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A Section Across a Tethyan Suture in Northwestern Turkey

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Abstract

A section across a major Tethyan suture in northwestern Turkey is described in detail. The suture of Early Tertiary age juxtaposes two continental blocks with distinct stratigraphic, structural, and metamorphic features. The Sakarya Zone in the north is represented by Permo–Triassic accretion-subduction complexes, which are unconformably overlain by Jurassic to Paleocene sedimentary rocks. The Anatolide-Tauride Block to the south of the suture consists of two tectonic zones. The Tavsanli Zone consists of a coherent blueschist sequence with Late Cretaceous isotopic ages. This blueschist sequence is tectonically overlain by Cretaceous oceanic accretionary complexes and peridotite slabs. The Bornova Flysch Zone consists of Triassic to Cretaceous limestone blocks in an uppermost Cretaceous to Paleocene flysch. The suture is represented by a N-vergent thrust fault separating lithologies from these two continental blocks.

The orogenic history of the region can be considered in two stages. In the Late Cretaceous, the northern margin of the Anatolide-Tauride Block was subducted under the Tethyan oceanic lithosphere and was metamorphosed in blueschist-facies conditions. Blueschists were largely exhumed by the latest Cretaceous or early Paleocene, prior to the continental collision. In the second stage, during the Paleocene, the continent-continent collision produced a doubly vergent orogen involving both S- and N-vergent thrusting, but did not lead to major crustal thickening.

Introduction

SUTURES ARE MAJOR tectonic lineaments that separate former lithospheric plates. Characterization of suture zones is important, as they contain evidence for the creation and destruction of former oceans and for the formation of orogenic belts. The Izmir-Ankara suture, which extends for over 1000 km in Turkey, represents the major Tethyan suture between Laurasia and Gondwana in the Turkish transect. For most of its length, the suture zone is covered by post-tectonic Neogene deposits, which partly explains why there are no detailed studies of this major suture zone. Here, we describe a section across the Izmir-Ankara suture in northwestern Turkey. The area studied is well exposed, and it shows a complete transect between the two continents; Miocene doming allows the study of deeper crustal levels, thus providing a three-dimensional cross-section across a Tethyan suture.

During the Late Paleozoic and Mesozoic, the Tethys formed a westward-narrowing oceanic embayment between the supercontinents Laurasia and Gondwana (e.g., Smith et al., 1981; Scotese and Golonka, 1992). The final closure of the Tethys during the Early Tertiary produced the Alpide orogenic belt, with a suture zone extending from the Western Alps to the Makran. The various continental fragments that make up present-day Turkey (Fig. 1) represent segments from both margins of the Tethyan ocean, as well as isolated continental blocks within this realm (Sengör and Yilmaz, 1981; Okay et al., 1996). Each of these continental fragments has characteristic stratigraphic, deformational, magmatic, and metamorphic features. The Istanbul Zone in the north has unambiguous Laurasian stratigraphic affinities with a well-developed Paleozoic sedimentary succession (Fig. 2). During the Late Cretaceous, prior to the opening of the Black Sea, it was attached to the East European and Moesian platforms, and thus to Laurasia, as an oceanic back-arc basin (Fig. 1) (Okay et al., 1994). During the Mesozoic, the Istanbul Zone was separated from the Sakarya Zone by the Intra-Pontide ocean (Sengör and Yilmaz, 1981). The Sakarya Zone to the south probably was an isolated continent within the Tethys during the Jurassic and Cretaceous. It shows strong latest Triassic deformation and regional metamorphism related to the obduction of an ensimatic

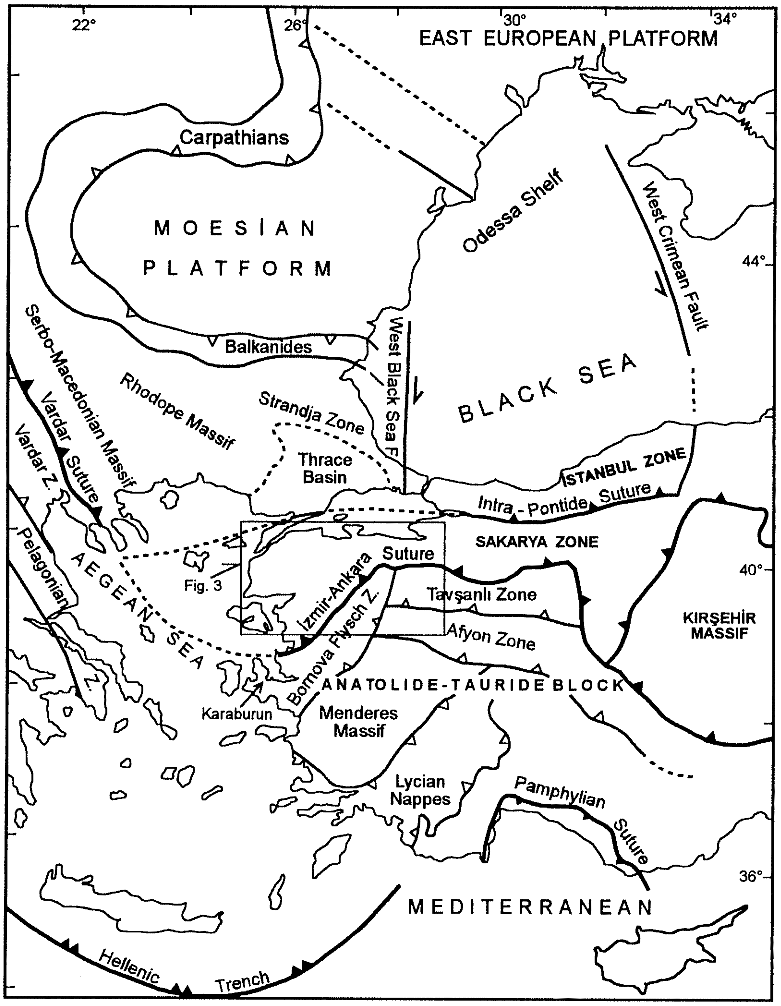

FIG. 1. Tectonic map of western Turkey and surrounding areas. The thick barbed lines show Mesozoic sutures with their primary subduction polarities. The thinner lines with open triangles indicate major intra-continental thrusts (after Okay et al., 1996).

magmatic arc of Permo–Triassic age over a Hercynian continental fragment (Okay et al., 1991, 1996). During the Mesozoic, the Vardar ocean separated the Sakarya Zone from the Anatolide-Tauride Block, which shows close stratigraphic affinities to the Gondwana margin (Fig. 2) but probably was separated from it by a narrow oceanic trough, the Pamphylian ocean (Fig. 1) (Sengör and Yilmaz, 1981). The closure of the Vardar ocean through N-dipping subduction during the Late Cretaceous was followed by Paleocene collision between the Sakarya Zone and the Anatolide-Tauride Block. This resulted in the internal imbrication and local regional metamorphism of the Anatolide-Tauride Block during the Tertiary (Sengör and Yilmaz, 1981). The contact between these two continental blocks in western Turkey is marked by the Izmir-Ankara suture (Fig. 1).

Geological Setting

The area studied around the town of Kepsut includes rocks from two former plates—the

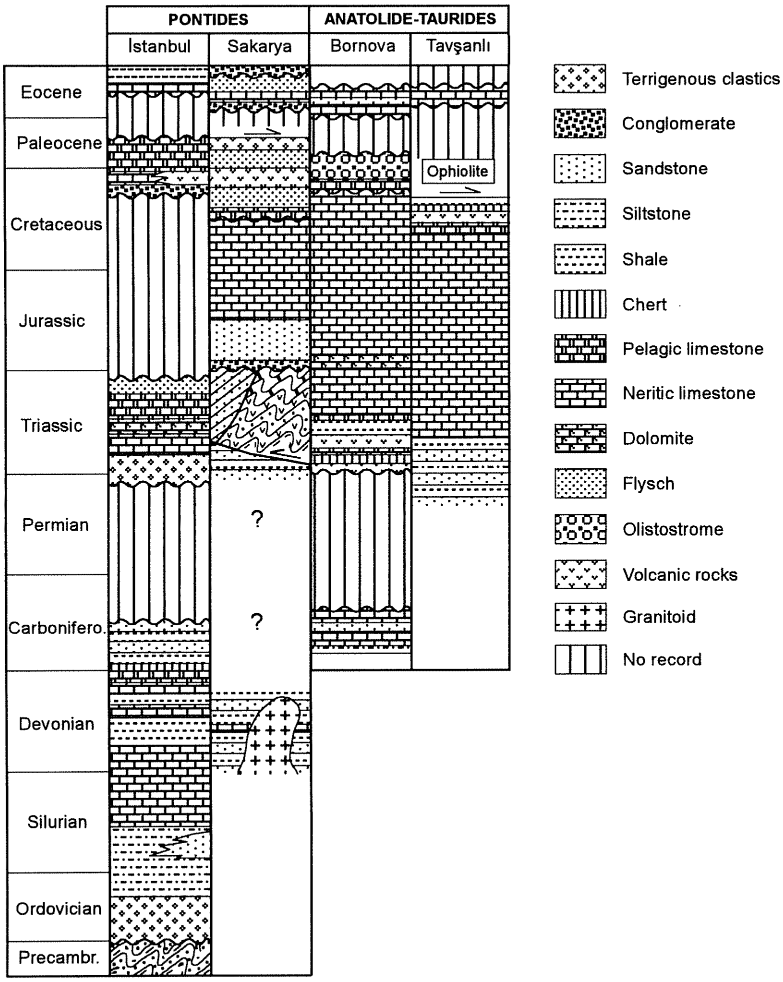

FIG. 2. Synthetic stratigraphic sections of the major tectonic units in northwestern Turkey.

Sakarya Zone in the north and the Anatolide-Tauride Block in the south. The latter is subdivided into the Tavsanli and Bornova Flysch zones (Figs. 3 and 4). Rocks belonging to these zones are unconformably overlain by Neogene sedimentary and volcanic rocks. The large-scale structure of the area is characterized by an elongated dome centered on the Çataldag Granodiorite of Miocene age (Fig. 5).

Sakarya Zone

The Sakarya Zone is represented by two formations in the Kepsut area: (1) a thick metabasite-micaschist-marble sequence called the Nilüfer Unit, which is tectonically overlain by (2) Permo–Triassic clastic rocks of the Orhanlar Greywacke. They both form part of the Karakaya Complex, representing Permo–Triassic subduction-accretionary units of the Tethys (Tekeli, 1981; Okay et al., 1991, 1996). The Karakaya Complex is unconformably overlain by an undeformed sedimentary succession starting with Lower Jurassic sandstones and conglomerates (Fig. 2). This cover sequence is absent in the Kepsut region, probably because of Early Tertiary erosion.

Nilüfer Unit/Permo–Triassic fore-arc sequence (?)

The Nilüfer Unit consists of a lower formation of metabasites over 1500 m in thickness—

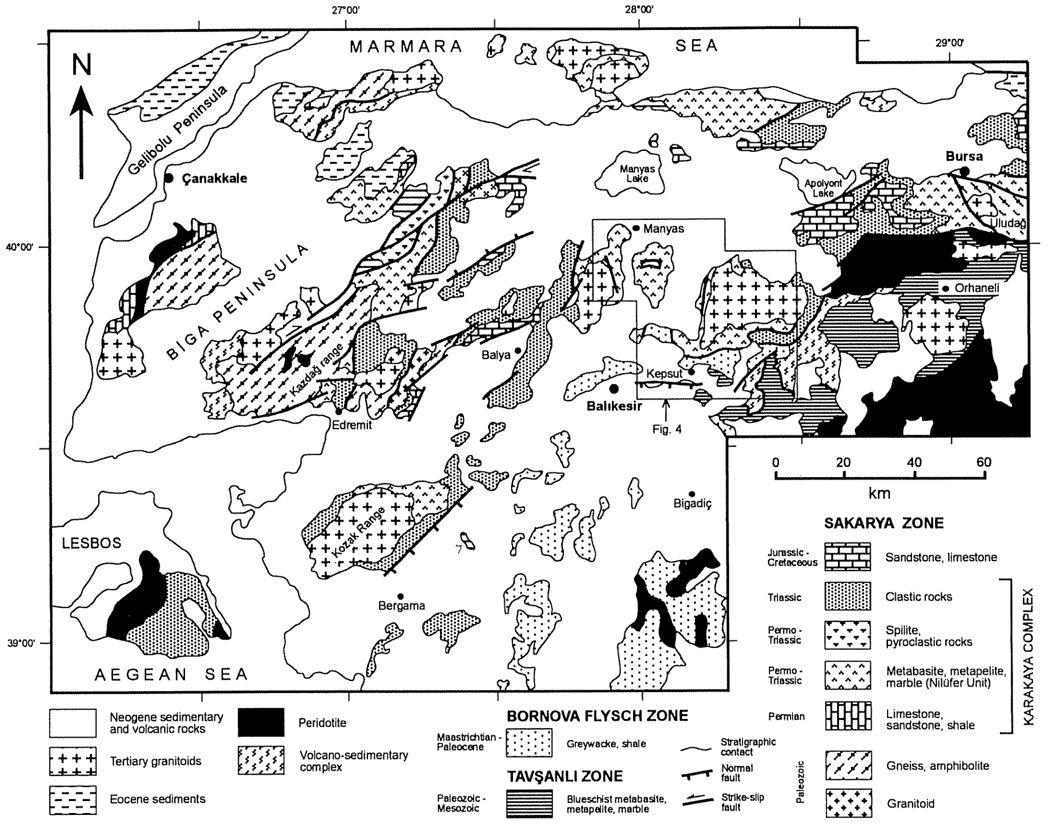

FIG. 3. Simplified geological map of northwestern Turkey (modified after Okay et al., 1996).

intercalated with metapelites, calc-schists, and marbles—and a stratigraphically overlying formation of homogeneous marbles exceeding 800 m in thickness. The base of the Nilüfer Unit is exposed only in the Kazdag and Uludag ranges outside the region studied (Fig. 3), where gneisses and amphibolites with mid-Carboniferous zircon ages lie tectonically beneath the Nilüfer Unit (Okay et al., 1996). The Nilüfer Unit is overlain, generally along a fault contact, by Triassic clastic rocks of the Karakaya Complex.

In the Kepsut region, rocks of the Nilüfer Unit have undergone a regional upper-greenschist-facies metamorphism and are completely recrystallized, with development of a strong foliation and a weak subhorizontal N-trending lineation. The gently dipping foliation wraps around Miocene granodiorite domes (Fig. 6), suggesting that it was subhorizontal prior to the intrusion of the granitoids. Metabasites make up 60% of the sequence and probably represent largely metatuffs; they are closely intercalated with metapelites, which form 25% of the sequence. Marbles and calc-schists form lensoid horizons up to several tens of meters thick in the metabasites and metapelites. The overlying carbonate unit consists of white, massive marbles locally with thin metachert bands. The mineral assemblage in the metabasites is actinolite/hornblende + albite/oligoclase + epidote + chlorite + leucoxene, whereas the intercalated micaschists comprise quartz + muscovite + biotite + chlorite ± garnet ± chloritoid.

In the Kozak region southwest of the area studied (Fig. 3), Kaya and Mostler (1992) have found Middle Triassic conodonts in carbonates intercalated with metabasites of the Nilüfer Unit. Recent Ar/Ar age determinations from

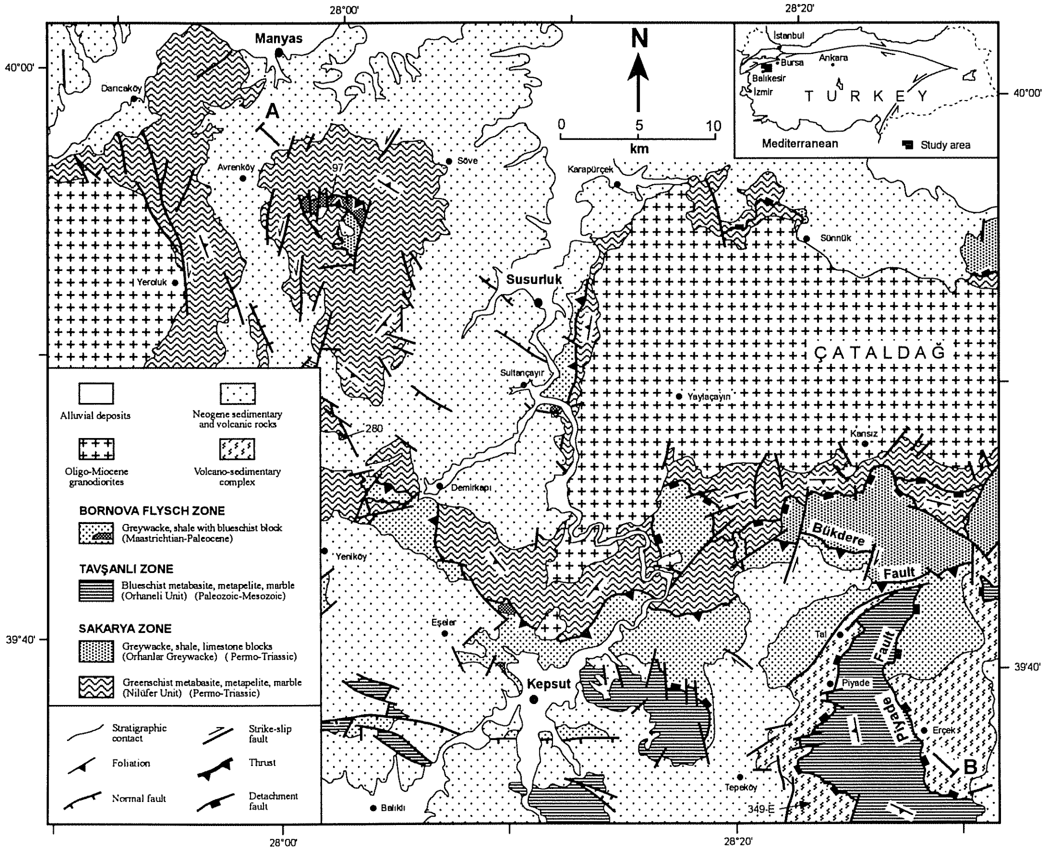

FIG. 4. Simplified geological map of the study area. For location, see Figure 3.

the Nilüfer Unit north of Eskisehir have yielded latest Triassic to earliest Jurassic ages (Monod et al., 1996), constraining the age of regional metamorphism to the latest Triassic, whereas the age of deposition of the Nilüfer Unit must be middle Triassic and earlier.

The Nilüfer Unit has a widespread distribution throughout the Sakarya Zone, with isolated outcrops extending eastward from the Biga Peninsula 1000 km to the eastern Pontides (cf. Figs. 1 and 3) (Okay et al., 1996). The intimate intercalation of metabasites with metasediments, the mafic nature of the magmatism and absence of intrusive magmatic rocks, and the allochthonous nature of the unit suggest that the Nilüfer Unit probably was deposited in a Permo–Triassic intra-oceanic fore-arc basin (Okay et al., 1996). However, an oceanic seamount origin for the Nilüfer Unit has been suggested by Pickett et al. (1993) on the basis of trace-element geochemistry of the metabasites.

Orhanlar Greywacke

The metabasite-marble-phyllite sequence of the Nilüfer Unit is overlain tectonically by strongly sheared, but unmetamorphosed, greywackes containing exotic blocks of limestone, chert, and mafic volcanic rock. The contact between this Orhanlar Greywacke and the underlying Nilüfer Unit, as observed south of Çataldag (Fig. 4), is a subhorizontal brittle fault.

The greywackes consist of quartz, lithic fragments (mainly acidic volcanic rocks), feldspar, and mica grains in a fine-grained clay matrix. The intense shearing in the Orhanlar Greywacke has destroyed most of the primary sedimentary fabrics. The greywackes contain exotic, grey, dark-blue, neritic Upper Permian limestone olistoliths ranging up to one kilometer in size. The Upper Permian (Murgabian-Midian) foraminifera in these olistoliths

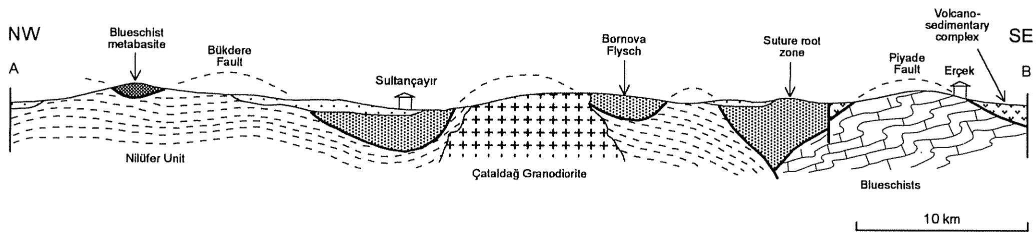

FIG. 5. Geological cross-section of the Kepsut area, illustrating the large-scale structure. For location, see Figure 4.

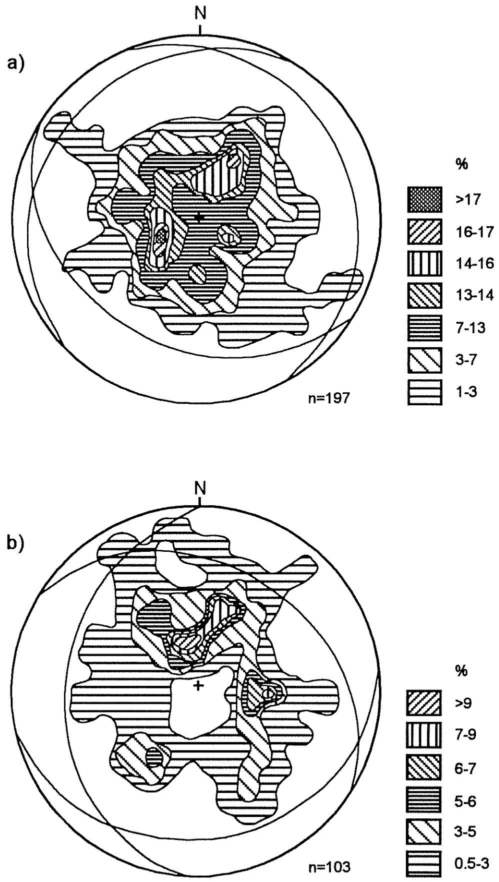

FIG. 6. Streographic plots of the foliation in the Nilüfer Unit. A. Around the Samli-Ilica pluton in the west. B. Around the Çataldag pluton in the east.

include: *Schubertella* sp., *Deckerella* sp., *Paleotextularia* sp., *Globivalvulina* sp., *Tetrataxis* sp., *Kahlerina* sp., *Dunbarula* sp., *Eotuberitina* sp., *Sumatrina* sp., *Rauserella* sp., *Afghanella* sp., *Eopolydiexodina* sp., *Geinitzina* sp., *Sphaironia* sp., *Climacammina* sp., *Cribrogerina* sp., *Glomospira* sp., *Nankinella* sp., *Hemigordius* sp., *Yangchienia* sp., *Pseudoendothyra* sp., and *Neoschwagerina* sp.

South of Lake Apolyont, the Orhanlar Greywacke is unconformably overlain by undeformed Jurassic sandstones and limestones (Fig. 3). This observation, and the presence of exotic Upper Permian limestone blocks in the Orhanlar Greywacke, constrain its age to the Triassic. The Orhanlar Greywacke probably was deposited during the latest Triassic collision of the ensimatic magmatic arc, represented in part by the Nilüfer Unit, with the Laurasian margin characterized by a Hercynian basement, as exposed in the Kazdag and Uludag ranges (Okay et al., 1996).

Tavsanli Zone (Anatolide-Tauride Block)

The Tavsanli Zone consists of a coherent blueschist sequence, called the Orhaneli Unit, tectonically overlain by a volcano-sedimentary complex and peridotite slabs. It represents the subducted northern continental margin of the Anatolide-Tauride Block (Okay, 1986).

Orhaneli Unit—A passive continental margin sequence metamorphosed under blueschist-facies conditions

The metamorphic rocks of the Orhaneli Unit in the region consist mainly of metapelites and overlying marbles, which have undergone a blueschist metamorphism strongly overprinted by a greenschist metamorphism. The metapelites, which form a sequence more than 800 m thick, have been transformed into micaschists and phyllites and exhibit well-developed foliation. The mineral assemblage in the metapelites is quartz + phengite + chlorite + albite. The metapelites also contain porphyroblasts of aggregates of sericitic white mica, which are interpreted as pseudomorphs after jadeite.

Similar pseudomorphs, as well as unaltered jadeite, are common in the metapelites in the adjacent area to the northeast (Okay and Kelley, 1994). The metapelites pass upward to a sequence of monotonous massive marbles over 1200 m thick. Farther east, north of Tavsanli, the marbles are succeeded by blueschist metabasites and metacherts exceeding 500 m in thickness (Okay, 1986). In the Kepsut region, both the marbles and the metapelites are tectonically overlain by a volcano-sedimentary complex and the Bornova Flysch (Figs. 4 and 5). However, a small klippe of blueschist metabasite occurs on top of the Nilüfer Unit and Orhanlar Greywacke south of Manyas (Figs. 4 and 5). The basal contact of the blueschist metabasite is an upper crustal, brittle, low-angle fault, marked by a thin slice of silicified serpentinite. This fault forms part of a major thrust fault, the Bükdere fault, that separates lithologies of the Sakarya Zone from that of the Anatolide-Tauride Block (Figs. 4 and 5). The metabasites in the klippe contain the mineral assemblage sodic amphibole + lawsonite + chlorite + sodic pyroxene + quartz + leucoxene. Blue sodic amphibole and lawsonite constitute the bulk of the rock (>80%). In the more massive metabasites, relict igneous augites are present; they are rimmed and partially replaced by sodic pyroxene.

Blocks of similar blueschist metabasites occur in the Bornova Flysch (Fig. 4). One metabasite sample from the blueschist klippe (sample no. 97) and one sample from the blueschist blocks in the Bornova Flysch (sample no. 280) were analyzed, employing a Camebax electron microprobe, at the University of Edinburgh. Operating conditions were generally 20-kV accelerating voltage, 20-nA beam current, and 10-μm beam size. Representative mineral compositions are listed in Table 1. Sodic amphiboles are crossite to magnesio-riebeckite in composition (Fig. 7). Lawsonites from both samples are close to end-member composition, with up to 2 wt% Fe_2O_3 (Table 1). Sodic pyroxenes, which form rims around relict igneous augites, are aegerine-jadeites with up to 65 mole% jadeite end member (Fig. 7). The presence of lawsonite and jadeite-rich sodic pyroxene indicates pressures of above 9 kbar and temperatures of less than 450° C for the blueschist metamorphism (Akyüz, 1995). Tighter P/T constraints were obtained by Okay and Kelley (1994) from the blueschist metapelites in the neighboring region (Fig. 3), where chloritoid-glaucophane-jadeite-bearing paragenesis indicates pressures of 20 ± 2 kbar and temperatures of 430° ± 30° C. Phengites from jadeite-bearing metapelites from the adjoining area to the east give Ar/Ar laser-probe ages of between 80 and 90 Ma, indicating a Late Cretaceous age for the blueschist metamorphism (Okay and Kelley, 1994). Although no fossils have been found in the coherent blueschist sequence, broad stratigraphic comparison with the Anatolide-Tauride Block suggests that the protoliths of the blueschist metapelites of the Tavsanli Zone represent Paleozoic clastic rocks, whereas the protoliths of the overlying marbles are Mesozoic platform carbonates (Fig. 2).

Volcano-sedimentary complex—A Tethyan oceanic accretionary complex

The volcano-sedimentary complex is composed of slices of serpentinite, pyroxenite, spilitized mafic volcanic and volcanoclastic rocks, radiolarian chert, pelagic shale, limestone, and rare blueschist tectonic blocks. The various slices range in thickness from 3 to 600 m and are juxtaposed without any discernible matrix. The volcano-sedimentary complex represents an oceanic accretionary complex that is particularly poor in clastic sedimentary rocks. Okay and Kelley (1994) reported Upper Cretaceous (Cenomanian to Maastrichtian) foraminifera from the pelagic limestone blocks in the volcano-sedimentary complex west of Orhaneli (Fig. 3). This indicates that the oceanic subduction and accretion continued at least up to Cenomanian time.

The volcano-sedimentary complex lies tectonically over the coherent blueschists of the Orhaneli Unit (Fig. 4). The contact is marked by a shallow to moderately steeply dipping fault, the Piyade fault (Figs. 4 and 5). Outside the area studied, the volcano-sedimentary complex is tectonically overlain by large ultramafic slabs (Fig. 3). Although the volcano-sedimentary complex appears unmetamorphosed in the field, petrographic studies have revealed that it has undergone an incipient blueschist metamorphism (Akyüz, 1995; Akyüz and Okay, 1995). In the mafic volcanic rocks, the igneous

TABLE 1. Representative Mineral Analyses from Blueschist Metabasites, wt%

	Sodic amphibole			Sodic pyroxene			Lawsonite			Chlorite			Pumpellyite
Sample:	97	280	349-E	97	280	349-E	97	280	349-E	97	280	349-E	349-E
SiO_2	55.24	56.44	56.08	57.28	55.14	57.98	40.83	40.95	41.72	27.57	30.47	28.24	38.90
TiO_2	0.09	0.21	0.29	0.06	0.66	0.01	0.34	0.16	0.38	0.04	0.03	0.02	0.05
Al_2O_3	3.03	5.63	7.92	15.94	11.62	17.98	31.57	32.28	32.43	15.85	15.84	15.99	26.80
Cr_2O_3	0.01	0.04	0.01	0.01	0.05	0.00	0.04	0.03	0.01	0.02	0.02	0.00	0.01
Fe_2O_3	21.92	19.36	15.03	7.56	10.79	5.18	1.80	0.85	0.46	23.64	21.22	26.68	3.87
MgO	8.45	8.04	8.10	1.98	4.24	2.10	0.09	0.07	0.09	18.73	18.81	14.85	1.71
MnO	0.29	0.21	0.34	0.09	0.12	0.05	0.03	0.00	0.06	0.69	0.35	0.25	0.26
CaO	0.63	1.62	2.70	3.73	5.79	3.97	16.98	17.12	16.80	0.27	0.25	0.08	21.68
Na_2O	7.01	6.61	5.75	13.00	9.86	12.23	0.03	0.00	0.03	0.04	0.04	0.02	0.27
K_2O	0.04	0.05	0.04	0.01	0.01	0.01	0.01	0.00	0.01	0.02	0.03	0.02	0.01
Total	96.71	98.21	96.26	99.66	98.28	99.51	91.72	91.46	91.99	86.87	87.06	86.15	93.55
Structural formula based on:	23 O	23 O	23 O	6 O	6 O	6 O	8 O	8 O	8 O	28 O	28 O	28 O	24.5 O
Si	7.94	7.97	8.04	2.01	2.01	2.03	2.07	2.07	2.11	5.80	6.37	6.14	6.35
Ti	0.01	0.02	0.03	0.00	0.02	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.01
Al^{IV}	0.06	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.20	1.63	1.86	0.00
Al^{VI}	0.46	0.91	1.34	0.66	0.50	0.74	1.89	1.92	1.93	1.74	2.27	2.23	5.15
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe^{3+}	1.54	0.87	0.11	0.21	0.16	0.04	0.08	0.04	0.02	0.44	0.00	0.00	0.47
Fe^{2+}	1.10	1.42	1.69	0.00	0.17	0.11	-	-	-	3.72	3.71	4.85	-
Mg	1.79	1.69	1.73	0.10	0.23	0.11	0.01	0.01	0.01	5.88	5.86	4.81	0.42
Mn	0.04	0.03	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.06	0.05	0.04
Ca	0.10	0.25	0.42	0.14	0.23	0.15	0.92	0.93	0.91	0.06	0.06	0.02	3.48
Na	1.96	1.81	1.60	0.88	0.69	0.83	0.00	0.00	0.00	0.02	0.02	0.01	0.08
K	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00
Total	15.01	15.01	15.01	4.00	4.01	4.01	4.98	4.98	4.99	20.01	19.99	19.98	16.00
Jadeite				0.66	0.50	0.74							
Aegirine				0.21	0.16	0.15							
Augite				0.13	0.34	0.11							

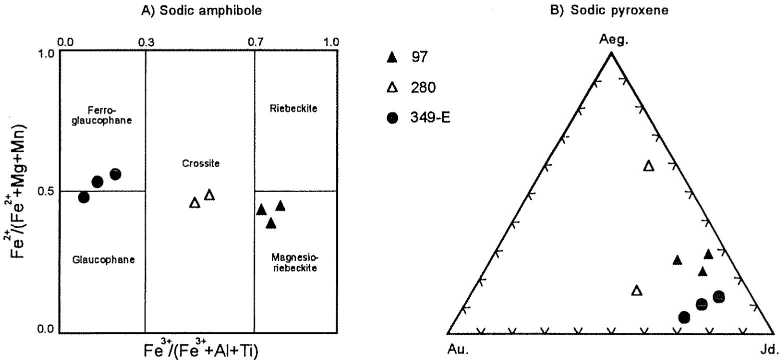

FIG. 7. Mineral compositions from the blueschists. A. Sodic amphibole. B. Sodic pyroxene.

augites are locally rimmed and partially replaced by sodic pyroxene, and plagioclase is locally replaced by lawsonite and pumpellyite. One such mafic volcanic rock (sample 349-E) was analyzed by electron microprobe. In this sample, the igneous augite is rimmed and veined by sodic pyroxene with up to 75% jadeite end member (Table 1, Fig. 7), whereas the plagioclase has been replaced by lawsonite and pumpellyite. The green igneous hornblendes have rims of blue sodic amphibole. The lack of recrystallization in the mafic volcanic rocks, the occurrence of lawsonite with pumpellyite, and sodic pyroxene with up to 75 mole% jadeite end member indicate metamorphic conditions of 7 ± 2 kbar and $200 \pm 50°$ C for the volcano-sedimentary complex (Akyüz, 1995).

The Bornova Flysch Zone (Anatolide-Tauride Block)

The Bornova Flysch is a thick, chaotically deformed, Upper Cretaceous to Paleocene clastic sequence with Mesozoic limestone and rare mafic volcanic, serpentinite, chert, and blue schist blocks (Okay and Siyako, 1993). Although the clastic rocks resemble those of the Orhanlar Greywacke, they are distinguished by the presence of Mesozoic, and the absence of Permo-Carboniferous, limestone blocks. In western Turkey, the Bornova Flysch forms a NNE-SSW-trending belt 50 km in width and 200 km in length between Izmir and Balikesir (Figs. 1 and 3). The area studied includes the northern end of this belt.

In the Kepsut area, the matrix of Bornova Flysch is composed mainly of greywacke and shale. Greywacke contains angular, medium-sorted quartz, feldspar, lithic fragments, mica, and chert grains in a clay-rich matrix. Intense shearing has destroyed almost all the primary fabrics. The dominant block type (>70%) is a neritic, massive to thickly bedded limestone, which ranges up to one kilometer in length. Limestone blocks from north of Balikesir have yielded Middle to Upper Triassic foraminifera—*Involutina* sp., *Nodosaria* sp., *Frondicularia* sp., and *Trochammina* sp.—whereas *Cuveolina* sp., characteristic foraminifera for the Late Cretaceous, was found in a limestone block from south of the village of Demirkapi. Erdogan (1990) and Okay and Siyako (1993) also have described Triassic to Upper Cretaceous limestone blocks from the Bornova Flysch Zone farther south (Fig. 3). In the limestone blocks, the Late Triassic to Turonian is represented by neritic massive carbonates, whereas the Senonian is represented by red pelagic limestones in *Couches Rouges* facies. In the individual blocks, the Senonian red pelagic limestones lie unconformably on the Triassic or Jurassic neritic limestones (Okay and Siyako, 1993). Some blocks of mafic volcanic rocks in the Bornova Flysch exhibit an incipient blueschist metamorphism, similar to that observed in the volcano-sedimentary complex. In the Bornova Flysch, there also are rare, and probably tectonic, blocks of blueschist metabasite up to 200 m long; the klippe of blueschist metabasite south of Manyas also may represent a large block within the Bornova Flysch. Toward the east in the region south of Çataldag (Fig. 4), the Bornova Flysch gradually merges into the volcano-sedimentary complex, with an increase in mafic volcanic and chert blocks.

The youngest blocks in the Bornova Flysch Zone are of Late Campanian or Maastrichtian age (Erdogan, 1990; Okay and Siyako, 1993), whereas Danian nannoplanktons were described from the carbonate-rich shales of the matrix in the Izmir region (Özer and Irtem, 1982). In the Akhisar region northeast of Izmir, undeformed Lower Eocene neritic limestone and sandstones lie unconformably over the Bornova Flysch (Akdeniz, 1980). These observations constrain the age of the Bornova Flysch to the latest Cretaceous–Paleocene.

Tethyan Suture

A suture can be defined as a fault or fault zone separating lithologies deposited on opposite sides of an ocean. By this definition, the Tethyan suture in the area studied is represented by the Bükdere fault, a N-vergent thrust fault, which emplaces Bornova Flysch and blueschists over the Nilüfer Unit and Orhanlar Greywacke of the Sakarya Zone (Figs. 4 and 5). This Bükdere fault can be followed for over 50 km in the area studied and wraps around the Çataldag Granodiorite. The fault plane dips steeply (60–70°) to the south and west, but it must have had shallower dips before the Miocene doming. It is an upper crustal fault characterized by a zone of cataclasis several tens of meters thick. The steeper dips of the Bükdere fault around the Cataldag Granodiorite result from Miocene updoming of this pluton. The age of movement along the Bükdere fault is constrained to Paleocene–Early Eocene, through the age of the Bornova Flysch and the earliest post-tectonic sediments of Middle Eocene age, which lie unconformably over the peridotite north of Tavsanli (Bas, 1986). As the Tavsanli Zone also is thrust southward over the Paleocene wild-flysch of the Afyon Zone (Fig. 1) (Göncüoglu et al., 1992), and as there is no evidence to show that the main blueschists of the Tavsanli Zone are tectonically underlain by the Sakarya Zone, the Bükdere fault must root south of Çataldag (Fig. 5). This indicates a northward translation of at least 40 km along the Bükdere fault.

Post-Tectonic Units

Lower Tertiary rocks are absent in the Kepsut area, and post-collisional Miocene volcanic, volcanoclastic, and terrigeneous sedimentary rocks unconformably cover all the older units (Fig. 4). The Miocene magmatism has affected large parts of northwestern Turkey (e.g., Ercan et al., 1985, 1990; Yilmaz, 1989) and produced calc-alkaline intermediate to acidic volcanic and plutonic rocks. The two large plutons in the area, the Cataldag pluton in the east and the Samli-Ilica pluton in the west (Fig. 4), are part of this Miocene magmatic province. They are both granodioritic in composition and have well-developed contact metamorphic aureoles with andalusite-bearing hornfelses. They have been dated by the K/Ar method as latest Oligocene–earliest Miocene in age (25 to 20 Ma) (Ataman, 1973; Bingöl et al., 1982, 1992). The Neogene sedimentary rocks, which are intercalated with the calc-alkaline volcanic rocks, give Early to Middle Miocene vertebrate and pollen ages (Bernor and Tobien, 1990; Ercan et al., 1990; Akyüz and Semiz, 1995). The Miocene sedimentary and volcanic rocks are cut by E- and SE-trending normal faults (Fig. 4) related to the N-S extension of western Anatolia since the Early Miocene (e.g., Dewey and Sengör, 1979; Seyitoglu and Scott, 1991).

Tectonic Evolution

The tectonic evolution of the region can be considered in three stages. The first stage (from the Jurassic to the beginning of the Late Cretaceous) is characterized by sedimentation on both sides of the Tethys ocean. During the second stage, in the Late Cretaceous, a large ophiolite body was obducted southward over the Anatolide-Tauride Block, and the deeply buried northern margin of the Anatolide-Tauride Block underwent HP/LT metamorphism. The third stage involved continent-continent collision during the Paleocene.

Sedimentation on both margins of the Tethys ocean (Jurassic–Early Cretaceous)

The Late Triassic deformation and metamorphism, which are characteristic features of the Sakarya Zone, are not observed in the Anatolide-Tauride units. This suggests that these

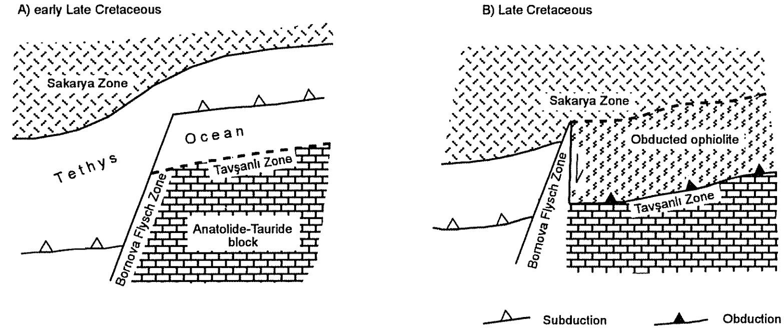

FIG. 8. Schematic diagrams showing the formation of the Bornova Flysch and the blueschists of the Tavsanli Zone (modified after Okay et al., 1996). A. Early Late Cretaceous carbonate sedimentation in the Bornova Flysch and Tavsanli zones. Tethyan oceanic lithosphere is consumed by an intra-oceanic subduction zone. B. Late Cretaceous ophiolite obduction over the Anatolide-Tauride Block, resulting in the HP/LT metamorphism in its northern margin, leading to the formation of the Tavsanli Zone. The obducted ophiolite bypasses the western margin of the Anatolide-Tauride Block, which is, however, fragmented and engulfed in the clastics producing the Bornova Flysch Zone.

two continental fragments were separated by the Tethys ocean since at least the Mid-Triassic. The Lower Jurassic to Upper Cretaceous sequence of the Sakarya Zone, which crops out on the Biga Peninsula and east of Bursa (Fig. 3), comprises Lower Jurassic sandstones and conglomerates, Middle Jurassic to Lower Cretaceous limestones, and Upper Cretaceous flysch with volcanic intercalations passing up gradually to Paleocene molasse (Fig. 2). The acidic to intermediate tuffs in the Upper Cretaceous flysch are believed to have been produced during the northward subduction of the Tethyan oceanic crust under the Sakarya Zone (Saner, 1980; Sengör and Yilmaz, 1981).

The limestone blocks in the Bornova Flysch were derived from a Mesozoic carbonate platform. Large parts of this platform are preserved on the Karaburun Peninsula and on Chios Island (Besenecker et al., 1968; Erdogan, 1990). Synthetic stratigraphy of this Bornova carbonate platform, on the basis of the age and lithology of the blocks, consists of Middle Triassic to Upper Cretaceous neritic carbonates several thousand meters thick, unconformably overlain by Senonian red pelagic limestones (Fig. 2). This sequence is similar to that generally found in the Anatolide-Tauride Block (e.g., Özgül, 1976; Sengör and Yilmaz, 1981). The position of the Bornova Flysch Zone immediately southeast of the suture suggests that, prior to its disruption, the Bornova carbonate platform represented the northwestern margin of the Anatolide-Tauride Block (Fig. 8). However, lithologies indicative of a passive continental margin, such as calciturbidites or pelagic micrites, are not found in the Bornova Flysch Zone, suggesting that this margin may have been a strike-slip margin rather than a normal passive continental margin (Fig. 8) (Okay et al., 1996). The marbles in the blueschist sequence represent the eastward continuation of this Mesozoic carbonate platform.

Deformation and metamorphism related to the obduction of ophiolites (Late Cretaceous)

The first pieces of evidence for compressional deformation in the Anatolide-Tauride Block are the Senonian pelagic limestones that unconformably overlie Triassic and Jurassic neritic carbonates in the Bornova Flysch Zone, suggesting erosion followed by deep subsidence of the Bornova carbonate platform. This probably was the result of obduction of ophiolites over the northern margin of the Anatolide-Tauride Block, causing flexure, erosion, and subsidence of the carbonate platform with the gradual approach of the ophiolite thrust sheet (Fig. 8). The progressive younging of the red pelagic limestones from Santonian in the northeast to Campanian in the southwest in the Bornova Flysch Zone indicates the southwestward vergence of the ophiolite thrust sheet (Okay and Siyako, 1993).

The Senonian also was a period of blueschist metamorphism in the Tavsanli Zone. The tectonic setting of the blueschists under the accretionary prisms and under the peridotite slabs, and the contemporaneity of the ophiolite obduction and the HP/LT metamorphism, suggest that the blueschist metamorphism was caused by the subduction of the northern margin of the Anatolide-Tauride Block under the oceanic lithosphere (Okay, 1986). The blueschists were rapidly exhumed and were at least partly exposed on the surface by the Maastrichtian, as judged from the blueschist detritus of this age in the turbiditic clastics of the Sakarya and Bornova Flysch zones (Okay et al., 1996). The exhumation of the blueschists probably was achieved by the delamination of the blueschists from their basement and their buoyoncy-related upward movement along the subduction zone (e.g., England and Holland, 1979; Wijbrans et al., 1993). In this mechanism, the blueschists must have been bounded by a normal fault at the top and a thrust fault at the base. The Piyade fault in the area studied, which juxtaposes the accretionary complex (buried not deeper than 20 km) over regional blueschists of the Orhaneli Unit metamorphosed at 60 km depth, represents the major detachment fault above the blueschists.

The absence of regional metamorphism in the Bornova Flysch Zone is striking. This observation, as well as the sharp bend in the suture west of the blueschist belt (Fig. 1), indicates that the ophiolite obduction largely bypassed this western margin of the Anatolide-Tauride Block (Fig. 8). This conclusion also is supported by the scarcity of ophiolite blocks within the Bornova Flysch Zone. However, the Bornova carbonate platform, which was bordered in the east by the SW-vergent ophiolite thrust sheets and in the west by the Tethys ocean, was fragmented and engulfed in clastics shed from the bypassing ophiolite and underlying accretionary prisms during latest Cretaceous and Paleocene time (Fig. 8).

The Senonian sequence in the Sakarya Zone, which is preserved east of Bursa (Saner, 1980), is characterized by flysch deposition with volcanic intercalations, possibly in a fore-arc setting. This observation, together with the absence of Senonian deformation in the Sakarya Zone, suggests that the continental collision had not occurred during the Senonian. Therefore, all the Senonian deformation and blueschist metamorphism in the northern margin of the Anatolide-Tauride Block is precollisional and related to ophiolite obduction. The situtation is similar to that in Oman, where ophiolite obduction and blueschist metamorphism occurred during the Senonian, although continent-continent collision has never taken place (e.g., Coleman, 1981; Michard et al., 1994; Searle et al., 1994).

Continent-continent collision (Paleocene)

During the Paleocene, in the Sakarya Zone east of Bursa, there was a transition from flysch to molasse sedimentation and N-vergent thrusting, which emplaced Jurassic limestones over the Paleocene molasse (Saner, 1980). These events mark the initiation of continent-continent collision between the Sakarya Zone and the Anatolide-Tauride Block. Also during the Paleocene, S-vergent thrust imbrication started in the Anatolide-Tauride Block, whereby the Tavsanli Zone was emplaced over the low-grade greenschist-facies metamorphic rocks of the Afyon Zone (Fig. 1) (Göncüoglu et al., 1992). This indicates a symmetrical orogen with N- and S-vergent thrusting. The N-vergent thrusting in the area studied is represented by the Bükdere fault, which connects to the blueschist klippe south of Manyas (Figs. 4 and 5). The Bükdere fault emplaces the Tavsanli and the Bornova Flysch zones over the Sakarya Zone. However, N-vergent thrusts were restricted to Paleocene time, and movement along them probably did not exceed a few tens of kilometers, in contrast to several hundred kilometers of southward thrusting in the Anatolide-Tauride Block, which episodically moved southward from the Paleocene in the north to the Miocene in the south in the Lycian nappes (Fig. 1) (Sengör and Yilmaz, 1981).

Inasmuch as the blueschists were partly exposed or were near the surface by Paleocene time, continental collision had no role in their exhumation. The situation is similar to that in Oman, where blueschists already are on the surface even though no continent-continent collision has yet occurred (e.g., Michard et al., 1994).

Jurassic and Cretaceous rocks of the Sakarya Zone are absent along the Izmir-Ankara suture, suggesting uplift and erosion along the suture zone during the Paleocene, possibly as a result of crustal thickening following continental collision. However, the erosion in the region north of the suture did not exceed four kilometers, which is the maximum thickness of the Jurassic–Paleocene sequence of the Sakarya Zone. Isolated exposures of Middle Eocene shallow-marine limestones east of Orhaneli (Bas, 1986) indicate that by the Mid-Eocene, the crust in northwestern Turkey was reduced to normal thickness.

Conclusions

The Tethyan suture examined here represents the upper, surficial part of a continent-continent collision zone. The suture can be identified as a N-vergent, low-angle thrust fault separating two continental fragments with different stratigraphic, structural, and metamorphic features. The suture zone is characterized by double-vergent structures forming a symmetrical orogen. Blueschists, which form a major belt south of the suture, were near or on the surface prior to the continental collision. Thus, continental collision played no role in their exhumation. The region immediately north of the suture is characterized by a maximum of four kilometers of erosion since the Paleocene continental collision. Considering that the continental crust in the region is of normal thickness at present (Makris, 1978), the continental collision appears not to have created unusually thick crust along this major suture zone.

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