The dynamothermal aureole of the Donqiao ophiolite (northern Tibet)

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Abstract: Metamorphic rocks found at the base of the Jurassic Donqiao ophiolite of northern Tibet are interpreted as a basal dynamothermal aureole produced during obduction of the massif. The rocks form a sequence some 8 m thick, varying from high-grade amphibolites at the contact with overlying harzburgites to greenschist facies metasedimentary rocks lower down. The mineral paragenesis is similar to other such aureoles, and indicates that temperatures in excess of 750°C may have been reached during metamorphism. The lack of high-pressure minerals suggests that the rocks were produced by subcretion in a relatively shallow dipping subduction zone. Ar–Ar geochronology on amphibole separates provides dates of 175–180 Ma for the displacement of the ophiolite, significantly older than the age of emplacement estimated from stratigraphic relationships. The ophiolite was clearly obducted very soon after its formation in a suprasubduction zone environment.

Résumé : Les roches métamorphiques trouvées à la base de l'ophiolite de Donqiao d'âge Jurassique, dans le Tibet septentrional, sont interprétées comme une auréole dynamothermique basale produite durant l'obduction du massif. Les roches forment une séquence de quelque 8 m d'épaisseur, variant d'amphibolites de degré élevé au contact des harzburgites sus-jacentes, et plus bas à des roches métasédimentaires de faciès des schistes verts. La paragenèse des minéraux est similaire à celle de d'autres auréoles, et elle indique que les températures au-dessus de 750°C ont pu être atteintes durant le métamorphisme. L'absence de nouveaux minéraux de pression élevée suggère que les roches furent engendrées par une subcrétion dans une zone de subduction qui a plongé à une profondeur relativement faible. La géochronologie Ar–Ar sur des concentrés d'amphibole fournit les dates de 175–180 Ma pour le déplacement de l'ophiolite, soit un âge considérablement plus ancien que celui déduit des relations stratigraphiques. Il n'y a pas de doute que l'ophiolite fut obductée peu de temps après sa formation dans une zone tectonique de suprasubduction. [Traduit par la rédaction]

Introduction

Metamorphic rocks found beneath the mantle peridotites of the Donqiao ophiolite of Tibet are considered to represent a dynamothermal aureole produced during initial displacement of oceanic lithosphere and its obduction onto the continental margin of the Qiantang terrane in the Mesozoic (cf. Malpas et al. 1973; Coleman 1977; Malpas 1979; Jamieson 1980). We have undertaken a study of these rocks to determine their conditions of formation and their age. Here, we describe the petrology and mineralogy of the metamorphic rocks, present new compositional data from the mineral phases, and report $^{40}Ar/^{39}Ar$ ages of hornblendes from amphibolites. The data may be used to model the origin of the aureole and place constraints on the tectonic evolution of the region.

Ophiolitic dynamothermal aureoles

The "obduction" of ophiolites and their incorporation into mountain belts is a complex tectonic process, which can broadly be divided into two stages (Malpas and Stevens 1977). The first stage involves the "displacement" of oceanic crust and upper mantle by subduction and underthrusting of oceanic lithosphere and the second, the "emplacement" of the ophiolite thrust slices onto continental margins, usually accompanied by some form of gravitational sliding and mélange formation. In some ophiolite complexes, especially among those that are well preserved and that are complete sections of the crust and upper mantle, it is not uncommon to find metamorphic rocks associated with the mantle peridotites. Previously described occurrences include those in Spain (Dickey 1970), southwest England (D.H. Green 1964), Serbia (Karamata 1968), Oman (Searle and Malpas 1980, 1982), Newfoundland (Malpas 1979; Jamieson 1980), and Cyprus (Malpas et al. 1992). At these localities, the metamorphic rocks are best preserved at the base of the ophiolites, or may occur as blocks and knockers in ophiolitic mélange where extensive transport of the thrust slices has dismembered the ophiolite stratigraphy. Commonly referred to as dynamothermal aureoles, the rocks can range in metamorphic grade from granulite facies to subgreenschist facies, and are considered to have been produced during the displacement stage of ophiolite obduction. Based on observations made at locations such as those listed above, a number of criteria have been established that characterize such aureoles (Searle and Malpas 1980):

1. The metamorphic rocks occupy a consistent stratigraphic position at the base of the ophiolite and underlie a thick ultramafic unit.

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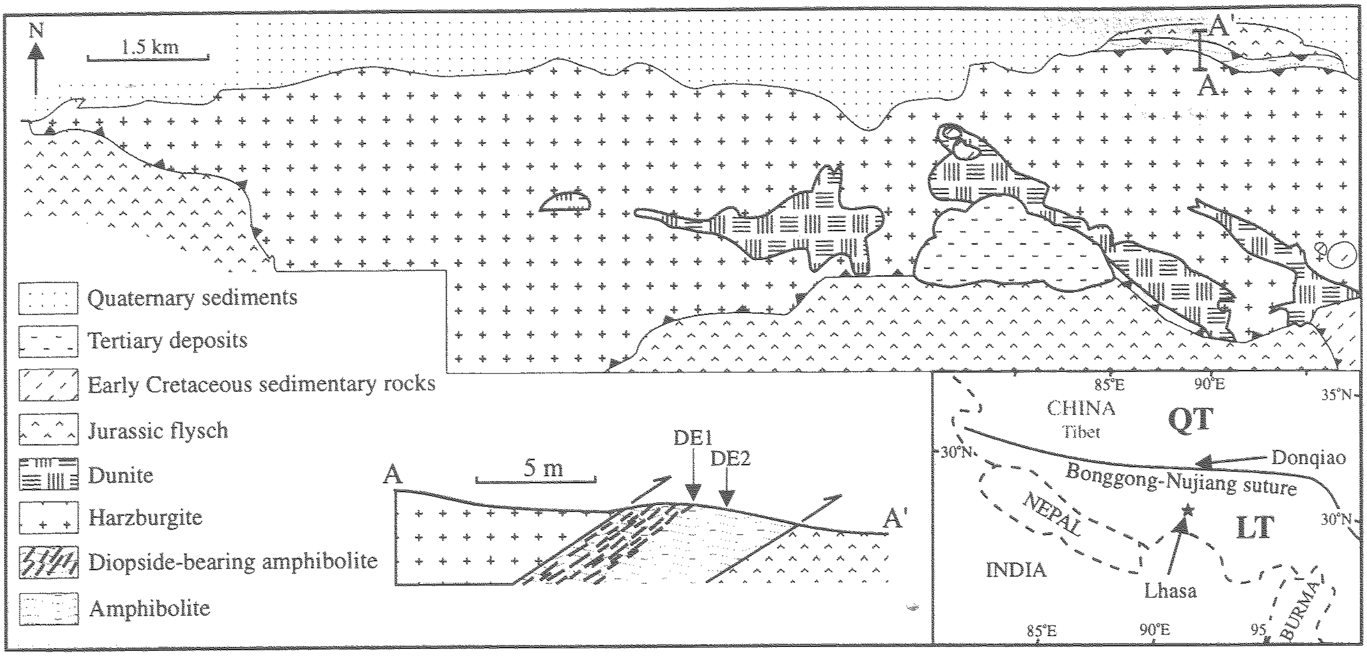
Fig. 1. Geological map of the Donqiao ophiolitic massif and cross section of its dynamothermal aureole. LT, Lhasa terrane; QT, Qiangtang terrane.



2. There is a general lack of intrusive phenomena (e.g., dykes, xenoliths, chilled margins) associated with the contact between the ultramafic and metamorphic rocks.
3. The metamorphic complexes characteristically have a narrow width, suggesting either a high thermal gradient, and (or) the selective removal of parts of the sequence during thrusting.
4. Where there has been no dismemberment, orientations of the metamorphic fabrics and the conditions of their formation are essentially the same in the basal ultramafic rocks and the metamorphic rocks.
5. There is rarely any evidence of high-pressure metamorphism in the aureole rocks. Neither jadeite, kyanite glaucophane, or lawsonite are reported and the assumption must be that metamorphism took place at shallow levels, perhaps by subcretion above a shallow-dipping subduction zone.
6. Where best preserved, such as in Newfoundland or Oman, the metamorphic rocks show an inverted metamorphic zonation from high-grade granulite or upper amphibolite facies immediately beneath the mantle peridotites to subgreenschist facies at lower levels.

Metamorphic rocks in these aureoles are generally polyphase deformed and exhibit mylonitic fabrics in places. Protoliths appear to have been basic igneous rocks, tuffaceous rocks, and a variety of sedimentary rocks, including siltstones, radiolarian cherts, and pelagic limestones. These have been transformed into garnetiferous amphibolites, actinolite, chlorite schists, micaceous schists, and marbles. In most cases, the low glaucophane content of the amphiboles (Malpas 1979; Searle and Malpas 1980, 1982; Ghent and Stout 1981; Malpas et al. 1992) and low jadeite composition of clinopyroxenes suggest relatively low pressures of crystallization, particularly in the presence of plagioclase and quartz. This seems a common and, as yet, unexplained feature of ophiolitic dynamothermal aureoles. Temperature estimates obtained from element distribution coefficients in coexisting minerals suggest maxima of the order of 700–800°C.

The metamorphic rocks of dynamothermal aureoles offer a unique opportunity to place age restraints on the initiation of ophiolite obduction. They are most amenable to $^{40}Ar/^{39}Ar$ geochronology, particularly on amphibole separates. Ages so determined have indicated that in many cases, initial ophiolite displacement closely followed the genesis of the oceanic lithosphere at a spreading centre. Residual heat from the recently formed ophiolite must have provided the dominant heat source for metamorphism, and frictional heating is unlikely to have supplemented this to any great extent (Malpas 1979).

The Donqiao ophiolite

The Donqiao ophiolite of northern Tibet lies along the Bangong–Naijiang suture (BNS), which separates the Lhasa and Qiangtang terranes of southwestern China (Fig. 1). A Jurassic age has been inferred for the complex from radiolaria in associated cherts. In addition, the ophiolite is overlain unconformably by shallow-water limestones and terrestrial sandstones of earliest Cretaceous age, which were deposited after its emplacement. These data suggest that the ophiolite was obducted in latest Jurassic to earliest Cretaceous time, about 140 Ma (F. Wang and Tang 1984). The ophiolite is considered to have formed in a suprasubduction zone environment (Girardeau et al. 1984, 1985, 1986), and like many other ophiolites formed in this way, was apparently emplaced very soon after its genesis.

Metamorphic rocks are closely associated with the diabases and peridotites of the Donqiao ophiolite. Girardeau et al. (1986) reported the chemical compositions of amphiboles from foliated amphibolites beneath the diabase complex, as well as amphiboles in the diabases of the nearby Baila massif. Beneath the harzburgites of the Donqiao massif, metamorphic rocks range from amphibolites to greenschist facies in an inverted metamorphic sequence not unlike that of the classic Newfoundland localities (Malpas 1979; Jamieson 1980).

At Donqiao, blocks of pillow lava, cumulate rocks, and mantle peridotites occur in a belt tectonically bounded by Jurassic phyllites and sandstones to the north and by limestones to the south (Girardeau et al. 1984). The Donqiao massif itself is a block of harzburgite that extends approximately 18 km along the strike of the belt and ranges from 3 to 5 km in width. The Early Cretaceous shallow-water and terrestrial deposits that unconformably overlie the massif consist of conglomerates at the base containing chromites derived from the ultramafic massif, succeeded by sandstones and limestones.

The harzburgites are coarse-grained rocks with granular to porphyroclastic textures, composed of olivine and orthopyroxene with small amounts of clinopyroxene and chromite. Pods and lenses of dunite, many hosting small chromitite bodies, and narrow pyroxenite dykes are also present.

The metamorphic rocks form a narrow ridge that extends for approximately 2 km along the northern margin of the massif (Fig. 1). They are typically dark grey to greenish grey and exhibit prominent banding. The metamorphic sequence is nowhere more than 8–9 m wide and shows considerable variation in metamorphic grade over this distance. Immediately adjacent to the ophiolite is a banded pyroxene hornfels composed of light green diopside crystals in a matrix of brown, microcrystalline material. In many samples the diopside occurs as bands of subhedral crystals up to 1 mm in dimension, but in rare cases may form relatively large porphyroblasts (2–3 mm). A few centimetres from the contact with the harzburgite, the diopside is partially retrograded to brown hornblende. Replacement appears to be confined to narrow zones, resulting in a banded rock with pale green layers rich in diopside and darker brown layers composed dominantly of brown amphibole. In the diopside-rich layers, brown amphibole is seen replacing the pyroxene along crystal margins and filling interstices between the crystals, apparently a retrograde effect. Garnet has been found in one sample (DM5) at 45 cm from the contact. Moving away from the peridotites, replacement of pyroxene by amphibole increases, and the rocks become amphibole mylonites in which a few narrow bands of granular diopside and rare diopside porphyroblasts are preserved. The brown hornblende forms small, generally equidimensional grains, between 0.2 and 0.4 mm in size, which show little preferred orientation, although the rock has an overall banded appearance. At a distance of approximately 1 m from the contact, no diopside is present and small amounts of brown biotite coexist with the brown hornblende, neither of which shows a prominent lineation. At approximately 1.5 m from the contact, brown hornblende is replaced by green hornblende, and by 2 m, the amphibolites are dominated by green hornblende with small amounts of albite and apatite. The rocks no longer display the banded appearance so prevalent higher up, although the amphibole is more acicular than the brown variety and displays a pronounced mineral lineation. Minor amounts of green chlorite rim some of the hornblende crystals.

Near the base of the aureole, 7–8 m from the contact with the peridotites, tight isoclinal folds are apparent. Here, the rocks are well-foliated quartz–mica schists in which relict protolith textures are still rarely preserved. In thin section, the hinges of folds are marked by concentrations of microcrystalline quartz. Fold limbs are highly sheared and attenuated. Sense of shear is clearly demonstrated by the development of C–S fabrics and ''fish structures.'' Relatively large (>1 mm) angular grains may represent relict crystals of rock fragments in the protolith, which at this level appear to have been volcanogenic sedimentary rocks. Such rocks are exposed in outcrops farther to the north, but in the immediate vicinity of the ophiolite are covered by Quaternary alluvium.

All of the rocks of the aureole are cut by narrow (1–3 mm wide) veinlets of zoisite and minor calcite. These are completely undeformed and typically cut the fabric of the host rocks at high angles. They presumably formed under brittle deformation conditions during thermal relaxation of the metamorphic rocks after thrusting and exhumation.

Mineralogy

Microprobe analyses of amphiboles, pyroxenes, plagioclase, mica, garnet, and zoisite from metamorphic rocks are presented in Table 1.

Amphiboles are collectively magnesiohornblendes (Fig. 2), but the brown amphiboles are markedly more Ti rich than the green varieties. In the presence of sphene, ilmenite, and magnetite, this equates with higher temperatures of metamorphism (Leake 1965; Raase 1974). The amphiboles cluster around the tremolite–actinolite – Al-pargasite join (Fig. 3), corresponding to a high-temperature rather than a high-pressure metamorphic trend. Clinopyroxene occurs only in the 2.5 m of amphibolites closest to the peridotites. All of the pyroxenes analyzed are diopside, with very little chemical variation. Plagioclases from greenschist facies metasedimentary rocks are clearly albitic in composition. In the amphibolites, the plagioclases are of intermediate composition. Garnet has only been recognized in one sample of amphibolite (DM5), collected 45 cm from the contact with the peridotites. It has an average composition of $Gr_{66}Al_{32}Py_1Sp_1$, suggesting the possibility of some retrogression to hydrogrossular, presumably as a result of rodingitization.

The mineral paragenesis, which occurs over a distance of 8 m, is similar to that described from the aureoles of the Bay of Islands ophiolite in western Newfoundland (Malpas et al. 1973; Malpas 1979) and Semail ophiolite of Oman (Searle and Malpas 1980), and suggests increasing temperatures of metamorphism towards the harzburgite contact (Jamieson 1980). However, at first glance, the metamorphic gradient of the Donqiao aureole appears steeper than that of the Bay of Islands. Prograde hornblende and intermediate plagioclase suggest that minimum temperatures of at least 475°C were achieved. The lack of prograde chlorite close to the peridotite contact suggests temperatures in excess of 550°C (Apted and Liou 1983). The occurrence of diopsidic clinopyroxene near the contact suggests that here temperatures might have reached as high as in the granulite facies, in excess of 750°C, assuming the oxygen fugacity was equivalent to the quartz–

Table 1. Representative analyses of metamorphic minerals from the aureole of the Donqiao massif.

Sample:	DM1	DE2	DM18	DM1	DM5	DM18	DE1	DM3	DM5
Mineral:	Amph B	Amph G	Amph G	Diop	Diop	Ab	Zo	Biot	Gar
Distance (m):	0.00	1.00	7.00	0.00	0.45	7.00	1.00	0.15	0.45
SiO_2	45.87	47.17	47.23	52.30	52.69	69.15	43.58	43.08	36.73
TiO_2	1.66	0.89	0.62	0.28	0.19	0.03	0.00	2.54	1.15
Al_2O_3	9.62	8.27	9.70	1.77	1.34	20.22	23.52	10.21	7.68
FeO	13.47	16.20	14.97	9.95	10.34	0.23	0.54	15.55	19.92
MnO	0.23	0.27	0.28	0.24	0.29	0.02	0.05	0.18	0.41
MgO	13.95	12.44	13.47	14.47	13.33	0.08	0.20	12.04	0.23
CaO	11.09	12.13	10.84	21.27	21.84	0.44	25.68	11.37	32.18
Na_2O	1.80	1.11	1.33	0.46	0.76	10.16	0.10	1.85	0.09
K_2O	0.46	0.14	0.10	0.01	0.01	0.18	0.03	0.87	0.00
P_2O_5	0.08	0.14	0.04	0.02	0.00	0.15	0.12	0.00	0.00
Total	98.23	98.76	98.58	100.75	100.79	100.65	93.82	97.68	98.40
Si	6.98	7.20	7.15	1.94	1.96	2.98	3.46	6.16	6.26
Ti	0.19	0.10	0.07	0.00	0.00	0.00	0.00	0.27	0.14
Al^{IV}	1.01	0.79	0.84	0.05	0.03	0.01	0.00	0.00	0.00
Al^{VI}	0.71	0.69	0.88	0.02	0.02	1.01	2.20	1.72	1.54
Fe	1.71	2.07	1.89	0.30	0.32	0.00	0.03	1.86	2.84
Mn	0.03	0.03	0.03	0.00	0.00	0.00	0.00	0.02	0.05
Mg	3.16	2.83	3.04	0.80	0.74	0.00	0.02	2.56	0.05
Ca	1.81	1.98	1.75	0.84	0.87	0.02	2.18	1.74	5.88
Na	0.53	0.32	0.39	0.03	0.05	0.85	0.01	0.51	0.02
K	0.09	0.02	0.01	0.00	0.00	0.00	0.00	0.15	0.00
P	0.01	0.03	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Sum	16.26	16.10	16.10	4.02	4.02	4.92	7.94	15.03	16.82
No. of O	24	24	20	6	6	8	12.5	22	24

Notes: Amph B, brown amphibole; G, green amphibole; Diop, diopside; Ab, albite; Zo, zoisite; Biot, biotite; Gar, garnet.

Fig. 2. Chemical classification of the amphiboles from the aureole of the Donqiao massif. Hbl, hornblende; Tsch, tschermakite.

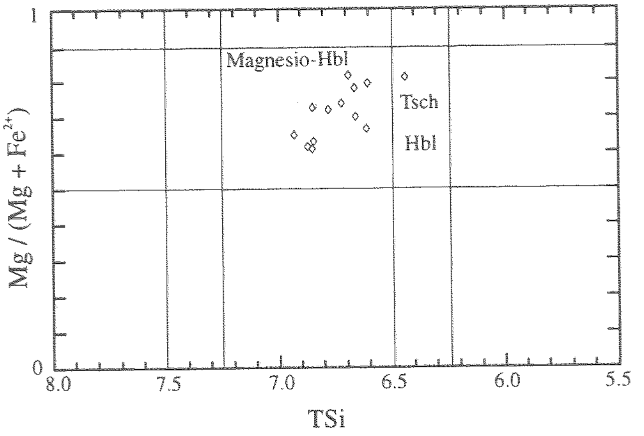
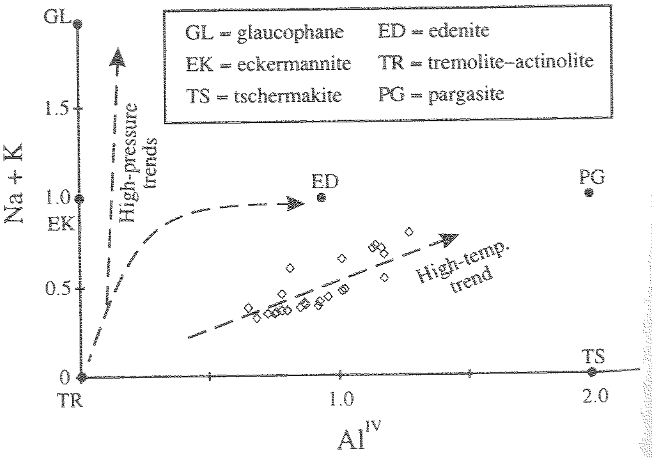


Fig. 3. Composition of amphiboles from the Donqiao metamorphic aureole in relation to high-temperature and high-pressure metamorphic trends.



fayalite–magnetite buffer (Spear 1981). However, no orthopyroxene such as in the Newfoundland examples, has been found and it is thus improper to call the rocks granulites.

Because there are no aluminosilicates and the mineral assemblage shows high variance, meaningful thermobarometry is difficult. Following the pioneer experimental work of Raheim and Green (1974, 1975), the distribution of iron and magnesium in coexisting garnet and clinopyroxene has been used as a geothermometer by various authors (e.g., Ellis and Green 1979; Graham and Powell 1984; Pattison and Newton 1988; T.H. Green and Adam 1991). The distribution coefficient $K_D = (FeO/MgO)_{gar}/(FeO/MgO)_{cpx}$ was originally thought to decrease with increasing temperature and be relatively insensitive to changes in chemistry reflected in minor components of the pyroxene or garnet solid solutions. However, the recent review by Berman et al. (1995) shows that K_D values depend on pressure and Ca content of garnet, as well as on temperature. An additional difficulty with using microprobe analyses is the estimation of actual Fe_2O_3/FeO ratios. If the rare Donqiao garnets are calculated as hydrogrossular, then K_D values indicate a temperature in the range of 280°C at 45 cm from the contact. Even applying all of the attendant caveats (Searle and Malpas 1982), this seems low for a garnet amphibolite produced at approximately 4 kbar (400 MPa) pressure (D.H. Green and Ringwood 1967), and confirms that the garnet and clinopyroxene are no longer in equilibrium as a result of retrogression. Indeed, given that thermobarometry using garnet and clinopyroxene–hornblende is so dependent on Ca content of the garnet, little sense can be made using the compositions here, which are so clearly a result of rodingitic alteration. Previous estimates of metamorphic temperatures for similar, unaltered assemblages from the Semail ophiolite of Oman are of the order of 800°C (Searle and Malpas 1980; Ghent and Stout 1981).

$^{40}Ar/^{39}Ar$ geochronology

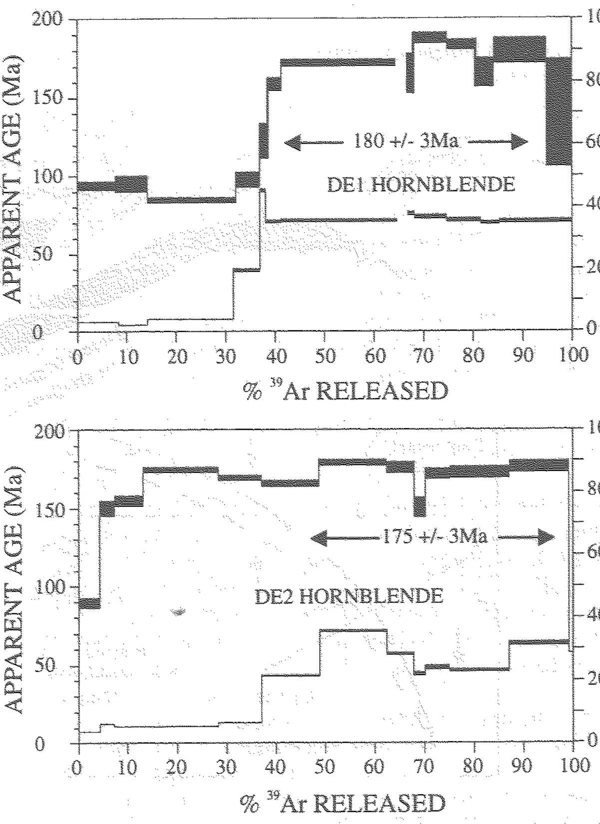
Two amphibole separates (DE1 and DE2) from the aureole have been analyzed for argon isotopes. The samples were taken from 1 and 2 m from the contact respectively and localities are shown in Fig. 1. The samples were irradiated in the McMaster University nuclear reactor and argon isotopic analyses were undertaken using a VG 3600 mass spectrometer coupled to an internal tantalum resistance furnace of the double-vacuum type. Hornblende MMhb-1, with an assumed age of 520 ± 2 Ma (Samson and Alexander 1987), was used as a standard for all analyses. Other experimental procedures follow those described by Muecke et al. (1988). Errors quoted are the 2σ analytical uncertainties; the estimated error in the irradiation parameter, J, is included, but no allowance is made for uncertainty in the age of the standard or in the values of the decay constants.

Both samples yield relatively discordant age spectra and variable $^{37}Ar/^{39}Ar$ (proportional to Ca/K). Initial gas, especially in the case of DE1, is characterized by low $^{39}Ar/^{39}Ar$ ratios and low, ca. 80–90 Ma, ages. The final approximately 50% of gas released from both samples gave more consistent ages (180 ± 3 Ma for DE1; 175 ± 3 Ma for DE2), along with higher $^{37}Ar/^{39}Ar$ ratios (Fig. 4).

Discussion

In many ways, the dynamothermal aureole of the Donqiao ophiolite is not unlike occurrences elsewhere in the world. In all of these, however, a major question is why there are no high-pressure metamorphic minerals. If indeed the complexes were produced during subduction, then blueschist facies minerals such as lawsonite and glaucophane might normally be expected. Their absence must relate to the depth and temperature of metamorphism and suggests a relatively shallow dipping subduction zone and high heat flow. Such conditions might be associated with oblique subduction or subduction "rollback," which facilitates ophiolite genesis by suprasubduction spreading (Fig. 5). It is to be remarked that all of the previously described occurrences of dynamothermal aureoles appear to be associated with suprasubduction zone ophiolites (references cited above). The subduction rollback model would certainly favour crustal extension and thinning immediately above the subduction zone, and high heat flow is to be expected in an area of magmatic activity. The process of subsequent exhumation of the subcreted metamorphic rocks is still not fully understood, but no doubt would be facilitated in a zone of crustal extension and mantle upwelling. This, however, remains an outstanding problem.

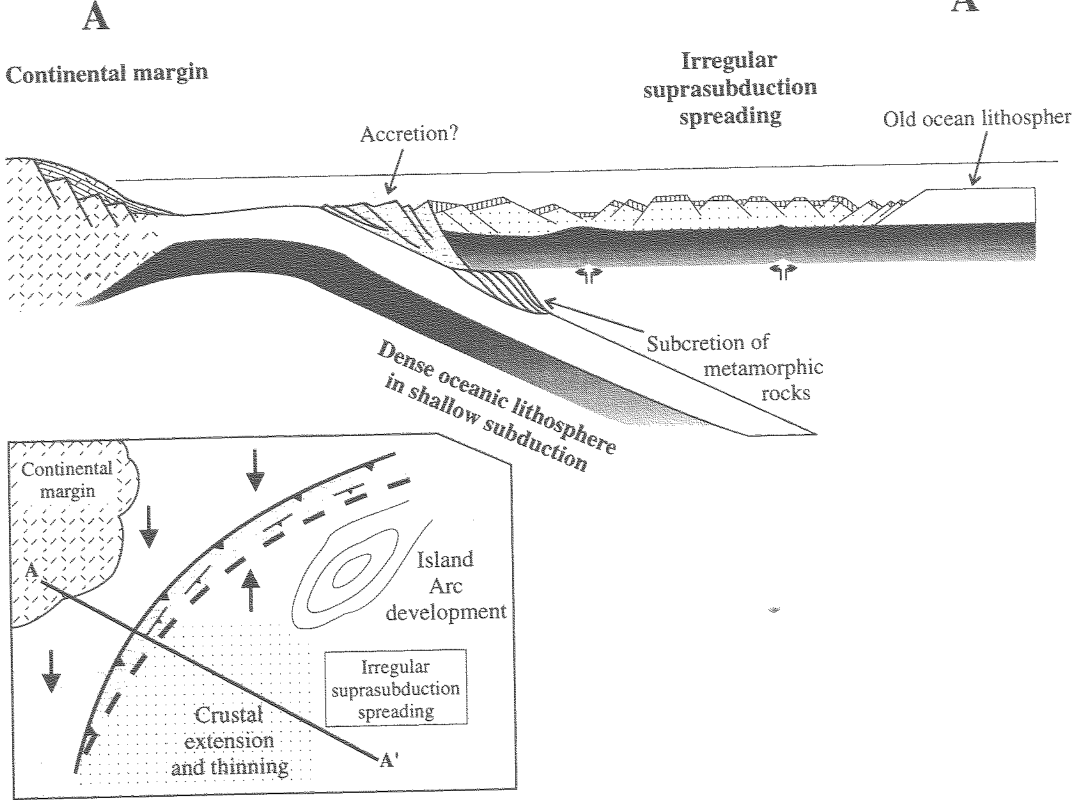
Fig. 4. $^{40}Ar/^{39}Ar$ spectra of the hornblendes (DE1 and DE2) from the aureole of the Donqiao massif.



Compared with the dynamothermal aureoles of the White Hills and Bay of Islands in Newfoundland, the Donqiao sequence is considerably thinner. It is unreasonable that this is simply due to a higher thermal gradient during metamorphism; rather, it is more likely a result of structural thinning of the metamorphic sequence during emplacement. Such reduction in the thickness of the complex may have taken place relatively early along the amphibolite-grade mylonite zones close to the present contact with the peridotites.

Ages of radiolarites and fossiliferous flysch deposits directly associated with the Donqiao ophiolite indicate that it was formed in the Jurassic (F. Wang and Tang 1984). On the basis of unconformably overlying Early Cretaceous sedimentary rocks, obduction is inferred to have occurred in latest Jurassic – earliest Cretaceous time, ca. 140 Ma (Girardeau et al. 1984, 1985, 1986; F. Wang and Tang 1984; X. Wang et al. 1984). However, the new Ar–Ar ages presented here provide a 175 Ma displacement age for the ophiolite. This Middle Jurassic age correlates well with a U–Pb metamorphic age of 171 ± 6 Ma for zircon and sphene from a K-feldspar–biotite–chlorite–epidote gneiss at Anduo, some 50 km east of Donqiao (Xu et al. 1985), suggesting that both metamorphic sequences were formed by the collision of the Lhasa and Qiantang terranes. The disparity in radiometric and stratigraphic ages of ophiolite obduction clearly indicates

Fig. 5. Model for the generation of the Donqiao ophiolite and its dynamothermal aureole in a suprasubduction zone setting.



the importance of obtaining accurate isotopic ages with which to date the displacement event. The stratigraphic evidence simply provides the minimum age for final emplacement of the thrust slices.

Ar–Ar ages of other volcanic rocks (basalts, andesites, and dacites) in the Donqiao area range from 80 to 120 Ma (Maluski et al. 1985, 1988; Coulon et al. 1986), much younger than the emplacement of the ophiolite and the collision between the two terranes. These volcanic rocks must be related to intrablock tectonic events.

Acknowledgments

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