Contrib. Mineral. Petrol. 70, 103–109 (1979)

Contributions to Mineralogy and Petrology

Isotopic Dating of the Emplacement of the Ultramafic Masses in the Serrania de Ronda, Southern Spain

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Abstract. A Rb-Sr analysis of suites of samples from a small intrusion of cordierite-bearing alkali granite into the peridotite of the Sierra Bermeja (Serrania de Ronda) yields an age of 22 ± 4 Ma ($\lambda = 1.42 \times 10^{-11}$ a^{-1}): Late Oligocene/Early Miocene. It is believed that the intrusion was derived from contact-anatectic melts produced along the hot ultramafic mass during and/or directly following its tangential, tectonic dislocation from a mantle diapir. Its age can thus be taken as dating the termination of the hot emplacement of the ultramafic masses. K-Ar dates of biotites and Rb-Sr dates of biotite/whole-rock pairs in contact-metamorphic wall rocks along the ultramafics mostly lie between 19.5 and 18.5 Ma. This probably indicates that about 19 Ma ago the contact-zones of the ultramafic masses had cooled down to the blocking temperature of biotite to Rb-Sr and K-Ar.

Introduction

The large ultramafic masses in the Betic Cordilleras of southern Spain (Serrania de Ronda) and the Rif of northern Morocco (Beni Bousera) are classified as continental-type (Nicolas and Jackson, 1972) Alpine peridotites (Kornprobst, 1969, 1970, 1974; Dickey, 1970). They mainly consist of dunite, harzburgite and orthopyroxene-rich lherzolite (Hernandèz-Pacheco, 1967; Kornprobst, 1969, 1970, 1974; Dickey, 1970; Aguilar et al., 1973). Opinions differ as to their emplacement age. Two stages of emplacement are generally distinguished, a first 'hot' and a second 'cold' stage (Kornprobst, 1969, 1970, 1974; Darot, 1974; Westerhof, 1975, 1977), but different hypotheses have been put forward regarding the timing of both stages. Most authors agree about the Oligocene/Miocene age of the second stage (e.g. Bourgois et al., 1972; Didon et al., 1973; Paquet, 1974; Westerhof, 1975, 1977), but the dates assigned to the first stage range from pre-Namurian or even Precambrian (e.g. Kornprobst, 1969, 1970, 1974) to Alpine (Blumenthal, 1928; Dürr, 1967; Mollat, 1968; Buntfuss, 1970; Paquet, 1974; Westerhof, 1975, 1977).

The emplacement mechanism of the ultramafic masses has been discussed by several authors (e.g. Loomis, 1972a and b, 1975; Lundeen, 1978; Westerhof, 1975, 1977). From these studies, the following sequence of events may be envisaged:

1. Diapiric intrusion in the deep crust under conditions of high pressure and high temperature (HP-HT). Dynamo-thermal aureoles developed along the contacts in the deep crustal, high-pressure granulite facies country rocks.

2. During the further upward movement of the ultramafic masses fragments of the HP-HT metamorphic rocks (kyanite-bearing kinzigites) were dragged along the contacts to higher crustal levels.

3. When the upward moving ultramafic masses arrived at intermediate crustal levels, the early HP-HT conditions gave way to medium pressure and high temperature (MP-HT). The heat from the peridotite caused the development of cordierite- and andalusite-bearing hornfelses and migmatites in the country rocks and in the transported HP-HT fragments from the deeper crust. Loomis (1975) reports that K-Ar dating of whole-rocks and micas from the contact rocks in the Serrania de Ronda and Beni Bousera suggests an Early Miocene age (about 22 Ma) for this phase of metamorphism, but his conclusion has recently been contested by Lundeen (1978).

4. Part of the ultramafic masses became involved in the Alpine overthrust movements while still hot and while the metamorphic processes giving rise to the MP-HT contact-aureole were still in progress (5.5 to 6.5 Kbar and $725 \pm 50°$ C according to Westerhof, 1975, 1977). Most of the exposed ultramafic rocks are therefore allochthonous masses in their present position.

0010-7999/79/0070/0103/$01.40

5. A final stage of 'cold' emplacement was related to Late Alpine (over)thrusting along the contacts of the ultramafic masses. This resulted in tectonic contacts between ultramafics and wall rocks and in numerous serpentine lenses along the thrust planes. The relations with the older high-temperature aureoles were obscured at many places.

In the Serrania de Ronda three major masses of ultramafic rocks can be distinguished, covering a total area of some 400 square kilometers. The largest mass occupies the Sierra Bermeja and Sierra Real between Marbella and Ronda. Smaller masses are exposed in the Sierra de Alpujata, NE of Marbella, and in the Sierra de Alcaparain some 30 km NE of Marbella. According to Westerhof (1975, 1977), the ultramafic rocks were emplaced in presumably Liassic and older sediments before or during the beginning of the northward thrust movements responsible for the initial empilement of the Alpine tectonic units (MP-HT stage of 'hot' emplacement). In their present situation the allochthonous ultramafics should form part of tectonic units which may be correlated with the Alpujarride nappe complex more to the east in the Betic Cordilleras.

Contact-Anatectic Melts

Irregularly shaped pods, lenses and dikes of leucocratic rock have been reported from the cordierite- and andalusite-bearing hornfelses and migmatites in the contact-aureoles along the ultramafic masses (Kornprobst, 1969, 1970, 1974; Loomis, 1972a; Dickey and Obata, 1974; Westerhof, 1975). These quartz-feldspar rocks are interpreted as derived from contact-anatectic melts, generated under the conditions of medium pressure and high temperature prevailing when the emplacing hot ultramafic masses had reached an intermediate level in the crust. In the Serrania de Ronda, Westerhof (1975) demonstrated that the 'venitic pegmatites' formed during this stage of MP-HT contact-metamorphism by seggregation of material from the cordierite-biotite mylonite schists.

Veins, veinlets and irregular pods of cordierite- and sillimanite-bearing quartz-feldspar rock occur locally within the peridotite (Hernandèz-Pacheco, 1967; Aquilar et al., 1973; Dickey and Obata, 1974). We observed them, for example, at several places in the large ultramafic mass of the Sierra Bermeja, especially in the marginal zone close to the contact with the country rocks. Such acid inclusions are here likewise interpreted as derived from contact-anatectic melts, generated in the country rocks by the heat of the emplacing ultramafic mass and then intruded into the peridotite (*back veining*). Whatever their genesis, the abundance of cordierite relates the consolidation of this rock to the MP-HT phase of emplacement and metamorphism. It was thought that such acid intrusives within the peridotite could provide an opportunity to date directly the time at which the emplacing hot ultramafic mass had reached the intermediate levels of the crust.

The Leucocratic Pod on the Puerta de Peñas Blancas

The largest acid intrusion in the ultramafic masses known to us is the quartz-feldspar pod on the Puerta de Peñas Blancas (altitude 980 m), north of Estepona in the Sierra Bermeja (Fig. 1). The pod covers an area of some 100 × 20 m and fresh, unweathered rock crops out in the recently blasted road cuts on the junction of the forest road to Los Reales with the road Estepona-Jubrique. Suites of samples were collected at this location.

The rocks are porphyric and mainly composed of quartz, normally zoned plagioclase (An_{20}-An_{10}) and perthitic K-feldspar (myrmekitic along the contacts with plagioclase), and minor cordierite (partially pinitized) and tourmaline (light bluish green to yellowish green). Accessories are zircon, fine-grained opaque minerals, biotite, fluorite, and dumortierite. Larger crystals of feldspar, cordierite and tourmaline are embedded in a fine-grained quartz-feldspar mass. All investigated rocks show a protoclastic texture, while the samples Alm 120–129 (Location 1) also display cataclasis. Chemically, the rocks are fairly homogeneous with an alkali granitic composition (Nockolds, 1954), although somewhat high in silica

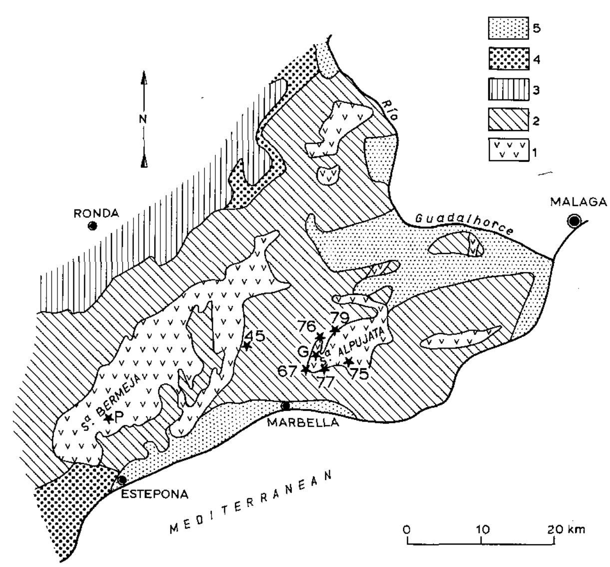

Fig. 1. Tectonic sketch map of the Serrania de Ronda, showing the outcrops of the ultramafic masses (simplified after Egeler and Simon, 1969, and Westerhof, 1975; 1977). Legend: **1:** ultramafic rocks. **2:** empilement of nappes (Betic Zone sensu stricto); **3:** External Zone; **4:** allochthonous flysch; **5:** post-nappe sediments. Asterisks, sampling sites. The figures 45 to 79 correspond to the sample numbers ALM 45 to 79. *P:* acid intrusive on the Puerta de Peñas Blancas (quartz-feldspar samples ALM 120 to 138 and peridotite sample ALM 130). *G:* Mina La Gallega (peridotite samples ALM 147 and 148, drill cores, depths 115 m and 165 m, respectively)

Table 1. Major element composition of some of the investigated samples from the quartz-feldspar pod on the Puerta de Peñas Blancas[a]

ALM	120	123	124	125	127	128	129	131	133	134	138
SiO_2	77.3	77.0	78.0	74.1	76.4	76.1	75.5	75.7	77.0	75.5	74.9
TiO_2	0.057	0.062	0.054	0.060	0.055	0.056	0.051	0.063	0.084	0.067	0.057
Al_2O_3	12.5	12.1	12.0	13.0	12.1	12.7	12.9	13.1	12.8	13.0	13.1
Fe_2O_3[b]	0.58	0.63	0.60	0.87	0.51	0.55	0.45	0.72	0.72	0.68	0.70
MnO	0.016	0.020	0.014	0.011	0.017	0.022	0.011	0.028	0.021	0.023	0.012
MgO	0.14	0.27	0.19	0.13	0.28	0.15	0.16	0.17	0.17	0.13	0.77
CaO	0.60	0.62	0.59	0.42	0.62	0.59	0.68	0.55	0.55	0.61	0.37
Na_2O	3.5	3.4	3.2	3.7	3.2	3.5	4.3	3.5	3.5	3.5	3.5
K_2O	4.3	3.8	4.4	4.3	4.3	4.3	3.6	4.5	4.2	4.5	4.6
P_2O_5	0.05	0.05	0.05	0.07	0.05	0.05	0.06	0.08	0.06	0.08	0.08
BaO	0.016	0.019	0.021	0.012	0.021	0.018	0.019	0.024	0.016	0.023	0.010
	99.1	98.0	99.1	96.7	97.6	98.0	97.7	98.4	99.1	98.1	98.1

[a] X-ray fluorescence analysis. Estimated absolute accuracies are (in percent): SiO_2, 1.5; TiO_2, 0.002; Al_2O_3, 0.4; Fe_2O_3, 0.01; MnO, 0.001; MgO, 0.06; CaO, 0.01; Na_2O, 0.3; K_2O, 0.1; P_2O_5, 0.01; BaO, 0.001

[b] Total Fe as Fe_2O_3

and very low in iron and magnesia (Table 1). Normative quartz and feldspars account for about 97% of the normative composition; the ratio Q:Or:Ab:An is approximately 37:28:32:3, corresponding to the eutectic mixture of Tuttle and Bowen's (1958) quartz-orthoclase-albite-water system under medium H_2O pressure. This composition is thus as should be expected in the case of generation of the granitic magma by processes of anatexis.

One sample from a brecciated zone (ALM 138) has about 3× as much magnesia as the other samples from the pod. This may reflect some introduction of magnesia along this zone from the environmental peridotite, possibly during the process of serpentinization.

Isotopic Measurements

In order to date the intrusion of the acid melts in the ultramafic masses (and thus the time at which the melts were generated in the wall rocks, i.e., the climax of the contact-metamorphism induced by the emplacing peridotites when they had reached intermediate crustal levels), 13 of the samples collected from the quartz-feldspar pod on the Puerta de Peñas Blancas were selected for Rb-Sr analysis. Seven were taken in a section with a length of 4 m close to the southern margin of the pod (location 1). Another suite of four samples comes from a section with a length of 2 m some 50 m to the north (location 2). One sample was analysed from half-way between both locations (location 3), while the last sample from the pod was taken in a brecciated zone (a small, steep fault) between the locations 2 and 3.

For comparison, Rb-Sr analyses were made on three samples from the peridotite. One sample (ALM 130) comes from close to the contact with the quartz-feldspar pod on the Puerta de Peñas Blancas (about 35 m south of location 1). The other two samples (ALM 147 and 148) are from core drillings at the site of the abandoned Cr-Ni mine of La Gallega (Fig. 1). All samples consist for the greater part of serpentinite.

Contemporaneously with the contact-anatectic melting, metamorphic (re)crystallization was induced in the country rocks along the contacts of the emplacing hot ultramafic masses. Isotopic age measurements were therefore also made on metamorphic minerals from six samples collected in the contact-aureoles close to the contact in the Sierra Bermeja/Sierra Real and in the Sierra de Alpujata. The samples are listed in Table 2 and the sampling sites are shown on the map of Fig. 1. Rb-Sr analyses were made on five biotite/whole-rock pairs. All biotites were also dated by the K-Ar method. Moreover, K-Ar ages were determined on biotite from two other locations.

Table 2. Investigated samples from contact zones ultramafic masses

Sample Number	Rock and location (Fig. 1)	Dating method
ALM 45	Sierra Real; biotite gneiss; *E* contact, about 9 km NW of Marbella	whole-rock/biotite Rb-Sr biotite K-Ar
ALM 67	Sierra de Alpujata; kinzigite; *W* contact, about 3 km NNE of Marbella	whole-rock/biotite Rb-Sr biotite K-Ar
ALM 75	Sierra de Alpujata; quartz-feldspar vein intrusive into the peridotite; about 9 km NE of Marbella	whole-rock/biotite Rb-Sr biotite K-Ar
ALM 76	Sierra de Alpujata; biotite hornfels; NW contact, about 9 km NNE of Marbella	whole-rock/biotite Rb-Sr biotite K-Ar
ALM 77	Sierra de Alpujata; biotite hornfels; SW contact, about 6 km NE of Marbella	whole-rock/biotite Rb-Sr biotite K-Ar
ALM 79	Sierra de Alpujata; biotite hornfels; *N* contact, about 11 km NE of Marbella	whole-rock/biotite Rb-Sr biotite K-Ar

Experimental Procedures and Constants

The Rb and Sr concentrations and Rb/Sr ratios of the whole-rocks were determined by X-ray fluorescence spectrometry, using a Philips PW 1450/AHP automatic spectrometer. All samples were measured as pressed-powder pellets; the mass-absorption corrections for both sample and external standard are based upon the Compton scattering of the Mo-Kα primary beam (Verdurmen, 1977). The biotites were analyzed for Rb and Sr by mass-spectrometric isotope dilution. Sr isotopic compositions were determined directly on unspiked Sr for whole-rocks and calculated from the isotope dilution runs for biotites. Most isotope measurements were made on a computer-controlled Varian CH5 mass-spectrometer with Faraday cage collector and digital output (value of normalised $^{87}Sr/^{86}Sr$ of the NBS 987 $Sr(CO_3)_2$ standard measured as 0.71016 ± 0.00008). Of the whole-rock/biotite pairs a number of older analyses was made on a 20 cm, 60° Nier-type mass-spectrometer with digital output and multiplier detection, the $^{87}Sr/^{86}Sr$ ratios being adjusted to the value 0.7081 in the Eimer and Amend $Sr(CO_3)_2$ standard (Table 5). The estimated overall limits of relative errors are 1% for XRF Rb/Sr, 1% for isotope dilution Rb and Sr, 0.05% for $^{87}Sr/^{86}Sr$ with the Varian CH5 mass-spectrometer, and 0.2% for $^{87}Sr/^{86}Sr$ with the mass-spectrometer with multiplier detection. For the peridotites, these limits are 10–25% for the XRF Rb/Sr determinations because of the low Rb and Sr contents. The overall limits of relative error are the sum of the estimated contributions of the known sources of possible systematic error and of the precision (2σ) of the total analytical procedures.

Major element compositions were determined by X-ray fluorescence spectrometry, using beads (320 mg sample + 4,200 mg $Li_2B_4O_7$ + 800 mg $LiBO_2$) relative to reference sample USGS-G2 (Flanagan, 1973).

Potassium was analysed by flame photometry with lithium internal standard and CsAl buffer. Argon was extracted in a bakeable glass vacuum apparatus and determined by isotope dilution techniques on a GD-150 mass-spectrometer. For K and Ar the relative accuracies are estimated at 1% and 2%, respectively.

The Rb-Sr isochrons were computed by means of least-squares regression analyses according to York (1966, 1967). Errors in the calculated isochron ages and initial $^{87}Sr/^{86}Sr$ ratios are quoted at the 95% confidence level as computed from the analytical data. The values of the Mean Squares Weighted Deviation (MSWD) were calculated according to McIntyre et al. (1966).

For the age calculations the following constants were used (IUGS recommended values): $\lambda^{87}Rb = 1.42 \times 10^{-11}\,a^{-1}$; $\lambda^{40}K_\beta = 4.962 \times 10^{-10}\,a^{-1}$; $\lambda^{40}K_e = 0.581 \times 10^{-10}\,a^{-1}$; isotopic abundance $^{40}K = 0.01167$ atom % total K.

Results

The Rb-Sr data obtained on the samples from the acid intrusive on the Puerta de Peñas Blancas are listed in Table 3 and plotted in the diagram of Fig. 2. Of the seven samples from location 1, six are linearly correlated and define an isochron of 22.6 ± 4.7 Ma with initial $^{87}Sr/^{86}Sr = 0.7219 \pm 0.0013$ (MSWD = 1.25). The seventh sample from this location (ALM 129) falls below the linear arrangement of the other samples and was omitted from the calculation. The four samples from location 2 all lie above the isochron of location 1, but they are themselves correlated according to another straight line corresponding to an isochron of 22.0 ± 8.2 Ma and initial $^{87}Sr/^{86}Sr = 0.7236 \pm 0.0024$ (MSWD = 0.65). The average of these two ages is 22 ± 4 Ma.

Table 3. Rb-Sr data quartz-feldspar pod Puerta de Peñas Blancas

Sample Number	Rb (ppm)	Sr (ppm)	Rb/Sr (Wt/Wt)	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$
Location 1					
ALM 120	219	41.7	5.247	0.72751	15.21
ALM 123	231	45.8	5.039	0.72654	14.60
ALM 124	209	48.3	4.322	0.72601	12.53
ALM 125	280	23.7	11.84	0.73283	34.34
ALM 127	202	54.5	3.706	0.72484	10.74
ALM 128	251	45.2	5.548	0.72688	16.08
ALM 129	188	59.9	3.140	0.72231	9.10
Location 2					
ALM 131	361	48.0	7.512	0.73032	21.78
ALM 134	341	48.8	6.989	0.73029	20.26
ALM 136	269	69.8	3.860	0.72697	11.19
ALM 137	360	40.3	8.924	0.73152	25.88
Location 3					
ALM 133	228	54.0	4.226	0.72426	12.25
Brecciated zone					
ALM 138	332	32.9	10.08	0.72799	29.22

Table 4. K-Ar data biotites contact zone

Sample Number	K (%)	Radiogenic ^{40}Ar (ppm × 10^3)	atmospheric ^{40}Ar (% total ^{40}Ar)	Age (Ma)
ALM 45	7.00	10.32	24	21.1 ± 0.6
	7.02	10.29	23	
ALM 67	6.56	8.94	31	19.5 ± 0.6
	6.57	8.88	27	
ALM 75	6.52	8.75	46	19.2 ± 0.6
	6.58	8.78	42	
ALM 76	6.79	9.07	44	19.0 ± 0.6
	6.78	8.89	35	
ALM 77	7.55	10.13	43	19.7 ± 0.6
	7.53	10.53	34	
ALM 79	7.37	10.07	48	19.5 ± 0.6
	7.38	9.92	41	

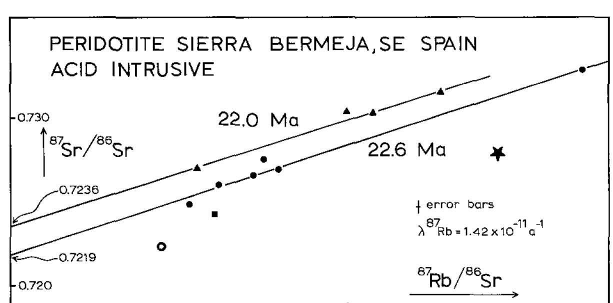

Fig. 2. Plot of Rb-Sr data from the acid intrusive in the peridotite on the Puerta de Peñas Blancas, Sierra Bermeja. *Open* and *closed circles*: location 1; *triangles*: location 2; *square*: location 3; *asterisk*: brecciated zone (see text). Separate isochrons are displayed by the data-points of locations 1 and 2, respectively. The *open circle* is not included in the isochron calculation of location 1

Table 5. Rb-Sr data whole-rock/biotite pairs contact zone

Sample Number	[a]	Rb (ppm)	Sr (ppm)	Rb/Sr (Wt/Wt)	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$	Age (Ma)[c]
ALM 45	WR	333	58.4	5.69	0.7925[b]		
					0.7926[b]	16.6	18.5 ± 0.7
	bio	1,765	3.37		1.205[b]	1,589	
		1,747	3.39		1.205[b]	1,580	
ALM75	WR	362	71.8	5.03	0.72571	14.6	
	bio	1,884	3.21		1.21170	1,784	19.4 ± 0.6
		1,879	3.13		1.22879	1,826	
ALM 76	WR	129	148	0.873	0.72441	2.53	
	bio	597	8.41		0.7820[b]	207	19.1 ± 1.3
		597	8.51		0.7775[b]	205	
ALM 77	WR	183	145	1.268	0.72430	3.68	
	bio	864	4.33		0.8790	587	18.6 ± 0.9
		882	4.37		0.8811[b]	594	
ALM 79	WR	214	113	1.896	0.74284	5.51	
					0.74306		
	bio	1,015	12.6		0.7950[b]	236	15.5 ± 1.1
		1,014	12.6		0.7929[b]	236	

[a] WR, whole-rock; bio, biotite
[b] Mass-spectrometry with multiplier detection
[c] Errors based upon the estimated analytical errors mentioned in the text

Table 6. Rb-Sr data of the peridotite

Sample Number	Rb (ppm)	Sr (ppm)	Rb/Sr (Wt/Wt)	$^{87}Sr/^{86}Sr$	$(^{87}Sr/^{86}Sr)_0$[a]
ALM 130	0.4	2.0	0.18	0.70733	0.70717
ALM 147	1.3	8.0	0.16	0.70797	0.70782
ALM 148	0.8	16.3	0.047	0.71052	0.71048

[a] Initial $^{87}Sr/^{86}Sr$ ratio 22.4 Ma ago

Both the sample from location 3 (ALM 133) and that from the brecciated zone (ALM 138) do not fit either of the isochrons.

The K-Ar and Rb-Sr data obtained on the minerals from contact-metamorphic country rocks close to the peridotite (Fig. 1) are listed in Tables 4 and 5. Of the six biotites, five have K-Ar ages between 19.0 and 19.6 Ma. The sixth K-Ar biotite age (Alm 45) is somewhat higher, in between the range of the other biotite ages and the Rb-Sr age of the acid intrusive in the peridotite.

Of the five biotite/whole-rock pairs, four produce Rb-Sr ages between 18.5 and 19.4 Ma. The fifth pair (ALM 79) yields a lower age, 15.5 Ma.

The Rb-Sr data of the three investigated peridotite samples are listed in Table 6. All show rather high initial $^{87}Sr/^{86}Sr$ ratios, varying between 0.7072 and 0.7105.

Discussion and Conclusions

As discussed above, we interpret the leucocratic veins, veinlets and pods in the ultramafic masses as intrusions of acid magma generated in the country rocks along the contacts by processes of contact-anatexis. This mode of origin is supported by the high initial $^{87}Sr/^{86}Sr$ ratios of 0.722 and 0.724 measured in the quartz-feldspar rocks on the Puerta de Peñas Blancas, which reflect a substantial pre-metamorphic history for the source rocks of the acid magma. Such high ratios disprove any possible direct genetic relation between the acid intrusive and the peridotite, for example a derivation of the acid magma from the ultramafic parent magma by processes of differentiation. The Rb-Sr isochron age of 22 ± 4 Ma can thus be taken as defining the time at which the contact-anatectic melts were generated and solidified.

The anatectic melts were formed during the phase of contact-metamorphism induced by the hot ultramafic masses and post-kinematic with respect to the youngest important folding phase in the Serrania de Ronda (Westerhof, 1975). For the western Sierra Bermeja this folding phase can be correlated with the tangential, tectonic emplacement of the ultramafic masses (Darot, 1974; Paquet, 1974; Westerhof, 1975). From these relationships it is concluded that the ultramafic masses became involved in the overthrusting movements during or shortly after their hot emplacement in the intermediate crust (Westerhof, 1975). Following the current time-scales of the Neogene (e.g. McDougall and Page, 1975; Pomerol, 1978) the boundary Oligocene/Miocene can be dated at 23 ± 1 Ma, so our age of 22 ± 4 Ma sets the contact-anatexis associated with this metamorphism in the Late Oligocene (Chattian)/Early Miocene (Aquitanian). The ultramafic masses cannot have remained hot enough to induce contact-metamorphism in the wall rocks for a prolonged period after their tectonic dislocation from the mantle diapirs, so the age of 22 ± 4 Ma can also be taken as most nearly approaching the termination of the stage of hot emplacement of the ultramafic masses.

Most biotite Rb-Sr and K-Ar ages lie between 19.5 and 18.5 Ma. These dates may be interpreted as cooling ages, reflecting the time after the climax of the contact-metamorphism at which the rocks had cooled down far enough for the biotite to become closed towards radiogenic Sr and Ar (the blocking temperature). An ambient temperature of $725 \pm 50°$ C has been deduced for the conditions of contact-metamorphism under which the anatectic melts were generated (Westerhof, 1975). The blocking temperature of the biotite is uncertain: in the Lepontine Alps the blocking temperature of biotite to both Rb-Sr and K-Ar is estimated at $300 \pm 50°$ C (Armstrong et al., 1966; Jäger et al., 1967), whereas for the metamorphic conditions in the Alpine belt on Naxos the blocking temperature to K-Ar is calculated at 360–400° C (Andriessen, 1978). Anyhow, there can be little doubt that between 22 ± 4 Ma and about 19 Ma ago the ambient temperature in the contact-zone of the ultramafic masses decreased some 300°, to 400° C.

One biotite K-Ar age (ALM 45) is significantly higher than the other biotite ages and approaches closely the Rb-Sr isochron age of the acid intrusion. If this is not a case of some inherited radiogenic Ar, the higher biotite age could indicate that in some parts of the contact-aureoles the cooling rate was higher. The Rb-Sr age of this biotite is significantly lower than the K-Ar age and falls in the general range, possibly suggesting that the chemical processes involving the exchange of radiogenic Sr continued for some time after the biotite became closed to the diffusion loss of radiogenic Ar.

The K-Ar ages reported by Loomis (1975) from metamorphosed Paleozoic and older rocks in the contact-aureoles of the Serrania de Ronda and Beni Bousera range from about 22 to 81 Ma for the whole-rocks and from about 20 to 35 Ma for the micas. Loomis interpreted these data in terms of cooling about 22 Ma ago, along with a retention of various proportions of the radiogenic Ar generated before the metamorphism, especially in porphyroblastic cordierite; biotites with higher ages (30 to 35 Ma) contain about 10 to 20% cordierite. This interpretation finds support in the $^{40}Ar/^{39}Ar$ age spectrum of one cordierite-bearing hornfels sample from the Serrania de Ronda obtained by Seideman (1976), which showed an age of 21.3 ± 0.5 Ma for the last step yielding reasonable quantities of gas. Lundeen (1978), however, postulated that the hot emplacement of the ultramafic masses should be dated by Loomis' biotite ages of 30 to 35 Ma, whereas his ages in the 20 to 25 Ma range should reflect resetting during overthrusting of a higher nappe complex.

Our isotopic age data indicate that the stage of hot emplacement of the ultramafic masses in the Serrania de Ronda was terminated 22 ± 4 Ma ago, supporting Loomis' interpretation. Subsequent cooling must have been rather fast and about 19 Ma ago the ambient temperature had decreased to below the blocking temperature of biotite to Rb-Sr and K-Ar.

One biotite/whole-rock pair (ALM 79) produces a significantly lower Rb-Sr age, 15.5 ± 1.1 Ma. The corresponding K-Ar age is higher and falls in the general range of biotite ages. This low age may very well be a case of incomplete Sr isotopic equilibration through the rock during the metamorphism, or of open-system behaviour of the whole-rock towards Rb-Sr. The possibility cannot wholly be excluded, however, that the low Rb-Sr age reflects a younger event of chemical processes involving exchange of radiogenic Sr from the biotite, leaving the K-Ar biotite system undisturbed.

The three investigated peridotite samples are essentially serpentinites, containing only relict grains of unaltered olivine, orthopyroxene and clinopyroxene along with minor amounts of picotite. It seems therefore obvious to relate both the spread and the rather high values of the $^{87}Sr/^{86}Sr$ ratios (0.7072–0.7105) to contamination with strontium enriched in ^{87}Sr during the process of serpentinization. Radiogenic Sr was in ample supply in case of any mechanism of serpentinization involving externally derived waters, as the country rocks already had a prolonged Rb-Sr history prior to the emplacement of the ultramafic masses.

Acknowledgments. The authors acknowledge the helpful discussions with Dr. P.A.M. Andriessen, Z.W.O. Laboratory of Isotope Geology, and Dr. O.J. Simon, Geological Institute of the University of Amsterdam. Mr. W. Drucker of the latter Institute assisted in collecting part of the investigated samples. A few samples from the contact-zone were provided by Dr. A.B. Westerhof. This work forms part of the research programme of the 'Stichting voor Isotopen-Geologisch Onderzoek', supported by the Netherlands Organisation for the Advancement of Pure Research (Z.W.O.).

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Received April 7, 1979; Accepted June 25, 1979