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Middle Permian plume-related magmatism of the Hawasina Nappes and the Arabian Platform: Implications on the evolution of the Neotethyan margin in Oman

René C. Maury,¹ François Béchenec,² Joseph Cotten,³ Martial Caroff,³ Fabrice Cordey,⁴ and Jean Marcoux⁵

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[1] Permian pillow basalts are commonly found in Oman either at the base of the Hawasina Nappes or within the Arabian Platform successions exposed in the Saih Hatat tectonic window. There is an ongoing debate on whether these lavas include normal mid-oceanic ridge basalts (NMORB) witnessing the Permian opening of the Neotethys or if they are plume-related magmas that are emplaced either on the Arabian Platform or on its thinned continental margin. We sampled these lavas from several paleontologically dated middle Permian sites. Four of them (Buday'ah, Rustaq, Al Ajal, and Wadi Wasit) are located within the Hawasina Nappes and are exposed as thrust slices overlain by the Samail Nappe, and one (Wadi Aday) is within the Arabian Platform units and is exposed in the Saih Hatat window. These lavas are associated with marine sediments deposited in environments ranging from proximal (Saih Hatat, Wadi Wasit, and base of the thrust pile of Al Ajal) to distal (Buday'ah, Rustaq, and top of the Al Ajal pile) with respect to the Arabian Platform. Major and trace element features of the basalts allow two groups to be recognized. Enriched high-Ti basalts similar to alkali basalts from intracontinental traps, rifted continental zones, and oceanic islands are exposed in Wadi Aday, Wadi Wasit, and at the structural base of the Al Ajal pile. Moderately enriched to slightly depleted low-Ti tholeiitic basalt magmas resembling the low-Ti flood basalts and those from seaward dipping reflector sequences are represented in Wadi Al Hulw in Saih Hatat, Buday'ah, Rustaq, and at the top of the Al Ajal thrust pile. Both groups show distinct plume-related trace element signatures, and they do not include typical NMORB. Although emplaced in shallow to deep submarine environments, these basalts provide

no direct evidence for a Neotethyan seafloor-spreading event in the Hawasina Basin. Instead, they were likely erupted through the crust of the already rifted and drowned Arabian continental margin. Thus, despite their characteristic plume-related geochemical signatures, the middle Permian basalts from Oman were not likely emplaced during the evolution of a typical volcanic rifted margin. We suggest that they originated from a mantle plume which ascended beneath the Arabian passive margin well after the initiation of seafloor spreading of the Neotethys.

INDEX TERMS: 3640 Mineralogy and Petrology: Igneous petrology; 8105 Tectonophysics: Continental margins and sedimentary basins (1212); 1020 Geochemistry: Composition of the crust; 8157 Tectonophysics: Plate motions—past (3040); 9614 Information Related to Geologic Time: Paleozoic; **KEYWORDS:** plume-related basalts, middle Permian, Neotethys, Hawasina Nappes, Arabian Platform, Oman. **Citation:** Maury, R. C., F. Béchenec, J. Cotten, M. Caroff, F. Cordey, and J. Marcoux, Middle Permian plume-related magmatism of the Hawasina Nappes and the Arabian Platform: Implications on the evolution of the Neotethyan margin in Oman, *Tectonics*, 22(6), 1073, doi:10.1029/2002TC001483, 2003.

1. Introduction

[2] Plume-related basalts display specific petrologic and geochemical signatures which are often preserved (at least partly) in paleovolcanic sequences. Their recognition in Permo-Triassic volcanic series that are very common in Eurasia is thus a potential tool to investigate past mantle dynamics [Nikishin *et al.*, 2002] as well as tectonic processes, e.g., rifting and oceanization [Wilson and Guiraud, 1998], particularly when the studied volcanic sequences are no longer found in their original position. For instance, the stages of the development of the Neotethys oceanic domain in the Mesogean chains have to be reconstructed from the remnants of this ocean and its margins, which are occasionally preserved in Nappes thrust onto continental margins or incorporated within Alpine folded chains.

[3] A Permo-Triassic opening of the Neotethys has been documented in various areas in the Himalayas [Acharyya, 1992; Gaetani and Garzanti, 1991; Garzanti *et al.*, 1994, 1996a, 1996b, 1999; Garzanti and Sciunnach, 1997; Robertson, 1998], Iran [Berberian and King, 1981; Sengör *et al.*, 1993], and Oman [Béchenec, 1988; Béchenec *et*

¹UMR 6538, Université de Bretagne Occidentale, Plouzané, France.

²Bureau de Recherches Géologiques et Minières, Nantes, France.

³UMR 6538, Université de Bretagne Occidentale, Brest, France.

⁴UMR 5125, Université Claude Bernard Lyon 1, Villeurbanne, France.

⁵UMR 7578, Université Paris 7 et Institut de Physique du Globe de Paris, Paris, France.

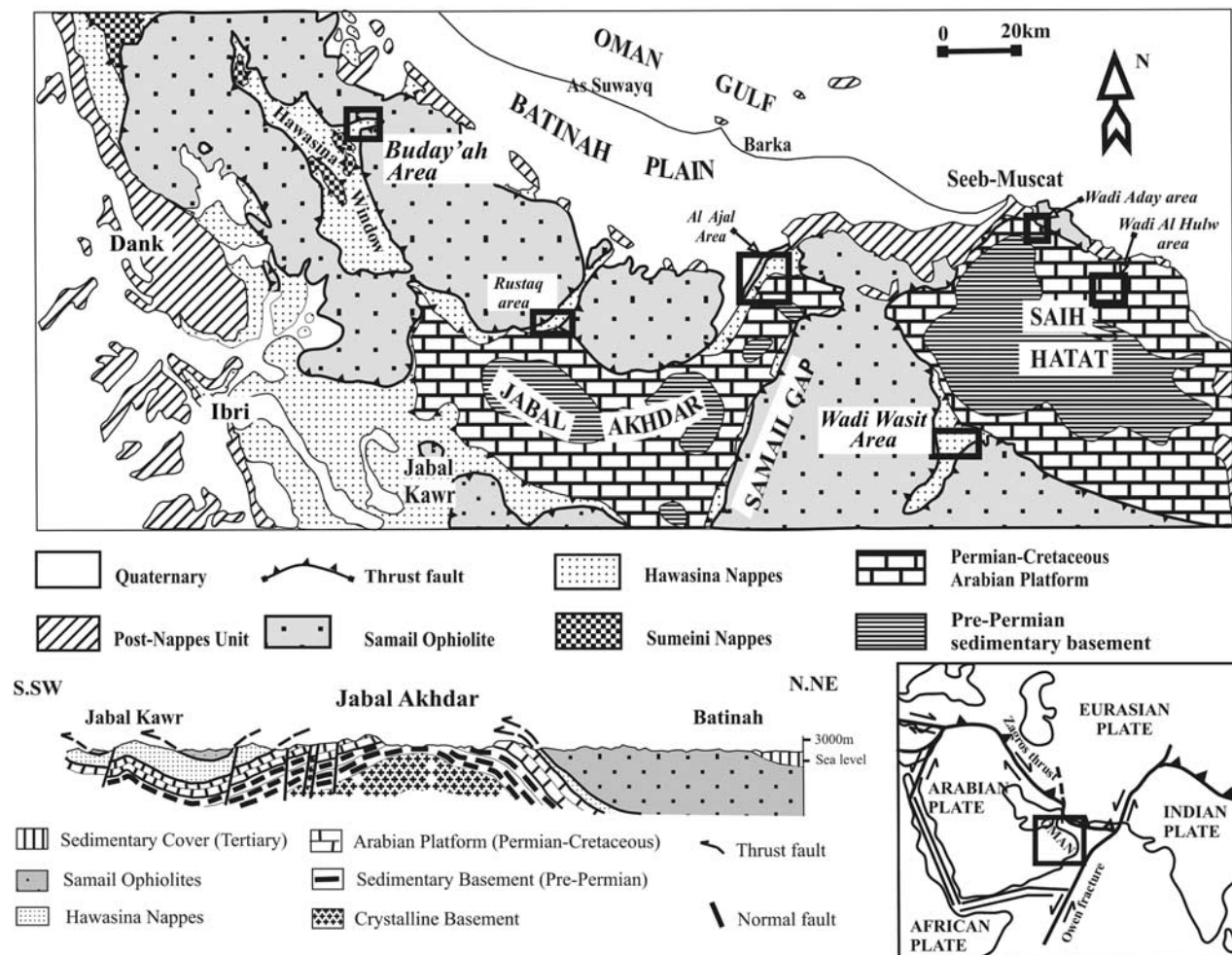


Figure 1. (top) Geological sketch map of the Oman mountains with location of the studied Permian lava occurrences (outlined with boldface) and (bottom) schematic SSW-NNE cross section perpendicular to the Nappes at the level of Rustaq.

al., 1988, 1990, 1991; *Rabu et al.*, 1990; *Robertson and Searle*, 1990; *Robertson et al.*, 1990; *Sengör et al.*, 1993; *Angiolini et al.*, 2003a, 2003b]. In Oman, there is an ongoing debate regarding the origin of the Permian to Triassic Hawasina Nappes. They are considered to have originated either from the Neotethys oceanic domain or from its rifted continental margins. The common occurrence of Permian pillowed basaltic flows at the base of the Hawasina Nappes has often been taken as evidence for oceanic crust formation [*Glennie et al.*, 1974; *Blendinger et al.*, 1990; *Stampfli et al.*, 1991; *Pilleuit et al.*, 1992, 1997], and thus these basalts are considered direct witnesses of the middle Permian Neotethys seafloor [*Stampfli and Pilleuit*, 1993]. Alternatively, it has been proposed that the material of the Hawasina Nappes formed on the continental crust of the Arabian Platform during rifting and/or breakup processes [*Lippard et al.*, 1986; *Béchenec*, 1988; *Béchenec et al.*, 1988, 1990, 1991].

[4] The purpose of this paper is to test these hypotheses using a set of new major and trace element analyses of

basalts from paleontologically dated middle Permian sites located either at the base of the Hawasina Nappes or within the Arabian Platform that is exposed in the northern part of the sultanate of Oman.

2. Geological Setting

2.1. Hawasina Nappes in Oman

[5] The Oman mountains are mainly known for the exceptional exposure of the Samail ophiolite that was obducted onto the Arabian Platform during the Late Cretaceous. Another important feature of the region is represented by a series of imbricated sedimentary and volcanic units sandwiched between platform successions and the Samail ophiolite. These units, referred to as the Sumeini and the Hawasina Nappes (Figure 1), are interpreted as continental slope and ocean basin (or distal continental margin) deposits, respectively, of the southern Tethyan Arabian margin at the end of the Paleozoic and the Meso-

zoic [Glennie *et al.*, 1974]. The history of this southern Tethyan passive margin began during the Permian with a broad marine transgression and an important igneous activity both on the edge of the platform and in the adjacent basin [Béchenec, 1988; Béchenec *et al.*, 1988, 1990, 1991; Blendinger *et al.*, 1990; Le Métour *et al.*, 1995; Pillevuit *et al.*, 1997; Crasquin-Soleau *et al.*, 1999].

2.2. Permian Basalt Occurrences

[6] Middle Permian basalt series belong either to the Saiq Formation, representing the Arabian Platform margins, or to the Al Jil Formation, which is located in the adjacent Hamrat Duru Basin, representing the proximal part of the wide Hawasina Basin. Six localities have been investigated (Figure 1).

2.2.1. Buday'ah

[7] Situated in the northeastern part of the Hawasina window (Figure 1), Buday'ah is the first locality where paleontologically dated middle Permian magmatism was identified from the study of radiolarian chert associated with a thick pillow lava series [Béchenec, 1988; De Wever *et al.*, 1988; Béchenec *et al.*, 1988, 1992a]. The latter consists of dark green to brown, slightly vacuolar pillow basalts ranging from 0.2 to 1 m in diameter, showing occasionally interpillow red carbonate (Figure 2). This volcanic lowermost member of the Al Jil Formation is capped by thin beds of red calcareous mudstone and by a 15- to 20-m-thick series of red radiolarian chert, partly silicified shaly mudstone, shale, and subordinated fine-grained calcarenite, recently dated as middle Permian (Wordian-Capitanian) [Cordey *et al.*, 2001]. This basal member is overlain by beige flaggy calcilutite and shale that have been dated elsewhere as Early Triassic [Pillevuit, 1993].

2.2.2. Rustaq

[8] Recognized by Béchenec [1988] and described in detail by Pillevuit [1993], this outcrop of middle Permian series is located in the hills NW of the Rustaq palm grove. It consists of a 60-m-thick sequence of dark basaltic pillow lavas with interpillow cavities filled up with red lime mudstone containing crinoids and ammonoids near the top of the succession (Figure 2). This basal part is capped by an 8- to 10-m-thick unit of Hallstatt-type, ammonoid-bearing red limestones associated with dolomitized limestones. The red to pink limestones contain ammonoids, crinoids, bryozoans, foraminifera, ostracods, and conodonts. The interpillow limestones and the ammonoid-bearing limestones have been dated as Wordian by Blendinger *et al.* [1992] and Pillevuit [1993] and, more recently, by Kozur *et al.* [2001] on the basis of conodont data.

2.2.3. Al Ajal

[9] In the Al Ajal area several stacked thrust sheets belonging to the Hamrat Duru (HD) group are exposed. Most of these sheets compose the following from base to top (Figure 2): (1) volcanic rocks capped by middle Permian red shale and radiolarian chert, (2) Lower Triassic platy calciturbidite and siltstone (Al Jil Formation [Béchenec *et al.*, 1992b]), and (3) Middle to Upper Triassic radiolarian

chert and *Halobia*-bearing limestone overlain by (4) Lower Jurassic brown turbiditic quartz-sandstone (Matbat Formation). Only the basal unit (HD1) includes younger turbiditic series of Middle Jurassic to Late Cretaceous age. A detailed mapping of these units (Figure 3), combined with the study of their sedimentary successions, allows us to document the piling up of five main thrust sheets, each of which is subdivided into many individual slices. From the structural base (HD1) to the top (HD4-HD5) these thrust sheets were deposited in proximal to distal settings with respect to the adjacent Arabian Platform. HD1 successions are composed of very coarse grained turbidites including abundant erosive channelized breccias. In HD2, olistoliths of shallow-marine carbonate locally coexist with breccia, coarse-grained and thick-bedded calcarenite, and turbiditic quartz-sandstone. In HD3, coarse-grained calciturbidite and breccia are less common, and within HD4 the Al Jil Formation mostly includes fine-grained calciturbidites. The sedimentary criteria are more difficult to determine toward the top of the structural pile because of a stronger tectonic overprint which prevents identification of the paleogeographic setting for the topmost unit (HD5).

[10] Pelagic sedimentary rocks of the Al Jil Formation in stratigraphic contact with HD3 volcanic rocks yielded radiolarians. Red siliceous limestone directly overlying volcanics contains rare and poorly preserved specimens of Albaillellidae. Three meters above, red chert interlayered with red siliceous shales and red micritic limestone released *Hegleria* sp., cf. *mammilla*, *Scharfenbergia* sp., and fragments of Latentifistulidae along with sponge spicules. Recrystallization of radiolarian shells prevents a precise biochronological correlation but indicates a Permian age with no further precision. This age is consistent with previous data obtained from sedimentologically similar Al Jil successions in Buday'ah and Wadi Wasit areas.

2.2.4. Wadi Wasit

[11] The Wadi Wasit area provides one of the most extensive exposures of the middle Permian Hawasina series as several stacked thrust sheets [Béchenec *et al.*, 1992b]. The basal part of most thrust units consists of basaltic pillow lavas associated with doleritic dikes (Figure 2) and associated locally with intercalations of chert, calcarenite, and debris flow deposits containing Lower and middle Permian reef boulders. This lava series (lower member of the Al Jil Formation) is capped by a 15- to 60-m-thick sedimentary or volcano-sedimentary succession made of cephalopod-bearing red carbonate, shale, coarse and fine-grained calcarenite, and tuffite. These strata contain cephalopods [Blendinger *et al.*, 1992] and reworked benthic foraminifera [Béchenec *et al.*, 1992b] of middle Permian (Wordian) age. The overlying, massive, clast-supported breccia, 5–20 m thick, partly or entirely dolomitized, contains reworked Upper Permian Lower Triassic [Krystyn *et al.*, 2003] reef boulders and is capped by a Lower Triassic [Pillevuit, 1993] series of calcilutite and shale (upper member of the Al Jil Formation).

2.2.5. Wadi Aday

[12] On the northern flank of the Saih Hatat window, along the Mascate-Quryat main road in Wadi Aday, the Permian Saiq Formation unconformably overlies the Late

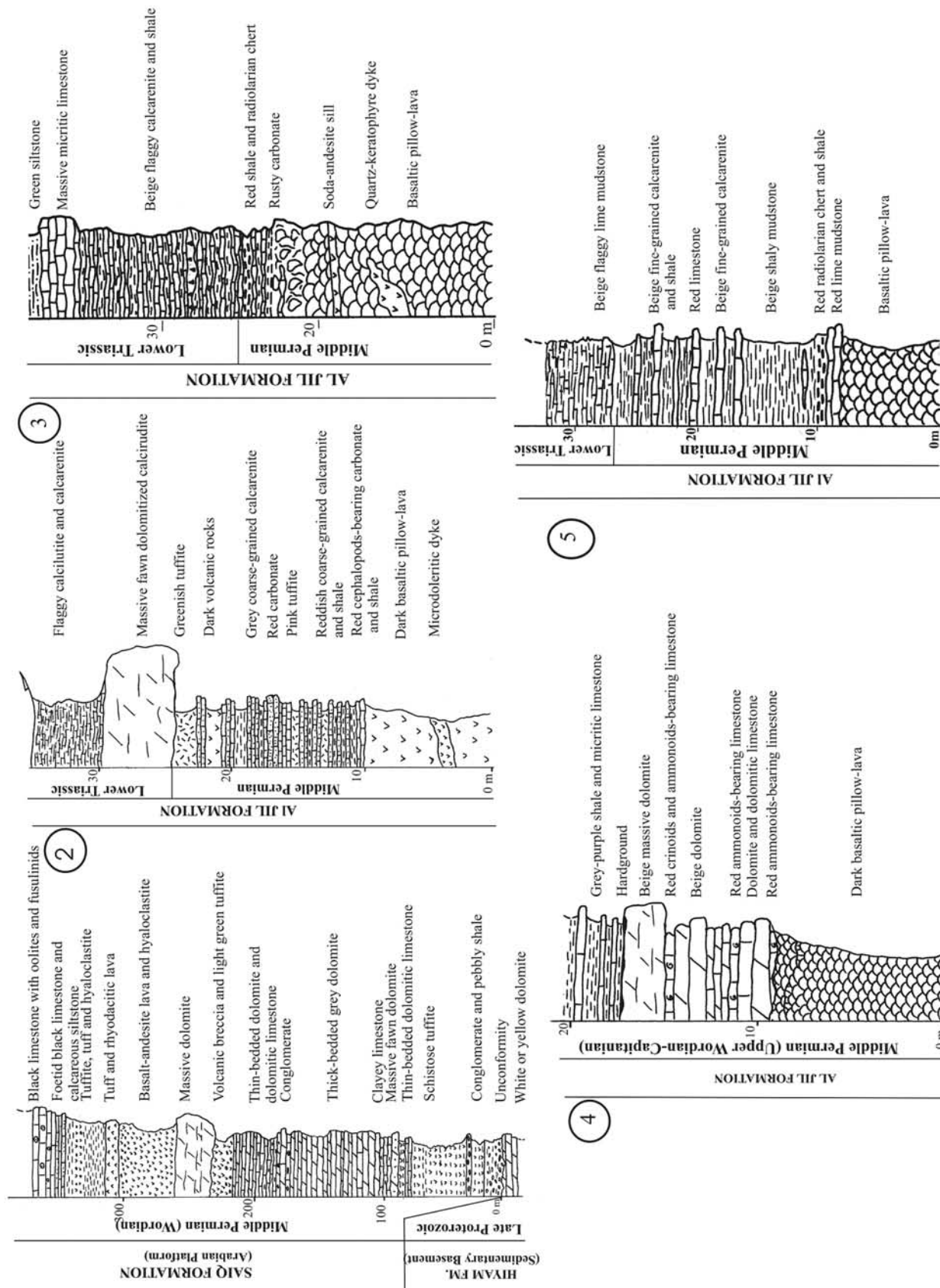


Figure 2. Stratigraphic positions of the studied lava piles. Sites are as follows: 1, Wadi Aday; 2, Wadi Wasit; 3, Al Ajal; 4, Rustaq; and 5, Buday'ah.

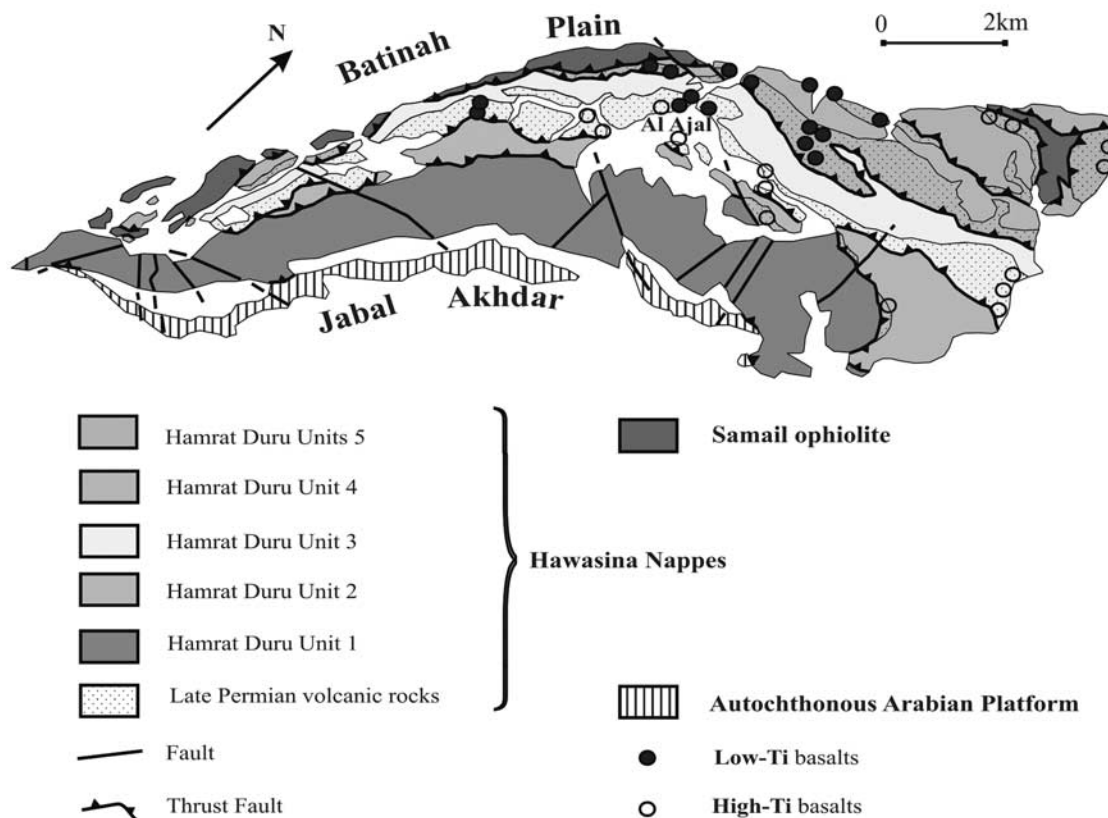


Figure 3. Geological sketch map of the Al Ajal area with location of the studied basaltic samples. Open circles indicate high-Ti basalts; solid circles indicate low-Ti basalts. See color version of this figure at back of this issue.

Proterozoic Hiyam Formation [Le Métour *et al.*, 1986; Le Métour, 1988]. The basal unit of the Saiq Formation, ~80 m thick, comprises a discontinuous layer of unsorted conglomerates composed of subangular pebbles of quartzite, quartz, and dolomite in a sandstone matrix overlain by schistosed metatuffites present as greyish-white mica-schist and micaceous quartzite. Toward the top of the unit, thin-bedded, brown, bioclastic dolomitic limestones are interbedded (Figure 2).

[13] This metatuffite basal unit is overlain by an ~150-m-thick monotonous limestone-dolomite series. A more varied lithology is noted in the upper part with thin-bedded dolomite, clayey limestone, and some lenses of calcirudite. Numerous bioclastic horizons found in these carbonate rocks contain largely recrystallized corals, bryozoans, crinoids, gastropods, and brachiopods. Benthic foraminifera, fusulinids, stafellids, and schwagerinids, indicative of a middle Permian (Wordian-Capitanian) age, have been identified in this carbonate unit [Le Métour *et al.*, 1992].

[14] A second volcanic unit, up to 120 m thick in the Wadi Aday area, overlies these limestones. It starts with a volcanic breccia including clasts of metalavas, metatuffs, and metahyaloclastites of basaltic-andesitic to dacitic composition, with subordinate volcanic arenites. A few dolerite dikes and sills are also present. A discontinuous level of yellow-brown dolostone up to ~30 m thick is interbedded

within the lower part of this unit and contains abundant corals and crinoids. This second volcanic unit is capped by a series of foetid thin-bedded black limestone with shaly siltstone interbeds overlain by thick-bedded bioclastic limestone and dolomitic limestone with pellets and oolites. These limestones are characterized by accumulations of fusulinids and abundant debris of corals, crinoids, gastropods, bryozoans, and large pelecypods.

2.2.6. Wadi Al Hulw

[15] In the northeastern part of the Saih Hatat window, i.e., the Wadi Al Hulw area [Le Métour *et al.*, 1992], the basal volcanic member of the Saiq Formation unconformably overlies the Ordovician Amdeh Formation. This member, particularly thick there (~500 m), is mainly made of metatuffites, and it is capped by a limestone-dolomite sequence about at least 150 m thick, made of thin-bedded grey metalimestones enclosing olistoliths of dolomitic marble and nodular metalimestone. At the interface between these two units a set of laccolites or sills crops out locally. Their doleritic texture has rarely survived because of a syntectonic high-pressure/low-temperature metamorphism that has also produced a well-defined schistosity. The limestone sequence is overlain by recrystallized black limestones which have been dated as middle to Late Permian (Wordian to Wuchapingian) [Le Métour, 1988]. Although the age of the doleritic intrusives

Table 1. Major and Trace Element Analyses of Selected Permian Submarine Basaltic Lavas^a

	Sample OM													
	243	244	02	40	37	31	225	236	15	19	17	22	06	91
Location	WA ^b	WA	WA	WW ^c	WW	WW	AA ^d	AA	R ^e	B ^f	B	B	AH ^g	AH
Type	HTi	HTi	HTi	HTi	HTi	HTi	HTi	LTi	LTi	LTi	LTi	LTi	LTi	LTi
SiO ₂	46.6	50	52.4	43.7	49	48	44.5	47.8	49.9	44.2	50.6	46.6	48.4	47.5
TiO ₂	3.67	2.72	2.15	3.28	2.94	2.08	2.23	1.01	1.86	2.12	1.69	1.1	1.73	1.42
Al ₂ O ₃	14.55	17.4	14.7	16	15.2	15.5	17.2	15.16	15.92	15.62	15.4	16.8	14.15	14.95
Fe ₂ O ₃	15.5	10.85	12.13	15.1	11.3	13.4	10.35	9.56	9.22	11.8	7.7	8.2	12.05	11.7
MnO	0.2	0.08	0.22	0.19	0.13	0.1	0.19	0.16	0.08	0.17	0.13	0.15	0.23	0.2
MgO	3.87	1	2.98	5.7	4.8	2.55	10.45	8.45	1.65	6.05	4.42	7.12	6.06	5.75
CaO	4.88	6.35	5.77	4.83	4.46	4.25	3.21	9.95	6.51	7.4	8.85	10.2	8.45	10.75
Na ₂ O	4.67	4.32	4.4	4.32	5.2	4.08	3.78	2.97	7.6	5.5	5.6	3.73	4.65	3.75
K ₂ O	2.13	2.25	1.92	1.31	0.46	2.26	0.6	0.86	0.23	0.06	0.03	0.75	0.23	0.08
P ₂ O ₅	0.63	0.59	0.92	0.58	0.7	1	0.48	0.12	0.3	0.33	0.25	0.15	0.2	0.15
loi ^h	2.49	4.32	2.24	4.58	5.59	6.17	6.36	3.85	6.66	6.43	4.59	5.06	3.76	3.73
Total	99.19	99.88	99.83	99.59	99.78	99.39	99.35	99.89	99.93	99.68	99.26	99.86	99.91	99.98
Rb	33	45	41	20.5	8.4	54.5	9.6	14.3	3.9	0.9	0.5	14.4	7.1	1.8
Sr	275	510	420	830	350	148	82	180	132	400	142	151	157	205
Ba	239	325	382	770	295	184	70	51	24	87	38	90	54	15
Sc	25.5	18.7	18.2	14.8	20	9	28	38	28	32	32	35	48	49
V	315	162	125	310	150	126	200	260	178	309	240	225	350	345
Cr	17	15	16	5	6	2	330	420	170	270	295	305	96	170
Co	48	32	27	48	23	26	42	42	30	52	42	40	54	39
Ni	27	19	15	39	5	17	157	150	73	136	170	79	56	56
Y	30	33.5	41	30.5	47	40.5	26.5	23	17.5	28	27	23	36	31.5
Zr	210	174	285	282	355	260	150	64	77	130	108	60	95	65
Nb	33	44.5	45	38.5	55	58	35	4.8	9.8	19.3	13.3	5.1	9.6	5.5
La	31	44	47	34	45	49	27	4.2	6.3	16	9.2	4.6	9.1	6.3
Ce	67	90	105	74	95	107	54	10	16	35	23	12.2	20	14
Nd	38	46.5	57	40.5	51	62	28.5	7	13.2	22	16.5	9.4	15.2	11
Sm	8.2	9.1	11.8	8.2	10.4	12.6	6.4	2.3	3.7	5.1	4.1	2.9	4.3	3.5
Eu	2.54	2.78	3.24	2.63	3.28	3.38	1.99	0.84	1.32	1.72	1.38	1.01	1.45	1.27
Gd	7.6	8.6	11	7.5	9.9	11	6	3.2	4.2	5.5	4.7	3.6	5.9	4.7
Dy	6	6.6	8.3	5.75	9.4	7.85	5.4	3.8	3.4	4.9	4.75	3.95	6.45	5.25
Er	2.6	2.8	3.7	2.8	4.7	3.7	2.4	2.3	1.4	2.6	2.7	2.2	3.6	3.1
Yb	1.92	2.22	2.47	2.34	3.48	2.73	2	2.26	1.1	2.33	2.55	2	3.27	2.8
Th	3.2	5.4	5.7	3	4.9	4.3	2.75	0.5	0.65	1.65	1.25	0.35	1.4	0.6

^aMajor elements in weight percent and minor elements in parts per million. HTi, high-Ti basalts; LTi, low-Ti basalts. Analytical methods shown in text.

^bWA, Wadi Aday.

^cWW, Wadi Wasit.

^dAA, Al Ajal.

^eR, Rustaq.

^fB, Buday'ah.

^gAH, Al Hulw.

^hLoss on ignition.

is not constrained, their geological position suggests a possible Permian age.

3. Geochemical Results

3.1. Sampling and Analytical Methods

[16] Samples were crushed into centimeter-sized chips, handpicked under the binocular microscope in order to eliminate altered parts, and finely powdered in an agate mortar. Major and trace element data were obtained by inductively coupled plasma-atomic emission spectrometry. International standards (AC-E, BE-N, PM-S, and WS-E from Centre de Recherches Pétrographiques et Géochimiques, Vandoeuvre-lès-Nancy, France, and JB-2 from Geological Society of Japan, Ibaraki, Japan) were used for calibrations

tests. Rb was measured by flame atomic emission spectroscopy. Relative standard deviations are $\approx 1\%$ for SiO₂, 2% for other major elements except P₂O₅ and MnO, and $\sim 5\%$ for trace elements. The analytical techniques are described by Cotten *et al.* [1995]. The corresponding chemical analyses of selected samples are listed in Table 1. Those of lavas showing loss on ignition (LOI) values higher than 8 wt % were systematically eliminated. Intermediate and acidic lavas displaying relatively high silica contents (>55 wt %), which are interfingering with basalts in some areas (e.g., Wadi Aday and Al Ajal), are not considered in this paper.

3.2. Major Elements and Rock Types

[17] Most of the studied basalts have well-preserved pillow morphologies. These lavas are subaphyric, with rare

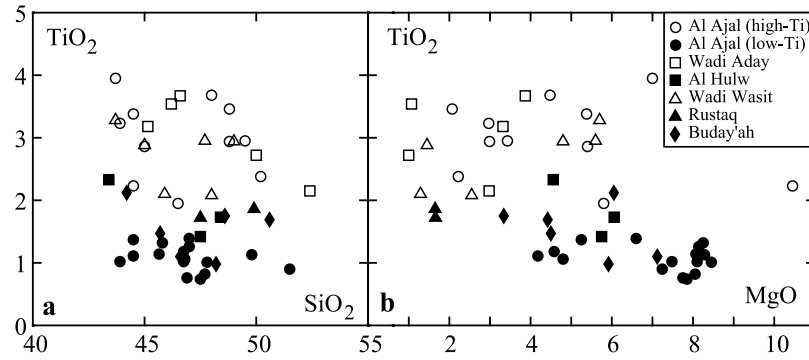


Figure 4. Plots of TiO_2 against (a) SiO_2 and (b) MgO for the studied lavas. Open symbols indicate high-Ti lavas; solid symbols indicate low-Ti lavas.

olivine, plagioclase, and preserved clinopyroxene phenocrysts set into a largely albitized and chloritized groundmass containing variable amounts of calcite and secondary quartz. In addition, samples from Saih Hatat have experienced various degrees of high-pressure metamorphism and contain epidote, actinolite, phengite, and even garnet (in Wadi Al Hulw dolerites). Collecting relatively fresh samples is usually difficult. LOI values range from 1 to 8 wt %, with a frequency peak between 4 and 5 wt %. If the silica contents of the basalts (44–53 wt %, Figure 4) do not seem considerably modified by postmagmatic processes, their $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios are extremely variable even within a single cross section, and some MgO contents, which are much too low given the typical basaltic petrography of the corresponding samples, are also likely to have been modified during alteration and/or metamorphism (Figure 4). The TiO_2 contents of the basalts vary from <1 wt % to 4 wt % and show a bimodal distribution. Thus two groups can be identified in Figure 4: low-Ti basalts ($\text{TiO}_2 < 2$ wt % and often <1.5 wt %) and high-Ti basalts ($\text{TiO}_2 \sim 2\text{--}4$ wt %).

[18] Figure 4 and Table 1 data show that the basalts from five out of the six studied localities belong to a single group: All those from Wadi Aday and Wadi Wasit are high Ti, whereas all but two of those from Wadi Al Hulw, Rustaq, and Buday'ah belong to the low-Ti group. In the $(\text{Ti} + \text{Cr})/(\text{Ca} + \text{Na})$ diagram of *Letierri et al.* [1982] the microprobe compositions of the preserved clinopyroxene phenocrysts from the low-Ti basalts plot within the field of those from modern alkali basalts, while those of the low-Ti basalts plot within the tholeiitic field (diagram not shown). Al Ajal samples are either low-Ti or high-Ti basalts (Figure 4), but the distribution of the two types in the thrust sheets HD2 through HD5 is not random (Figure 3). Indeed, all samples from HD4 (the most distal unit according to sedimentary criteria) are low Ti, while those from HD2 (the closest to the Arabian Platform) and HD5 (no reliable sedimentary data) belong to the high-Ti type. HD3 samples are either high Ti or low Ti, the former ones being located near the structural base of the HD3 unit.

3.3. Trace Element Features

[19] The contents in large ion lithophile elements (LILE) of our samples are highly variable (Table 1), and these

elements display irregular and very spiky distributions on incompatible multielement patterns (diagrams not shown). These features indicate that their compositions probably have been modified by postmagmatic processes. The smooth slopes of rare earth element (REE) patterns (Figures 5 and 6) and multielement patterns including REE, Y, Th, and the high field strength elements Nb, Zr, and Ti (Figure 7), on the other hand, suggest that these elements might have retained near-primary concentrations. As shown by the Al Ajal REE patterns (Figure 5), the low-Ti and high-Ti groups do not overlap with respect to the light REE and middle REE contents (Figure 6) which are clearly higher in the high-Ti samples. High-Ti basalts display typical enriched patterns that are similar to those of modern alkali basalts and very high concentrations in the most incompatible “immobile” elements (e.g., Th and Nb, Figure 7). REE and multielement patterns of the low-Ti basalts range from moderately enriched to flat or even slightly depleted, the latter being rather similar to that of average NMORB but showing lower heavy REE contents (Figure 6).

[20] With respect to low-Ti samples, high-Ti basalts display clearly higher Th/Yb, La/Yb, Nb/Yb, and similar ratios (Figure 8) usually considered typical of ocean island basalts (OIB), whereas the La/Nb ratios of the two groups

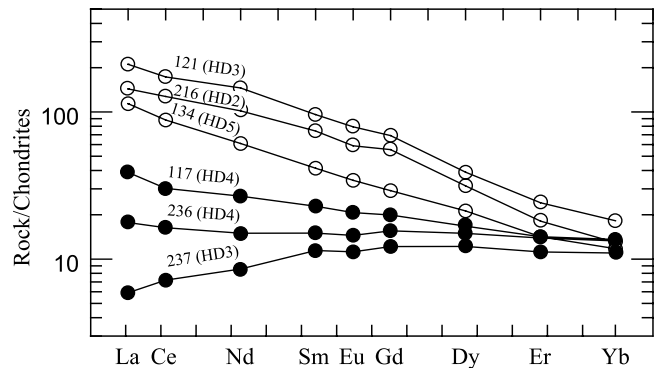


Figure 5. Rare earth element (REE) patterns of representative Al Ajal basalts normalized to the chondrite of *Sun and McDonough* [1989]. Open circles indicate high-Ti lavas; solid circles indicate low-Ti lavas.

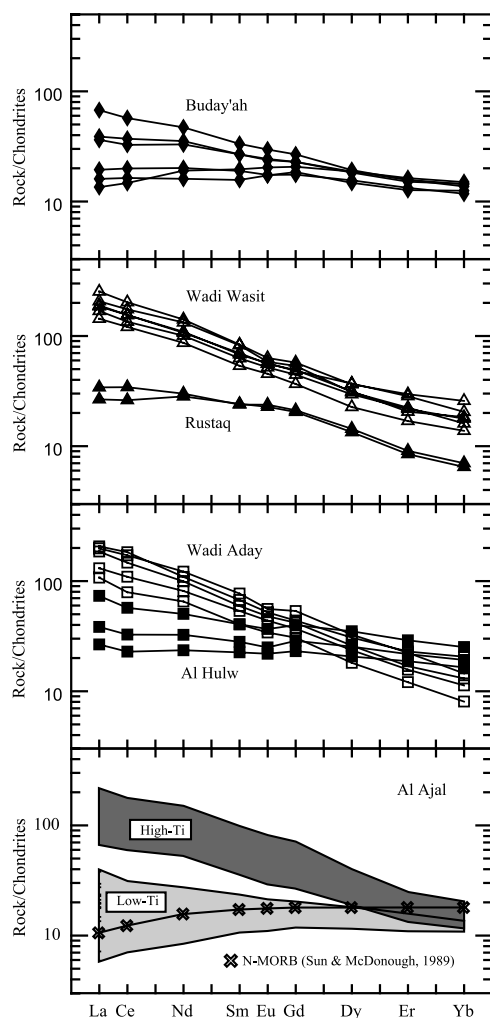


Figure 6. REE patterns of representative Permian basalts normalized to the chondrite of *Sun and McDonough* [1989]. The pattern of average normal mid-oceanic ridge basalt (NMORB) from the same authors is shown for comparison. Data for Al Ajal basalts are shown as envelopes. Symbols are as in Figure 4.

are similar. More generally, the incompatible element patterns of these two groups do not overlap with respect to the most incompatible elements (Figure 7), which are clearly higher in the high-Ti samples. The rough positive correlations between La/Yb, Th/Yb, Nb/Yb, and TiO_2 that are documented in Figure 8 illustrate the variable enrichments in incompatible elements of the studied basalts. The scatter observed especially among the high-Ti basalts might reflect the combined effects of fractional crystallization, partial melting, and source heterogeneities.

4. Discussion

4.1. Magmatic Affinities of the Middle Permian Basalts

[21] The fact that the REE and multielement patterns of some of the low-Ti tholeiitic basalts are flat or slightly

depleted (Figures 5, 6, and 7) does not necessarily imply that they represent genuine NMORB. Indeed, the latter are usually more depleted in the most incompatible elements (e.g., Th and Nb) than they are in the middle Permian Oman samples. In the Y/15-Nb/8-La/10 diagram [*Cabanis and L  colle*, 1989] shown in Figure 9, our samples all plot near the fence separating the fields of MORB and alkali basalts from those of continental basalts. All but two of the low-Ti basalts display La and Nb enrichments equivalent to those of weakly enriched or enriched MORB, whereas the high-Ti samples appear similar to alkali basalts. *Fitton et al.* [1997] have shown that a plot of $\log(\text{Nb}/\text{Y})$ against $\log(\text{Zr}/\text{Y})$ distinguishes NMORB from plume-related basalts, owing to the relative deficiency in Nb of the former. According to this plot (Figure 10), only 3 out of 48 studied basalts could be termed a true NMORB, as both low-Ti and high-Ti samples plot within the field of plume-related Icelandic basalts.

[22] Interactions between ascending flood basalts and continental crust, which have been documented in many sequences [*Gibson et al.*, 1995; *Pik et al.*, 1998, 1999; *Fitton et al.*, 1998a], include selective enrichments in large ion lithophile elements (LILE) and variable La/Nb and its equivalent ratios. It is difficult to document such features for the Permian Oman basalts because of the mobility of LILE during postmagmatic alteration. However, the relative constancy of La/Nb ratios, which are close to or lower than unity for most samples (Figures 8 and 9), suggests that with a few possible exceptions, crustal contamination was not a major process in their evolution.

4.2. Comparison With Younger Basaltic Associations

[23] Continental flood basalts are usually classified into TiO_2 -rich (or high-Ti) and TiO_2 -poor (or low-Ti) associations [*Lightfoot et al.*, 1990; *Peate et al.*, 1992; *Wooden et al.*, 1993], with the former carrying a genuine plume-related geochemical signature close to that of OIB. The latter are thought to derive from either greater degrees of melting or a more depleted source and have generally been contaminated

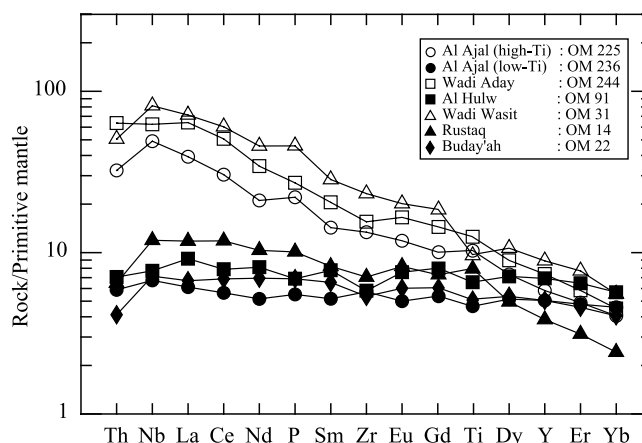


Figure 7. Multielement patterns of selected Permian lavas normalized to the primitive mantle of *Sun and McDonough* [1989]. Symbols are as in Figure 4.

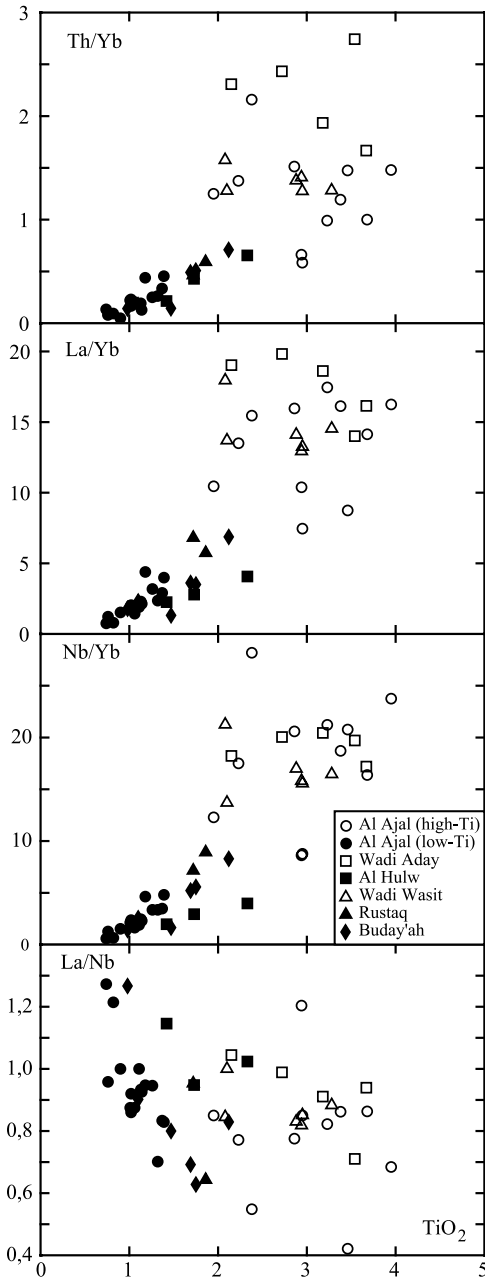


Figure 8. Plots of Th/Yb, La/Yb, Nb/Yb, and La/Nb ratios against TiO_2 contents. Symbols are as in Figure 4.

by the continental lithosphere during their ascent [Gibson *et al.*, 1995; Pik *et al.*, 1998, 1999]. Basalts from the seaward dipping reflector sequences (SDRS) of the north Atlantic igneous province are usually TiO_2 poor (and generally more depleted in incompatible elements) compared to their continent-based equivalents [Saunders *et al.*, 1997]. They tend to evolve progressively toward NMORB with time [Fitton *et al.*, 1998b; Larsen *et al.*, 1998], through increasing degrees of partial melting and/or derivation from increasingly depleted mantle sources [Fram *et al.*, 1998] and vanishing crustal contamination [Fitton *et al.*, 1998a]. In this context a genuine depleted (NMORB type) geochemical signature is generally

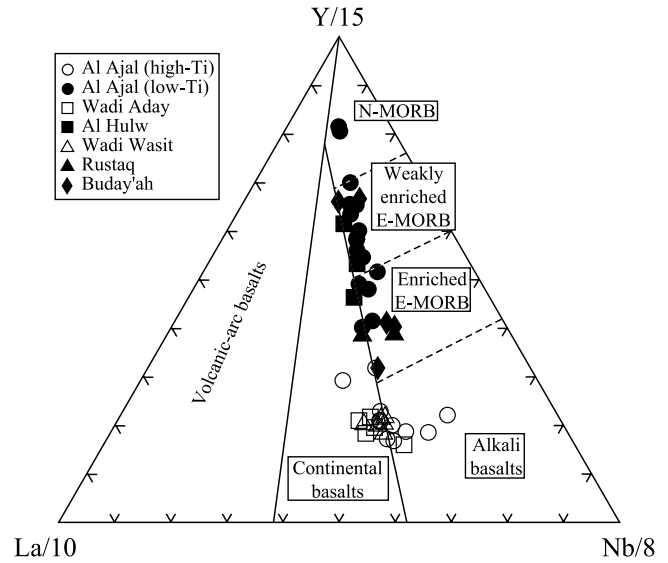


Figure 9. Plot of the studied lavas in the Y-Nb-La diagram of Cabanis and L  colle [1989]. Symbols are as in Figure 4.

considered specific of postbreakup basalts [Saunders *et al.*, 1997; Larsen and Saunders, 1998; Larsen *et al.*, 1999; Saunders *et al.*, 1999].

[24] The geochemical results presented above show several striking features. First, the compositions of the studied Permian basalts (Figures 4–8) match very well those of either low-Ti or high-Ti basalts from SDRS and continental flood basalt provinces, both considered plume-related, and are clearly different from NMORB (Figure 10). Second, both groups plot near the boundary between oceanic and continental basalt associations in Figure 9, a feature that is consistent with their emplacement through a thinned continental margin. Furthermore, there are no progressive transitions between the two groups which plot in clearly distinct domains in most geochemical diagrams. In addition, with

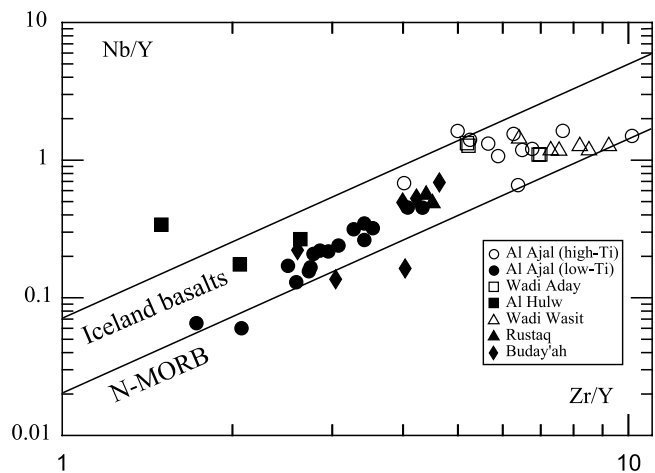


Figure 10. Nb/Y versus Zr/Y logarithmic plots. The fields of NMORB and Iceland neovolcanic basalts are taken from Fitton *et al.* [1997]. Symbols are as in Figure 4.

the exception of Al Ajal, each occurrence displays a distinctive high-Ti (Wadi Aday and Wadi Wasit) or low-Ti (Wadi Al Hulw, Rustaq, and Buday'ah) affinity. Even in the Al Ajal thrust pile, the two groups display well-defined locations with high-Ti basalts at the base and low Ti near the top (Figure 3). Finally, there is a clear correlation between magmatic types and their sedimentary environments (Figure 2), since high-Ti lavas are associated with proximal basin deposits (Wadi Aday, Wadi Wasit, and base of the Al Ajal thrust pile) and low-Ti basalts are associated with more distal sediments (top of the Al Ajal pile, Rustaq, and Buday'ah). These features suggest that the studied submarine basalts could have been originally emplaced in different parts of the thinned Arabian continental margin, either close to the continent (e.g., Wadi Aday) or in more distal settings (Rustaq and Buday'ah). The apparent lack of genuine NMORB in our set suggests that the truly oceanic part of the middle Permian Tethys was not "sampled" by the Hawasina Nappes, although Ocean Drilling Program (ODP) Leg 163 results have shown that NMORB-type depleted lavas might also be emplaced onto the continental margin during the postbreakup stage [Larsen *et al.*, 1999; Saunders *et al.*, 1999].

4.3. Geodynamic Implications

[25] The occurrence of pillowed basaltic lava flows at the base of the Hawasina successions has often been considered evidence for oceanic crust building [Glennie *et al.*, 1974; Blendinger *et al.*, 1990; Stampfli *et al.*, 1991; Pillevuit *et al.*, 1997]. Alternatively, it has been proposed that the sedimentary and magmatic successions of the Hawasina Nappes were deposited on a thinned continental crust [Lippard *et al.*, 1986; Béchenec, 1988; Béchenec *et al.*, 1988, 1990, 1991]. As discussed in sections 4.1 and 4.2, our data clearly support the latter interpretation and suggest that the studied basalts were likely derived from a mantle plume underlying the continental crust of the Tethyan Arabian margin. High-Ti basalts that likely resulted from low melting degrees of its enriched margin were emplaced in proximal position with respect to the continent (Wadi Aday, Wadi Wasit, and the structural base of the Al Ajal pile). Low-Ti basalts (Buday'ah, Rustaq, and top of the Al Ajal thrust pile) originated closer to the plume core, either from higher degrees of melting or from a more depleted source, and were emplaced oceanside with respect to the high-Ti ones. These units were later obducted onto the Arabian Platform. In Al Ajal the low-Ti basalts were thrust over the high-Ti lava sequence.

[26] Despite the fact that the middle Permian Hawasina Basin floor was represented by thin continental crust, the emplacement of the studied submarine volcanics might have been coeval with the onset of seafloor spreading in a more distal setting or might even postdate it as suggested by tectonic events noted both on the Arabian shield and, more generally, in NE Gondwana regions. The tectonic events include the following in particular: (1) doming and major block faulting of the northeastern part of the Arabian plate during late Early Permian [Le Métour *et*

al., 1994; Al-Belushi *et al.*, 1996]; (2) middle Permian thermal subsidence, crustal extension, and volcanic activity related to the formation of the Arabian margin, including the carbonate Arabian Platform, the continental slope (Al Aridh and Sumeini), and the Hawasina Basin [Béchenec, 1988; Béchenec *et al.*, 1988, 1991; Pillevuit *et al.*, 1997]; and (3) continental breakup of Gondwana with northward drifting of the Iran/Mega-Lhasa microcontinent. Indeed, since Stöcklin's [1968, 1974] research it is acknowledged that central Iran moved away from the Gondwana (Arabian) margin as a consequence of the opening of the Neotethys and the concomitant closure of the Paleotethys. Such a process is illustrated in the Tethys Project maps [Baud *et al.*, 1993a, 1993b] and is discussed by Stampfli *et al.* [1991], Ricou [1994], and Marcoux and Baud [1996]. The Permian motion of the Iran Block has been documented from subsidence curves [Saidi *et al.*, 1997] and palaeomagnetic data [Besse *et al.*, 1998]. Both studies indicate that the separation of central Iran from the Arabian margin started as early as Lower Permian and thus that spreading at the Neotethys ridge axis was operating then. Recent stratigraphic, petrographic, and paleontological data obtained on the Al Khlat, Saiwan, and Khuff Formations of interior Oman [Angiolini *et al.*, 2003a, 2003b] strongly support this interpretation and lead to the conclusion that the initiation of seafloor spreading in the Neotethys ocean north of Oman occurred during mid-Early Permian (mid-Sakmarian), i.e., some 18 Myr prior to the emplacement of the studied Wordian basalts.

[27] The presence of plume-related geochemical signatures (similar to those of high-Ti and low-Ti lavas from flood basaltic provinces, i.e., traps and seaward dipping reflector sequences) in middle Permian basalts from Oman does not necessarily imply that they were generated and emplaced in the same tectonic setting, i.e., volcanic rifted margins. In addition to the 18-Myr time gap between the onset of spreading and the emplacement of the studied basalts, several lines of evidence suggest that they were erupted within an already rifted area, essentially similar to a nonvolcanic passive margin. Indeed, during the middle Permian the geological features of the Oman margin were not similar to those of typical volcanic passive margins [e.g., Callot *et al.*, 2001; Menzies *et al.*, 2002]. For instance, the width of the Hawasina Basin is estimated to be several hundred kilometers, and possibly even 500 km [Béchenec *et al.*, 1988], which is much larger than commonly observed on volcanic margins. Furthermore, there is no evidence for doming and/or uplift of the Oman margin during middle Permian. Instead, this period is generally considered to be marked by thermal subsidence, as demonstrated by the major Wordian transgression onto the Upper Proterozoic units of the Jabal Akhdar rift shoulder [Stampfli *et al.*, 1991; Béchenec *et al.*, 1991]. Moreover, the evidence that the distal units of the Hawasina Nappes were thrust over the proximal units during the obduction process (Al Ajal) might be interpreted as indicating the reactivation as thrust faults of normal seaward dipping faults like those of nonvolcanic passive margins. Additional arguments are offered by field studies of the middle Permian volcanic sequences them-

selves. Although their total thickness is unknown, there is no evidence for successions thicker than a few hundred meters (Al Ajal and Wadi Wasit), which is much less than the average thicknesses of SDRS. In addition, all the studied volcanic flows (pillow basalts) were erupted below sea level at depths ranging from shallow to deep as indicated by the associated sediments. These data suggest their emplacement within an already rifted and drowned margin, while the SDRS basalts are almost exclusively subaerially emplaced. Thus, despite the obvious difficulties in reconstructing a fossil passive margin preserved mostly in Nappes, our preferred interpretation is that the Oman middle Permian volcanics originated from a mantle plume which ascended beneath an Arabian passive margin which was already rifted and drowned well after the initiation of seafloor spreading of the Neotethys.

5. Conclusions

[28] The middle Permian submarine basalts of the Neotethyan margin in Oman display major and trace element signatures typical of plume-related magmatism. Their compositions are similar to those of high-Ti and low-Ti lavas emplaced as flood basaltic provinces (traps and seaward dipping reflector sequences) on continents undergoing rifting and breakup. They do not show the depleted (NMORB character) features of typical basalts associated with spreading at the axis of oceanic ridges. Thus the substratum of the Hawasina Basin was not oceanic crust, as postulated by several authors, but rather the thinned continental margin of the Arabian Platform.

[29] More specifically, high-Ti basalts are characteristic of some Hawasina Nappes exposed in Wadi Wasit and the base of the Al Ajal thrust pile as well as the Saih Hatat

window (Wadi Aday). They were emplaced in proximal position with respect to the continent and likely derived from low degrees of melting of the enriched rim of a mantle plume located oceanward of Arabia. Low-Ti basalts possibly generated closer to the plume core were emplaced in more distal parts of the Hawasina Basin, (Buday'ah, Rustaq, and top of the Al Ajal pile). Locally (Al Ajal), they were ultimately thrust over the high-Ti ones, with the bulk of the Hawasina Nappes then being underthrust beneath the Samail ophiolitic Nappe. The existence of geochemical variations correlated with the structural position of basaltic pillow lavas within the Al Ajal thrust pile is an uncommon and noteworthy feature which might be expected to occur in other areas, e.g., the Himalayas.

[30] The plume-related geochemical signatures of the middle Permian basalts from Oman do not necessarily imply that they were emplaced during the evolution of a volcanic rifted margin. In addition to the ~18-Myr time gap between the onset of seafloor spreading during the mid-Sakmarian [Angiolini *et al.*, 2003a, 2003b] and the emplacement of the Wordian basalts, several lines of geological evidence (including the shallow to deep submarine emplacement of the Oman basalts) suggest that they were erupted within an already rifted and drowned area, essentially similar to a nonvolcanic passive margin.

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- M. Caroff and J. Cotten, UMR 6538, Université de Bretagne Occidentale, 6 Avenue Le Gorgeu, F-29285 Brest, France. (caroff@univ-brest.fr; cotten@univ-brest.fr)
- F. Cordey, UMR 5125, Université Claude Bernard Lyon 1, F-69622 Villeurbanne, France. (fabrice.cordey@univ-lyon1.fr)
- J. Marcoux, UMR 7578, Université Paris 7 et Institut de physique du globe de Paris, 4 place Jussieu, F-75252 Paris, France. (marcoux@ipgp.jussieu.fr)
- R. C. Maury, UMR 6538, Université de Bretagne Occidentale, Place Nicolas Copernic, F-29280 Plouzané, France. (rene.maury@univ-brest.fr)
-
- F. Béchenec, Bureau de Recherches Géologiques et Minières, BP 92342, F-44323 Nantes, France. (f.bechenec@brgm.fr)

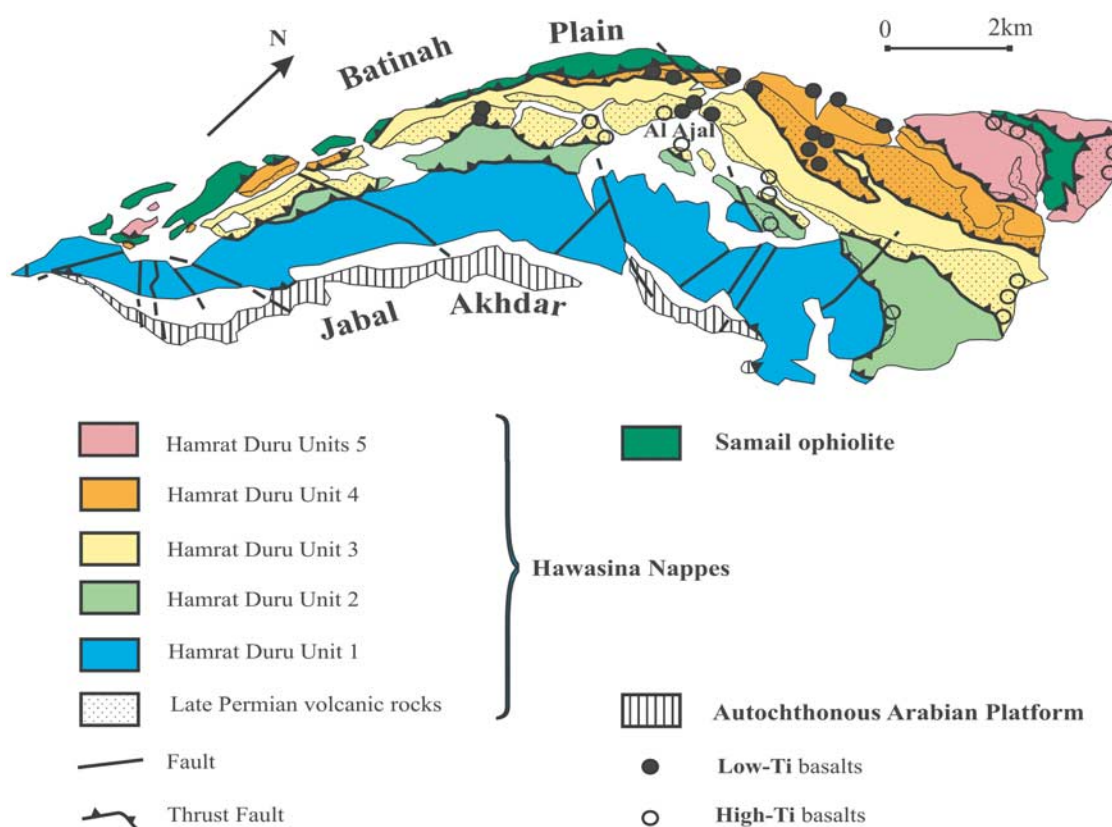


Figure 3. Geological sketch map of the Al Ajal area with location of the studied basaltic samples. Open circles indicate high-Ti basalts; solid circles indicate low-Ti basalts.