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1 Triassic alkaline magmatism of the Hawasina Nappes:
2 post-breakup melting of the Oman lithospheric mantle
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4
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24
25 **ABSTRACT**

26 Middle to Late Triassic lavas were sampled within three tectonostratigraphic groups of the Hawasina Nappes in
27 the Oman Mountains. They are predominantly alkali basalts and trachybasalts, associated with minor sub-
28 alkaline basalts, trachyandesites, trachytes and rhyolites. Their major, trace elements and Nd-Pb isotopic
29 compositions are very similar to those of the Permian plume-related high-Ti basalts which also occur in the
30 Hawasina Nappes. The Triassic lavas derive from low-degree melting of an enriched OIB-type mantle source,
31 characterized by $\epsilon\text{Nd}_i = 0.3\text{-}5.3$ and $(^{206}\text{Pb}/^{204}\text{Pb})_i = 16.96\text{-}19.31$ (for $t = 230$ My). With time, melting depths
32 decreased from the garnet + spinel to the spinel lherzolite facies and the degree of melting increased. The oldest
33 are distinguished from the others by unradiogenic Nd and Pb signatures, with $\epsilon\text{Nd}_i = -4.5$ to -1.2 and
34 $(^{206}\text{Pb}/^{204}\text{Pb})_i = 16.35\text{-}17.08$, which we attribute to their contamination by Arabo-Nubian lower crust. The lavas
35 likely derived from the Oman lithospheric mantle, the original DMM-HIMU signature of which was overprinted
36 during its pervasive metasomatism by the Permian plume-related melts. We suggest that these lavas were
37 emplaced during post-breakup decompression-triggered melting in the Middle Triassic during global kinematic
38 reorganization of the Tethyan realm.

40 **1. Introduction**

41

42 Petrologic and geochemical studies of ancient oceanic crust and continental margins can
43 be used to reconstruct the dynamics of past rifting and oceanization processes. The Middle
44 Permian opening of the Neotethyan Ocean (Besse et al., 1998) separated Gondwana from
45 Cimmerian continental blocks (Ricou, 1994; Stampfli and Borel, 2002). It led to the formation
46 of passive continental margins south of the Neotethys Ocean, i.e. on the northern edges of the
47 Australian, Indian, Arabian and African shields. Cretaceous to Neogene convergence between
48 Laurasia and Gondwana (Stampfli and Borel, 2002) then led to the disappearance of
49 Neotethyan oceanic crust. Fragments of its southern margins were incorporated into Alpine
50 collisional belts in the Himalayas, Oman, Zagros, Syria, Cyprus, Turkey and Greece
51 (Coleman, 1981, Fig. 1a).

52 These inverted margin fragments carry remnants of successive magmatic episodes, which
53 can be used to constrain the formation and development stages of the southern Neotethyan
54 margin. For instance, Middle Permian flood basalts are widespread in NW Indian (Panjal
55 Traps) and Oman (Saih Hatat and Hawasina nappes Fig. 1a). Their plume-related
56 geochemical features suggest that the breakup of Gondwana was associated with the
57 emplacement of an intraplate volcanic province and associated volcanic-type margins
58 (Garzanti et al., 1999; Maury et al., 2003; Lapierre et al., 2004; Chauvet et al., 2008).
59 Younger (post-breakup) volcanic sequences are generally tectonically associated with
60 Tethyan ophiolitic nappes, from the Himalayas to the eastern Mediterranean (Fig. 1a). Within
61 these nappes, volcanic rocks are stratigraphically associated with late Middle to Late Triassic
62 pelagic sediments and/or reef limestones. In the Oman Mountains, these Triassic post-breakup
63 volcanic series have been considered as tectonically inverted intra-oceanic plateaus or
64 seamounts (Glennie et al., 1974; Searle et al., 1980; Searle and Graham, 1982; Robertson and
65 Searle, 1990; Stampfli et al., 1991; Pillecuit, 1993; Pillecuit et al., 1997), as well as their
66 equivalents in the Himalayas (Ahmad et al., 1996; Robertson, 1998; Corfield et al. 1999) and
67 Mediterranean sequences (Syria: Al Riyami and Robertson, 2002; Cyprus: Lapierre et al.,
68 2007; Chan et al., 2008; Turkey: Maury et al., 2008; Greece: Monjoie et al., 2008).
69 Alternatively, the Oman Triassic lavas have been interpreted as remnants of a second rifting
70 episode of the Arabian continental margin (Lippard et al., 1986; Béchenec et al., 1988, 1990,
71 1991).

72 A new petrologic and geochemical investigation (major and trace elements and Nd, Pb
73 isotopes) of Middle to Late Triassic lavas from the allochthonous units of the Oman
74 Mountains allows us to address these two hypotheses.

75

76 **2. Geological setting**

77

78 The Arabian continental margin of the Neotethys ocean formed during Permo-Triassic
79 times (Béchenec et al., 1988; Robertson and Searle, 1990). Reconstructions of this margin
80 (Glennie et al., 1974; Béchenec, 1987) suggest the occurrence of a continental platform
81 (Saiq Fm.), a continental slope (Sumeini Group), and basinal environments (Hawasina units).
82 In the Oman Mountains, remnants of several basins are exposed in the Hawasina Nappes,
83 which are sandwiched between the autochthonous Arabian platform and the Semail ophiolitic
84 nappe (Fig. 1b; Bernouilli and Weissert, 1987; Béchenec et al., 1988). They include Middle
85 Permian (Murghabian) to Late Cretaceous sedimentary and volcanic units.

86 Béchenec (1987) and Béchenec et al. (1988, 1990, 1993) distinguished four
87 tectonostratigraphic groups within the Hawasina Nappes tectonic pile (Fig. 1c,d). From the
88 base to the top, they are the Hamrat Duru, Al Aridh, Kawr and Umar Groups (Fig. 1d). These
89 groups were emplaced either in proximal (Hamrat Duru) or distal (Umar) pelagic basins, in a
90 trench or slope (Al Aridh) or as an isolated carbonate platform (Kawr). While the Hamrat
91 Duru basin appeared during the Middle Permian major rifting event, the three others (Al
92 Aridh, Kawr and Umar Groups) formed during Middle to Late Triassic (de Wever et al.,
93 1990). Because they are mainly found within tectonic slices, the remnants of the Hawasina
94 Triassic carbonate platform were also named Oman Exotics (Glennie et al., 1974; Searle and
95 Graham, 1982; Robertson and Searle, 1990) and the Umar Group volcanics correspond to the
96 Haybi Volcanics of Searle et al. (1980). The latter authors performed geochemical analyses on
97 a Permian and Triassic sample set coming from the northern part of the Oman Mountains.

98 Middle to Late Triassic volcanic sequences (ca. 10 to 100 m-thick) and associated
99 magmatic intrusions occur (i) below and within the pelagic sediments of the Umar Group
100 (Sinni Fm.); (ii) below and within the Kawr platform carbonates (Misfah Fm.); (iii) below the
101 Al Aridh Group slope/trench deposits (Sayfam Fm.); and finally (iv) within the pelagic
102 deposits of the Hamrat Duru Group (Matbat Fm.). Synsedimentary megabreccias intercalated
103 within the proximal successions of the Hawasina Nappes (Watts, 1990; Pillevuit, 1993)
104 suggest contemporaneous tectonic activity. This Middle to Late Triassic tectono-magmatic
105 event occurred 30 to 40 My after the Middle Permian opening of Neotethys (Béchenec,
106 1987; Pillevuit, 1993; Baud et al., 2001).

107

108 **3. Sampling and petrography**

109

110 In this study, lavas from the Umar and Kawr Groups were sampled in the central part of the
111 Oman Mountains, near the western termination of the Jabal Akhdar anticline (Al Qurti and
112 Misfah localities, Fig. 1c,d). Additional samples were collected from three other Umar sites
113 (Sinni, Sayjah and Aqil villages, Fig. 1c). The Al Aridh Group volcanics were sampled on the
114 SW and NW flanks of the Jabal Buwaydah. Coeval volcanics from Hamrat Duru Group were
115 not studied.

116

117 *3.1. The Umar Group*

118 The Umar Group is directly overthrust by the Semail ophiolite (Fig. 1c,d). Its Triassic
119 succession includes three lithofacies (UmV₁₋₃, Béchenec, 1987; Beurrier et al., 1986) which
120 are well exposed as a succession of tectonic slices in the Al Qurti section (Appendix A). The
121 15 samples collected along this section exhibit the largest petrologic diversity of our suite,
122 with, from base to top, basalts, trachyandesites, trachytes and rhyolites. The basal unit
123 (UmV₁) corresponds to a 100 m thick succession of basaltic pillow-lavas, often tubular and
124 dominated by subaphyric to porphyritic vesicular basalts with dispersed clinopyroxene
125 phenocrysts (Om04-10, -11, -12). The second unit (UmV₂) includes basaltic flows capped
126 with pelagic sediments (Om04-18, -19) and trachyandesitic pillowed lavas (Om04-17, -24, -
127 27), successively overlain by hyaloclastites and volcanogenic debris flows. The latter contain
128 rhyolitic lava blocks with plagioclase (Om04-29) and quartz grains (Om04-34, -35). The third
129 unit (UmV₃), emplaced between the Kawr and Umar Groups, corresponds to columnar-
130 jointed plugs showing trachytic textures with Na-rich plagioclase microcrysts and rare biotite
131 phenocrysts (Om04-37, -38).

132

133 *3.2. The Kawr Group*

134 In the Hawasina nappes, the Kawr Group outcrops mainly south of the western
135 termination of Jabal Akhdar anticline, in several mountains capped by high carbonate cliffs
136 (Jabal Misht, Jabal Misfah, Jabal Kawr, and Jabal Ghul; Fig. 1c). Its stratigraphy (Béchenec,
137 1987; Pillevuit, 1993) has been defined on the northern and eastern slopes of Jabal Misfah
138 (Appendix A). A 50 m thick basal volcanic unit, dated Ladinian-Carnian (Pillevuit, 1993) is
139 made up of massive and pillowed basaltic flows, hyaloclastites and tuffites. These volcanics
140 are successively overlain by Ladinian-Carnian to Rhaetian marly limestones, by thick and
141 massive platform limestones crosscut by numerous basaltic dikes and sills, and finally by
142 Jurassic to Cretaceous pelagic deposits. Among the 23 samples (Appendix A) collected from
143 the Kawr Group, 11 come from the basal volcanic unit and 12 from the dykes and intrusive
144 bodies. The basal flows, as well as the sills and dykes, show aphyric (Om04-52 and -54),

145 microlitic (Om04-56, -59, -66), or highly porphyritic textures with abundant clinopyroxene
146 phenocrysts (Om04-55, -57, -58).

147

148 *3.3 The Al Aridh Group*

149 The Al Aridh Group mainly outcrops along the southern flank of the Oman Mountains
150 (Fig. 1c). It includes a basal volcanic sequence overlain by breccia horizons dated
151 Middle/Late Triassic to Santonian (Béchenec et al., 1993). Seven samples were collected
152 from two sites in Jabal Buwaydah, located south of the Jabal Kawr (Fig. 1c). The first one
153 (“Buwaydah 1” in Fig. 1c) exposes a 40 m thick sequence of sills and massive flows,
154 intercalated with basaltic pillows and overlain by a trachyandesitic flow. In the second
155 locality (“Buwaydah 2” in Fig. 1c), the 150 m thick volcanic succession is capped by cherts
156 and pelagic limestones dated Carnian to basal Norian (de Wever et al., 1990). The Al Aridh
157 Group samples are porphyritic basaltic to trachyandesitic lavas with serpentinized olivine,
158 fresh clinopyroxene and Fe-Ti oxides phenocrysts.

159

160 **4. Geochemical data**

161

162 *4.1. Analytical methods*

163 Sixty one samples (31 from the Umar, 23 from the Kawr and 7 from Al Aridh Group)
164 were selected for petrographic and geochemical analysis. These rocks were pulverized in an
165 agate mill and analysed using methods similar to those described in previous papers (see
166 Chauvet et al., 2008 and references therein). Major elements and a set of trace elements
167 (shown in italics in Table 1 and Appendix B) were determined by inductively coupled
168 plasma-atomic emission spectrometry (ICP-AES) at the Université de Bretagne Occidentale
169 in Brest, following the procedures of Cotten et al. (1995) and using international standards for
170 calibration tests (AC-E, BE-N, JB-2, PM-S, WS-E). Rb contents were measured by flame
171 atomic emission spectroscopy. Relative standard deviations were ~ 1 % for SiO₂ and 2 % for
172 other major elements except P₂O₅ and MnO (0.01%), and ~ 5 % for trace elements.
173 Additional trace element contents (Table 1) were measured by ICP-MS at the Université
174 Joseph Fourier in Grenoble on 45 samples (27 from Umar, 14 from Kawr and 4 from Al
175 Aridh), using the procedures of Barrat et al. (1996) and BHVO-2, BEN and BR-24 standards.
176 Analytical errors were less than 3 % for trace elements except Cs (<5%).

177 Isotopic Nd and Pb data (Table 2) were corrected for *in situ* decay using an average age of
178 230 Ma (Ladinian-Carnian). All the Hawasina samples were leached twice in 6N HCl during
179 30 minutes at 100°C before acid digestion and Nd and Pb chemical separation in order to
180 avoid or minimize alteration effects (see below). Nd (semi-dynamic acquisition) isotopic

181 ratios of 21 samples labelled Om-29 to Om-207 were measured at LMTG, Université Paul
182 Sabatier, Toulouse, on a Finnigan MAT 261 multicollector mass spectrometer using the
183 analytical procedures of Lapiere et al. (1997). Results on standards yielded
184 $^{143}\text{Nd}/^{144}\text{Nd} = 0.511958 \pm 34$ ($n = 6$) for the Neodymium Rennes Standard (Chauvel and
185 Blichert-Toft, 2001). $^{143}\text{Nd}/^{144}\text{Nd}$ measured ratios were normalized for mass fractionation
186 relative to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. In addition, 39 samples were selected for lead separation and
187 leached with 6N tridistilled HCl during 30 minutes at 85°C before acid digestion (36-48 hours
188 in ultrapure HF and HNO₃ acids). Pb blanks were less than 40 pg. Lead isotopes and Nd
189 isotopic ratios of samples labelled “Om04-” and “Om05-” and Pb were measured on a Nu-
190 plasma 500 multicollector magnetic-sector ICP-MS at the Ecole Normale Supérieure in Lyon.
191 Details about chemical separations and isotope analytical measurements including
192 reproducibility, accuracy and standards, can be found in Bosch et al. (2008) and references
193 therein.

194

195 *4.2. Alteration and sample selection*

196 Ancient lavas are altered, a process that disturbs their major and trace element patterns
197 and complicates calculation of initial isotopic ratios. Although our samples were carefully
198 selected in the field, none of them is devoid of post-magmatic minerals and they often display
199 numerous fractures filled with calcite, iron oxides and/or smectites. Pillow groundmass and
200 vesicles contain variable amounts of calcite, zeolites and clays. In addition, the occasional
201 presence of chlorite suggests that some Hawasina basin lavas underwent hydrothermal
202 alteration or low-grade greenschist metamorphic conditions.

203 The loss on ignition (LOI) values of analyzed samples range from 2 to 13 wt.%, with
204 more than half of them below 6 wt.% (Table 1 and Appendix B). Major elements analyses
205 have been recalculated to 100% (volatile-free basis). The highest LOI values (> 10 wt.%)
206 were measured in the Umar Group vesicular pillow lavas and in the Kawr Group intrusions,
207 the groundmass of which is totally replaced by zeolites and calcite. Despite the high LOI
208 values of the studied samples, SiO₂, MgO, Al₂O₃, P₂O₅ and TiO₂ contents variations from
209 mafic to felsic lavas are relatively regular, and consistent with the petrographic (thin section)
210 features of these rocks. In contrast, the large and erratic variations of CaO and Na₂O/K₂O at a
211 given SiO₂ or MgO content (Table 1, Appendix B) or at a given “immobile” trace element
212 content (e.g. Zr) suggests the mobility of alkaline and alkaline earth elements during
213 alteration and/or recrystallization.

214 The analyzed samples display rather regular chondrite- and primitive mantle-normalized
215 trace element patterns (Appendix C), with the exception of large ion lithophile elements
216 (LILE). For instance, Rb, Ba and Sr exhibit strong negative or positive anomalies in

217 multielement patterns which could have been generated either by their remobilization during
218 post-magmatic processes (hydrothermalism and/or weathering) or by contamination processes
219 during the evolution of their parental magmas. Nevertheless, the erratic behavior of Ca, Na, K
220 and LILE is particularly obvious for samples showing the highest LOI and/or the largest
221 amount of post-magmatic minerals. Thus, no attempt was made to use them to constrain
222 igneous processes. In contrast, La, Nd, Sm, U and Pb correlate well with Th (Appendix D)
223 and with high field strength elements (HFSE, not shown in Appendix D). These features
224 suggest that the REE and HFSE contents of the studied samples, as well as their Pb and Nd
225 isotopic compositions, represent reliable tools to investigate the petrogenesis of Hawasina
226 Triassic lavas.

227 Sample selection for Pb isotopic analyses (39 samples out of the 54 analyzed for Nd,
228 Appendix D) was aimed to eliminate the most altered samples and to account for the observed
229 petrologic and geochemical variations. In the Pb and U *versus* Th diagrams (Appendix D), a
230 majority of analyzed samples display Th/U and Th/Pb ratios close to the OIB mean values.
231 However, despite a drastic sample selection, significant dispersions of Pb and U
232 concentrations are still observed, particularly for Om-49 and Om-52 (Aqil), Om04-40 and -43
233 (Sayjah), Om04-12, -34 and -35 (Al Qurti). Related strong anomalies in multielement patterns
234 and unusual ratios ($\text{Th/U} < 2.5$ and $\text{Th/Pb} > 5$) might indicate either post-magmatic alteration
235 or open-system processes during magma ascent through the Arabian lithosphere.

236

237 4.3. Major elements and rock types

238 The analyzed lavas exhibit a wide range of SiO_2 (42 to 75 wt.%) and MgO contents
239 (0.7 to 13 wt.%, Appendix B and Fig. 2a), even though mafic rocks ($\text{SiO}_2 < 53$ wt.% and
240 $\text{MgO} > 3$ wt.%) are dominant. This chemical diversity is particularly obvious for the Umar
241 samples which range from mafic to felsic (45-75 wt.% SiO_2 , 11.1-0.7 wt.% MgO, Appendix
242 B). Among mafic lavas characterized by $\text{SiO}_2 < 53$ wt.% and a basaltic-type petrographic
243 assemblage in thin section, samples with $\text{MgO} > 6$ wt.% were classified as basalts ($n = 26$)
244 and samples with $3\% < \text{MgO} < 6$ wt.% as trachybasalts ($n = 16$). Both types have high P_2O_5
245 ($0.18 < \text{P}_2\text{O}_5 < 1.58$ wt.%) and high TiO_2 contents ($1.5 < \text{TiO}_2 < 3.6$ wt.%, Fig. 2b), with
246 $\text{TiO}_2 < 2$ wt.% for only 7 out of 42 samples (Appendix B). These features are typical of
247 alkaline magmas (Wilson, 1989). Despite the erratic behavior of alkali elements, a large
248 majority of our sample set consistently plots within the alkaline field in the total alkali *versus*
249 silica diagram (Fig. 2c). The very low $\text{Na}_2\text{O} + \text{K}_2\text{O}$ values of Umar Si-rich lavas (Om04-29, -
250 34 and 35) are probably linked to the widespread alteration of their groundmass.

251

252 4.4. Trace elements

253 Most Hawasina Triassic basalts and trachybasalts show enrichment in LREE and
254 depletion in HREE and Y, features that are characteristic of intraplate magmas (Sun and
255 McDonough, 1989; Willbold and Stracke, 2006). Their multielement patterns are very similar
256 to OIB patterns (Fig. 3a,b), with enrichments culminating at Nb (Appendix C). When plotted
257 in the *Zr/Ti versus Nb/Y* and *Nb/Y versus Zr/Y* diagrams (Fig. 4a,b), most of the samples
258 yield Nb/Y ratios higher than 1, consistent with an alkaline affinity (Winchester and Floyd,
259 1977). In Fig. 4b, the studied mafic lavas plot within the field of alkali basalts from the
260 Icelandic Neo-Volcanic Zone and away from the fields of Icelandic tholeiites and N-MORB
261 (Fitton et al., 1997; Kokfelt et al., 2006).

262 The multielement diagrams of the Umar samples cluster into two main geochemical
263 groups. The first (and by far the largest) one displays high enrichments in the most
264 incompatible elements together with fractionated patterns ($La/Yb_N > 15$, Fig. 3a) and Nb/Y
265 ratios higher than 1. This population hereafter referred to as the “alkali group”, includes all
266 the samples from the UmV₁ basal unit of the Umar Group (Al Qurti section) and most UmV₂
267 lavas. The second group exhibits less fractionated patterns, with a lesser enrichment in the
268 most incompatible elements and a more subdued depletion in the least incompatible elements
269 ($5 < La/Yb_N < 15$, Fig. 3a, Appendix C). It includes a few lavas (Om-29, Om04-40, Om04-51,
270 Om-42 and -52 from UmV₂ unit of the Umar Group) that display Nb/Y ratios lower than 1,
271 together with rather low Zr/Ti ratios (Fig. 4a). As these features are consistent with either a
272 mildly alkaline or even sub-alkaline (Om04-40) affinity, this group will be referred to as the
273 “sub-alkaline group”.

274

275 4.5. Nd and Pb isotopes

276 4.5.1. Nd isotopic data

277 The initial Nd isotopic ratios of 54 analyzed samples range from 0.51211 to 0.51261
278 (i.e. ϵNd_i from +5.32 to -4.45; Table 2). The 44 positive ϵNd_i values are distributed among all
279 the studied units, whereas the 10 negative ϵNd_i values are associated to the alkaline lavas of
280 the Al Qurti UmV₁ (5 samples) and Sinni (5 samples) sections of the Umar Group (Table 2).
281 ϵNd_i values of the 31 Umar samples cluster into three main groups characterized by (i)
282 unradiogenic ϵNd_i values ($-4.5 < \epsilon Nd_i < -1.2$), (ii) radiogenic ϵNd_i values ($2 < \epsilon Nd_i < 4.4$), and
283 (iii) intermediate ϵNd_i values, including two samples (Om04-40 and Om-97) with ϵNd_i of
284 0.52 and 0.34, respectively. The ϵNd_i of the latter two Umar groups encompass those of Kawr
285 flows and Al Aridh lavas ($0.7 < \epsilon Nd_i < 4.1$ and $1.2 < \epsilon Nd_i < 3.2$), while Kawr intrusions yield
286 more radiogenic Nd isotopic ratios with $3.1 < \epsilon Nd_i < 5.3$ (Table 2).

287

288 4.5.2. Pb isotopic data

289 In Pb-Pb isotopic diagrams (Fig. 5a,b), Hawasina samples plot within an array subparallel
290 to the Northern Hemisphere Reference Line (NHRL; Hart, 1984). Umar samples (n=23)
291 exhibit highly variable Pb isotopic ratios, including both the most and the least radiogenic Pb
292 compositions in our data set. They range from 16.35 to 19.31 for $(^{206}\text{Pb}/^{204}\text{Pb})_i$, from 15.28
293 to 15.64 for $(^{207}\text{Pb}/^{204}\text{Pb})_i$ and from 35.91 to 39.09 for $(^{208}\text{Pb}/^{204}\text{Pb})_i$ (Table 2). Kawr and Al
294 Aridh samples plot between these extremes. Kawr intrusions exhibit a wide range of Pb ratios
295 which straddle that of the Kawr flows and Al Aridh samples. In the Pb-Pb correlation
296 diagrams, the five samples that show the highest deviations from the main trend in Th-U and
297 Th-Pb diagrams (Appendix C) generally plot within the OIB field, with the exception of the
298 Om04-34 rhyolite which yields very unusual Pb ratios (Table 2). Such initial recalculated
299 ratios could be linked to an overcorrection due to its particularly high Th contents compared
300 to its low Pb concentration (Appendix B). Thus, this sample will not be considered in the
301 following discussion.

302

303 *4.5.3. Pb versus Nd isotopic ratios*

304 With the exception of Kawr intrusions, which exhibit highly variable Pb isotopic ratios
305 together with a restricted range of ϵNd_i values, the studied sample set shows a rough positive
306 correlation in the ϵNd_i versus $(^{206}\text{Pb}/^{204}\text{Pb})_i$ diagram (Fig. 5c). The observed scatter indicates
307 that at least two isotopic end-members contributed to the geochemical signatures of the
308 Hawasina Triassic magmatism (Fig. 5a,b,c).

309

310 **5. Discussion**

311

312 *5.1. Fractionation, assimilation coupled with fractional crystallization and partial melting* 313 *effects*

314 The Umar UmV₂ trachyandesites, trachytes and rhyolites (Om04-17, -24, -27 and Om04-
315 34 to -38) have negative Eu (and Ti) anomalies that are absent from UmV₁ and UmV₂ basaltic
316 flows (Appendix C). The decrease of Al₂O₃ contents and Eu/Eu* ratios with increasing silica
317 content (for SiO₂ > 53 wt.%, Fig. 6a,b) suggest that the Eu negative anomaly is correlated to
318 plagioclase fractionation. However, a closed-system fractional crystallization process is not
319 consistent with most REE variations. Indeed, UmV₂ basalts and trachyandesites (Om04-17 to
320 27) exhibit similar enrichments in La, but higher HREE and Y contents than UmV₁ basalts
321 (Fig. 3a, Appendix C). Moreover, in Figure 6c, a jump in (La/Yb)_N ratios is observed between
322 UmV₁ basalts and UmV₂ lavas. The whole sample set displays positive correlations between
323 La and (La/Yb)_N (Fig. 6d), which are not consistent with closed-system fractionation.

324 The isotopic signatures of the studied lavas could be an intrinsic feature of their mantle
325 source(s), or acquired *via* assimilation processes during magma ascent and/or storage within
326 the Arabian lithosphere. Among our set, Umar samples exhibit the largest scatter of both SiO₂
327 contents and εNdi values. Their SiO₂ contents and trace elements ratios were plotted against
328 εNdi values (Fig. 6e) to check the assimilation hypothesis. Umar alkali basalts seem to have
329 preferentially sampled the Nd and Pb unradiogenic component. On the other hand, the silica-
330 rich Umar lavas (UmV₂ trachyandesites, trachytes and rhyolites) exhibit εNd_i higher than
331 those of basaltic lavas. Therefore, the relationships between the isotopic Nd signature and the
332 silica contents of analyzed lavas are opposite to those expected for a shallow (upper) crustal
333 assimilation process coupled with fractional crystallization (DePaolo, 1980), an increase of
334 SiO₂ and a decrease in εNd_i.

335 The studied mafic lavas display (La/Yb)_N variations dependant from variable La contents
336 (Fig. 6d) and from significant variations of the HREE (trend 1 in Fig. 7a). A sample subset
337 shows, in contrast, significant evolution of Yb contents (Fig. 7c) and (Sm/Yb)_N ratios, without
338 significant variations of La contents (trend 2 in Fig. 7a,b). As garnet has high distribution
339 coefficients for HREE, (La/Yb)_N and (Sm/Yb)_N ratios are sensitive to the amount of residual
340 garnet during partial melting (Caroff et al., 1997). An increasing melting degree of garnet-
341 bearing lherzolite leads to a rapid decrease of La/Yb ratio without major Yb fractionation
342 (Luhr et al., 1995). In contrast, increasing melting of spinel lherzolite will involve a more
343 rapid Yb fractionation without significant variation of La/Yb ratio (Fig. 7c). In Figure 7c,
344 Umar mafic lavas define two main trends delineated by the two grey domains. UmV₂ sub-
345 alkaline basalts characterized by low (La/Yb)_N ratios (< 10) show significant (Sm/Yb)_N
346 variations with highly variable Yb contents. They might derive from variable amounts of
347 partial melting degrees (F ~ 5 to 10%) of a garnet-free lherzolithic source. In contrast, the older
348 UmV₁ alkali basalts, which display high (La/Yb)_N ratios (> 15) and low Yb contents
349 (< 2 ppm) might derive from a lower amount (F ~ 3 to 6 %) of partial melting of a deeper
350 (garnet+spinel-bearing) lherzolithic source. The Kawr and Al Aridh mafic lavas plot between
351 the two Umar groups (Fig. 7c) and could have been generated at intermediate depths.

352

353 5.2. Evidence for source heterogeneity

354 The investigated mafic lavas display geochemical features similar to OIB and continental
355 intraplate basalts, i.e. (i) incompatible element enrichments (Fig. 3) and (ii) Nd and Pb
356 isotopic compositions clearly distinct from MORB (Fig. 5c). The most Nd- and Pb-radiogenic
357 samples plot within the OIB field (Fig. 5), while the least Nd- and Pb-radiogenic ones (Umar
358 alkali basalts) plot close to the Enriched Mantle 1 end-member (EM 1, Zindler and Hart,
359 1986; Fig. 5c). Their principal mantle source is distinct from the Depleted MORB Mantle

360 (DMM) in that the highest ϵNd_i value is +5.3 (Table 2). Moreover, the isotopic signatures of
361 the Umar alkali basalts suggest a contribution of another source, one characterized by strongly
362 enriched LREE patterns (Fig. 3a) relatively high La/Nb and Th/Nb ratios (Fig. 8a,b) and
363 negative ϵNd_i signatures ($-4.5 < \epsilon\text{Nd}_i < -1.2$) (Figs. 5c and 8).

364 In addition, the $(\text{La}/\text{Sm})_N$ versus ϵNd_i plot (Fig. 8c) shows that the LREE enrichment of
365 the basaltic samples is not coupled with Nd isotopic ratios. Indeed, it is greatest in the low
366 ϵNd_i group (Umar basalts) and in the high ϵNd_i Kawr platform intrusions. In this diagram, the
367 occurrence of two distinct isotopic groups and the lack of continuous trends suggest that the
368 studied samples do not derive from the melting of variable mixes of two main mantle
369 components. In that respect, they differ from most hotspot lavas which usually plot along
370 linear trends connecting a depleted and an enriched mantle component in diagrams of Nd and
371 Pb isotopic ratios and incompatible trace elements (Phipps Morgan and Morgan, 1999).

372

373 *5.3. Possible geochemical imprint of the Arabian lithosphere*

374 In the Ti/Y versus ϵNd_i plot (Fig. 8d), the studied basalts and trachybasalts show
375 geochemical signatures characteristic of high-Ti continental flood basalts ($\text{Ti}/\text{Y} > 300$ -350;
376 Hawkesworth et al., 1992; Gibson et al., 1995; Peate and Hawkesworth, 1996; Pik et al.,
377 1998, 1999). Highly variable ϵNd_i values such as those observed for Hawasina lavas are often
378 a characteristic of continental basalts. They are generally interpreted as markers of
379 interactions between asthenosphere-derived melts and the local continental crust or the
380 subcontinental lithospheric mantle (Saunders et al., 1992; Lightfoot et al, 1993; Sharma,
381 1997). As shown in Figs. 8a-b, the low ϵNd_i lavas from the Umar display a slight but
382 significant depletion in Nb. This feature might be attributed to interactions with the local
383 continental lithosphere, e.g. the lower crust or subcontinental lithospheric mantle.

384 The Arabo-Nubian shield includes oceanic terranes that formed and accreted during the
385 Neoproterozoic Pan-African orogeny (Stern, 1994; Stein and Goldstein, 1996). These terranes
386 are characterized by radiogenic Nd and Pb isotopic ratios ($+2 < \epsilon\text{Nd}_i < +9$; Stoesser and Frost,
387 2006; Andersson et al., 2006). In addition, mafic and felsic granulites and peridotites, locally
388 exhumed or found as xenoliths within Cenozoic lavas, sample of the Arabo-African lower
389 continental crust and lithospheric mantle (Fig. 9). Their isotopic characteristics define a large
390 domain of variation with, for instance, radiogenic Pb compositions ($^{206}\text{Pb}/^{204}\text{Pb} > 18$) and
391 positive ϵNd_i signatures for Zabargad granulites and peridotites (Lancelot and Bosch, 1991;
392 Hamelin and Allègre, 1988). Moreover, xenoliths from the Arabo-African lithospheric mantle
393 also display radiogenic Nd ratios ($0.5135 < ^{143}\text{Nd}/^{144}\text{Nd} < 0.5129$), associated to $^{206}\text{Pb}/^{204}\text{Pb} >$
394 17: these values are intermediate between DMM and high- μ (HIMU) end-members (Fig. 9).
395 In addition, the predominant HIMU isotopic signature ($^{206}\text{Pb}/^{204}\text{Pb} = 18.60$ to 19.55) of

396 Neogene-Quaternary intraplate basalts in Syria, Saudi Arabia and Yemen, has been
397 interpreted as inherited from the Arabian lithospheric mantle (Bertrand et al., 2003).

398 The positive ϵNd of the Arabian lithospheric mantle (Fig. 9b) precludes it as the main
399 source of the studied lavas, which have negative ϵNd values. Conversely, both the Nd and Pb
400 isotopic ratios of the studied lavas plot within the compositional range of the Arabian upper
401 and lower crusts. In particular, the isotopic compositions of alkali UmV₁ basalts match those
402 of mafic granulites from the Yemen lower crust (Baker et al., 1997). This feature together
403 with their slight Nb depletion suggests that the UmV₁ lavas signature might result from
404 assimilation of lower crustal materials (Fig. 8a,b).

405

406 *5.4. A Triassic Neotethyan plume beneath the Oman margin?*

407 The OIB-like characteristics and predominantly alkali basaltic features of the Triassic
408 Hawasina lavas have led many former authors (Glennie et al., 1974; Searle et al., 1980; Searle
409 and Graham, 1982; Robertson and Searle, 1990; Stampfli et al., 1991; Pillevuit, 1993;
410 Pillevuit et al., 1997) to consider them as hotspot-related intra-oceanic plateaus or seamounts.
411 They might derive from either a genuine Triassic mantle plume or a still active Tethyan
412 plume inherited from the Permian magmatic history. However, any isotopic (Figs. 5c and 10)
413 or trace element (Fig. 4b) evidence for a depleted mantle component in their source is lacking.
414 Conversely, Triassic depleted tholeiites occur in the Mamonia Complex, Cyprus (Lapierre et
415 al., 2007), in Baër Bassit, Syria (Perez, 2006) and in Othrys, Greece (Monjoie et al., 2008).
416 The isotopic signatures of Mediterranean Triassic volcanics (Fig. 10) are consistent with a
417 mixing between the depleted upper mantle (main source of Mamonia, Baër Bassit and Othrys
418 depleted tholeiites) and two mantle enriched components, HIMU and EM 2 (Perez, 2006;
419 Lapierre et al., 2007; Maury et al., 2008). In contrast with the Oman case, none of these
420 volcanics involved the contribution of lower crustal components with negative ϵNd_i to their
421 genesis (Fig. 10). This feature suggests that they were emplaced on the Neotethyan oceanic
422 floor rather than on a continental margin.

423 In addition, the hypothesis of a Triassic plume beneath the Oman margin does not fit
424 available geological and chronological constraints. The preserved Triassic lava piles are less
425 than 100 m thick, and thus very small with respect to plume-related magmatic successions
426 such as traps, oceanic islands or rift-related series. The comparison of the Kawr platform with
427 an intra-oceanic atoll built on the top of a seamount (Pillevuit, 1993; Pillevuit et al., 1997) has
428 been invalidated by recent fieldwork (Basile and Chauvet, 2009). In addition, there is no
429 evidence for magmatic activity in the Oman margin between the Permian (Wordian-
430 Capitanian, ca. 265 Ma old) and the Middle-Late Triassic (Ladinian-Carnian, ca. 230 Ma old)

431 events. This time gap is inconsistent with the hypothesis of survival of a Neotethyan plume
432 since the Permian event.

433

434 *5.5. An alternative hypothesis: melting of the Oman lithospheric mantle modified by the*
435 *Permian plume.*

436 Alkali basaltic magmas can be emplaced in regions removed from a mantle plume,
437 providing that a distensional tectonic regime causes the uprise and partial melting of enriched
438 lithospheric mantle (Wilson, 1989). Passage over an active mantle plume can indeed modify
439 considerably the composition of the oceanic (Dupuy et al., 1993; Chauvel et al., 1997) or
440 continental (Hawkesworth et al., 1990; Saunders et al., 1992; Lightfoot et al., 1993)
441 lithospheric mantle, mainly through melt-induced metasomatism (Harry and Leeman, 1995;
442 Downes, 2001). For instance, enriched pargasite-bearing mantle xenoliths from Morocco
443 record the pervasive metasomatism of a depleted Proterozoic sublithospheric mantle by
444 Tertiary plume-related HIMU-type alkaline melts which obliterated its initial composition
445 (Raffone et al., 2009). The HIMU signature of Cenozoic alkali basalts from western Europe
446 and their mantle xenoliths is attributed to mantle metasomatism of an heterogeneous
447 lithospheric mantle by melts from an Early Tertiary asthenospheric plume (Hoernle et al.,
448 1995; Downes, 2001). To test such a process, we have compared the compositions of the
449 studied Triassic Hawasina lavas and those of their predecessors, i.e. the Permian Hawasina
450 basalts which are clearly plume-related (Maury et al., 2003; Lapierre et al., 2004).

451 The Permian Hawasina basaltic piles include high-Ti alkali melts and low-Ti tholeiitic
452 melts (Fig. 11a), the latter displaying low $(La/Sm)_N$ ratios (Fig. 11b) and either slightly
453 enriched or slightly depleted multielement patterns (Fig. 11c). On the basis of Nd and Pb
454 isotopic data, Lapierre et al. (2004) defined three different geochemical groups. Group 1 low-
455 Ti tholeiitic basalts are characteristic of the most distal environments of the Hawasina
456 Permian basin. They have variable but radiogenic Nd isotopic ratios ($3.8 < \epsilon Ndi < 11.1$, Fig.
457 12a,b), together with rather homogeneous Pb isotopic ratios (Fig. 12c). Group 2 high-Ti alkali
458 basalts are systematically associated with the proximal basin environments, and are more
459 enriched in La, Th and Nb than Group 1 basalts (Fig. 11b,c). They are characterized by less
460 radiogenic Nd isotopic ratios ($3.1 < \epsilon Ndi < 4.9$; Fig. 12a,b). Finally, Group 3 includes high-Ti
461 and low-Ti basalts (Fig. 11a) that erupted onto the continental platform of the Arabian
462 margin, except for one basalt from the distal basin (top left of Fig. 11c). These Group 3
463 basalts are systematically enriched in the most incompatible trace elements and they have
464 unradiogenic Nd isotopic ratios ($-2 < \epsilon Ndi < 1.6$) and Pb isotopic ratios similar to those of
465 Group 2 lavas (Fig. 12).

466 The trace element compositions of the Triassic Hawasina volcanics are overall very
467 similar to those of Groups 2 and 3 high-Ti Permian basalts (Fig. 11c). Moreover, with the
468 exception of Kawr intrusions and UmV₁ alkali basalts, the Nd and Pb isotopic compositions
469 of Triassic Hawasina basalts match those of Groups 2 and 3 Permian basalts (Fig. 12). The
470 UmV₁ basalts show Nd and Pb compositions less radiogenic than those of Group 3 lavas (Fig.
471 12c).

472 The above comparison shows that a component equivalent to that which generated the
473 Permian Group 1 distal tholeiites has not been detected in the studied samples. Conversely,
474 the Hawasina Triassic lavas are isotopically similar to Permian Groups 2 and 3 lavas,
475 respectively (Fig. 12c). It is therefore possible to consider the OIB-type source of Permian
476 Group 2 alkali basalts as identical or closely similar to the source of most Triassic volcanics
477 (UmV₂ unit, Kawr intrusions and the majority of Al Aridh lavas). It might thus represent the
478 main mantle reservoir underlying the Arabian margin since Middle Permian times
479 (component A in Fig. 12a,b). The Kawr intrusions, which display higher La/Sm and La/Nd
480 ratios than other Triassic lavas, could derive from low-degree melting of this source (trend B
481 in Fig. 12a,b).

482 In the La/Nb, (La/Sm)_N and La/Nd *versus* εNdi diagrams (Figs. 8a and 12a,b), Kawr
483 basaltic flows plot between the main radiogenic and unradiogenic components. Trend C,
484 drawn in (La/Sm)_N and La/Nd *versus* εNdi plots, suggests that their source might be a mixture
485 between OIB-type mantle (component A) and an enriched component. This trend has no
486 equivalent among the Permian basalts, but the number of samples defining it is too limited for
487 detailed interpretation.

488 Finally, the trend towards EM 1 (Fig. 12c) of Permian Group 3 and Triassic UmV₁ alkali
489 basalts might result from their interaction with the lower crust (trend D in Fig. 12a,b).
490 According to Lapierre et al. (2004), contamination of Group 3 Permian lavas would involve
491 rocks similar in composition to the gneissic granulites of Zabargad Island. In contrast, UmV₁
492 basalts have Nd and Pb isotopic ratios that are lower than those of Zabargad granulites (Fig.
493 9), and more consistent with the composition of mafic lower crustal xenoliths (Baker et al.,
494 1997).

495 In short, we propose that Permian plume-related alkaline melts metasomatized the Oman
496 lithospheric mantle during their ascent towards the surface, overprinting its initial DMM-
497 HIMU signature. Thirty-five million years later, a post-breakup extension induced partial
498 melting of this metasomatized mantle, and generated the Triassic basaltic magmas. During
499 their ascent, some of the oldest and deepest melts (UmV₁ basalts) interacted with rocks from
500 the lower continental crust.

501

502 5.6. Tectonic framework of the Triassic volcanic event

503 Coeval (Ladinian – Carnian) volcanic sequences were emplaced all along the southern
504 Tethyan realm. They were interpreted either as belonging to the southern Neotethyan
505 continental margin series (e.g. Béchenec et al., 1988, 1991) or alternatively as oceanic island
506 on the Neotethyan oceanic floor (Stampfli et al. 1991; Pillevuit et al., 1997). The lower crustal
507 contamination suffered by the oldest Triassic basalts in the Umar basin (UmV₁) indicates that
508 distal parts of the Hawasina basin overlay continental crust during the Triassic. The
509 concomitant synsedimentary destabilizations of its continental slope and basin environments
510 (Watts, 1990; Pillevuit, 1993) suggest a link between the Triassic magmatic event and
511 extensional (post-breakup) tectonic reactivation of the Permian structures.

512 The Neotethys opened between the northern edge of Gondwana and the Cimmerian
513 continental blocks. These blocks drifted northward during the subduction of the Paleotethys
514 beneath the Southern Laurasia active margin (Besse et al., 1998). At the end of the Middle
515 Triassic (Anisian), Paleotethyan subduction ended and was replaced by that of the Neotethys
516 (Saidi et al., 1997; Besse et al., 1998). In geodynamic reconstructions, this subduction jump is
517 generally linked to a global kinematic reorganization of the Tethyan realm. It is either
518 attributed to a Neotethys ridge jump (Dercourt et al., 1993; Besse et al., 1998; Vrielynck and
519 Bouysse, 2001), or to a change from a transtensional to a distensional regime in the Neotethys
520 accretion system (Ricou, 1994). Both processes might lead to a reactivation of the extensional
521 tectonic structures inherited from the Permian breakup. The resulting extension might have
522 caused convective thinning of the subcontinental lithosphere similarly to that in the Basin and
523 Range province (Fitton et al., 1991; DePaolo and Daley, 2000). We suggest that this thinning
524 led to the decompression-triggered partial melting of the Arabian uprising mantle, and to the
525 emplacement of the Triassic Hawasina basalts.

526

527 6. Conclusions

528

529 1. Middle to Late Triassic volcanic rocks from the Hawasina Nappes are predominantly
530 alkali basalts, with minor associated sub-alkaline basalts, trachyandesites, trachytes and
531 rhyolites. Most of them are geochemically very similar to the more abundant Permian plume-
532 related high-Ti basalts, which also occur in the Hawasina Nappes.

533 2. The Triassic basalts derive from low-degree melting of an enriched OIB-type mantle
534 source, characterized by $0.3 < \epsilon Nd_i < 5.3$ and $^{206}Pb/^{204}Pb_i = 16.96-19.31$. With time, the degree
535 of partial melting increased and the corresponding depths decreased from the garnet + spinel
536 to the spinel lherzolite facies. Some of the oldest and deepest melts (UmV₁ unit of Umar
537 Group) are distinguished from the others by their unradiogenic Nd and Pb signature, with -

538 $4.5 < \varepsilon\text{Nd}_i < -1.2$ and $^{206}\text{Pb}/^{204}\text{Pb}_i = 16.35\text{-}17.08$. We attribute these features to contamination
539 by the lower continental crust of the Oman margin.

540 3. The Triassic Hawasina lavas show no evidence for a depleted mantle source, such as
541 those documented for the Permian tholeiitic low-Ti basalts of Oman and the Triassic oceanic
542 island-type tholeiites of Cyprus. The ca. 35 My time span between their emplacement and that
543 of their Permian equivalents suggests that they were not related to prolonged activity of the
544 Tethyan plume. We propose instead that they originated from the partial melting of the Oman
545 lithospheric mantle, the original DM-HIMU signature of which was overprinted during its
546 pervasive metasomatism by Permian plume-related melts.

547 4. The origin of the Hawasina Triassic volcanism is tentatively attributed to a post-
548 breakup decompression-triggered melting event linked to an extensional remobilization of the
549 earlier tectonic structures of the Oman margin. This remobilization was possibly a
550 consequence of the global kinematic reorganization of the Tethyan realm during the Middle
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552

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568

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947 **Figure captions**

948

949 Fig. 1. Geological setting. a) The Tethyan Suture (ophiolites and associated mélanges)
950 after Coleman (1981), with locations of the main late Carboniferous, Permian and Triassic
951 volcanic sequences associated to the Neotethyan margins inverted segments (mainly from
952 Garzanti et al., 1999). b) Simplified geological map of the Oman Mountains and associated
953 main structural units (after Glennie et al., 1974). c) Sampling locations on the geological map
954 of the Hawasina nappes (after Béchenec, 1987 modified by de Wever et al., 1990). Sampling
955 sites coordinates of Sinni: 23°25'4''N - 57°09'2''E; Sayjah: 23°11'23''N - 57°51'58''E;
956 Aqil: 22°47'8''N - 57°48'4''E (Om-45); 22°47'2''N - 57°51'3''E (Om-52); 22°47'5''N -
957 57°48'2''E (Om-42); 22°47'9''N - 57°48'4''E (Om-48 and -49); Jabal Buwaydah 1:
958 22°53'6''N - 57°05'7''E; Jabal Buwaydah 2: 23°00'8''N - 57°00'E. d) Regional cross section
959 according to Béchenec (1987).

960

961 Fig. 2. Selected major element plots for the Triassic Hawasina basin lavas. a) MgO
962 (wt.%), b) TiO₂ (wt.%) and c) Na₂O+K₂O (wt.%) *versus* SiO₂ (wt.%) plots. The trend
963 separating alkaline and tholeiitic fields in c) is from MacDonald and Katsura (1964) and the
964 lava nomenclature from Le Bas et al. (1986).

965

966 Fig. 3. Chondrite and primitive mantle-normalized trace elements patterns of (a) Umar
967 Group samples. b) Comparison between multielement patterns of selected Kawr and Alridh
968 Groups basalts and trachybasalts with OIB patterns and the compositional field of the alkaline
969 Umar Group samples from the Al Qurti UmV₁ unit and the Sinni village (grey array).
970 Chondrite, primitive mantle and OIB compositions are from Sun and McDonough (1989).

971

972 Fig. 4. a) Zr/Ti *versus* Nb/Y discriminating diagram of Winchester and Floyd (1977). b)
973 Plot of Triassic Hawasina basalts and trachybasalts in the Nb/Y *versus* Zr/Y diagram of Fitton
974 et al. (1997) together with Iceland plume-related picritic, tholeiitic and alkaline primary
975 basalts (MgO > 8 wt.%) of the Neo-Volcanic Zone, and the Kolbeinsey and Reykjanes ridge
976 basalts (Kokfelt et al., 2006). Note the deviation towards low Nb/Y values for samples with
977 La/Nb < 1.

978

979 Fig. 5. Initial Pb and Nd isotopic compositions of Triassic Hawasina lavas. Plots of a)
980 (²⁰⁷Pb/²⁰⁴Pb)_i, b) (²⁰⁸Pb/²⁰⁴Pb)_i and c) εNdi against (²⁰⁶Pb/²⁰⁴Pb)_i. The compositional fields of
981 Indian and Atlantic MORB are compiled from the Petrological Database of the Ocean Floor
982 (PETDB). Compositional fields of OIB, mantle isotopic components HIMU (for High-μ), EM
983 1 and EM 2 (for Enriched Mantle 1 and 2) and the NHRL (Northern Hemisphere Reference
984 Line) are from Zindler and Hart (1986).

985

986 Fig. 6. a) and b) Al₂O₃ (wt.%) and Eu/Eu* *versus* SiO₂ (wt.%) diagrams for Al Qurti
987 samples of the Umar Group c) (La/Yb)_N ratios of Al Qurti samples plotted against their
988 stratigraphic position. d) and e) (La/Yb)_N *versus* La(ppm) and εNd_i *versus* SiO₂ (wt.%)
989 diagrams for all Triassic Hawasina samples.

990

991 Fig. 7. Selected REE plots. a) and b) (La/Yb)_N and La *versus* (Sm/Yb)_N plots for
992 Hawasina Triassic basalts and trachybasalts. The meaning of arrows (1) and (2) is explained
993 in the text. c) La/Yb and Yb (ppm) variations during non-modal partial melting (F values:
994 partial melting degrees) of garnet and spinel lherzolite sources “s” containing different
995 proportions of these minerals (100% Gt – 0% Sp, 50 % - 50 %, 30% - 70%, 0% Gt – 100%
996 Sp). In this model developed by Luhr et al. (1995), source “s” is assumed to be enriched
997 relative to chondrite, with La = 6 * Ch (1.79 ppm) and Yb = 1.5 * Ch (0.31 ppm). This model
998 was used by Luhr et al. (1995) for primitive basalts with Mg# > 68 to limit the fractionation
999 effects related to magmatic differentiation. As the iron contents of the studied basalts may
1000 have been modified by post-magmatic processes, their MgO contents are used to check the

1001 primitive character Hawasina Triassic basalts. Samples with MgO > 7 wt.% are identified by
1002 thick and doubled symbols.

1003

1004 Fig. 8. Plots of the ϵNd_i of Triassic Hawasina basalts and trachybasalts against: a) La/Nb;
1005 b) Th/Nb; c) $(\text{La}/\text{Sm})_N$ and d) Ti/Y. MORB and OIB compositions are from Sun and
1006 McDonough (1989). SCLM (Sub-Continental Lithospheric Mantle) composition is from
1007 McDonough (1990) and the compositions of LC and UC (Lower and Upper continental Crust)
1008 from McLennan (2001).

1009

1010 Fig. 9. Nd and Pb isotopic compositions of Triassic Hawasina volcanics recalculated at
1011 $t = 230$ My, compared to the published fields of the Arabian sub-continental lithospheric
1012 mantle and the regional upper and lower crusts. E. Pr.: Early Proterozoic, Ar: Archean, L. Ar.:
1013 Late Archean. MORB, OIB, EM 1 and EM 2 are from Zindler and Hart (1986); NHRL is
1014 from Hart (1984); Arabian lithospheric mantle is from Shaw et al. (2007 - Jordan), Baker et
1015 al. (2002, 1997 – Yemen and Southern Red Sea), Hamelin and Allègre (1988 – Zabargad
1016 Island), Blusztajn et al. (1995 – Saudi Arabia). Sudanese crust is from Davidson and Wilson
1017 (1989); Yemen and Saudi Arabia upper crust is from Whitehouse et al. (2001); Baker et al.
1018 (2000); Hegner and Pallister (1989); the lower mafic crust is from Cohen et al. (1984 -
1019 Tanzania), Altherr et al. (1990) and G. Chazot and J. A. Baker (unpublished data presented as
1020 a composition field in Baker et al., 1997 – Arabia and Yemen); the gneissic lower crust is
1021 from Lancelot and Bosch (1991 – Zabargad Island).

1022

1023 Fig. 10. Nd and Pb isotopic compositions (at $t = 230$ My) of Triassic intraplate volcanic
1024 sequences from Oman and the Eastern Mediterranean occurrences. Data are from this work
1025 (Oman); Lapierre et al., 2007 (Cyprus); Maury et al., 2008 (Turkey); Perez, 2006 (Syria);
1026 Monjoie et al., 2008 (Greece).

1027

1028 Fig. 11. Geochemical comparison between the Permian and Triassic lavas from the Oman
1029 margin. All Permian data are from Lapierre et al. (2004) and Maury et al. (2003). a) and b)
1030 plots of TiO_2 (wt.%) and $(\text{La}/\text{Sm})_N$ versus Th (ppm) for basalts from the two magmatic
1031 events. c) Primitive mantle-normalized multielement patterns of the Permian Groups 1, 2 and
1032 3 and of the Triassic basalts and trachybasalts.

1033

1034 Fig. 12. a) and b) Plots of $\epsilon(\text{Nd})_i$ values versus $(\text{La}/\text{Sm})_N$ and La/Nd ratios for the Permian
1035 Groups 1, 2 and 3 (Lapierre et al., 2004) and the Triassic basalts and trachybasalts. c) $\epsilon(\text{Nd})_i$
1036 versus $(^{206}\text{Pb}/^{204}\text{Pb})_i$ diagrams. All isotopic data are recalculated at $t = 230$ My. The meaning

1037 of A, B, C and D in diagrams a) and b) is explained in the text. MORB, OIB and primitive
1038 mantle reference values are from Sun and McDonough (1989).

1039

1040 **Table captions**

1041

1042 Table 1. Major element (wt.%) and trace element (ppm) compositions of representative
1043 Triassic lavas (whole set shown in Appendix A). Trace element compositions measured by
1044 ICP-AES are shown in italics and those obtained by ICP-MS in normal numbers. B: basalts
1045 ($\text{SiO}_2 < 53$ wt.% and $\text{MgO} > 6$ wt.%); TB: trachybasalts ($\text{SiO}_2 < 53$ wt.% and $\text{MgO} = 3$ to
1046 6 wt.%); DB: basaltic dolerite; TA: trachyandesite; T: trachyte; R: Rhyolite. Analytical
1047 methods explained in the text.

1048

1049 Table 2. Nd and Pb actual and initial (“i” for $t = 230$ My) isotopic compositions with their
1050 uncertainties ($\pm 2 \sigma$) for Triassic volcanics from the Hawasina nappes. Analytical methods
1051 explained in the text.

1052

1053 **Appendix**

1054

1055 Appendix A. Selected sampling sites. a) Cross section and sample locations in the Al
1056 Qurti site of the Umar Group (Fig. 1c). b) Stratigraphic column of the basal 300 m of the
1057 Kawr Group at Jabal Misfah (Fig. 1c) and location of samples.

1058

1059 Appendix B. Major element and trace element compositions of Triassic lavas from the
1060 Hawasina Nappes. Trace element compositions measured by ICP-AES are shown in italics
1061 and those obtained by ICP-MS in normal numbers. B: basalts ($\text{SiO}_2 < 53$ wt.% and $\text{MgO} >$
1062 6 wt.%); TB: trachybasalts ($\text{SiO}_2 < 53$ wt.% and $\text{MgO} > 3$ wt.%); DB: basaltic dolerite; TA:
1063 trachyandesite; T: trachyte; R: Rhyolite. Analytical methods explained in the text.

1064

1065 Appendix C. Chondrite and primitive mantle-normalized trace elements patterns of
1066 Middle to Late Triassic lavas from the Hawasina Nappes. Chondrite and primitive-mantle
1067 compositions are from Sun and McDonough (1989).

1068

1069 Appendix D. Plots of La, Nd, Sm, U and Pb against Th (ppm) for Triassic Hawasina
1070 samples. The linear trends reported on some diagrams correspond to the average Th/U and
1071 Th/Pb ratios of OIB (Sun and McDonough, 1989).

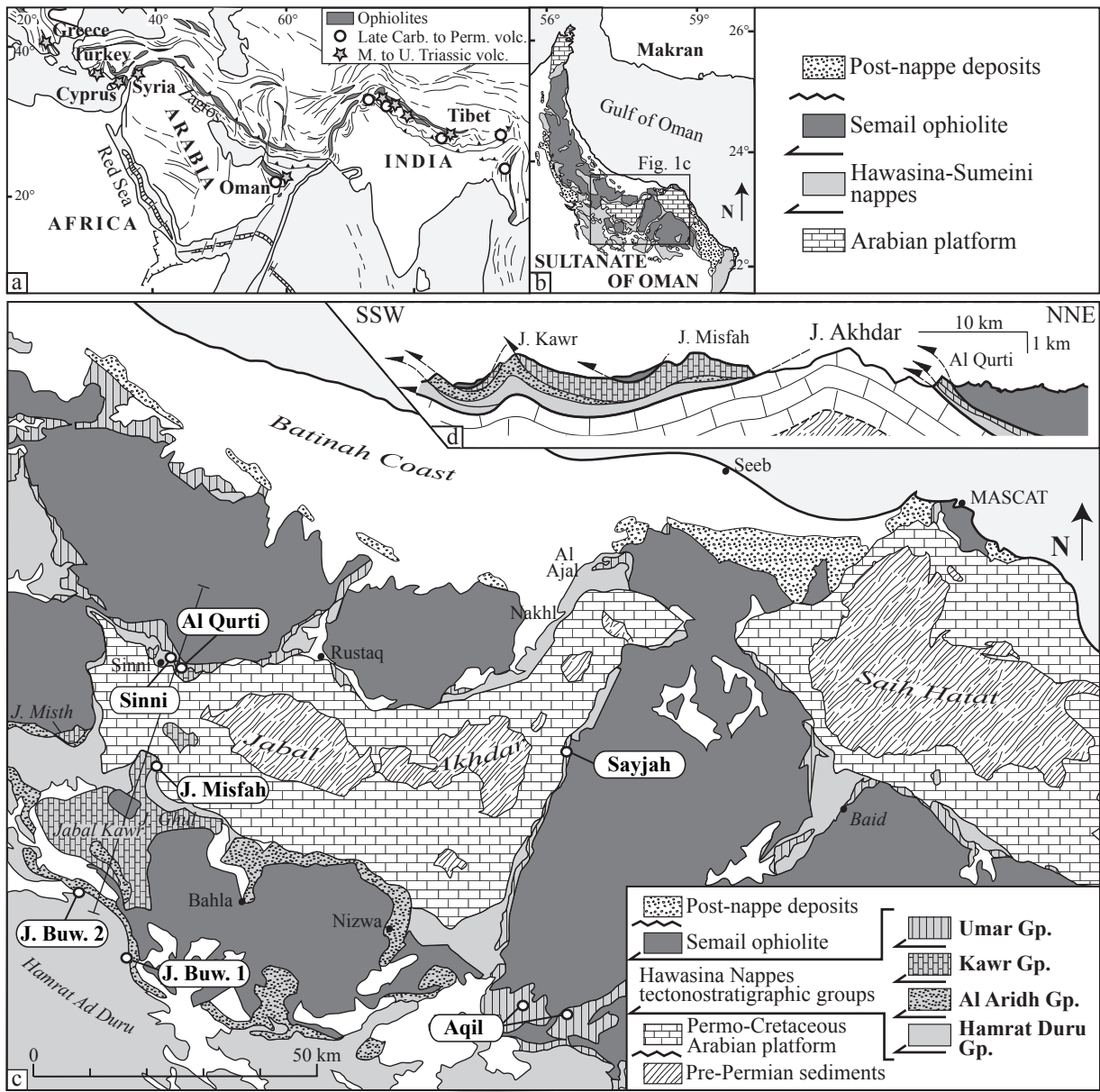


Fig. 1

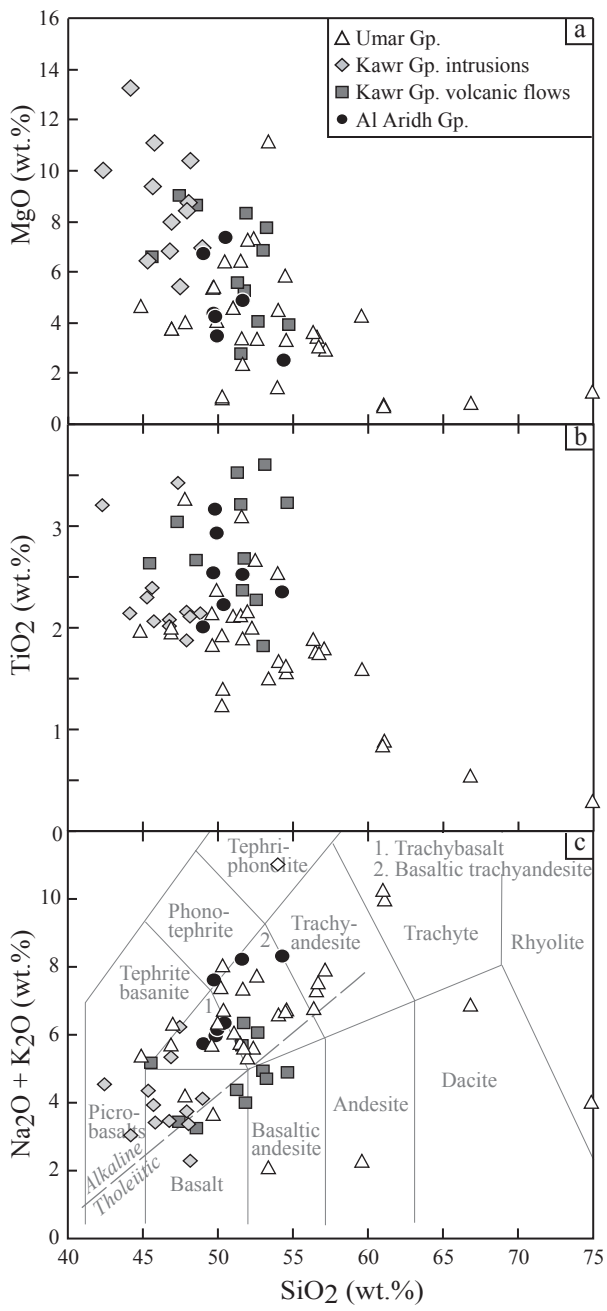


Fig. 2

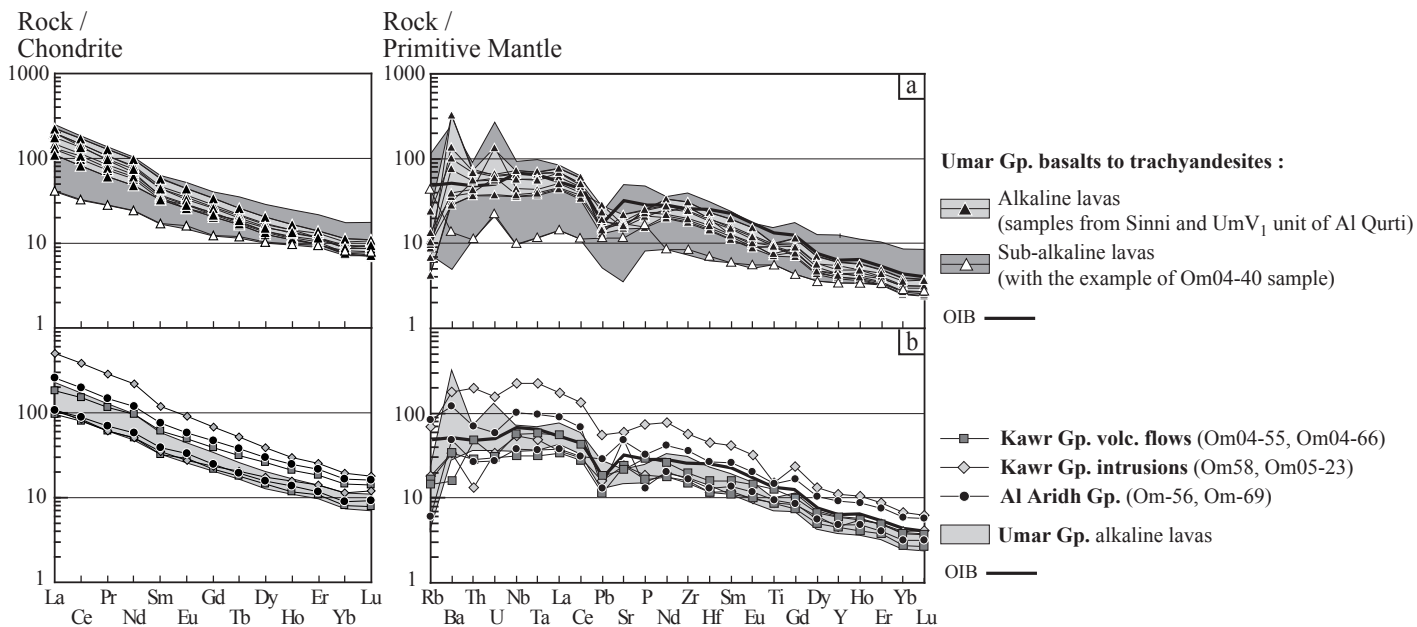


Fig. 3

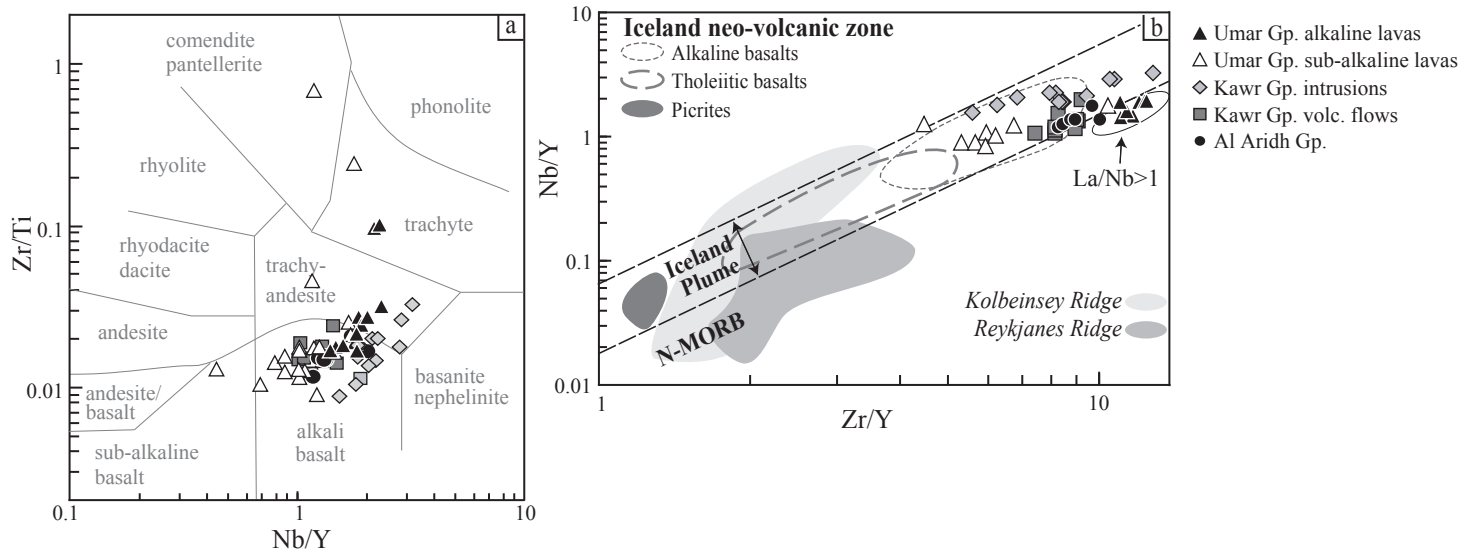


Fig. 4

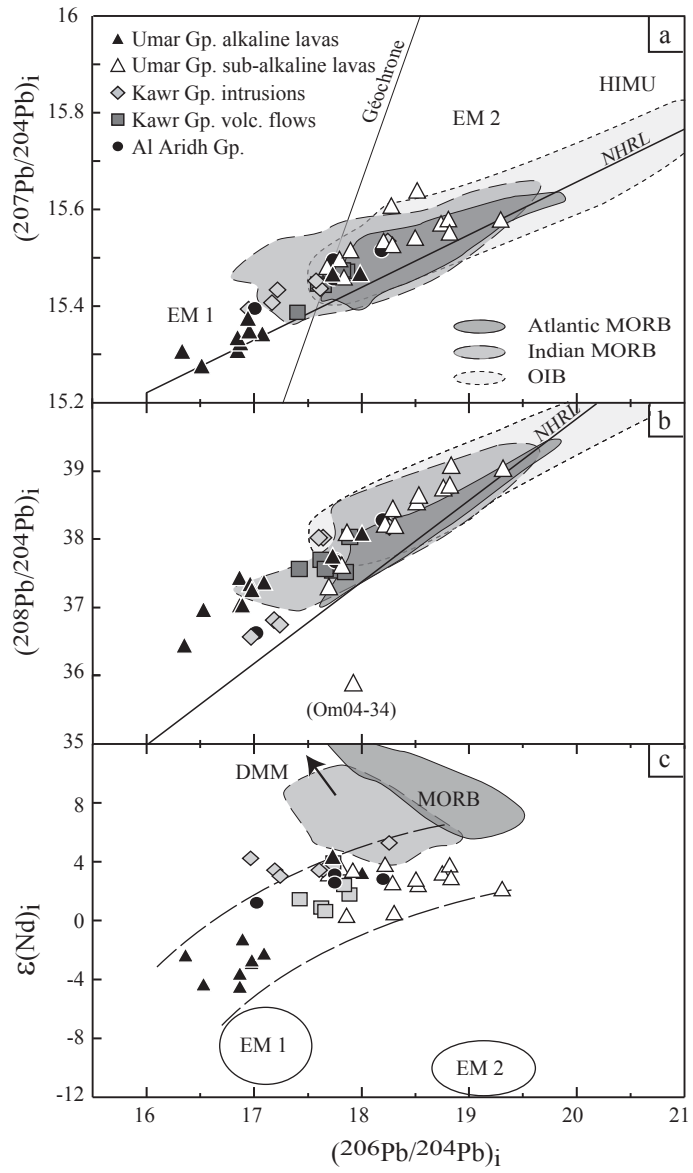


Fig. 5

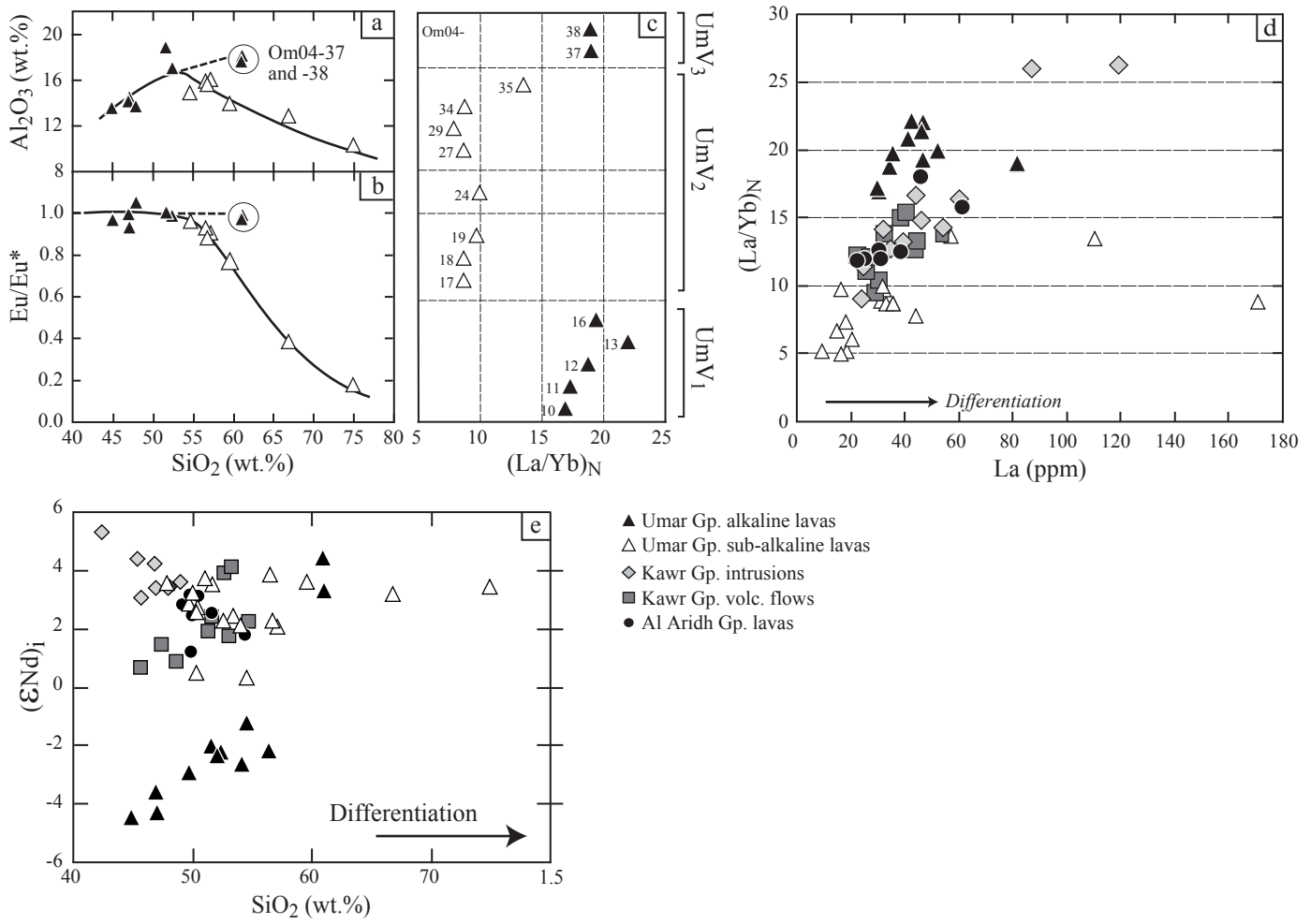


Fig. 6

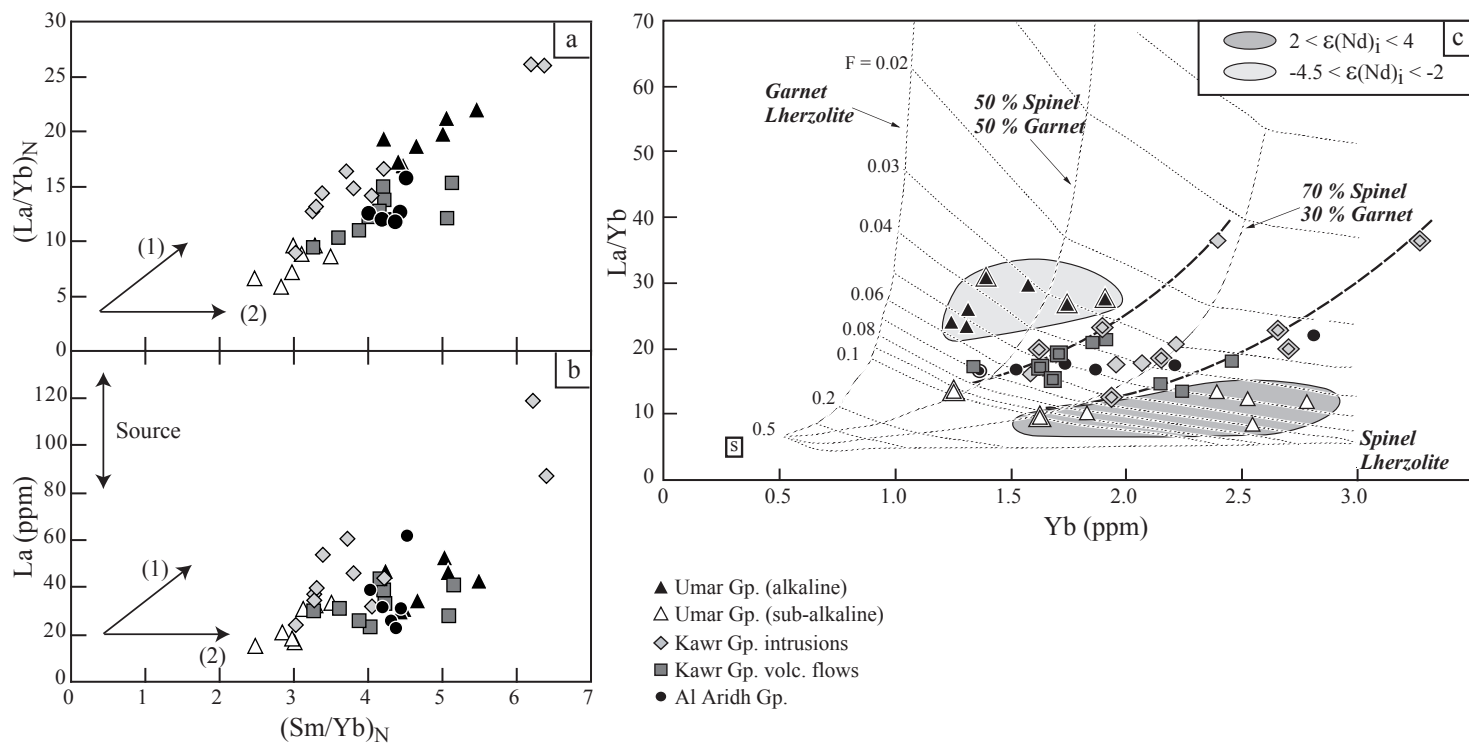


Fig. 7

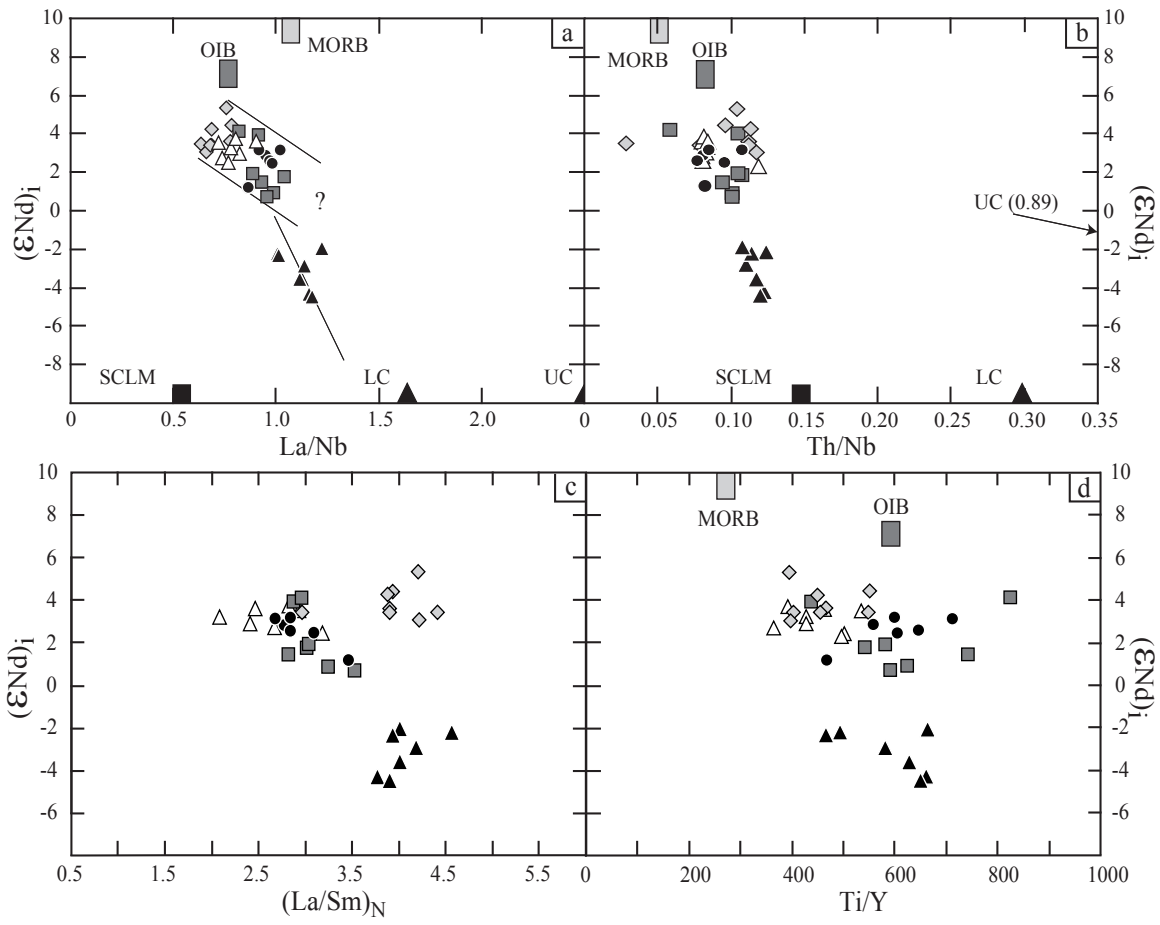


Fig. 8

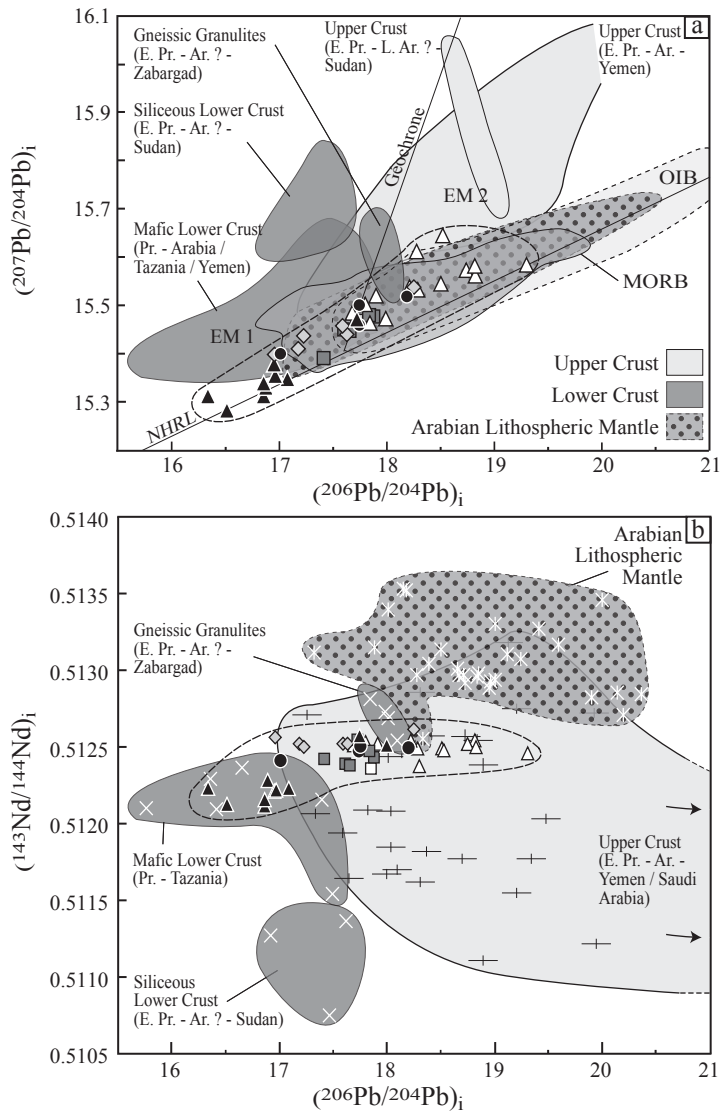


Fig. 9

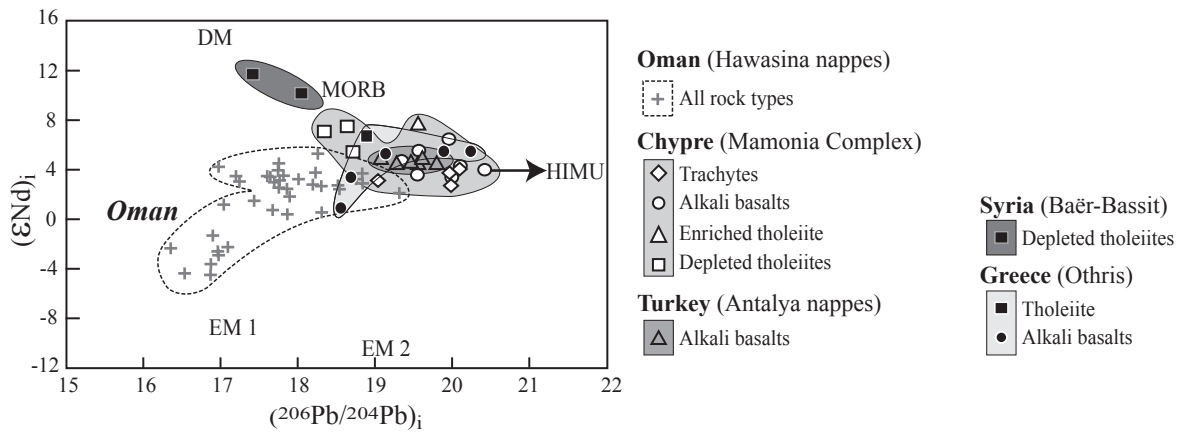


Fig. 10

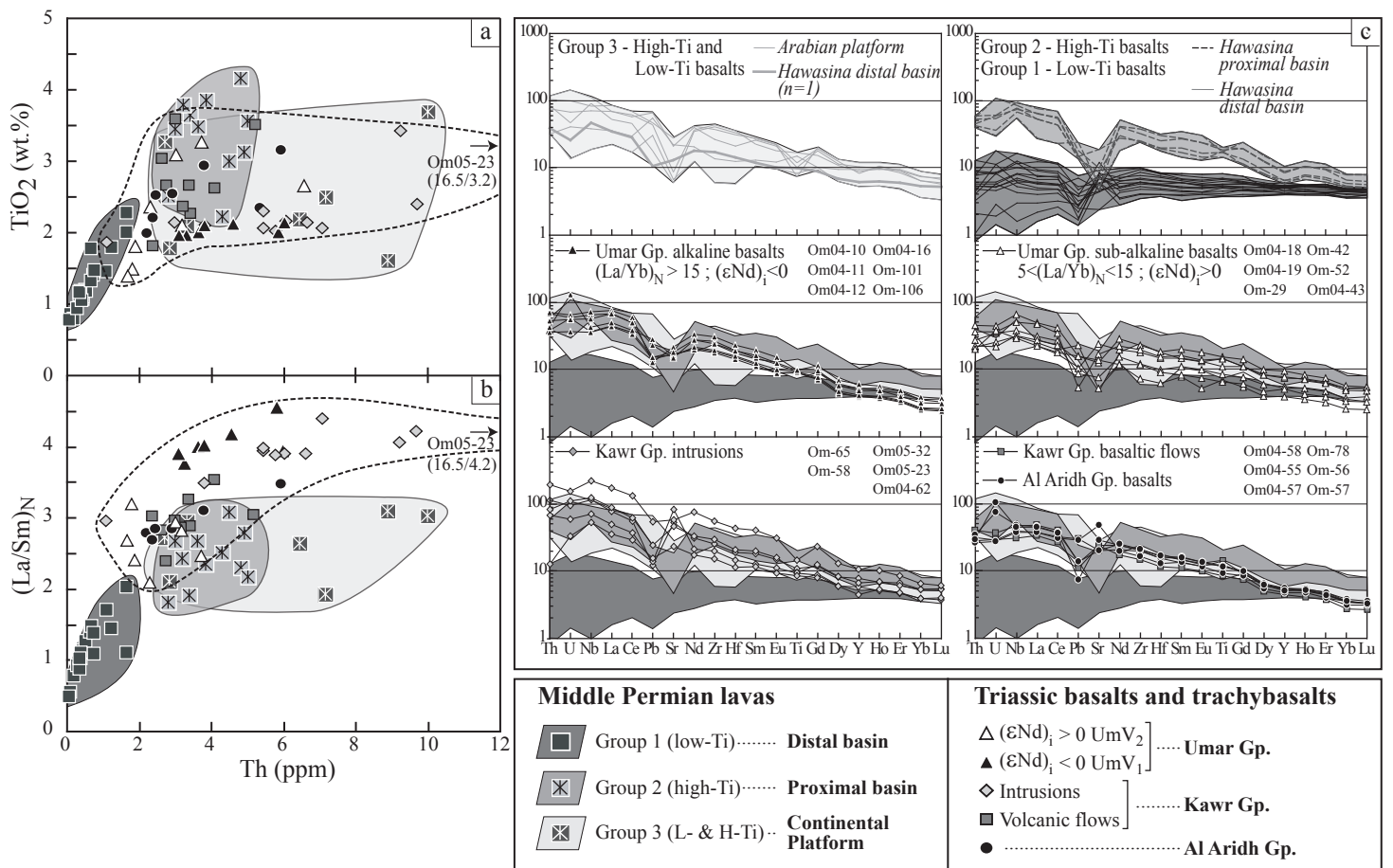


Fig. 11

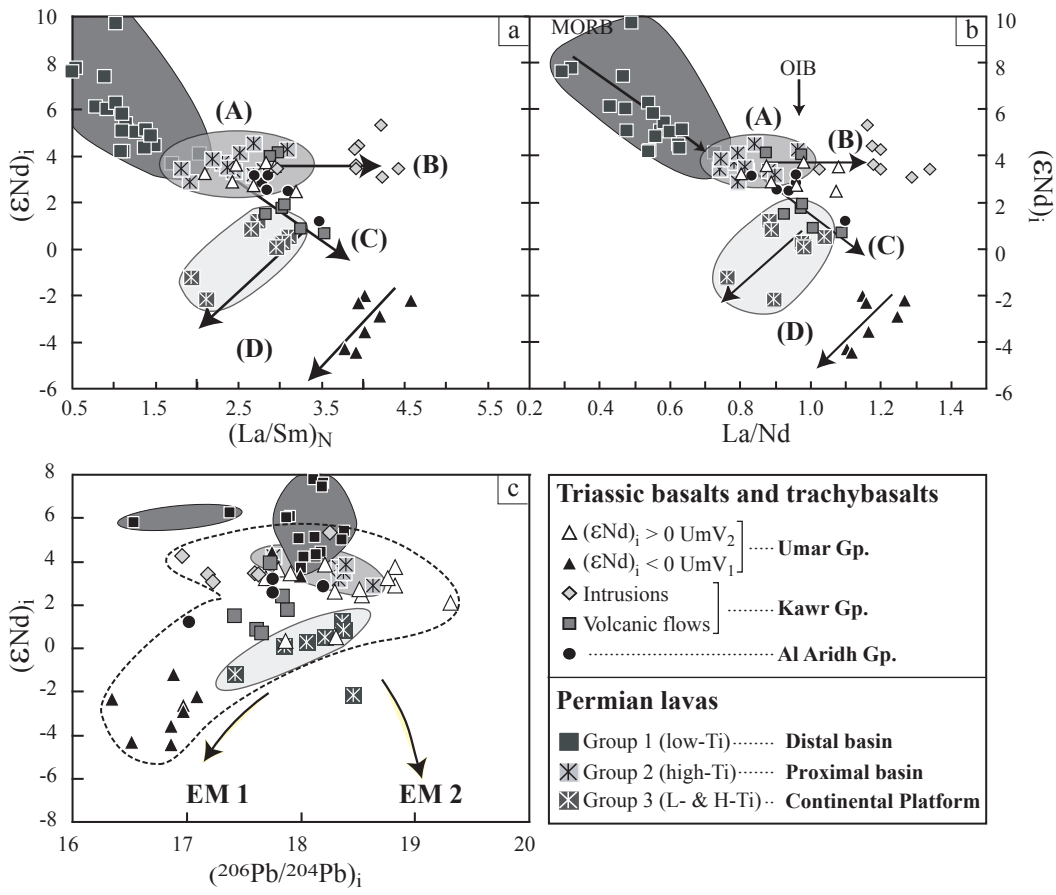


Fig. 12

Table 1

Stratigraphic Gp. and position	Umar Group - Sinni Fm.									Kawr Group - Misfah Fm.			
	UmV ₁ alkaline lavas					UmV ₂ sub-alkaline lavas				Volcanic Flows		Intrusions	
	Al Qurti			Sinni		Al Qurti			Sayjah	Jabal Misfah			
Location	Om04-11	Om04-13	Om04-16	Om-101	Om-106	Om04-24	Om04-29	Om 04-35	Om04-40	Om04-55	Om 04-57	Om- 58	Om05-23
Rock Type	TB	TA	BD	B	TB	TA	TA	R	TA	B	B	B	B
Major Elements (wt. %) recalculated on a volatile-free basis													
SiO ₂	44.9	54.6	52.4	52.0	49.7	56.5	59.6	66.8	50.3	53.1	48.6	48.0	42.4
TiO ₂	1.96	1.57	2.01	2.14	2.13	1.77	1.59	0.54	1.22	1.81	2.65	1.87	3.21
Al ₂ O ₃	13.6	14.9	17.0	15.2	14.8	15.9	13.9	12.9	15.1	14.8	15.0	16.2	12.7
Fe ₂ O ₃	9.88	5.81	9.14	9.61	8.81	8.38	12.27	6.07	7.68	11.93	9.37	12.01	15.84
MnO	0.13	0.11	0.16	0.14	0.14	0.11	0.14	0.29	0.10	0.22	0.19	0.13	0.25
MgO	4.66	3.31	7.35	7.21	5.38	3.41	4.25	0.83	1.02	6.85	8.63	8.75	10.00
CaO	19.08	12.48	5.79	7.87	12.83	5.88	5.34	5.48	16.83	6.02	11.79	9.29	9.47
Na ₂ O	4.95	6.41	4.36	4.47	5.43	6.67	0.35	5.30	5.96	4.36	2.83	2.66	1.39
K ₂ O	0.43	0.34	1.23	0.78	0.22	0.64	1.92	1.56	1.40	0.56	0.37	0.68	3.10
P ₂ O ₅	0.45	0.50	0.55	0.53	0.53	0.70	0.67	0.22	0.35	0.35	0.52	0.40	1.58
Vol.-free total*	99.93	99.66	99.44	99.69	99.68	99.17	99.22	99.42	100.03	99.59	99.91	99.49	99.52
LOI	10.82	9.15	5.30	3.99	6.15	5.44	2.85	7.54	12.09	3.17	4.47	7.45	4.51
Trace elements (ppm)													
Sc	20	11	19	33	28	20	13	1	22	34	36	10	18
V	220	142	190	283	235	99	33	7	93	220	190	105	99
Ni	107	45	105	185	187	205	4	5	56	191	164	235	128
Co	32	18	31	46	41	29	17	3	18	44	44	59	39
Cr	200	64	161	355	400	162	2	4	190	454	385	300	155
Cs	0.17	0.09	0.61	0.37	0.18	0.40	0.24	0.46	1.74	0.17	0.06	0.18	0.98
Rb	6.2	4.3	15.2	6.7	2.7	11.1	29.7	18.0	27.0	10.1	2.8	11.5	43.1
Ba	198	2293	701	943	218	84	195	418	93	235	393	235	1243
Th	3.10	6.40	5.84	6.01	4.58	4.12	6.58	16.06	0.92	2.39	3.40	1.10	16.54
U	0.78	1.34	1.27	1.37	1.17	0.87	1.65	2.69	0.46	0.62	0.78	0.70	3.24
Nb	25.59	47.52	46.68	51.82	41.03	36.51	64.31	136.66	6.85	21.92	33.19	38.26	157.63
Ta	1.51	2.75	2.65	2.84	2.29	2.28	3.54	7.88	0.47	1.26	2.01	1.96	9.10
Pb	2.63	3.33	4.33	2.39	2.80	3.28	3.11	5.29	2.14	2.05	2.44	2.88	10.10
Sr	364	353	315	463	384	271	74	200	244	492	504	500	1237
Zr	200	302	295	346	273	190	437	783	93	164	232	174	630
Hf	4.43	5.94	6.05	7.20	5.92	4.34	9.37	17.12	2.15	3.55	5.04	3.56	13.60
Y	18.09	20.17	24.43	27.59	21.94	28.96	55.27	75.70	15.28	20.03	25.36	20.47	49.01
La	30.01	46.54	47.10	52.69	46.74	31.75	44.46	110.67	9.65	22.79	32.84	24.28	119.00
Ce	59.51	84.53	89.88	105.22	88.64	63.08	95.92	221.24	19.97	47.95	70.31	51.87	233.93
Pr	6.95	9.03	10.14	12.17	9.97	7.26	11.83	25.31	2.65	5.79	8.21	5.81	27.34
Nd	26.90	31.97	37.16	45.45	37.49	28.33	47.37	93.56	11.33	23.39	32.60	23.71	102.62
Sm	4.96	5.52	6.65	8.62	7.20	5.99	10.37	17.76	2.61	4.87	6.51	5.28	18.23
Eu	1.49	1.63	2.00	2.56	2.10	1.82	2.61	2.08	0.93	1.65	2.06	1.60	5.26
Gd	4.22	4.65	5.40	6.81	5.71	5.79	10.01	14.49	2.55	4.38	5.54	4.83	13.83
Tb	0.61	0.66	0.79	0.96	0.80	0.93	1.63	2.31	0.44	0.66	0.83	0.77	1.93
Dy	3.23	3.48	4.23	5.15	4.32	5.34	9.09	12.77	2.61	3.61	4.56	4.41	9.70
Ho	0.61	0.67	0.80	0.94	0.80	1.04	1.79	2.46	0.55	0.66	0.85	0.89	1.68
Er	1.58	1.82	2.13	2.32	1.94	2.86	4.82	6.63	1.57	1.78	2.16	2.31	4.17
Yb	1.25	1.52	1.75	1.91	1.58	2.29	4.09	5.88	1.37	1.34	1.71	1.94	3.27
Lu	0.18	0.23	0.27	0.28	0.23	0.33	0.61	0.83	0.20	0.20	0.24	0.30	0.46

* : Volatile-free total (not recalculated to 100%)

Table 2

	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{147}\text{Sm}/^{144}\text{Nd}$	$(^{143}\text{Nd}/^{144}\text{Nd})_i$	$\epsilon\text{Nd}(t)$	$^{206}\text{Pb}/^{204}\text{Pb}$		$^{207}\text{Pb}/^{204}\text{Pb}$		$^{208}\text{Pb}/^{204}\text{Pb}$	
					Measured	Initial	Measured	Initial	Measured	Initial
Umar Group - Sinni Fm. - Al Qurti										
Om04-10	0.512294 ± 8	0.114	0.51212	-4.29	17.4943 ± 4	16.52	15.3298 ± 4	15.28	37.8082 ± 1.2	36.96
Om04-11	0.512282 ± 15	0.112	0.51211	-4.45	17.5206 ± 5	16.86	15.3451 ± 6	15.31	37.9099 ± 1.5	37.05
<i>Om04-11 dup.</i>	<i>0.512317 ± 8</i>		<i>0.51215</i>			<i>16.86</i>		<i>15.31</i>		<i>37.05</i>
Om04-12	0.512329 ± 8	0.113	0.51216	-3.58	18.0601 ± 5	16.86	15.3981 ± 7	15.34	37.9644 ± 1.7	37.45
Om04-13	0.512437 ± 9	0.104	0.51228	-1.21	17.7923 ± 8	16.89	15.3738 ± 8	15.33	38.4578 ± 2.4	37.04
Om04-16	0.512392 ± 34	0.108	0.51223	-2.20	17.7423 ± 6	17.08	15.3805 ± 5	15.35	38.3722 ± 1.4	37.38
Om04-17	0.512644 ± 6	0.130	0.51245	2.08						
Om04-18	0.512734 ± 8	0.138	0.51253	3.59						
Om04-19	0.512739 ± 5	0.143	0.51252	3.54						
Om04-24	0.512732 ± 8	0.128	0.51254	3.86	18.8267 ± 7	18.21	15.5678 ± 7	15.54	39.1755 ± 2.2	38.23
Om04-27	0.512651 ± 6	0.127	0.51246	2.30						
Om04-29	0.512726 ± 5	0.132	0.51253	3.61	19.0324 ± 6	17.80	15.5617 ± 5	15.50	39.2381 ± 1.5	37.63
Om04-34	0.512692 ± 8	0.115	0.51252	3.45	18.7785 ± 15	17.91	15.5614 ± 13	15.52	41.0226 ± 3.8	35.91
Om04-35	0.512679 ± 6	0.115	0.51251	3.21	18.8748 ± 7	17.69	15.5437 ± 12	15.48	39.6130 ± 1.8	37.30
Om04-37	0.512668 ± 9	0.103	0.51251	3.34	18.7146 ± 6	18.00	15.5079 ± 6	15.47	38.9815 ± 1.6	38.10
<i>Om04-37 dup.</i>	<i>0.512644 ± 8</i>		<i>0.51249</i>							
Om04-38	0.512726 ± 4	0.104	0.51257	4.44	19.0516 ± 9	17.74	15.5368 ± 7	15.47	39.2490 ± 2.9	37.71
Umar Group - Sinni Fm. - Sayjah										
Om04-40	0.512578 ± 9	0.139	0.51237	0.52	18.7916 ± 8	18.30	15.5522 ± 11	15.53	38.5080 ± 3.1	38.19
Om04-42	0.512671 ± 9	0.130	0.51247	2.59	18.9639 ± 6	18.29	15.6414 ± 7	15.61	39.0166 ± 2.5	38.42
Om04-43	0.512665 ± 9	0.131	0.51247	2.45	18.8248 ± 7	18.53	15.6553 ± 7	15.64	38.9572 ± 1.9	38.63
Umar Group - Sinni Fm. - Aqil										
Om-42	0.512705 ± 10	0.143	0.51249	2.88	19.5056 ± 38	18.83	15.5908 ± 83	15.56	40.0108 ± 8.3	39.09
Om-45	0.512737 ± 12	0.135	0.51253	3.73	19.4132 ± 5	18.82	15.6080 ± 16	15.58	39.6322 ± 1.6	38.78
Om-48	0.512621 ± 11	0.107	0.51246	2.30						
Om-49	0.512630 ± 12	0.119	0.51245	2.12	22.9014 ± 41	19.31	15.7637 ± 73	15.58	40.5965 ± 7.3	39.03
Om-52	0.512693 ± 13	0.140	0.51248	2.74	19.1322 ± 11	18.51	15.5731 ± 25	15.54	38.9681 ± 2.5	38.53
Umar Group - Sinni Fm. - Sinni										
Om-29	0.512733 ± 9	0.150	0.51251	3.23	19.6348 ± 11	18.76	15.6148 ± 33	15.57	39.6663 ± 3.3	38.74
Om-97	0.512560 ± 10	0.133	0.51236	0.34	18.4306 ± 11	17.86	15.4878 ± 38	15.46	39.0129 ± 3.5	38.09
Om-99	0.512380 ± 10	0.115	0.51221	-2.63	17.7599 ± 11	16.97	15.3899 ± 43	15.35	38.2116 ± 4.3	37.25
Om-100	0.512406 ± 10	0.111	0.51224	-2.02						
Om-101	0.512395 ± 8	0.115	0.51222	-2.33	17.6334 ± 7	16.35	15.3730 ± 22	15.31	38.2907 ± 2.2	36.45
Om-106	0.512368 ± 7	0.116	0.51219	-2.90	17.9091 ± 6	16.97	15.4220 ± 20	15.37	38.5366 ± 2	37.33
Om-107	0.512397 ± 8	0.110	0.51223	-2.15						
Kawr Group - Misfah Fm. - Jabal Misfah volcanic flows										
Om04-52	0.512740 ± 3	0.131	0.51254	3.92	18.4416 ± 16	17.73	15.5010 ± 5	15.46	38.6140 ± 0.6	37.54
Om04-55	0.512621 ± 4	0.126	0.51243	1.75	18.5782 ± 8	17.88	15.5096 ± 9	15.47	38.9022 ± 1.7	38.03
Om04-56	0.512652 ± 4	0.125	0.51246	2.40	18.3903 ± 18	17.85	15.5036 ± 5	15.48	38.7267 ± 0.6	37.51
Om04-57	0.512569 ± 2	0.121	0.51239	0.88	18.3430 ± 7	17.62	15.4823 ± 11	15.45	38.7372 ± 0.6	37.70
Om04-58	0.512609 ± 4	0.128	0.51242	1.46	18.0598 ± 9	17.42	15.4213 ± 7	15.39	38.4593 ± 2	37.55
<i>Om04-58 dup.</i>					<i>18.0597 ± 11</i>		<i>15.4220 ± 11</i>		<i>38.4589 ± 2.8</i>	
Om04-63	0.512558 ± 6	0.120	0.51238	0.67	18.1177 ± 15	17.66	15.4658 ± 5	15.44	38.4996 ± 0.6	37.56
<i>Om04-63 dup.</i>	<i>0.512568 ± 4</i>		<i>0.51239</i>		<i>18.1186 ± 16</i>		<i>15.4666 ± 5</i>		<i>38.5041 ± 0.5</i>	
Om04-66	0.512629 ± 3	0.125	0.51244	1.92						
Om-207	0.512649 ± 7	0.127	0.51246	2.26						
Om-66	0.512725 ± 12	0.114	0.51255	4.11						
Kawr Group - Misfah Fm. - Jabal Misfah intrusions										
Om-58	0.512721 ± 15	0.135	0.51252	3.44	18.1451 ± 7	17.60	15.4832 ± 17	15.46	38.3142 ± 1.7	38.03
Om-61	0.512705 ± 9	0.118	0.51253	3.63						
Om-62	0.512743 ± 10	0.116	0.51257	4.42						
Om-65	0.512696 ± 10	0.119	0.51252	3.43	18.8151 ± 6	17.63	15.4988 ± 15	15.44	39.2059 ± 1.5	38.03
Om04-61	0.512698 ± 6	0.120	0.51252	3.43	18.0065 ± 14	17.18	15.4503 ± 5	15.41	38.1773 ± 0.4	36.82
Om04-62	0.512742 ± 7	0.120	0.51256	4.27	18.0312 ± 16	16.96	15.4503 ± 6	15.40	38.1788 ± 0.7	36.56
Om05-23	0.512776 ± 3	0.107	0.51261	5.32	19.0003 ± 11	18.25	15.5746 ± 3	15.54	39.4324 ± 0.4	38.19
Om05-32	0.512678 ± 5	0.119	0.51250	3.06	19.2816 ± 16	17.23	15.5398 ± 5	15.43	40.0011 ± 0.6	36.74
Al Aridh Group - Sayfam Fm. - Jabal Buwaydah										
Om-56	0.512689 ± 10	0.134	0.51249	2.82	18.4473 ± 7	18.20	15.5283 ± 18	15.52	38.5951 ± 1.8	38.28
<i>Om-56 dup.</i>	<i>0.512703 ± 11</i>		<i>0.51250</i>							
Om-57	0.512659 ± 15	0.124	0.51247	2.54	19.7132 ± 9	17.75	15.5563 ± 20	15.46	38.4000 ± 2	37.67
Om-67	0.512597 ± 12	0.109	0.51243	1.79						
Om-69	0.512589 ± 10	0.124	0.51240	1.19	18.1816 ± 7	17.02	15.4554 ± 23	15.40	38.4655 ± 2.3	36.61
Om-75	0.512645 ± 12	0.118	0.51247	2.45						
Om-78	0.512701 ± 9	0.131	0.51250	3.15	20.4541 ± 10	17.76	15.6349 ± 38	15.50	39.3558 ± 3.8	37.69
Om-80	0.512685 ± 8	0.121	0.51250	3.14						