J. King Saud Univ., Vol. 15, *Science* (2), pp. 71-80, Riyadh (A.H. 1423/2003)

Metamorphic History of Gabbroic Blocks within the Ar Ridayniyah Ophiolitic Melange, Eastern Arabian Shield, Saudi Arabia

Ahmad Al-Saleh
Geology Department, King Saud University,
Riyadh, Saudi Arabia

(Received 14/3/1422 H; accepted for publication 4/1/1423 H)

Abstract. The Al-Amar suture marks the collisional boundary between the Afif and Ar Rayn terranes of the eastern Arabian Shield. Numerous ophiolite occurrences are reported from this suture; many of which are made up of a serpentinite melange that encloses blocks of varying oceanic lithologies. The Ar Ridayniyah melange is exposed in a narrow linear belt near the eastern periphery of the suture. Most of the blocks are massive serpentinites with some gabbros and rare basalts, all of which are set in a matrix of highly sheared serpentinite. The gabbros contain secondary assemblages indicative of two phases of metamorphism; the first is an ocean-floor event, but the second is a medium-pressure short-lived episode that reached up to epidote-amphibolite conditions. It is believed that this second phase is the product of the final collisional event between the two enclosing terranes which took place at c. 610 Ma.

Introduction

The eastern Arabian Shield is believed to have originated through the amalgamation of a number of allochthonous terranes that were accreted onto the Afif micro-continent during the late Proterozoic in the period from 680 to 650 Ma [1,2]. The Afif itself is believed to be a composite terrane [3] containing within its southern part a segment of pre-late Proterozoic crust that may extend all the way down to the gneissic terranes of Yemen [4]. The Al-Amar suture (Fig. 1) that separates the Afif from the much-smaller Ar Rayn block was reactivated during the final collisional orogeny between 620-570 Ma [5]. This broad belt of metagreywackes (known as the Abt schist) contains scattered remnants of ophiolitic material that were crucial in revealing the back-arc nature of the intervening oceanic basin, and the timing of basin inversion [6].

Basin closure was followed by a period of crustal shortening and westward-directed thrusting [7]. Among the most prominent thrusts is the major Ar Ridayniyah fault; it extends in a N-S direction for a distance of about 120 km close to the eastern margin of the suture (Fig. 1). Within the northern segment of this fault is the Ar Ridayniyah ophiolitic melange, which contains abundant blocks of mafic and ultramafic rocks set in matrix of sheared serpentinite. Uplift $^{40}Ar/^{39}Ar$ ages from the metabasites coincide on c. 610 Ma [8], thus indicating complete degassing and probably resetting of mineral equilibria during crustal ascent. The aim here is to try and investigate the validity of this assumption, and if possible gain more knowledge of the P-T conditions that prevailed within the Al-Amar suture during the uppermost Proterozoic; this will in turn shed more light on the nature of the final orogeny of the eastern shield.

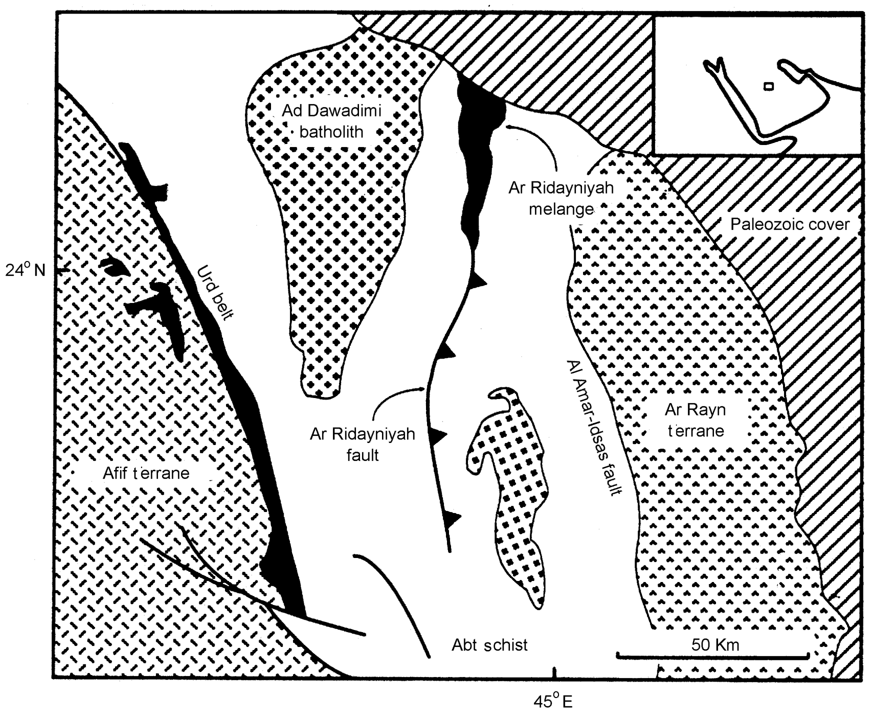


Fig.1. Simplified geologic map of the easternmost Arabian Shield, showing the location of the Ridayniyah fault and melange zone within the Al-Amar suture.

Petrography and mineral chemistry

Most of the olistoliths in the Ar Ridayniyah melange are massive serpentinites; the rest are mainly metagabbros with well-preserved igneous textures. Samples collected for microscopic examination and probe analysis were taken from these metagabbros as well as from localized amphibolite shear bands usually located close to the sole thrust. Mineral analyses were carried out on the CAMECA Camebax electron probe facility at the University of Manchester, and a representative set of results is listed in Table 1.

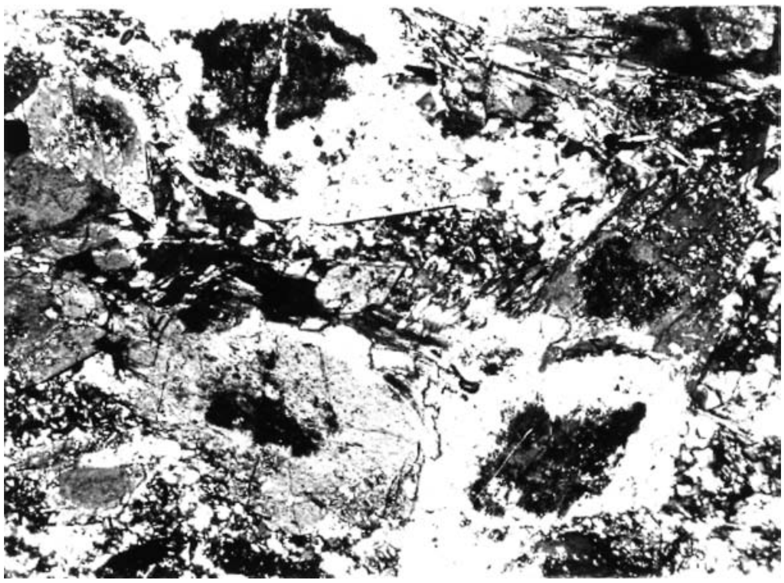
Table 1. Representative microanalyses of selected minerals from the Ridayniyah metagabbros

Element	Plagio-clase	Plagio-clase	Augite	Clino-zoisite	Actino-lite	Horn-blende	Horn-blende	Sphene
SiO_2	61.24	61.51	50.15	39.34	52.55	41.42	41.85	30.19
TiO_2	0	0	3.21	0	0	0.37	0.3	38.55
Al_2O_3	24.55	24.32	1.78	28.98	3.66	15.16	15.52	1.04
FeO	0	0	8.23	6.04	10.75	14.36	14.99	0
MnO	0	0	0.38	0	0	0.27	0	0
MgO	0	0	13.23	0	16.04	9.69	9.83	0
CaO	5.38	5.07	21.28	23.52	12.16	11.79	11.54	28.11
Na_2O	8.89	9.6	0.6	0	1.03	2.23	2.51	0
K_2O	0	0	0	0	0	0.72	0.49	0
Cr_2O_3	0		0.45	0	0	0	0	0
P_2O_5	0	0	0	0	0	0	0	0
Total	100.06	100.5	99.31	97.88	96.19	96.01	97.03	97.89

The gabbroic blocks retain their original macroscopic appearance, and in some cases typical ophitic textures are preserved (Fig.2a). The mineralogy of these metagabbros is rather simple, being made up originally of Ca-rich plagioclase and clinopyroxene that are now largely replaced by an assemblage of actinolite, clinozoisite, hornblende and sodic plagioclase. No evidence of the previous existence of olivine or orthopyroxene is preserved. Some of the gabbros have undergone complete amphibolitization while others retain some clinopyroxene rimmed by actinolite or hornblende (Fig.2b), and twinned laths of plagioclase partly altered to a mixture of clinozoisite and untwinned polygonal plagioclase ($An_{23\text{-}30}$). The igneous plagioclase has undergone a change in composition, probably through solid diffusion, and is now of the same composition as the metamorphic plagioclase. The Urd gabbros are in general highly aluminous and have original plagioclase compositions approaching that of anorthite [6]; this change in chemistry during metamorphism would explain the abundance of clinozoisite in the Ridayniyah metagabbros.

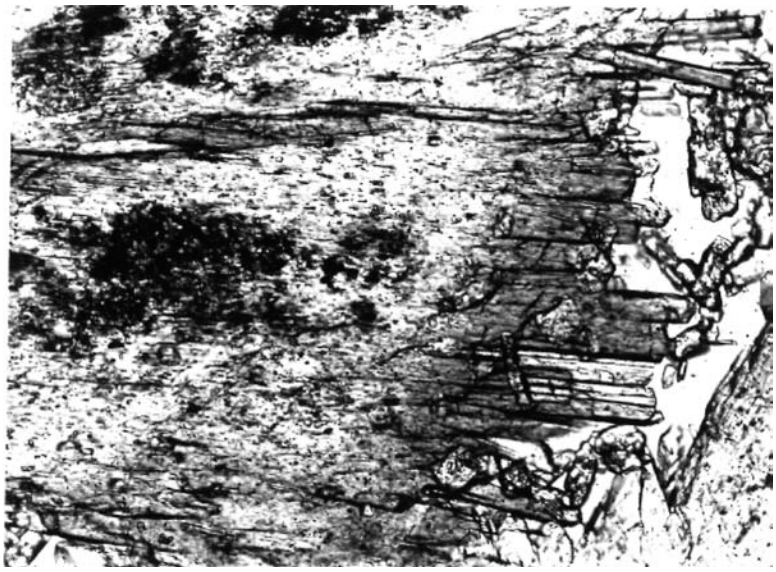
Most of the hornblendes are edenitic in composition and have actinolitic cores that had formed presumably after augite; in some samples the hornblende is present only as a thin rim of radiating prisms nucleating on actinolite (Fig. 2c). Hornblende needles are common in the matrix of most rocks. Sphene is present in abundance either as thick rims around ilmenites (Fig.2d) or as disseminated minute crystals inside amphiboles; these often impart a very dark tone on the host grains (Fig. 2a).

(a)

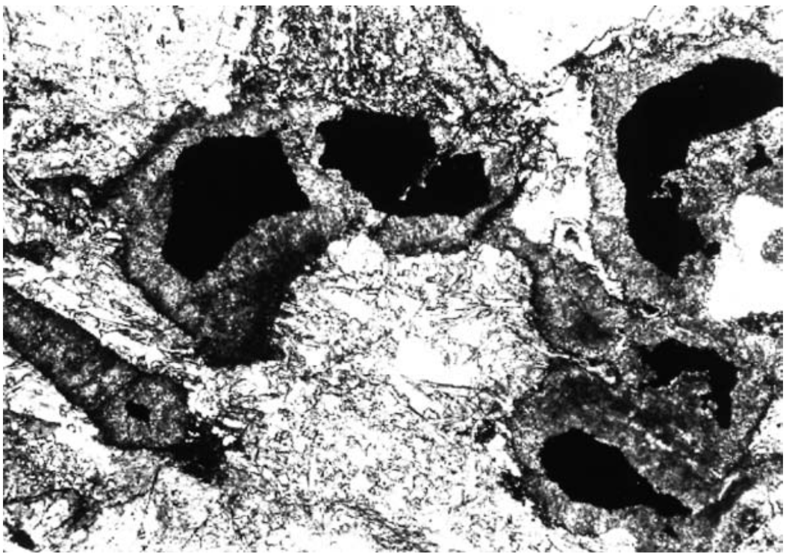


(b)

Fig. 2. (a) Relict ophitic texture defined by altered plagioclase enclosed by hornblende (after cpx), the dark color of the hornblende is due to minute inclusions of sphene; (b) Hornblende grains with dark pyroxene cores (XP light).



(c)



(d)

Fig. 2. (c) Hornblende needles growing on actinolite, the high relief mineral in the groundmass is clinozoisite; (d) Thick rims of sphene replacing igneous ilmenite.

Thermobarometry

The high variance assemblages of the Ridayniyah metabasites preclude the use of many of the conventional techniques of thermobarometry. However, a thermometer for such rocks was proposed by Blundy & Holland [9] based on the reaction:

edenite + 4 quartz = tremolite + albite

this requires the presence only of hornblende and plagioclase in a silica-saturated matrix. Blundy & Holland [10] elaborated on this approach to take into account non-ideal mixing in both phases, and also added a second reaction:

edenite + albite = richterite + albite

Both thermometers were applied to the Ridayniyah metagabbros using well-equilibrated pairs of polygonal plagioclase and small hornblende prisms from the groundmass; large and relict grains were avoided. The results obtained over a pressure range of 0-15 kbars are shown in Table 2. For the assemblages at hand the reactions are not very sensitive to pressure, and for any given value of that variable the temperatures calculated lies within a very narrow range. Pressures higher than 10 kbars are unlikely to have occurred in the Ridayniyah melange since no blueschist-eclogite assemblages were encountered. This is corroborated by the fact that temperatures at a pressure value of 10 kbars are close to or even beyond the highest limit expected for an epidote-amphibolite.

Table 2. Metamorphic temperatures calculated from hornblende-plagioclase pairs using the two thermometers of Blundy & Holland [10] over a range of pressure values

P (kbar)	0	5	10	15
T (ed-tr)	544	607	669	732
T (ED-RI)	553	615	677	749

Comparison of the hornblende compositions from the Ridayniyah metagabbros with the empirical results of Laird & Albee [11] rules out a low-pressure origin owing mainly to their high content of alkali elements, especially Na. In terms of metamorphic grade, the Ridayniyah hornblendes correlate well with the compositions of calcic amphiboles from epidote-amphibolites intercalated with garnet-zone pelites; these rocks are believed to have formed at pressures of 5.4-5.7 kbar and temperatures of 500-525°C [11]. Such estimates of temperature are about 100°C below those obtained using the hornblende-plagioclase thermometers.

The observed replacement of ilmenite by sphene is a significant indicator of pressure. According to the experimental work of Spear [12] the growth of this mineral in basaltic amphibolites is inhibited by low-pressure conditions (<2 kbars); below this approximate limit, ilmenite becomes the stable Ti-bearing phase.

It is reasonable to infer from the above results and observations that pressure condition between 5-10 kbars, and temperatures of 500-650°C had prevailed during the growth of the hornblende-oligoclase-clinozoisite-sphene assemblage. This range of P-T conditions is broadly compatible with the conditions expected in the epidote-amphibolite sub-facies.

Discussion and Conclusions

Like the rest of the ophiolites within the Al-Amar suture, the Ar Ridayniyah gabbros display clearly the effects of static ocean-floor metamorphism [5,13]. In those other ophiolites, the primary mineral assemblage was completely lost except for some remnants of clinopyroxenes in the cores of amphibole grains; however, the original igneous texture was largely preserved with little or no planar fabrics developing. This pervasive event reaches up to actinolite grade and in some cases amphibolite facies conditions are attained; the compositions of amphiboles attest to their origin in a low-pressure environment [5]. It was observed that metamorphism always begins with the highest-grade assemblage which is then overgrown (or overprinted) by lower grade mineralogies presumably due to the lowering of heat flow as the rocks move away from the spreading center. The final and lowest-grade assemblage is usually one where the plagioclase and clinopyroxene are replaced by very fine aggregates of albite-clinozoisite and chlorite-quartz respectively. The Ridayniyah gabbros do not bear the marks of such intense hydrothermal alteration, probably due to their uplift by diapiric serpentinite to higher crustal levels along a transform fault (Fig. 3a). The association of transform faults with serpentinite protrusions is well documented from modern and ancient examples [14,15].

The main difference, however, between the Ridayniyah mafic rocks and their counterparts from other ophiolitic segments on the margins of the Al-Amar suture is the presence of a prograde assemblage of epidote-amphibolites supplanting greenschist minerals. As seen from the chemistry of hornblendes, this assemblage had formed under pressure conditions unlike those expected in the oceanic realm. It is more appropriate to assume that they are the products of the final collisional orogeny between the Ar Rayn and Afif terranes. During that event, which started c. 620 Ma [5], westward-directed thrusting of the Abt schist was accompanied by burial of the Ridayniyah melange to a depth of no less than 10 km (Fig. 3b), thus inducing medium-pressure metamorphism.

It appears that this burial was short-lived as evidenced by the abundance of relict minerals. Rapid uplift to higher crustal levels probably took place along the Ridayniyah Fault (Fig. 3c) at c. 610 Ma as indicated by the $^{40}Ar/^{39}Ar$ ages from the metagabbros [8]. This final orogeny is probably coeval with the collision of East and West Gondwana

[16], which might have occurred in the central Arabian Shield [17]; therefore, the metamorphism and rapid exhumation of the Ridayniyah gabbros is considered here as a manifestation of this event.

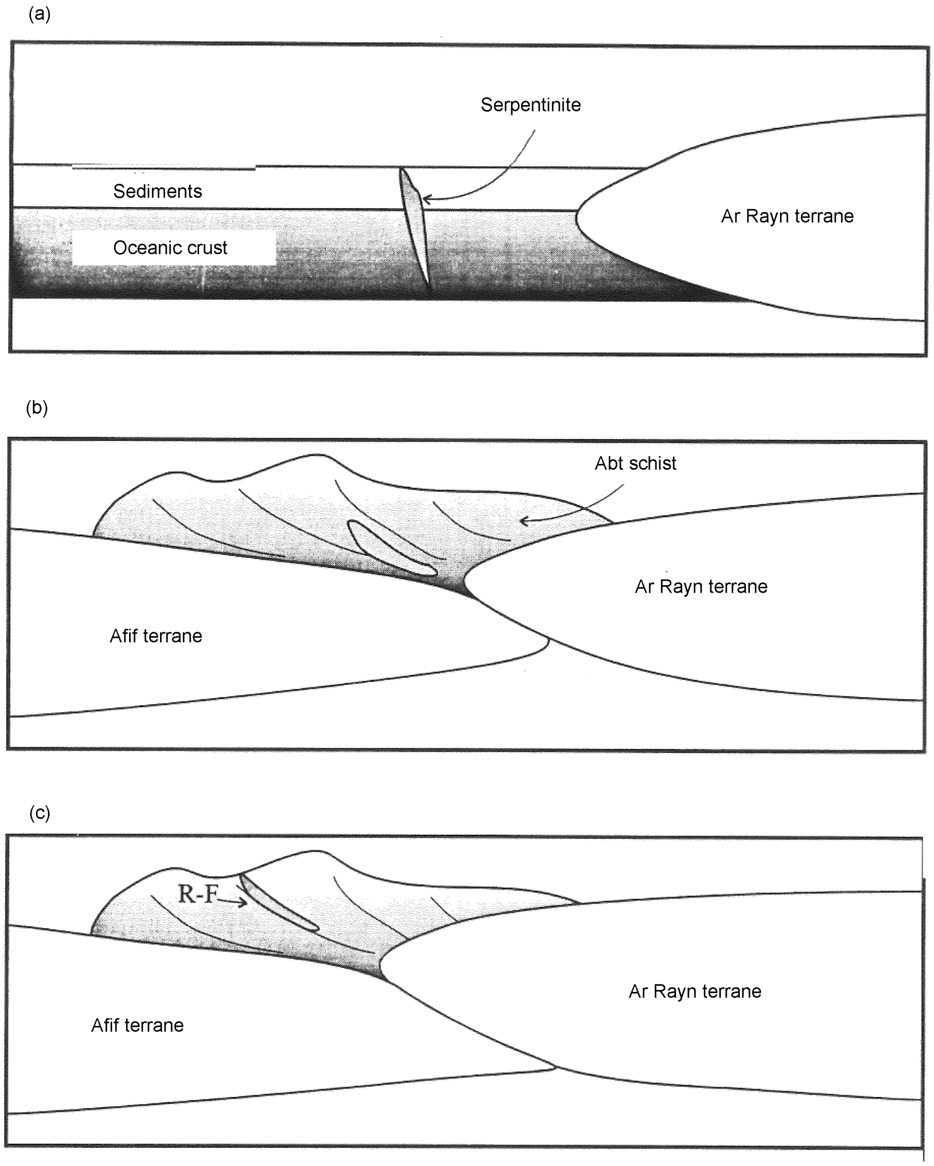


Fig. 3. Successive stages in the metamorphic history of the Ridayniyah melange. (a) Rise of the serpentinite probably as a diapir along a transform fault; (b) Collision of the Afif and Ar Rayn terranes and burial of the melange within the Abt pile; (c) Movement of the serpentinite along the Ridayniyah fault (R-F) to its final position within the Al-Amar suture.

References

[1] Johnson, P.R. and Stewart, I.C.F. "Magnetically Inferred Basement Structure in Central Saudi Arabia." *Tectonophysics*, 245 (1995), 37-52.

[2] Al-Saleh, A.M. "Terrane Amalgamation and the Late Proterozoic Growth of the Eastern Arabian Shield." *Arabian Gulf Journal of Scientific Research*, 16 (1998), 283-295.

[3] Stoeser, D.B. and Stacey, J.S. "Evolution, U-Pb Geochronology, and Isotope Geology of the Pan-African Nabitah Orogenic Belt of the Saudi Arabian Shield". In: El Gaby, S. and Greiling, R. (Eds.), *The Pan African Belt of NE Africa and Adjacent Areas*. Braunschweig vieweg, (1988), 227-288.

[4] Windley, B.F, Whitehouse, M.J, Mahfood, A.O. and Ba-Bitat, M.A.O. "Early Precambrian Gneiss Terranes and Pan-African island Arcs in Yemen: Crustal Accretion of the Eastern Arabian Shield." *Geology*, 23 (1996), 131-134.

[5] Al-Saleh, A.M, Boyle, A.P. and Mussett, A.E. "Metamorphism and $^{40}Ar/^{39}Ar$ Dating of the Halaban Ophiolite and Associated Units: Evidence for Two-stage Orogenesis in the Eastern Arabian Shield." *Journal of the Geological Society*, 155 (1998), 165-175.

[6] Al-Saleh, A.M, and Boyle, A.P. "Neoproterozoic Ensialic Back-arc Spreading in the Eastern Arabian Shield: Geochemical Evidence from the Halaban Ophiolite." *Journal of African Earth Sciences*, 33 (2001), 1-15.

[7] Badri, M. "Crustal Structure of Central Saudi Arabia Determined from Seismic Refraction Profiling." *Tectonophysics*, 185 (1991), 357-374.

[8] Al-Saleh, A.M, and Boyle, A.P. "Structural Rejuvenation of the Eastern Arabian Shield During Continental Collision: $^{40}Ar/^{39}Ar$ Evidence from the Ar Ridayniyah Ophiolitic Melange." *Journal of African Earth Sciences*, 33 (2001), 135-141.

[9] Blundy, J.D. and Holland, T.J.B. "Calcic Amphibole Equilibria and a New Amphibole-plagioclase Geothermometer." *Contributions to Mineralogy and Petrology*, 104 (1990), 208-224.

[10] Blundy, J.D. and Holland, T.J.B. "Non-ideal Interactions in Calcic Amphiboles and Their Bearing on Amphibole-plagioclase Thermometry." *Contributions to Mineralogy and Petrology*, 116 (1994), 433-447.

[11] Laird, J. and Albee, A. "Pressure, Temperature and Time Indicators in Mafic Schist: Their Application to Reconstructing the Polymetamorphic History of Vermont." *American Journal of Science*, 281 (1981), 127-175.

[12] Spear, F.S. "An Experimental Study of Hornblende Stability and Compositional Variability in Amphibole." *American Journal of Science*, 281 (1981), 697-734.

[13] Al-Shanti, A.M. and Gass, I.G. "The Upper Proterozoic Ophiolite Melange Zones of the Easternmost Arabian Shield." *Journal of the Geological Society*, 140 (1983), 867-876.

[14] Bonnati, E. "Serpentinite Protrusions in the Oceanic Crust." *Earth and Planetary Science Letters*, 32 (1976), 107.

[15] Spray, J.G. and Roddick, J.C. "Evidence for Upper Cretaceous Transform Fault Metamorphism in West Cyprus." *Earth and Planetary Science Letters*, 55 (1981), 273-291.

[16] Stern, R.J. "Arc Assembly and Continental Collision in the Neoproterozoic East African Orogen: Implications for the Consolidation of Gondwanaland." *Annual Reviews of Earth and Planetary Science*, 22 (1994), 319-351.

[17] Shackleton, R.M. "The Final Collision Zone Between East and West Gondwana: Where Is It?" *Journal of African Earth Sciences*, 23 (1996), 271-287.

التاريخ التحوّلي لكتل الجابرو ضمن خليط الردينية الأوفيوليتي، شرق الدرع العربي، المملكة العربية السعودية

أحمد محمد الصالح

قسم الجيولوجيا، كلية العلوم، جامعة الملك سعود، ص.ب. ٢٤٥٥،
الرياض ١١٤٥١، المملكة العربية السعودية

(قدّم للنشر في ١٤٢٢/٣/١٤هـ؛ وقبل للنشر في ١٤٢٣/١/٤هـ)

ملخص البحث. يمثل درز الإمار الحد التصادمي بين إقليميْ عفيف والرين في شرق الدرع العربي. تم تدوين منكشفات أوفيوليتية كثيرة من هذا الدرز، وأغلبها مكّون من خليط السربنتينايت الذي يحتوي كتلا من صخور محيطية متنوعة. ينكشف خليط الردينية في حزام طولي ضيق قرب الحافة الشرقية لهذا الدرز. أغلب الكتل هي من السربنتينايت الكتلي مع بعض الجابرو والقليل من البازلت، وكل هذه الصخور موجودة في وسط من السربنتينايت شديد التشوه. يحتوي الجابرو على تجمعات ثانوية تدل على حدوث فترتين من التحوّل، الفترة الأولى هي حادثة محيطية، ولكن الثانية هي عبارة عن مرحلة قصيرة من الضغط المتوسط التي وصلت إلى ظروف سحنة الابيدوت-امفيبولايت. من المعتقد أن هذه الفترة الثانية ناتجة من الاصطدام النهائي بين الإقليمين المتجاورين والذي حدث قبل حوالي ٦١٠ مليون سنة.