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^{40}AR/^{39}AR DATING OF PLUTONIC ROCKS FROM JERSEY, CHANNEL ISLANDS

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Two ^{40}Ar/^{39}Ar hornblende cooling ages have been determined from undeformed and unmetamorphosed plutonic rocks exposed on Jersey. Appinite from Le Nez (south-eastern plutonic complex) records a post-magmatic cooling age of 563 ± 1 Ma which defines a limit for deposition and subsequent regional deformation and metamorphism of host Brioverian volcanosedimentary sequences. A 472 ± 1 Ma post-magmatic cooling age was determined for hornblende from granodiorite at Sorel Point (north-eastern plutonic complex) and confirms previous isotopic evidence suggesting Ordovician magmatism on Jersey.

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INTRODUCTION

A variety of granite and associated basic to intermediate intrusions comprise three plutonic complexes exposed on the Channel Island of Jersey. These were emplaced into a deformed and metamorphosed volcanosedimentary sequence which has been correlated with Brioverian successions exposed in north-western France. Previously reported Rb-Sr whole-rock isochron ages from granites exposed on Jersey have been interpreted to suggest a broad continuum of plutonic activity from c. 550 to c. 425 Ma (Bland, 1984, 1985). K-Ar ages (Adams, 1976) for hornblende- and biotite-bearing rocks also suggest a protracted history. However, the reliability of the previously published data has sometimes been questioned. Possible non-closed system Rb-Sr behaviour resulting from magmatic and post-magmatic processes, is indicated by petrographic characteristics, and may mean that published ages for the granites are unreliable. The K-Ar ages, obtained by conventional methods, may have been affected by partial isotopic disturbance and/or excess argon, so that it is unclear how reliably any given age records initial emplacement. In an effort to better evaluate previously reported geochronologies, ^{40}Ar/^{39}Ar mineral analyses have been carried out. The advantage of this method is that progressive heating of a single sample evolves separate batches of Argon (Ar) which are dated independently. Assessment of the resulting age spectrum allows identification of contamination, partial isotopic rejuvenation and excess argon so that greater confidence may be placed on the interpretation of the data.

GEOLOGICAL SETTING

The Cadomian orogen in the North Armorican Massif developed within a late Precambrian active continental margin setting (D'Lemos *et al.,* 1990; Dupret *et al.,* 1990; Rabu *et al.,* 1990). In northern parts of the massif early Cadomian magmatic arc-related plutons were deformed and metamorphosed along with host Palaeo-Proterozoic basement prior to c. 600 Ma (Dallmeyer *et al.,* 1991a). Volcanic sequences and sedimentary rocks mainly derived from Cadomian arcs, were deposited into marginal and/or back-arc basins to form the Brioverian succession (Rabu *et al.,* 1990; Dupret *et al.,* 1990). Regional deformation and metamorphism of the Brioverian succession around the Baie de St Brieuc occurred c. 590-570 Ma (Guerrot and Peucat, 1990; Dallmeyer *et al.,* 1991b). The age of Brioverian volcanism in some areas (e.g. Jersey) has been argued to be significantly younger (c. 530 Ma, Duff, 1978). Arc-related calcalkaline plutonism, which is post-tectonic with regards to local host rocks, is recorded in the Channel islands, at La Hague and in the Trégor region (Brown *et al.,* 1990). The precise timing of this plutonism has been debated (e.g. Brown *et al.,* 1990; Dallmeyer *et al.,* 1992).

Recent ^{40}Ar/^{39}Ar mineral age data (Dallmeyer *et al., 1992)* suggest a c. 570 Ma age for post-tectonic magmatism on Guernsey and bring into question the geological significance of previously published Rb-Sr whole-rock isochron ages which span the Cambrian through to the Silurian (Adams, 1967, 1976; Bland, 1984, *1985;* D'Lemos, 1987a,b; Power *et al.,* 1990).

GEOLOGY OF JERSEY

Low-grade metasedimentary rocks of the Jersey Shale Formation and conformably overlying metavolcanic rocks of the Jersey Andesite and Jersey Rhyolite Formations are exposed along central portions of the Jersey coast (Figure 1) and in central parts of the island. They exhibit open north-south-trending folds and an associated cleavage which developed during anchizone to low greenschist, facies metamorphism.

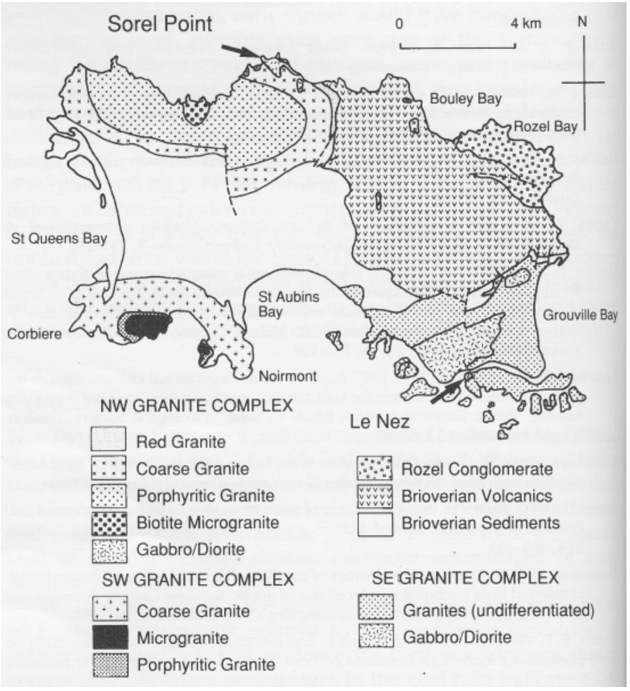

Figure 1: Geological map of Jersey (after Bland, 1984) showing sample localities.

A Rb-Sr whole-rock isochron age of 533 ± 16 Ma has been reported from the Jersey Andesite Formation (Duff, 1978), although the reliability of this age as dating eruption has been questioned (e.g. Bishop and Mourant, 1979). Plutonic complexes are exposed in south-eastern, south-western and north-western Jersey. They are composite and together comprise a range of compositions from olivine gabbro, through hornblende gabbro, diorite and granodiorite, to granite. Detailed descriptions of the complexes have been provided by Wells and Wooldridge (1931); Bland (1984) and Salmon (1987). Early workers attributed the complex nature of contact zones between basic and granite units and the origin of intermediate lithologies to a solid-state metasomatic alteration of basic rock during emplacement of granitic magmas (e.g. Wells and Wooldridge, 1931; Bishop and Key, 1983). Recent workers (Topley and Brown, 1984; Salmon, 1987, 1991) and argue that field, petrographic and geochemical features are primary and result from interaction between co-existing magmas. The plutonic complexes are generally undeformed and unmetamorphosed. Contacts are discordant to host rock structures. Contact metamorphic porphyroblasts overgrow the pre-existing cleavage in semi-pelitic host rocks. Together, these features demonstrate that the igneous complexes are younger than the host volcano-sedimentary sequences. In north-eastern Jersey, the post-orogenic Rozel Conglomerate Formation unconformably overlies the Jersey Andesite Formation.

PREVIOUS GEOCHRONOLOGY

The first Rb-Sr isotopic studies of Jersey plutons were undertaken by Adams (1967, 1976). Bland (1984) considered these whole-rock isochron ages unreliable because they were based on analyses of different components from each complex which could not be confidently assumed to have isotopically homogenized during formation. Bland (1984, 1985) reported results of Rb-Sr whole-rock analyses of six granitic units in the south-western and north-western complexes identified from geochemical and petrographic characteristics and considered to represent discrete isotopically homogenized magma pulses. The span of ages suggested a punctuated continuum of plutonic activity in Jersey from the Cambrian to Silurian. Although Bland's (1985) data were analytically precise, the geological significance of the ages may be questioned on a number of grounds. Internal contacts between several units within individual complexes are gradational or irregular, suggesting penecontemporaneous magma mobility which is inconsistent with significant time periods between emplacement of individual magma pulses. The granites display abundant textural evidence which suggest variable inhomogeneous mixing. Therefore, individual magma pulses may not have been isotopically homogenized. Widespread sericitization of feldspar, chloritization of mafic phases, and locally developed cataclastic textures (associated with mineralized fault zones) demonstrate significant post-magmatic alteration and indicate the possibility of post-magmatic Rb and/or Sr redistribution.

Adams (1967, 1976) reported conventional K-Ar hornblende and biotite ages for various lithologies of the plutonic complexes which range between c. 580 and c. 440 Ma. In conjunction with Rb-Sr wholerock isochron and mineral ages, the data were interpreted by Adams (1976) to record periods of plutonism at c. 570 and c. 520-480 Ma. The span of K-Ar ages was suggested to reflect protracted cooling.

ANALYTICAL METHODS

Hornblende was separated from crushed and size-fractioned samples by standard magnetic and heavy-liquid techniques. Final purification was achieved by hand picking. The concentrates were wrapped in aluminium foil packets, encapsulated in sealed quartz vials and irradiated for 40 h at the TRIGA Reactor at the US Geological Survey, Denver. Variations in the flux of neutrons along the length of the irradiation assembly were monitored with standards. The samples were incrementally heated until fusion in a double-vacuum resistanceheated furnace, following methods described by Dallmeyer and GilIbarguchi (1990). Measured isotopic ratios were corrected for total system blanks and the effects of mass discrimination. Interfering isotopes produced during irradiation were corrected using the factors reported by Dalrymple *et al.* (1981) for the TRIGA Reactor.

Apparent ^{40}Ar/^{39}Ar ages were calculated from corrected isotopic ratios, following the methods described by Dallmeyer and Keppie (1987). Intralaboratory uncertainties have been calculated by statistical propagation of uncertainties associated with the measurement of each isotopic ratio (at 2 SD of the mean) through the age equation. Interlaboratory uncertainties are c. 1.25 to 1.5% of the quoted age. Total-gas ages have been computed for each sample by appropriate weighting of the age and per cent ^{39}Ar released within each temperature increment. A 'plateau' is considered to be defined if the ages recorded by two or more contiguous gas fractions (with similar apparent K/Ca ratios), each representing >4% of the total ^{39}Ar evolved (and together constituting >50% of the total quantity of ^{39}Ar evolved), are similar within ± 1% intralaboratory uncertainty. Analysis of the MMhb-1 standard indicates that apparent K/Ca ratios may be calculated through the relationship (0.518 ± 0.005) x ^{39}Ar/^{37}Ar corrected. Portionsof the analyses have been plotted on ^{36}Ar/^{40}Ar versus ^{39}Ar/^{40}Ar isotope correlation diagrams. Regression techniques followed the methods of York (1969). A mean square of the weighted deviates (MSWD) has been used to evaluate isotopic correlations.

RESULTS

Although samples were collected from all major lithologies on Jersey, most could not be dated reliably by the ^{40}Ar/^{39}Ar method because separation of suitable mineral concentrates was impossible. In most granitic lithologies, pure hornblende or biotite concentrates could not be separated because of partial mineralogical replacement resulting from magmatic and post-magmatic processes, while in basic lithologies, hornblende is commonly intimately associated with clinopyroxene. Pure hornblende concentrates were prepared from two samples where field and petrographic evidence allow confident assignment of the hornblende to a primary igneous origin. Hornblende was extracted from appinite pegmatite at Le Nez and from hornblende-biotite granodiorite at Sorel Point (Figure 1). ^{40}Ar/^{39}Ar analytical data are listed in Table 1 and are portrayed as incremental age and apparent K/Ca spectra in Figures 2 and 3.

APPINITE, LE NEZ: SOUTH-EASTERN PLUTONIC COMPLEX

Hornblende-plagioclase pegmatite was collected from an appinitic pod associated with layered gabbroic and dioritic rocks at Le Nez (Bishop and Key, 1983, 1984; Topley and Brown, 1984). Slightly zoned brown hornblende (up to 10 x 30 mm) occasionally exhibits a hollow-core

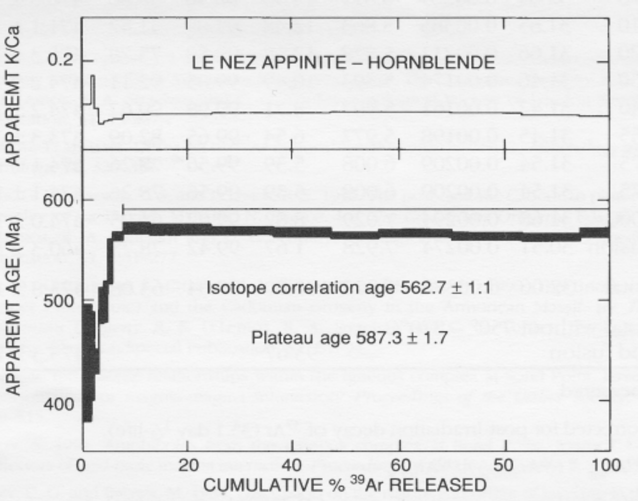

Figure 2: ^{40}Ar/^{39}Ar apparent age and apparent K/Ca spectra for a hornblende concentrate from appinite at Le Nez, south-east Jersey. Analytical uncertainties (2σ, intralaboratory) are represented by vertical width of bars, horizontal width of bars show % Ar released during each successive heating step. Experimental temperatures increase from left to right. For this and Figure 3, isotope correlation ages are given for plateau increments defined by the horizontal line above the spectra.

TABLE 1: ^{40}Ar/^{39}Ar analytical data for incremental heating experiments on two hornblende concentrates from posttectonic plutons, Jersey, Channel Islands

Le Nez Appinite

J = 0.009160

Release temp (°C)	^{40}AR/ ^{39}AR^1	^{36}AR/ ^{39}AR^1	^{37}AR/ ^{39}AR^2	^{39}AR (% of total)	%^{40}AR (% non-atmos.)^3	^{36}Ar$_{ca}$ %	Apparent age (Ma)^4
650	94.54	0.22015	4.743	1.68	31.59	0.59	437.4 ± 29.2
750	44.97	0.04991	2.917	0.54	67.72	1.59	444.6 ± 22.1
825	45.28	0.05328	5.375	0.78	66.17	2.74	438.8 ± 5.8
860	44.99	0.03845	8.374	0.95	76.23	5.92	495.2 ± 9.0
880	43.07	0.0307	7.568	0.83	80.34	6.7	498.8 ± 10.3
895	42.05	0.01613	7.329	0.84	90.05	12.36	539.3 ± 11.0
910	43.32	0.01335	7.043	2.08	92.18	14.35	564.5 ± 2.2
930	41.99	0.00647	6.213	4.93	96.62	26.14	572 ± 2.7
940	41.22	0.00403	5.954	11.88	98.26	40.21	571.1 ± 2.6
950	40.77	0.00296	5.909	11.75	99.01	54.38	569.5 ± 1.7
960	40.68	0.00313	5.879	10.68	98.87	5111	567.7 ± 2.4
970	40.27	0.00235	5.767	9.18	99.41	66.76	565.4 ± 1.3
985	40.28	0.00196	5.744	13.73	99.69	79.51	566.8 ± 1.7
1005	39.98	0.00166	5.905	13.52	99.95	96.97	564.5 ± 1.7
1025	39.89	0.00175	6.246	11.07	99.95	97.06	563.5 ± 1.8
Fusion	40.38	0.00223	6.309	5.55	99.61	76.82	567.8 ± 2.1
Total	41.62	0.00793	5.982	100	97.03	63.63	561.9 ± 2.8
Total without 650° - 910°C				92.29			567.3 ± 1.7

Sorel Point Granodiorite

J = 0.009535

Release temp (°C)	^{40}AR/ ^{39}AR^1	^{36}AR/ ^{39}AR^1	^{37}AR/ ^{39}AR^2	^{39}AR (% of total)	%^{40}AR (% non-atmos.)^3	^{36}Ar$_{ca}$ %	Apparent age (Ma)^4
750	36.68	0.03307	2.511	1.5	73.89	2.07	415.3 ± 5.2
810	35.47	0.0259	5.623	1.17	79.68	5.9	431.9 ± 4.5
840	38.47	0.02575	5.766	0.63	81.41	6.09	472.9 ± 7.0
870	36.8	0.01627	5.405	1.36	88.1	9.03	487.4 ± 4.1
890	32.86	0.00485	5.608	13.62	96.99	31.42	480.2 ± 2.6
900	32.04	0.00269	5.811	14.95	98.96	58.8	478 ± 1.9
910	31.85	0.00385	5.863	12.48	97.89	41.42	471.1 ± 1.5
920	31.66	0.00211	5.878	12.68	99.5	75.78	475.3 ± 1.4
960	31.46	0.00174	5.893	10.49	99.85	92.11	474.2 ± 1.8
940	31.42	0.00161	5.907	8.71	99.98	99.67	474.2 ± 1.1
955	31.45	0.00198	5.977	6.54	99.65	82.09	473.3 ± 1.2
975	31.54	0.00209	6.008	5.39	99.56	78.26	474.1 ± 1.1
975	31.54	0.00209	6.008	5.39	99.56	78.26	474.1 ± 1.1
1000	31.68	0.00294	7.029	8.82	99.02	64.95	474 ± 1.0
Fusion	30.51	0.00274	7.928	1.67	99.42	78.75	460.3 ± 3.2
Total	32.06	0.00386	5.922	100	98.04	63.08	473.8 ± 1.6
Total without 750° - 870°C and fusion				93.67			475.3 ± 1.5

[1] measured.

[2] corrected for post-irradiation decay of ^{37}Ar (35.1 day $^1/_2$-life).

[3] $[^{40}\text{Ar}_{\text{tot.}} - (^{36}\text{Ar}_{\text{atmos.}})]/^{40}\text{Ar}_{\text{tot.}}$.

[4] calculated using correction factors of Dalrymple *et al. (1981)*; 2σ, intralaboratory errors.

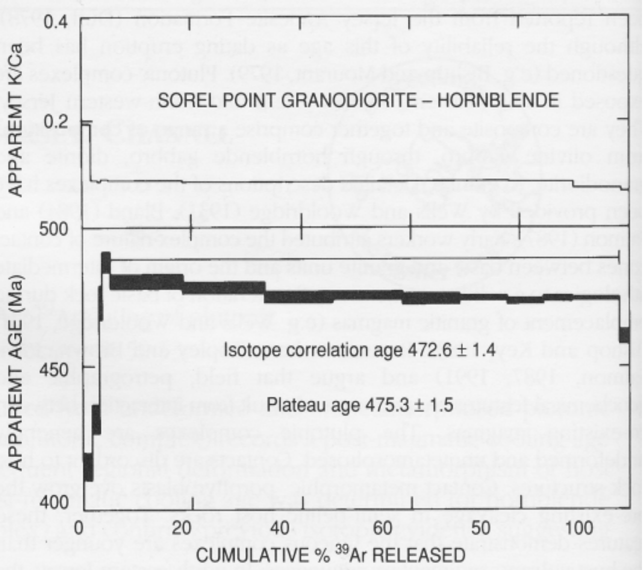

Figure 3: ^{40}Ar/^{39}Ar apparent age and apparent K/Ca spectra for a hornblende concentrate from granodiorite at Sorel Point, north-west Jersey (see caption to Figure 2).

skeletal morphology attributed to rapid crystal growth within a volatile-rich melt. The concentrate displays an internally discordant ^{40}Ar/^{39}Ar age spectrum in which variable apparent ages are recorded at low experimental temperatures (Figure 2). These ages are matched by fluctuations in apparent K/Ca ratios which suggest that the experimental evolution of argon occurred from compositionally distinct and relatively non-retentive phases. These could be represented by: (i) very minor optically undetectable mineralogical contaminants in the amphibole concentrates; (ii) petrographically unresolvable exsolution or compositional zonation within constituent amphibole grains; (iii) minor chloritic replacement of amphibole; and/or (iv) intracrystalline inclusions. The 930°C to fusion increments comprise c. 92% of the total ^{39}Ar evolved from the concentrate. These increments are characterized by similar apparent K/Ca ratios suggesting that the experimental evolution of gas occurred from a compositionally uniform population of intracrystalline `sites'. These nine increments record similar apparent ages corresponding to a plateau of 567.3 ± 1.7 Ma. The plateau data yield a well-defined ^{36}Ar/^{40}Ar versus ^{39}Ar/^{40}Ar isotope correlation (MSWD = 1.22) with an inverse ordinate intercept of 475.2 ± 32.1 Ma. This is larger than the ^{40}Ar/^{36}Ar ratio in the present-day atmosphere and suggests slight intracrystalline contamination with extraneous argon components. By using the inverse abscissa intercept (^{40}Ar/^{39}Ar) in the age equation a plateau isotope correlation age of 562.7 ± 1.1 Ma is produced. Because the calculation of isotope correlation ages does not require assumption of a ^{40}Ar/^{36}Ar ratio they are more reliable than ages calculated directly from the ^{40}Ar/^{39}Ar analytical data. The c. 560 Ma age defined for the Le Nez sample is therefore considered geologically significant and is interpreted to date post-magmatic cooling through the temperature required for intracrystalline retention of argon within constituent hornblende grains. Harrison (1981) indicated that closure temperatures for argon systems within igneous hornblende are not significantly affected by compositional variations. He suggested that values of 500 ± 25°C are appropriate for the range of cooling rates likely to be encountered in most geological settings.

GRANODIORITE, SOREL POINT: NORTH-WESTERN PLUTONIC COMPLEX

Unzoned green hornblende was separated from coarse-grained granodiorite at Sorel Point. The granodiorite forms a continuous narrow sheet (0.1 to 10 m) between the porphyritic microgranite mass of the northern-most extreme of Sorel Point and the gabbroic/dioritic rocks which form the bulk of the Sorel Point headland. The contact between the granodiorite and the dioritic/gabbroic rocks is interpreted to result from magma co-mingling, and hence the granodiorite is considered to be the same age as most of the basic rocks at Sorel Point (Salmon, 1987). The concentrate displays internally discordant apparent age and apparent K/Ca spectra.

K/Ca spectra, with characteristics generally similar to those described for the Le Nez Appinite sample (Figure 3). The 890 to 1000°C increments comprise c. 94% of the gas evolved from the concentrate and are characterized by generally similar apparent K/Ca ratios. The nine increments define a 475.3 ± 1.5 Ma plateau age. Isotope correlation of the plateau data yields an inverse ordinate intercept of 382.2 ± 15.5 Ma and an age of 471.6 ± 1.4 Ma (MSWD = 1.02). This is considered geologically significant and is interpreted to date postmagmatic cooling through c. 500°C.

DISCUSSION AND CONCLUSIONS

The 563 ± 1 Ma ^{40}Ar/^{39}Ar hornblende age for the Le Nez sample is comparable with the c. 570 Ma ^{40}Ar/^{39}Ar post-magmatic mineral cooling ages reported for four components from the Northern Igneous Complex exposed on Guernsey (Dallmeyer *et al.,* 1992), to post-magmatic cooling ages from the Fort Tourgis quartz diorite of Alderney, and the Moulinets quartz diorite of La Hague (authors' unpublished data). Together these data suggest widespread c. 570-560 Ma post-tectonic calc-alkaline magmatism in the northern part of the Armorican Massif.

Although not in direct contact, field relationships from the igneous complexes as a whole strongly indicate a younger age for the Le Nez appinite than the deformation and regional low-grade metamorphism of the Jersey Shale and Volcanic sequences. The c. 560 Ma age for the south-eastern plutonic complex thus provides a limit for the deposition and subsequent regional deformation and metamorphism of the Brioverian rocks of Jersey and is consistent with ^{40}Ar/^{39}Ar cooling ages recorded for metamorphosed Brioverian rocks exposed around the Baie de St Brieuc (Dallmeyer *et al.,* 1991b). The new age data implies that the 533 ± 16 Ma Rb-Sr whole-rock isochron age reported by Duff (1978) for the Jersey Andesite Formation does not record eruption and thus removes the isotopic basis for correlation with supposed Cambrian hyperbyssal and extrusive volcanic units of the Trégor region (Auvray, 1979; Dupret *et al,* 1990).

The c. 470 Ma age for the granodiorite at Sorel Point is significantly younger than all other mineral ages determined by ^{40}Ar/^{39}Ar methods for Cadomian intrusions in the Channel Islands-La Hague region. It is similar to the K-Ar ages provided by Adams (1976) and, within error, is similar to the Rb-Sr whole-rock isochron age of 465 ± 10 Ma reported by Bland (1984; 1985) for the volumetrically dominant Porphyritic Granite member of the northwestern plutonic complex. The c. 470 Ma age is, however, significantly older than the age quoted for the microgranite exposed adjacent to the basic to intermediate rocks at Sorel Point. The welldefined plateau pattern of the ^{40}Ar/^{39}Ar release spectra demonstrates that the c. 470 Ma age is not an artefact of partial resetting, but records the age of cooling through c. 500 C. Complete rejuvenation of the amphibole during later post-emplacement heating is inconsistent with the preservation of a wide variety of igneous disequilibrium textures (Salmon, 1991). Therefore, the ^{40}Ar/^{39}Ar data do record an Ordovician magmatic event. The regional significance of this event is uncertain. However, there is a broad similarity in age to Palaeozoic (Ordovician ?) volcanic sequences in the Maine Graben (Dupret *et al.,* 1990) and to volcanic rocks interbedded with the Plourivo-Plouezec red beds of north Brittany (Auvray *et al.,* 1980).

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