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Discovery of two ophiolite complexes of different ages in the Khoy area (NW Iran)

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Abstract

New field and laboratory studies on the ophiolite of Khoy (northwestern corner of Iran) lead to the discovery that there are not one, but two ophiolitic complexes in the Khoy area: (1) an *old, poly-metamorphic ophiolite*, whose oldest metamorphic amphiboles yielded a Lower Jurassic apparent ^{40}K–^{40}Ar age, and whose primary magmatic age should logically be pre-Jurassic (Upper-Triassic?); (2) a younger *non metamorphic ophiolite* of well dated Upper Cretaceous age. ***To cite this article: M. Khalatbari-Jafari et al., C. R. Geoscience 335 (2003).***

Résumé

Découverte de deux complexes ophiolitiques d'âges différents dans la région de Khoy (Iran nord-occidental). De nouvelles études cartographiques, géochimiques et géochronologiques de l'ophiolite de Khoy (Iran nord-occidental) mènent à la conclusion qu'il y a non pas un, mais deux complexes ophiolitiques dans la région de Khoy : (1) un *ancien complexe ophiolitique poly-métamorphique*, dont les plus anciennes amphiboles ont livré un âge isotopique ^{40}K–^{40}Ar Jurassique inférieur, et dont l'âge primaire (magmatique) devrait être anté-Jurassique (Trias supérieur ?) ; (2) un *complexe ophiolitique non métamorphique* plus jeune et bien daté du Crétacé supérieur. ***Pour citer cet article : M. Khalatbari-Jafari et al., C. R. Geoscience 335 (2003).***

Keywords: NW Iran (Khoy); ophiolites; metamorphism; ^{40}K–^{40}Ar ages; Palaeozoic; Mesozoic; Cainozoic

Mots-clés : Nord-Ouest de l'Iran (Khoy) ; ophiolites ; métamorphisme ; âges ^{40}K–^{40}Ar ; Paléozoïque ; Mésozoïque ; Cénozoïque

Version française abrégée

1. Introduction

Le massif ophiolitique de Khoy (Fig. 1A) se situe au nord-ouest de la ville de Khoy, dans l'Azerbaidjan iranien. Ce massif peu connu est daté du Crétacé

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supérieur sur les cartes géologiques à 1 : 250 000 et 1 : 100 000 publiées par le service géologique d'Iran [1,4,11]. Hassanipak et Ghazi [5] ont donné récemment une première description pétrographique de l'ophiolite de Khoy et des roches métamorphiques associées, et montré que ses laves ont une composition de type MORB. Leur carte géologique est malheureusement très fantaisiste, et leurs échantillons non localisés. Ghazi et al. [3] ont décrit, sous l'ophiolite, une semelle métamorphique montrant un gradient thermique inverse, dont les amphiboles ont fourni un « âge plateau » ^{40}Ar–^{39}Ar de 104 à 110 Ma. Selon ces auteurs, les métagabbros ophiolitiques ont donné des âges plateau à 154–158 Ma ; par ailleurs, les microfaunes récoltées dans les calcaires pélagiques interstratifiés entre les coulées basaltiques à *pillow lavas* ont livré des âges proches de la limite Albien–Cénomanien, soit autour de 100 Ma. Il y aurait donc plus de 50 Ma de différence d'âge entre les gabbros et les basaltes ophiolitiques, ces derniers étant un peu plus jeunes que la tectonique d'obduction (semelle métamorphique). Ces résultats, peu cohérents, sont difficilement interprétables.

Nous présentons ici les résultats de levés cartographiques détaillés et de nouvelles études de laboratoire suggérant l'existence de *deux complexes ophiolitiques d'âges différents* dans la région de Khoy, ce qui permet de résoudre ces apparentes contradictions.

2. Description géologique de la région de Khoy

Cinq grandes unités géologiques ont été reconnues dans ce travail dans la région de Khoy (Fig. 1B) ; elles sont disposées suivant des bandes cartographiques orientées NW–SE, et peuvent être décrites de la manière suivante, en allant du nord-est au sud-ouest.

2.1. Unité 1 : la marge occidentale du bloc central iranien

Cet ensemble de formations affleure au nord-est de la ville de Khoy, et appartient à la *Central Iran Zone* définie par Stöcklin [16,17]. On y retrouve une série sédimentaire paléozoïque allant, avec des lacunes, du Cambrien au Permien, surmontée par des dépôts sédimentaires d'âge Crétacé, puis par des sédiments d'âge Oligo-Miocène et Quaternaire.

2.2. Unité 2 : le complexe métamorphique oriental

Cette bande de roches métamorphiques (Fig. 1C) comprend essentiellement des amphibolites (dont les affinités géochimiques vont des MORB aux basaltes de type « supra-subduction », Fig. 2A), associées à des paragneiss, des micaschistes, des métaquartzites, des calcschistes et des marbres. Ces roches, qui ont parfois atteint les conditions de l'anatexie commençante, sont affectées par de nombreuses zones de cisaillement ductile. Elles comprennent aussi de *grandes écailles tectoniques de roches ophiolitiques métamorphisées*, essentiellement des péridotites serpentinisées (lherzolites et harzburgites foliées à textures porphyroclastiques mantelliques), et des ortho-amphibolites (métagabbros intrusifs).

2.3. Unité 3 : le complexe volcano-sédimentaire à turbidites du Crétacé supérieur

En contact tectonique avec l'unité précédente, cet ensemble repose en transgression sur les laves de l'ophiolite de Khoy s.s., situées au sud-ouest, et comprend (Fig. 1E) des sédiments flyschoïdes rythmiques riches en fragments de laves et des coulées de laves basaltiques, andésitiques et ankaramitiques, associées à des niveaux sédimentaires calcaires à *Globotruncana*, datés du Crétacé supérieur au Paléocène inférieur.

2.4. Unité 4 : l'ophiolite non métamorphique de Khoy s.s., d'âge Crétacé supérieur

Ce puissant complexe ophiolitique (Fig. 1D) se compose d'une séquence mantellique lherzolitique serpentinisée, de petits corps intrusifs de gabbros lités dans les péridotites, le tout surmonté par une épaisse séquence de laves basaltiques sous-marines, essentiellement sous forme de *pillow lavas* accompagnés de coulées massives, restes de lacs fossiles, sills et dykes basaltiques, brèches hyaloclastiques et abondantes brèches épiclastiques de démantèlement. Les *pillows* sommitaux sont associés à des niveaux de calcaires pélagiques à *Globotruncana* du Crétacé supérieur. Aucune trace d'un complexe filonien de diabases n'a pu être observé. Les basaltes ont des affinités géochimiques de type T-MORB, et sont recoupés par des dykes isolés de diabases de nature calco-alcaline « supra-subduction » (Fig. 2B).

2.5. Unité 5 : le complexe métamorphique occidental

Il s'agit d'une série de roches épimétamorphiques, d'âge et d'appartenance inconnus, qui affleurent au sud-ouest de la zone cartographiée. Elles sont rétrocharriées sur des calcaires et conglomérats d'âge Paléocène, eux-mêmes charriés sur la bordure méridionale de l'unité des péridotites ophiolitiques.

3. Datations paléontologiques

Les calcaires pélagiques interstratifiés avec les laves basaltiques sous-marines des unités 3 et 4 décrites ci-dessus ont livré des microfaunes caractéristiques dans 54 localités différentes, essentiellement des associations à *Globotruncana* du Crétacé supérieur.

Les calcaires liés aux *pillow lavas* ophiolitiques (unité 4) ont livré des microfaunes d'âge Turonien à Campanien (92 à 72 Ma). Les calcaires liés aux turbidites supra-ophiolitiques (unité 3) ont livré des microfaunes d'âge Santonien (87 à 83 Ma), et ces mêmes turbidites remanient des fragments de calcaires pélagiques dont les microfaunes sont d'âge Santonien à Campanien. Les calcaires roses associés aux *pillow lavas* supra-ophiolitiques ont des microfaunes d'âge Campanien à Maastrichtien (83 à 65 Ma). Enfin, le membre volcano-sédimentaire coiffant la série supra-ophiolitique comporte des calcaires pélagiques et des radiolarites contenant des microfaunes d'âge Maastrichtien à Paléocène inférieur (72 à 59 Ma).

4. Nouvelles datations par la méthode ^{40}K–^{40}Ar

24 échantillons, localisés sur la Fig. 1C et D, ont été sélectionnés et datés par la méthode ^{40}K–^{40}Ar (Tableau 1) sur minéraux séparés (amphiboles, muscovites, biotites et plagioclases). Ces datations concernent, d'une part, le complexe métamorphique oriental et ses écailles méta-ophiolitiques associées (Fig. 1C), d'autre part les roches plutoniques de l'ophiolite de Khoy non métamorphique (Fig. 1D).

Les nombreux résultats sur le complexe métamorphique oriental montrent un large étalement des âges apparents obtenus sur lots de minéraux séparés et suggèrent une *longue histoire métamorphique polyphasée*, marquée par quatre périodes majeures. (1) *Jurassique inférieur* (197–181 Ma) : les âges apparents les plus anciens ont été trouvés à la fois dans les métagabbros ophiolitiques et dans les amphibolites à grains fins de la sous-unité m1 (Fig. 1C). Les pegmatites à quartz-muscovite recoupant ces amphibolites ont un âge apparent de $181 \pm 4{,}2$ Ma. L'âge magmatique primaire des métagabbros ophiolitiques devrait donc être antérieur à ce métamorphisme (Trias supérieur ?). (2) *Jurassique moyen* (160–155 Ma) : ces âges ont été trouvés également dans les métagabbros ophiolitiques et dans les micaschistes à deux micas. (3) *Crétacé inférieur* (121–112 Ma) : on trouve ces âges essentiellement dans des zones de cisaillement ductile affectant les roches métamorphiques, et les métagabbros ophiolitiques. (4) *Crétacé supérieur* (93 à 69 Ma) : ces âges sont montrés surtout par les micaschistes et les intrusions granitiques à pegmatitiques qui les recoupent et un gabbro à amphibole faiblement métamorphique (à $82{,}4 \pm 4{,}6$ Ma).

Deux datations effectuées sur les plagioclases des gabbros lités de l'ophiolite non métamorphique de Khoy ont confirmé leur âge Crétacé supérieur (100 à 72 Ma), âge cohérent avec celui des *pillow lavas* susjacents (Turonien à Campanien, soit 92 à 72 Ma). Une diabase porphyrique, recoupant ces gabbros, a donné un âge apparent de 65 Ma.

5. Conclusions

Ces nouvelles données nous permettent de conclure sur trois points.

(1) Il y a de toute évidence *deux complexes ophiolitiques d'âges différents* dans la région de Khoy.
(2) Le complexe métamorphique oriental, dont l'âge du métamorphisme va du Jurassique inférieur au Crétacé supérieur, n'est pas une semelle métamorphique infra-ophiolitique, comme l'ont suggéré Hassanipak et Ghazi [5], mais représente très vraisemblablement un *complexe métamorphique de subduction*, affectant essentiellement une lithosphère océanique néo-téthysienne, subductée sous l'Iran central pendant tout le Mésozoïque [13], et les sédiments associés.
(3) L'ophiolite non métamorphique de Khoy, d'âge Crétacé supérieur, présente toutes les caractéristiques d'une *dorsale océanique « lente »*, de type dorsale médio-Atlantique (manteau résiduel lherzolitique indiquant un faible taux de fusion partielle, plutons gabbroïques intrusifs dans le

manteau supérieur, absence de complexe filonien de diabases, laves très porphyriques) [6].

1. Introduction

The ophiolite of Khoy is located in the northwestern corner of the Iranian Azerbaijan province, extending till the Turkish border (Fig. 1A). The geology of the Khoy area is still poorly known, and there are very few reports about its geological features. After a very general description by Khamineni and Mortimer [7], this area was mapped at various scales by the Geological Survey of Iran (GSI): the sheet of Khoy at 1:250 000 was published first [4], followed by two sheets at 1:100 000 scale, the sheet of Khoy [11], and the adjacent sheet of Dizaj [1], with many useful geological information. On these sheets, the GSI geologists identified clearly *a complete ophiolite complex of Upper Cretaceous age*, including serpentinites and peridotites, gabbros, diabases and basaltic pillow lavas.

More recently, Hassanipak and Ghazi [5] gave a first dataset on the petrology and geochemistry of the Khoy ophiolite. In this paper, the authors distinguished, in the ophiolitic volcanic sequence, a lower pillow basalt unit, displaying REE patterns intermediary between E-MORB and N-MORB profiles, and an upper massive basalt unit with E-MORB-type REE patterns. According to them, the REE patterns for the gabbros and diorites indicate that the crustal rock suite was derived by fractional crystallization from a common basaltic melt, generated by 20–25% partial melting of a simple lherzolite source. In their conclusion, the authors suggest that the "Khoy ophiolite is equivalent to the inner group of Iranian ophiolites (e.g., Nain, Shahr-Babak, Sabzevar, Tchehel Kureh and Band e Zyarat, Fig. 1A), and was formed as a result of closure of the northwestern branch of a narrow Mesozoic seaway which once surrounded the Central Iranian microcontinent". Unfortunately, their description of the geology of the Khoy area is extremely schematic and often erroneous, and the analysed samples are not located.

Ghazi et al. [3] proposed the existence beneath the ophiolite of a basal metamorphic zone, displaying an inverse thermal gradient, ranging from amphibolite to the greenschist facies. Based on ^{40}Ar–^{39}Ar dating, these authors present two ^{40}Ar–^{39}Ar plateau ages of 158.6 ± 1.4 Ma and 154.9 ± 1.0 Ma for hornblende gabbros, and conclude that the plutonic rocks of the Khoy ophiolite were formed during Late Jurassic. They present also four ^{40}Ar–^{39}Ar plateau ages of about 104 to 110 Ma for hornblendes from amphibolites within the basal metamorphic zone, concluding to a tectonic emplacement of Mid-Albian age for the ophiolite complex. As the pelagic limestones interbedded with the ophiolitic pillow lavas give microfaunas of somewhat younger ages (Upper Albian to Lower Cenomanian, around 100 Ma), the authors have some difficulties to explain how the plutonic gabbros and the volcanic pillow lavas in the same ophiolite complex show a difference in age of more than 50 Ma, and how the pillow lavas can be younger than the metamorphic sole, supposed to mark the beginning of the detachment and obduction process.

We present here the results of new field and laboratory studies, leading to the distinction of *two ophiolitic complexes in the Khoy area*, which resolves many apparent contradictions.

2. Geological description of the Khoy area

The Khoy area exposes five main geological units, grossly forming NW–SE stripes (Fig. 1B). From northeast to southwest: (1) the southern continental margin of the Central Iranian Block; (2) the eastern metamorphic unit, including an old meta-ophiolitic complex; (3) the supra-ophiolitic turbiditic and volcanic-sedimentary zone; (4) the non-metamorphic Upper Cretaceous Khoy ophiolite; (5) the western metamorphic unit.

2.1. The southern continental margin

The southern continental margin of the Central Iranian Block is exposed to the NNE of Khoy, with basal Precambrian to Cambrian formations, overlain in disconformity by Permian sediments. These Palaeozoic formations are overlain tectonically by Jurassic and Lower Cretaceous sediments, and finally by Miocene to Pliocene–Quaternary deposits. These formations belong to the Central Iran Zone units, as defined by Stöcklin [16,17].

2.2. The eastern metamorphic unit

The eastern metamorphic unit contains four main sub-units (labelled m1, m2, m3 and m4). Sub-unit m1 consists of micaschists, amphibolites (with typical supra-subduction trace element patterns, Fig. 2A) and gneisses, crosscut by quartz-muscovite veins at the base (Fig. 1C). Gneisses containing rotated quartz and feldspar megacrysts are more and more abundant going up in the section.

Sub-unit m2 consists of fine-grained amphibolites (showing MORB-like trace element patterns, Fig. 2A), greenschists, metavolcanics, locally interbedded with metaquartzites and leptynitic gneisses. It shows tight isoclinal folds, corresponding to three successive deformations marked by foliations S1, S2, and locally S3. This sub-unit includes *huge tectonic slices of meta-ophiolitic plutonic rocks*, composed of well-foliated lherzolitic and harzburgitic tectonites, as well as associated ultramafic meta-cumulates. These ultramafic rocks are crosscut by abundant sills and dikes of meta-gabbros (amphibolites), whose flat REE patterns suggest a MORB-like oceanic origin (Fig. 2A).

Both sub-unit m3 (greenschists, metavolcanic schists, meta-ankaramites), and sub-unit m4 (greenschists), show low-grade metamorphism and were tectonically emplaced with the other sub-units (Fig. 1C).

The m2 sub-unit is intruded by the gneissic-granitic intrusion of Qorol-Ajai, and its related quartz–feldspar–muscovite-bearing dikes and veins, which crosscut both the m2 sub-unit and the gneisses of the m1 sub-unit.

2.3. The supra-ophiolitic turbiditic and volcanic-sedimentary unit

The supra-ophiolitic turbiditic and volcanic-sedimentary unit is exposed along a wide strip developed to the southwest of the eastern metamorphic complex, with systematic tectonic contacts (Fig. 1E). The meta-ophiolite is thrust over this unit in the north of the studied area. This unit includes turbidites at the base, with coarse-grained breccias lenses containing reworked limestone pebbles, and also angular to rounded basaltic fragments of various origins. Some of these show flat REE patterns, whereas others show enrichment in light REE, with a negative anomaly of Nb typical of supra-subduction lavas. Higher in the sequence, volcanic breccias and pillow basalts show also flat REE patterns, with sometimes a weak Nb negative anomaly (Fig. 2B).

2.4. The non-metamorphic ophiolite complex of Khoy

The non-metamorphic ophiolite complex of Khoy is composed of sepentinized peridotites, layered gabbros, isolated diabasic dikes, and a huge volcanic pile made of alternatively phyric and aphyric pillow basalts, massive sheet flows and interbedded hyaloclastic breccias and tuffs (Fig. 1D). Huge epiclastic slope breccias with abundant carbonate matrix are developed on top of this volcanic pile. Diabase sills and dikes, and some picrite/wehrlite dikes crosscut the volcanics. The REE patterns of the pillow basalts and picrites are flat, without any visible negative Nb or Ti anomalies, and show a slightly positive slope toward LREE (Fig. 2B). These basalts are typical E-MORB type basalts, as already recognized by Hassanipak and Ghazi [5]. On the other hand, isolated diabase dikes are well differentiated and show clear Nb and Ti negative anomalies, analogous to those observed in pillow basalt reworked fragments from the volcanic-sedimentary unit.

We did not find any trace of a diabase sheeted dike complex, contrarily to previous descriptions [5], and we did not observe the effects of any regional metamorphism, except those due to early oceanic hydrothermal circulations. We refute the idea of a ‘massive lava unit’ lying over a ‘pillow lava unit’, as claimed by these authors [5], but found that the massive basaltic flows (less than 10% of the whole extrusive sequence) are interbedded within the pillow lava pile at all levels, as is usual on modern oceanic ridges [6].

2.5. The western metamorphic unit

The western metamorphic unit consists of low-grade metamorphic rocks (greenschists), whose age and origin are presently not known. They are thrust back over limestones and conglomerates of Palaeocene age, themselves thrust over the southern margin of the Upper Cretaceous ophiolitic unit.

This western metamorphic unit may represent an eastern extension of the Pütürge–Bitlis metamorphic zone of eastern Turkey [9,14], but this remains very speculative.

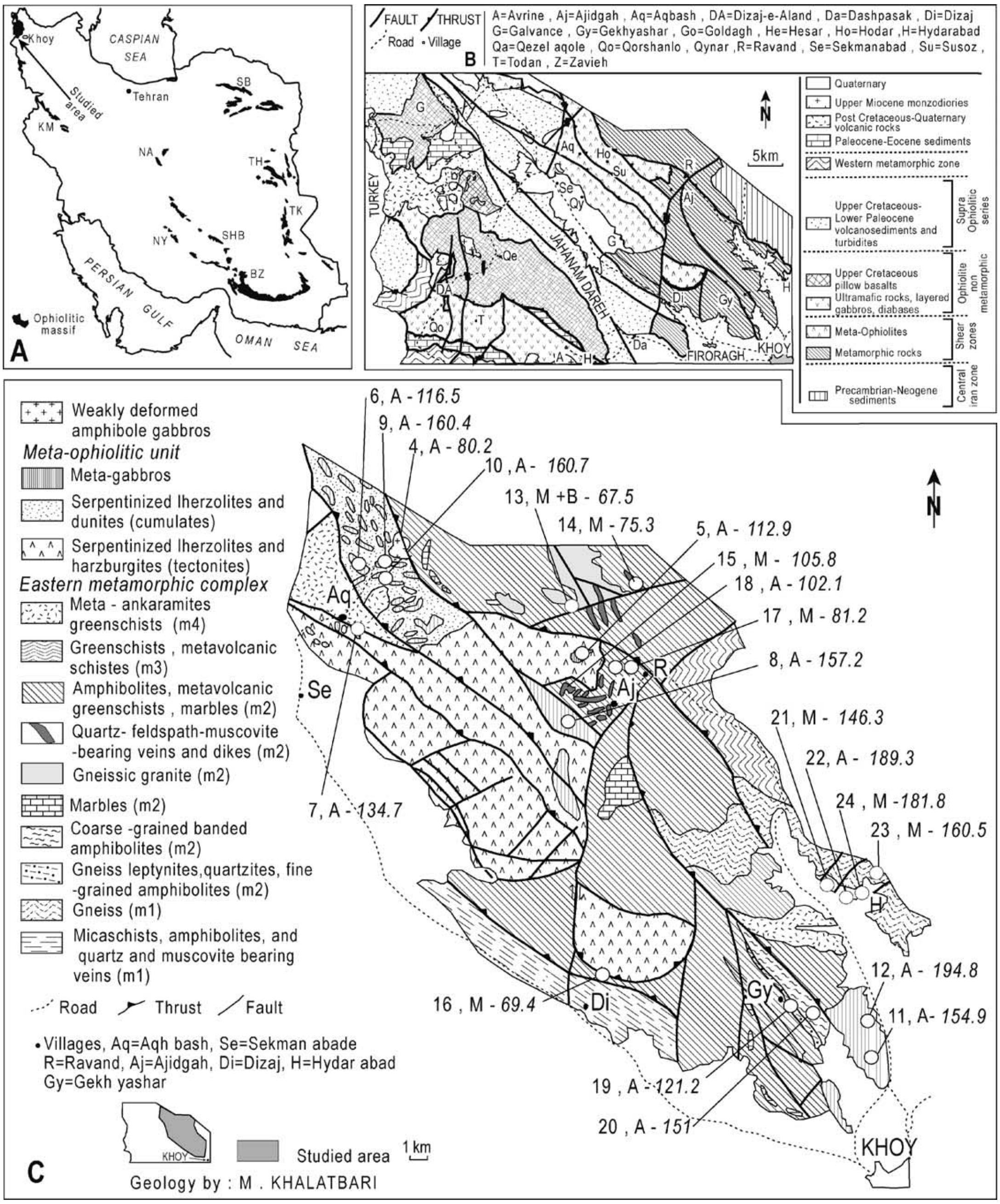

Fig. 1. Geological maps and sampling sites of the Khoy area. (**A**) Distribution of the ophiolite belts in Iran after Emami et al. [2], and location of the Khoy area. Main Iranian ophiolite complexes: **BZ**, Band e Ziyarat; **KM**, Kermanshah; **NA**, Nain; **NY**, Neyriz; **SB**, Sabzevar; **SHB**, Shar Babrak; **THL**, Torbat Hydariyah; **TK**: Tchehel Kureh. (**B**) Schematic map of the main geological units of the Khoy area described in the text. (**C**) Geological map of the eastern metamorphic complex and associated meta-ophiolites (Unit 2 in the text), and location of samples dated by $^{40}K/^{40}Ar$ method. The first number refers to Table 1; letters **M**, **B** and **A** refer to muscovite, biotite and amphibole, respectively (mineral separates used for dating), and the last number gives the apparent age obtained (Ma). (**D**) Geological map of the non-metamorphic, Upper Cretaceous ophiolite of Khoy (Unit 4 in the text) and related formations, with location of the gabbro samples dated by $^{40}K/^{40}Ar$ method (Table 1). (**E**) Geological map of the supra-ophiolitic turbidites and volcanic-sedimentary unit (Unit 3 in the text), and related formations.

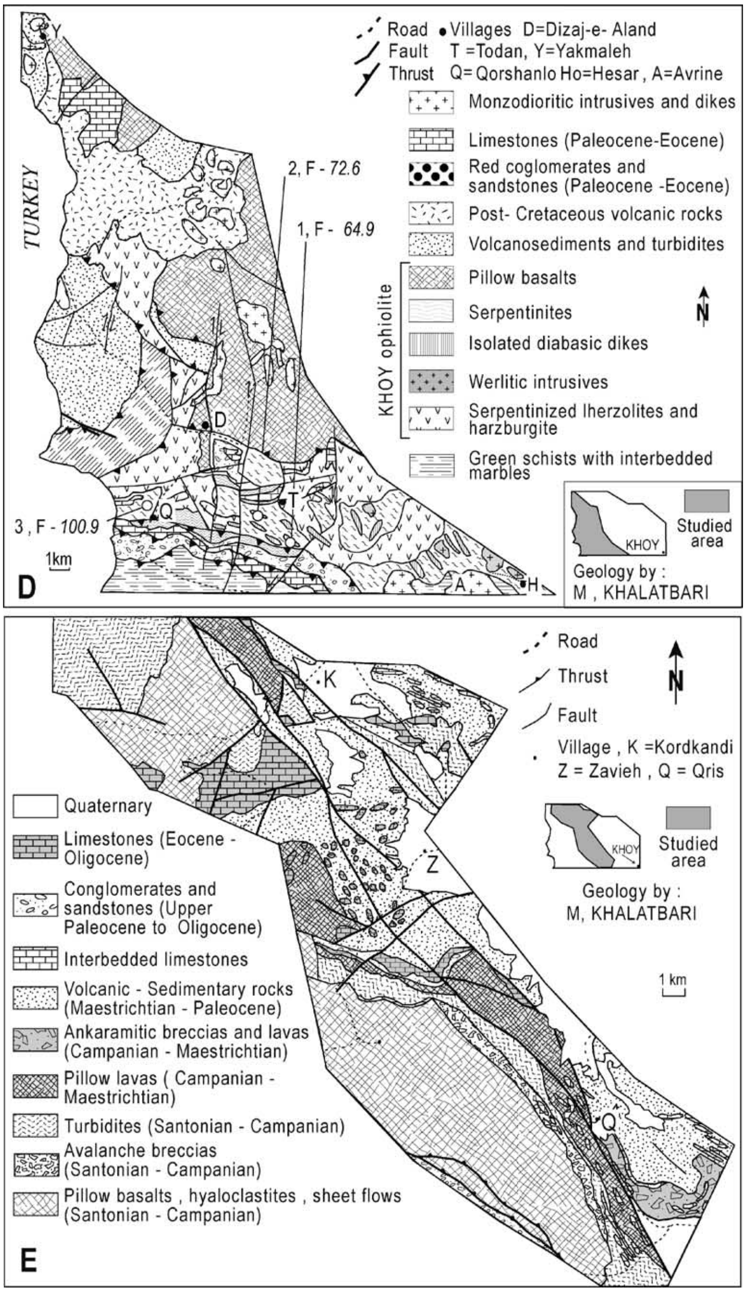

Fig. 1. Cartes géologiques et de l'échantillonnage du secteur de Khoy. (**A**) Localisation des ceintures ophiolitiques d'Iran et du secteur d'étude, d'après [2]. Principaux complexes ophiolitiques iraniens : **BZ**, Band e Ziyarat ; **KM**, Kermanshah ; **NA**, Nain ; **NY**, Neyriz ; **SB**, Sabzevar ; **SHB**, Shar Babrak ; **THL**, Torbat Hydariyah ; **TK**, Tchehel Kureh. (**B**) Carte schématique des unités géologiques principales, décrites dans le texte, du secteur de Khoy. (**C**) Carte géologique du complexe métamorphique oriental et des méta-ophiolites associées (unité 2 du texte) et localisation des échantillons datés par la méthode $^{40}K/^{40}Ar$. Le premier numéro renvoie au Tableau 1 (première colonne) ; les lettres **M**, **B** et **A** symbolisent la phase séparée et datée, respectivement la muscovite, la biotite et l'amphibole, enfin le dernier nombre représente l'âge isotopique, en Ma. (**D**) Carte géologique de l'ophiolite de Khoy non métamorphique (unité 4 du texte) et des formations voisines. (**E**) Carte géologique de l'unité comportant des turbidites supra-ophiolitiques et des formations volcano-sédimentaires (unité 3 du texte), ainsi que des formations voisines.

3. Palaeontological dating

The sediments interbedded with the submarine lavas in several non-metamorphic units described here contain by places abundant microfauna. These microfossils, collected in 54 different localities by one of us (MKJ), were determined by the Palaeontological Group of the GSI, and permitted the dating of their host-sediments. The units concerned by such palaeontological dating are detailed in Fig. 1 D and E. Hereafter is the list of the diagnostic microfossils found in these units, with the corresponding inferred ages.

3.1. Ophiolitic pillow basalt sequence

The thin limestone beds and lenses between the pillow basalts gave abundant microfauna of Turonian–Santonian–Campanian age: *Globotruncana lapparenti tricarinata, Globotruncana lapparenti lapparenti, Globotruncana renzi, Globotruncana concarata, Globotruncana arca, Globotruncana gansseri, Globotruncana falsostuarti, Globotruncana lapparenti, Globotruncana ventricosa, Globotruncana conica, Globotruncana helvetica, Globotruncana fornicata, Globotruncana* sp., *Heterohelix* sp., Radiolarians. These data confirm the Upper Cretaceous age of the pillow lava pile.

3.2. The supra-ophiolitic avalanche debris and slope breccias unit

The supra-ophiolitic avalanche debris and slope breccias unit includes pelagic limestones in the matrix of the breccias, which contain *Globotruncana* sp. and Radiolarians of Upper Cretaceous age.

3.3. The supra-ophiolitic turbiditic unit

The supra-ophiolitic turbiditic unit contains reworked and autochthonous limestones. The reworked limestones contain microfauna of *Santonian–Campanian* age (and even Campanian–Maastrichtian in one sample), with the following fossils: *Globotruncana lapparenti tricarinata, Globotruncana lapparenti lapparenti, Globotruncana arca, Globotruncana lapparenti, Globotruncana bulloides, Globotruncana gansseri, Globotruncana confusca, Globotruncana stratiformis, Hedbergella* sp., *Heterohelix* sp., Radiolarians. The autochthonous and grey limestone beds in the turbidites, however, contain faunas of Santonian age with the following fossils: *Globotruncana* sp., *Heterohelix* sp., *Heterohelix reossi.*

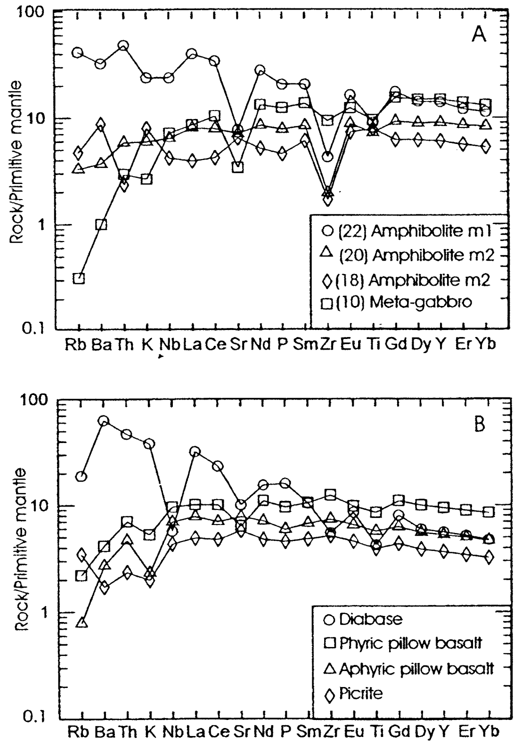

Fig. 2. New trace element patterns, normalized to primitive mantle compositions [18], obtained on whole rock samples by ICP/AES (Analyst: J. Cotten, UBO). (**A**) Selected patterns from the eastern metamorphic complex, showing both MORB-like and supra-subduction patterns (Unit 2). (**B**) Selected patterns from the non-metamorphic Upper Cretaceous ophiolitic lavas showing MORB-like patterns, and one intrusive diabase dike, with typical supra-subduction characteristics (Nb, Zr and Ti negative anomalies).

Fig. 2. Nouveaux spectres multi-élémentaires normalisés au manteau primitif [18] de roches analysées par ICP/AES (J. Cotten, analyste, UBO) provenant (**A**) du complexe métamorphique oriental (unité 2 dans le texte) et (**B**) de l'ophiolite non métamorphique du Crétacé supérieur montrant un profil de MORB et celui d'un dyke de diabase présentant les anomalies négatives en Nb, Zr et Ti caractéristiques des laves des domaines supra-subduction.

3.4. Supra-ophiolitic pillow basalt unit

This unit contains some interbedded cherts, radiolarites and pink limestones with the following microfaunas, supposed to be of *Campanian–Maastrichtian* age: *Globotruncana calcarata, Globotruncana* aff. *falsostuarti, Globotruncana* sp., *Hedbergella* sp., *Lenticulina,* Radiolarians.

3.5. Supra-ophiolitic volcanic-sedimentary sequence

This upper member of the supra-ophiolite formations contains some pinkish limestones and radiolarites with microfauna of *Upper Cretaceous–Lower Palaeocene* age, specially in the pinkish limestones, in particular: *Globotruncana* cf. *stuarti, Globotruncana catarata, Globotruncana stuartiformis, Globotruncana arca, Globigerina* sp., *Heterohelix* sp., *Cibicides* sp., *Lagena* sp., *Rotalia* sp., Miliolids, Radiolarians.

There are also well exposed Upper Palaeocene to Oligocene limestones, resting tectonically over the ophiolitic pillow basalts, and also as many tectonic 'exotic' blocks over the supra-ophiolitic volcanic-sedimentary unit. The following microfauna were found in the southern part of the Khoy area: *Assilina* sp., *Discocyclina* sp., *Operculina* sp., *Flosculina patticilat., Alveolina* sp., *Alveolina (Floculina)* sp., *Opertorbitolites* sp., and other microfouna found in the northern area: *Volvulina* sp., *Cympolia cf. hetrachi, Broechella* sp., *Rotalia viennotti* sp., *Heterostegina* sp.,*Operculina* sp., *Asterigerina* sp., *Rotalia* sp., *Amphistegina* sp., *Victoriella* sp., *Peneroplis* sp., Miliolids, Bryozoans, *Subterranophyllum thomas., Lithothamnium* sp.

4. New isotopic ^{40}K/^{40}Ar ages and interpretations

Twenty-four rock samples were selected from different geological units, and mineral separates of amphiboles, muscovites, biotites, and feldspars were dated by ^{40}K/^{40}Ar method (Table 1). Ages are calculated using the recommended constants in [15], and errors are quoted after [8].

4.1. ^{40}K/^{40}Ar dating of the eastern metamorphic unit and its associated meta-ophiolite complex

As shown in Table 1, the separated amphiboles, biotites and muscovites in this unit display a wide range of apparent ages, suggesting a *long polyphased metamorphic history*. We propose to distinguish four groups of chronological events. These ages are interpreted as reflecting the time when the different minerals passed below their respective isotopic temperature closures [19].

4.1.1. Lower Jurassic group (197–181 Ma)

The oldest isotopic ages are found in two rock types: (a) amphibole-rich pegmatitic metagabbros from the meta-ophiolite association (Fig. 1B and C). In these metagabbros, showing spectacular ductile deformations, there are locally (site 12, Fig. 1C) small blocks of weakly deformed gabbros with Lower Jurassic apparent ages (197.3 $\pm$ 10.1 to 192.3 $\pm$ 2.9 Ma). These ages suggest that the primary cooling age of these gabbros was somewhat older, perhaps Upper Triassic. (b) Fine-grained amphibolites exposed in the base of the (m1) metamorphic group, with a range between 196.3 $\pm$ 10.7 and 182.3 $\pm$ 4.3 Ma. The quartz–muscovite pegmatite veins crosscutting these amphibolites have an apparent age of 181.8 $\pm$ 4.2 Ma.

4.1.2. Middle Jurassic group (160–155 Ma)

The second group of isotopic ages is found in the following metamorphic facies.

(a) For amphiboles of metagabbros and ortho-amphibolites from the meta-ophiolitic complex, at 160.8 $\pm$ 12.7 and 160.7 $\pm$ 12.9 Ma (north of Aghbash village), and at 155.6 $\pm$ 11.9 Ma (east of Ajidgah village). Under microscope, they show amphiboles that replaced the frame of pyroxenes; there are also abundant recrystallized plagioclases with abundant triple junctions, indicating ductile deformations in shear fault zones [10].
(b) In the (m1) metamorphic group, the muscovites of the gneisses of Hydarabad village (160.5 $\pm$ 3.7 Ma) and the amphiboles from the amphibolites of Gheh Yashar village (151.0 $\pm$ 11.5 Ma). Also, well-crystallized micaschists gave both muscovites and biotites with an apparent age of 146.3 $\pm$ 3.4 Ma. They are exposed with the fine-grained amphibolites [1]. Under microscope, the gneisses of Hydarabad show rotated feldspar porphyroclasts and twinned coarse grained quartz crystals with mortar textures, embedded by the foliation. These macroscopic and microscopic features indicate an older metamorphic event, eventually older than Middle Jurassic.

Table 1
New $^{40}K/^{40}Ar$ dating on mineral separates from lavas and metamorphic rocks in Khoy area. Numbers (1 to 24) in column 1 refer to sampling locations indicated in Fig. 1 C, D and E

Tableau 1
Nouvelles données $^{40}K/^{40}Ar$ sur minéraux séparés à partir des laves et des roches métamorphiques du secteur de Khoy. Les numéros 1 à 24 de la colonne 1 renvoient à la localisation des échantillons datés dans la Fig. 1 C, D et E

Figure	Sample	Location	Rock type	Dated fraction	Average age	Age ± error (Ma)	K_2O (wt%)	$^{40}Ar_R$ (10^{-7} cm^3 g^{-1})	$^{40}Ar_R$ (%)	Analysis number
			Upper Cretaceous non metamorphic ophiolite							
1	00-3KH56	S. Todan	Porphyric diabase dike in gabbro	Plagioclase		64.9 ± 3.8	0.13	2.77	35.0	5881
2	00-3KH190	S. Todan	Isotropic gabbro	Plagioclase		72.6 ± 5.0	0.046	1.10	19.5	5891
3	01-2KH211	Qorshanlo	Plagioclase vein in gabbro	Plagioclase		100.7 ± 6.0	0.25	8.34	31.6	5890
			Meta-ophiolitic unit within the Eastern metamorphic complex							
4	99-KH92	North Aghbash	Weakly deformed gabbro	Amphibole	80.2 ± 4.6	82.4 ± 4.6	0.106	2.88	42.5	5894
						77.9 ± 4.6	0.106	2.72	31.1	6000
5	99-KH242	West Ravand	Metagabbro	Amphibole		112.9 ± 8.6	0.175	6.57	69.2	5632
6	99-KH134	North Aghbash	Metagabbro	Amphibole		116.5 ± 6.0	0.215	8.34	67.2	5664
7	00-3-KH14	South Aghbash	Metagabbro	Brown amphibole		134.7 ± 7.1	0.245	11.05	53.0	5665
8	00-3-KH9	East Ajidgah	Metagabbro	Amphibole		155.6 ± 11.9	0.165	8.64	69.8	5630
9	99-KH102	North Aghbash	Metagabbro	Amphibole	160.4 ± 12.7	160.8 ± 12.7	0.052	2.82	40.4	5631
						160.0 ± 12.4	0.052	2.81	47.4	5655
10	99-KH145	N. Aghbash	Metagabbro	Amphibole		160.7 ± 12.9	0.057	3.09	35.9	5633
11	99-KH359a	North Khoy	Amphibole pegmatitic gabbro	Amphibole		154.9 ± 11.8	0.17	8.86	66.9	5676
12	99-KH291b	North Khoy	Amphibole pegmatitic gabbro	Amphibole	194.8 ± 10.1	192.3 ± 2.9	0.492	32.2	91.0	5646
						197.3 ± 10.1	0.492	33.1	90.8	5656
			Eastern metamorphic complex							
13	00-4KH78	Qorol-Ajai	Gneissic granite	Muscovite and biotite		67.5 ± 1.6	7.06	156.6	76.8	5990
14	00-4KH69	Qorol-Ajai	Gneissic dike	Muscovite		75.3 ± 1.8	10.37	257.0	73.9	5874
15	99-KH357	Ajidgah	Quartz, feldspar, muscovite vein	Muscovite		93.5 ± 1.5	8.9	275.3	78.4	5303
16	99-KH314	North Dizaj	Micaschist	Muscovite		69.4 ± 1.6	6.56	149.6	82.6	5991
17	00-3KH7	Ajidgah	Micaschist	Muscovite		81.2 ± 1.2	7.07	189.2	92.5	5644
18	99-KH-358	Ajidgah	Amphibolite	Amphibole	102.1 ± 5.4	102.3 ± 5.3	0.27	9.16	71.8	5645
						103.9 ± 5.4	0.27	9.31	67.5	5675
						100.1 ± 5.4	0.27	8.96	49.2	5323
19	99-KH353	Ghekh yashar	Fine-grained amphibolite	Amphibole		121.2 ± 6.2	0.46	18.6	75.5	5648
20	99-KH191	Ghekh yashar	Amphibolite	Amphibole		151.0 ± 11.5	0.195	9.90	63.5	5663
21	00-4KH71	Hydarabade	Micaschist	Muscovite and biotite		146.3 ± 3.4	8.03	394.4	93.7	5892
22	01-4KH81	Hydarabade	Fine-grained amphibolite	Amphibole	189.3 ± 10.7	182.3 ± 4.3	0.48	29.7	74.8	5982
						196.3 ± 10.7	0.48	32.1	75.7	5998
23	01-4KH76	Hydarabade	Gneiss	Muscovite		160.5 ± 3.7	8.7	470.7	84.6	5981
24	01-4KH97	Hydarabade	Quartz and muscovite vein	Muscovite		181.8 ± 4.2	9.78	603.2	93.3	5865

4.1.3. Lower Cretaceous group

The third group of isotopic ages was found in the metamorphic complex (m1, m2) and in the meta-ophiolitic gabbros. They include: (a) two ages of amphiboles at 121.2 ± 6.2 Ma from the fine-grained and recrystallized amphibolites (north Ghekh Yashar village), and 102.1 ± 5.4 Ma from the amphibolites of Ajidgah village; (b) two ages obtained from the amphiboles of meta-ophiolitic gabbros, at 116.5 ± 6.0 Ma (north Ajidgah) and 112.9 ± 8.6 Ma (west Ravand). This metamorphism of Lower Cretaceous age is associated with thick ductile shear zones oriented NW–SE to north–south, affecting both the metamorphic complex and the meta-ophiolites, with evidences of incipient partial melting.

4.1.4. Upper Cretaceous group

The muscovites of the micaschists from Ajidgah gave an age of 81.2 ± 1.2 Ma. The pure muscovites separated from micaschists north of Dizaj give an age of 69.4 ± 1.6 Ma (Maastrichtian), which can be related to tectonic events that caused the S3 deformation appearing locally in the metamorphic complex. In the vicinity of Qorol-Ajai village, a gneissic granite intrusion crosscuts the metamorphic rocks, extending to the north, out of the studied area. Many quartz-feldspar-bearing dikes and veins, probably related to this granite, crosscut the metamorphic rocks. The separated pegmatitic muscovites from granitic veins from Ajidgah give an age of 93.5 ± 1.5 Ma, coarse-grained muscovites of other granitic dikes in the vicinity of Qorol-Ajai give an age of 75.3 ± 1.8 Ma, and the separated muscovites and biotites from the Qorol-Ajai granite–gneiss yield an age of 67.5 ± 1.6 Ma.

Finally, the separated fine-grained amphiboles from a weakly deformed gabbro in the meta-ophiolites gave a Late Cretaceous age of 80.2 ± 4.6 Ma (average of two measurements, Table 1).

4.2. $^{40}K/^{40}Ar$ dating of the non-metamorphic ophiolite of Khoy

The non-metamorphic ophiolite of Khoy is much more difficult to date by the K/Ar method, because of the absence of amphiboles and the very low primary potassium contents of the separated plagioclases. Two isotopic ages were obtained on plagioclases from the layered gabbros (location in Fig. 1D). The first one is at 100.7 ± 6.0 Ma, from the feldspars of plagioclase-rich veins in the layered gabbros close to Qorshanlo village. These veins formed parallel to the magmatic layering, or cutting it at low angle. This value may indicate the probable cooling age of the layered gabbros. The second value obtained is 72.6 ± 5.0 Ma from an isotropic gabbro vein, south of Todan village, crosscutting the layered gabbros. These isotopic ages are compatible with the palaeontological data obtained on the ophiolitic pillow basalts (Campanian to Santonian, that is, 92 to 72 Ma). A third isotopic age close to the Upper Cretaceous–Lower Palaeocene boundary, at 64.9 ± 3.8 Ma, was obtained from the plagioclase phenocrysts of a porphyritic diabasic dike crosscutting the gabbros.

5. Discussion and conclusions

The new data presented in this paper concerning the ophiolites of the Khoy area may be discussed through the following points:

5.1. There are not one, but two ophiolite complexes outcropping in the Khoy area

Several contradictions, particularly in the ^{40}K–^{40}Ar dating compared to the palaeontological dating, disappear if we consider that there are two distinct ophiolite complexes in the Khoy area:

5.1.1. An older meta-ophiolitic complex

The *oldest ophiolites* form huge tectonic slices within the eastern metamorphic complex. They are themselves totally recrystallized in the amphibolite facies, and their oldest metamorphic amphiboles give ^{40}K–^{40}Ar apparent ages ranging from Lower to Middle Jurassic (from about 197 Ma to about 160 Ma).

Ghazi et al. [3] obtained two ^{40}Ar–^{39}Ar plateau ages on the amphiboles of two metagabbros belonging obviously to this complex, with apparent ages of 158.6 ± 1.4 and 154.9 ± 1.0 Ma, respectively. They deduced erroneously that “rocks from this ophiolite were formed during the Late Jurassic”. Clearly these ages are dating a *metamorphic event*, not a magmatic accretion stage. Besides, our data show that there is not one metamorphic event, but at least four metamorphic episodes: Lower Jurassic, Middle Jurassic, Lower Cretaceous and Upper Cretaceous, respectively. The first three episodes affect both the meta-ophiolites and their metamorphic host-rocks, suggesting a common metamorphic history. The youngest episode (Upper Cretaceous) affects mainly weakly metamorphosed granitic and gabbroic plutons and dykes, intrusive in the metamorphic series. We suggest therefore that the eastern metamorphic complex consists of several slab fragments of various Mesozoic ages, piled up and tectonically stacked in a subduction accretion complex, developed beneath the Central Iran Block margin. The primary magmatic age of the oldest meta-ophiolites should be somewhat older than our oldest metamorphic age (197 Ma), that is, *at least of Upper Triassic age.*

Subduction began after the collision of the Central Iran Block with Eurasia during Middle Upper Triassic [13], trapping and stacking the early Tethyan oceanic lithosphere. Several slab fragments of various Mesozoic ages are probably piled up as tectonic slices in the metamorphic complex. We refute the idea that this metamorphic complex may represent an infra-ophiolitic metamorphic sole, as suggested in [5]. As attested by our geochronological data, the ophiolites and associated sedimentary series were metamorphized together during various metamorphic episodes.

5.1.2. A younger non-metamorphic ophiolite

The *youngest ophiolites* outcrop in the western part of the studied area. They do not show any trace of regional metamorphism. The pillows still have their delicate glassy crust, and the layered gabbros are amphibole-free, displaying numerous cumulate structures and textures. Their Upper Cretaceous age is attested (1) by the abundant microfauna found in the pelagic limestones interbedded within the extrusive sequence; (2) by ^{40}K–^{40}Ar data carried on the plagioclases of some leucogabbroic veins in the layered gabbros. This complex has thus the same age as other well-known ophiolites of western Iran, Turkey and Oman, belonging to the peri-arabic 'ophiolitic crescent' [12]. All these ophiolites, devoid of regional metamorphism, were obducted during Late Cretaceous over the southern continental margin of the Neo-Tethys ocean (Arabian-African platform), or over 'Gondwanian' continental fragments, detached from the Gondwana block during Permian–Triassic times.

5.2. The non-metamorphic ophiolite of Khoy represents a piece of a slow-spreading oceanic ridge from the Neo-Tethys Ocean

The stratigraphy and structural organization of the non-metamorphic ophiolite of Khoy is typical of a slow-spreading ridge environment. (1) The lower part of the ophiolite, exposed to the southwest, consists of a lherzolitic residual mantle sequence, containing typically small intrusive bodies of layered gabbros. (2) The extrusive sequence rests directly over the serpentinized lherzolites and associated gabbros. *No trace of any sheeted diabase dike complex was observed.* This is an important divergence we have with Hassanipak and Ghazi [5], who described a diabase sheeted dike complex "developed in several locations", and show important surfaces covered by "diabases" on their very schematic map. (3) The extrusive sequence is mainly composed of pillow lava flows (more than 90%), and a few massive lava flows. These oceanic basalts are frequently highly phyric, with concentration of plagioclase phenocrysts.

These features indicate rather low partial melting rates (lherzolitic residue) typical of slow-spreading oceanic ridges (Mid-Atlantic Ridge, Southwest Indian Ridge). The absence of a diabase sheeted dike complex, the scarcity of fluid sheet flows or lava lakes, and the frequency of phyric pillow lavas are also well-known characteristics of slow-spreading oceanic ridges [6].

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References

[1] B. Amini, J. Radfar, M. Khalatbari, A. Behrudi, Geological map of the Dizaj Quadrangle, Scale 1:100 000, Geological Survey of Iran, 1993.

[2] M.H. Emami, M.M. Sadegi, S.J. Omrani, Magmatic map of Iran, Scale 1:1 000 000, Geological Survey of Iran, 1993.

[3] M. Ghazi, E. Pessagno, A. Hassanipak, M. Kariminia, K. Campbell, Tectonogenesis of the Khoy ophiolite, NW Iran: results from biostratigraphic/chronostratigraphic and $^{40}Ar/^{39}Ar$ studies, in: Int. Conf. Geology of Oman, Abstract Volume, Sultan Qaboos University, Oman, 2001, pp. 34–35.

[4] M. Ghorashi, S. Arshadi, Geological map of the Khoy Quadrangle, Scale 1/250 000, Geological Survey of Iran, 1978.

[5] A. Hassanipak, M. Ghazi, Petrology, geochemistry and tectonic setting of the Khoy ophiolite, northwest Iran: implications for Tethyan tectonics, J. Asian Earth Sci. 18 (2000) 109–121.

[6] T. Juteau, R. Maury, The Oceanic Crust, from Accretion to Mantle Recycling, Springer-Praxis, Chichester, UK, 1999.

[7] D.C. Khamineni, C. Mortimer, The structural environment of Khoy region, NW Iran, Geol. Rundschau (1975) 831–835.

[8] G.A. Mahood, R.E. Drake, K–Ar dating young rhyolitic rocks: a case study of the Sierra la Primavera, Mexico, Geol. Soc. Am. Bull. 93 (1982) 1232–1241.

[9] A. Michard, H. Whitechurch, L.-E. Ricou, R. Montigny, E. Yazgan, Tauric subduction (Malatya-Elazig provinces) and its bearing on tectonics of the Tethyan realm in Turkey, in: J.E. Dixon, A.H.F. Robertson (Eds.), The Geological Evolution of the Eastern Mediterranean, Spec. Publ. Geol. Soc. London 17 (1985) 361–373.

[10] C.W. Passchier, R.A.J. Trouw, Microtectonics, Springer-Verlag, Berlin, 1995, 283 p.

[11] J. Radfar, B. Amini, A. Behrudi, M. Khalatbari, Geological map of the Khoy Quadrangle, Scale 1:100 000, Geological Survey of Iran, 1993.

[12] L.-E. Ricou, Le croissant ophiolitique péri-arabe. Une ceinture de nappes mise en place au Crétacé supérieur, Rev. Géogr. Phys. Géol. Dyn. 13 (1971) 327–350.

[13] L.-E. Ricou, Tethys reconstructed: plates, continental fragments and their boundaries since 260 Ma from Central America to Southeastern Asia, Geodin. Acta (1994) 169–218.

[14] A.M.C. Sengör, Y. Yilmaz, Tethyan evolution of Turkey: a plate tectonic approach, Tectonophysics 75 (1981) 181–241.

[15] R.H. Steiger, E. Jäger, Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology, Earth Planet. Sci. Lett. 36 (1977) 359–362.

[16] J. Stöcklin, Structural history and tectonics of Iran: a review, Am. Assoc. Pet. Geol. Bull. 52 (1968) 1229–1258.

[17] J. Stöcklin, Possible ancient continental margins in Iran, in: C.A. Burke, C.L. Drake (Eds.), The Geology of Continental Margins, Springer, New York, 1974, pp. 873–887.

[18] S.S. Sun, J.D. McDonough, Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and process, in: Magmatism in the Ocean Basins, Geol. Soc. Spec. Pap. 42 (1989) 313–345.

[19] I.M. Villa, Isotopic closure, Terra Nova 10 (1998) 42–47.