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Geological History of the Mediterranean

The Mediterranean has a very complex geological history, mostly spanning the last 200 million years. Interactions between the European/Asian and African continents have created and destroyed several seas, of which the Mediterranean is but the most recent. The geological complexity, the landscape and the climate of this region have long attracted geologists. The best compilation of their work, at least for the European side of the Mediterranean, is *The Geology of Europe*.² The geology of Greece and Turkey has also been treated in detail in two books,^{127, 34} as have the mineral deposits.^{172, 24} Here we will give an outline of the geology of the Mediterranean, but will deal in more detail with the Aegean and adjacent areas. More details of the geology are given in the regional chapters 3-16.

The geological framework

The Mediterranean region has a complex internal geological history, but the external events that controlled the development of this region are simpler to explain, and we will start there. Our history begins 190 million years ago, in the Mid-Jurassic period. Although there are many rocks older than this in the region, we are uncertain of the position of the continents in earlier times, and hence cannot reconstruct the earlier history of plate tectonics.

The North Atlantic Ocean did not exist in the Early Jurassic period and both Africa (more correctly Gondwanaland: Africa with other continents) and Eurasia (Europe and Asia) were united with the North American continent to form a super-continent named Pangea (Fig. 2.1). Between the future continents of Africa and Eurasia there was a

wedge-shaped ocean, named Tethys (after the daughter of the earth-goddess Gaia), which opened out to the east where it joined the other oceans. This state of affairs changed when the North Atlantic Ocean began to form about 190 million years ago.

A new plate margin started to form with the rifting of the continent along huge normal faults, following closely the position of an older ocean that had closed up to form the Appalachian, Caledonian and Scandinavian Mountains. New crust was created in the rift, forming a new ocean, the North Atlantic. Initially this rifting was concentrated in the south, separating Africa from North America, and moving it to the east. The position of continental rifting, and new ocean formation, moved slowly to the north, like a tear, and by about 110 million years ago Eurasia had started to separate from North America.

During the next period, the southern parts of the Atlantic Ocean continued to form more rapidly than those in the north, forcing the African plate to rotate in a clockwise direction about an axis in the Atlantic off Gibraltar, closing up the Tethys Ocean. This rotation slowed down considerably when the Arabian part of the African continent hit Eurasia, producing the mountains of Turkey, and has now almost ceased. Of course, within this framework there is much detail. For example, continental fragments originally attached to Africa, such as much of Italy and parts of Greece, have broken off, crossed the closing ocean and hit Eurasia. It is this part of the story that will be expanded below. But first we must deal with some of the special terms commonly used in Alpine and Aegean geology.

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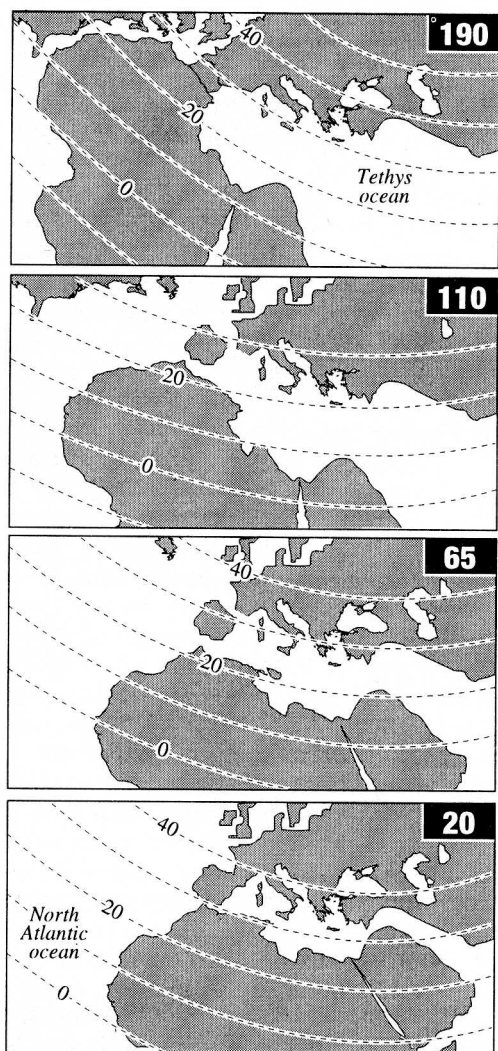


Fig. 2.1. Overall evolution of the African, Eurasian and North American continents during the last 190 million years.⁵⁶ Dashed lines indicate the approximate latitudes. The modern outlines of the continents are shown here so that places may be easily located, but these were not the actual coastlines at the time.

Isopic zones and massifs

The overall geology of the Alpine region has traditionally been described in terms of isopic zones and massifs. Isopic zones are groups of widespread rocks that share a common history, both in the ancient environments of deposition

of sediments (deep ocean, shallow sea, continent, etc.) and their faulting and folding. They were originally continental fragments, islands, oceanic ridges or parts of the ocean floor. Isopic zones may be hundreds of kilometres long, and up to several kilometres thick. They are bounded by faults, commonly shallow-dipping thrust faults, formed during regional compression, and are hence nappes or groups of nappes. These compressions have also stacked the isopic zones up onto each other and against the massifs.

Massifs are blocks of metamorphic and plutonic rocks, formerly assumed to be much older and more resistant to folding and faulting than adjacent sediments. Nowadays the distinction between massifs and rocks of the other isopic zones is not so clear: some of the metamorphism is quite recent, and parts of the massifs may not be much older than adjacent sedimentary rocks. Massifs are better considered as slightly lower levels of the continental crust exposed by faulting or erosion.

The isopic zones and massifs of the Aegean were once a series of continents, continental margins, deep troughs and ocean basins (Figs. 2.2, 2.3, 2.4). The present geographic distribution of these zones is now very different as they were piled up on top of each other during the Alpine crustal compression (see later). The various groups of rocks will be described in order from the 'internal' zones of the north-east to the 'external' zones of the south-west.

The most extensive area of metamorphic and plutonic rocks in the Aegean region is the Rhodope massif in Greek Thrace and Bulgaria, and the adjacent Serbo-Macedonian massif to the west (Fig. 2.2). These massifs may continue under the Thrace basin into north-eastern Turkey, as the Sakarya zone (or Western Pontides). All these massifs have long and complex histories, which may stretch back into the Precambrian epoch over 600 million years ago. They were partly metamorphosed and faulted during the Alpine compressions. More recently granites have been emplaced and volcanic rocks erupted.

The Vardar (Axios) isopic zone lies to the west of the massifs, and continues northwards into the former Yugoslavia (Fig. 2.2). To the

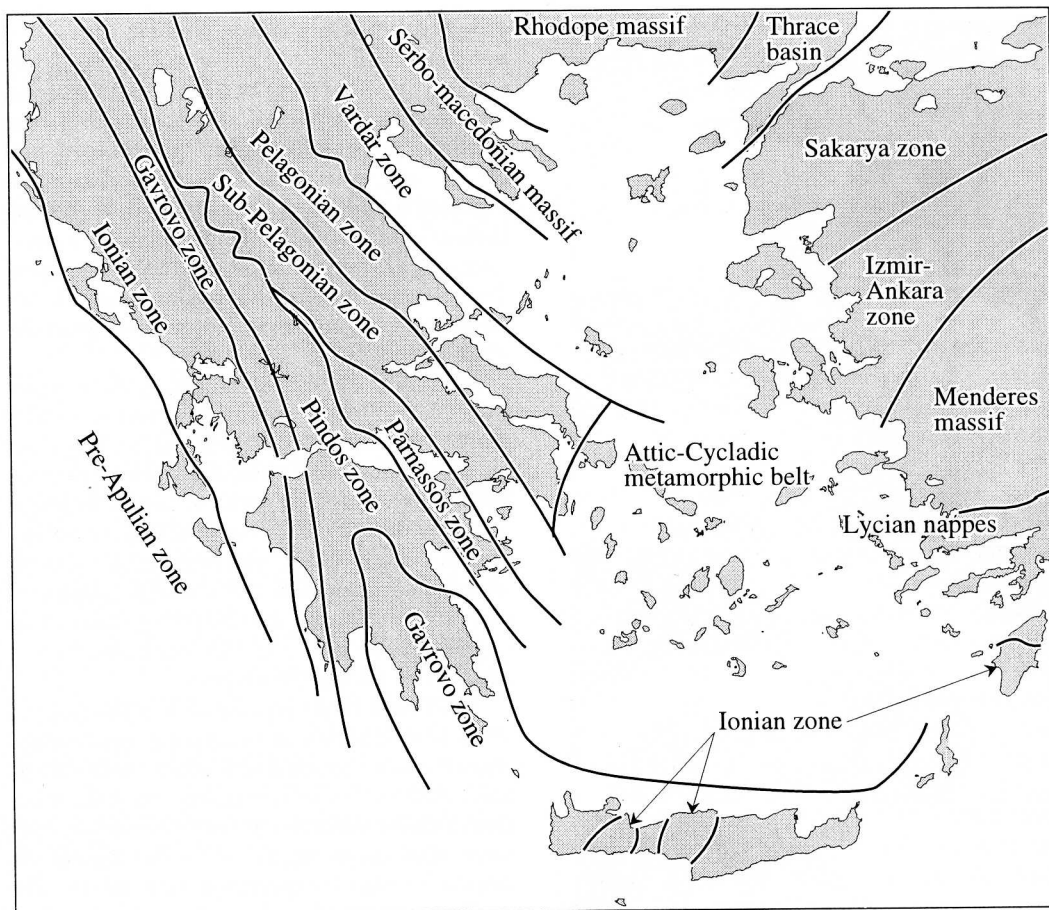


Fig. 2.2. Isopic zones and massifs of the Aegean region.

east it sweeps under the Aegean Sea, possibly to reappear in Chios. It may continue on the Turkish mainland as the Izmir-Ankara zone. It is a complex zone that has been sub-divided by some geologists into separate zones. However, it is dominated by Mesozoic deep-water sediments and ophiolites, and is hence an old ocean basin, part of Tethys. Within this basin were a number of older continental fragments, expressed as ridges.

The next isopic zone is the Pelagonian, which is exposed in much of eastern peninsular Greece. During the Triassic and Jurassic periods shallow-water limestones were deposited on this continental fragment, in an environment similar to that of the Bahamas today.

Some geologists consider that the Pelagonian zone continues to the south as the Attic-Cycladic metamorphic belt (or massif). The oldest rocks are schists, gneisses and granites some of which may be Palaeozoic. However, many of the rocks are similar in age to those of the adjacent zones, and some metamorphism was the result of the Alpine compressions.

The Menderes massif starts near the Aegean coast and extends far into central Turkey (Fig. 2.2). It is geologically similar to the Attic-Cycladic metamorphic belt but also shows some affinities with metamorphic rocks in Africa. It is not clear if it was separate from the Attic-Cycladic metamorphic belt, or merely a lateral extension.

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The Sub-Pelagonian zone is the great belt of ophiolites and associated rocks (limestones, cherts) of the Aegean, and continues to the north into Albania (Fig. 2.2). It may continue to the south-east within the Lycian nappes of Turkey. These rocks were originally part of a continental margin, between the Pelagonian continent and the Pindos Ocean. The region was lifted up during the Late Jurassic and Early Cretaceous. After a period of emergence, reef limestones were deposited during the Late Cretaceous. During the Oligocene and Miocene a deep continental trough developed, which filled up with up to 5 km of continental and shallow-water sediments, called molasse, and deep water flysch sediments.

The Parnassos zone is only exposed in south-central Greece. For most of the Triassic to the Palaeocene this small continental fragment was under shallow water, and limestones were formed. When the region was dry land tropical weathering produced bauxite deposits. These rocks were followed by flysch, which terminated with conglomerates in the late Eocene, indicating nearby mountain-building.

The Pindos zone crops out in central Greece and the Peloponnese, but is much more extensive as it underlies or rode over much of the other zones. Its sediments were mostly deposited in a deep oceanic trough, but there are no ophiolites in this zone. During the early part of its history it was a true ocean basin.

The Gavrovo zone (in places called the Tripolitza zone) is narrow along the coast of Albania and in central Greece, but widens out in the Peloponnese. Like the Parnassos and Pelagonian zones, this region was a continental fragment for the early part of its history. Initially, during the Mesozoic, thick shallow-water limestones were deposited. However, in late Eocene times mountains had been formed and they shed flysch sediments onto the limestones, almost completely covering them up.

The Ionian zone comprises much of Epirus, and parts of the Ionian islands and Peloponnese. Like the Pindos zone, in early times this zone was an area of deep water, but probably floored by thin continental crust. Again it contains Mesozoic limestones deposited in a trough. As in the Gavrovo zone, and for the

same reasons, flysch makes its appearance in the Eocene.

The most external (westerly) zone is the Pre-Apulian, and it barely touches our region. It comprises little deformed sediments of both deep and shallow water origin, and is really part of the Apulian platform of Italy. It is a block of continental crust.

To these zones and massifs we must add the Thrace basin of north-western Turkey. It is not a true isopic zone as it was formed after most of the Alpine compressions, in response to movements of the North Anatolian fault zone, which divides the Eurasian plate from the Turkish plate. A large thickness of sediment was deposited here from the Early Tertiary onwards, but recently sedimentation has ceased and depression of the crust has shifted southwards to the Sea of Marmara.

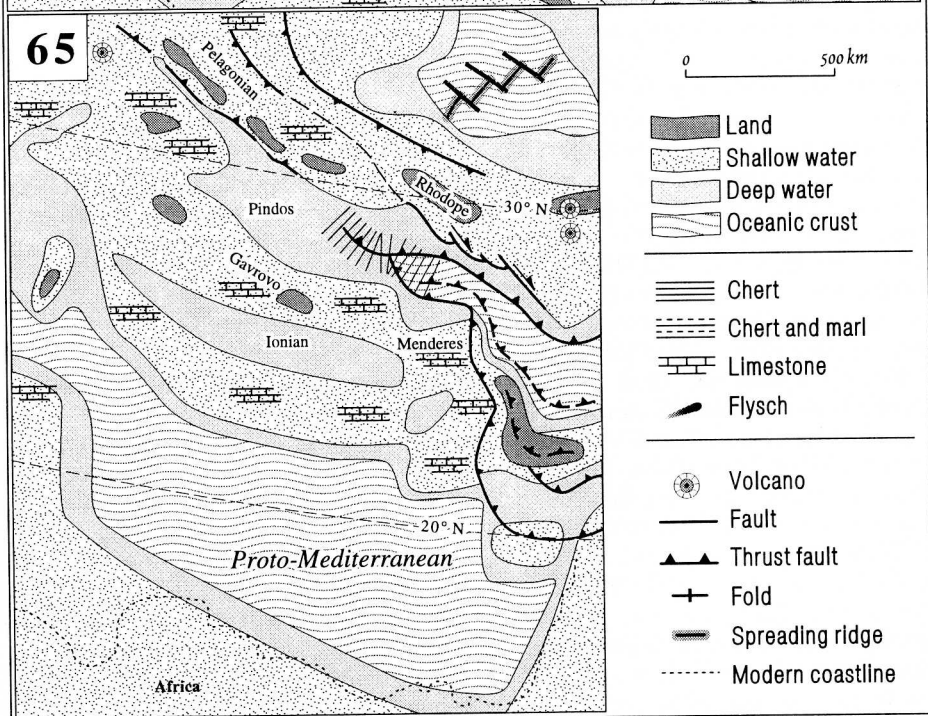
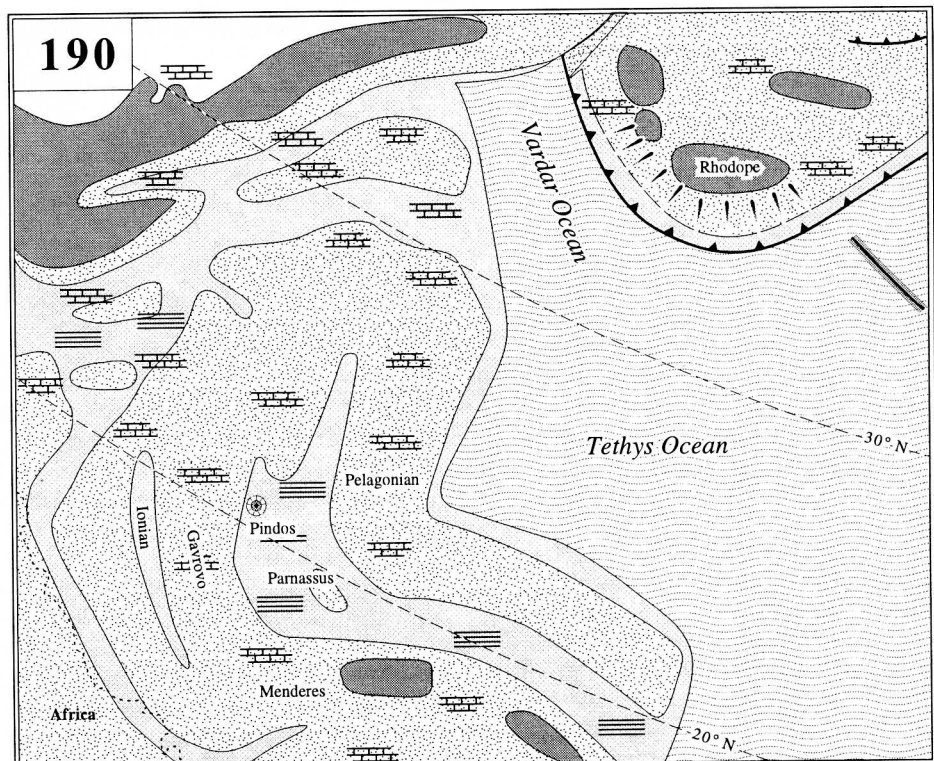
Thus overall the various zones and massifs represent an alternation of micro-continent, deep troughs on continental crust and true ocean basins (Fig. 2.4). Next we will trace the interactions between these units and their assembly into the present Aegean region.

The geological development of the Aegean

There have been many different reconstructions of the history of the Mediterranean region, but here we will follow that of Dercourt et al.⁵⁶ which is the most comprehensive. The overall history is that of the closure of an ocean basin filled with islands and underwater ridges and the thrusting of each component onto the adjacent parts generally to the north and east (Figs. 2.3, 2.4).

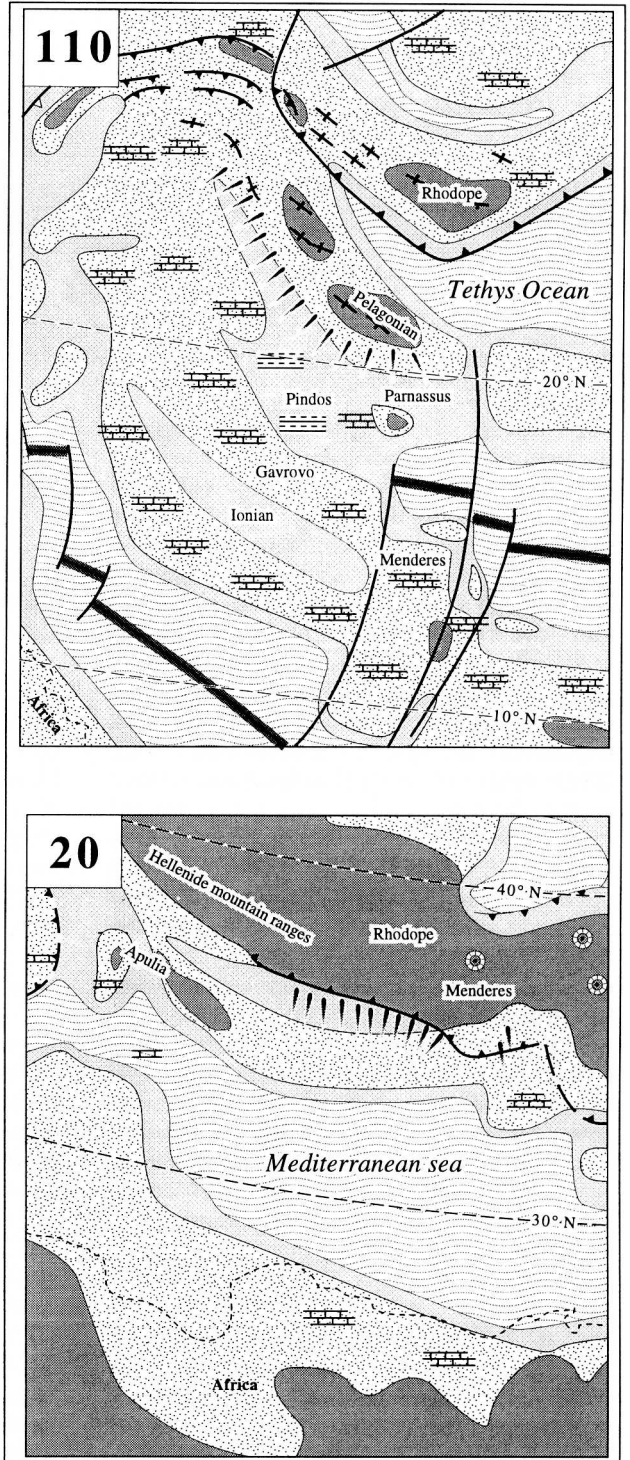
In the Early Jurassic, 190 million years ago, the Rhodope and Serbo-Macedonian massifs and the Sakarya zone lay along the north shore of the Tethys Ocean. These rocks are considered to be the southern margin of the Eurasian continent. To the south a subduction zone plunged northwards under the continent. All the other zones lay further south, adjacent to the African continent. Between was a wedge of true ocean, part of the Tethys Ocean.

The Pelagonian, Parnassos and Gavrovo zones were continental platforms, covered by



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Fig. 2.3. Ancient positions of the isopic zones of the Aegean region for 190, 110, 65 and 20 million years ago.⁵⁶ Most of these zones, except the Rhodope massif, originally lay adjacent to the African continent. The abundant limestones of the Aegean region formed in these warm, mostly shallow, seas. Convergence of Africa and Eurasia forced the Tethys sea to close up, but at the same time a new ocean basin, the early Mediterranean, opened up to the south. Expansion of the basin separated the Aegean isopic zones from Africa and helped to force them against Eurasia.



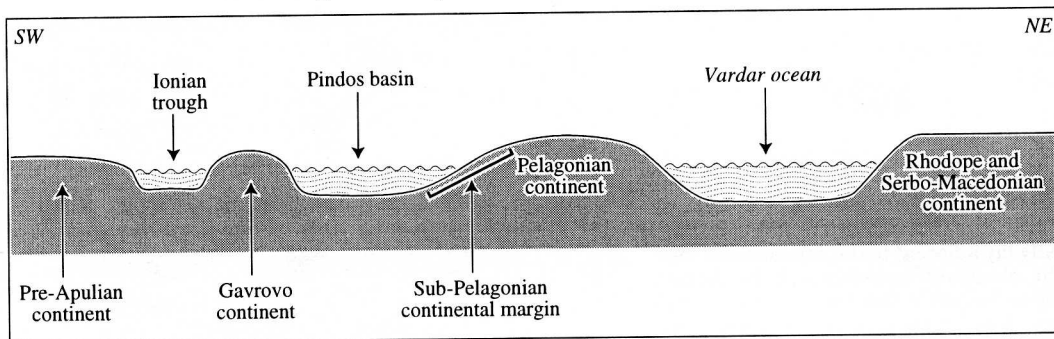


Fig. 2.4. Schematic section across the Aegean region before compression. The Pre-Apulian, Gavrovo and Pelagonian continental zones were covered with shallow seas for much of the time.

shallow, warm tropical seas, where limestones were deposited in an environment similar to that of the Bahamas today (Fig. 2.4). The Ionian zone was a deep trough on the African continental shelf and the Pindos basin was floored by true oceanic crust. The Sub-Pelagonian zone was the continental margin adjacent to this basin. This arrangement was relatively stable until the end of the Jurassic (130 million years ago) when parts of the Sub-Pelagonian continental margin and Pindos basin were thrust eastwards onto the Pelagonian continental platform.

A major change had occurred by the Mid-Cretaceous, about 110 million years ago; a new plate boundary had formed south of the Pre-Apulian zone and an ocean basin, the Proto-Mediterranean, was growing. This new ocean detached from Africa the zones that would later form the Aegean region and Apulia (southern Italy). As there was relatively little change in the positions of Eurasia and Africa, the Tethys Ocean basin to the north had to close up. It was partly subducted beneath Eurasia and partly piled up against the massifs as in the Vardar zone. As the Pelagonian zone neared Eurasia the regional compression was converted into uplift by movements along thrust faults. Parts of the Pelagonian zone above water shed flysch sediments into the Pindos Ocean basin to the south-west. Similarly the Parnassos continental fragment was raised above sea-level and intense tropical weathering produced bauxite and laterite deposits.

During the next period the Aegean isopic zones were forced to the north by expansion of the ocean to the south. Ocean basins were subducted and/or thrust westwards over the adjacent zones. Continental fragments were similarly stacked, one on top of the other. By 35 million years ago all that remained of the vast platform once attached to the African mainland were the Ionian and Pre-Apulian zones. Even the Menderes massif had been welded onto Eurasia. By 20 million years ago the Ionian zone had almost been completely consumed, and continental crust, albeit thinner than normal, linked Apulia and the Hellenide mountain ranges.

The overall process of regional compression has continued in the Ionian islands to this day, but elsewhere in the Aegean major regional expansion became important. This expansion has shaped much of the landscape of the Aegean and continues today.

Subduction of oceanic crust northwards beneath the Aegean started during the Miocene, or possibly a little earlier, initially along an east-west line (Fig. 2.5). The crust above the subduction zone arched upwards to form the non-volcanic Hellenic arc, now represented by the islands of Crete, Karpathos and Rhodes, the western edge of the Peloponnese, and south-eastern Turkey.¹³ Further north melting of the subducted slab, and the overlying mantle, produced the volcanoes of the South Aegean volcanic arc and the more diffuse, but important, Early Miocene volcanic rocks in the western Aegean and Turkey. Volcanism con-

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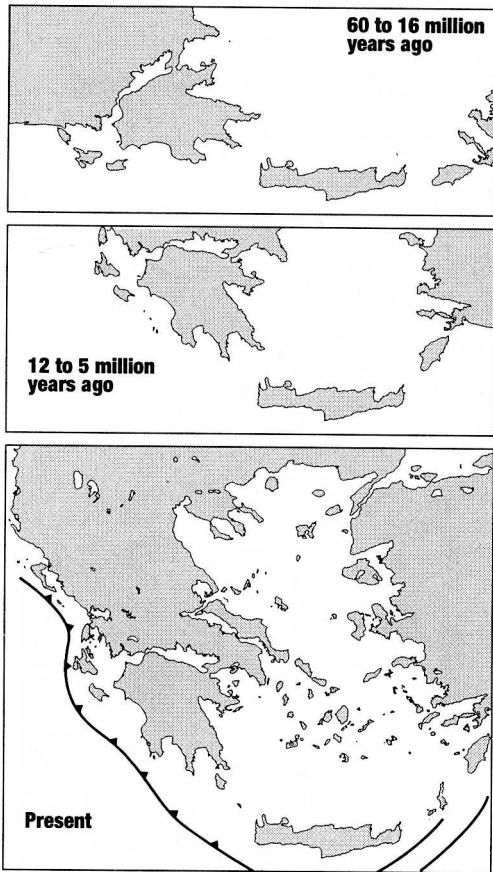


Fig. 2.5. Evolution of the Hellenic arc over the last 60 million years.¹³⁷ Initially the arc ran almost straight, east/west. The curvature developed by expansion of the crust north of the Aegean arc, forming the present Aegean Sea.

tinues now on the islands of Thera (Santorini) and Nisyros.

Crustal extension associated with the subduction was concentrated in the region north of Crete, above the subduction zone, so that the initially straight subduction zone was inflated into the curve we see today (Fig. 2.5).¹³⁷ This extension was coupled to overall plate motions, so that a large part of the region has experienced Neogene extension. At the surface the crust has responded to this extension by developing grabens and horsts. The orientation of these structures is rather variable, but many are approximately north-west/south-east, al-

though some of the youngest faults in the Peloponnese and Crete are north/south. It is these grabens and horsts that have produced many of the mountains and valleys, as well as the islands.

Mention should be made of an unusual event that occurred about six million years ago: The Mediterranean sea almost completely dried up.¹¹⁷ This happened when tectonic forces closed up the Straits of Gibraltar. Rivers flowing into the basin, principally from the Black Sea, were insufficient to maintain sea-level and the sea dried out, except for a few saline lakes like the modern Dead Sea. There may even have been a salty waterfall at Gibraltar, also feeding the lakes. Evaporation of water from the lakes produced deposits of gypsum and other minerals.

The present plate tectonic configuration of the Aegean region is rather complex and the details are much disputed (Fig. 2.6, Plate 2).²⁶⁰ The African plate is moving north-east with respect to Europe and descending along a subduction zone underneath the Aegean plate. To the east the plate motions are almost parallel to the plate boundary, hence the relative motion is taken up by strike-slip faulting. Still further east, towards Cyprus, the subduction zone resumes. In the north the Anatolian plate that carries much of Turkey is moving westwards with respect to Europe, and most of this motion is taken up by a strike-slip fault, the North Anatolian Fault zone. This fault runs across the northern Aegean Sea, as the North Aegean Trough, and fades out somewhere near Volos. The motion is also taken up by a number of parallel faults to the south in western Turkey and the Aegean. There are no simple plate boundaries within peninsular Greece to link up the major structures; motions are shared between a number of smaller faults of all types.

Geologically recent events

During the last cool interval of the glacial period, about 130,000 to 20,000 years ago, the climate of the Aegean was moist and cool. Glaciers were restricted to the highest mountains on the Greek and Turkish mainlands, and the island of Crete. Sea-level was considerably

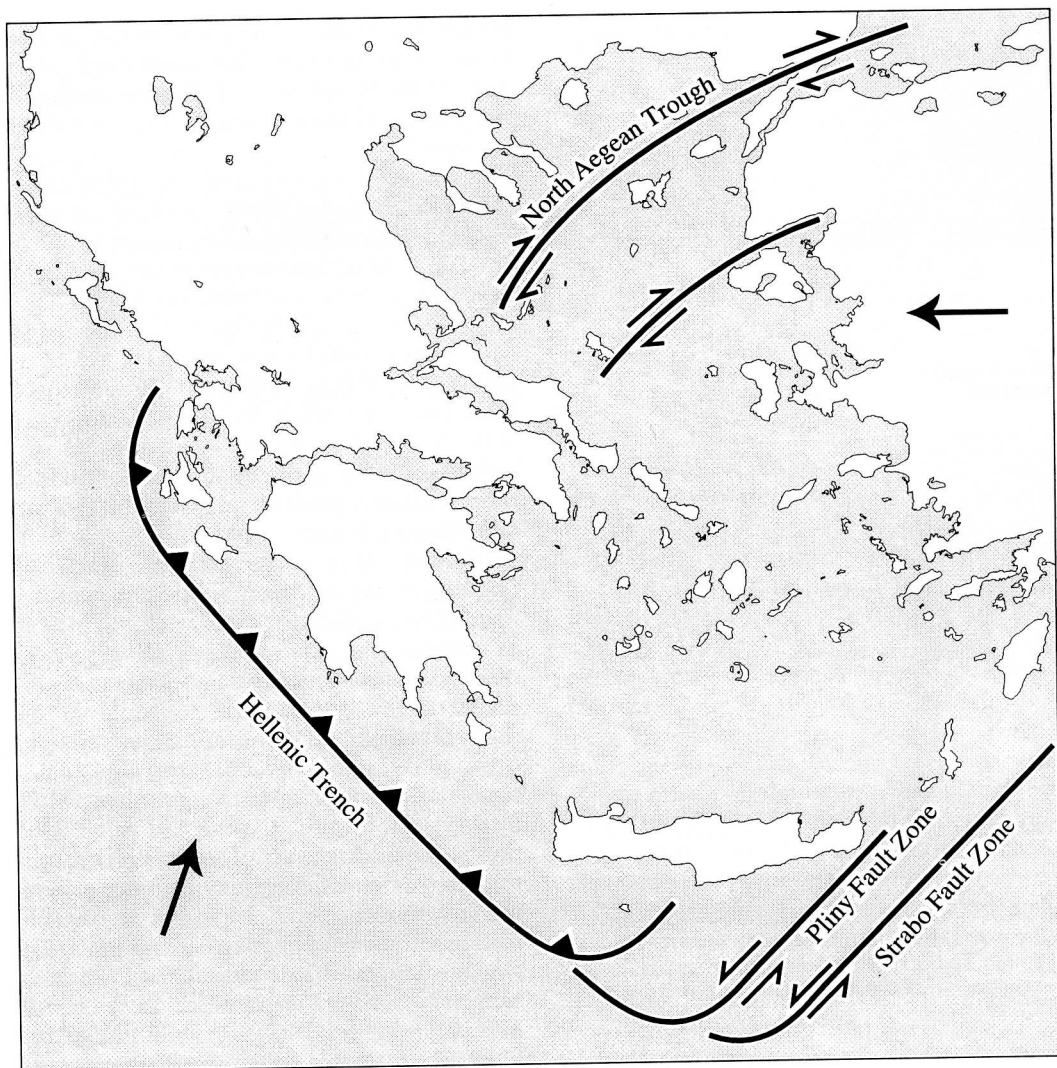


Fig. 2.6. The present-day plate tectonics of the region (after 260).

lower than it is today, and hence the river-beds were steeper and there was rapid erosion. Mountains were deeply incised and broad, flat valleys were developed. It is this landscape that we see in Greece today, modified by post-glacial effects. Many of the red and brown soils were produced during this period.

At the end of the last glacial period the warming was accompanied by a rapid increase in sea-level. The sea invaded the valleys, form-

ing deep inlets, which were rapidly filled in by sediments transported by the rivers. The alluvial sediments that fill most Mediterranean valleys have been divided into the 'older' and 'younger' fills, originally thought to have been two synchronous events.²⁷⁷ However, it is clear that in many places there are several different younger fills, which are not synchronous. The older fill was produced by erosion associated with the post-glacial warming, but the cause of

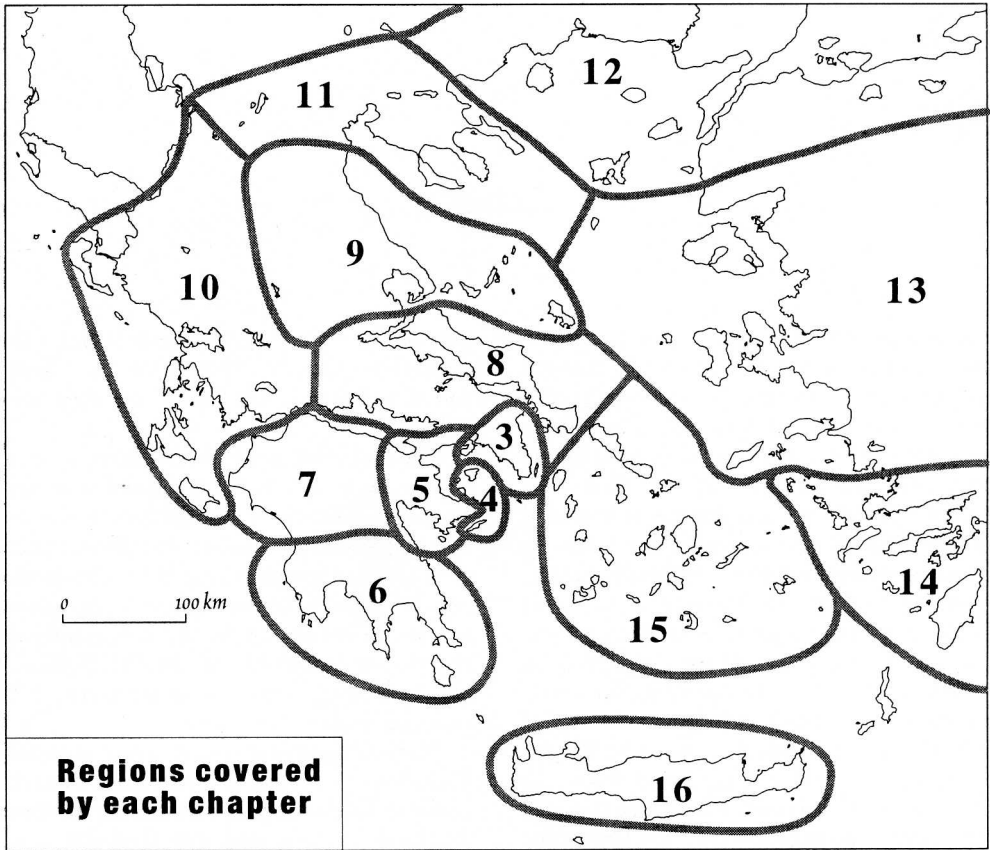


Fig. 2.7. The regions covered by Chapters 3 to 16.

the younger fill(s) is more problematical. It was originally suggested that it was due to the climate becoming drier, but there is little evidence for significant changes over the whole

region.^{191, 235, 237} A more likely cause is deforestation produced by people and maintained by grazing animals.^{270, 271}