

Stratigraphy and geochemistry of pillow basalts within the ophiolitic mélange of the Izmir–Ankara–Erzincan suture zone: implications for the geotectonic character of the northern branch of Neotethys

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Abstract The Izmir–Ankara–Erzincan suture zone of Turkey is a broad zone of ophiolitic mélange containing numerous fragmented blocks ranging in age from Triassic to Cretaceous. Stratigraphic sequences for various mélange units are compared, together with the geochemistry of associated basaltic pillow lavas of Cretaceous age. A review of geochemical data for the pillow lavas demonstrate: (a) a dominant group of alkalic basalts with enriched incompatible elements, variable Zr/Y and Zr/Nb ratios, and (b) a range of tholeiitic basalts with slightly depleted to mildly enriched (normalized) rare earth patterns, $(La/Yb)_N$ 0.4–3.0, and generally low Zr/Y ratios. The alkalic basalts can be chemically matched to Pacific Ocean seamounts, although the close association of red radiolarites and cherts suggests that many basalts represent the margins of such structures, rather than the main seamount edifice. Nd–Sr isotope data are typical for ocean island basalts and represent an admixture of a dominant EM-1 source and a depleted MORB-like source. Enhanced $\delta^{18}O$ compositions are a consequence of submarine alteration and not crustal contamination. Tholeiitic compositions have affinities with both N- and E-type MORB, although most are probably representative of tholeiitic ocean islands. Overall

the basalts are mainly representative of structures built on the ocean floor, rather than the oceanic crust itself, being scraped off the subducting crust and preserved in the mélange of the accretionary wedge.

Keywords Suture zone · Mélange · Basaltic pillow lavas · Eruptive environment · Seamounts

Introduction

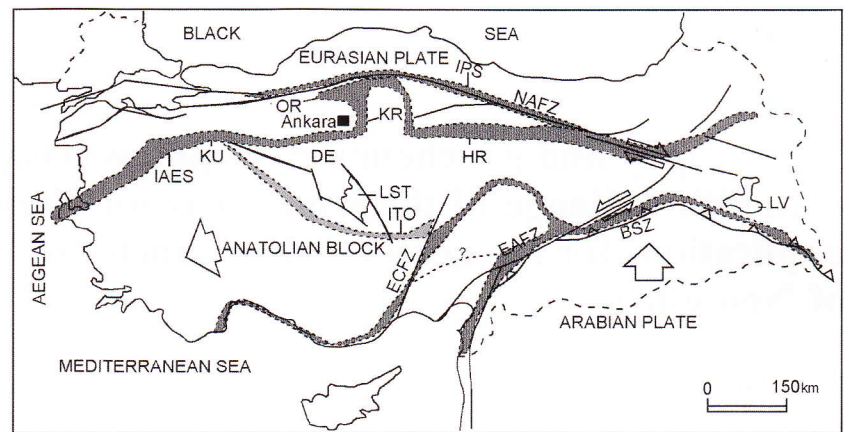
Zones of tectono-sedimentary mélange are a feature of many fragmented ophiolites throughout Turkey (e.g., Hall 1976; Özkaya 1982; Floyd et al. 1991; Collins and Robertson 1997), although it was the coloured mélange exposed in central Anatolia between Kırıkkale and Ankara that was recognized by Bailey and McCallien (1953) and named the Ankara mélange. This broad mélange zone consists of fragmented and mixed rocks (Akyürek 1981; Norman 1984) ranging in age from Triassic to Cretaceous, and is situated within the east–west trending Izmir–Ankara–Erzincan (IAE) suture zone of central Turkey (Sengör and Yılmaz 1981).

Much of the early stratigraphy and structural interpretation of the region east of Central Anatolia, together with the naming of the tectonically imbricated units, was carried out by Norman (1972) and Akkök et al. (1984). Current interpretations of this complex suture zone suggest that the thrust-bound mélange units originally represented a fore-arc accretionary prism that accumulated before the continental collision that partly closed the northern branch of Neotethys (Görür et al. 1984; Norman 1984; Koçyigit 1991). Ophiolitic material of predominantly Lower Cretaceous age, and representing the ocean floor of this

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Fig. 1 Ophiolite belts of Turkey. *OR* Orhaniye-Memlik region, *KR* Kılıçlar region, *HR* Hafik region, *DE* Dereköy (Haymana) region, *KU* Kütahya region, *IPS* Inner Pontide suture, *IAES* İzmir-Ankara-Erzincan suture, *ITO* Inner Tauride Ocean, *BSZ* Bitlis Suture Zone, *NAFZ* North Anatolian fault Zone, *EAfZ* East Anatolian Fault Zone, *ECfZ* Ecişehir Fault Zone, *LST* Lake Salt, *LV* Lake Van



Neotethys seaway, is now largely found in the Anatolian Nappe (Koçyigit 1991).

At present there is little stratigraphic interpretation of the geographically separate blocks of Cretaceous ophiolitic mélangé exposed within the same suture zone. In many cases megablocks or olistoliths, that sit in a largely serpentinitic matrix, have not been studied in detail nor have their relationship to other blocks in the mélangé. Equally important is the determination of the actual age of blocks containing basaltic pillow lavas by utilizing the faunal content of intra-pillow limestone and chert infillings. A number of basaltic blocks from the Dereköy region (see *DE* in Fig. 1), southwest of Ankara, have recorded Callovian–Hauterivian ages (Rojay et al. 2001), although much volcanic development is considered to have been largely in the Valanginian–Barremian interval of the early Cretaceous (Rojay et al. 2004). However, the detailed stratigraphy of selected ophiolitic mélangé bodies exposed to the northwest and southwest of Ankara has been given by Gökten et al. (1988, Pre-Late Campanian) and Rojay and Süzen (1997, Cenomanian–Turonian) (see *OR* in Fig. 1), as well as in an easterly direction to the north of the Sivas Basin around the Hafik region (Gökten and Kelling 1991, Pre-Late Palaeocene) (see *HR* in Fig. 1). Much further to the west of Ankara (near Kütahya; see *KU* in Fig. 1), Önen (2003) examined ophiolitic rocks of the IAES and concluded that dykes and gabbros exhibited a back-arc tholeiitic character, in contrast to the dominant ocean island alkaline basalts around Ankara (Çapan and Floyd 1985).

Objectives

Many megaclasts within the ophiolitic mélangé are largely composed of basaltic pillow lavas that present

the dismembered volcanic portion of the northern branch of the Neotethys seaway (Sengör and Yılmaz 1981) during the early Campanian–Middle Eocene interval. The aim of this paper is determine the geochemical features and geotectonic environment of the volcanic segment of this oceanic crust along its roughly east–west extension by comparing the stratigraphic setting and geochemistry of separate basaltic blocks.

Pillow lavas of the Orhaniye (NW Ankara), Kılıçlar (E Ankara) and Hafik (N Sivas) regions in northern Central Anatolia are examined in this paper (Fig. 1). A 0.5 km thick basalt lava section at Kılıçlar village (near the Kızılırmak valley; *KR* in Fig. 1), which displays a regular magmatic stratigraphy, has already been determined by Floyd (1993) and added for comparison. All geochemical data is interpreted utilizing the same set of diagrams for the determination of the characteristics and petrogenesis of the basalts. In addition, unpublished isotope data for basaltic blocks around Kılıçlar are also presented and discussed.

Metabasite blocks in mélanges

Many mélanges are considered to have been produced in, and subsequently exhumed from, subduction zones and/or developed in the fore-arc region of an accretionary wedge from mainly ocean lithosphere components (e.g., Hall 1980; Aalto 1986; Macpherson et al. 1990; Koçyigit 1991; Jones et al. 1993; Parkinson 1996). The basites are invariably metamorphosed with low-grade metabasalts (generally pumpellyite and greenschist facies), amphibolites and blueschists derived from basaltic or gabbroic parents, and with serpentinitized ultramafics also. A geochemical evaluation of the tectonic setting of the metabasite blocks highlights the

following features: (a) most are representative of basalts from either mid-ocean ridges (MORB) or oceanic islands and seamounts with enriched characteristics (OIB), and (b) that island arc basalts (either tholeiites or calc-alkali high-alumina) are relatively rare, although drilling and dredging in relatively young fore-arc regions (e.g., Mariana forearc) have revealed the association of MORB, OIB and arc-related tholeiites and boninites (Bloomer 1983; Johnson and Fryer 1990). Silicic volcanics and basic volcanoclastics, also presumably derived from an adjacent arc, are rarer still.

However, the association of the dominant types of metabasites (MORB, OIB) in mélanges reflects the association of ocean floor with attendant seamounts pedestals, the latter of which were fragmented and scraped off as the main portion of the ocean floor was subducted (Kobayashi 1985; Ogawa and Taniguchi 1989).

Geochemical analysis

A representative selection of basaltic pillow lava samples were collected from the Orhaniye (NW Ankara) and Hafik (N Sivas) mélangé segments of the

Izmir–Ankara–Erzincan ophiolitic suture zone (Fig. 1). These were analysed for major oxides and a selection of trace elements using an ARL8420 XRF quantometer at the Geochemical Laboratories of Keele University, UK, calibrated against c.30 international and internal standards. Details of methods, accuracy and precision are given in Floyd and Castillo (1992). For comparison samples from the Kılıçlar segment (with REE) were added to the data set. REE were analysed by INAA at Activation Laboratories, Canada. In addition a set of Kılıçlar metabasites that were previously analysed for Sr, Nd and O isotopes, but only briefly discussed (Floyd and Satir 1994), are also incorporated. Isotopic data was obtained in the Isotope Laboratories of Tübingen University by Professor M. Satir and colleagues.

All the basaltic samples are altered to varying degrees with the original magmatic mineralogy replaced by low-grade minerals (largely pumpellyite facies associations), together with late-stage variable carbonate development. Because of the chemical effects of such alteration (e.g., Thompson 1991), only selected immobile trace elements were employed to determine petrogenetic relationships and geochemical discrimination of tectonic setting (e.g., Floyd and Winchester 1978; Pearce and Norry 1979).

Fig. 2 Geological map of the Memlik region (from Gökten et al. 1988)

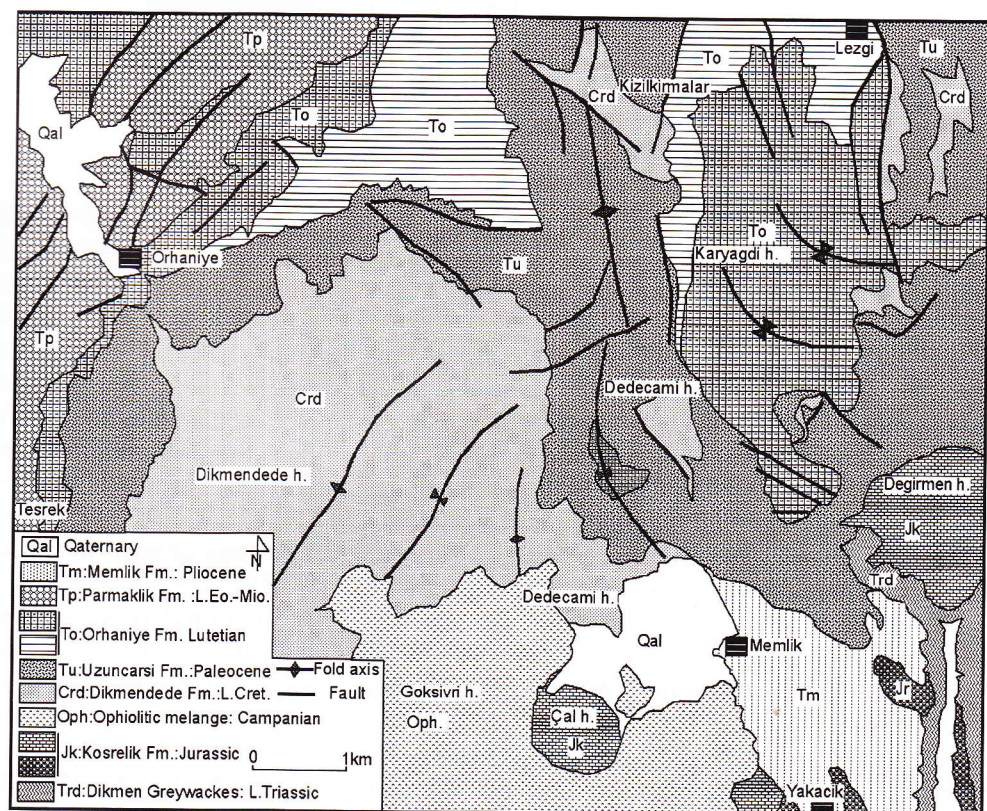


Fig. 3 Stratigraphic columnar section of the Memlik region

AGE	FOR.	Thic k m.	SYMBOL	EXPLANATION
Kuvat.	Qal	100<		Unconsolidated pebble, sand, silt and clay
				Unconformity
L. Eocene-L. Pliocene	Memlik	120		Unconsolidated pebble, sand, silt and clay, limnic lmst and andesite blocks
				Unconformity
E. Pliocene	Parmak.	320		Limnic lmst, claystone, sandstone, some volcanics
Eocene	Orhaniye To	500		Shallow marine limestones: Nummulites spp.
		280		Marl and claystone, transitional facies to marine conditions
Paleocene	Uzunarsı Tu	500		Fluvial conglomerates
				Unconformity
Campanian	Dikmen Crd	550		Turbiditic sandstone and shale alternation: Globotruncana spp.
				Unconformity
Pre-Campanian	Oph. mel.			Ophiolitic melange: serpentinite, pillow lavas etc.
				Tectonic
Dogger-Malm	Kosrelik J	250		Limestones, chert pebbles
Liassic				Basal conglomerates with granite pebbles, at the top Ammonitico-Rosso facies
				Unconformity
Late Triassic	Dikmen Trd			Metagreywackes and metaschist alternation

Orhaniye-Memlik region

Stratigraphy

This region exhibits the initial opening period of the Neotethys oceanic branch in the early Liassic (Fig. 2). The basement is represented by the Dikmen greywackes of Late Triassic age (Akkök et al. 1984) of the Karakaya orogen, and includes Permian limestone olistoliths of various sizes. In the Orhaniye region this unit is overlain by early Liassic mass flow conglomerate which contains pebbles of a granite type not seen exposed anywhere in Turkey today (Gökten et al. 1988). This unit represents evidence for the opening of Neotethys. The conglomerate is followed by “Ammonitico Rosso” facies which grades into pelagic limestones of Malm age (Fig. 3). These are tectonically overlain by ophiolitic mélangé with a pillow basalt

layer that maintains a more or less uniform stratigraphy in various separate outcrops. The ophiolitic mélangé is unconformably overlain by Campanian flysch sediments, which are followed unconformably by fluvial Paleocene conglomerates which grade into Lutetian marine nummulitic limestones. The disappearance of Lutetian marine conditions in this region suggests that the collisional phase with the demise of the northern branch of Neotethys had been completed.

Petrology of basaltic pillow lavas

In the Orhaniye-Memlik region the dismembered pillow lava section of the ophiolitic mélangé covers large areas and displays a regular stratigraphy throughout its c.100 m thickness. Although the unit was open to subsequent alteration, volcanic glass in the groundmass is often fresh and unaltered. Most pillow basalts display

Table 1 Geochemistry of selected basaltic pillow lavas from the Orhaniye-Memlik region

Sample	EG1	EG2	EG3	EG4	EG5	EG6	EG7	EG8	EG9
Major oxides (wt%)									
SiO ₂	30.61	44.37	49.30	39.29	46.67	43.19	45.73	41.29	43.24
TiO ₂	0.95	1.59	1.96	1.47	1.89	2.77	1.69	2.63	2.62
Al ₂ O ₃	8.33	14.00	15.13	11.85	12.86	13.22	14.03	13.07	12.63
Fe ₂ O ₃	0.85	1.52	0.79	1.35	1.56	1.73	1.60	1.80	1.77
FeO	4.81	8.60	4.44	7.67	8.84	9.79	9.05	10.18	10.04
MnO	0.15	0.19	0.11	0.22	0.26	0.21	0.12	0.22	0.18
MgO	2.49	3.42	2.79	3.47	4.17	4.23	4.10	5.33	5.62
CaO	27.98	14.43	15.15	17.97	13.43	12.69	11.00	11.34	11.78
Na ₂ O	1.46	3.13	3.07	2.38	3.55	3.82	5.32	3.60	4.09
K ₂ O	1.20	1.28	0.32	1.50	0.55	0.74	0.65	0.57	0.27
P ₂ O ₅	0.51	0.34	0.34	0.48	0.57	0.40	0.45	0.37	0.36
LOI	20.96	7.82	7.45	12.26	5.94	7.63	7.05	8.72	7.47
Total	100.30	100.69	100.85	99.91	100.29	100.42	100.79	99.12	100.07
Trace elements (ppm)									
Ba	129	195	336	220	363	296	203	269	200
Ce(X)	27	24	27	25	64	34	16	46	38
Cl	13	176	161	272	58	41	4	96	142
Cr	172	467	160	268	374	231	297	236	233
Cu	30	95	79	44	72	60	52	74	59
Ga	16	17	20	20	20	20	17	18	22
La(X)	14	6	8	11	26	5	23	13	14
Nb	21	22	16	27	39	43	22	41	41
Nd(X)	28	18	24	14	39	17	37	14	28
Ni	126	183	78	189	209	191	119	154	169
Pb	17	21	14	13	21	21	20	25	21
Rb	25	30	4	28	9	17	18	13	7
S	175	152	231	165	147	144	171	158	156
Sr	289	363	294	370	473	445	236	374	303
Th(X)	10	10	4	5	14	10	3	8	11
V	125	175	189	203	219	216	199	241	227
Y	19	24	39	23	26	22	26	22	21
Zn	175	162	93	172	133	127	126	122	116
Zr	101	119	180	128	187	161	117	155	152

(X) = determined by XRF

a variety of intergranular, intersertal, porphyritic and subophitic textures, often in the same sample. Hypidiomorphic plagioclase (labradorite) phenocrysts are abundant and surrounded by plagioclase laths or microphenocrysts which form the bulk volume of the samples. The rest of the matrix is composed of devitrified or altered glass (epidotized and chloritized) and occasional pyroxene microphenocrysts, together with skeletal olivine phenocrysts. Some phenocrysts exhibit magmatic corrosion on their crystal edges by the groundmass. Plagioclase is often kaolinized, whereas olivine relicts are variably replaced by serpentine, and carbonate with talc. Patchy chloritization and carbonate replacement are a common feature of the finer grained matrix. Additionally all the basalts were originally vesicular, but now have infillings of predominantly calcite, chlorite and clay minerals. Some samples are cross-cut by quartz-filled microcracks.

Geochemistry of basaltic pillow lavas

Geochemical data for this region is listed in Table 1 and illustrated in Fig. 4, where the Zr content is used as an indication of the degree of chemical evolution or fractionation of the basalts. Based on their Nb/Y ratios and generally high incompatible element contents (Winchester and Floyd 1977) all the samples are alkalic basalts that have undergone some degree of fractionation. As seen in Fig. 4a, compatible elements such as Cr show an expected decrease with progressive Zr content due mainly to pyroxene fractionation, although the scatter might reflect a degree of mobility on alteration. The lower Nb contents for two samples with high Zr probably reflect ilmenite or magnetite fractionation. Other incompatible elements, such as Ti and Y (Fig. 4b, c), show that two chemical series are present with Zr/Y ratios of 5.0 and 7.5, that could

Fig. 4 Selected elements plotted against Zr content for Orhaniye-Memlik area basaltic pillow lavas

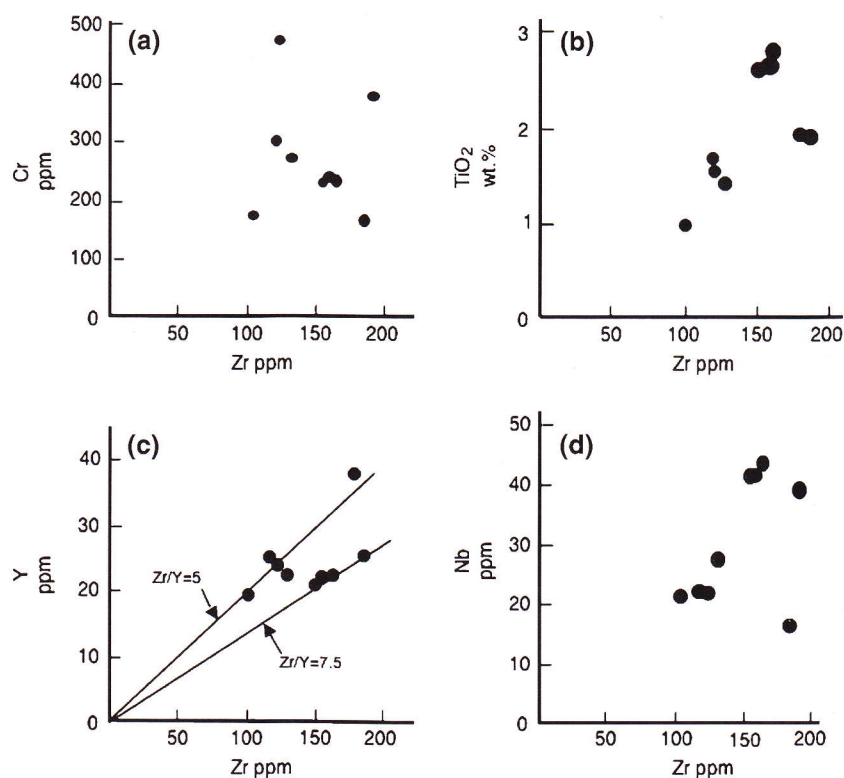
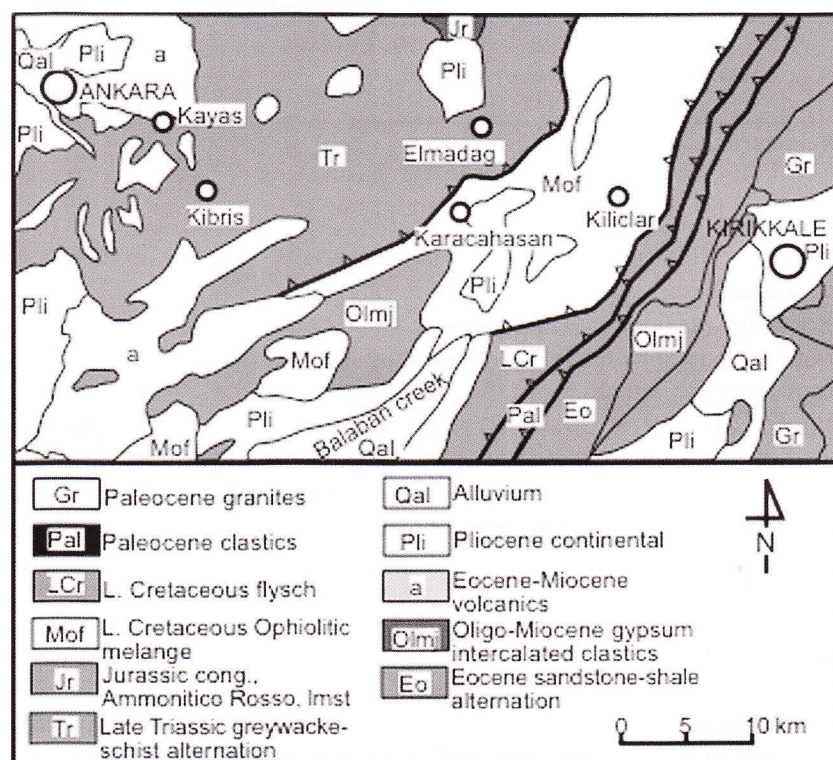


Fig. 5 Geological map of the area between Ankara and Kırıkkale



reflect variable partial melting of a common garnet-bearing source (cf. Kılıçlar; Floyd 1993).

Kılıçlar region

Stratigraphy

The region is located east of Ankara around Elmadag town (Fig. 5) and bears features suggesting the closure

of an oceanic realm (Gökten et al. 1988) with the production of an accretionary prism (Koçyigit 1991). The lithological units from Late Triassic to Lutetian age display an imbricated structure which is specific to the Ankara region, and represents the type locality for the closing of Neotethys by the end of the Middle Eocene. Here the epimetamorphic unit of Late Triassic alternating greywackes and schists (Dikmen greywackes) lies tectonically on the top of the whole sequence. Tectonically underlying this unit are Cretaceous

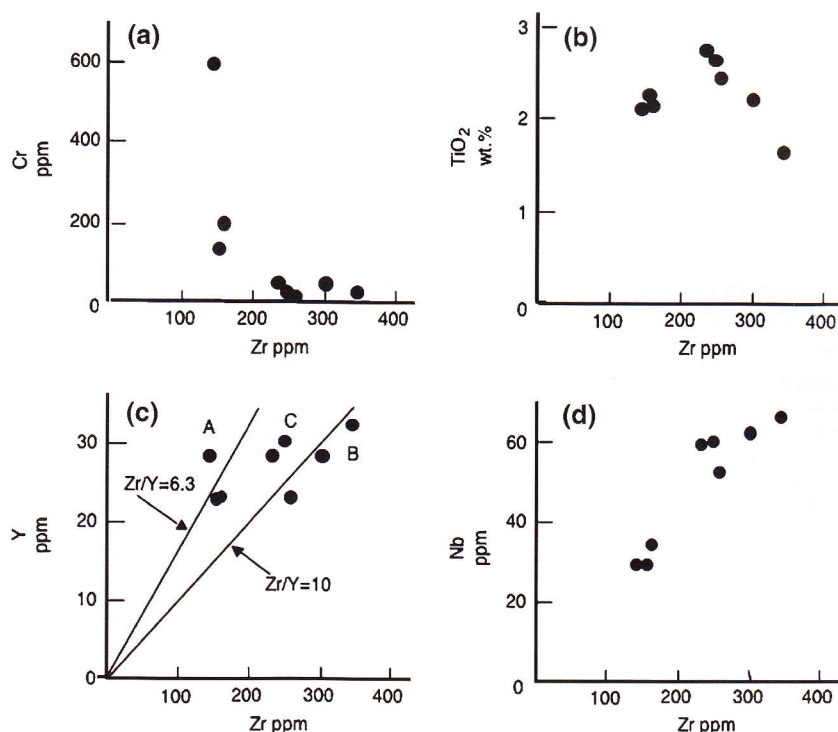
Table 2 Geochemistry of selected basaltic pillow lavas from the Kılıçlar section

Sample Height (m) 71	KIL-3 71	KIL-7 79	KIL-10 90	KIL-15 139	KIL-22 242	KIL-30 304	KIL-34 355	KIL-39 428
Major oxides (wt%)								
SiO ₂	36.05	49.85	47.46	46.23	42.95	45.79	45.83	46.38
TiO ₂	2.43	1.64	2.63	2.73	2.15	2.09	2.24	2.21
Al ₂ O ₃	16.78	15.75	15.66	14.75	13.84	13.97	14.54	16.34
Fe ₂ O ₃	12.26	7.48	11.40	12.05	12.13	13.29	11.08	9.04
MnO	0.21	0.15	0.13	0.13	0.14	0.10	0.11	0.11
MgO	3.29	1.56	5.91	5.43	4.02	2.15	4.70	3.40
CaO	21.02	9.36	7.41	10.33	14.28	12.26	11.74	8.94
Na ₂ O	0.67	9.74	3.92	4.50	3.86	4.69	4.18	4.53
K ₂ O	0.10	0.81	2.17	0.41	0.26	0.03	0.83	2.14
P ₂ O ₅	0.79	0.72	0.72	0.61	0.40	0.43	0.39	0.76
LOI	6.13	6.44	2.31	3.02	5.85	5.35	4.58	6.16
Total	99.72	100.49	99.72	100.20	99.87	100.15	100.22	100.01
Trace elements (ppm)								
Ba	57	147	1529	169	132	63	218	448
Ce(X)	81	131	90	90	55	56	49	92
Cl	163	178	123	90	88	72	134	55
Cr	11	22	18	44	192	589	128	43
Cu	41	34	78	80	65	69	72	35
Ga	26	17	19	17	19	25	22	18
La(X)	45	48	47	61	17	26	28	42
Nb	52	66	60	59	34	29	29	62
Nd(X)	45	59	46	45	36	31	32	46
Ni	42	17	36	61	124	201	53	63
Pb	15	11	10	11	11	10	11	10
Rb	5	18	16	8	4	3	10	24
S	80	109	101	182	93	89	79	88
Sr	154	488	623	568	381	281	181	526
V	196	63	247	228	234	291	231	130
Y	23	32	30	28	23	28	23	28
Zn	95	113	95	99	79	163	67	80
Zr	258	345	249	235	162	145	155	302
Rare Earth Elements (ppm)								
La	41.48	52.71	46.84	37.62	25.62	25.54	24.30	48.52
Ce	84.84	106.83	94.63	79.83	51.00	46.25	49.23	94.07
Pr	9.68	11.83	10.85	9.28	6.13	6.30	5.85	10.28
Nd	37.92	42.42	40.90	36.41	24.10	25.63	23.34	37.44
Sm	7.48	7.66	7.83	7.37	5.05	5.56	5.12	7.00
Eu	2.34	2.35	2.44	2.30	1.69	1.86	1.69	2.18
Gd	6.81	6.67	7.03	6.77	5.01	5.67	5.07	6.14
Dy	5.97	6.05	5.99	5.75	4.50	5.16	4.63	5.39
Ho	0.99	1.06	1.00	0.96	0.75	0.87	0.77	0.91
Er	2.60	2.60	2.57	2.46	1.89	2.30	2.01	2.40
Yb	2.08	2.50	2.04	1.91	1.53	1.77	1.56	2.04
Lu	0.32	0.42	0.33	0.30	0.24	0.28	0.24	0.33

Fe₂O₃* = all Fe as Fe₂O₃

(X) = determined by XRF

Fig. 6 Selected elements plotted against Zr content for Kılıçlar area basaltic pillow lavas



ophiolitic mélangé units which include Jurassic limestone blocks of various sizes. In previous studies (Norman 1975) the epimetamorphic Late Triassic series have been called “metamorphic mélangé” and the Late Cretaceous flysch as the “blocky mélangé”. The Late Cretaceous flysch is tectonically overlain by an early Late Cretaceous ophiolitic mélangé, the outcrops of which are common throughout the Elmadag region. The Paleocene-aged unit of the region, namely the Dizilitaşlar formation (Norman 1975), is tectonically overlain by this Late Cretaceous flysch sedimentation. Various dismembered and stratigraphically coherent

pillow lava-bearing blocks of the mélangé are exposed around and to the north of Kılıçlar village (Fig. 5).

Petrology of basaltic pillow lavas

The 0.5 km Kılıçlar section exhibits both pillowed and massive basaltic lavas in about equal proportions. Plagioclase-phyric and clinopyroxene-plagioclase-phyric basalts are common, although aphyric basalts occur towards the top of the magmatic sequence (Floyd 1993). The basalts are generally well-evolved alkalic basalts with some bearing brown magmatic amphibole.

Table 3 Strontium, neodymium and oxygen isotope data for Kılıçlar basaltic pillow lavas

Sample	KIL-3	KIL-7	KIL-10	KIL-22	KIL-30	KIL-38
Rb–Sr data						
Rb ppm	5	18	16	4	3	46
Sr ppm	154	488	623	381	281	370
$^{87}\text{Rb}/^{86}\text{Sr}$	0.090	0.110	0.074	0.030	0.031	0.360
$^{87}\text{Sr}/^{86}\text{Sr}$ measured	0.704461 ± 16	0.704601 ± 11	0.704159 ± 13	0.703918 ± 11	0.703908 ± 13	0.704571 ± 13
$^{87}\text{Sr}/^{87}\text{Sr}$ at 100 Ma	0.704333 ± 15	0.704445 ± 11	0.704054 ± 13	0.703875 ± 11	0.703864 ± 13	0.704059 ± 13
Sm–Nd data						
Sm ppm	7.48	7.66	7.83	5.05	5.56	n.d
Nd ppm	37.92	42.42	40.90	24.10	25.63	n.d
$^{147}\text{Sm}/^{144}\text{Nd}$	0.119	0.109	0.115	0.127	0.131	0.120
$^{143}\text{Nd}/^{144}\text{Nd}$ measured	0.512780 ± 6	0.512752 ± 11	0.512671 ± 11	0.512667 ± 8	0.512694 ± 10	0.512720 ± 8
$^{143}\text{Nd}/^{144}\text{Nd}$ at 100 Ma	0.512702 ± 8	0.512681 ± 11	0.512671 ± 11	0.512667 ± 8	0.512694 ± 10	0.512720 ± 8
ϵ_{Nd} at 100 Ma	3.8	3.4	3.2	3.1	3.6	4.1
O data						
$\delta^{18}\text{O}$	11.9	16.4	15.1	14.8	14.5	17.3
LOI (wt%)	9.94	6.44	2.31	5.85	5.35	13.09

Table 4 Geochemistry of selected basaltic pillow lavas from the Hafik region

Sample numbers	HAF70	HAF70A	HAF71	HAF73	HAF74	HAF75	HAF77	HAF79	HAF80	HAF80A	HAF81	HAF82	HAF83	HAF84	HAF87
Major oxides (wt%)															
SiO ₂	46.84	47.83	44.78	49.72	46.27	48.58	47.43	48.71	48.07	37.71	51.21	46.34	48.70	51.58	39.47
TiO ₂	1.03	1.25	1.00	1.55	1.18	1.33	0.88	0.91	0.86	2.42	1.41	1.19	1.44	1.54	1.43
Al ₂ O ₃	15.66	14.61	15.32	14.62	14.63	14.59	14.09	14.31	13.92	11.53	13.93	14.39	15.28	14.36	11.96
Fe ₂ O ₃	1.42	1.75	1.33	1.71	1.52	1.66	1.26	1.52	1.37	1.07	1.34	1.48	1.67	1.91	1.18
FeO	8.04	9.88	7.48	9.70	8.59	9.39	7.13	8.63	7.78	6.09	7.58	8.38	9.44	10.79	6.68
MnO	0.12	0.18	0.12	0.23	0.17	0.17	0.14	0.17	0.13	0.21	0.14	0.17	0.19	0.20	0.10
MgO	6.07	7.48	6.45	6.79	5.92	7.46	6.01	7.78	6.90	4.20	7.74	5.47	6.65	5.06	4.08
CaO	11.30	10.18	13.93	7.94	12.62	9.52	13.37	11.09	12.84	17.65	6.05	12.71	9.73	6.84	17.03
Na ₂ O	3.65	3.30	2.93	3.95	3.15	3.62	3.46	3.66	3.53	4.17	4.81	2.79	3.71	3.97	3.94
K ₂ O	0.70	1.16	0.34	1.03	0.61	0.28	0.35	0.20	0.32	0.42	0.51	0.41	0.15	0.70	1.10
P ₂ O ₅	0.12	0.12	0.11	0.18	0.15	0.12	0.11	0.10	0.09	0.58	0.14	0.14	0.17	0.11	0.23
LOI	5.38	2.68	6.24	2.96	4.79	2.92	5.64	3.53	4.28	13.77	3.17	6.56	3.12	3.45	12.16
Total	100.33	100.42	100.03	100.38	99.60	99.64	99.87	100.61	100.09	99.82	100.03	100.03	100.25	100.51	99.36
Trace elements (ppm)															
Ba	60	44	50	127	51	31	24	32	36	167	63	39	52	120	185
Ce(X)	9	7	10	10	7	7	9	9	6	50	8	7	9	7	24
Cl	73	186	135	163	170	235	204	177	184	237	156	115	127	456	185
Cr	313	102	312	125	153	155	232	202	209	48	242	296	275	50	232
Cu	75	74	69	71	86	75	183	75	37	49	78	63	64	32	91
Ga	3	15	10	14	8	13	11	8	8	17	7	11	21	14	11
La(X)	2	2	2	6	8	2	2	2	2	28	2	2	1	1	16
Nb	6	4	5	11	9	5	4	3	3	27	6	7	12	3	31
Nd(X)	2	6	23	10	6	12	6	2	2	20	2	10	6	6	13
Ni	114	75	114	80	71	84	104	90	90	131	94	94	108	28	133
Pb	8	10	12	10	10	12	10	7	10	12	9	15	10	13	13
Rb	15	6	9	19	15	8	9	8	9	13	14	11	9	21	48
S	135	166	202	142	234	152	181	236	145	175	131	147	196	171	141
Sr	127	158	93	119	68	138	71	131	112	218	133	120	104	194	136
Th(X)	1	2	1	1	3	1	1	2	1	5	3	2	1	1	9
V	223	316	220	328	293	322	251	269	245	180	320	287	300	434	234
Y	22	33	22	34	28	34	25	24	21	37	29	34	34	29	20
Zn	73	83	71	90	79	82	74	74	54	107	50	88	89	95	74
Zr	72	81	69	109	85	85	61	57	55	237	95	83	113	85	118

(X) = determined by XRF

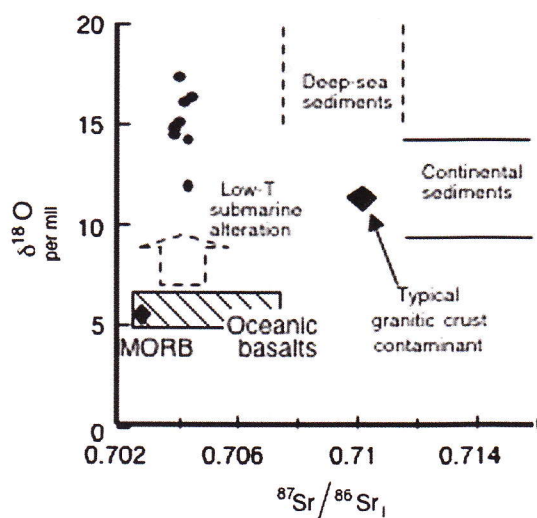


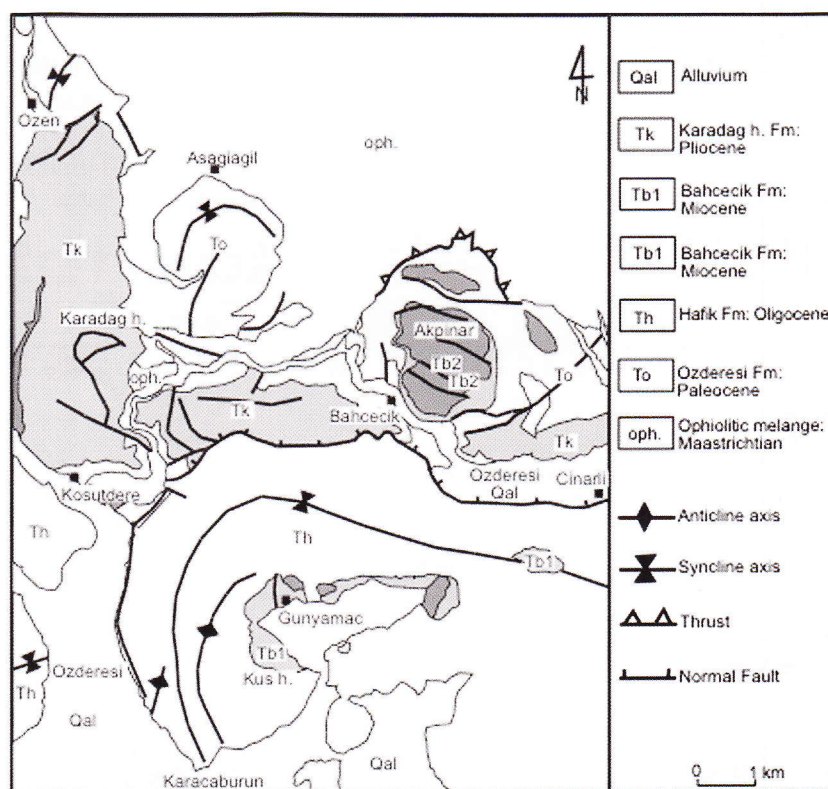
Fig. 7 Oxygen-strontium isotope distribution in Kılıçlar basaltic pillow lavas relative to oceanic basalts and sediments (data from James 1981; Saunders et al. 1988)

Most show superimposed pumpellyite facies assemblages, although the latest alteration is characterised by smectite-carbonate and variable zeolite development.

Geochemistry of basaltic pillow lavas

A selection of analytical data, together with REE, are presented in Table 2 (taken from Floyd 1993) and illustrated in Fig. 6. The alkalic basalts (with Nb/Y

Fig. 8 Geological map of the Hafik region, northern boundary of the Sivas Tertiary basin (from Gokten and Kelling 1991)



AGE	FORM	SYMBOL	EXPLANATION
QUAT			Unconformity — Qal: Alluvium
PLIOCENE	Karadagtep		Loose conglomerate, sandstone, siltstone and locally thin limnic limestone
			Unconformity —
EMIO CENE	Bahcecik		Reefal limestone, Miogypsina spp., Lamellibranchia
			Beach sandstone
			Unconformity —
OLIGOCENE	Hafik		Varigated coloured conglomerate, sandstone, siltstone and, gypsum lens and diapirs
			Unconformity —
SPARNATIAN	Ozderesi		Conglomerate, sandstone
			Conglomerate lobes and sandstone alternations
			Lagoonal conglomerate and sandstone alternations: <i>Ostrea uncifera</i> , <i>Batillana</i> spp., <i>Melanopsis</i> sp.
			Grey shales
			Sandstone and shale alternation with plant remains
			Unconformity —
L. CRETA.	Oph Mel		Ophiolitic melange: Serpentinite, radiolarite, pillow lavas, red limestone blocks with <i>Globotruncana</i> sp.

Fig. 9 Stratigraphic columnar section of the Hafik region

ratios from 1.0 to 2.5) are well-evolved with compositions ranging from basalts to hawaiites and display fractionated REE patterns with $[Ce_N/Yb_N]$ between 7

and 12 (see later). As noted by Floyd (1993) three chemical series are present in the Kılıçlar section (labelled A, B and C), separated by different Zr/Y ratios (Fig. 6c) and variable Cr contents reflecting differential fractionation of pyroxene and to a lesser extent amphibole (Fig. 6a).

Little isotope data has been published for any of the metabasites within the ophiolitic mélange units, apart from a reconnaissance study by Floyd and Satir (1994), which included metabasalts from the Kılıçlar section. The data for Sr, Nd and O isotopes are shown in Tables 3 and 4.

Fresh MORB and OIB generally exhibit a narrow range of $\delta^{18}\text{O}$ values (6.0 ± 0.5 ‰; Muehlenbachs and Clayton 1972), whereas $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are more variable, although MORB has a typically low average value of 0.7025 relative to most OIB (Saunders et al. 1988). As seen in Fig. 7, Kılıçlar alkali basalts have restricted Sr ratios (c. 0.704), well within the common range of ocean islands, but elevated $\delta^{18}\text{O}$ (12–17 ‰). A consequence of submarine weathering of basalts is an enhancement of the $\delta^{18}\text{O}$ ratios and a feature which is characteristic of many low-grade altered ophiolitic basites (Muehlenbachs and Clayton 1972; Spooner et al. 1974). This would appear to be the case with the Kılıçlar alkali basalts, which also exhibit high LOI contents reflecting the presence of secondary hydrated minerals, whereas mixing with sediment or other contaminants has not apparently

changed their O or Sr isotopic values (Fig. 7) and can thus, be ruled out.

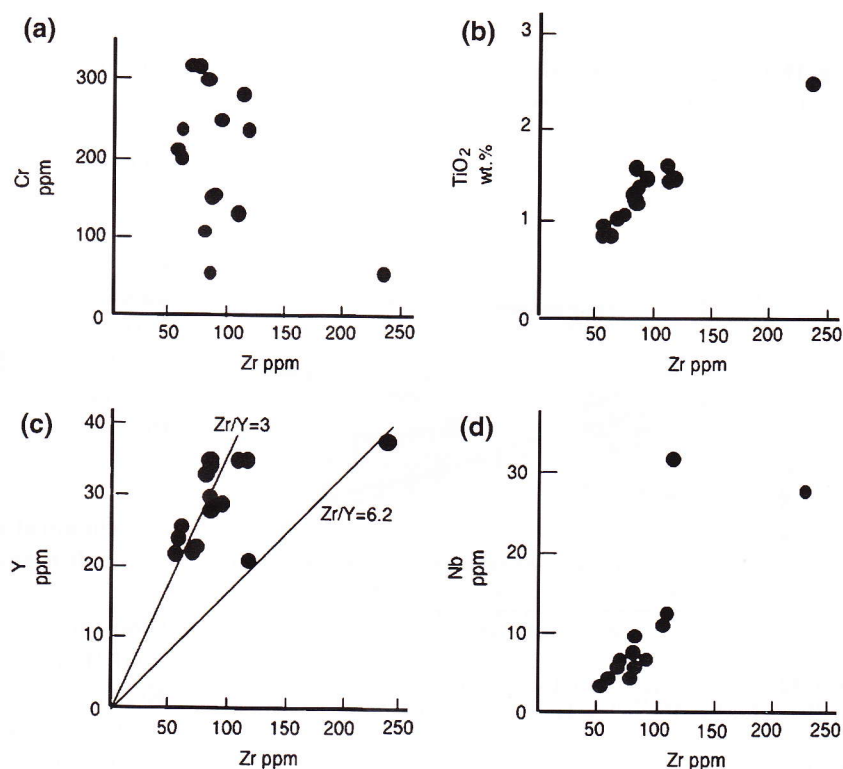
Hafik region

Stratigraphy

The ophiolitic mélange exposed here forms the basement of the Sivas Tertiary sedimentary basin (Fig. 8) and represents the southern extension of the large Çamlıbel ophiolitic body (Yılmaz 1981) within the IAE suture zone.

In the far north of the Sivas basin the ophiolitic mélange has been thrust on top of Neotethyan Jurassic limestones or Late Triassic metamorphics of the Sakarya continent (Karakaya orogen). In the Hafik region the ophiolitic mélange is unconformably overlain by Late Paleocene age lagoonal sediments (Fig. 9) which rapidly grade into the fan deltaic deposits (Özderesi formation) which characterize the margin of the Sivas basin (Gökten and Kelling 1991). The unconformably overlaying Hafik formation is composed of mainly clastic and interbedded evaporitic sediments, and is followed by shallow marine sediments of the Bahcecik formation (Early Miocene age). Finally, continental clastic sediments of the Karadag formation of Pliocene age unconformably covers all the former lithologies of the region.

Fig. 10 Selected elements plotted against Zr content for Hafik area basaltic pillow lavas



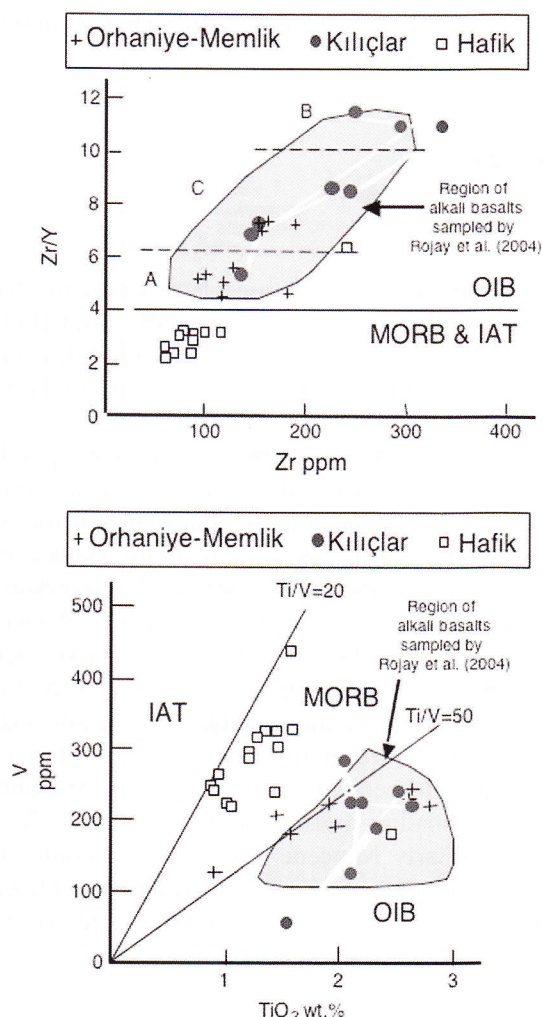


Fig. 11 Geochemical discrimination of tectonic environment for basaltic pillow lavas derived from various ophiolitic mélangé blocks

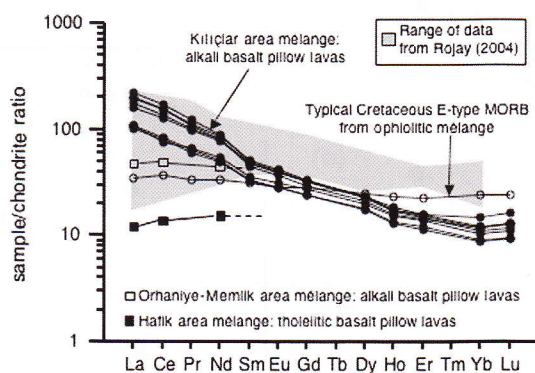


Fig. 12 Comparison of chondrite-normalized rare earth element patterns for basaltic pillow lavas from various blocks within the Cretaceous ophiolitic mélangé. Cretaceous E-type MORB from Floyd (1993)

Petrology of basaltic pillow lavas

Most of the samples have (or did have) a glassy matrix with quenched variolitic textures composed of radiate plagioclase and scattered plagioclase microlites. Much of the original glass has devitrified. Phenocrysts are common and include hypidiomorphic plagioclase and euhedral/subhedral pyroxene and olivine. Minute opaque anhedral minerals (probably magnetite) are common throughout. Small vesicles are common and filled with secondary minerals such as quartz, carbonate and zeolites. The plagioclase microlites and phenocrysts show variable argillization (kaolinite) and silicification (quartz). The mafic minerals are often replaced by epidote and carbonates, whereas olivines are serpentinized. In contrast, some coarser-grained samples are holocrystalline in character suggesting that they may be dyke-like dolerite intrusions. Here, intersertal textures are common with hypidiomorphic plagioclase phenocrysts occurring as laths. Euhedral olivine and augite phenocrysts have been variably replaced by serpentine and chlorite.

Geochemistry of basaltic pillow lavas

Figure 10 shows some of the geochemical features of these basalts. There appears to be two chemical series present distinguished by Zr/Y ratios (3 and 6.2; Fig. 10c), which display a broad decrease in Cr content (Fig. 10a) probably due to fractionation by spinel (not seen in thin section) and pyroxene (which occur as phenocrysts). Titaniferous oxides do not appear to have played much of part in the fractionation sequence as suggested the lack of any marked decrease in Ti content (Fig. 10b). Most samples have low Nb/Y and Zr/Y ratios which indicate that they represent a series of depleted tholeiites, and thus, a different magma series to some of the other pillow basalts sampled to date. Although XRF-determined light REEs are not very reliable, averaged data suggests that they have small LREE-depleted patterns (see later), unlike the enriched patterns typical of many mélangé basalts of this suture zone (Floyd 1993).

Geochemical discrimination and identification of basalt types

From this, and previous geochemical studies (e.g., Tankut and Gorton 1990; Floyd 1993; Tankut 1984; Rojay et al. 2001, 2004), most of the Cretaceous basaltic blocks within the suture zone represent two main groups: (a) a dominant group are alkalic basalts

with relatively enriched geochemical features similar to many ocean island basalts (OIB) and (b) various tholeiitic basalts with low, but variable incompatible element contents and normalized light REE patterns ranging from slightly depleted to mildly enriched. An additional group with calc-alkali characteristics were recorded by Capan and Floyd (1985) and interpreted as arc-related basalts, although these had not been recognized in previous studies. The above simple division of the alkali and tholeiitic basalts and their chemically discriminated environments is summarized in Fig. 11. In general, OIB (predominantly alkalic basalts) relative to the tholeiite group, have Zr/Y ratios >4 (Pearce and Norry 1979), Ti/V ratios >50 (Shervais 1982) and very low Zr/Nb ratios (<7), together with enriched (chondrite-normalized) light REE patterns (Fig. 12).

However, in the light of the chemical variation displayed from a number of oceanic environments (especially results from DSDP/ODP), it is important to re-evaluate this simple dichotomy of OIB-type seamounts versus tholeiitic ocean floor and obtain a better understanding of the origins of the basaltic components of the suture zone. Similarly, the application of highly incompatible element ratios (e.g., Zr/Nb) and radiogenic isotopes (e.g., Sm/Nd and Rb/Sr systematics) could also have a bearing on the nature of the mantle sources from which the basalts were originally derived (see next section).

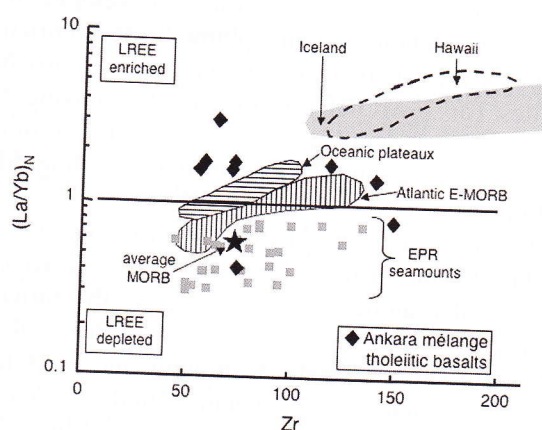


Fig. 13 Relative light-to-heavy REE fractionation (as chondrite normalized La/Yb ratio) for tholeiites from different oceanic environments. Ankara mélange data from Floyd (1993); Tankut (1984); Rojay et al. (2004). Other data: average MORB (Sun and McDonough 1989); East Pacific Rise (EPR) axial seamounts (Allen et al. 1989); Atlantic E-MORB (Tarney et al. 1979); Oceanic plateaux (Mahoney et al. 1993); Iceland (Gibson et al. 1982); Hawaii (Basaltic Volcanism Study Project 1981)

Alkalic basalts

Because of their similarity to OIB it is generally assumed that these basaltic pillow lavas were derived from seamounts that developed on the ocean floor prior to dismemberment (e.g., Capan and Floyd 1985; Norman 1975; Floyd 1993; Rojay et al. 2001, 2004). However, alkalic basalts are also known from other oceanic environments, including aseismic ridges (e.g., late basalts from the Walvis Ridge; Humphris and Thompson 1983), early, mid-plate, seamount development (e.g., Loihi seamount, Hawaii; Frey and Clague 1983); late-stage development of tholeiite-dominated islands (e.g., Hawaiian chain; Clague 1987); deep-sea sills (e.g., Pigafetta Basin, W. Pacific; Floyd et al. 1992) and plume-hijacked ocean ridges (e.g., Iceland; O'Nions and Gronvold 1973). In many of the above cases the alkalic basalts are minor and closely associated with abundant and voluminous tholeiites, a feature that is not readily apparent in the mélange block assemblage. Although direct chemical comparisons can be made with alkalic seamounts from the Pacific Ocean (e.g., Floyd 1993), the associated sediments may, in some cases, preclude the basalts as being part of the main seamount edifice. For example, the Kılıçlar section, with debris flows of volcanoclastic and pelagic material closely associated with the extrusion of basalts suggests that it may represent the outer arch-moat region of a seamount rather than the seamount itself (Floyd 1993), or when associated with reefal and radiolarite debris, the slumped apron of an adjacent seamount (Rojay et al. 2004). In other cases where interbedded pelagic sediments are lacking or any sedimentary intra-pillow fill is largely missing, the mélange blocks could represent a deeper or earlier portion of a seamount structure. Because of the relatively small pillow lava sections exposed in some of the blocks, interpretations tend to be generalized but broadly favour structures built on the seafloor.

Tholeiitic basalts

This group is generally considered to have an affinity to some form of MORB, possibly reflecting a range from normal- to enriched-types of ocean floor. However, apart from pillow lavas from Hafızdursun Yayla (N of Kılıçlar) (Floyd 1993) and the Halik area studied here there appear to be no basalts with strongly depleted N-type MORB affinities (that is, with $(La/Yb)_N < 1$). In fact, even these basalts have higher than expected Nb contents (>2.5 ppm Nb for N-MORB) and only very slight light REE depletion patterns (Fig. 12). Apart from these few examples, the rest of the

Fig. 14 Comparison of Ce/Y and Zr/Nb ratios for Kılıçlar basaltic pillow lavas with alkalic basalts from ocean island basalt (OIB) environments (data from various sources; Loihi seamount data from Frey and Clague 1983)

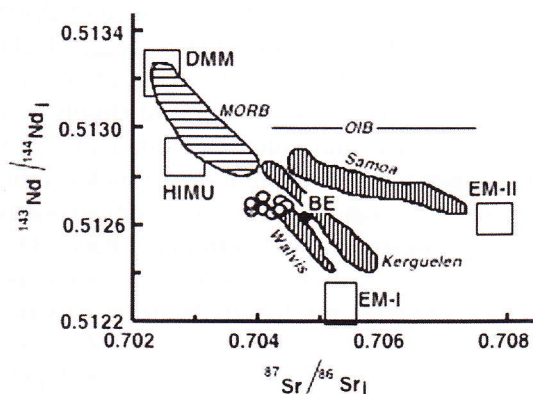
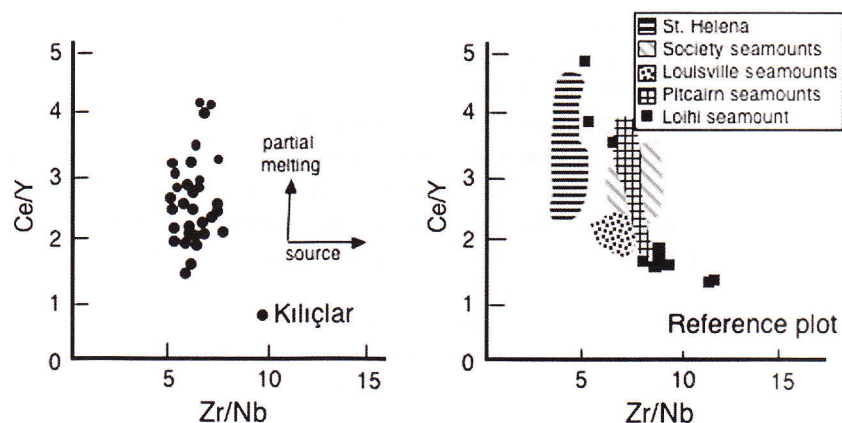


Fig. 15 Neodymium-strontium isotope distribution in Kılıçlar basaltic pillow lavas relative to MORB, selected oceanic islands (OIB) and mantle end-member reservoirs (data from Zindler and Hart 1986; Hart 1988)

identified tholeiites are generally more incompatible element enriched, with low Zr/Nb ratios (<10), and exhibit flat to mildly enriched normalized REE patterns (Fig. 12). These features have often been used to suggest an affinity with E-MORB (e.g., Floyd 1993; Rojay et al. 2004), that is, a spreading ridge contaminated by a nearby plume. However, distinguishing whether these tholeiites really represent actual ocean floor (formed at a spreading centre) or volcanic structures built on the oceanic basement (intra-plate tholeiitic OIB) remains a problem, because chemical discrimination is difficult due to the overlap of compositions from these environments. However, normalized REE patterns are typically flat for enriched-types of MORB, whereas those for ocean island tholeiites are usually convex to varying degrees (Jones et al. 1993). As exhibited in Fig. 13, normalized (La/Yb) ratios differ in their degree of light to heavy fractionation for E-MORB and oceanic plateau relative to tholeiite-dominated ocean islands, such as Iceland and Hawaii. Based on the little data available from the Ankara

mélange, this suggests that a few tholeiites are akin to E-MORB, although the majority might represent oceanic islands, albeit with more primitive (i.e., lower Zr) compositions. Certainly, the one unifying feature is that both E-MORB segments of ocean crust and ocean islands/seamounts are related to mantle plumes. Thus, the presence of some remnant N-MORB segments and the close association of dominant ocean islands/seamounts might suggest that an enriched ridge chemistry (E-MORB) might be expected, as well as off-ridge seamounts of both alkalic and tholeiitic compositions.

Mantle sources of the mélange basalts

The above geochemical assessment of the tectonic environment suggests that at least two primary mantle compositions were involved in the generation of the basalts: depleted asthenosphere for the development of the N-MORB tholeiites and plume-hosted, enriched mantle, for the alkalic OIB. The presence of enriched tholeiites (or E-MORB) represents the mixing between the depleted and enriched sources, such as might be generated by a plume adjacent to a spreading ridge (Schilling et al. 1985).

Stable trace elements (Table 2) and radiogenic isotope data (Table 3) that are available for the Kılıçlar section basalts can be used to characterize the enriched OIB mantle source. Figure 14 compares these alkalic basalts with various Pacific seamounts and St Helena island in the Atlantic Ocean. Changes in the Ce/Y ratio (representing light to heavy fractionation of the REE, Y as a heavy REE proxy) are largely a reflection of the degree of partial melting involved in the generation of the volcanics, together with minor pyroxene fractionation. The Zr/Nb ratio, on the other hand, often characterizes the nature of the enriched source, being largely unaffected by partial melting (except at very

low degrees) and fractional crystallization. As shown in Fig. 14 many seamount basalts exhibit vertical trends at variable Zr/Nb, similar to the Kılıçlar basalts, suggesting that the latter were also derived from a similar, but variably enriched mantle source.

Detailed studies of the Nd–Sr isotope systematics of basalts has allowed the identification of specific mantle end-member compositions, such as depleted MORB mantle (DMM), high $^{238}\text{U}/^{204}\text{Pb}$ ratio mantle (HIMU) and two enriched mantle components (EM-I and EM-II) (Zindler and Hart 1986; Hart 1988); mixing between these end-members can produce a range of basalt compositions. As seen in Fig. 15, the isotopic range exhibited by different OIB-types (e.g., Samoa, Walvis Ridge) can be generated by mixing these fundamental sources. The Kılıçlar basalts (Fig. 15) plot at one end of the Walvis Ridge basaltic trend and could represent mixing between an enriched EM-I source and a minor component of a more depleted source similar to DMM. Humphris and Thompson (1983) interpret the Walvis Ridge variation, in general, as the mixing between an enriched Tristan da Cunha-type plume source and a depleted source. It is suggested that the Kılıçlar alkalic basalts may have been derived from a broadly similar source mix, but less dominated by EM-I.

Discussion

The timing of the emplacement of segments of the ophiolitic *mélange* along the Izmir–Ankara–Erzincan (IAE) suture zone show some age differences from west to east. This may be caused by a number of factors, including: (a) the oblique collision of the northward subducted plate, (b) irregularities or embayments of the overriding plate, and (c) the width of the oceanic IAE suture zone may well have differed along its east–west direction. While the first ophiolite emplacement occurred in pre-Campanian time to the northwest of Ankara in the west, it occurred later in the Hafik region in the east. Both in the Orhaniye-Memlik and Hafik regions the ophiolite emplacements are stratigraphically shown at their original levels. In the Haymana region (Dereköy *mélange*; see DE in Fig. 1) the *mélange* sheet is seen as a package thrust onto the Lutetian-aged transition zone sediments (shelf to deep marine) with its root zone further north around the Memlik region. However, in the sedimentary matrix of the Dereköy *mélange* some faunal evidence reveals a late Jurassic–early Cretaceous age (Callovian–Hauterivian) (Altınır 1991; Altınır and Özkan 1991; Rojay et al. 2001, 2004). In this case, the stratigraphical position of the ophiolitic

mélange is as important as the age obtained from its matrix.

The formation of the ophiolitic *mélange* in the trench of the northward subducting IAE zone may have started by early Cretaceous time, with collision in the pre-Campanian (Gökten et al. 1988) that lasted until the end of the Middle Lutetian. In the Elmadag region to the east of Ankara (including the Kılıçlar area) the ophiolitic *mélange* (classic Ankara *mélange* of Bailey and McCallien 1953) has an imbricated structure, representing the Anatolian Nappe or accretionary prism of Koçyigit (1991). The ages of the juxtaposed thrust units in this accretion are Late Cretaceous with flysch sedimentation (the Ilıcınar and Bölükdağ formations of Norman 1984) and the Paleocene-aged sedimentary Dizilitaclar formation (Norman 1984). Thus the first emplacement time of the *mélange* in the Elmadag region can be accepted as early Late Cretaceous.

In terms of the geochemical characters of the *mélange* basalts, the dismembered pillow lavas of the Orhaniye-Memlik and Kılıçlar regions show similar features, representing basalts from alkalic seamounts. In both these regions the red radiolarites and cherts form the second significant member in terms of the bulk volume of the ophiolitic *mélange* assemblage, and this feature points to a tectonic subenvironment on the outskirts or margins of a seamount complex with extensive silica deposition. A similar interpretation for the southward transported *mélange* sheet during the late Lutetian and exposed in the Dereköy (Haymana) region has been given by Rojay et al. (2001, 2004). The geochemistry of the Hafik region ophiolitic pillow lavas suggests a MORB-type affinity, and while they are associated with pelagic red limestones of late Cretaceous age, radiolarites and cherts are rare (Gökten and Kelling 1991). To the south of this area, in the Sivas basin, radiolarites are the main constituents of the ophiolitic *mélange* again and are associated with thick peridotites that represent sampling of deeper crustal/mantle levels (Gökten 1993). The rare arc-related calc-alkali basalts recorded in the Ankara *mélange* (Çapan and Floyd 1985) have not been subsequently found elsewhere, although their existence may be explained by the closeness of the collisional front to an active arc associated with the subduction zone.

The observable thickness of the ophiolitic *mélange* sheet in all the studied regions does not exceed more than a few kilometers, so the oceanic crust of the IAEZ (representing the northern branch of Neotethys) may have been thinner than big ocean realms, with crustal thicknesses of c.5–7 km, if subduction erosion was minimal.

During the stacking of the ophiolite sheets on accretion the uppermost parts are largely preserved in the observed outcrops. However, to the northwest and the northeast of Ankara high-level seamount basalts predominate, whereas further east (Hafik region) basalts of the actual ocean crust are exposed, together with deeper oceanic peridotites. Consequently along the west-to-east extension of the IAE suture zone deeper levels of ocean crust appear to have been tectonically sampled and preserved. The tectonic environment interpretation of the Kütahya ophiolites (Önen 2003) suggests they may not belong to the oceanic crust of the northern branch of Neotethys, even though their formation age is Turonian, not dissimilar to the Ankara region ophiolitic mélange (see KU on Fig. 1). Instead these ophiolites may have been formed in an isolated back-arc basin in the Anatolian block to the north of the subduction zone that consumed the IAEZ ocean crust.

Acknowledgments Professor M. Satir and his team, Tübingen University, are thanked for the invaluable isotope data on the Kılıçlar basalts of which only a preliminary report had previously been published (Floyd and Satir 1994). The production of XRF analytical data was greatly helped by the expertise of David Emley of the School of Earth Sciences & Geography, Keele University. The reviewers are thanked for their comments that improved the overall presentation of the paper.

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