Old orogens

Since Early Proterozoic times, Wilson cycles have operated, each beginning with the break-up of continents, evolving into the stage with a mature ocean framed by passive continental margins, and concluding with subduction and collision (Ch. 11). Remnants of oceans, present as ophiolite complexes in orogens, are the best indication of plate tectonic processes and mountain building. However, ophiolites older than 800 Ma are uncommon. Older ophiolite complexes do exist that resemble those in young Alpine orogens. They were derived from oceans formed 2500 to 2000 Ma ago by the break-up of Archean cratons and 1600 to 600 Ma by the break-up of the supercontinents Panotia and Rodinia. Examples are the Zunhua-Wutaishan ophiolite in northeast China, the Purtuniq ophiolite in northeast Canada, and the Jormua ophiolite in Finland (**Fig. 12.1**). These ophiolites suggest that oceanic crust at that time was at least as thick as in modern oceans (ca. 6 km). Probably oceanic crust was generally even thicker than today and thus reflects a hotter mantle with a higher percentage of basaltic melts beneath the mid-ocean ridges. In the mentioned examples, the ocean became subducted; this led to collision of the opposing continents and mountain building, similar to the case in younger Earth history. In fact, the Early Proterozoic Wopmay orogen in Canada shows an evolutionary history (including the sedimentary record) that resembles modern orogens in much detail; therefore, it is generally accepted that the plate tectonic processes at that time closely mimicked those of the present.

Most old orogens are no longer topographically prominent and are strongly eroded; therefore, only originally deeply buried rock units are generally preserved. The geologist can only reconstruct the evolution of such an orogen from the record in the metamorphic rocks and from structural features.

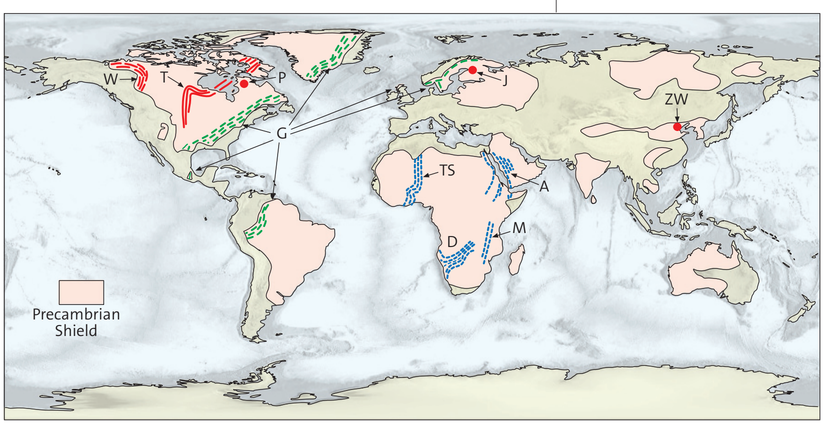
2500–2000 million years old ophiolites

The Archean North China craton encompasses large parts of northeast China. West and east of Beijing, the fragmented *Zunhua-Wutaishan ophiolite belt* stretches over several hundred kilometers (**Fig. 12.1**; Polat et al., 2006). It contains harzburgite and dunite with chromite as well as gabbro and basalt. Despite their tectonic and metamorphic overprint, some basalts reveal their original pillow structure. Sulfide mineralization is associated with the basalts and is interpreted as products from black smokers. The great interest of this ophiolite belt is its age: chromites and volcanic rocks yielded ages between 2550 and 2500 Ma thus establishing the oldest known ophiolite – the ocean, from which it derived, opened and closed before the Archean/Proterozoic boundary (2500 Ma). During the ensuing continent-continent collision, parts of the ocean floor were sandwiched between continental blocks, tectonically dismembered, and imbricated with continental material.

The oldest North American crust, the Canadian Shield, contains a complex network of Early Proterozoic orogens that formed between ca. 2000 and 1800 Ma by crustal growth and the continent-continent collision of Archean cratonic blocks. The metamorphosed *Purtuniq ophiolite complex* is part of the 500 km-wide Trans-Hudson orogen that crosses Hudson Bay (**Fig. 12.1**) and consists of several tectonostratigraphic terranes. The 2000 Ma-old ophiolite encompasses 5 km-thick tholeiitic basalts that contain preserved pillow structures despite their deformation, a dike complex, and gabbros (Scott et al., 1992). The dikes are partly split into half-dikes (see **Fig. 5.3**). A younger magmatic sequence is also tholeiitic but differs from the older one by its trace element and isotope chemistry; it represents the plutonic level of a volcanic edifice that formed from a hot spot similar to that of Hawaii.

The *Jormua ophiolite complex* is the northernmost exposure of a chain of ophiolite fragments in

▼ **Fig. 12.1** Present-day distribution of Precambrian shield areas. Orogens and localities described in the text are shown. *Early Proterozoic*: ZW: Zunhua-Wutaishan ophiolite. J: Jormua ophiolite. P: Purtuniq ophiolite. T: Trans-Hudson orogen. W: Wopmay orogen. *Middle Proterozoic*: G: Grenville orogen. *Panafrican orogenic belts (Late Proterozoic)*: A: Arabian-Nubian Shield. D: Damara-Katanga orogen. M: Mozambique belt. TS: Trans-Sahara belt.



W. Frisch et al., *Plate Tectonics*, DOI 10.1007/978-3-540-76504-2_12,

the Baltic Shield of Finland. Radiometric dating shows that by 1970 Ma, an Archean craton broke apart and formed an ocean that subsequently closed at 1900 Ma by continent-continent collision. The resulting Svekokarelian orogeny embraced large parts of Sweden and Finland (Kontinen, 1987). The Archean rocks across the broad flanks of the ophiolites are penetrated by numerous basaltic dikes oriented subparallel (NNW-SSE) to the ophiolite chain. They indicate the extensional rifting stage in the continental crust before its break-up. The Outokumpu complex at the southern end of the Finnish ophiolite chain contains important ore deposits including copper, cobalt, and zinc that were formed by volcanic exhalations on the sea floor. They closely resemble modern deposits of black smokers along mid-ocean ridges (Ch. 5).

The Wopmay orogen in Canada

The Wopmay orogen in the Canadian Northwest Territories (**Fig. 12.1**) developed between ca. 2100 and 1800 Ma. It describes a complete Wilson cycle and represents a collision orogen between two Archean cratons (Hoffman, 1980). The evolution of the eastern passive continental margin after continental break-up in N-S direction is well documented by the sedimentary sequences that are overprinted by metamorphism. It is the earliest detailed example of a passive continental margin that corresponds to modern patterns.

Through the formation of a rift system, a larger Archean continent split up. The main rift system developed two triple junctions of the RRR type. The failed third arm of each became inactive and filled with thick sediments. These are the earliest documented aulacogens (Ch. 4). The rifts are associated with strongly alkaline intrusions including carbonatites, rocks that are unknown from the Archean era but occur in the Early Proterozoic. Rifting, accompanied by alkaline magmatic suites, is characteristic of stable continental crust that breaks apart such as occurred along Pangaea later in the Phanerozoic.

The sedimentary sequences of the Wopmay orogen were stacked in several nappes . Reconstruction across the nappes reveals several zones, from east to west, inner shelf, outer shelf, and continent slope. During nappe thrusting, turbidites were deposited that were derived from the advanding nappes to form thick flysch sequences in front of the thrust units. The flysch sedimentation eventually graded into molasse sedimentation that indicates the uplift of a mountain range in the hinterland. Interestingly, this molasse includes the oldest eolian deposits on Earth.

The Grenville orogenic cycle and the formation of the supercontinent Rodinia

The Grenville orogen, named after a settlement near Montreal, Canada, generated a long mountain belt that stretched from southern Scandinavia through a strip in Scotland, eastern Greenland, and large parts of eastern North America to South America (**Fig. 12.1**). When North America is fit against Europe and South America in the Pangaean reconstruction, the trend of the orogen is perfect. This orogeny also describes a Wilson cycle that initiated with continent break-up around 1300 Ma. In the area of the Great Lakes, eastern Canada, and southern Greenland, the activity of hot spots and related rifting reflect the break-up process. An expression of this activity is alkaline intrusions, flood basalts, and dike swarms trending parallel to the margins of the later Grenville orogen (rift related) or radial with reference to the center of a hot spot. Numerous aulacogens branch off from the orogen with a high angle.

In the United States and Canada, the orogen consists of metamorphosed sequences that contain several basic-ultrabasic rock complexes interpreted as ophiolites. The ophiolitic rocks are partly transformed into glaucophane schists and eclogites that are among the oldest-known high-pressure metamorphic rocks (see below). In the area of the Great Lakes, the ophiolites are overlain by tholeiites, typical of primitive island arcs, and then by andesites. This island-arc sequence is intruded by large bodies of granodiorite and granite, which together with the andesites, indicate a mature stage of island arc magmatism. Thus, an evolution from primitive to mature island arc can be reconstructed. Two large fault zones separate the island arc sequence from gneisses that represent two different continents. Collision of these continents marks the orogenic climax and started around 1100 Ma. The Wilson cycle therefore lasted for approximately 200 m. y. The Grenville orogeny and related orogens assembled the supercontinent Rodinia (see **Fig. 6.7**), which by 750 Ma started to disintegrate.

The Panafrican orogeny and the formation of Gondwana

The break-up of Rodinia initiated an episode of high crustal mobility in the region of the continents of the present southern hemisphere. This occurred because of the rapid generation of new oceanic crust and its subsequent subduction. The welding together of dispersed continental pieces led to the formation of a complex network of mountain belts near the end of the Precambrian at approximately 550 Ma. The result of these events was the creation of the giant continent Gondwana, a large landmass that included the present southern continents plus India, as well as parts of present North America and Europe. Although it was not a single, unified orogenic event, this orogenic period is called Panafrican orogeny. Actually, a number of continental blocks and island arc systems collided over a period of 200 to 250 m.y. In the region of the Arabian-Nubian Shield, the area encompassing the Arabian Peninsula and large parts of Egypt and Sudan, a complicated system of island arcs evolved that resemble the present setting in the western Pacific region. The term Panafrican orogeny originated because the event welded together the different parts of present-day Africa, as well as other regions.

In the area of the Arabian-Nubian Shield (Fig. 12.1) on either side of the Red Sea, several Late Proterozoic island arc complexes separated by ophiolite belts can be discerned. The ophiolites and associated large volumes of calc-alkaline magmatic rocks correspond in detail to events documented in rock complexes of the Phanerozoic (Frisch and Al Shanti, 1977). Some ophiolites contain a nearly complete profile through oceanic crust including sheeted dike complexes. Some ophiolites have been interpreted as backarc oceanic crust. The island arcs evolved from a primitive stage with basalts and andesites to a mature stage with andesites, dacites, and rhyolites intruded by diorites and granodiorites. Sedimentary rocks, though of minor volume, consist of mainly sandstones and graywackes that contain the debris from the eroded volcanics. Widespread Kuroko-type mineral deposits are also present (Ch. 7).

The Arabian-Nubian Shield was situated along the margin of Gondwana, whereas other Panafrican mountain belts formed by collision of continental masses and therefore cross interior parts of Gondwana. Panafrican collisional orogens that underwent a Wilson cycle in Late Proterozoic times are the Mauritanian and the Trans-Sahara mountain belt in northwestern Africa, the Damara orogen in southwestern Africa, and the Mozambique belt in eastern Africa. In the Trans-Sahara orogen the oldest-known paired metamorphic belt has been reported: a high-pressure belt with eclogite facies and a high temperature belt with cordierite-bearing gneisses.

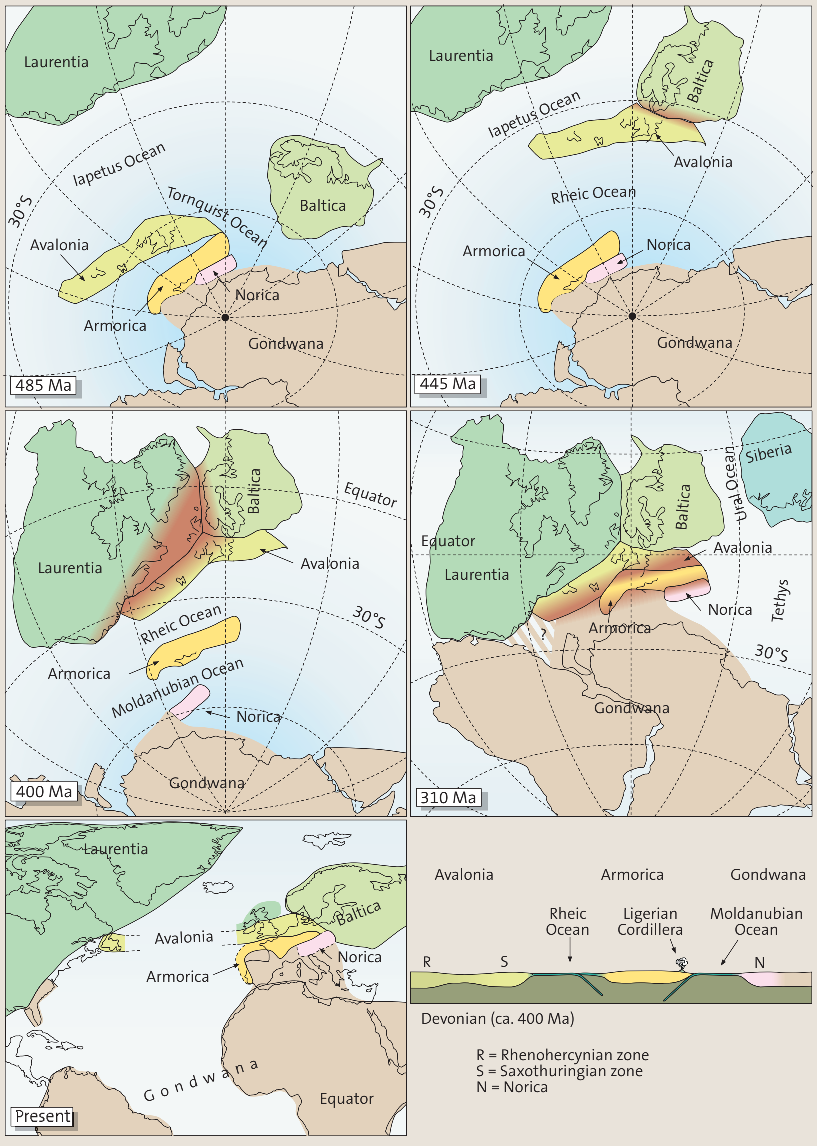
Some eclogites of the *Trans-Sahara mountain belt* (**Fig. 12.1**) contain coësite and hence experienced burial to at least 80 km depth (Jahn et al., 2001). Their age of 620 Ma makes them the oldest ultrahigh-pressure metamorphic rocks (Ch. 7). Eclogites and glaucophane schists are rare in the Precambrian. Archean eclogites are known only indirectly (Ch. 10), with one exception: the 2600 Ma old eclogites of the Churchill province in Canada. Approximately 2000 Ma-old eclogites are reported from Tanzania, and 1070 Ma-old eclogites occur in the Grenville orogen. Additionally, 900 Ma- and 700 Ma-old glaucophane schists were found in China. Probably a higher temperature gradient in the upper mantle in early Earth history prevented the exhumation of high-pressure metamorphic rocks without destroying the high-pressure minerals. The rare or missing occurrence of such rocks is therefore not a stringent argument against their former existence.

In Europe the Panafrican orogeny is expressed in the *Cadomian mountain belt* (named after the French town Caen, *Latin Cadomus*). The rocks were originally positioned at the northern margin of Africa (Gondwana) and formed between 700 and 550 Ma. Cadomian rocks are found in the Armorican Massif (Bretagne and Normandie), in the Bohemian Massif, on the Iberian Peninsula, and in basement complexes of the Alps. In fact, the complete continental basement of the Variscan orogen of Europe was bound to Africa (see below) where it was affected by the Panafrican-Cadomian orogeny. Cadomian rocks have also been found in many parts of eastern North America and parts of eastern Mexico, and more recently in the Cordilleran areas of Canada and the USA. These rocks were rifted from Gondwana in the Paleozoic and Mesozoic and are referred to as peri-Gondwanan terranes. Because all these terranes became overprinted by later orogenies, they are not shown as "Precambrian shields" in **Figure 12.1**.

Gondwana was welded together during the Panafrican orogenic cycle in the late Precambrian and early Paleozoic. Subsequently, pieces were rifted from its northern and western margins and incorporated into North America and Europe in the middle Paleozoic. In the late Paleozoic, all the pieces were integrated during the Variscan and Alleghenian orogenies to form the supercontinent Pangaea. Collectively, these events occurred within a timespan of less than 300 m.y.

The Caledonides – a Wilson cycle around the Iapetus Ocean

The Caledonian orogen of northern Europe and coeval Acadian orogen of northeastern North America describe a Wilson cycle that began ~600 Ma in the Late Proterozoic and culminated in the Silurian and Devonian ~400 Ma. The Iapetus Ocean opened in a similar position as the present North Atlantic Ocean, between Laurentia (North America), Baltica (northern Europe), and Gondwana (including Africa as well as southern, western, and central Europe) (**Fig. 12.2**). During the early Paleozoic, Avalonia rifted from Gondwana as a minor continent named after the Avalon Peninsula in Newfoundland. Avalonia collided with Baltica in the Late Ordovician (time not well constrained), and Avalonia/Baltica with Laurentia at the Silurian-Devonian boundary, thus terminating the Caledonian cycle. The resulting Alpine-style mountains may have been similar in height to the highest mountains on Earth today. Presently the Caledonian orogen is found on both sides of the Atlantic Ocean: in East Greenland, Spitsbergen, along the western coast of Scandinavia, on the British isles, and along the eastern coast of North America well into the Arctic. It continues southward into the Appalachians where it became overprinted by the collision between Laurentia and Gondwana in Late Paleozoic times.



◀ **Fig. 12.2** Plate tectonic evolution of the Caledonian, Appalachian, and Variscan mountain belts in the Paleozoic era (modified after Tait, 1997). The sketch maps show the settings in the Early and Late Ordovician (485, 445 Ma), the Early Devonian (400 Ma), the Late Carboniferous (310 Ma), and today.

The significance of Scotland and the Greek mythology

The definition of the Caledonides as an independent orogen is based on the work of Eduard Suess (1885). The name derives from the Latin word for Scotland: Caledonia. The term "Iapetus", however, derives from Greek mythology: Iapetos, one of the titans, was the son of Uranos (Heaven) and Gaia (Earth). Two of his sisters, Tethys and Rhea, also lent their names to oceans in Earth history (see below). Okeanos ("ocean") was one of his brothers. At the time of the Iapetus Ocean, northwestern Scotland was part of Laurentia, whereas today Avalonia is split between North America and Europe (**Fig. 12.2**). Incidentally, when plate tectonics mentions an "ocean", generally the areas underlain by oceanic crust are meant. The term "continent", in turn, includes the shelf areas under the sea, because they are underlain by continental crust.

In the Scottish Caledonides George Barrow developed his concept of index minerals in the late 19th century, delineating metamorphic zones (Barrow, 1893). He discerned zones with characteristic metamorphic minerals in schists of the Dalradian (Late Precambrian to Cambrian) and demonstrated that rock bodies that experienced different metamorphic conditions became exposed at the surface one beside the other by later folding and erosion. The pressure-dominated regional metamorphism was named after him (see **Fig. 7.24**), characterized, amongst others, by the index mineral kyanite.

It can be said that the birth of modern geology in the late 18th century originated from the early studies of the Caledonian orogeny. On a precipitous headland of Scotland, Hutton described his famous unconformity where Devonian arkose of the Old Red Sandstone (see below) overlies folded Silurian flysch and graywacke (Hutton, 1795). Hutton correctly surmised that complicated events necessary to generate such an outcrop must have taken vast amounts of geologic time and that the Earth was, therefore, very old.

The Iapetus Ocean had its trend in approximately a SSW-ENE direction (**Fig. 12.2**). According to paleomagnetic data, the coastline of Laurentia was positioned close to the equator, ca. 10–20° S, in the Ordovician (495–440 Ma). The African-South European coast on the other side of the ocean was at a high southern latitude of 60–70° S. The South Pole was situated in the western Sahara. Cosequently, the width of the Iapetus Ocean was a minimum of ~5000 km, a dimension similar to that of the modern Atlantic Ocean. Baltica rapidly drifted from medium southern latitudes (60–30° S) to an equatorial position. Avalonia probably rifted from Gondwana in the Early Ordovician and collided along its eastern margin with Baltica (**Fig. 12.2**). Avalonia and Baltica were separated by the Tornquist Sea (named after a German geologist of the early 20th century), a branch of the Iapetus Ocean that was subducted during the northward drift of Avalonia. The mountain belt generated by this collision now stretches from Denmark, through northern Germany to Poland and is poorly known because it is almost completely veiled by younger sedimentary sequences. Also, the collision was strongly oblique, nearly transform, so the amount of structural deformation probably was slight. Not so in the case of the collision of Avalonia with Laurentia where Avalonia smacked directly head-on into the larger continent.

Due to the different latitudinal positions and the large distances between the coasts, clearly differentiated faunas and sedimentary facies developed on both sides of the Iapetus Ocean (Cocks and Fortey, 1982). During the Early Ordovician, limestones with warm water faunas were deposited on the Laurentian shelf, and limestones with faunas indicating moderate temperatures on the Baltic shelf. In contrast, the Gondwanan shelf was characterized by faunas indicating a cool environment and by clastic sediments, because the carbonate production in cool climates is low. Glaciers formed moraines in the region of the Sahara. The faunas on both margins of the Iapetus Ocean became mixed in the Late Ordovician and indistinguishable in the Silurian. This reflects the northwad drift of Avalonia in the Ordovician and the progressive closure of the Iapetus Ocean in the Silurian. The Gondwanan margin remained in latitudes ca. 60° S until the end of the Silurian.

Around the Silurian-Devonian boundary, ca. 415 Ma, the collision of Laurentia with Baltica led to intense nappe stacking in Scandinavia. The nappe stack was thrust over the foreland of the Baltic Shield for great distances and the event marks the termination of the Caledonian orogeny. The Baltic continental margin was buried by a W-dipping subduction zone and shortened by approximately 400 km. Ophiolites of the Iapetus Ocean were also subducted but eventually thrust over the Scandinavian nappe stack. Parts of the ophiolilte package and the rocks of the continental margin experienced high-pressure and ultrahigh-pressure metamorphism. In the fjords and islands south of Trondheim, eclogites and gneisses contain coësite and diamonds with diameters to 50 micrometers (0.05 mm) as inclusions in other high-pressure minerals. The diamonds and associated minerals indicate that the rocks were buried more than 130 km (Dobrzhinetskaya et al., 1995).

The Caledonian-Acadian orogen contains paired Devonian molasse belts, the Old Red Sandstone and "Catskill facies" (several geologic formations) that developed on the east and west flanks respectively of the large continent-continent collision. Both of these units contain abundant arkose, sandstone and conglomerate rich in feldspar that was derived from the hinterlands of the mountain belt. These deposits are now known from Central Europe to Spitsbergen and in North America from Tennessee and North Carolina to the Canadian Arctic and Alaska. The molasse formed on extensive river systems, coastal plains, and in shallow marine settings within large foreland basins that flanked both sides of the Caledonides. The sedimentary rocks are mostly red because they formed under oxidizing conditions and contain iron derived from the weathering of igneous and metamorphic rocks.

The Variscides – a broad mountain belt in central Europe

The Variscan orogeny (named after the tribe of the Variscans in Franconia, Germany; the term Hercynian orogeny that is used as a synonym, refers to the Harz (Hercynian) Mountains in Germany, this term, however, is largely abandoned) took place from the Devonian through the Carboniferous and, based on its timing, marks the direct continuation of the Caledonian orogeny. In Caledonian times the eastern margin of Laurentia collided with part of Avalonia, whereas the margin of the large continent Gondwana was still remote. However, in Variscan time the two large continents collided and the Caledonian (Acadian) mountain belt along the eastern coast of North America became overprinted by later orogenic movements that persisted into the Permian. In Europe, both orogens, Caledonian and Varsican, are spatially separated; the collision of Laurentia and Baltica and the closure of the Iapetus Ocean terminated the orogenic events along the Caledonian collision zone. The Variscan orogeny followed farther south and formed an orogenic belt as much as 1000 km wide, the southernmost part of which was later overprinted by the Alpine orogeny. Large parts of Spain, France, and Germany were involved in the Variscan orogen and its basement almost everywhere was overprinted on the older Cadomian orogeny.

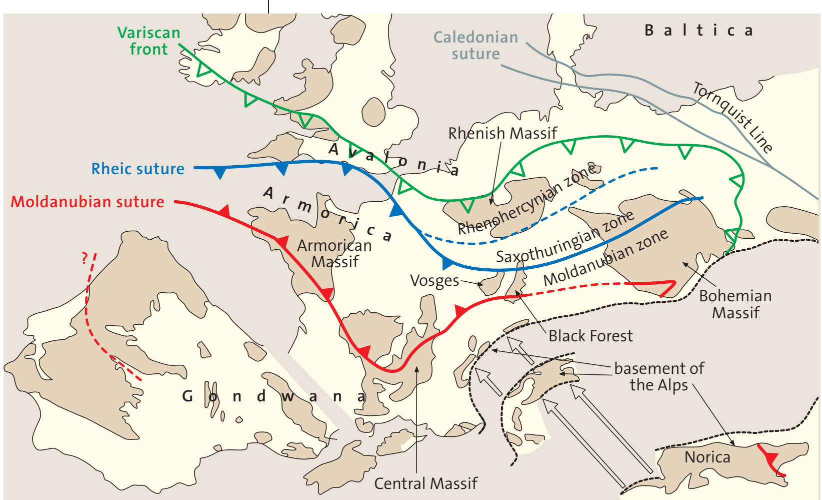
The classical subdivision of the Middle European Variscides contains three main tectonic units, from north to south, the Rhenohercynian, the Saxothuringian, and the Moldanubian zones (**Fig. 12.3**; Kossmat, 1927). Ophiolite and subduction-related magmatic complexes were once thought to be rare. This led to the proposal by German geologists in the 1970's that the Variscides were an intra-continental orogen, not formed by continent collision but rather by compressive deformation of a broad strip of continental crust. More recent studies have provided strong support for a plate tectonic scenario concerning the Variscan orogeny as both ophiolite bodies indicating oceanic realms and calc-alkaline magmatic suites and high-pressure metamorphic rocks indicating subduction are now well known. A portion of these rocks are contained in the basement of the Alps and were neglected for a long time in the reconstructions of the Variscides. Moreover, the concept of Kossmat has to be revised because evidence for a suture zone – indicating continent collision – has been found within the Moldanubian Zone.

The northward drift of Avalonia caused the opening of an oceanic realm in its wake, the Rheic Ocean (Rhea, sister of Iapetos) (**Fig. 12.2**). The Rhenohercynian and Saxothuringian Zone, the latter wedging out towards the west (**Fig. 12.3**), were part of Avalonia and therefore part of Baltica/Avalonia during the Devonian. A remnant of the Rheic Ocean, which was subducted towards the south, is the Lizard ophiolite complex along the southern coast of Cornwall in SW England which is part of the Variscides and belongs to the Rhenohercynian Zone. Near the Silurian-Devonian boundary, the crust between the Rhenohercynian and Saxothuringian Zones experienced some extension and thinning but this process did not lead to a separation (**Fig. 12.2**: profile). The closure of the Rheic Ocean occurred during the Devonian and Carboniferous and is marked by the formation of a north-vergent nappe stack.

The Armorican Massif, the French Central Massif, the Vosges, Black Forest, and the Bohemian Massif are all part of the Moldanubian Zone that contains the second important suture zone of the Variscides, the Moldanubian suture. The Armorican Terrane or Armorica is located between the Rheic and the Moldanubian suture. It represents a small continent that, like Avalonia, split off from Gondwana and drifted ahead of it towards the north (**Fig. 12.2**). Armorica probably separated from Gondwana in the Silurian and reached tropical latitudes in the Early Devonian as indicated by coral reefs. In its wake the Moldanubian Ocean opened (Franke, 2002). The closure of this ocean led to the collision of Gondwana, now drifting rapidly northward, with the northern continent containing the welded terranes. The Moldanubian subduction dipped towards the north and thus created a south-vergent nappe stack. Above the subduction zone on the Armorican Terrane, a subduction-related magmatic belt formed, the Ligerian Cordillera (**Fig. 12.2**: profile).

The Moldanubian suture stretches from Bretagne via the southern Black Forest (see box) to the Eastern Alps (Fig.12.3). In its eastern part the collision occurred in the Early Carboniferous, in its western part it already started in the Devonian. This scissor-like closure is the result of oblique collision of irregular continental margins. Both the Moldanubian and the Rheic suture zone contain high-pressure to ultrahigh-pressure metamorphic rocks, the former with coësite bearing eclogites (Central Massif), the latter with diamond bearing gneisses (Saxonian Erzgebirge).

By welding together Laurentia/Baltica, commonly called Laurussia, with Gondwana and incorporating the continental fragments and island arcs in between, most continents worldwide were unified in the incipient Pangaea supercontinent by the Late Carboniferous. During and after formation of the European Variscides, westward movement of Gondwana led to compression in the Appalachians, an event that persisted into Permian and completed the orogenic process there. Also in Permian times the Urals were formed by the collision of Siberia with Baltica (**Fig. 12.2**). The birth of Pangaea was finalized.



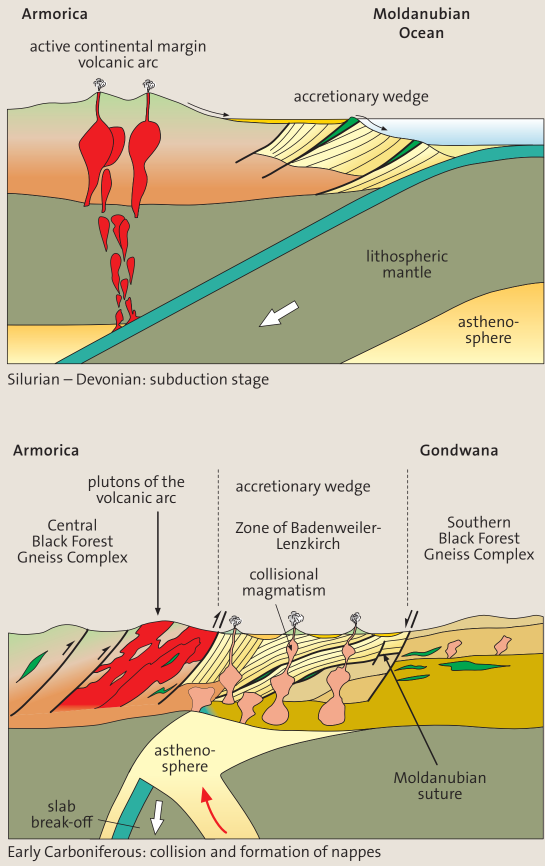
▼ **Fig. 12.3** Geological sketch map of the European Variscides (modified after Franke, 2002). The Rheic suture and the Moldanubian suture show opposite polarity of thrusting. Iberia is rotated back to its Late Paleozoic position.

A Variscan suture in the southern Black Forest

Two highly metamorphosed gneiss complexes in the central and the southern Black Forest (Schwarzwald) are separated by the Badenweiler-Lenzkirch Zone, an area comprised of a weakly metamorphosed sequence of detrital sedimentary rocks ranging in age from Ordovician to Early Carboniferous. The Central Black Forest Gneiss Complex contains splinters of ophiolites with eclogites. Radiometric dating yielded Ordovician ages for the formation of the ocean floor rocks. The eclogites, formed during subduction of the ocean floor, yielded Early Carboniferous ages (Chen et al., 2003). The entire area of the southern Black Forest experienced south-vergent nappe stacking in the Early Carboniferous. A tectonic unit at the southern margin of the Central Black Forest Gneiss Complex was interpreted to be the remnant of the plutonic level of subduction-related magmatism. To the south of this zone was a deep-sea trench along a convergent continental margin in which argillitic and sandy sediments including graywackes were deposited and subsequently inbricated in an accretionary wedge, now the Badenweiler-Lenzkirch Zone (**Fig. 12.4**).

Recent research revealed a suture zone in the southern Black Forest, along which the collision between two continent masses occurred (Hann et al., 2003). This suture marks the boundary between Armorica to the north and Gondwana to the south. Although the suture itself lacks ophiolites, several important characteristics were discovered that enabled the reconstruction of a subduction zone adjacent to an oceanic realm (**Fig. 12.4**). Dating of the magmatic rocks and the eclogites proved the persistence of subduction activity for at least 100 m.y. (Silurian to Early Carboniferous), hence the subducted ocean must have had a considerable width, far in excess of 1000 km. This scenario orchestrates well with the drift of Gondwana from high to low southern latitudes during the same interval of time (**Fig. 12.2**).

Following collision in the Early Carboniferous, the subducted oceanic part of the plate broke off and enabled the asthenosphere to ascend to the base of the crust (**Fig. 12.4**). This process caused heating of the crust and the formation of large volumes of granitic melts. The granites penetrated the crust as a number of plutonic bodies.



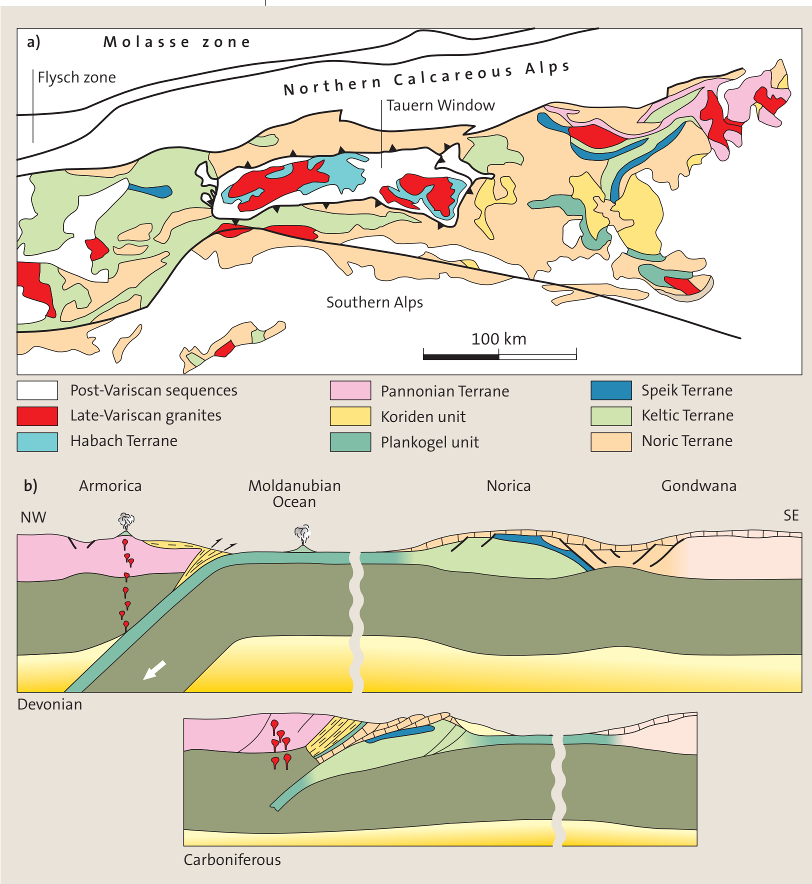
▲ **Fig. 12.4** Geological evolution of the Moldanubian suture zone in the southern Black Forest (Hann et al., 2003). South is to the right.

The Variscan orogen in the Alps

Portions of the Variscan orogen were later involved in the Alpine orogeny and therefore form most of the basement of the Alps. The rocks exposed in the Alps, the southern Variscides, experienced south-vergent nappe stacking. The Alpine overprint included strong deformation and metamorphism that veils the older structures and makes reconstuction of the Variscan processes difficult. However, modern methods enable astonishingly good insights into this older episode of mountain building.

The basement of the Western Alps is the direct continuation of the southern Central Massif and the southern Black Forest and was thus part of Gondwana until its collision during the Variscan orogeny (Fig.12.3). In the Eastern Alps, the restoration of the original arrangement of crustal blocks is much more difficult because of the Austroalpine mega-unit (see **Fig. 13.6**). During the Alpine orogeny, this complex was thrust for long distances over those units exposed in the Western Alps. However, the Austroalpine basement was also part of Gondwana although it was partially split off from this large continent before the Variscan collision. The Austroalpine unit consists of several tectonic units, each defined by different characteristics. This led to a geodynamic interpretation in the frame of the terrane concept (Ch. 9).

The northeastern part of the Austroalpine basement comprises the *Pannonian Terrane* (**Fig. 12.5**) that experienced deformation and metamorphism during the Devonian. Present is a subduction-related magmatic complex that can be correlated with the Ligerian Cordillera in the western Armorican continent (**Fig. 12.2**: profile). Northward subduction of the Moldanubian ocean floor enabled the



▲ **Fig. 12.5** Paleozoic terranes in the Eastern Alps that were assembled during the Variscan orogen (Frisch and Neubauer, 1989).

formation of the Koriden unit, an accretionary wedge with probable flysch deposits that formed in a deep-sea trench (**Fig. 12.5**). These deposits were welded along the southern margin of Armorica. Ophiolite bodies of the Plankogel unit, a tectonic mélange, became also accreted. The Plankogel unit includes ocean floor remnants, basalts of an intra-oceanic seamount, and limestones and sandstones that float in an argillitic matrix; these components were all metamorphosed to amphibolite facies conditions in both Variscan and Alpine times. The Plankogel unit represents the Moldanubian suture zone and is therefore considered to be the continuation of the suture exposed in the southern Black Forest (see box). In contrast to the suture in the Black Forest, the rocks in the Eastern Alps are highly metamorphosed and numerous ophiolites are present. Ophiolites were also found in the Central Massif along this suture zone (Matte, 2001).

During subduction of the Moldanubian Ocean, a continental fragment rifted from Gondwana and opened an oceanic area in a scissor-like manner, wider towards the east. This continental fragment is named the Noric Terrane or Norica (**Fig. 12.2, 12.5**). The *Noric Terrane* is a composite terrane that forms the greatest portion of the Austroalpine basement. It consists of the older Cadomian basement, a magmatic arc of Late Proterozoic and Early Cambrian age. Large volumes of volcanic and plutonic rocks were added to the crust during Cadomian times. The Noric Terrane consists of two smaller terrane units. The magmatic arc is represented by the *Keltic Terrane* and the backarc basin is represented by the *Speik Terrane*. The arc collided with Gondwana in the early Paleozoic and the backarc ocean floor, the Speik Terrane, was thrust over the arc, the Keltic Terrane. The resulting amalgamation formed the composite basement of the Noric Terrane (**Fig. 12.5**).

The basement of the Noric Terrane was covered by a sedimentary sequence that spanned the Ordovician to Early Carboniferous. The sedimentary rocks contain some intraplate volcanic horizons that represent crustal distension that culminated in the scissor-like separation of Norica. Collision between the Noric and Pannonian terranes occurred in concert with the closure of the Moldanubian Ocean in the southern Black Forest and the Bohemian Massif (**Fig. 12.3**). The oeanic wedge between Norica and Gondwana became part of another large oceanic realm, the Paleotethys Ocean (Tethys, another sister of Iapetos) that widened considerably towards the east and merged with the giant Panthalassa Ocean (see **Fig. 4.8**: Permian). Additional continental fragments rifted from Gondwana to open the Neotethys Ocean in the Triassic.

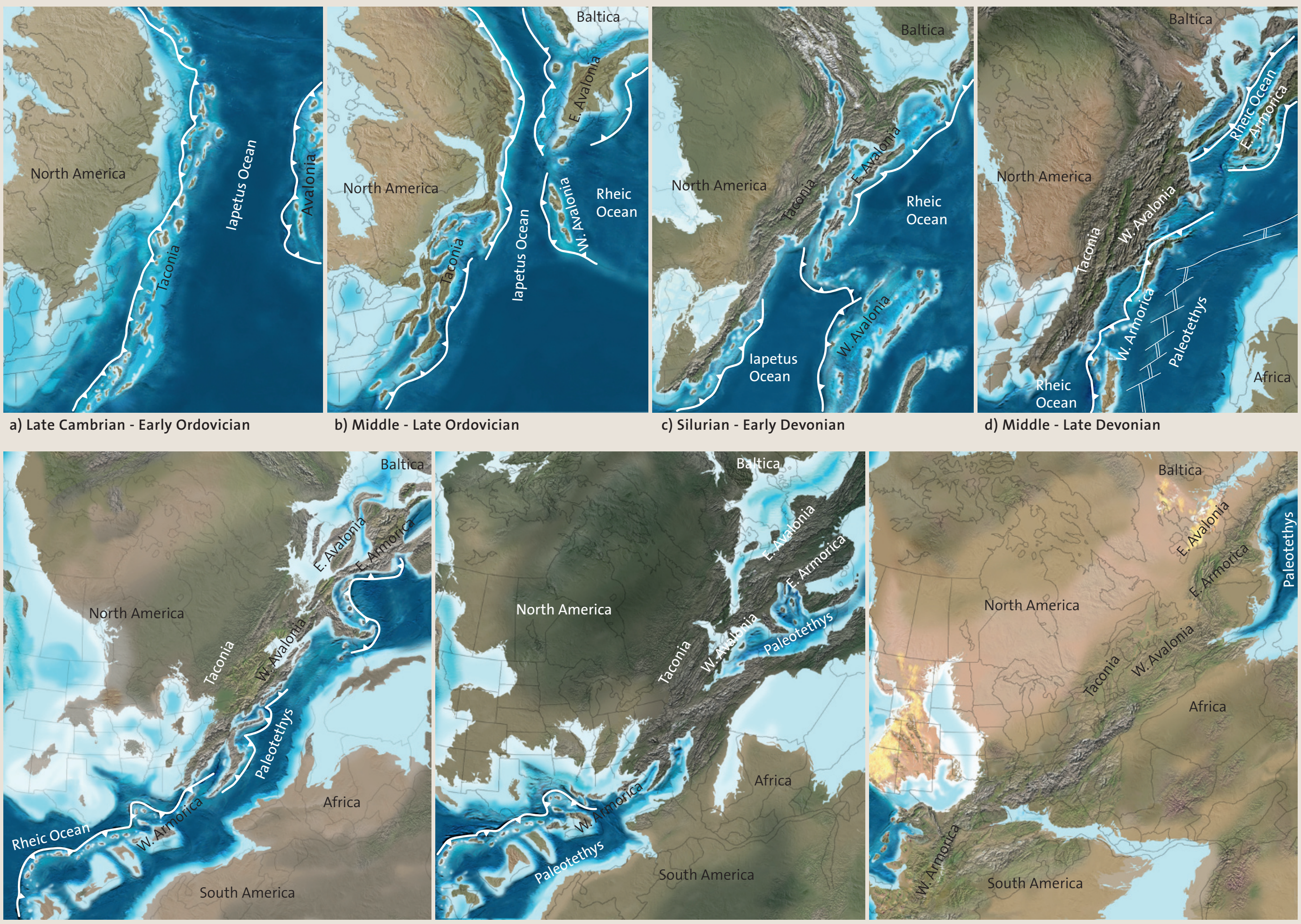
The *Habach Terrane*, exposed in the Tauern Window in the Eastern Alps, consists of a completely different nature. It is not part of the Austroalpine but rather is part of the structurally lower Penninic mega-unit of the Alpine nappe edifice (see **Fig. 13.6**). It probably formed somewhere in the oceanic widths to the east where its position relative to the other terranes remains unknown. It developed as an island arc on oceanic crust from the Late Proterozoic for more than 300 m.y. until terminated by the Variscan orogeny. During the Variscan orogeny, the Habach Terrane became sandwiched between colliding continental blocks and was amalgamated as part of supercontinent Pangaea. Partial melting during collision and persistent subduction activity along the Tethys continental margin generated large volumes of granitic melts that intruded into the ocean floor and thick island arc sequences in the Carboniferous. The granites were transformed to gneisses during the Alpine orogeny. The association of island arc volcanics, largely metamorphosed to greenschists and related rocks, and granites resembles Archean granite greenstone belts (Ch. 10).

Paleozoic mountain building in eastern and southern North America

The Appalachian Mountains today form a low mountain range that stretches from the Maritime Provinces of eastern Canada to northern Georgia. The Appalachians were not overprinted by later orogeny, hence part of their original form is still intact. However, parts are missing including much of the ancient hinterland that now lies below the Atlantic Coastal Plain or was destroyed by the opening of the Atlantic Ocean. The basement of the Appalachians ranges from crystalline rocks formed during the Grenville orogeny to various crystalline blocks of ancient terranes that were deformed, intruded, and metamorphosed during the various phases of Appalachian orogenies. In general, three main orogenic events have been traditionally recognized although modern research has complicated this interpretation somewhat. Most Appalachian events have general correlatives to the events discussed above in Europe.

The main structural trends of the Appalachians plunge under the Atlantic and Gulf Coastal Plains but deep seismic reflections trace the orogen under the Mississippi River Embayment westward into Arkansas and Oklahoma where it reappears as the Ouachita Mountains. From there, correlation proceeds southwestward into the Marathon Mountains of Texas and from there southward into northern Mexico. The complexity and number of orogenic events of this great mountain chain generally increases from SW to NE – the Marathons and Ouachitas have one major event each, the Southern Appalachians several events, and the Central and parts of the Northern Appalachians may have five or more major events.

The oldest orogenic event widely recognized in eastern North America is the *Taconic orogeny*, named for the Taconic Mountains between New York and Vermont, and coeval *Grampian orogeny* of Scotland and *Humberian orogeny* of Maritime Canada. Remember that Scotland was part

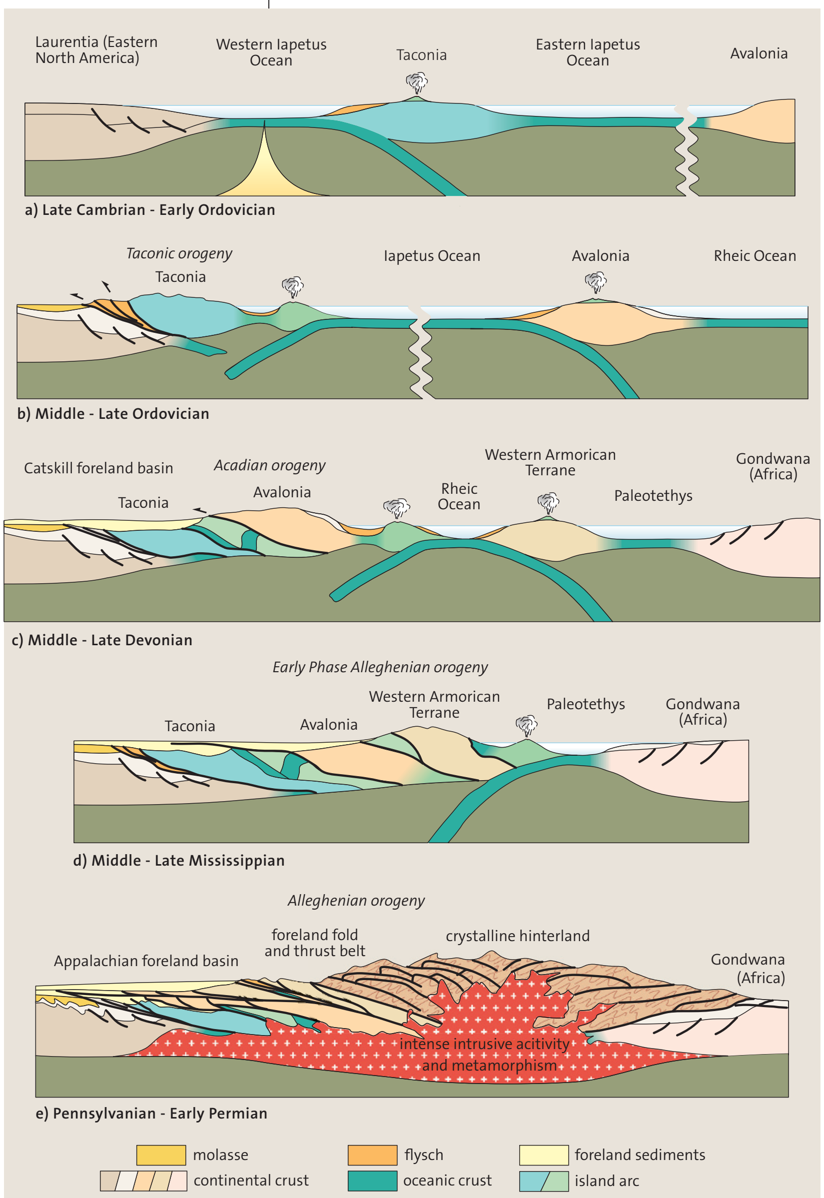


a) Late Cambrian - Early Ordovician
b) Middle - Late Ordovician
c) Silurian - Early Devonian
d) Middle - Late Devonian
e) Early Mississippian
f) Middle - Late Mississippian
g) Pennsylvanian - Early Permian

▼ **Fig. 12.6** Paleogeographic maps that show evolution of Appalachian Mountains during Paleozoic. Note that Paleotethys corresponds to Moldanubian Ocean in **Fig. 12.2** of Laurentia during the Paleozoic. The Taconic orogeny has been dated as Middle Ordovician to Early Silurian, older in Scotland and Canada and younger in New England. The orogeny was originally defined by thrust sheets in the Taconic Mountains in which deep-water flysch was thrust over marine shelf deposits. Subsequent work has documented Taconic intrusives, metamorphic sequences, and ophiolites. A well-developed foreland basin sequence of Late Ordovician and Silurian age is present across much of the western Appalachians, especially in New York State. The Taconic and related orogens have been interpreted as the result of collisions between island arc complexes and the microcontinents on which they were built with the eastern margin of Laurentia. Laurentia was the lower plate of the subduction zone so the arcs were thrust over the larger continent (**Fig. 12.6a,b, 12.7a,b**). The microcontinents may have originated as rifted slivers from North America during the opening of the Iapetus Ocean. Arcs were built on the microcontenents and then obducted onto North America. The Taconic and related orogenies may partially correlate in time and orogenic style with the *Finnmarkian orogeny* of west Baltica, generally considered the earliest phase of the Caledonian orogeny. Because the arcs and microcontinents associated with these early orogenies were intra-oceanic, their collisions did not close the Iapetus Ocean, only parts of it.

As Avalonia joined Baltica, the two bore down on NE Laurentia and the ensuing collision generated the Salinian and Main phases of the *Acadian orogeny*. The collision was slightly oblique so that Greenland, then part of Laurentia, and Baltica collided along their respective northern coasts in the Middle Silurian and scissored southward so that in New England, the collision with West Avalonia was Early and Middle Devonian (**Figs. 12.6c,d, 12.7c**). The Baltica-Greenland collision was described above. Farther south from the Maritimes of Canada to the central Appalachians, the orogeny generated major thrusting, metamorphism, and intrusion of major granite batholiths. Substantial portions of the Atlantic Coast states were accreted to eastern Laurentia (compare **Fig. 12.6c and 12.6d**). The well-developed foreland basin to the west received clastic sediment from the high mountains; variously called the Catskill or Acadian foreland basin, it is the North American equivalent to the Caledonian foreland basin of Europe in which the famous Old Red Sandstone was deposited.

As described above, the earliest phases of the Variscan orogeny involved arc tectonics and ophiolite obduction, Lizard ophiolite and Ligerian orogeny. Similar events occurred at various places in the Appalachians, especially New England, as various arcs and backarc basins accreted onto the continent. The accreted Meguma Terrane, now part of



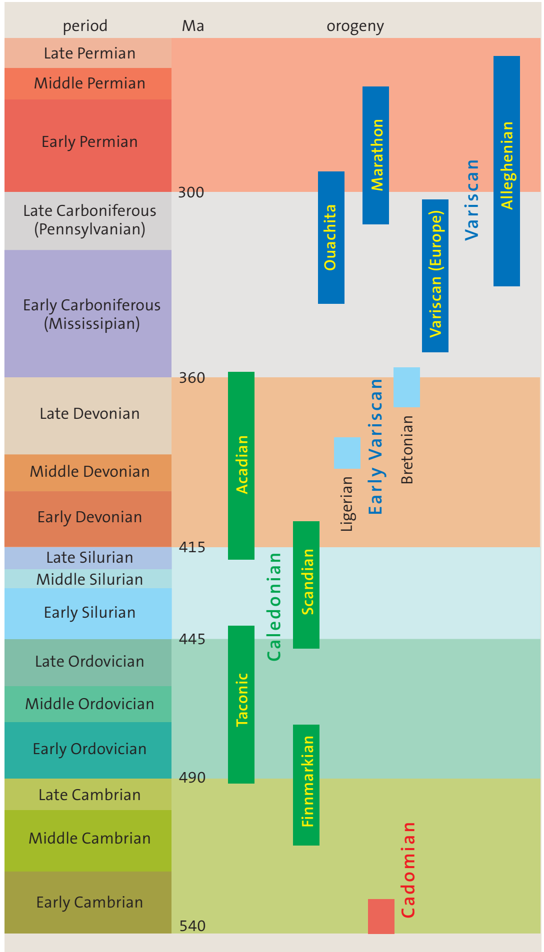
◀ **Fig. 12.7** Schematic cross sections that show events in evolution of Appalachian Mountains during five time segments shown in **Fig. 12.6**. (a) Iapetus Ocean prior to Taconic orogeny (see **Fig. 12.6a**); (b) Taconic orogeny (see **Fig. 12.6b**); (c) Avalonia collides with Laurentia during Acadian orogeny and closure of Iapetus Ocean as Hun Terrane (Western Armorican Terrane) rifts from Gondwana (see **Fig. 12.6d**); (d) accretion of Hun Terrane; late phase of Acadian (north) to early phase of Alleghenian (south) orogenies (see **Fig. 12.6f**); (e) Alleghenian orogeny marks final collision of Gondwana and Laurentia to form Appalachian Mountains and Pangaea (see **Fig. 12.6g**).

How many orogenies?

As the discussions of the orogenies of Europe and North America imply, many orogenic events affected southern Laurussia, the name for combined Laurentia, Baltica, and Western Europe, during the Paleozoic. As the discussion of terranes in Chapter 9 implied, terrane analysis is full of complexity and controversy. Such complexity can be difficult to resolve where ribbon terranes are doubled or tripled; did such duplication happen before the terranes docked and therefore the duplication represents separate collisional orogenies, or did the duplication occur after docking through transform motions? In the later case, only one orogenic event may have occurred. Like many sciences, geology has both lumpers and splitters. One geologists' major orogeny with several phases is another geologists' multiple orogenies. The collision of microcontinents must involve at least one subduction zone, possibly more. As discussed in Chapter 7, arcs undergo changes, some of which result in deformation – orogeny. Therefore, arcs can complicate the orogenic picture.

The Caledonian orogeny presents an example of multiple orogenies being miscorrelated and incorrectly linked to the "type Caledonian" orogeny. A classic study by McKerrow et al. (2000) illustrated this folly and traced the history of study of the Caledonian orogeny and used this history to refine and limit a term that was being used incorrectly. Their basic conclusion was that the term "Caledonian orogeny" should only be applied to those events directly related to the closing of the Iapatus Ocean – the collision of Baltica, Avalonia, and, Laurentia and associated island arcs.

So how many orogenies occurred prior to and during the assembly of Pangaea in the present North Atlantic region? There may never be an answer to this question. **Figure 12.8** is a compilation of many of the terms that have been used to define Caledonian-Appalachian-Variscan orogenies and their subdivisions. Each term is related to the area and time frame that it represents, thus resulting in duplication of terms. Some represent relatively minor events such as island arc collapse or collision and others stand for major continent-continent collisions. One thing seems certain – there appears to be nearly continuous orogeny at some place in the Paleozoic as the Iapetus, Rheic, and other oceans closed and Pangaea was assembled.



◀ **Fig. 12.8** Ages of orogenies and orogenic phases related to the assembly of western Pangaea (compiled from Ziegler, 1990; McKerrow et al., 2000; and Hatcher, 2002). Red shows the Cadomian orogeny, the basement to many later events. Green marks the classic Caledonian orogeny and the closing of Iapetus Ocean as defined by McKerrow et al. (2000). Pale blue marks early phases of the Variscan orogeny and deep blue marks the events that assembled Pangaea and closed the latest Paleozoic oceans, the Variscan and Alleghenian orogenies. Note that time scale bar is linear. Modified from Blakey (2007).

the continental shelf along Nova Scotia, may have been a straggler of West Avalonia and later collided with Laurentia or was driven into the continent by younger, incoming terranes. The next succession of incoming terranes, recently named the West Hun Terrane (named for the Huns, a marauding band of peoples that hassled the Roman Empire at its fall), was part of a larger succession of ribbon continents that rifted off Gondwana and accreted to Europe and North America closing the Rheic Ocean (**Fig. 12.6d,e, 12.7c**). Armoricia (from the Celtic-Roman word Ar(e)morica for Bretagne and Normandy) formed the large island to the NE of **Fig. 12.6d** and described above in the Variscan orogeny was part of this chain as were parts of what are now eastern North America from New England to Mexico. We prefer the older term, Armorica, for the whole complex. In North America, the accretion of these terranes was very complicated and strongly time-transgressive, older to the northeast, younger to the southwest. They generated the late phases of the Acadian orogeny and early phases of the Alleghenian orogeny as well as the *Ouachita and*

Marathon orogenies (**Fig. 12.6e–g, 12.7d,e**), the latter of which culminated in the Permian. Some of these terranes may have "escaped" around the southern margin of North America and are now incorporated in Cordilleran terranes in California!

Regardless of how many terranes accreted in how many events to eastern Laurentia, the culminating *Alleghenian orogeny* involved the final collision between Gondwana and eastern Laurentia (**Fig. 12.6g, 12.7e**) and the supercontinent Pangaea was born. But the Alleghenian orogeny was not everywhere equal. As the maps in **Figure 12.6** show, the eastern and southern margins of Laurentia were extremely irregular and consisted of various salients (large protruding areas) and reentrants (large embayments). The Reguibat promontory on the African portion of Gondwana struck the prominent salient between Pennsylvania and North Carolina head on. The collision closed the gap between the two in scissors-fashion from north to south. Farther north in New England, the collision was a glancing blow and deformation was minor. To the south of North Carolina, Laurentia took a sharp bend to the west and the force was also deflected. Here, pieces of the ribbon continent of the West Hun Terrane and their leading island arcs yielding a glancing blow to generate the Ouachita and Marathon orogenies; some geologists debate that South America never directly collided with North America.

The Alleghenian orogeny generated great volumes of igneous rock, especially plutons, in the main area of intense deformation described above. Metamorphism accompanied the plutonism and great nappes, now mostly eroded, and thrust sheets were driven westward over North America (**Fig. 12.7e**). A huge foreland basin developed in which was deposited sandstone and mudstone and the largest coal reserves on Earth. Much of this basin, especially its eastern portion, is now eroded. Each of these features diminishes to both the north and south of the present Central and Southern Appalachians. The Alleghenian orogeny is the North American equivalent of the Variscan orogeny, although as explained below, much of the former is younger than its European counterpart.

The Ouachita and Marathon orogenies along southern Laurentia are of a completely different orogenic style and are commonly called "soft collisions. Only the forelands remain and in each, tremendous volumes of deep-water flysch were thrust over the continental shelf of Laurentia. The colliders are deeply buried under kilometers of Gulf Coastal Plain sediment and are believed to be oceanic arcs that fringed accreting terranes. The terranes are also buried, although some appear on deep seismic profiles. Permian deformation in the Marathon Mountains of West Texas marks the youngest datable event of the Appalachian history of eastern and southern North America, although undatable thrusting in the Central Appalachians likely lasted well into the Permian. In the Pennsylvanian, stresses on North America were apparently so great that parts of the craton were deformed by high-angle reverse faults to form the Ancestral Rocky Mountains (**Fig. 12.6g**)

Not much is known about Appalachian events in Mexico and Central America and what is known is strongly debated. A few deep wells have penetrated Cadomian crust in places like Honduras, Oaxaca, and Yucatan. The presumed terranes that they represent have been correlated to the Armorician (West Hun) Terrane discussed above. In other places Paleozoic or Precambrian structures occur in the subsurface and on seismic records, but it is difficult to resolve Appalachian events from older Grenville events in such areas, especially where both may be present.