene,

including the development of staircases of terraces (left side of the diagram). Accumulation of coverbeds and loess (Stage 2), the recent Holocene (Stage 3), and modern processes (Stage 4) (right side of the diagram)



**Fig. 1.10** Simplified geomorphic map of Germany. Data: BGR (2003), Pfeffer (2003), Glaser et al. (2007), CGIAR-CSI (2018)

transported huge amounts of gravel and created vast plains, e.g., around the city of Munich. In different glacial cycle-braided river systems created staircases of terraces in the catchment of the Danube. These rivers incised into the Tertiary sediments of the Molasse Basin (Region V). Penck and Brückner (1909) were the first geomorphologists who mapped and proved the repeated extent of the Pleistocene alpine ice advances. They developed the geomorphological model of the typical glacial sequence (glacier tongue basin-terminal moraine-glacio-fluvial outwash plain/terrace) and distinguished these sequences according to the morphostratigraphy in alphabetic order, giving them names of small rivers in the German Alpine foreland. Starting from the oldest to the youngest sequence, they were named Günz, Mindel, Riss, and Würm. Transfluence of ice masses from the Inn valley contributed significantly to the central Isar-Loisach Lobe. Overdeepened valleys have been subject to massive sediment redistribution in the Late Glacial. In addition, overdeepening of valleys contributed to massive landsliding and rock-slope failures in the mountains.

Figure 1.10 provides a simplified geomorphological map including the main landscape elements.

### 1.1.4 The Climate of Germany

Climatic conditions in Germany are controlled by the location in the humid mid-latitudes between 55°N and 47°N, the location in respect of the major pressure cells (subtropical Azores High, Iceland Low, and the extension of the Siberian anticyclone towards Russia-Scandinavia in the winter), the distance to the sea, the effects exerted by the warm Gulf Stream in the Atlantic Ocean, and the orography (Weischet and Endlicher 2000). The general outlines of climate of Germany are a temperate and marine western part, which is characterized by cool winters and warm summers, and a humid continental part in the east displaying cold winters, and less precipitation and higher temperatures in summer as compared to the west (Schönwiese 2020). These differences are reflected in the distribution of major biogeographical zones, whose boundaries are indicated on Fig. 1.1.

Although modified by factors such as cloudiness, altitude, and relief, there is a general increase in solar radiation and temperature from north to south. This is due to the higher angle of incidence in the south which compensates the longer daylight in the summer in northernmost parts of Germany, which receives more than one hour more daylight at the summer solstice than the southernmost parts. In contrast, at the winter solstice, daylight length in the southernmost parts of Germany exceeds that of the northernmost parts by more than one hour (Weischet and Endlicher 2000). The north-south gradient in temperature is also indicated in the phenological data, e.g. the apple blossom

occurs about two to three weeks earlier in the southern parts of Germany as compared to the areas in the north at the city of Hamburg (Glaser and Schönbein 2007). In addition, the pattern of temperature is influenced by the distance to the sea and orographic effects. The distance to the sea and the effects of the Gulf Stream are indicated in the west-east gradient of temperature. The western parts of Germany receive more heat from the warm Gulf Stream and are characterized by a lower annual temperature amplitude than the eastern parts, which are also located closer to the cold anticyclonic winds blowing from the Siberian High in the winter (Schönwiese 2020).

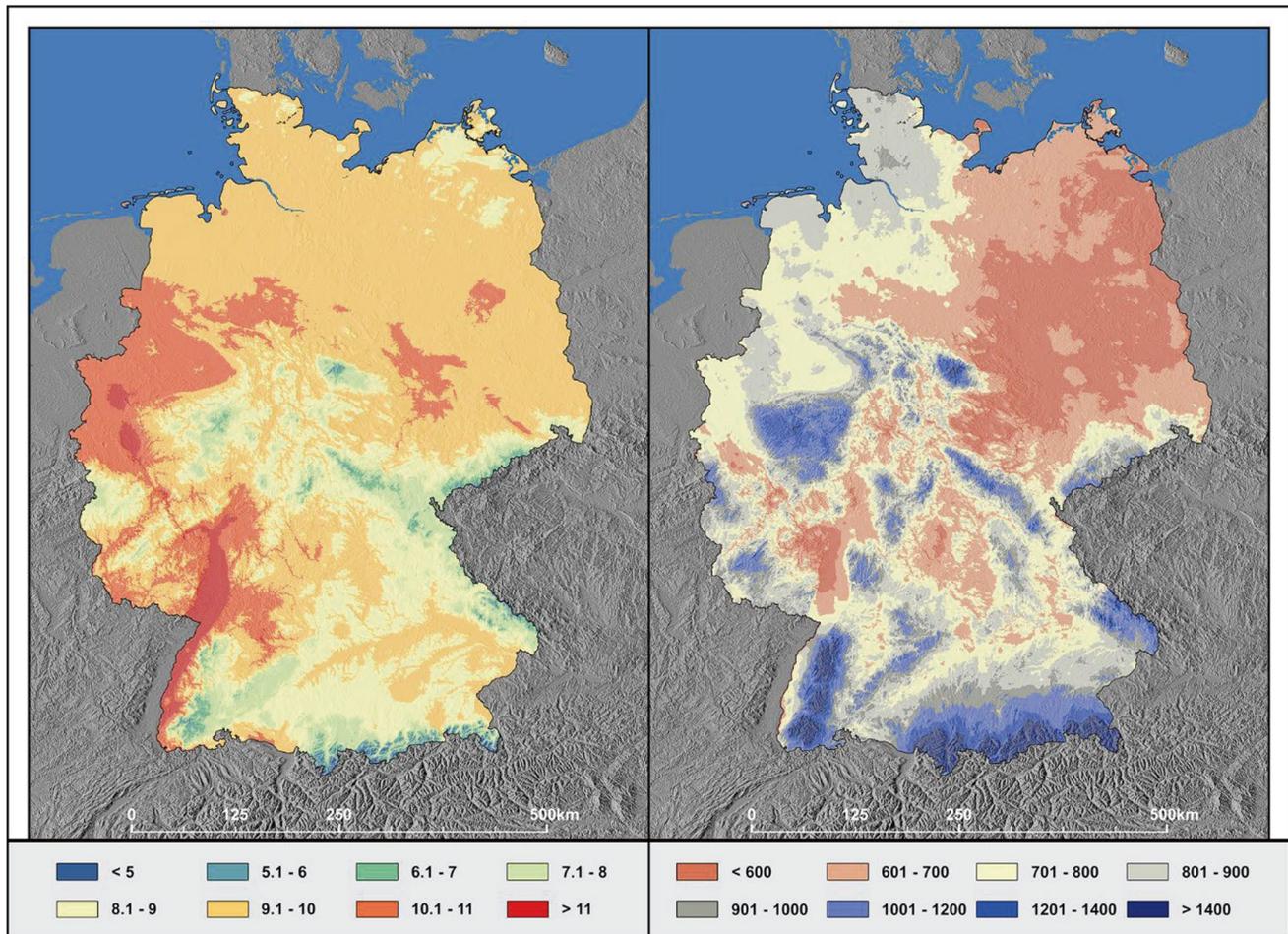
Mean annual temperature decreases with altitude. This is indicated by the lower temperatures in the Central Uplands, in the mountain ranges on the flanks of the Upper Rhine Rift, in the eastern mountain ranges, and in the Alps (Fig. 1.11). The warmer regions are usually located in the lowlands and basins, where the warmest area is located in the Upper Rhine Graben.

Throughout the year, the angle of incidence of the sun varies between 12 and 66° (Weischet and Endlicher 2000). Therefore, factors related to slope orientation effectively determine the local heating characteristics. In mountain ranges, slope orientation is an important factor for agriculture, e.g., the location of vineyards on slopes with southerly orientation. With respect to geomorphological processes, slope orientation tends to control weathering processes via temperature such as the frequency of frost, the availability of moisture, and the duration of snow cover. The effects of slope orientation on geomorphological processes are indicated in asymmetric valleys which formed during the cold phases of the Pleistocene.

The weather in Germany is strongly influenced by the location of the path of the westerlies and the seasonal north-south movement of the subpolar front. The subtropical high (Azores High) over the ocean in the south and the polar high in the north act as major pressure cells for moving air masses. Westerlies and the subpolar front divide tropical, moist, and warm air masses from dry arctic air (Hidore and Oliver 1993).

Zonal flow is characterized by air flowing from west to east. This circulation pattern is associated with cyclones and anticyclones. During zonal flow conditions, warm, wet air from the subtropics is carried towards the north and cold arctic air towards the south. In Germany, zonal flow is associated with air masses from the Atlantic Ocean, which are responsible for the temperate and marine climatic conditions. Onshore this is indicated in an increase in humidity, cloud cover, and precipitation, all closely associated with frontal passages. Heavy rainfalls form during the occluded stage of the cyclogenesis.

In contrast, when the temperature gradient between the equator and the pole decreases, the strength of the zonal



**Fig. 1.11** Climate of Germany 1991–2020. Left: Mean annual air temperatures (in °C), right: Mean annual precipitation (in mm). *Data source* CGIAR-CSI (2018), DWD (2021)

flow diminishes and the westerlies are looping into a meridional flow (Hidore and Oliver 1993; Glaser and Schönbein 2007). As a function of the location of the southward looping Rossby waves, the weather in Germany is influenced by air masses from the southerly or northerly directions.

In specific cases, cold air becomes isolated from the looping westerlies (Rossby waves) and is cut off (Hidore and Oliver 1993; Rohli and Vega 2011). Depending on the location of the isolated cold air, weather conditions are influenced by air masses from easterly and south-easterly areas. A prominent example is the cut-off of cold air above the Balearics in the Mediterranean Sea which is also termed Genoa low-pressure system or Vb cyclone. The Genoa low-pressure system forms above the Mediterranean Sea and takes up heat and moisture (Weischet and Endlicher 2000), moving on a track towards Central Europe. The moist and warm air masses are responsible for heavy rainfalls in southern and southeastern Germany and massive rainstorms in the Northern Alps (Nissen et al. 2013). The opposite case is the isolation of warm, moist subtropical air from the

northward looping westerlies. This results in a blocking of lows (blocking action) as the high diverts the cyclones coming from westerly directions (Kautz et al. 2022). In summer, the large-scale subsidence associated with the blocking anticyclone results in a cloud-free sky and radiative warming of the ground surface. Long-lasting anticyclonic conditions may lead to heat waves and droughts (Kautz et al. 2022). Depending on the season and the location of the isolated subtropical air mass, weather conditions are influenced by easterly and south-easterly winds and high-pressure conditions near the surface. If the high is located at the Scandinavian coast during the summer, weather conditions in Germany are characterized by inflow of dry continental air and high temperatures. During the summer, isolated warm air above Central Europe results in warm and dry weather conditions (Weischet and Endlicher 2000). During the winter this situation is characterized by cold conditions. The temperature inversion prevents the upward convection and the exchange of air to the higher atmosphere. The latter is often associated with hazy and foggy conditions.

Different circulation patterns control the distribution of weather conditions as they transport different air masses towards Central Europe. As a function of the properties of source region and of the surfaces which have been passed on, they display a different temperature and moisture content. According to Weischet and Endlicher (2000) and Glaser and Schönbein (2007), air masses reaching Central Europe from north-westerly to south-westerly directions are dominating with 65%. These include modified polar, marine polar, modified tropical, and marine tropical air masses. About 13% of the air masses are reaching Central Europe from northerly and north-easterly directions (modified polar air, continental polar air from Russia, and continental arctic air). About 1.8% of the air masses are derived from easterly and south-easterly areas (continental tropical air, modified continental air from Russia, and modified continental and maritime tropical air from the Sahara).

Coastal areas are characterized by more frequent and stronger wind, and by a more moderate annual temperature amplitude. The lower temperature amplitude is due to higher capacity of the ocean water to store heat which is associated with a temporal delay of warming and cooling of the ocean water (Rohli and Vega 2011). The slightly higher precipitation amount in the coastal areas is associated with the contrasting friction between the water surface and the land surface. The higher friction of the land surface decelerates the wind, which, in turn, enhances the convergence of the air, and increases cloudiness and precipitation (Weischet and Endlicher 2000). As the mean annual precipitation decreases with increasing distance from the ocean, the western parts of Germany receive about 700–800 mm while precipitation in the eastern parts is only about 550–600 mm (Glaser and Schönbein 2007).

Towards the south, the Central Uplands display a marked increase in the annual precipitation. Precipitation amounts generally increase with altitude (Fig. 1.11). A striking feature in this region is the contrasting pattern of high precipitation in the mountains and low precipitation amounts in the basins. As the mountains represent an orographic barrier for the westerly winds, airflow is impeded at the western flanks of the mountains and uplifted. The orographic damming effect results in heavy rainfalls, while the air at the leeward flank of the mountains subsides. This is associated with a reduced cloud cover and warmer conditions in the basins. As noted by Glaser and Schönbein (2007), the rain shadow effect is also influencing the precipitation amounts in the mountains of eastern Germany.

Westerly winds and the rain shadow effect exerted by the roughly north–south running mountain range of the Vosges result in specific climatic conditions in the Upper Rhine Graben (Fig. 1.11). This region represents the warmest region in Germany (Weischet and Endlicher 2000). The temperature of the coldest month is always above

0 °C (Glaser and Schönbein 2007). Supporting factors are the location in the lee side of the Vosges which effectively reduces the influence of cyclonic passages from the west-erlies. Subsiding air associated with a low cloud cover and a relatively high solar radiation result in an increase of temperature. Convective rainfalls are dominating during the summer (Glaser and Schönbein 2007).

In the South German Scarplands, the precipitation pattern shows a close correspondence with relief characteristics. Basins receive less precipitation while the rise of *cuestas* is associated with increasing precipitation (Fig. 1.11). A notable exception is the higher precipitation in the Kraichgau basin. This is associated with the lack of highly elevated mountains in the west, which enables the passage of cyclonic fronts into this area (Glaser and Schönbein 2007). Increased precipitation amounts are also recorded at the elevated *cuesta* of the Swabian and Franconian Alb. Towards the east precipitation increases in the Bavarian Forest and the Fichtel Mountains, though the precipitation amounts are strongly influenced by the rain shadow effects of the more westerly located mountain ranges. Relatively low precipitation amounts are characterizing the Danube lowland which is located in the rain shadow of the Black Forest (Glaser and Schönbein 2007). In the Alps the precipitation amounts are closely associated with the increase in altitude, which can result in doubling rainfall amounts in a few kilometres horizontal distance, e.g., from the Garmisch Basin to the Zugspitze summit.

Besides the mean climatic conditions, which appear to be typical for the humid mid-latitudes, Germany has experienced marked extreme weather events, even in the last decades. These include severe storms, extreme warm and dry years, and extreme rainfall events leading to devastating floods. The extreme warm and dry years of 2003 and 2018 were associated with extremely low water levels in the rivers and lakes. Even major rivers such as the Rhine and the large reservoirs were strongly affected by dry conditions during these years (Koppe et al. 2004; Mühr et al. 2018). Low water levels strongly affected the inland waterway transport and operations of power plants. Among other ecological effects, large areas covered with spruce stands were damaged by the higher spruce tree mortality combined with the spread of bark beetles.

During the winter of 1993, flooding of the Rhine at Cologne was associated with long-lasting heavy rainfalls in December. In 1995, prior to flooding there was a period characterized by abundant precipitation of snow in the mountains of the Central Uplands, which caused the development of a thick snow cover at higher elevations and of saturated soils in the lower parts of the mountains. This period was followed by the inflow of warmer continental air which caused rapid melting of the snow cover. In the following days, the passage of lows from the west

was associated long-lasting heavy rainfalls. The combined effects of snow melt, saturated soils, and rainfalls resulted in the flooding of the Rhine at Cologne (Engel 1999).

Extreme rainfall events in the warmer seasons are often associated with specific atmospheric circulation patterns. Summer flooding is often related to the Genoa low-pressure system in the Mediterranean Sea and a track termed 'Vb-track'. During slow meridional flow, this track transports warm and moist air towards the eastern and southern parts of Central Europe (Mudelsee et al. 2004; Rudolf and Rapp 2003; Weischet and Endlicher 2000). When the Vb air masses reach the German Alps, daily rainfall intensities up to 180 mm/day have been recorded, e.g., in 2005. Weather conditions related to the Vb-track have triggered extreme rainfalls in the summer of 1997 in the upper Oder River catchment. The low brought warm moist air from the Mediterranean and long-lasting heavy rainfalls (Landesumweltamt Brandenburg 1998). In the summer of 2002, flooding at the Elbe River was also triggered by extreme rainfalls which were associated with the passage of lows from the Vb-track (Rudolf and Rapp 2003). A somewhat smaller flood in 2009 affected the city of Dresden and in spring 2013, low-pressure systems moving with the Vb-track resulted in heavy rainfalls and severe flooding in eastern and Southern Germany.

The meteorological conditions which triggered the devastating flash floods in the summer of 2021 (12 to 16 July) in the western part of Germany in the Eifel Mountains and in parts of its foreland displayed a different circulation pattern. Extreme rainfalls were associated with a cut-off low-pressure system which has formed over Central Europe and a slowly approaching low-pressure system moving from France to Germany. In addition, orographic and dynamic uplift of the moist warm air and damming effects exerted by the Eifel-Ardenne mountains contributed to extreme rainfalls (Tradowsky et al. 2023). Total rainfall reached 175 mm in two days (Tradowsky et al. 2023), caused severe flash floods, and more than 180 fatalities. Although extreme rainfall events, presumably enhanced by global warming, remain the major causes of flooding, human interference in the drainage basins, floodplain, and river channel morphology appears to have enhanced the effects of flooding (Lehmkuhl et al. 2022).

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