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# THE MESOZOIC SUTURES OF TETHYS

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Translated from "Mezozoyskiye sutury Tetisa," *Geologiya i razvedka*, 1988, No. 11, pp. 3-21. The author is with the Geological Institute of the USSR Academy of Sciences. This paper reviews the status of the large and difficult task of tracing the sutures that mark the docking of microcontinents to the southern margin of Eurasia from Central Europe to Tibet—a task complicated by the bifurcation of sutures around landmasses and the displacements of the sutures by the subsequent Alpine orogeny as the main mass of Gondwana collided.

Throughout the Mesozoic and Cenozoic, the Eurasian continent grew by the accretion first of the microcontinents of the Tethys Ocean, and then of the continents of Gondwana. As they approached Eurasia, the microcontinents cut marginal basins with an oceanic crust off from Tethys. Collision of the microcontinents with Eurasia led to the closure of such basins and the formation of oceanic sutures. The sutures formed within a particular interval are combined under a common name. An important stage of collision of the microcontinents with Eurasia was in the Cretaceous, when the sutures of the meso-Tethys ocean formed. In using this term, it must be kept in mind that the presence of Meso-Tethys sutures does not mean disappearance of the ocean that separated the continents of the northern and southern groups. The Meso-Tethys sutures are the result of the collision of the microcontinents of Tethys with Eurasia.

Whether any particular territory belongs to the Eurasian or the African-Arabian domain can be determined by the facies and biogeographic communities of the Liassic, as that was a time of strongly contrasting paleogeographic conditions in Tethys and on its margins. Study of the Liassic ammonite faunas has enabled M. Neumayr to distinguish the Middle European and Mediterranean faunal provinces in Europe. Middle European species of Lower Jurassic ammonites occur in extra-Alpine Europe. In the Carpathian region the ammonite fauna is contained in Liassic deposits of two facies types. A clastic-carbonate facies contains Mediterranean and Middle European ammonite species in approximately equal quantities. Lithologic studies have shown that the terrigenous material came from the northern borderlands of the Mesozoic Tethys and that the deposits were formed on the shelf of the Eurasian continent.

The second facies type includes the condensed sections through deep-sea carbonate deposits of the "ammonitico rosso" facies and its analogs. Mediterranean ammonite species are strongly dominant. These deposits were formed on the continental slope and in the marginal seas of the African continent. The deep-water zone of Tethys was an obstacle to the penetration of European fauna to the African margin. This "filter" functioned in Pliensbachian and South Tethys biogeographic provinces, separated by a deep-sea "barrier."

The relationship between these biogeographic provinces can be readily seen from the distribution of Liassic brachiopod communities [42, 55]. Figure 1 shows the brachiopod localities in which the number of species characteristic of one province exceeds by twice or more the number of species of the other biogeographic province. The difference between these biogeographic provinces can also be established by the Liassic and Dogger benthic foraminiferal faunas. The geographic range of the Pliensbachian genus *Orbitopsela* and the Bathonian species *Satorina apulensis* characterizes the South Tethys province, and that of *Orbitammina elliptica* the North Tethys province [25].




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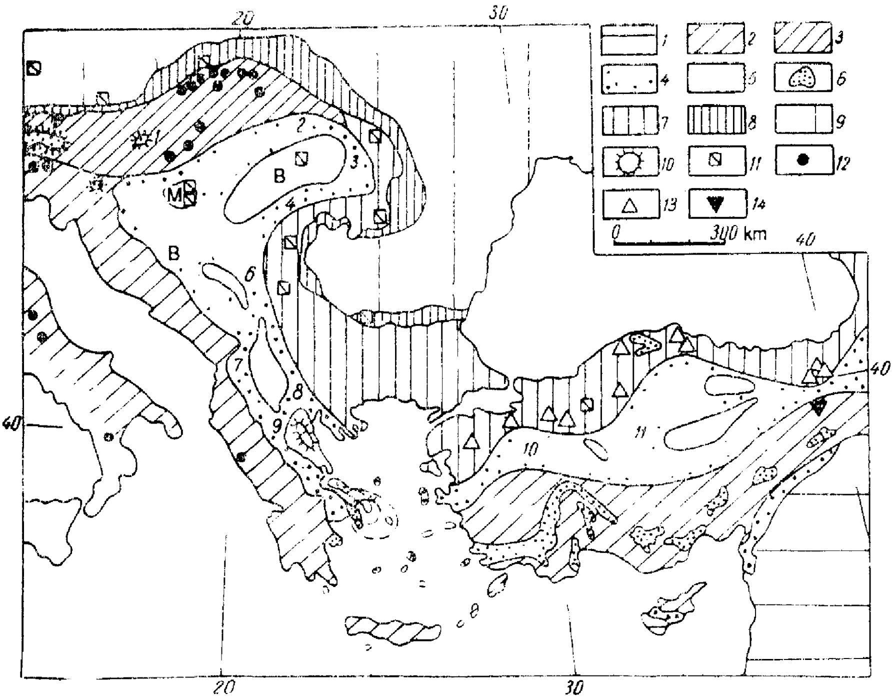

FIGURE 1. Eastern Europe and Asia Minor: 1) Arabian continent; 2-3) African-Arabian margin of Mesozoic Tethys: 3) Hemer-Tatra megazone, 4-5) region of occurrence of ophiolites (5) median massifs); 6) ophiolitic allochthons isolated from root zone; 7-8) Eurasian margin of Mesozoic Tethys: 7) Rhodope-Iran megazone, 8) flysch zones of Carpathians and Balkans); 9) Eurasian continent; 10) tectonic windows; 11-12) Liassic brachiopod localities [42, 55, 56]: 11) North Tethys community, 12) South Tethys community; 13-14) Liassic ammonite localities in Asia Minor [24]: 13) North Tethys communities, 14) South Tethys communities.

We now consider the present position of the Meso-Tethys sutures in the Alpine belt from the Alps to Tibet.

### African-Arabian Margin of Mesozoic Tethys

An inner and an outer belt (megazone) can be distinguished on the African-Arabian margin. Neritic facies predominate in the Jurassic rocks of the inner megazone. Tectonic zones included in this megazone are the Dalmatian, Kruya and Karst zones in the Dinarides; the Gavrovo, Tripolitsa, Ionian and Parnassus zones in the Hellenides; the Ida zone on Crete; and the Arkhangelos zone on Rhodes. The rocks of the inner megazone made up the Adriatic microcontinent, which belonged to the African-Arabian domain.

In the outer megazone the Jurassic sections are condensed, and consist predominantly of pelagic limestones and radiolarites formed on the continental slope and in marginal seas. The outer megazone comprises the Budva and Krasta-Tsukali zones in the Dinarides, the Pindus zone in the Hellenides, the Etkhia and Mangasa zones on Crete, the Adra zone on Carpathos and the Profitis Elias zone on Rhodes. Tectonic nappes made up of Jurassic pelagic rocks are also known in the Taurus and Inner Zagros Ranges. Because of the extensive development of overthrusts, the rocks of the inner and outer megazones do not always occupy the position corresponding to their name in the present-day structure.

To the African-Arabian domain also belongs the Hemer-Tatra megazone, which encompasses the inner western Carpathians, the Middle Hungarian mountains and part of the eastern Carpathians. In the west, this megazone continues into the Eastern Alps. The Hemer-Tatra megazone, which now occupies an allochthonous position [4], overlies rocks of the Meso-Tethys oceanic crust, which are exposed in tectonic windows (Fig. 1, No. 1) near Wechsel and Rechnitz in Austria and around Köseg in Hungary. The Jurassic deposits of the Hemer-Tatra megazone include, besides crinoid limestones, extensive pelagic limestones and radiolarites. The pelagic rocks are developed in the Liassic and Dogger sections of the Tatrides, the Dogger and Malmian sections in the Fatrik zone, the Liassic sections in the Veporides, and the Dogger sections in the Khronik zone.

The South Tethys community of Liassic brachiopods occur in the Austro-Alpine imbricate thrust sheets, the Southern Alps, the Appenines, the Hellenides, in the inner zones of the western Carpathians and in the Middle Hungarian mountains. South Tethys ammonites of the Liassic are also known in the Middle Hungarian mountains [39], as are South Tethys benthic foraminifera of Early and Middle Jurassic age in the outer zones of the Dinarides [25]. In Asia Minor, the South Tethyan biogeographic province of the Taurus has been established on the basis of benthic foraminifera and ammonites (Fig. 1).

## Eurasian Margin of Mesozoic Tethys

On the Eurasian margin are extensively developed rocks of the pre-Alpine continental crust, over which a cover of Mesozoic sedimentary deposits is preserved. The Jurassic section consists of nearshore and continental coal-bearing and clastic deposits. The marine strata of the Liassic contain a fauna of the North Tethys type. This Rhodope-Iran marginal zone includes the Marmarosh overthrusts of the eastern Carpathians, the Gaetian overthrusts of the Southern Carpathians, the Serbian-Macedonian and Rhodope massifs, the Sredna Gora and Stara Planina zones of the Balkanides, the Sakariya massif and the Pontides in Asia Minor, the Samkhet-Kafan, Artvin-Bolnis, Adzharo-Trialety, Georgian (Dzirul'), Gagra-Dzhav and Talysh zones of the Caucasus, the Elbrus Range and Central Iran.

The Jurassic deposits unconformably overlie pre-Paleozoic, Paleozoic and Triassic rocks. In the Carpatho-Balkan region, the Jurassic in many cases is not present in the section. In the Gaetian overthrusts, the rocks of Jurassic age are a series (500 m) of conglomerates, sandstones and clay shales with coal seams. Ammonites were found in the shales and a fossil flora in the coals [46].

The Jurassic in the Pontides has a similar structure. In the eastern Pontic region the Liassic consists of a cyclical terrigenous series with plant remains and coal horizons (the Kil'kit formation). Of subordinate importance are spilite, diabase, keratophyre, and trachyandesite flows and tuffs. The volcanics are in part subaerial and in part subaqueous. In the Kil'kit River valley the volcanics include a horizon of limestones with numerous Sinemurian-Pliensbachian ammonites [29]. The volcanic activity can be attributed to the opening of the Mesozoic Tethys. The Liassic ammonites in the Western and Eastern Pontic regions are of the European type [24, 37]; the fauna has been described from many localities (Fig. 1). The Upper Jurassic ammonites of the Pontides also belong to the North Tethys biogeographic province [38].

In the Dzirul' crystalline massif, the Liassic section begins with a series (up to 700 m thick) of tuffs, sandstones, and conglomerates, with interbedded carbonaceous shales containing a flora of ginkgos and ferns. The tuffs and metamorphic rocks are overlain, with an erosional hiatus, by quartzose and arkosic sandstones (up to 200 m thick) in which coal inclusions have been found. The upper part of the section (up to 300 m thick) is made up of limestones with ammonites and brachiopods of Middle and Late Liassic age. The ammonite fauna is represented by a mixture of Mediterranean and Middle European species such as is usual in the North Tethys biogeographic province [16, 17].

In the Artvin-Bolnis zone the Liassic deposits overlie the metamorphic rocks of the Loki and Khrami massifs. The lower part (up to 400 m thick) of the Loki section is made up of sandstones with lenses of coals, with plant remains and also Sinemurian-Pliensbachian ammonites. Above these lies a series (up to 500 m thick) of cyclically alternating sandstones, siltstones, and argillites with ammonites of Pliensbachian, Toarcian, and Aalenian ages. The Liassic sections on the periphery of the Loki massif and in the Shamkhor anticlinorium of the Somkhet-Kafan tectonic zone are similar [5, 13].

In the Iranian Talysh and Elbrus mountains and in Central Iran, the Rhaetian, Liassic and part of the Dogger are represented by a thick terrigenous coal-bearing series known as the Shemshak formation. This formation is coarsely cyclical: continental (alluvial, lacustropaludal) and nearshore marine deposits alternate in the section. In the Iranian Talysh Mountains the section (1000 m thick) is composed of argillites, siltstones and sandstones with thin interbedded conglomerates and limestones. These deposits contain a Lower Liassic flora and molluscs (ammonites and pelecypods) ranging from Sinemurian to Bajocian in age [32]. The flora of the Shemshak province belongs to the Eurasian biogeographic province.

In the Elbrus Range the Liassic section resembles that in the Talysh Mtns. Coal measures with producing coal seams are present in the Central Elbrus Mtns. The number of coal-bearing horizons and thin beds of marine limestones decreases northeastward. The thickness of the Shemshak formation in the Elbrus Range ranges up to 4000 m. A Lower Liassic flora was found in the lower part of this formation, Toarcian-Aalenian ammonites in the middle, and a Middle Jurassic flora in the upper part. The Shemshak formation is overlain by limestones with an Upper Bajocian marine fauna [15, 33]. In the Northern Elbrus, sedimentation occurred under continental conditions. The sedimentary material was brought in by rivers flowing from north to south. The Southern Elbrus region was an area of alluvial-deltaic and lagoonal-deltaic deposits.

West of the Elbrus Range, the Shemshak formation is found all the way to Lake Urmia, and in Central Iran to the main overthrust of the Zagros Mtns. Northwest of Isfahan, the thickness of these deposits reaches 2000 m.

In Northeastern Iran, in the Binalud Mountains, are clastic continental-nearshore formations of Rhaetian-Liassic age. In the Iranian Kopet-Dag Range these rocks (the Kashafrud formation) lie unconformably on clastic-volcanogenic deposits with a fauna of Late Triassic age [22]. In the eastern Kopet-Dag Range (the Mozduran Mountains) the thickness of the coal-bearing Rhaetian, Liassic and partly Dogger rocks is almost 2000 m. Farther east, Liassic coal measures are developed in the northern foothills of the Hindu Kush Range, the Afghan-Tadzhik depression, and the Central and Northern Pamir regions. Coal-bearing Jurassic rocks also occur on the Turanian platform and in the Tien Shan region.

In the Carpathians and the Caucasus, the Rhodope-Iran megazone in Jurassic and Early Cretaceous time was separated from the Eurasian continent by marginal marine basins. In the Carpathians and the Balkans, flysch deposits were formed in these basins; they now lie in the Rakhovo-Belotissen zone, the area of the Severin overthrust and the Cisbalkan zone. The suture of the basin, which closed in the middle of the Cretaceous, is located in the eastern and southern Carpathians. In the southern Carpathians it is marked by the ophiolites of the Severin overthrust. The ophiolitic complex consists of ultrabasites, gabbros, and Upper Jurassic oceanic basalts [46]. On the Severin allochthon lies the Gaetian nappe of crystalline rocks.

In the Eastern Carpathians a similar structural position (beneath the Marmarosh nappes of crystalline rocks) is occupied by the Kamennyy Potok ("black shale") nappe. This allochthon contains Upper Jurassic basalts, but no gabbros or ultrabasites have been found in it. Trace element patterns in these basalts indicate that they are intracontinental basalts formed within a rift structure [50]. The extent of opening of the basin marked by this sutural zone was clearly different in the different parts of the basin. Farther south the suture probably continues into the Porech zone of Eastern Serbia.

In the Caucasus the deposits of the marginal marine basin occupy the flysch zone of the Greater Caucasus. In Jurassic time, flysch was formed in the Toarcian-Aalenian and Callovian-Kimmeridgian stages. Volcanic rocks are extensively developed within the Jurassic formations. The Lower and Middle Liassic sections in Svanetia, Racha, and Kakhetia contains calcic-alkalic lavas and tuffs. In Pliensbachian-Toarcian, Aalenian and Bajocian time, tholeiitic spheroidal lavas and hyaloclasts were formed in the Chkhaltin-Layla tectonic zone. These lavas show a petrochemical zonality, with slightly alkalic varieties near the basin margins. The volcanics do not form continuous series, but are everywhere interlayered with sedimentary rocks, which predominate in the section. The Liassic, Aalenian, and Bajocian rocks are also penetrated by numerous diabase sills and dikes [12]. The fauna of Liassic and Dogger ammonites in the Greater

Caucasus shows that the region belonged to the North Tethys biogeographic province [16, 17].

East of the Caspian Sea, there is no point in distinguishing the Rhodope-Iran marginal zone: here there are neither ophiolites nor Alpine flysch zones such as might separate the megazone from the Turanian and Tien Shan regions.

### Ophiolite Zones and Sutures of Meso-Tethys

Over a large part of the region under consideration, the Eurasian and African-Arabian domains are separated by a megazone in which oceanic volcanics and ophiolites are developed. In most cases the oceanic volcanics are of Jurassic and Early Cretaceous age, but some are Triassic. In Figs. 1 and 2 the megazone is shown as including ophiolitic allochthons, which are probably connected with their root regions. Isolated rootless ophiolitic allochthons are marked by a special symbol outside the megazone.

In the Dinarides, the ophiolitic megazone (Fig. 1) includes the Zlatibor (5), Serbian (7) and Kopaniok (6) zones, and in the Hellenides the Vardar (8) and Otris-Pelagonian (9) zones. Within, and locally on, the ophiolites lie masses of Paleozoic and older rocks. Many of these massifs were probably microcontinents within Tethys. In the Dinarides-Hellenides the largest are the Pelagonian massifs (Attic-Cyclades, Thessalian and Western Macedonian) and Golia. Fragments of the rocks of these massifs are known in the flysch and olistostromes of the Dinarides, beginning with the Berriasian.

The ophiolitic megazone occupies a large part of the area of the Pannonian basin. In the southern part of the Apuseni mountain massif, within the Mures zone (Fig. 1, No. 4), ophiolites of Jurassic age are found. The ophiolite zone continues northeastward beneath the over of younger deposits of the Transylvanian basin. The evidence for its existence consists of the Transylvanian ophiolitic nappes of the eastern Carpathians (Fig. 1, No. 3). The age of the Transylvanian ophiolites is in the interval from the Middle Triassic to the Neocomian [49]. The Mures ophiolites have been traced westward beneath the cover of young deposits to the area of Belgrade—that is, to the Vardar-Kopaniok ophiolite zone. Another branch of the Vardar-Kopaniok ophiolite zone extends northwestward all the way to the Danube River valley.

In the northern part of the Pannonian basin, the rocks of the ophiolite association occur in the Bükk Mountains (Fig. 1, No. 2), where mafic spheroidal lavas, gabbros, and ultrabasites are exposed at the surface. These lavas are probably of Liassic age. Between the Bükk and Matra mountains, around the Darno line, are outcrops of gabbro-diabases, a complex of diabase dikes, spheroidal lavas, radiolarites, and tuffs. Petrochemical and geochemical studies of the volcanic rocks (including trace element patterns) have led to the conclusion that they belong to the abyssal tholeiite group [36, 48]. South of the Balaton-Darno line, rocks of the ophiolitic association have been revealed by boreholes drilled into the basement of the Great Hungarian basin, in the watershed areas between the Drava and Danube, the Danube and Tisza, and east of the Tisza rivers. Gabbros, spilites and diabases, overlain by radiolarites, have been found in these borehole sections [42]. The volcanogenic-radiolarite part of the section is Jurassic or Early Cretaceous in age [52]. Farther northeast, similar sections have been penetrated by boreholes drilled into the basement of the Transcarpathian basin [8]. The volcanic rocks of the ophiolitic association described here, judging by their petrological characteristics, are ocean tholeiites.

The zone under consideration, in which rocks of the Mesozoic ophiolite association are developed, has a southwesterly trend and in the area of Zagreb approaches the ophiolite zone of the Dinarides. It can be concluded that the ophiolite belt extends from the sub-Pelagonian zone of the Hellenides through the Zlatibor and Serbian zones of the Dinarides into the northern part of the Pannonian basin. The northwestern boundary of this belt is the Balaton—Darno line, although farther north some outliers of Mesozoic ophiolites (the Meliata series) may lie in allochthonous position on the Hemerides [42] or crop out in windows [44]. On the whole, the structure of the greater part of the Pannonian basin (to the Balaton—Darno line in the northwest) resembles that of the Vardar-Pelagonian part of the megazone, although there are probably less ophiolites in the Pannonian part of the zone, and the area of the microcontinents is considerably larger. Zones with oceanic volcanics and ophiolites (Zlatibor, Igal-Bükk and Mures-Transylvanian) mark the boundaries of the megazone in the Pannonian basin. Similar zones probably

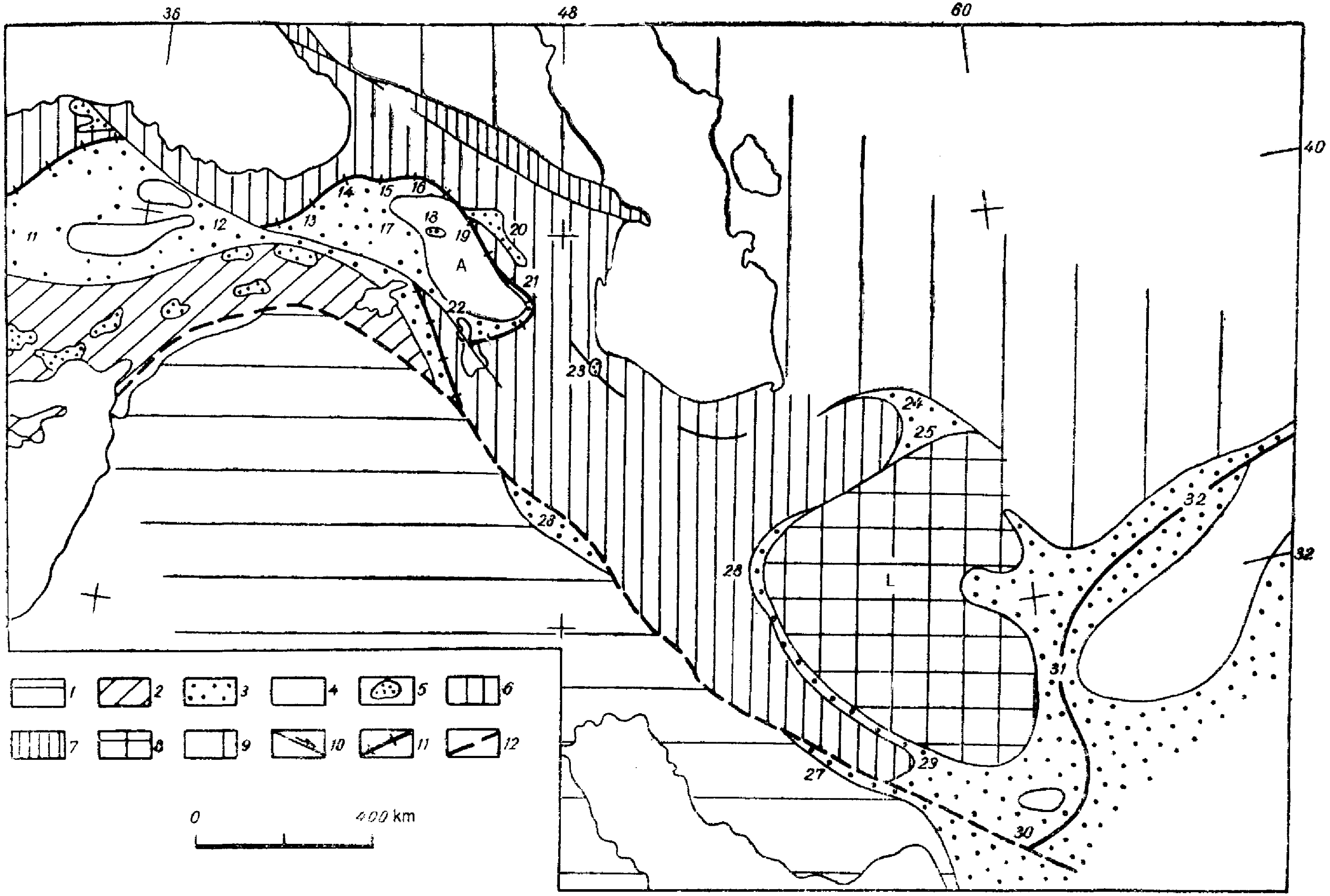


FIGURE 2. Caucasus and Iran: 1) Arabian continent; 2) African-Arabian margin of Mesozoic Tethys; 3-4) region of occurrence of ophiolites (4) median massifs); 5) ophiolitic allochthons isolated from root zone; 6-7) Eurasian margin of Mesozoic Tethys: 6) Rhodope-Iran megazone, 7) flysch zone of Caucasus; 8) Lut massif; 9) Eurasian continent; 10) Anatolian strike-slip fault; 11-12) oceanic sutures: 11) Meso-Tethys, 12) Neo-Tethys.

separate the massifs (Bikhor, Mechek and other smaller one), which have a pre-Alpine continental basement.

In the area of the Bikhor (Fig. 1, letter B) and Mechek (Fig. 1, letter M) massifs, the Lower Liassic is represented by paralic coal measures such as are common to the sections through the margin of the Eurasian continent. The communities of Liassic ammonites and brachiopods studied in these median massifs belong to the North Tethys biogeographic province [40, 42]. The Bikhor and Mechek microcontinents probably gravitated toward the Eurasian continent.

North of the Pannonian basin, the boundary between the African and Eurasian domains is the Pjenina klippe zone. The Jurassic section here is composed of siliceous-carbonate deposits of the neritic and pelagic facies. In the transverse section through the Pjenina zone, the neritic facies of the Jurassic are distributed symmetrically with respect to the plagic rocks, enabling the relicts of the deep-sea basin and the submarine uplifts bordering it to be distinguished. The structure of this zone is extremely compressed. Its present width ranges from several hundred meters up to several kilometers, although its length exceeds 700 km.

There are no outcrops of ophiolites in the Pjenina zone. Rock fragments of the ophiolitic association are known only among the clastic materials in the sandstones and gritstones of Cretaceous and Paleogene age. The Pjenina zone is probably the suture of the marginal basin of Tethys. This zone took on the role of boundary between domains of African and Eurasian origin only in the Neogene, after the Hemer-Tatra megazone was moved and overthrust upon the rocks of the Meso-Tethys oceanic crust [4]. The true suture of the Mesozoic ocean basin is now hidden beneath the Hemer-Tatra mass overthrusts.

The position of the suture of Meso-Tethys can be more exactly determined south of the Pannonian basin. The ophiolites here make up nappes that have been overthrust southwestward. The root zone of these thrust sheets is in the Vardar tectonic zone, along which the Meso-Tethys suture must also be drawn.

The megazone under consideration can be traced within the region of the Aegean Sea by the outcrops of ophiolites on islands of the Cyclades archipelago. Allochthonous outliers of ophiolitic thrust sheets also occur on the islands of Crete and Rhodes. The megazone continues in Asia Minor, within the Izmir-Anatolian ophiolite zone (Figs. 1 and 2, Nos. 10-11), which is a complex of melanges of various types and ages, masses of ultrabasites, and also massifs with a pre-Alpine continental crust. Besides the Jurassic and Cretaceous ophiolites, rocks of a pre-Jurassic ophiolite association occur; the latter may be regarded as relicts of the paleo-Tethys ocean [51, 53].

The melange with a serpentinite matrix in the Izmir-Anatolian zone contains blocks of rocks of the ophiolite association and sedimentary rocks. The basalt blocks have been found to contain thin beds of jaspers and limestones with a fauna dating from all epochs of the Jurassic and Early Cretaceous, down to the Aptian age [11]. Another type of melange has a matrix in the form of terrigenous flysch and, judging by Tekeli's description [53], is a tectonized olistostrome series. It is unconformably overlain by clastic deposits of Late Triassic to Liassic age. West of Ankara, the olistostrome lies tectonically on metamorphosed ophiolites: serpentinized ultrabasites, basic lavas with glaucophane, radiolarites and cherty limestones. The large ultrabasite massifs (Mikhalychchik, Erzindzhan and others) are made up of serpentinized dunites, peridotites, pyroxenites, harzburgites and gabbros. These rocks have tectonic contacts with the host-rock series. According to K-Ar dates, the pyroxenites have ages of 306 ± 40 Ma [53].

In the Eastern Pontic region, the boundary of the ophiolite megazone is marked by ophiolites in the Kil'kit River valley (Fig. 2, No. 12). Here rocks of the ophiolite association are found in the Agvanis and Berdig mountains along the Eastern Anatolian fault: ultrabasites, gabbros, and metamorphosed volcanics, overlain by slightly metamorphosed Jurassic clastic deposits. An ophiolite association of Cretaceous age occurs in the same area [51].

To the east, the ophiolite zone of Anatolia bifurcates. Of greater interest here is the northern (Lesser Caucasus) zone. The rocks it separates belonged during the Paleozoic to Gondwana and Laurasia, and in Jurassic time were located on different shores of the Tethys ocean.

From the Kil'kat River valley the ophiolite zone extends northeastward into the Chorokh River basin. Around the upper reaches of the Kil'kat and Chorokh rivers and in the Krasu (Euphrates) River valley is a serpentinite melange with blocks of basalts, radiolarites and sedimentary rocks. In the Chorokh-Karasu watershed (Fig. 2, No. 13) the melange is unconformably overlain by rudistid limestones of Senonian age. Along the middle reaches of the Chorokh River (Fig. 2, No. 14), a section through the ophiolite association is exposed that includes serpentinized ultrabasites, gabbros, amphibolites, tholeiitic spheroidal lavas and cherty shales. The upper part of the section is made up of shales and sandstones with a Liassic fauna. Unconformably above these, lie shallow-water deposits of Late Jurassic and Early Cretaceous age [51].

Farther east the zone continues in Soviet Armenia. In the Amasiya area (Fig. 2, No. 15) the ophiolites occur in the Mumukhan Mountains. Here they are represented by a serpentinite melange, within which lie large bodies of serpentinized ultrabasites (peridotites, dunites, pyroxenites), gabbros, gabbronorites and troctolites. Blocks of basic lavas, radiolarites, metamorphic rocks, and also sedimentary rocks of Late Cretaceous age have been found. The ophiolitic melange is overlain by a thin cover of marmorized Upper Cretaceous limestones, which have a tectonic base. In the melange zone the unconformable stratigraphic occurrence of Senonian basal conglomerates on the melange may be seen [19]. The Amasiya ophiolite belt (4 × 12 km) has an imbricate structure of steeply dipping tectonic plates. Both the plates and the inclusions in the serpentinite melange are oriented along the ophiolite zone. Mylonites are extensively developed. The internal structure of the Amasiya zone is consistent with its position on the site of an oceanic suture.

The eastward continuation of this ophiolite zone is in the Shirak and Bazum ranges (Fig. 2, No. 16), where numerous ultrabasite outcrops are known—chiefly within the Cretaceous rocks. On the south slopes of the Shirak Range (near Karmrakar), peridotites and gabbros crop out from beneath the cover of Upper Senonian carbonate deposits. Their contact with the Cretaceous deposits is tectonic and lies parallel to the bedding in the Upper Senonian rocks.

Farther east, in the Bazum Range on the Gerger-Chernaya watershed, are serpentinitized pyroxenites, olivine gabbros, basalts, and radiolarites, which are in tectonic relationships with the Albian carbonate-clastic deposits and Paleogene volcanic rocks. Still farther east, the ophiolites crop out at the surface in the Dzknachet River basin and have been found in boreholes drilled at the northwestern end of Lake Sevan and on its southern shore, at Karchakhpyur (Fig. 2, No. 19). The Karchakhpyur borehole passes through pyroxenites, gabbros and diabases [18].

From Lake Sevan the Lesser Caucasus ophiolite zone continues beneath a cover of young deposits in the Zangezur Range, where the ophiolitic association forms a tectonic melange in the Zangezur fault zone. Peridotites, serpentinites, olivine gabbros, troctolites, listwanites, spilites, andesites and trachyandesites, radiolarites, and other siliceous rocks are found here. The upper age limit of this association is fixed by the occurrence of ophiolitic rocks in the conglomerates of Senonian age [18]. Southeast of the Zangezur Range, in the Karadag Mountain of Iran (Fig. 2, No. 21), ophiolites overlain by pelagic limestones of Late Cretaceous age have been described. The ophiolites make up tectonic thrust sheets; the obduction occurred in the Late Cretaceous [27].

Northeast of the Lesser Caucasus zone are the ophiolites of the Sevan zone (Fig. 2, No. 20), which form a system of overthrust torn away from their roots. These nappes lie on the rocks of the Rhodope-Iran megazone. The effusive-siliceous part of the Sevan ophiolite association contains fauna of Middle and Late Jurassic, Early Cretaceous, and early Late Cretaceous ages. The overthrusting of these ophiolites took place in the Cenomanian-Coniacian ages [9, 18, 19]. In the Sevan zone the ophiolite melange has also been found to contain gabbro-diabases and andesite porphyrites, whose K-Ar age is 291 ± 3 Ma [6]. Southwest of the Lesser Caucasus zone is the Vedinskaya zone of allochthonous ophiolites (Fig. 2, No. 18), where the ophiolite thrust sheets lie on the rocks of the Armenian median massif. It is quite likely that the Lesser Caucasus zone is the root zone of the Sevan-Akerinskiy and Vedinskiy ophiolitic allochthons [43].

In northeastern Iran is an interesting tectonic node; unfortunately, little information is available on its geology. Northwest of this area the Lesser

Caucasus ophiolite zone contains sutures of two former oceans (Paleo-Tethys and Meso-Tethys), but eastward and southward of it these sutures diverge rapidly. At any rate, in the western Elbrus Range the Eurasian coal measures of Liassic age lie stratigraphically on carbonate rocks of the Late and Early Triassic, typical of the Gondwana section [32].

At the northwestern end of the Elbrus Range, in the Iranian Talysh (Bogrov-Dag) Mountains, rocks of an ophiolitic association are exposed west of Resht (Fig. 2, No. 23). There is not much information on these ophiolites. Peridotites and gabbros are mentioned, and protrusions of serpentinites within the Liassic rocks have been described. The serpentinites are associated with rodingites and greenschists. Pebbles of ultrabasites have been found in the Jurassic conglomerates. The stratigraphic section through the Iranian Talysh Mountains contains basalts, andesites and tuff of Silurian and Devonian age. Alkalic rocks have been found among the Devonian volcanics [22, 28, 32]. It does not seem possible to date the Resht ophiolite association from the available literature data. North of the Iranian Talysh and Elbrus ranges there are no Gondwanan facies of the Upper Paleozoic and Triassic. It is therefore reasonable to draw the suture of the Paleozoic Tethys through the northern part of the Iranian Talysh Mountains and the Caspian Sea into the region of Khorasan. Some investigators [28] consider the Resht ophiolites to be evidence of this oceanic suture.

The traces of the suture of Meso-Tethys are lost south of Zangezur and the Iranian Karadag Mountains, because of the scantiness of information on this region. It was shown above that in Eastern Europe, Asia Minor, and the Caucasus, this suture is the southern boundary of the region of terrigenous and nearshore Liassic coal measures. Using this information, one can determine the position of the suture in Iran. Liassic coal measures are found north and northeast of the Lesser Caucasus ophiolite zone, southeast of the Armenian highland in the Iranian Talysh Mountains, and south of the Armenian highland in central Iran, all the way to Lake Urmia in the west. Thus the region of the Liassic continental and paralic facies surrounds the Armenian highland on the north, east and south. In the southwest, the area of these facies borders on the Main Zagros overthrust. Beyond this boundary, in the High Zagros, the Liassic and Dogger sections are composed of marine, predominantly carbonate deposits. It can be concluded that the Meso-Tethys suture runs south of the Armenian median massif, from the ophiolites of the Zangezur Range and the Iranian Karadag Mountains to Lake Urmia and beyond—toward the Sinendedzh-Sirzhan zone. This suture most likely runs across the Khoy ophiolites at the northern end of Lake Urmia.

The Khoy ophiolites (Fig. 2, No. 22) form a melange consisting of ultrabasites, radiolarites, diabases, tuffs, pelagic limestones and clay shales. These rocks contain a fauna of Late Cretaceous age. The melange is overlain by Eocene flysch [22]. The Khoy ophiolites are probably the connecting link between the northern (Lesser Caucasus) and the southern branches of the ophiolite megazone. The southern branch extends from the Anatolian zone to the Karaköse ophiolites (Fig. 2, No. 17) and can be traced southeastward between Lake Van and Lake Urmia toward the Zagros Range. Ophiolite zones evidently fringe, on all sides, the Armenian highland, which in the Early Mesozoic was a microcontinent, but now is a median massif within the Alpine folded belt.

The Armenian median massif (Fig. 2, letter A) includes the Ankavan-Megri (Yerevan-Ordubad, Miskhan) and Dzhul'fa tectonic zones. Its pre-Alpine basement is made up of platform deposits of the Gondwana type (Paleozoic and Triassic) and metamorphic rocks of supposedly Precambrian age. The Liassic is represented by a series (up to 300 m thick) of basalts and tuffs. The volcanics have a weakly alkalic tholeiitic composition with high titanium contents; they are close to the intracontinental rift basalts [10]. In the area of the Daralagez Range, within limestone interbedded with the volcanics, Ye. A. Uspenskaya has found Liassic belemnites. Above the volcanics lies a series (up to 200 m thick) of clays, sandstones, and limestones with Bajocian and Bathonian ammonites. The ammonite fauna indicates that these deposits belong to the South Tethys biogeographic province [16, 17]. Thus the Armenian microcontinent belongs to the African-Arabian domain and during the Jurassic was located in the southern part of Tethys.

Thus the Mesto-Tethys suture surrounds the Armenian median massif on the north, east and south, and south of Lake Urmia approaches the Neo-Tethys suture. The latter, which formed in the

Cenozoic as a result of the collision of the Arabian continent with Eurasia, bends around the northern projection of the Arabian platform, runs southeastward along the boundary of the Sirindezh-Sirzhan zone and the High Zagros, and thence across Makran and Baluchistan, continuing into the Himalayas.

Around the Neo-Tethys suture are nappes of Mesozoic ophiolite, which were obducted onto the Arabian plate at the end of the Cretaceous. These ophiolites are the remnants of an ocean basin that formed in the Triassic as a result of the break-up of the margin of the Arabian plate. The upper thrust sheets also contain carbonate rocks of the northern edge of the ocean basin [9]. Fragments of this basin are distributed along the periphery of the Arabian platform from Oman in the southeast to Syria and perhaps Cyprus. In the Zagros Mountains, the ophiolites of this peri-Arabian Mesozoic ocean basin have been preserved in the Kermanshah area around Lake Neyriz.

In the vicinity of Kermanshah (Fig. 2, No. 26) are thrust sheets composed of radiolarites and limestones of Mesozoic age, serpentinites, gabbros, and a complex of diabase dikes and serpentinite melange. The serpentinite melange is transgressively overlain by Oligocene deposits. K-Ar age determinations on the diabases from the sheeted dike complex ($81 \pm 4$ Ma) and diorite dikes within the serpentinites ($86 \pm 8$ Ma) indicate the Late Cretaceous age of these rocks [11, 34]. In the Lake Neyriz area (Fig. 2, No. 27) is a large tectonic nappe of serpentinites, containing blocks of peridotites and rodingites. This is underlain by a plate of serpentinite melange, beneath which again (also in allochthonous occurrence) are radiolarites of Jurassic to Neocomian age. The serpentinites of the ophiolite and the serpentinite melange are transgressively overlain by shallow-water Upper Senonian limestones [11, 28].

As a result of the Cenozoic collisions, the Mesozoic suture of the peri-Arabian ocean basin came to be located close to the Neo-Tethys suture. In the present structure these two oceanic sutures almost coincide.

Mesozoic ophiolites are extensively developed on the boundaries of the Lut median massif (Fig. 2, letter L). Its eastern half is an high of metamorphic rocks of Paleozoic or pre-Paleozoic age, on which lies a cover of Mesozoic and Cenozoic deposits. The western part of the massif consists of an alternation of grabens and horsts. The grabens are filled with Jurassic and Cretaceous deposits. The Liassic here is represented by the thick (up to 4000 m) Shemshak coal measures, the lower part of which contains a flora of Late Triassic and Liassic age [15]. In the northern part of the median massif (in the Shotori Mountains), within the terrigenous rocks, is a bed of limestone with a marine fauna of Sinemurian age. The upper boundary of the formation on the Lut massif probably does not go beyond the limits of the Liassic, since the overlying limestones contain goniatites of Upper Toarcian, Aalenian, and Bajocian age. This fauna, which was found in the southern part of the massif (near Kerman), indicates that the region belongs to the North Tethys biogeographic province [41].

The Lut massif is bordered by ophiolite zones: the Nain-Baft zone to the west (Fig. 2, Nos. 28-29), the Dorune-Dzhagatay zone to the north (Fig. 2, Nos. 24-25), the Dzhaz-Murian zone to the south (Fig. 2, No. 30) and the Zabol-Baluh zone to the east (Fig. 2, No. 31). These zones are filled with melange, which contains ultrabasites, basic lavas and pelagic sedimentary rocks. The age of the sedimentary rocks in the clasts is from Late Turonian to Maastrichtian. K-Ar determinations on the basic volcanics and gabbros also indicate a Cretaceous age [28, 34].

At the northern boundary of the Lut massif lies a thick ophiolitic melange (Fig. 2, No. 25). Farther north, in the Sabzevar area, the ophiolites form several massifs in the Dzhagatay Range (Fig. 2, No. 24). Besides the ophiolite melange, here one can see the full section through the ophiolite association. In its lower part lie harzburgites and dunites, cut by gabbro dikes. In the marginal part of the massif of harzburgites, rocks such as lherzolites, cumulate peridotites, gabbro-norites and troctolites have been described. Above these lies an association of sheeted diabase dikes, and on these in turn lies a volcanogenic-sedimentary series consisting of basic lavas with pillow structures (20%), pyroclastites (70%), radiolarites, and pelagic limestones with Campanian-Maastrichtian *Globotruncana*. The extrusives are a low-titanium type. The Sabzevar area also contains amphibolites, glaucophane, and green schists and coarse clastic deposits with rock fragments of the ophiolitic association. These are overlain by Paleocene limestones. In addition, protrusions of ophiolite melange within the Upper Cretaceous limestones have been described [11, 35, 45].

There is a tendency to associate the ophiolitic zone of the Dzhagatay Range oceanic suture with the Karadag and Zangezur ophiolites, drawing the suture line along the Elbrus Range [27, 28]. In connection with this, the presence of Cretaceous tholeiitic and alkalic volcanics in the Elbrus is sometimes mentioned, but the basis for such constructions is the Late Alpine folded structure of the region. On the whole, there are few arguments for drawing the Mesozoic oceanic suture in the Elbrus Range. If it did exist here, Western Iran would have been a microcontinent in the Mesozoic Tethys, located near the Eurasian plate.

In the Zebol-Baluh zone on the eastern boundary of the Lut massif, the ultrabasic rocks are represented by harzburgites, dunites, and lherzolites. They form an ophiolitic melange in which gabbros also are present. On the melange lie spheroidal basalts with horizons of hyaloclasts, radiolarites, and pelagic limestones with a Turanian-Maastrichtian microfauna. The petrochemistry of the basalts indicates an affinity to mid-ocean-ridge tholeiites. Ophiolites of the southern margin of the Lut median massif formed under similar tectonic conditions [35, 54]. In the Zabol-Baluh zone the ophiolites are associated with a thick section of Upper Cretaceous flysch containing radiolarites and other deep-sea deposits that differ sharply from the contemporaneous carbonate formations in the interior of the Lut massif. The zones of development of Mesozoic oceanic crust are interconnected, almost surrounding the Lut massif. The suture of this ocean basin is now represented by faults, along which the ophiolites "bleed" out. Such faults connect the Dorune-Dzhagatay ophiolite zone through the Nain-Baft and Dzhaz-Murian zones with the Zabol-Baluh zone. The Late Alpine faults and folds of the Zabol-Baluh zone have a dextral strike-slip pattern. There are no data indicating that this zone continues northward and connects with the Dorune-Dzhagatay ophiolites. It may be supposed that the Lut block was almost surrounded by Mesozoic oceanic rift structures, but it was perhaps not completely separated by them from the Eurasian plate.

East of the Lut massif, the Meso-Tethys suture is located in southern Afghanistan. Liassic continental and paralic coal-bearing facies are extensively developed in northern Afghanistan (north of the Herirud-Hindu Kush fault), and also are known south of the fault, in the Rude Kafgan area [17]. The Meso-Tethys suture must be sought farther south—in the Farakhrud tectonic zone (Fig. 2, No. 32). On the northern and southeastern margins of the latter and in its central part, rocks of the ophiolite association crop out. The largest ultrabasite bodies are located along the Khashrud and Gilmend faults, on the southeastern boundary of the zone. The ultrabasites (serpentinites, serpentinized peridotites and dunites) are contained within thick Upper Jurassic-Lower Cretaceous deposits, consisting of basic and intermediate lavas with beds and lenses of siltstones, phyllites, cherts and limestones [7].

The Meso-Tethy suture runs along the Farakhrud zone southwestward to the Lut block and can be traced thence through the Zabol-Baluh and Dzhaz-Murian ophiolite zones to the Neo-Tethys suture.

In the northeastward direction and the Farakhrud zone wedges out, cut off by the faults of the Hindu Kush Range. The Herirud-Hindu Kush fault and its western continuation, the Zebak-Mun'yan fault, are dextral strike-slips. The continuation of the Meso-Tethys suture is displaced along the fault slip and lies in the Afghan part of the Badakhshan territory (Fig. 3). Beyond, the suture extends into the Rushan-Pshart fault zone, which separates the central and southern Pamir regions [14].

In the Badakhshan regions of Afghanistan, north of the Meso-Tethys suture (in the Lal Range and in the Shiva River valley) are continental coal measures (5000 m thick) with a flora of Late Triassic, Liassic and Dogger age [7]. These continue in the central Pamir region, where they are known as the Vamarskaya and Kokuybel' formations. In the Rushan-Pshart zone and farther south, deposits of the continental slopes of both margins of Meso-Tethys have been preserved. Rocks of the oceanic crust of Meso-Tethys are exposed in the Wakhan Range, in the Bashgumbez window [21]. They consist of ultrabasites and a thick series of tholeiitic and alkalic olivine basalts. Interbedded tuffaceous strata contain a microflora of Mesozoic age.

Farther east, the continuation of the Meso-Tethys suture is displaced by the Pamir-Karakorum strike-slip fault and is located in Central Tibet (Fig. 3), where it is known as the Bangong-Nutszyan suture

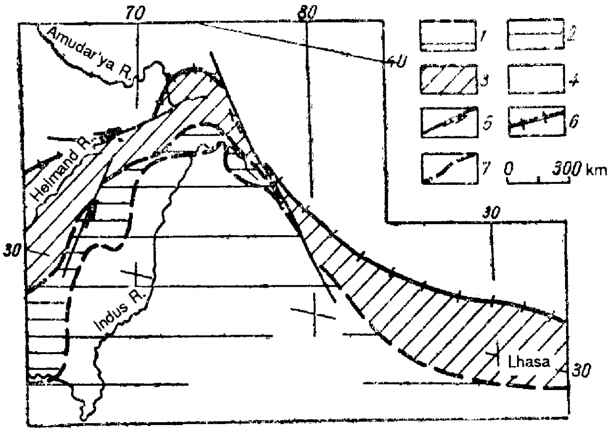


FIGURE 3. Pamir Range and Tibet: 1) Indian continent; 2) rocks of island arcs and marginal seas of Neo-Tethys; 3) rocks of Helmand-Lhasa microcontinent of Mesozoic Tethys; 4) Eurasian continent; 5) strike-slip faults; 6-7) oceanic sutures: 6) of Meso-Tethys, 7) of Neo-Tethys.

[20]. It has been traced all the way across Tibet and onward into Southeast Asia. The ophiolitic section of the Bangong zone includes ultrabasites, gabbros, a sheeted dike complex, spheroidal basaltic lavas, and Malmian deep-sea deposits overlying them. The ophiolites are unconformably overlain by Aptian-Albian rocks. The geochemical characteristics of the basalts testify to their formation in a small ocean basin at the rear of an island arc.

The Bangong-Nutszyan suture separates the Lhasa (in the south) and the Dzhangtang massifs. In Jurassic time the Dzhangtang massif was the margin of the Eurasian continent, and the Lhasa massif a part of the vast Helmand-Lhasa microcontinent, which also included the Southern Pamir region and southern Afghanistan (Fig. 3).

Thus two northern branches of Tethys were located in the region under consideration: the Carpatho-Lesser Caucasus and the Afghan-Tibetan, both of which were closed in Cretaceous time. Between them, in the area now occupied by the Zagros Range structures, an ocean basin probably existed on into the Neogene. In the southern part of Tethys during the Mesozoic was the peri-Arabian marginal sea with an oceanic crust, separated from the open ocean by a carbonate platform. The aforementioned main branches of Mesozoic Tethys themselves had branches, of which the sutures of small basins—the Kamennyy Potok—Porech, Nain-Baft, and others—now remain.

The Carpatho-Lesser Caucasus suture in the western Carpathians is covered by a vast allochthon—the Hemer-Tatra massif. From the western Carpathians this suture runs across the Panonian basin into the Vardar ophiolite zone and beyond, to the ophiolites of the Izmir-Anatolian zone. The Meso-Tethys suture, displaced along the Anatolian dextral strike-slip fault extends from the Eastern Pontic region to the Lesser Caucasus, where it is marked by the ophiolites of the Mumukhan Mountains and the Shirak, Bazum, and Zangezur Ranges. Through the Iranian Karadag mountains it can be traced as far as Lake Urmia and the Anatolian strike-slip fault. Once again displaced along a strike-slip fault, the Carpatho-Lesser Caucasus Meso-Tethys suture ends in the western Zagros Mountains near the Neo-Tethys suture.

The Afghan-Tibet suture in the Pamir region is located in the Rushan-Pshart zone. The eastern continuation of this suture, displaced along the Pamir-Karakorum dextral strike-slip fault, is in central Tibet. West of the Pamir this suture, also displaced along a strike-slip fault, continues into the Farakhrud zone of Afghanistan, whence, through the Zabol-Baluk and Dzhaz-Murian ophiolite zones, it approaches the Neo-Tethys suture.

## Meso-Tethys Sutures and Alpine Deformations

In Tertiary time, as a result of the attachment of the Indian and Arabian subcontinents to Eurasia, a large part of the Tethys ocean was closed and the sutures of Neo-Tethys, the chief of which are shown in Figs. 2 and 3, formed. A consequence of the collision of these continents was the great tectonic deformations and creation of the present structure of the Alpine Belt. The Mesozoic sutures of Tethys were also deformed in this process. The folded structure of the Alpine belt was formed under conditions of transverse compression and reduction of the belt. Let us attempt to estimate the magnitude of this reduction.

The magnitude of the deformation of a folded geologic terrane can be determined if the pre-folding position of marker horizons or some other markers is known. Our task is to study the deformations in plan, reflecting the movement of masses of the crust in the horizontal direction. The scale of these movements can be estimated by comparing the present position of the Meso-Tethys sutures with their reconstructed position in the geologic past. This estimate of the deformations is not prevented by displacements associated with reduction of ocean area, because the sutures of Meso-Tethys are located in a region of continental crust that has existed since the Late Cretaceous.

Our reconstruction of the position of the Carpatho-Lesser Caucasus suture in the Late Cretaceous (Fig. 4) is based on paleomagnetic studies [2-4, 26, 30]. In the Lesser Caucasus and the Western Pontic region paleomagnetic data were obtained on the Upper Cretaceous rocks overlying the ophiolites that mark the Meso-Tethys suture, and in the Carpathians near this suture. The reconstruction of its position in the Late Cretaceous, within the Carpathian-Pontic sector, is based on a restoration of the initial form of the tectonic structures which now make up structural arcs in the region [4, 30]. In the Lesser Caucasus, data on the initial form of the structures were used [1, 3], along with paleomagnetic latitude determinations obtained for the Upper Cretaceous rocks of the Sevan Range in the immediate vicinity of the Meso-Tethys suture [3]. Comparison of the Late Cretaceous reconstructions of the oceanic sutures with their present position enables them to be traced back beyond the internal deformations of the Alpine belt in the Cenozoic. The migration of the sutures is a consequence of the reduction of the crust in the northern part of the Alpine belt during the formation of its nappe-fold structure. Displacement of the Carpatho-Lesser Caucasus suture reaches a maximum at the vertex of the Arabian syntaxis—about 1500 km. The direction of displacement was across the Alpine belt. In the west, the amplitude decreases to 400 km at the boundary of the Hellenides with the Dinarides (direction of displacement along the belt), increasing in the region of the Carpathian loop and again decreasing toward the Eastern Alps.

Since the sutures of Meso-Tethys are within the Alpine belt, the amplitude of their displacement is less than the transverse shortening of the belt. The amount of this shortening can be estimated in the region of the Arabian syntaxis by comparing the paleomagnetic latitudes established for the Late Cretaceous on the Arabian platform and in Dagestan—at the northern boundary of the Alpine belt [3]. According to these data, the distance between the northern margin of the Arabian projection and the territory of Dagestan in the Late Cretaceous was $22 \pm 4°$, whereas at the present time the geographic latitudes of these regions differ by only 6°. Consequently the Alpine belt was narrowed here by $1800 \pm 450$ km. The transverse shortening of the Alpine belt can also be determined on the basis of conclusions concerning the movement of the African-Arabian plate resulting from study of the magnetic anomalies in the Atlantic Ocean. According to these data, the distance between Arabia and Eurasia decreased in the Cenozoic by approximately 2000 km [9].

The magnitude of displacement of the Afghan-Tibet suture in the Cenozoic can be calculated by using the paleomagnetic results obtained in the Northern Pamir region and in southern Tibet. The results of study of the paleomagnetism in the Northern Pamir region [2] testify to a northward movement of the zone during the Alpine orogeny of 600-700 km (relative to Eurasia). This information is on the outermost zone of the Afghan-Tibet suture. These tectonic structures did not converge in the Pamir region until the Late Cenozoic. Their convergence was accompanied by an extensive development of overthrusts in the Central Pamir region. Paleomagnetic data on the Cretaceous in the Northern Pamir indicate that in post-Cretaceous time the Meso-Tethys suture moved northward more than 600 km, but do not permit determination of the full amplitude of its displacement.

Paleomagnetic data on southern Tibet [23], which were obtained on Aptian-Albian rocks (the Taken formation) and Paleogene andesites (60-48 million years) in the Lhasa block (south of the Afghan-Tibet suture) lead to more definite conclusions. The deposits of the Taken formation were formed after the closing of Meso-Tethys and the development of

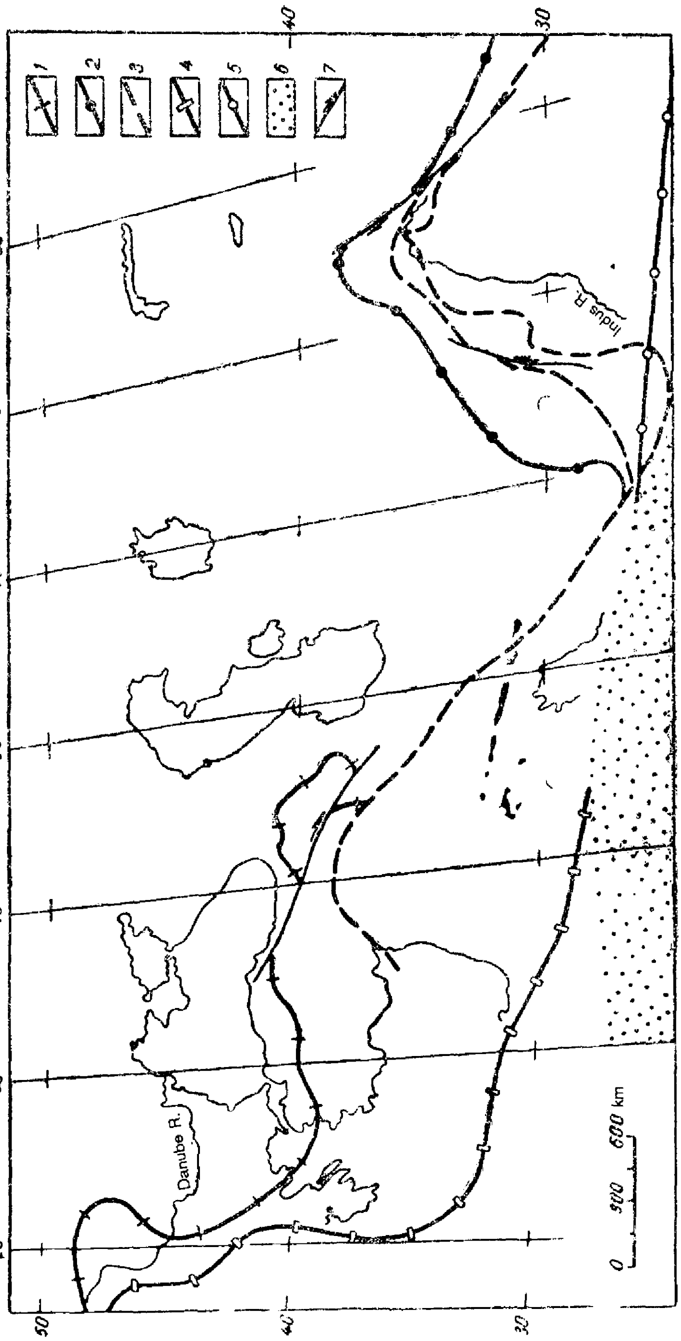


FIGURE 4. Transport of Meso-Tethys sutures in Cenozoic: 1-3) present positions of: 1) Carpatho-Lesser Caucasus (Meso-Tethys) suture, 2) Afghan-Pamir (Meso-Tethys) suture, 3) Neo-Tethys sutures; 4-6) reconstructed position for Late Cretaceous of: 4) Carpatho-Lesser Caucasus suture, 5) Afghan-Pamir suture, 6) Neo-Tethys sutures; 7) strike-slip faults.

its suture. These paleomagnetic studies have shown that throughout the Late Cretaceous, Paleogene, and Early Eocene, the paleolatitude of the Lhasa block did not change significantly, but that over the past 50 million years the block has moved northward by 2000 ± 850 km relative to the stable mass of Eurasia. To this magnitude must be added the transverse rotation of the belt in the region of the Himalayas. The initial width of the Himalayan tectonic zones was reconstructed by the method of balanced cross sections in the territory of Kohistan [31]. According to these data, the region enclosed between the Neo-Tethys suture and the main boundary overthrust fault of the Himalayas underwent a transverse shortening of 470 km as a result of these folded-overthrust deformations. The magnetic anomalies of the Indian Ocean floor also indicate that the Indian continent, after the beginning of collision, moved 2000-2500 km closer to Eurasia.

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