



# An early Miocene age for a high-temperature event in gneisses from Zabargad Island (Red Sea, Egypt): mantle diapirism?

Delphine Bosch, Olivier Bruguier

## ► To cite this version:

Delphine Bosch, Olivier Bruguier. An early Miocene age for a high-temperature event in gneisses from Zabargad Island (Red Sea, Egypt): mantle diapirism?. Terra Nova, 1998, 10, pp.274-279. hal-03879504

**HAL Id: hal-03879504**

**<https://hal.science/hal-03879504>**

Submitted on 30 Nov 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

## An early Miocene age for a high-temperature event in gneisses from Zabargad Island (Red Sea, Egypt): mantle diap...

Delphine Bosch


*Terra Nova*

### Cite this paper

Downloaded from [Academia.edu](#) 

[Get the citation in MLA, APA, or Chicago styles](#)

### Related papers

[Download a PDF Pack](#) of the best related papers 



[Proterozoic melting in the northern peridotite Massif, Zabargad Island: Os isotopic evidence](#)  
Jonathan Snow

[Mantle exhumation in an early Paleozoic passive margin, northern Cordillera, Yukon](#)  
Stephen Johnston

[Geochemical study \(major, trace elements and Pb–Sr–Nd isotopes\) of mantle material obducted ont...](#)  
Delphine Bosch

# An early Miocene age for a high-temperature event in gneisses from Zabargad Island (Red Sea, Egypt): mantle diapirism?

D. Bosch\* and O. Bruguier

Laboratoire de Géochimie Isotopique, CNRS-UMR 5567, cc 066, Université de Montpellier II, Place E. Bataillon, 34095 Montpellier Cedex 05, France

## ABSTRACT

U–Pb zircon data from a felsic gneiss located at the contact zone with the central peridotite body of Zabargad Island (Red Sea, Egypt) provide an age of  $23.2 \pm 5.9$  Myr consistent with the  $^{238}\text{U}$ – $^{206}\text{Pb}$  age of the youngest concordant grain ( $22.4 \pm 1.3$  Myr). Concordant grains indicate new zircon growth and/or resetting whereas slightly discordant analyses suggest participation of an older zircon component whose age cannot be defined precisely. SEM back-scattered imaging further reveals the occurrence of zoned domains almost completely erased by complex internal structures attributed to extensive

recrystallization under metamorphic conditions. The 22.4 Myr Miocene age is thus interpreted as dating a high-temperature metamorphic event. The proximity between the studied sample and the peridotite supports previous conclusions which regard parts of the peridotites from Zabargad Island as an asthenospheric mantle diapir which intruded the thinned Pan-African continental crust during the early stages of the Red Sea opening.

Terra Nova, 10, 274–279, 1998

## Introduction

In the last decade, much attention has been focused on the tectonothermal and geochemical evolution of rocks outcropping on Zabargad Island (Red Sea, Egypt). This island, though of limited size ( $\approx 4 \text{ km}^2$ ), has an almost unique geodynamic setting, 50 km west of the Red Sea axis, and reveals a close association of mafic/ultramafic rocks with a metamorphic gneiss complex. Understanding the geodynamic evolution of the island was expected to elucidate the processes operating in a young rift-setting environment and crust/mantle interface tectonics. Since the first work of Bonatti *et al.* (1981), however, genetic models have been limited by the scant data on the timing of juxtaposition between the peridotites and the gneisses, as well as the nature of the mafic/ultramafic rocks. One interpretation considers the peridotites as an asthenospheric mantle diapir intruding a Pan-African continental crust during the early stages of the Red Sea opening (e.g. Nicolas *et al.*, 1987). The few attempts to date the time of intrusion of the peridotites are consistent with this view. Nicolas *et al.* (1985), for example, inferred a K–Ar age of  $23 \pm 7$  Myr for amphiboles extracted from an amphibolite. This value concurs with the more precise Ar–Ar age ( $18.7 \pm 1.3$  Myr) given by hornblende extracted from a pegmatoidal pocket of a coarse grained hornblendite

in harzburgite (Trieloff *et al.*, 1997). Both ages are identical, within errors, of a  $18.4 \pm 1.0$  Myr zircon age obtained by Oberli *et al.* (1987). Although there is a good agreement between the three methods, Oberli's zircon value has been presented only in an abstract, thus making it difficult to properly evaluate. K–Ar and Ar–Ar ages have also been questioned for decoupling of parent and daughter nuclides (Villa, 1990), or for their meaning in terms of a geological event (uplift, hydrothermalism or emplacement age) due to their known susceptibility to low-grade events. An alternative interpretation considers the peridotites and the gneisses to be Pan-African (Brueckner *et al.*, 1988, 1995) and that juxtaposition of both rock types occurred shortly after differentiation from a common depleted mantle source  $\approx 700$  Ma. This is apparently supported by the so-called SLAP error-chron resulting from alignment of whole rock peridotite samples and CPX separates in the Sm–Nd isochron diagram (Brueckner *et al.*, 1988). This model, however, has been challenged in two recent papers on the grounds of fluid inclusion (Boullier *et al.*, 1997) and noble gases and argon chronological studies (Trieloff *et al.*, 1997). In both models, gneisses are seen to represent remnants of the Pan-African continental deep crust left behind during opening of the Red Sea rift. Pan-African ages for the metamorphic gneiss complex are well established by Sm–Nd and Rb–Sr mineral isochrons (Lancelot and Bosch, 1991; Brueckner *et al.*, 1995) as well as by a zircon Pb–Pb evaporation

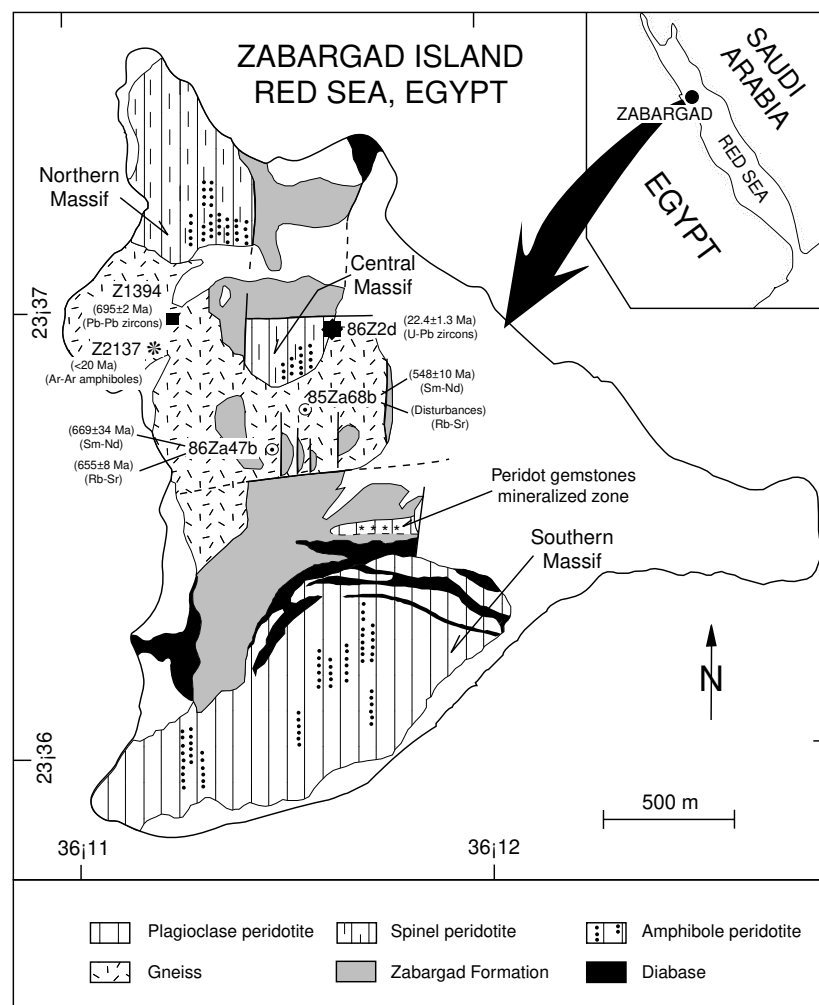
date (Brueckner *et al.*, 1995) from a felsic gneiss located a few hundred metres from the contact zone, between the central peridotite body and the gneisses. These ages, however, provide no constraints on the timing of juxtaposition of gneisses and peridotites. In order to solve this fundamental problem, and because of the known resistance to alteration of the mineral zircon, we focused on the U–Pb dating of single zircon grains extracted from a felsic gneiss located at the contact zone with the central peridotite body.

## Geological setting

Located about 90 km south-east of the Râs Bânas peninsula and about 50 km west of the Red Sea axis, Zabargad island (Fig. 1) presents a petrographic association dominated by three bodies of fresh ultramafic rocks. The southern body is constituted by plagioclase peridotites with a great abundance of diabase dikes at the contact with the overlying metasedimentary formation. The central and northern massifs are spinel lherzolites. Three generations of amphiboles are present in all three peridotite bodies and have been classified into three generations related to distinct metasomatic events (Agrinier *et al.*, 1993). The northern and central massifs are in contact with a complex polygenic assemblage constituted by Pan-African granulite-facies gneisses (Bosch, 1990; Lancelot and Bosch, 1991; Brueckner *et al.*, 1995) equilibrated at a depth of over 30 km (Boudier *et al.*, 1988) and by igneous pyroxenites and gabbros un-

\*Correspondence:

E-mail: bosch@dstu.univ-montp2.fr



**Fig. 1** Geological sketch map of Zabargad Island (modified after Bonatti *et al.*, 1981) indicating location of the studied sample (86Z2d). Samples dated by other authors and mentioned in the text are also shown: (■) felsic gneiss Z1394 (Brueckner *et al.*, 1995); (★) Monotype Sorts) dolerite Z2137 (Villa, 1990); (○) mafic granulite 85Za68b and felsic granulite 86Za47b (Lancelot and Bosch, 1991). Cenozoic sediments blank.

derplated at the base of the crust and recrystallized into mafic granulites before and during the early stages of the Red Sea rifting (Bonatti and Seyler, 1987; Seyler and Bonatti, 1988). Nicolas *et al.* (1985) and Boudier *et al.* (1988) provided evidence that away from the contact with the peridotites the shear strain and associated recrystallizations decrease rapidly in the metamorphic complex. Finally, diabase dykes and sills cross-cut all rock units including the gneisses and the peridotites. Diabases are abundant within the southern peridotitic body and at the contact between this massif and the Zabargad Metasedimentary Formation (see Fig. 1) where they promoted the growth of gem peridotites (Clochiatti *et al.*, 1981;

Bosch, 1991; Boudier and Nicolas, 1991). Chronological data available on diabases are rather scarce so that their age is not known precisely. Villa (1990) suggests an age younger than 20 Myr, concurring with the tholeiitic magmatism occurring 18–24 Ma along the western coast of Saudi Arabia and related to the early history of the Red Sea opening (Coleman *et al.*, 1979; Feraud *et al.*, 1991). Unmetamorphosed Middle to Upper Miocene evaporites discordantly overlay the Zabargad Metasedimentary Formation.

### Analytical procedure

The minerals were extracted and prepared for analysis according to stan-

dard techniques (e.g. Bosch *et al.*, 1996; Pidgeon *et al.*, 1996) where only the best quality grains (nonmagnetic, transparent and free of visible inclusions, fractures and cores) were selected for analysis. Single grains were subsequently processed according to Bruguier *et al.* (1997), but using the dissolution capsules designed by Parrish (1987) which significantly reduced Pb blanks. Isotopic measurements were carried out on a VG Sector mass spectrometer using a Daly detector. Because all common lead can be ascribed to blank Pb ( $15 \text{ pg} \pm 50\%$ ), its isotopic composition was measured precisely and used to determine the isotopic composition of radiogenic Pb. Corrected isotopic ratios, regression lines and intercepts were calculated according to Ludwig (1987). Analytical uncertainties are listed in Table 1 as  $2\sigma$  and uncertainties in ages as 95% confidence levels.

### Results and discussion

The studied sample (86Z2d) was collected at the contact zone between the gneisses and the central peridotite body. It corresponds to a fine-to medium-grained felsic gneiss containing *c.* 80% of quartz and plagioclase with iron oxides. Zircons are typically translucent, colourless to light pink and with rare inclusions. They present strong rounding of their external shapes suggesting partial dissolution preferentially occurring at the terminations of the crystals. This rounding is associated with the development of multifaceted surfaces, a morphological feature commonly found in high-grade metamorphic zircons (e.g. Kröner *et al.*, 1997) but also on zircons affected by high-temperature contact metamorphism (Davis *et al.*, 1968). SEM imaging of the grains reveals complex internal structures and the presence of two zircon components (see Fig. 2a,b). In most crystals examined, zoned domains are erased and survive as relics in restricted parts of the grains. The internal structure of the grain shown in Fig. 2(a) is consistent with penetrative migration of impurity components within the crystal lattice and, according to Vavra *et al.* (1996), is attributed to resorption at the surface of the grains. The grain presented in Fig. 2(b) is slightly different as it shows a massive, structureless outer part replacing the original zircon. Although affected by a strong round-

**Table 1** Conventional single grain U–Pb isotopic data for zircons from the felsic gneiss 86Z2d, Zabargad Island, Red Sea, Egypt

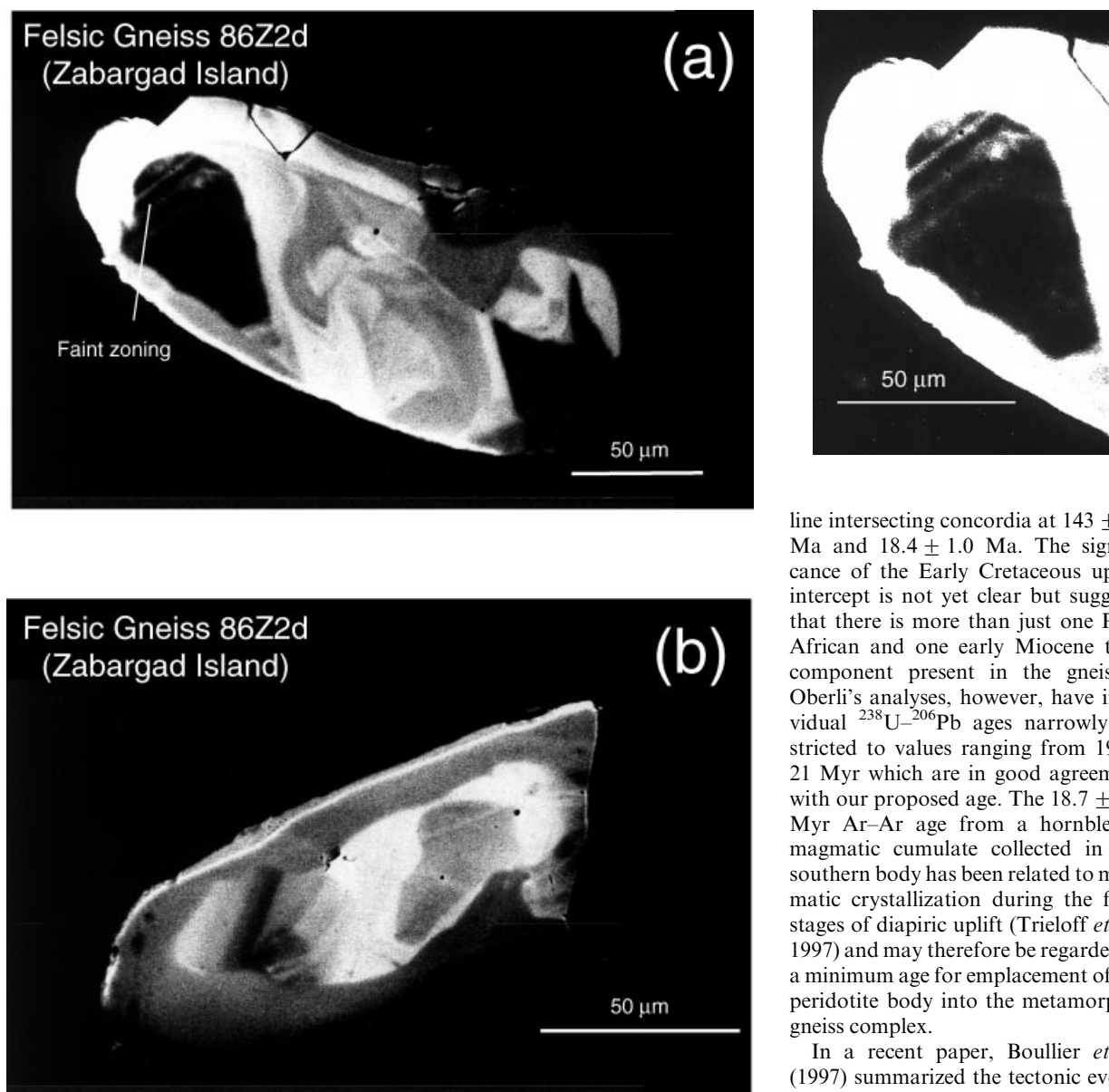
Sample <sup>1</sup>	Weight (mg)	U (ppm) <sup>2</sup>	Pb (ppm) <sup>3</sup>	<sup>206</sup> Pb/ <sup>204</sup> Pb <sup>4</sup>	<sup>208</sup> Pb/ <sup>206</sup> Pb <sup>4</sup>	<sup>206</sup> Pb/ <sup>238</sup> U (± 2 σ) <sup>4</sup>	<sup>207</sup> Pb/ <sup>235</sup> U (± 2 σ) <sup>4</sup>	<sup>207</sup> Pb/ <sup>206</sup> Pb (± 2 σ)	Apparent <sup>206</sup> Pb/ <sup>238</sup> U	Ages <sup>207</sup> Pb/ <sup>235</sup> U	(Myr) <sup>207</sup> Pb/ <sup>206</sup> Pb	ρ
Felsic Gneiss 86Z2d												
1.Zr, mf, elg, c	0.0147	436	1.5	26.75	0.1420	0.00348 ± 20	0.0219 ± 30	0.0457 ± 53	22.4 ± 1.3	22.0 ± 3.0	–18.5	0.50
2.Zr, mf, rd, c	0.0128	568	2.2	43.89	0.1927	0.00354 ± 69	0.0228 ± 46	0.0467 ± 35	22.8 ± 4.5	22.9 ± 4.6	32.0	0.93
3.Zr, mf, rd, lp	0.0243	399	2.4	102.34	0.3319	0.00403 ± 03	0.0266 ± 13	0.0480 ± 22	25.9 ± 0.2	26.7 ± 1.3	96.8	0.48
4.Zr, mf, rd, lp	0.0132	609	2.7	69.20	0.2937	0.00380 ± 53	0.0258 ± 37	0.0487 ± 22	24.5 ± 3.4	25.9 ± 3.7	134.5	0.98
5.Zr, mf, elg, lp	0.0104	689	3.7	69.75	0.4552	0.00417 ± 29	0.0288 ± 21	0.0501 ± 10	26.8 ± 1.9	28.8 ± 2.1	198.4	0.96

Notes: <sup>1</sup>grains were selected from nonmagnetic separates at full magnetic field in Frantz Magnetic Separator and air abraded following Krogh (1982); mf = multifaceted; rd: rounded; elg = elongated; c = colourless; pk: light pink. <sup>2</sup>Radiogenic lead <sup>3</sup>Measured, uncorrected ratio. <sup>4</sup>Ratio corrected for fractionation and blank. Blank lead isotopic composition, 204: 206: 207: 208 = 1, 18.31, 15.59, 37.88, ± 0.10, 0.11 and 0.13% for the <sup>206</sup>Pb/<sup>204</sup>Pb, <sup>207</sup>Pb/<sup>204</sup>Pb and <sup>208</sup>Pb/<sup>204</sup>Pb ratios, respectively. Pb and U fractionation correction = 0.15%/amu (± 0.05, 2 σ<sup>73</sup>). Pb blanks = 15 pg (± 50%); U blanks = 5 pg (± 50%). Isotopic ratios and absolute uncertainties in the Pb/U and <sup>207</sup>Pb/<sup>206</sup>Pb ratios calculated following Ludwig (1987). Errors refer to last digits. U half-lives and isotopic abundance ratios from Jaffey *et al.* (1971).

ing, the crystal roughly preserved a prismatic shape and the observed peripheral domain more likely resulted from a resorption-induced recrystallization. These morphological features are in agreement with the grains being originally magmatic zircons strongly disturbed during a subsequent metamorphic event. In the concordia diagram (Fig. 3), all points are close to concordant and fall on a chord with a lower intersection at  $23.2 \pm 5.9$  Myr and an upper intersection, which is the result of a long extrapolation, at  $949 \pm 691$  Myr (MSWD = 0.7). The latter is considered without any age signification. Analysis 5, however, is discordant and points to an old zircon component with a minimum <sup>207</sup>Pb/<sup>206</sup>Pb age of  $\approx 200$  Myr. The  $22.4 \pm 1.3$  Myr U–Pb age of the concordant analysis 1 is therefore tentatively taken as our best estimate for new growth and recrystallization of the zircon grains. The reason for this pervasive recrystallization is not straightforward, however. Two alternative interpretations can be proposed which have different implications for the geodynamic evolution of the Red Sea area. Brueckner *et al.* (1995) proposed that the huge diabase sill at the contact with the southern peridotite massif was responsible for a pervasive hydrothermal event and suggested that the  $18.4 \pm 1.0$  Myr U–Pb zircon age obtained by Oberli *et al.* (1987) dates zircon growth under hydrothermal conditions, although the latter authors interpreted it as corresponding to the emplacement age of the peridotites. This view is consistent with a Pan-African origin of the Zabargad peridotites (Brueckner *et al.*, 1988). Conversely, it could be proposed

that the analysed zircons reflect new growth or recrystallization during contact metamorphism developed at the vicinity of an ascending mantle diapir. In this view, emplacement of the peridotites in the Pan-African granulite gneisses took place early in the Red Sea opening. Previous studies have highlighted the possible growth of new zircons during contact metamorphism (Gulson and Krogh, 1975) and the progressive resetting of U–Pb ages towards hot intrusive bodies (Davis *et al.*, 1968). In the latter case, evidence has been presented that Pb loss can reach up to 80% of the unaffected material for zircons located < 1 m from the contact. Experimental investigations of the disturbance of the U–Pb isotopic systems under hydrothermal conditions (Pidgeon *et al.*, 1966; Sinha *et al.*, 1992) also revealed the ability of hydrothermal and metamorphic fluids to dissolve and transport elements, and that up to 61% of the radiogenic lead can be leached out of the zircons. The morphologies of the zircons analysed herein, however, are not consistent with those observed for natural or synthetic hydrothermally grown zircons (Caruba *et al.*, 1975; Kurat *et al.*, 1982; Rubin *et al.*, 1989). Such zircons occur in veins and present very irregular or even amoeboid shapes (see fig. 4 of Rubin *et al.*, 1989) or, alternatively, they may be well crystallized, euhedral, probably zoned and mm–cm in size (see figs 6 and 7 in Caruba *et al.*, 1975; fig. 9 in Kurat *et al.*, 1982). Thus, the observed morphological features suggest a metamorphic origin and the proximity of the studied sample to the peridotite body implies that zircon growth and recrystal-

lization were brought about by contact effect. Independent arguments for contact metamorphism are provided by the  $695 \pm 2$  Myr age obtained by Brueckner *et al.* (1995) on zircons extracted from a felsic gneiss (Z1394) located c. 300 m westward of the central peridotite body. The lack of isotopic disturbances in the evaporation age spectrum obtained by these authors is in agreement with high temperatures restricted to the vicinity of the peridotite. While Pan-African Rb–Sr and Sm–Nd chronological information could be determined from a felsic granulite located 250 m away from the contact (sample 86Za47b from Lancelot and Bosch, 1991), a mafic granulite 85Za68b (op cit.) sampled 115 m from the central peridotite body gave no Rb–Sr age information but still preserved a Pan-African Sm–Nd age (see Fig. 1); both are consistent with a thermal gradient towards the peridotite. Interestingly, the two apparently conflicting hypotheses mentioned above (contact metamorphism vs. hydrothermalism) could be combined in the sense that contact metamorphism is classically associated with fluid production emanating from both the intrusive bodies and wall-rocks (Hanson, 1995). In peridotites the occurrence of two amphibole generations, whose growth was linked to hot hydrous fluids released during the diapiric uplift (Agrinier *et al.*, 1993), is consistent with such a model. In any case, the possibility that the large diabase sill could be responsible for the  $\approx 22$  Myr zircon age can be dismissed as the diabase crosscuts and is therefore younger than the southern peridotite body which has been dated at  $18.7 \pm 1.3$  Myr on magmatic horn-



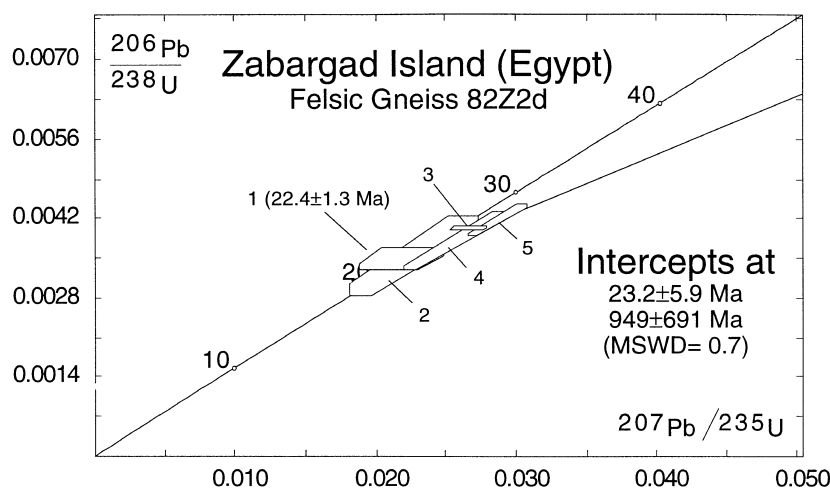
**Fig. 2** SEM back-scattered electron images of zircons from the felsic gneiss 86Z2d. Prior to SEM analyses, grains were etched by HF vapours for one minute. (a) Translucent colourless rounded grain showing flow structures accompanying resorption. Faint relics of magmatic zoning survive in the left part of the grain (see enlargement). (b) Resorbed broken grain showing an outer structureless domain resulting from resorption-induced recrystallization.

nde (Trieloff *et al.*, 1997). Thus, new zircon growth and recrystallization at 22.4 Ma cannot be linked to an hydrothermal event induced by diabase emplacement. The Ar–Ar age mentioned above further indicates that the peridotite was still hot during the Miocene. This strongly suggests that the U–Pb zircon age reported herein could be

related to a metamorphic/hydrothermal episode associated with intrusion of the Zabargad peridotites. Although slightly older, this early Miocene age is in good agreement with that provided by Oberli *et al.* (1987). These authors reported U–Pb analyses from zircons collected near the central peridotite body that spread along a discordant

line intersecting concordia at  $143 \pm 11$  Ma and  $18.4 \pm 1.0$  Ma. The significance of the Early Cretaceous upper intercept is not yet clear but suggests that there is more than just one Pan-African and one early Miocene time component present in the gneisses. Oberli's analyses, however, have individual  $^{238}\text{U}$ – $^{206}\text{Pb}$  ages narrowly restricted to values ranging from 19 to 21 Myr which are in good agreement with our proposed age. The  $18.7 \pm 1.3$  Myr Ar–Ar age from a hornblende magmatic cumulate collected in the southern body has been related to magmatic crystallization during the final stages of diapiric uplift (Trieloff *et al.*, 1997) and may therefore be regarded as a minimum age for emplacement of the peridotite body into the metamorphic gneiss complex.

In a recent paper, Boullier *et al.* (1997) summarized the tectonic evolution of the mafic/ultramafic rocks of Zabargad Island and associated gneissic complex as resulting from at least five stages. There is a consensus concerning the first stage which is attributed to the Pan-African cycle (550–700 Ma) and which is regarded as a major event leading to crust production and high-grade metamorphism with temperatures of 800–850°C and pressure  $c.10$  kb (Boudier *et al.*, 1988). It is still unclear, however, whether the subsequent evolution of the Zabargad peridotites is related to the Pan-African cycle (Brueckner *et al.*, 1988, 1995) or to the opening of the Red Sea rift (Nicolas *et al.*, 1987; Boudier *et al.*, 1988). Boullier *et al.* (1997), following Dupuy *et al.* (1991), proposed an alter-



**Fig. 3** U–Pb concordia diagram for single zircon grains from the felsic gneiss 86Z2d. All samples represented by symbols sized according to their 2  $\sigma$  error.

native model where the Northern and Central peridotite bodies represent parts of a metasomatized Pan-African lithospheric mantle intruded by an asthenospheric mantle diapir represented by the Southern massif. Our new U–Pb age substantiates the proposition that the Central peridotite body is also part of the mantle diapir which intruded the thinned Pan-African lithosphere during early Miocene times. Finally, Zabargad ultramafics from the Southern and Central massifs also record a large range of P–T conditions, with the highest values being 1280°C and 27 kb (Kurat *et al.*, 1993). These are very different to the equilibration conditions of the Pan-African granulites (see above; Boudier *et al.*, 1988) and further supports the fact that the Central and Southern peridotite bodies more likely constitute an asthenospheric mantle diapir which rose to shallow levels in the crust during the early stages of the Red Sea opening as already proposed on the grounds of geophysical data (Styles and Gerdes, 1983). However, the question remains open whether the Northern peridotite body is also part of the mantle diapir or constitutes a piece of a Pan-African lithospheric mantle wedge dredged upward with the gneissic complex as suggested earlier (Brueckner *et al.*, 1988, 1995; Dupuy *et al.*, 1991).

### Acknowledgements

A. Nicolas and F. Boudier are greatly thanked for providing sample for this study

and for constant stimulating scientific exchanges. The paper greatly benefited for constructive reviews by H.K. Brueckner, F. Oberli, and one anonymous reviewer.

### References

- Agrinier, P., Mevel, C., Bosch, D. and Javoy, M., 1993. Metasomatic hydrous fluids in amphibole peridotites from Zabargad Island (Red Sea). *Earth Planet. Sci. Lett.*, **120**, 187–205.
- Bonatti, E., Hamlyn, P.R. and Ottonello, G., 1981. The upper mantle beneath a young oceanic rift. Peridotites from the island of Zabargad (Red Sea). *Geology*, **9**, 474–479.
- Bonatti, E. and Seyler, M., 1987. Crustal underplating and evolution in the Red Sea rift: uplifted gabbro/gneiss crustal complexes on Zabargad and Brothers Islands. *J. Geophys. Res.*, **92**, 12803–12821.
- Bosch, D., 1990. Evolution géochimique initiale et précoce d'un rift. Systématique isotopique Pb Sr et Nd du diapir mantellique de Zabargad, de son encaissant gneissique et de son hydrothermalisme. Conséquences géodynamiques et métallogéniques. Unpubl. doctoral dissertation, University of Montpellier II, 231pp.
- Bosch, D., 1991. Introduction d'eau de mer dans le diapir mantellique de Zabargad (Mer Rouge) d'après les isotopes du Sr et du Nd. *C. R. Acad. Sci. Paris*, **313**, 49–56.
- Bosch, D., Bruguier, O. and Pidgeon, R.T., 1996. The evolution of an Archean Metamorphic Belt: a conventional and SHRIMP U–Pb study on accessory minerals from the Jimpard Belt, Yilgarn craton, West Australia. *J. Geol.*, **104**, 695–711.
- Boudier, F. and Nicolas, A., 1991. High-temperature hydrothermal alteration of peridotite, Zabargad Island (Red Sea). In: *Orogenic Lherzolites and Mantle Processes* (M.A. Menzies *et al.*, Eds). *J. Petrol., Spec. Issue*, 243–253.
- Boudier, F., Nicolas, A., Ji, S., Kienast, J.R. and Mevel, C., 1988. The gneiss of Zabargad Island: deep crust of a rift. *Tectonophysics*, **150**, 209–227.
- Boullier, A.M., Firdaous, K. and Boudier, F., 1997. Fluid circulation related to deformation in the Zabargad gneisses (Red Sea rift). *Tectonophysics*, **279**, 281–302.
- Brueckner, H.K., Elhaddad, M.A., Hamelin, B., Hemming, S., Kröner, A., Reisberg, L. and Seyler, M., 1995. A Pan African origin and uplift for the gneisses and peridotites of Zabargad Island, Red Sea: a Nd Sr, Pb and Os isotope study. *J. Geophys. Res.*, **100**, 22,283–22,297.
- Brueckner, H.K., Zindler, A., Seyler, M. and Bonatti, E., 1988. Zabargad and the isotopic evolution of the sub-Red Sea mantle and crust. *Tectonophysics*, **150**, 163–176.
- Bruguier, O., Lancelot, J.R. and Malavieille, J., 1997. U–Pb dating on single detrital zircon grains from the Triassic Songpan-Ganze flysch (Central China): provenance and tectonic correlations. *Earth Planet. Sci. Lett.*, **152**, 217–231.
- Caruba, R., Baumer, A. and Turco, G., 1975. Nouvelles synthèses hydrothermales du zircon: substitutions isomorphiques; relation morphologie-milieu de croissance. *Geochim. Cosmochim. Acta*, **39**, 11–26.
- Clochiatti, R., Massare, O. and Jehanno, C., 1981. Origine hydrothermale des olivines gemmes de l'île de Zabargad (St John), Mer Rouge, par l'étude de leurs inclusions. *Bull. Mineral.*, **104**, 354–360.
- Coleman, R.G., Hadley, D.G., Fleck, R.G., Hedge, C.T. and Donato, M.M., 1979. The Miocene Tihama Asir ophiolite and its bearing on the opening of the Red Sea. In: *Proc. Symp. Evol. Mineralization Arabian Nubian Shield. Inst. Appl. Geol. Bull. (Jeddah)*, **1**, 173–179.
- Davis, G.L., Hart, S.R. and Tilton, G.R., 1968. Some effects of contact metamorphism on zircon ages. *Earth Planet. Sci. Lett.*, **5**, 27–34.
- Dupuy, C., Mevel, C., Bodinier, J.L. and Savoyant, L., 1991. Zabargad peridotite: evidence for multistage metasomatism during Red Sea rifting. *Geology*, **19**, 722–725.
- Feraud, G., Zumbo, V., Sebai, A. and Bertrand, H., 1991.  $^{40}\text{Ar}/^{39}\text{Ar}$  age and duration of tholeiitic magmatism related to the early opening of the Red Sea rift. *Geophys. Res. Lett.*, **18**, 195–198.
- Gulson, B.L. and Krogh, T.E., 1975. Evidence for multiple intrusion, possible resetting of U–Pb ages, and new crystallization of zircons in the post-tectonic intrusions ('Rapakivi granite')

- and gneisses from South Greenland. *Geochim. Cosmochim. Acta*, **39**, 65–82.
- Hanson, R.B., 1995. The hydrodynamics of contact metamorphism. *Bull. Geol. Soc. Am.*, **107**, 595–611.
- Jaffey, A.H., Flynn, D.F., Glendenin, L.E., Bentley, W.C. and Essling, A.M., 1971. Precision measurement of the half-lives and specific activities of  $^{235}\text{U}$  and  $^{238}\text{U}$ . *Phys. Rev.*, **4**, 1889–1906.
- Krogh, T.E., 1982. Improved accuracy of U–Pb zircon ages by the creation of more concordant systems using an air abrasion technique. *Geochim. Cosmochim. Acta*, **46**, 637–649.
- Kröner, A., Jaeckel, P., Reischmann, T. and Kroner, U., 1997. Further evidence for an early Carboniferous (c. 340 Ma) age of high-grade metamorphism in the Saxonian granulite complex. *Geol. Rdsch.*, **86**, 751–766.
- Kurat, G., Niedermayr, G. and Prinz, M., 1982. Peridot von Zabargad, Rotes Meer. *Der Aufschluss*, **33**, 169–182.
- Kurat, G., Palme, H., Embey-Isztin, A. *et al.*, 1993. Petrology and geochemistry of peridotites and associated vein rocks of Zabargad Island, Red Sea. *Egypt. Min. Petrol.*, **48**, 309–341.
- Lancelot, J.R. and Bosch, D., 1991. A Pan African age for the HP-HT granulite gneisses of Zabargad Island: implications for the early stages of the Red Sea rifting. *Earth Planet. Sci. Lett.*, **107**, 539–549.
- Ludwig, K.R., 1987. Isoplot200, a plotting and regression program for isotope geochemists, for use with HP series 200 computers. *U.S.G.S. Open-File Report*, 85–513.
- Nicolas, A., Boudier, F., Lyberis, N., Montigny, R. and Guennoc, P., 1985. L'île de Zabargad (Saint-Jean): témoin clé de l'expansion précoce en Mer Rouge. *C. R. Acad. Sci. Paris*, **301**, 1063–1068.
- Nicolas, A., Boudier, F. and Montigny, R., 1987. Structure of Zabargad Island and early rifting of the Red Sea. *J. Geophys. Res.*, **92**, 461–474.
- Oberli, F., Ntaflos, T., Meier, M. and Kurat, G., 1987. Emplacement age of the peridotites from Zabargad Island (Red Sea): a zircon U–Pb isotope study. *Terra Cognita (Abstr.)*, **7**, 334.
- Parrish, R.R., 1987. An improved microcapsule for zircon dissolution in U–Pb geochronology. *Chem. Geol.*, **66**, 99–102.
- Pidgeon, R.T., Bosch, D. and Bruguier, O., 1996. Inherited zircon and titanite U–Pb systems in an Archean Katrine syenite from southwestern Australia: implications for U–Pb stability of titanite. *Earth Planet. Sci. Lett.*, **141**, 187–198.
- Pidgeon, R.T., O'Neil, J.R. and Silver, L.T., 1966. Uranium and lead isotopic stability in a metamict zircon under experimental hydrothermal conditions. *Science*, **154**, 1538–1540.
- Rubin, J.N., Henry, C.D. and Price, J.G., 1989. Hydrothermal zircons and zircon overgrowths, Sierra Blanca Peaks, Texas. *Am. Miner.*, **74**, 865–869.
- Seyler, M. and Bonatti, E., 1988. Petrology of gneiss-amphibolite lower crustal unit from Zabargad Island, Red Sea. *Tectonophysics*, **150**, 177–207.
- Sinha, A.K., Wayne, D.M. and Hewitt, D.A., 1992. The hydrothermal stability of zircon: Preliminary experimental and isotopic studies. *Geochim. Cosmochim. Acta*, **56**, 3551–3560.
- Styles, P. and Gerdes, K.D., 1983. St. John's Island (Red Sea): a new geophysical model and its implications for the emplacement of ultramafic rocks in fracture zones and at continental margins. *Earth Planet. Sci. Lett.*, **65**, 353–368.
- Trieloff, M., Weber, H.W., Kurat, G., Jessberger, E.K. and Janicke, J., 1997. Noble gases, their carrier phases, and argon chronology of upper mantle rocks from Zabargad Island, Red Sea. *Geochim. Cosmochim. Acta*, **61**, 5065–5088.
- Vavra, G., Gebauer, D., Schmid, R. and Compston, W., 1996. Multiple zircon growth and recrystallisation during polyphase Late Carboniferous to triassic metamorphism in granulites of the Ivrea Zone (Southern Alps): an ion microprobe (SHRIMP) study. *Contr. Miner. Petrol.*, **122**, 337–358.
- Villa, I.M., 1990.  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of amphiboles from Zabargad Island (Red Sea) is precluded by interaction with fluids. *Tectonophysics*, **180**, 369–373.

Received 16 April 1998; revised version accepted 17 February 1999