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High $\delta^{18}O$ and possible pre-eruptional Rb-Sr isochrons in cordierite-bearing Neogene volcanics from SE Spain

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Abstract. O- and Sr-isotope data are reported for cordierite-bearing dacites and andesites forming part of the Neogene volcanic province of SE Spain. The almandine-bearing biotite-cordierite-labradorite dacite from the Cerro del Hoyazo with its numerous inclusions of metamorphic and igneous rocks has been studied in some detail. A syngenetic derivation of the Hoyazo dacite magma and part of its inclusions (interpreted as restite) by means of anatexis of (semi-)pelitic rocks has previously been proposed.

$\delta^{18}O$ values and $^{87}Sr/^{86}Sr$ ratios, thought to be closely representative of the original *magmas*, vary from +12.2 to +15.6 and 0.7095 to 0.7171, respectively. The metamorphic rock inclusions have $\delta^{18}O$ values (+13.0–+16.2) comparable to the range for the volcanics. These results support an anatectic origin for the entire suite of cordierite-bearing volcanics. The inclusions of basic igneous rocks in the Hoyazo dacite have, in comparison with the dacite, lower $\delta^{18}O$ values (+11.1–+13.1) and equal to lower $^{87}Sr/^{86}Sr$ ratios (0.7081–0.7112), confirming an independent origin.

The six analysed samples of the Hoyazo dacite show a strong linear correlation of $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ which, if interpreted as an isochron, yields an age of 210±17 Ma. Similar linear arrays for samples from the Mazarrón and Mar Menor areas yield nearly concordant ages. Samples for the Vera area define a 535±22 Ma line. These linear correlations may be interpreted either as (1) mixing lines, in which case the indicated ages have no geological meaning, or (2) true isochrons dating pre-eruptional events of the parent (meta-)sediments.

Introduction

This paper reports O- and Sr-isotope data for a suite of cordierite-bearing calc-alkaline to shoshonitic rocks occurring along the Mediterranean coast of SE Spain. The suite forms part of the Neogene volcanic province extending roughly from Cabo de Gata to Cartagena (Fig. 1). The area is located within the Betic Cordilleras which form part of the Alpine orogenic belt. A pre-Tertiary basement of metamorphic rocks is overlain discordantly by a cover of intercalated Tertiary post-orogenic sediments and volcanics. K-Ar age measurements date the volcanic activity at between 15.2 and 6.6 Ma for the calc-alkaline to shoshonitic rocks (Cabo de Gata-, Cartagena- and Hoyazo-types), between 7.0 and 5.7 Ma for the ultrapotassic rocks in the vicinity of Murcia and Vera and between 2.8 and 2.6 Ma

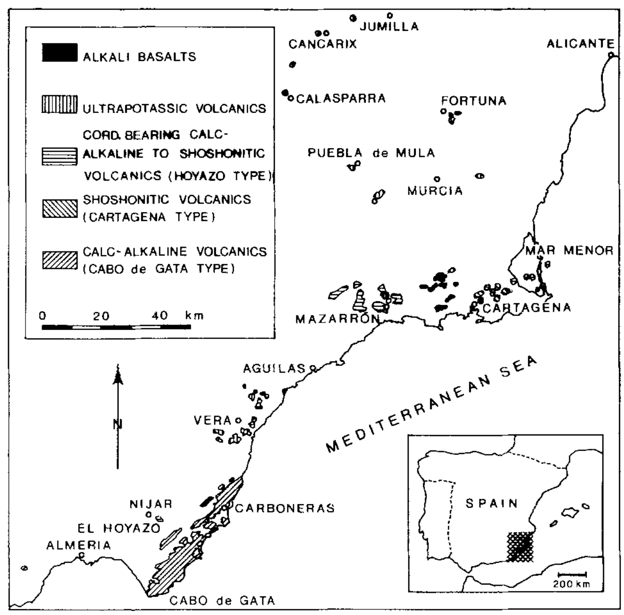

Fig. 1. The Neogene volcanic province of SE Spain. After López Ruiz and Badiola (1980) and Bellon et al. (1983)

for the alkali basalts near Cartagena (Bellon et al. 1983; Nobel et al. 1981).

One particular occurrence, the almandine-bearing biotite-cordierite-labradorite dacite from the Cerro del Hoyazo with its abundant rock inclusions, has received special attention in this investigation. Both the dacite and the various types of inclusions have been analysed for their O- and Sr-isotope composition. A syngenetic derivation of the Hoyazo dacite magma and part of its inclusions (which were interpreted as restite) by means of anatexis of (semi-)pelitic rocks in the crust has been proposed by Zeck (1968, 1970). López Ruiz and Badiola (1980), however, favour magma genesis at mantle depths, involving partial melting of a subducted crustal slab, and they believe the majority of rock inclusions to be xenoliths incorporated in the magma by accident.

O- and Sr-isotope measurements of the entire Neogene volcanic province of SE Spain have been undertaken in order to help solve some of the petrogenetic problems regarding the origin and possible interrelations of the different suites of the province. The present paper deals only with the cordierite-bearing suite (the Hoyazo type).

Table 1. Major- and trace-element compositions of selected cordierite-bearing volcanics from SE Spain

	Hoyazo						Vera	Mazarrón	Mar Menor
	56201 a	74z24a	56250	z10767	z10768	75z144	56203	56207	56228
SiO_2	64.13	64.22	63.20	64.17	64.37	63.80	65.02	63.74	61.29
TiO_2	0.64	0.66	0.61	0.64	0.63	0.67	0.56	0.58	0.65
Al_2O_3	16.98	17.17	16.66	16.97	16.71	17.01	15.42	15.87	16.11
Fe_2O_3	1.29	1.05	2.23	1.36	0.92	0.68	1.34	1.01	1.72
FeO	3.66	3.85	2.58	3.62	3.60	3.71	2.71	3.40	4.41
MnO	0.07	0.07	0.07	0.07	0.06	0.05	0.05	0.07	0.09
MgO	1.56	1.53	1.87	1.55	1.47	1.90	1.95	2.01	4.64
CaO	2.21	2.09	2.62	2.14	2.09	2.63	2.80	2.36	5.10
Na_2O	2.15	2.15	2.09	1.79	2.21	2.20	2.55	2.21	1.91
K_2O	3.59	3.63	3.32	3.68	3.73	3.47	3.79	4.29	1.89
P_2O_5	0.20	0.19	0.19	0.20	0.20	0.17	0.33	0.34	0.14
volat.	3.25	3.07	4.26	3.11	3.12	2.75	2.91	3.70	2.15
Total	99.73	99.68	99.70	99.70	99.11	99.04	99.43	99.58	100.10
norm. c	6.03	6.38	5.34	6.68	5.77	5.31	2.84	4.13	1.98
Rb	149	149	136	146	143	147	229	228	110
Sr	321	578	369	343	321	1,208	829	479	175
Ba	991	683	636	1,394	1,059	1,354	1,301	1,552	262
Zr	167	179	171	169	169	184	228	219	127
Y	32	28	28	29	31	29	29	28	31
Nb	14	15	14	15	15	16	17	20	9
Cu	25	21	24	31	26	–	21	20	13
Ni	32	26	39	30	27	–	33	31	60

Mode of occurrence, petrography and geochemistry

The cordierite-bearing calc-alkaline to shoshonitic suite in SE Spain occurs in four centres: Cerro del Hoyazo, Vera, Mazarrón and Mar Menor. It is composed of andesites and dacites, following the nomenclature of Peccerillo and Taylor (1976). Geochemically the suite is distinguished by the rather strong peraluminous character (high corundum in the CIPW norm) and the high content of incompatible elements, compared with the majority of calc-alkaline rocks (e.g. Gill 1981, p 6). However, the contents of these elements vary somewhat between the four main centres; the Mar Menor samples, for example, have close to "average" incompatible element concentrations. Table 1 gives the major and trace element composition of representative samples from the four centres.

In the cordierite-bearing volcanics, inclusions of metamorphic rocks are abundant. These consist mainly of almandine-biotite-sillimanite gneiss, quartz-cordierite rock and spinel-cordierite hornfels. Another type of inclusion, occurring most abundantly in the Hoyazo dacite, is represented by igneous rocks, predominantly of basic composition (in the main "basaltoid rock" and "quartz-rich gabbro" as named by Zeck 1968, 1970), but cordierite-bearing quartz-diorites also occur.

The volcanics are porphyritic and have a glassy matrix (in part devitrified) which constitutes 50–80 vol. % of the rocks. Plagioclase and in some samples orthopyroxene are the dominant phenocrysts in the SiO_2-poorer samples. Biotite and quartz are important in the relatively SiO_2- and K_2O-rich samples. Cordierite is a major constituent (commonly in the range 5–10 vol. %) in all but a few samples. Sanidine, garnet, andalusite and sillimanite are minor constituents, but are commonly very conspicuous. Concerning the occurrence at Hoyazo, Zeck (1968, 1970) interpreted plagioclase, biotite, euhedral cordierite and sillimanite as crystallization products of the melt, whereas garnet, anhedral cordierite, anhedral and corroded quartz, fibrolite/biotite streaks and andalusite were regarded as mono-crystal inclusions derived from the metamorphic rock inclusions. The cordierite-bearing volcanics around Vera, Mazarrón and Mar Menor show both petrographic and geochemical similarities to the Hoyazo dacite (e.g. mineralogy and normative corundum) and the Mazarrón and Mar Menor occurrences carry metamorphic rock inclusions comparable to those from Hoyazo.

Analytical techniques

Representative portions of pulverized specimens were used for both O- and Sr-isotope analyses.

O-isotopes: Oxygen was liberated by reaction with BrF_3, and O_2 converted to CO_2 before mass-spectrometric analyses. The apparatus used is similar to that described by Clayton and Mayeda (1963), and is installed at the Institute of Petrology, University of Copenhagen. Mass-spectrometry was performed on a Varian MAT 250 triple collector instrument. Replicate determinations were performed on 80% of the presented analyses. Several analyses of the NBS 28 reference sample yielded an average $\delta^{18}O = +9.66$ (rel. to SMOW). Estimated absolute accuracy is ± 0.2 δ-units.

Sr-isotopes: The samples for Sr-isotope analysis were prepared by standard ion-exchange methods. Sr-isotope ratios were measured on unspiked preparations with a Varian MAT TH5 instrument at the Institute of Petrology, University of Copenhagen. The results were corrected for fractionation and normalized to $^{87}Sr/^{86}Sr = 0.7080$ for the E&A $SrCO_3$ standard. The experimental precision of single determinations is estimated by the average 2σ as ± 0.0002 for the $^{87}Sr/^{86}Sr$ ratio. Reproducability of the E&A standard was

$^{87}Sr/^{86}Sr = 0.70805 \pm 0.00024$ (2σ for 17 determinations). Rb/Sr ratios were measured on a Philips PW 1410/20 XRF spectrometer with an overall accuracy of 1% (2σ).

The $^{87}Sr/^{86}Sr$ ratios have not been corrected for ^{87}Rb decay since eruption. For the volcanics and most rock inclusions the correction would be insignificant.

Isotopic results, discussion of primary versus secondary values

$\delta^{18}O$ values and $^{87}Sr/^{86}Sr$ ratios are listed in Table 2, together with SiO_2, K_2O, Rb and Sr concentrations. The locations of the analysed samples are given in the appendix.

Three samples from Mazarrón, 56208, 56217 and 56219, which show petrographic and compositional evidence of strong alteration, differ from the rest of the Mazarrón samples in both $\delta^{18}O$ values and $^{87}Sr/^{86}Sr$ ratios. As this paper focusses on the magma-forming processes, these three samples are not considered further. The remaining analysed volcanics show little or no petrographic evidence of post-magmatic alteration except for devitrification of the glassy matrix which has occurred in most samples. However, it is necessary to consider post-eruptive processes, e.g. water-rock interactions that might have occurred leaving little or no petrographic evidence, but which could have altered the isotopic composition of the volcanics. High $\delta^{18}O$ values could result from such an event (Taylor 1978).

If the syngenetic origin of the dacite and the (supposed) restite inclusions proposed by Zeck (1968, 1970) is correct, the high and very similar $\delta^{18}O$ values of the volcanics and the inclusions can hardly be explained by a post-eruptive hydrothermal event. One would expect that the strongly differing tectures of volcanics and inclusions – the first being a glass-rich rock, the second a holocrystalline rock – as well as their different mineralogy would result in varying susceptibilities towards O-isotope exchange and thus $\delta^{18}O$ values would be expected to differ. The observed similarity in $\delta^{18}O$ values for the volcanics and their (supposed) restite inclusions could thus suggest that the O-isotope composition of the volcanics are nearly representative of the original *magmas*. Two biotite separates from Hoyazo samples 56201a and z10768 yielded $\delta^{18}O$ values of +12.8 and +11.0, respectively. The O-isotope equilibrium fractionation at magmatic temperatures between a whole rock of granitic composition and biotite is around +1.5–+3.0 (Javoy 1977, assuming $\delta^{18}O_{\text{whole rock}} = \delta^{18}O_{\text{plag(An 30)}}$, Taylor 1978). The fractionations observed for the Hoyazo samples are +2.8 for 56201a and +2.5 for z10768. It seems likely that these magmatic fractionation values would have been changed if hydrothermal alteration had occurred. Presumably the glassy matrix would have been affected preferentially thereby tending to raise the whole rock-biotite fractionation value. Therefore, the observed values are taken as a further indication that the O-isotope composition of the volcanics are close to primary.

By inference, the Sr-isotope composition of the volcanics is also believed by the present writer to be largely primary. A further argument for this is the strong linear correlation of $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ in the volcanics, as reported below. Such systematic variation can hardly be explained by post-eruptional processes in rocks of Neogene age.

Concerning the whole rock results of the unaltered volcanics and their inclusions, the following are the most important observations:

(i) The volcanics from the four main centres are all high and somewhat variable in $\delta^{18}O$ (+12.2–+15.6). Even within a small occurrence like Hoyazo, the variation is pronounced (+13.1–+15.6).
(ii) The metamorphic rock inclusions have $\delta^{18}O$ values (+13.0–+16.2) comparable to the range for the volcanics.
(iii) The inclusions of igneous rocks in the Hoyazo dacite show, in comparison with the dacite itself, equal or lower $\delta^{18}O$ values (+11.1–+13.1 for the basic igneous rocks, and +15.5 for the sample of cordierite-bearing quartz-diorite).
(iv) The volcanics are high and variable in $^{87}Sr/^{86}Sr$ ratios (0.7095–0.7171).
(v) The $^{87}Sr/^{86}Sr$ ratios of the metamorphic rock inclusions (0.7153–0.7303) are generally much higher than the ratios for the volcanics.
(vi) The inclusions of igneous rocks have, in comparison with the Hoyazo dacite itself, lower and more uniform $^{87}Sr/^{86}Sr$ ratios for the "quartz-rich gabbro" and "basaltoid rock" types (0.7098–0.7112 and 0.7081–0.7085, respectively), and higher variable $^{87}Sr/^{86}Sr$ ratios for the cordierite-bearing quartz-diorite type (0.7213–0.7258).

Interpretation and discussion

O-isotopes, Cerro del Hoyazo

The dacite yields an average $\delta^{18}O = +14.3$ (range +13.1–+15.6). As argued above, these values are thought to be close to representative of the original melts. The values fall within Taylor's (1978) "high ^{18}O" group and are comparable to values for calc-alkaline igneous rocks from the Tuscan Igneous Province, Central Italy (Taylor and Turi 1976). The $\delta^{18}O$ values of the Tuscan rocks vary from ca. +11 to +16. Such values, together with (1) the ubiquitous presence of normative corundum, (2) the common occurrence of cordierite and (3) high $^{87}Sr/^{86}Sr$ ratios (0.7130–0.7200), were though to indicate the involvement of alumina-rich sedimentary or metasedimentary rocks in the genesis of the Tuscan magmas (Taylor and Turi 1976). The Hoyazo dacite satisfies all of these criteria (Sr isotopes are discussed below). The O-isotope results thus strongly indicate that (meta-)sediments played a major role in the formation of the Hoyazo magma.

One might speculate that the Hoyazo dacite represents magma of mantle origin contaminated by sedimentary material (e.g. by assimilation). The observed O-isotope values of +13.1–+15.6 would, however, require very high proportions of the (proposed) sedimentary end-member (>70%). This is because most continent-derived sediments have $\delta^{18}O$ values of ca. +12 to +16, whereas most magmas of primary mantle origin have $\delta^{18}O$ values of ca. +5.5–+6.5 (e.g. Magaritz et al. 1978). Such high degrees of assimilation would require that the magma was exceptionally superheated which is generally considered unlikely (e.g. Carmichael et al. 1974, p 68). Therefore, such a process was probably not important in the origin of the Hoyazo dacite. The proposal by Zeck (1968, 1970) that the magma was derived (wholly) by anatexis of (semi-)pelitic rocks is thus supported by the O-isotope results. The Hoyazo dacite is clearly an S-type volcanic rock (Chappell and White 1974; O'Neil et al. 1977).

The spread in $\delta^{18}O$ values for the Hoyazo dacite is, as argued above, probably to a large extent a primary mag-

Table 2. O- and Sr-isotope compositions and some elemental compositions of cordierite-bearing volcanics and their inclusions from SE Spain (56204, 56205 and 56227 carry little or no cordierite). * Indicates samples which show petrographic evidence of strong alteration

	$\delta^{18}O$	$^{87}Sr/^{86}Sr$	%		ppm	
			SiO_2	K_2O	Rb	Sr
Hoyazo volcanics						
56201a	+15.6	0.7139	64.13	3.59	149	321
74z24a	+13.8	0.7124	64.22	3.63	149	578
56250	+15.4	0.7129	63.20	3.32	136	369
z10767	+13.1	0.7138	64.17	3.68	146	343
z10768	+13.5	0.7138	64.37	3.73	143	321
75z144		0.7110	63.80	3.47	147	1,208
alm-bi-sill gn incl.						
z3ho		0.7282	40.62	3.50	177	176
z4ho	+14.5	0.7303	42.76	3.68	165	273
z11ho	+14.1	0.7211	38.90	3.23	152	71
z87ho	+14.9	0.7277	48.70	2.46	108	590
sp-cord hf incl.						
z59ho		0.7172	42.06	0.60	30	63
z65ho	+13.0	0.7234	36.29	3.24	171	29
z100ho		0.7186	37.76	2.68	145	66
qz-cord rock incl.						
66z62	+16.2	0.7215	65.32	1.10	56	32
66z99	+15.7	0.7153	62.40	1.00	52	30
z107ho		0.7189	52.77	1.79	84	29
"qz-rich gabbro" incl.						
z58ho		0.7098	56.59	0.81	16	502
z67ho	+11.1	0.7110	55.04	1.21	50	418
z68ho		0.7112	59.44	1.26	51	570
"basaltoid rock" incl.						
66z56	+12.7	0.7081	52.69	1.59	68	514
66z58a	+13.1	0.7083	52.67	1.54	65	502
z204		0.7085	51.03	2.69	98	617
cord qz-diorite incl.						
66z69		0.7258	68.69	0.99	43	333
66z73		0.7213	63.43	1.87	115	530
z91ho	+15.5	0.7231	57.90	2.39	156	647
Vera volcanics						
56203	+14.9	0.7124	65.02	3.79	229	829
56204	+14.9	0.7162	60.91	4.30	273	581
56205	+13.7	0.7152	66.66	5.98	281	660
z10704	+15.1	0.7095	66.59	3.06	210	1,270
Mazarrón volcanics						
56206	+15.0	0.7163	63.68	4.14	223	476
56207	+14.8	0.7163	63.74	4.29	228	479
56208*	+13.7	0.7136	66.41	4.72	218	492
56209	+14.9	0.7162	63.36	4.19	224	473
56210	+14.9	0.7164	63.12	4.46	225	495
56213	+13.8	0.7171	64.08	4.26	222	391
56217*	+16.0	0.7178	66.85	5.78	203	459
56219*	+11.5	0.7102	64.86	3.36	143	506
alm-bi-sill gn incl.						
56214		0.7190	42.03	4.23	191	419
Mar Menor volcanics						
56227	+12.2	0.7150	61.97	2.21	114	247
56228	+13.3	0.7164	61.29	1.89	110	175
56231	+14.9	0.7171	61.87	2.33	118	160
z10739	+14.0	0.7167	61.83	2.09	116	162
j8932	+12.8	0.7128	60.24	1.46	72	192
cord hf incl.						
56229	+13.1	0.7242	43.46	0.81	28	52

matic feature. As fractional crystallization (and probably other magmatic processes) induce only very moderate $\delta^{18}O$ changes (about 1 δ-unit) between whole rocks due to the high equilibration temperatures, this spread must be largely inherited from the (meta-)sedimentary parent. It follows that different parts of the magma were not homogenized.

The analysed inclusions of almandine-biotite-sillimanite gneiss, spinel-cordierite hornfels and quartz-cordierite rock have an average $\delta^{18}O$ value (+14.4) and a range (+13.0–+16.2) similar to the values of the dacite host. This is compatible with their proposed syngenetic origin (Zeck 1968, 1970). Quartz-cordierite rock inclusions ($\delta^{18}O = +15.7$–$+16.2$) have the highest $\delta^{18}O$ values among the analysed metamorphic inclusions followed by the almandine-biotite-sillimanite gneiss inclusions ($\delta^{18}O = +14.1$–$+14.9$) and the spinel-cordierite hornfels inclusion ($\delta^{18}O = +13.0$). This sequence probably represents an approach to equilibrium fractionation at elevated temperatures, as quartz is known to be among the most ^{18}O-rich minerals and spinel among the most ^{18}O-poor minerals (Taylor 1978).

The basic igneous rock inclusions, which have a rather "average" calc-alkaline composition and mineralogy, have exceptionally high $\delta^{18}O$ values (+11.1–+13.1). They differ, for example, from Central Andean calc-alkaline plutonic and volcanic rocks with $\delta^{18}O$ values of ca. +7 to +8 (Longstaffe et al. 1983). The high values at Hoyazo suggests that O of supracrustal origin was incorporated in the inclusions. The $\delta^{18}O$ values may have been raised through reaction with the surrounding dacitic melt or, alternatively, the ^{18}O enrichment might be ascribed to an event pre-dating the incorporation of the "quartz-rich gabbro" and "basaltoid rock" inclusions in the dacite.

The $\delta^{18}O$ value of one cordierite-bearing quartz-diorite inclusion (+15.5) falls within the range of the values for the dacite, and is consistent with an origin as an early precipitation product from the anatectic melt under plutonic conditions (Zeck 1968, 1970).

O-isotopes, Vera, Mazarrón and Mar Menor

The O-isotope composition of these centres is similar to that of the Hoyazo dacite, i.e. ^{18}O-rich. Averages and ranges are: Vera +14.7 (+13.7–+15.1), Mazarrón +14.7 (+13.8–+15.0) and Mar Menor +13.4 (+12.2–+14.9). A cordierite-rich hornfels inclusion from Mar Menor has a $\delta^{18}O$ value of +13.1. Together with the other geochemical and mineralogical evidence listed above (normative corundum and the occurrence of Al-rich minerals), the O-isotope compositions of both volcanics and the inclusion strongly suggest that the origins of the Vera, Mazarrón and Mar Menor magmas are similar to that of the Hoyazo dacite, i.e. the magmas formed by partial melting of (semi-)pelitic rocks.

Sr-isotopes, Cerro del Hoyazo, Vera, Mazarrón and Mar Menor

The $^{87}Sr/^{86}Sr$ versus $\delta^{18}O$ diagram. Samples from the four centres of cordierite-bearing volcanics in SE Spain have been plotted on a $^{87}Sr/^{86}Sr$ vs. $\delta^{18}O$ diagram (Fig. 2) along with data for Central Andean plutonics and volcanics (Longstaffe et al. 1983), the Banda Arc volcanics (Magaritz et al. 1978) and the volcanics of anatectic origin from Tuscany (Taylor and Turi 1976). The $^{87}Sr/^{86}Sr$ vs. $\delta^{18}O$ diagram demonstrates, on the basis of two essentially independent isotope systems (Taylor 1978), a clear difference between melts derived from supracrustal material and melts which originated in the mantle or from mantle-derived rocks in the crust. The high $^{87}Sr/^{86}Sr$ ratios of the Spanish samples are compatible with the origin from supracrustal rocks that is also indicated by the O-isotope and other evidence. The coinciding fields in Fig. 2 of the SE Spanish and Tuscan rocks are therefore not surprising. Furthermore, the cordierite-bearing volcanics from the Banda Arc fall within the same field; these rocks have probably been derived by partial melting of pelitic meta-sediments in the crust at depths of ca. 25 km (Whitford and Jezek 1977; Magaritz et al. 1978).

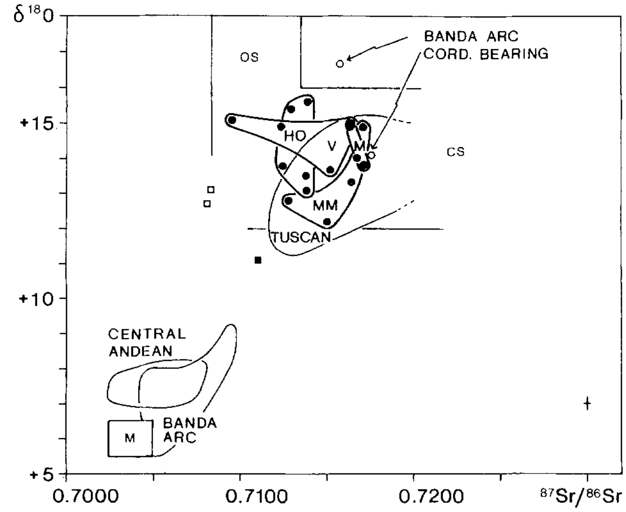

Fig. 2. $^{87}Sr/^{86}Sr$ vs. $\delta^{18}O$ plot of the cordierite-bearing volcanics from SE Spain. HO = Hoyazo, V = Vera, M = Mazarrón, MM = Mar Menor. Open squares are "basaltoid rock" inclusions and filled square is a "quartz-rich gabbro" inclusion from the Hoyazo dacite. Tuscan data are from Taylor and Turi (1976), Banda Arc data are from Magaritz et al. (1978) and the Central Andean data are from Longstaffe et al. (1983). The isotope composition of mantle rocks (M), continent derived sediments (CS) and deep ocean sediments (OS) are also shown (after Magaritz et al. 1978). A bar indicates the analytical uncertainty

In contrast, the Central Andean magmas of Fig. 2 have probably been generated in the upper mantle or mafic lower crust and have evolved without significant involvement of supracrustal rocks, although some $^{87}Sr/^{86}Sr$ ratios have probably been modified by isotopic exchange between magma and crust (Longstaffe et al. 1983). The somewhat higher $\delta^{18}O$ values and $^{87}Sr/^{86}Sr$ ratios of part of the cordierite-free andesites from the Banda Arc were explained by an origin in a mantle that had been contaminated by melts derived from a subducting crustal slab. The O- and Sr-isotope compositions of the contaminating melts were suggested to be similar to those of the cordierite-bearing lavas (Magaritz et al. 1978).

The three inclusions of "quartz-rich gabbro" and "basaltoid rock" inclusions in the Hoyazo dacite which have been analysed for both their O- and Sr-isotope compositions have also been plotted in Fig. 2. It is clear that these calc-alkaline rocks have unusually high $\delta^{18}O$ values and $^{87}Sr/^{86}Sr$ ratios. As mentioned in a previous section, their

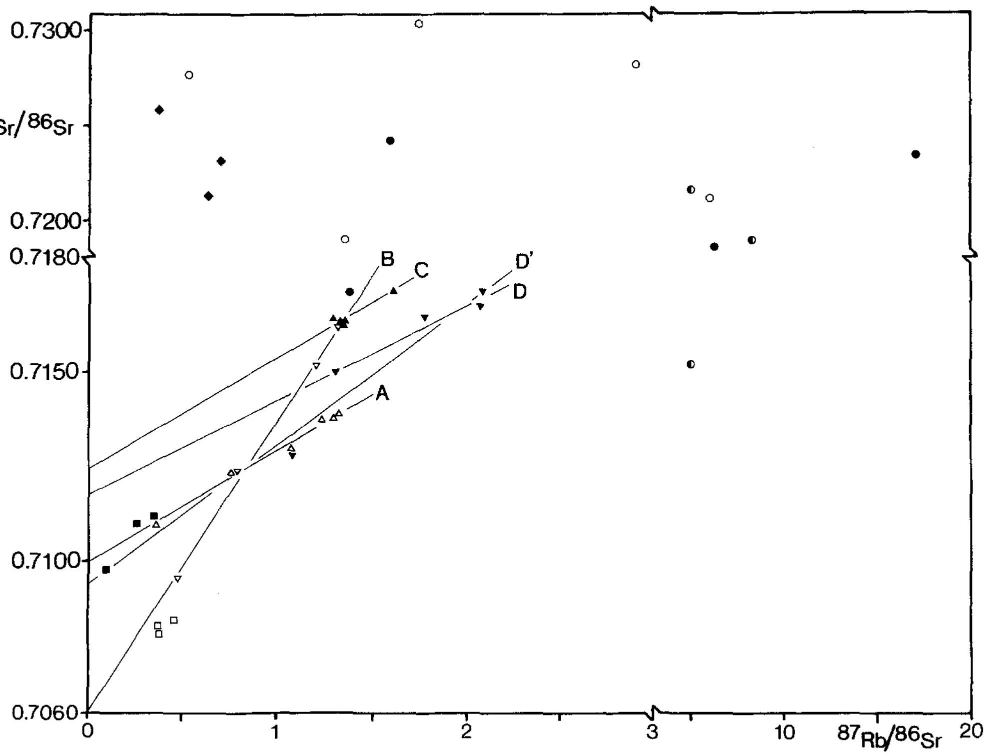

Fig. 3. $^{87}Sr/^{86}Sr$ vs. $^{87}Rb/^{86}Sr$ plot of the cordierite-bearing volcanics from SE Spain and their inclusions. Open upwards-pointing triangles = Hoyazo volcanic, open downwards-pointing triangles = Vera volcanics, filled upwards-pointing triangles = Mazarrón volcanics, filled downwards-pointing triangles = Mar Menor volcanics, open circles = almandine-biotite-sillimanite gneiss inclusions, filled circles = spinel-cordierite hornfels inclusions, partly filled circles = quartz-cordierite rock inclusions, diamonds = cordierite-bearing quartz-diorite inclusions, open squares = "basaltoid rock" inclusions, filled squares = "quartz-rich gabbro" inclusions. Lines of best fit: (A): Hoyazo, 210±17 Ma; (B): Vera, 535±22 Ma; (C): Mazarrón, 199±58 Ma; (D): Mar Menor, 173±23 Ma excluding sample j8932; (D′): Mar Menor, 257±16 Ma including sample j8932

high $\delta^{18}O$ values could have been derived by interaction with the surrounding dacite. The uniform $^{87}Sr/^{86}Sr$ ratios (Table 2) within each rock type, however, argue against exchange of Sr isotopes. It is thus possible that the basic magmas initially possessed both high $\delta^{18}O$ values and high $^{87}Sr/^{86}Sr$ ratios. Evidently, more data are needed before attempting a more precise interpretation. The different $^{87}Sr/^{86}Sr$ ratios of the "quartz-rich" gabbro and "basaltoid rock" inclusions suggest that they were derived from two independent magmas.

The $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ diagram. The six samples of the Hoyazo dacite that have been analysed for their Sr-isotope composition show a strong linear correlation of $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ (Fig. 3) which, if interpreted as an isochron, gives an age of 210±17 Ma (initial $^{87}Sr/^{86}Sr$ = 0.7100±3, MSWD = 2.40). Similarly, the Mazarrón samples define a 199±58 Ma line (initial $^{87}Sr/^{86}Sr$ = 0.7125±12, MSWD = 1.84) and the Mar Menor samples a 173±23 Ma line (initial $^{87}Sr/^{86}Sr$ = 0.7118±6, MSWD = 5.54)[1]. The Vera samples lie along a 535±22 Ma line (initial $^{87}Sr/^{86}Sr$ = 0.7061±3, MSWD = 8.42). All calculations were made according to McIntyre et al. (1966) with $\lambda_{87Rb} = 1.42 \times 10^{-11}\ y^{-1}$, and errors given are 2σ values.

1 Sample j8932 was omitted from this calculation. If it is included the line of best fit yields: age = 257±16 Ma, initial $^{87}Sr/^{86}Sr$ = 0.7095±4, MSWD = 36.64

Table 3. Some feasible interpretations of the linear $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ correlations of the cordierite-bearing volcanics of SE Spain

The linear $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ correlations may represent:
1. mixing lines (i.e. they are fictitious isochrons), that is, the indicated ages have no geological meaning
2. true isochrons yielding pre-eruptional ages which could date:
a) the anatectic events producing the peraluminous melts
b) pre-anatectic events in the parent (meta-)sedimentary rocks

All four centres have a proven Neogene eruption age (e.g. Zeck 1968; López Ruiz and Badiola 1980). The eruption age of the Hoyazo dacite has been estimated at 11.9 Ma from a biotite K-Ar measurement (P.M. Holm 1984, pers. comm.). Some feasible interpretations of the strong linear correlations in the $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ diagram are listed in Table 3, and will be discussed briefly.

1. *Mixing lines.* With coordinates of $^{87}Sr/^{86}Sr$ and 1/Sr a straight line may be approximately fitted to the data points (Fig. 4). A straight line in such a diagram is consistent with two-component mixing, though it does not prove such a process. The Hoyazo samples especially are compositionally *very* homogeneous except for their contents of Sr and Ba (Table 1). There are no correlations between $^{87}Sr/^{86}Sr$ ratios and elements other than Sr. In contrast, Faure et al. (1974) found that basalts from Antarctica, which were

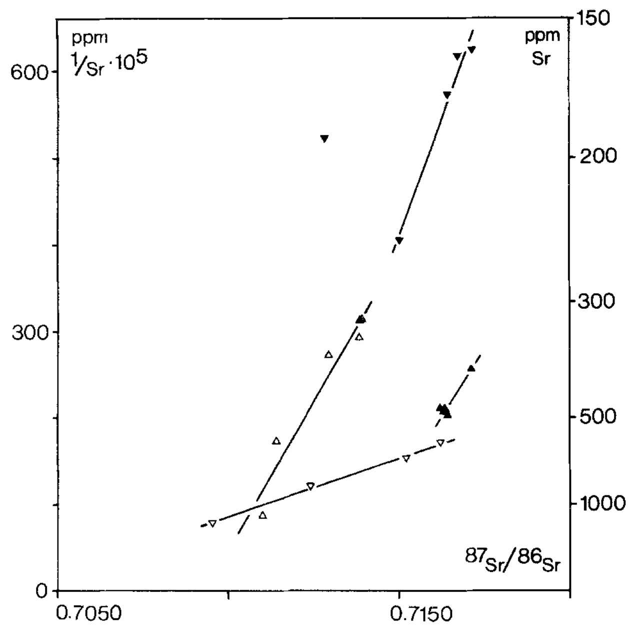

Fig. 4. $^{87}Sr/^{86}Sr$ vs. $1/Sr \times 10^5$ plot of the cordierite-bearing volcanics from SE Spain. Same symbols as in Fig. 3

thought to have resulted from hybridization of tholeiitic magma by assimilation of granitic rocks, showed strong linear correlations between initial $^{87}Sr/^{86}Sr$ and $1/Sr$ *as well as* all major oxide components. At Hoyazo, element variations due to a mixing process must have involved only Sr. Magma mixing in the magma chamber prior to eruption involving compositionally similar components (except for Sr) is a possibility that could have produced the appearance of an isochron, although homogenization must have been thorough as no microstructural evidence for such a process has been found in the volcanics. However, the variation of primary O-isotope compositions (discussed above) indicates that different part of the magma were not homogenized.

2. *True isochrons.* The nearly concordant ages of the Hoyazo, Mazarrón and Mar Menor lines with different initial $^{87}Sr/^{86}Sr$ ratios is apparently in favour of an isochron interpretation for the linear $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ correlations. The isochron ages could thus represent pre-eruptional events in the crust, implying that the Rb-Sr isotope systems survived the heating connected with the eruptional events unchanged. Roddick and Compston (1977) have pointed out that the volume throughout which Sr-isotope equilibration is effective, the specific distribution of Rb/Sr ratios, and not least the sampling strategy determine whether such an inherited isochron can be found. Concerning the last mentioned point, the finding of a pre-eruptional isochron would be especially surprising at Hoyazo considering the closeness of sample locations (within an area of 0.7 km^2).

Regarding the Hoyazo dacite, Zeck (1968, 1970) gave two possibilities for the physical state of the anatectic complex when basic magma (which he suggested triggered the eruption and was incorporated in the dacite as "quartz-rich gabbro" and "basaltoid rock" inclusions) approached the anatectic zone. It could have been (i) in a liquid state with some restite material or (ii) essentially in a solid state and forming a migmatite complex. In the second case it was suggested that the heat supplied by the basic magma caused a remelting of the leucosomes of the migmatite complex. It could be speculated that the ca. 173–210 Ma Rb-Sr ages obtained for the Hoyazo, Mazarrón and Mar Menor samples belong to the anatectic event of possibility (ii). Similarly, the Vera age of c. 535 Ma may indicate an older independent anatectic event. However, it is also possible that the anatectic events were yet other examples of thermal episodes, which did not erase older Rb-Sr isotope systems. The (proposed) isochron ages could thus represent pre-anatectic events in the parent (semi-)pelitic rocks.

If all samples of melts of the anatectic systems were homogenized with respect to their $^{87}Sr/^{86}Sr$ ratios at the time of anatexis, and since that time (i.e. during remelting and eruption) have behaved as closed systems, the restite origin of the metamorphic rock inclusions proposed by Zeck (1968, 1970) would imply that these inclusions also equilibrated with the melts in terms of their Sr-isotope composition. The (supposed) restite inclusions and the inclusions of cordierite-bearing quartz-diorite form a bewildering scatter in the $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ diagram (Fig. 3). The lack of fit of the supposedly cogenetic restite and melt to a single straight line may be seen as evidence against a restite origin for the metamorphic inclusions. However, their large scatter in the $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ diagram must be accounted for by any explanation of their origin. It is considered likely that a metasomatic process was involved. Microstructural indications that removal of Rb or Sr (isotopes), or both, from the inclusions in question could have occurred prior to eruption, do exist (Zeck 1968, 1970 – the development of the "second" and "third" mineral assemblages). Therefore, the Rb-Sr isotope data are not believed by the present writer to necessarily disprove the restite hypothesis.

In conclusion, the question remains whether the strong linear correlations in the $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ diagram are mixing lines or true isochrons. At present, a conclusive answer is not available. Simple two-component mixing may be a possible, though rather improbable, explanation; it requires the coming together of two components differing only in Sr content. Multi-component mixing would seem to lean even more heavily on the element of chance. On the other hand, the isochron interpretation only finds support in the fact that nearly concordant ages have been obtained for suites of samples with different initial $^{87}Sr/^{86}Sr$ ratios (the Hoyazo, Mazarrón and Mar Menor centres). More substantial support for an isochron interpretation would be the finding of similar radiometric ages for the pre-Tertiary rocks of the region. Such data have, as far as the present writer is aware, not been published.

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Note added in proof

Recently Halliday and Mitchell (1984, Earth Planet Sci Lett 68:229–239) have reported a clustering of K-Ar ages between 210 and 230 Ma (range 119–285 Ma) for clays associated with a hydrothermal event in the Pedroches Batholith, South Central Spain. Based on a comparison with age data from other areas they propose that a major ca. 210–230 Ma hydrothermal event occurred throughout the North Atlantic region. It could be speculated that the ca. 173–210 Ma Rb-Sr "ages" presented in the present paper correspond to such an event.