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Dating Events of Acid Plutonism through the Paleozoic of the Western Iberian Peninsula

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ABSTRACT

On the basis of field relationships the Hercynian granites in the western part of the Iberian Peninsula are usually divided into two broad groups, designated as "younger" and "older" granites, respectively. Rb-Sr whole-rock isochron analyses have been carried out on suites of samples from younger granites, from undeformed older granites, and from strongly tectonized older granites (gneissic granites). The Rb-Sr isochron age of the younger granites is 280 ± 11 million years (Carboniferous-Permian boundary). The undeformed older granites yield an age of 298 ± 10 million years (approximately Upper Westphalian). Four samples of gneissic granites suggest an age of 349 ± 10 million years (Upper Devonian or Dinantian). The ages are discussed in relation to the geological setting of the granites.

Biotites and muscovites, both from Hercynian granites and from Hercynian metamorphosed pre-Hercynian granites, yield K-Ar ages between 270 and 287 million years. Rb-Sr ages of biotites and muscovites range from 276 to 294 and from 286 to 305 million years, respectively. This pattern of ages may be related to regional cooling at the end of Hercynian orogenesis.

Pre-Hercynian plutonic rocks are preserved in western Galicia (granodiorites, granites and per-alkaline granites) and in Alto Alentejo (granites, per-alkaline granites and syenites). A Rb-Sr whole-rock isochron analysis sets an Upper Ordovician age for this plutonism (about 460–430 million years ago).

From geologic relationships it is evident that this Upper Ordovician plutonism had an anorogenic character. The plutonism is discussed in relation to the Caledonian mobile belt, from the point of view of a pre-Continental Drift reconstruction of the northern Atlantic. It is suggested that the Upper Ordovician acid plutonism in the western Iberian Peninsula is contemporaneous with the post-orogenic uplift of the Caledonian fold belt to the west.

1. Introduction

The Hercynian "Hesperic Massif" covers north-western, western and central Spain and the greater part of Portugal (cf. inset Fig. 2). It consists of Paleozoic and Precambrian rocks, folded, metamorphosed and extensively invaded by magmas of granitic to granodioritic composition during the Hercynian orogenesis. Metamorphism in this orogen is characterized by mainly low-pressure mineral assemblages, as seems to be the normal situation for the whole Hercynian orogenic belt of Europe (ZWART, 1967).

The chronological order of Hercynian granite emplacements in this orogen has been studied extensively in central and northern Portugal and in north-western Spain.

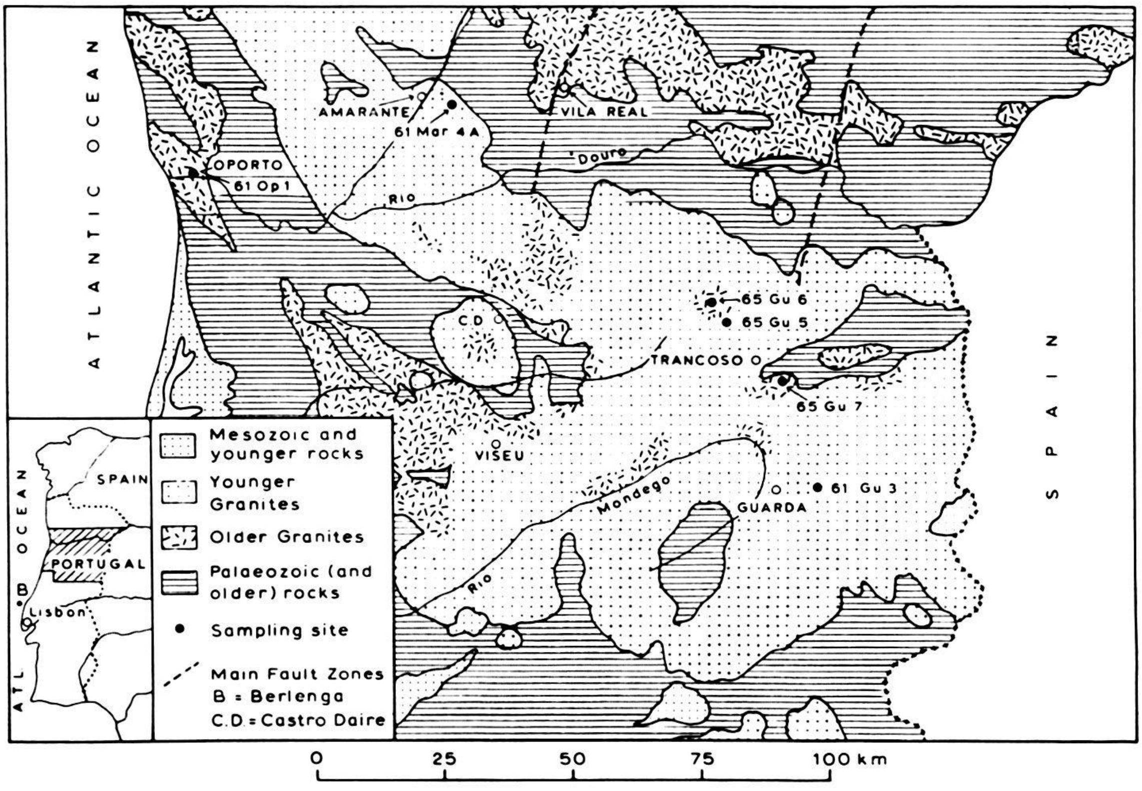

Fig. 1. Simplified geological sketch map of part of central and northern Portugal (mainly after OEN, 1960), showing the locations of the samples analysed (see also the Appendix). The sampling site 61 Ber 2 is at the island of Berlenga (B at the key map).

In central and northern Portugal, in the region between, roughly, 40.1° and 41.3° N. lat. (cf. Fig. 1), such investigations were carried out during the last two decades by students of the University of Amsterdam (e.g., WESTERVELD, 1956; SCHERMERHORN, 1956; OEN, 1960). The Hercynian area of western Galicia, north-western Spain (Fig. 2), has been the subject of investigations for many years by I. PARGA-PONDAL and, since 1956, also by students of the University of Leiden (PARGA-PONDAL, e.g., 1935, 1956, 1963; DEN TEX, 1966; FLOOR, 1966-a, 1966-b, 1968). On the basis of structural relations, the Hercynian granites in both areas can be divided into groups of "younger" and "older" granites. The younger granites are clearly post-tectonic and have intrusive relationships towards the older granites. In eastern Galicia, R. CAPDEVILA arrives at a similar division of the Hercynian granites into two groups (CAPDEVILA & VIALETTE, 1965).

In a recent discussion of the granitic area of central and northern Portugal by OEN (1960 and private communication), the younger granites are defined as epizonal, essentially discordant, allochthonous plutons and intrusive complexes surrounded by aureoles of contact-metamorphism. The older granites, on the other hand, are mesozonal, essentially concordant, allochthonous granite plutons occurring in granite belts associated with zones of low-pressure, Abukuma-type regional metamorphism. The younger granites in western Galicia, designated as the "post-kinematic biotite granite series" (FLOOR, 1966-b), are equivalent to part of the younger granites in central and northern Portugal (OEN ING SOEN and P. FLOOR, private communication). However, the older granites in western Galicia form a very complex group of rocks, showing either intrusive or migmatitic relations with their wall rocks. In the present study, this group includes both the megacrystal granodiorite series and the two-mica granite series (various two-mica granites, anatexites and migmatites). Also classed in this group are various two-mica gneissic granites, although these rocks were strongly tectonized and are thus obviously older than the other, not or only weakly deformed granitic rocks. (See, e.g., PARGA-PONDAL, 1956, 1963; DEN TEX, 1966; FLOOR, 1966-b.)

Evidently, the older granites in western Galicia are partly sub-autochthonous rocks emplaced at a deeper crustal level than the older granites in the Portuguese area under consideration. According to FLOOR (1968), western Galicia is a relatively deeply eroded part of the Hercynian orogen, whereas higher levels of the orogen are exposed in northern Portugal and eastern Galicia.

Locally, the Hesperic Massif contains features showing that a pre-Hercynian basement, with a record of earlier orogenic and igneous histories, was involved in the Hercynian orogen. In western Galicia, plutonic and metamorphic rocks of the original basement, tectonized and completely recrystallized during the Hercynian orogeny, are clearly preserved in the discontinuous narrow belt of granite-gneisses, paragneisses, amphibolites and schists between Malpica and Túy (Fig. 2). Outside this belt, another complex of granite-gneisses is found west and north of Lalín in the southern and eastern part of a discontinuous arc of metamorphic basic and ultrabasic rocks that extends from Carballo through Santiago, Lalín and Mellid to Cabo Ortegal. (See the discussions by, e.g., PARGA-PONDAL, 1956, 1963; DEN TEX, 1966; FLOOR, 1966-a, 1966-b; DEN TEX & FLOOR, 1966.)

The Galician orthogneisses range in composition from granodioritic to per-alkaline granitic, the latter type containing minerals such as riebeckite, aegirine and astrophyllite (FLOOR, 1966-b).

Various ages have been assigned to these pre-Hercynian granites, which were gneissified during the Hercynian orogeny: from Precambrian (PARGA-PONDAL, 1956) ranging to Early Hercynian (CARLÉ, 1945). However, preliminary Rb-Sr investigations on two granite-gneiss samples from the Vigo area indicated a Lower Paleozoic (in the order of 475 to 500 million years) age for their emplacement (PRIEM et al., 1966). Locally, it was observed that these Lower Paleozoic granites have invaded and contact-metamorphosed metasedimentary series showing imprints of an even older regional metamorphism (FLOOR, 1966-b).

In Portugal, acid plutonic rocks pre-dating the Hercynian orogenesis are reported from the Elvas-Portalegre area in the southern part of the country (in the so-called "Massif of Evora", cf. THADEU, 1958). These rocks were the subject of many publications. For recent discussions on the geology and petrography of these pre-Hercynian rocks, the reader is referred to TEIXEIRA & TORRE DE ASSUNÇÃO (1957, 1958) and FERNANDES (1961). Both granite-gneisses and per-alkaline riebeckite- and aegirine-bearing rocks occur, the latter generally having syenitic, occasionally nepheline syenitic compositions. (See Fig. 3.)

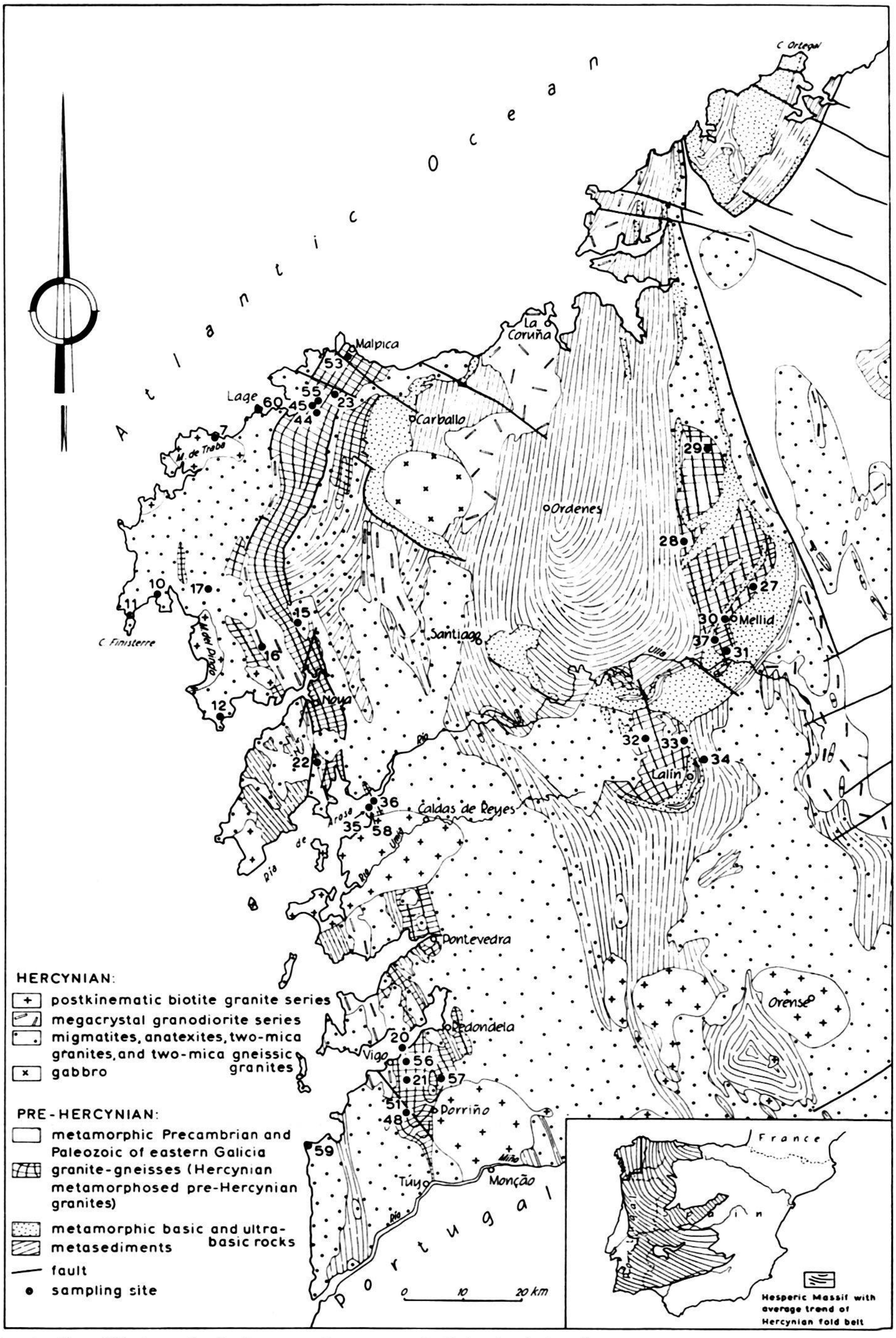

Fig. 2. Simplified geological map of western Galicia (mainly after Parga Pondal, 1963, and unpublished reports of the Dept. of Petrology, University of Leiden), showing the locations of the samples analysed. The numbers 7–60 correspond to the sampling sites 61 Cor 7–68 Cor 60 (see also the Appendix).

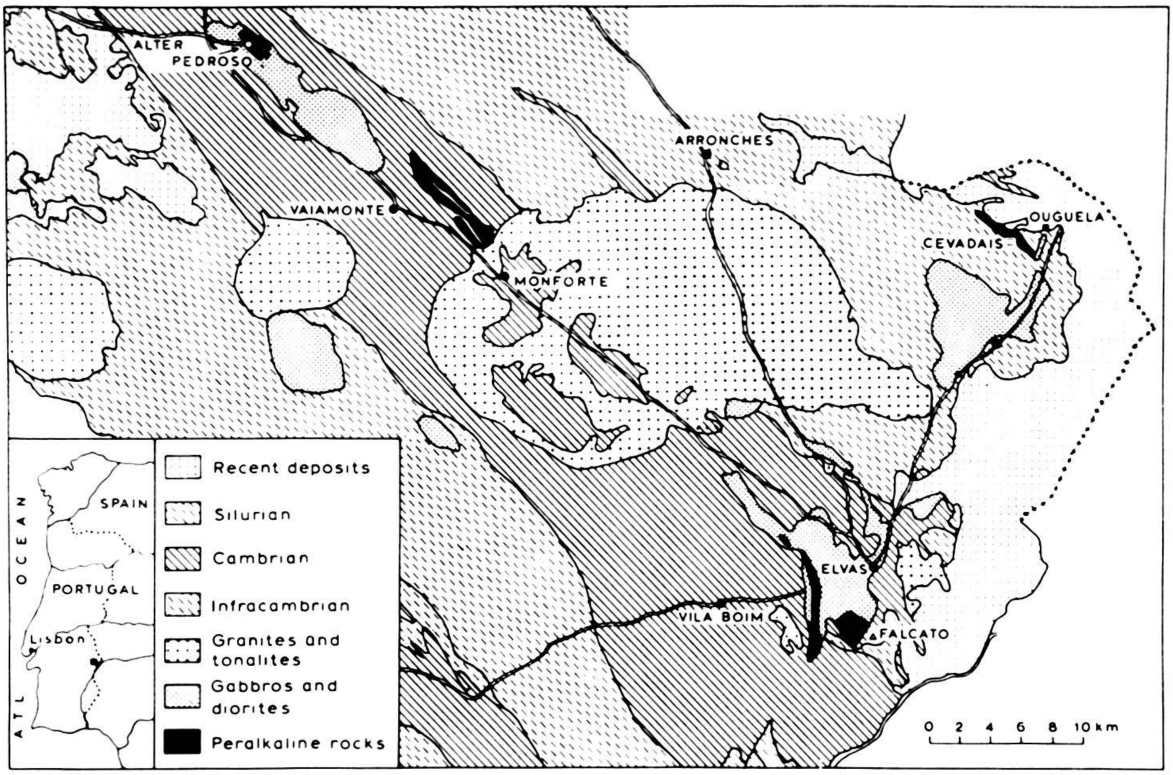

Fig. 3. Simplified geological map of the Elvas-Alter Pedroso area, Alto Alentejo (after TEIXEIRA & TORRE DE ASSUNÇÃO, 1957). The samples 66 Porta 1, 66 Porta 2 and 68 Porta 8 come from the massif of alkaline rocks around Alter Pedroso. The samples 66 Porta 3 and 68 Porta 9–11 were collected in the massif of Cevadais. The sampling site 66 Porta 4 is outside the map area (Portalegre, 22.5 km N of Monforte). (See also the Appendix).

The present study reports and discusses the results of age measurements on
(1) Hercynian "younger" granites (6 whole-rocks and 2 separated micas),
(2) Hercynian "older" granites (9 whole-rocks and 6 separated micas),
(3) Hercynian gneissic granites (4 whole-rocks), and
(4) pre-Hercynian granite-gneisses and syenitic rocks (21 whole-rocks and 2 separated micas from western Galicia and 8 whole-rocks from Alto Alentejo).

The whole-rocks were measured according to the Rb-Sr method. Micas were dated by the Rb-Sr and K-Ar methods. The locations of the samples investigated are shown in Figure 1, Figure 2 and Figure 3 (see also the Appendix). Some of the data included in this paper have been reported before by PRIEM et al. (1965, 1966, 1967).

2. Analytical procedures

(a) Rb-Sr measurements

Splits of crushed and pulverized whole-rock samples were analysed for their Rb and Sr contents either by stable isotope dilution, or by X-ray fluorescence spectrometry, or by both methods. Micas were analysed by stable isotope dilution only. A spike enriched in ^{86}Sr was used for the earlier measurements; later we used a spike enriched in ^{84}Sr and ^{86}Sr. The isotope measurements were made on a 20 cm, 60° mass-spectrometer, utilizing thermal ionization and multiplier detection. A single (Ta) filament source was employed for Sr measurements, whereas Rb analyses were made with a double (Re) filament source. $^{87}Sr/^{86}Sr$ ratios were measured directly on unspiked strontium or, for samples with relatively high Rb/Sr ratios, calculated from isotope-dilution runs. All ratios were normalized for $^{88}Sr/^{86}Sr = 8.3752$ to correct for effects of mass discrimination. For the earlier series of measurements, the signals of the ion beams were recorded in the conventional way on a chart recorder; later, a digital method of recording and analysing the mass-spectrum data was used.

The X-ray fluorescence data were obtained on a semi-automatic X-ray spectrometer equipped with a 2 kW Mo X-ray rube and a (200) LiF analysing crystal. Mass absorption coefficients for both external reference standard and sample were estimated by the measurement of the intensity of the Compton scattering of the Mo Kα primary beam.

(b) K-Ar measurements

Potassium determinations were made by flame-photometry with a lithium internal standard and a Cs-Al buffer. Argon was extracted in a bakeable glass vacuum apparatus and determined by standard isotope dilution techniques (using ^{38}Ar as tracer) in a Reynolds-type glass mass-spectrometer; the measurements were made by the static method.

(c) Constants used

All calculations were made using the following constants:

$$\begin{aligned} {}^{87}\mathrm{Rb}:\lambda &= 1.47\times 10^{-11}\,\mathrm{yr}^{-1}, \\ {}^{40}\mathrm{K}:\lambda_e &= 5.85\times 10^{-11}\,\mathrm{yr}^{-1}, \\ \lambda_\beta &= 4.72\times 10^{-10}\,\mathrm{yr}^{-1}, \text{ and} \\ \text{abundance } {}^{40}\mathrm{K} &= 0.0118 \text{ atom } \% \text{ total K.} \end{aligned}$$

3. Rb-Sr whole-rock age studies of the Hercynian granites

The analytical data are recorded in Table 1 (younger granites), Table 2 (older granites) and Table 3 (gneissic granites). The appropriate data are plotted in an isochron diagram of $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ (Fig. 4). Isochrons of the younger and older granites were obtained by least-squares fits of each group of sample points, following the computation method proposed by WILLIAMSON (1968). A relative weight was assigned to each pair of coordinates based upon assumed standard errors of 0.6% and 2% for the measured $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios, respectively. The errors quoted for the isochron ages and the initial $^{87}Sr/^{86}Sr$ ratios are the standard errors as calculated from the analytical data.

The six data-points of younger granites are fairly well linearly correlated. They define an isochron of 280 ± 11 million years with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7046 ± 0.004.

For the nine older granites analysed, the slope of the calculated isochron corresponds to an age of 298 ± 10 million years and the intercept to an initial $^{87}Sr/^{86}Sr$ ratio of 0.709 ± 0.0014. However, the data-points display a somewhat larger scattering

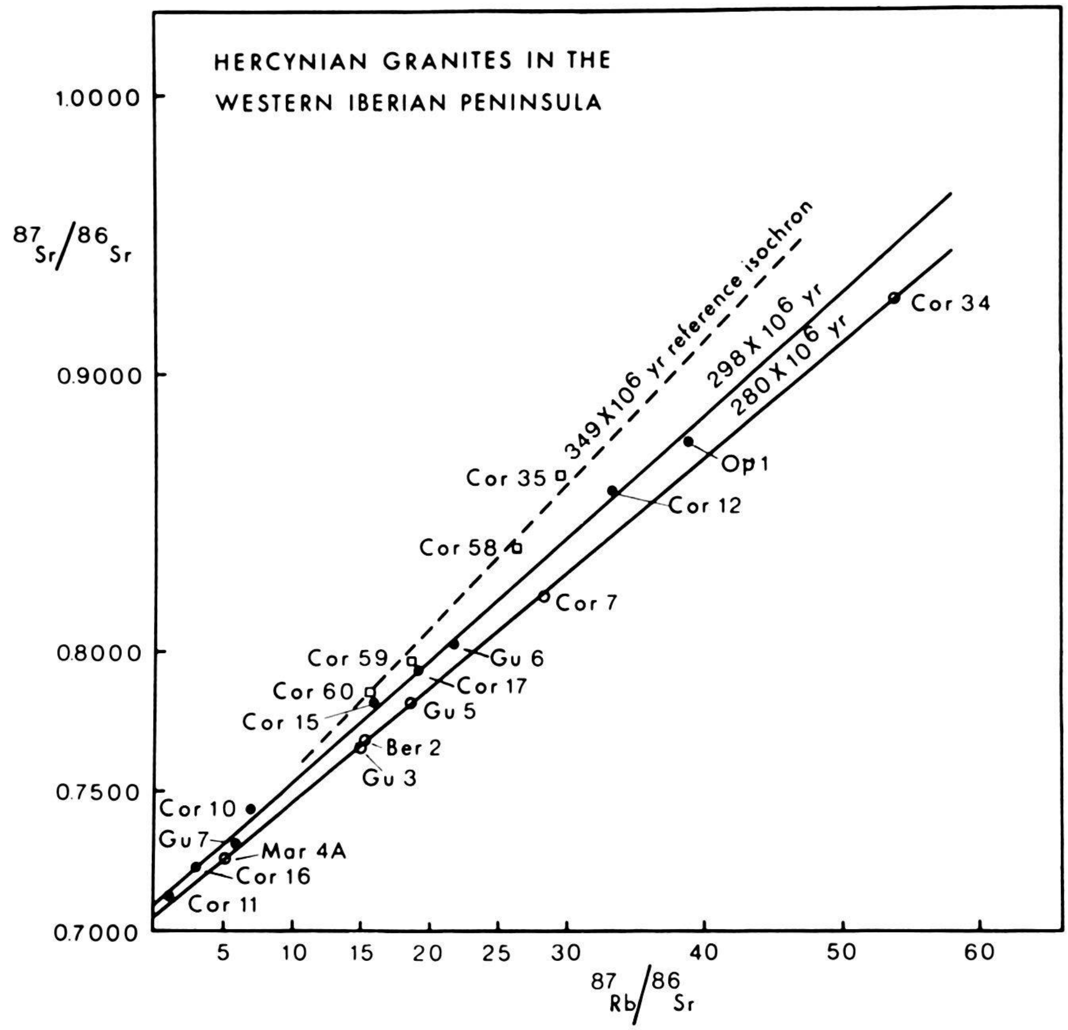

Fig. 4. Whole-rocks isochron diagram of the Hercynian granites investigated. Open circles, "younger" granites; closed circles, "older" granites; open squares, gneissic granites. Specimen numbering as in tables 1, 2 and 3.

around the best-fitted straight line. This may be partly due to the fact that the older granites form a much more heterogeneous group, possibly emplaced over a duration of time sufficiently long to be reflected in some scattering of data-points in the isochron diagram. Furthermore, especially in western Galicia, they often have a somewhat migmatitic character, occasionally containing abundant inclusions of pelitic wall rock material. Part of the scatter thus may reflect the presence of some inherited radiogenic ^{87}Sr. Finally, some of these rocks might not have remained completely closed systems in terms of Rb-Sr during nearby intrusions of younger granites.

Only four samples of the gneissic granites were analysed. In the isochron diagram these points lie all above the isochron of the older granites, but they do not fit closely to a straight line. Furthermore, these samples have only a relatively narrow range in Rb/Sr ratios. Calculation of an isochron is, therefore, not warranted. The individual ages of the samples, assuming an initial $^{87}Sr/^{86}Sr$ ratio of 0.705, range from 330 to 369 million years, averaging 349 ± 10 million years. In the isochron diagram of Figure 4, a 349 million years isochron is shown as a "reference isochron".

The order of ages obtained for the three groups of Hercynian granites is in agreement with the geological relations. Following the "Geological Society Phanerozoic time-scale" (1964), these ages indicate that the emplacement of all Hercynian granites studied took place through the Carboniferous, possibly from the Upper Devonian up into the Lower Permian. Concerning the timing of the successive Hercynian granite emplacements, it is clear that the younger granites were intruded close to the Carboniferous-Permian boundary. Our data further suggest that the older granites were emplaced in, approximately, Upper Westphalian time, while an Upper Devonian or Lower Carboniferous (Dinantian) age may be assigned to the gneissic granites. Additional data are required in order to define more precisely the age of this oldest group of Hercynian granites.

Table 1. Whole-rock Rb-Sr studies on Hercynian "younger" granites from Portugal and western Galicia (Fig. 4).

Sample Nr.	Rb ppm Wt.	Sr ppm Wt.	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$
Portugal				
61 Gu 3	317	62.3	0.7663[a]	14.93
	316	61.6	0.7662[a]	
	321	62.2	0.7655[a]	
	315			
65 Gu 5	303	47.1	0.7813[a]	18.48
	302	48.4	0.7810[a]	
61 Mar 4A	306	173	0.7250[a]	5.10
	305	174	0.7256[a]	
61 Ber 2	257	50.3	0.7667[a]	15.11
	262	49.5	0.7683[a]	
Western Galicia				
61 Cor 7	331	34.0	0.8215[a]	28.25
	334	34.9	0.8167[a]	
67 Cor 34	457	25.1	0.9266	53.85
		25.0	0.9271	

[a]) Direct measurement on unspiked sample.

In contrast to the group of older granites, the gneissic granites show effects of strong deformation. This implies that orogenic folding movements have occurred between the emplacements of both groups of granites, while no important Hercynian deformations have taken place afterwards. From geologic evidence in central and northern Portugal, WESTERVELD (1956) and SCHERMERHORN (1956) concluded to the presence of a major Hercynian folding phase of pre-Westphalian D age. SCHERMERHORN argues that this phase, for which he suggests a Middle Westphalian age, is the first and most important of the four Hercynian folding phases that can be distinguished. Our age data seem to support SCHERMERHORN's conclusions.

Table 2. Whole-rock Rb-Sr studies on Hercynian undeformed "older" granites from western Galicia and northern Portugal (Fig. 4)[1].

Sample Nr.	Rb ppm Wt.	Sr ppm Wt.	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$
Western Galicia				
61 Cor 10	316	133	0.7435 0.7432[a])	6.90
61 Cor 11	269	691	0.7135 0.7110[a])	1.13
61 Cor 12	447	39.4	0.8598[a]) 0.8559[a])	33.33
61 Cor 15	375	69.0	0.7811[a]) 0.7828[a])	15.85
61 Cor 16	226	217	0.7203 0.7265[a])	3.02
61 Cor 17	459	70.2	0.7938[a]) 0.7934[a])	19.09
Northern Portugal				
65 Gu 6	421 420	57.4 55.5	0.8013[a]) 0.8047[a])	21.77
65 Gu 7	312 305	152 151	0.7303[a]) 0.7307[a])	5.90
61 Op 1	390 390 386 391	29.5 29.7 29.1 29.6	0.8771[a]) 0.8768[a]) 0.8732[a]) 0.8770[a])	38.81

[1]) The gneissic granites, which on the map of Fig. 2 are taken together with the anatexites, migmatites and two-mica granites as one group, are not included in this table (see Table 3).

[a]) Direct measurement on unspiked sample.

Table 3. Whole-rock studies on Hercynian gneissic granites from western Galicia (Fig. 4).

Sample Nr.	Rb ppm Wt.	Sr ppm Wt.	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$	Age[a]) million years
67 Cor 35	297 300[b])	29.8 29.8[b])	0.8640	29.42	369
68 Cor 58	333[b])	37.1[b])	0.8391[c]) 0.8363[c])	26.31	343
68 Cor 59	333[b])	52.0[b])	0.7954[c]) 0.7962[c])	18.69	330
68 Cor 60	362[b])	68.0[b])	0.7849[c]) 0.7860[c])	15.48	352

[a]) Calculated with an assumed initial $^{87}Sr/^{86}Sr$ ratio of 0.705. Maximum analytical error for the individual ages estimated at $\pm 5\%$.

[b]) Measured by X-ray fluorescence spectrometry.

[c]) Direct measurement on unspiked sample.

4. Rb-Sr and K-Ar ages of micas from Hercynian granites and gneisses

The analytical data and calculated Rb-Sr and K-Ar ages of the micas dated are listed in Table 4 and Table 5, respectively. Figure 5 shows a histogram of measured ages. In this histogram is also included the Rb-Sr age of 282 million years measured by BONHOMME et al. (1961) on biotite from the Castro Daire granite in Portugal (a younger granite, cf. SCHERMERHORN, 1956). Further, the histogram contains the Rb-Sr ages measured in eastern Galicia by CAPDEVILA & VIALETTE (1965) on biotite and muscovite from an older granite (the Guitiriz two-mica granite) and biotite from a younger granite (the Lugo-Castroverde biotite granite); these ages are 276, 301 and 276 million years, respectively.

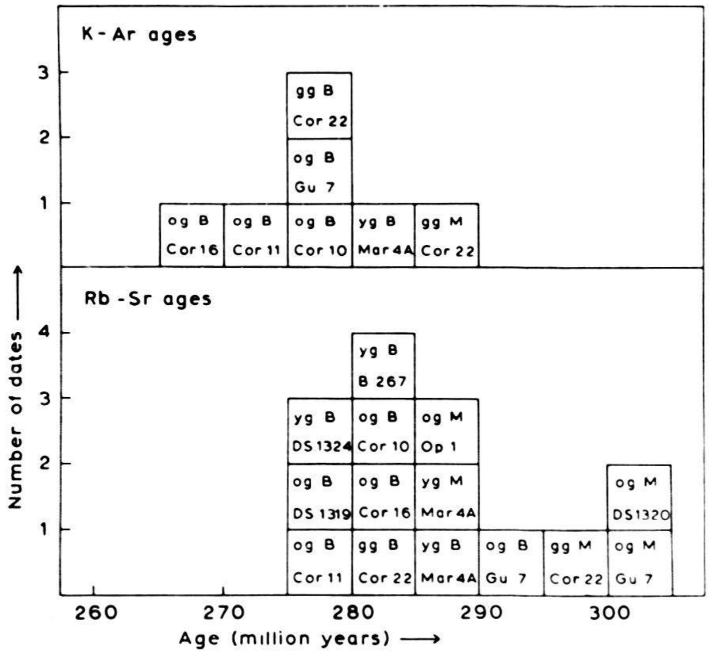

Fig. 5. Histogram of K-Ar and Rb-Sr mica ages. Specimen numbering as in tables 4 and 5. The sample B.267 was analysed by BONHOMME et al. (1961), while the samples DS.1319, DS.1320 and DS.1324 were measured by CAPDEVILA & VIALETTE (1965). B, biotite; M, muscovite; yg, Hercynian "younger" granite; og, Hercynian "older" granite; gg, gneiss-granite (pre-Hercynian granite metamorphosed in Hercynian time).

All micas have K-Ar ages between 270 and 287 million years. The Rb-Sr ages are somewhat higher: from 276 to 294 million years for biotites, and from 286 to 305 million years for muscovites. The K-Ar ages of both biotites and muscovites and most of the biotite Rb-Sr ages are equal to or slightly younger than the Rb-Sr whole-rock isochron age of the younger granites, regardless of the emplacement age of the granite in which they occur. Obviously, these ages reflect not so much the time of crystallization of the micas, but rather the time when the regional temperature of the rocks fell below the threshold values above which argon and, in biotites, radiogenic strontium were able to diffuse out of the minerals as soon as they were formed, and below which such diffusion virtually ceased. This regional heating could have been connected with the emplacement and cooling of the younger granites. The higher Rb-Sr ages (+10 to 20 million years) found in muscovites from older granites and a granite-gneiss may be interpreted as indicating that muscovite became a closed system to radiogenic strontium at a somewhat higher temperature.

Table 4. Rb-Sr mica ages in the Hercynian orogen of western Galicia and northern Portugal (Fig. 5).

Sample Nr.	Mineral	Rb ppm Wt.	Sr ppm Wt.	$^{87}Sr/^{86}Sr$	rad. ^{87}Sr ppm Wt.	Age[a]) million years
"Younger" granites in northern Portugal						
61 Mar 4A	muscovite	630	12.5	1.3593	0.756	286
		630	12.5	1.3581	0.751	
61 Mar 4A	biotite	1216	7.3	3.2528	1.451	287
		1216	7.3	3.2123	1.446	
"Older" granites in western Galicia						
61 Cor 10	biotite	1373	4.27	6.924	1.614	282
61 Cor 11	biotite	1054	9.4	2.2298	1.223	278
61 Cor 16	biotite	1074	3.93	5.507	1.257	281
"Older" granites in northern Portugal						
65 Gu 7	biotite	1151	4.82	4.931	1.408	294
65 Gu 7	muscovite	859	11.1	1.8208	1.089	305
		855	10.8	1.8466	1.085	
61 Op 1	muscovite	1262	4.24	6.449	1.524	289
		1256	4.33	6.146	1.504	
Granite-gneisses in western Galicia (Pre-Hercynian granites recrystallized during the Hercynian orogenesis)						
66 Cor 22	biotite	1105	2.54	11.188	1.283[b])	285
		1057	2.52	11.181	1.275[b])	
66 Cor 22	muscovite	905	4.97	3.8384	1.160[b])	300
		952	5.15	3.7353	1.172[b])	

[a]) Maximum error estimated at ±4%.
[b]) Initial $^{87}Sr/^{86}Sr$ ratio calculated using a graphical analysis according to COMPSTON, JEFFERY & RILEY (1960).

5. Rb-Sr whole-rock isochron analysis of the pre-Hercynian granitic and syenitic rocks

The analytical data are reported in Table 6. Figure 6 shows an isochron diagram of $^{87}Sr/^{86}Sr$ versus $^{87}Rb/^{86}Sr$ in which the appropriate data of the measured samples are plotted. Isochrons were calculated by means of a least-squares regression analysis in the same way as described in chapter 3. The errors quoted are the standard errors as calculated from the analytical data.

For the granite-gneisses from western Galicia, an isochron has been fitted to 18 of the 21 samples analysed. Three samples, 68 Cor 44, 51 and 55, depart rather widely to the right from this best-fitted straight line and were therefore not included in the calculations. The isochron defines an age of 438 ± 7 million years and an initial $^{87}Sr/$

Table 5. K-Ar mica ages in the Hercynian orogen of western Galicia and northern Portugal (Fig. 5).

Sample Nr.	Mineral	K % Wt.	rad. ^{40}Ar ppm Wt.	Atmospheric ^{40}Ar (% total ^{40}Ar)	Age[a]) million years
"Younger" granites in northern Portugal					
61 Mar 4A	biotite	7.61	0.164	9.1	
		7.64	0.170	4.3	285
			0.164	3.1	
"Older" granites in western Galicia					
61 Cor 10	biotite	7.46	0.158	9.0	277
		7.51			
61 Cor 11	biotite	7.95	0.165	5.8	273
		7.95			
61 Cor 16	biotite	7.86	0.163	6.0	270
		7.98			
"Older" granites in northern Portugal					
65 Gu 7	biotite	7.57	0.161	43.1	
		7.53	0.159	8.7	278
			0.160	7.0	
Granite-gneisses in western Galicia (Pre-Hercynian granites recrystallized during the Hercynian orogenesis)					
66 Cor 22	biotite	7.37	0.162	6.4	280
		7.43	0.155	13.1	
66 Cor 22	muscovite	8.84	0.193	15.1	287
		8.81			

[a]) Maximum error estimated at $\pm 3\%$.

^{86}Sr ratio of 0.710 ± 0.0014. It may be noted that sample 61 Cor 20, being a much higher point than the other 17 data-points, has a disproportionally strong influence on the slope of this isochron. If this sample is omitted, then the slope of the computed isochron would correspond to an age of 429 ± 8 million years and the intercept to an initial $^{87}Sr/^{86}Sr$ ratio of 0.711 ± 0.0015.

Of the eight measured samples from Alto Alentejo, six show a linear arrangement in the isochron diagram. They define an isochron having a slope corresponding to an age of 466 ± 12 million years and an initial $^{87}Sr/^{86}Sr$ ratio of 0.703 ± 0.003. Two data-points, 66 Porta 3 and 68 Porta 9, lie below this best-fit line and were omitted from the computations. The 466 ± 12 million years isochron approaches closely the isochron of the granite-gneisses from western Galicia.

The data-points of the samples 68 Cor 44, 51 and 55, 61 Porta 3 and 68 Porta 9 lie beneath the overall linear array of all other samples from Alto Alentejo and western Galicia. This may be interpreted as indicating that these rocks did not constitute completely closed systems with regard to Rb and Sr during the Hercynian metamorphism. Such could especially apply to the samples 61 Porta 3 and 68 Porta 9. Having very low Sr contents (6.14 and 2.5 ppm, respectively) and coming from a small lense (cf. Fig. 3), these rocks must have been very susceptible to loss of radiogenic ^{87}Sr during the metamorphism.

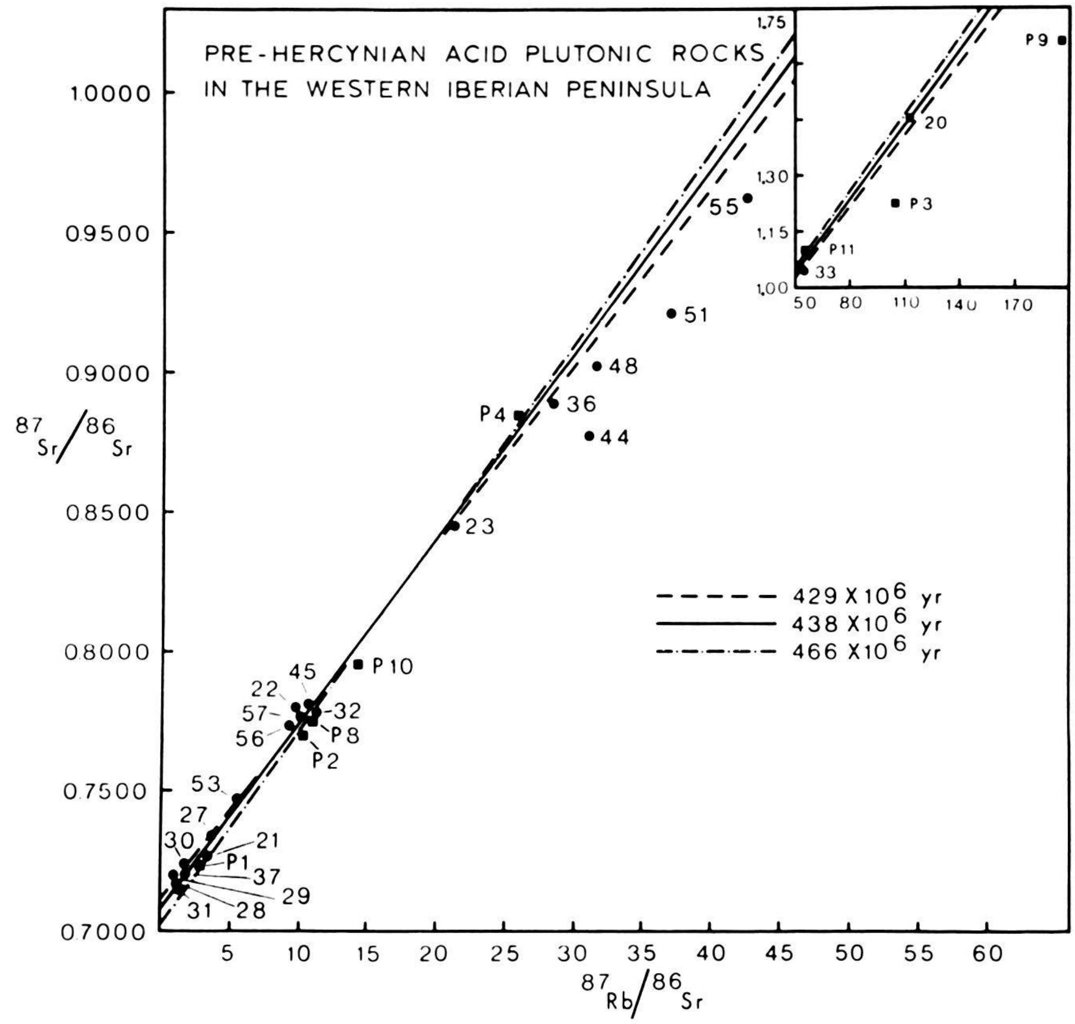

Fig. 6. Whole-rocks isochron diagram of the pre-Hercynian acid plutonic rocks investigated. The specimen numbers 20–57 (closed circles) correspond to 61 Cor 20–68 Cor 57, P1–P11 (closed squares) to 66 Porta 1–68 Porta 11 (Table 6).

There is also some scattering of the linearly correlated data-points. This may in part likewise be due to slight disturbances of the Rb-Sr systems during the Hercynian metamorphism. However, it must also be kept in mind that the samples taken together in the above isochron analyses do not represent strictly contemporaneous intrusions. For instance, FLOOR (1966-b) presented evidence to show that in western Galicia the per-alkaline granites are younger than the granodioritic-granitic suite, with intrusions of basic dykes in between. The time span of the acid plutonism may thus have been sufficiently long to be reflected in some scatter of the data-points in the isochron plot.

Additional age work will be needed in order to study the time interval between the intrusions of the per-alkaline granitic and the granodioritic suites. At this stage of the investigations, the interval between about 460 and 430 million years ago may be accepted for the time span in which the successive plutonic intrusions took place, in western Galicia granodiorites, granites and per-alkaline granites, and in Alto Alentejo granites, per-alkaline granites and syenites. Following the "Geological Society Phanerozoic time-scale" (1964), an Upper Ordovician age can thus be assigned to this episode of acid plutonism.

Table 6. Whole-rock Rb-Sr studies on pre-Hercynian acid plutonic rocks from western Galicia and Alto Alentejo (Fig. 6).

Sample Nr.	Rb ppm Wt.	Sr ppm Wt.	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$
Western Galicia				
61 Cor 20	264	7.34	1.455	111.73
61 Cor 21	137	131	0.7268[b])	3.03
66 Cor 22	248	74.9	0.7813[b])	9.73
	247	73.1	0.7752[b])	
66 Cor 23	210	28.1	0.8476[b])	21.39
	205	28.8	0.8438[b])	
67 Cor 27	126	99.3	0.7335[b])	3.67
67 Cor 28	82.0	205	0.7170	1.16
			0.7167[b])	
67 Cor 29	78.3	208	0.7167	1.09
			0.7230[b])	
67 Cor 30	58.9	101	0.7186	1.69
			0.7254[b])	
67 Cor 31	72.6	182	0.7154	1.16
			0.7146[b])	
67 Cor 32	184	48.6	0.7776	11.03
			0.7783[b])	
67 Cor 33	152	8.6	1.0523	53.23
67 Cor 36	351	36.1	0.8891	28.62
67 Cor 37	87.7	148	0.7206	1.72
			0.7198[b])	
68 Cor 44	219[a])	20.8[a])	0.8773[b])	31.04
			0.8773[b])	
68 Cor 45	179.5[a])	49.0[a])	0.7818[b])	10.69
			0.7791[b])	
68 Cor 48	291[a])	27.2[a])	0.9019[b])	31.56
			0.9038[b])	
68 Cor 51	281[a])	22.5	0.9216[b])	37.00
			0.9216[b])	
68 Cor 53	132.5[a])	70.2	0.7448[b])	5.49
			0.7457[b])	
68 Cor 55	151	10.6	0.9626	42.47
	151[a])	10.5[a])	0.9625[b])	
68 Cor 56	151[a])	47.7[a])	0.7739[b])	9.22
68 Cor 57	187[a])	54.8[a])	0.7760[b])	9.96
			0.7760[b])	
Alto Alentejo				
66 Porta 1	64.9	71.3	0.7227	2.64
			0.7239[b])	
66 Porta 2	183	53.5	0.7712	9.96
			0.7704[b])	
66 Porta 3	212	6.14	1.2237[b])	105.11
			1.2206	

Table 6 (continuation)

Sample Nr.	Rb ppm Wt.	Sr ppm Wt.	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$
66 Porta 4	255	28.6	0.8870 0.8815[b])	26.26
68 Porta 8	110[a])	29.9[a])	0.7771[b]) 0.7751[b])	10.73
68 Porta 9	155 155 154[a])	2.5 2.5 (2.3[a]))	1.714 1.703	197.80
68 Porta 10	77.1[a])	15.6[a]) 16.2	0.7954 0.7970[b])	14.34
68 Porta 11	155 152[a])	8.1 7.8[a])	1.112 1.088[b])	57.46

[a]) Measured by X-ray fluorescence spectrometry.
[b]) Direct measurement on unspiked sample.

6. The Upper Ordovician plutonism in the western Iberian Peninsula

Our data clearly demonstrate that the pre-Hercynian basement of the western Iberian Peninsula is marked by invasions of acid plutonic rocks in Upper Ordovician time, about 460 to 430 million years ago. According to FLOOR (1966-b), these plutonic masses have intruded metasedimentary series recording an even older event of regional metamorphism. It is thus evident that the Hercynian orogen of Portugal and western Spain involved reactivation of older sialic basement, and did not result in accretion of new continental crustal material.

There is general agreement that Caledonian orogenic disturbances were absent or very weak in Spain and Portugal. Only some tectonism in Upper Cambrian time, evidenced by local angular unconformities between geosynclinal Infracambrian-Cambrian series and quartzites of the basal Ordovician, may be correlated with Caledonian movements elsewhere. No unconformities occur in the Ordovician-Silurian-Devonian sequence, but gradual changes in facies and occasional hiatus in sedimentation may record oscillations of epeirogenic nature. (See, e.g., the discussions by CARRINGTON DA COSTA, 1952, and SCHERMERHORN, 1956.) Therefore, the Upper Ordovician igneous events in the western Iberian Peninsula obviously had an anorogenic character.

A pre-Continental Drift reconstruction of the northern Atlantic (Fig. 7) shows that the plutonic activities now under discussion seem to have occurred in a zone roughly parallel to the Caledonian mobile belt, about 300–400 km E. from the eastern margin of this belt. It has been argued by MOORBATH (1967) and MOORBATH et al. (1968) that in the Caledonides of Scotland and western Ireland the main Caledonian metamorphism and granite emplacements occurred between about 530 and 500 million years ago. The abundance of mineral dates between 460 and 400 million years (clustering around 430–440 million years) should reflect post-orogenic uplift, cooling and unroofing of the Caledonian massifs in Ordovician time. A similar

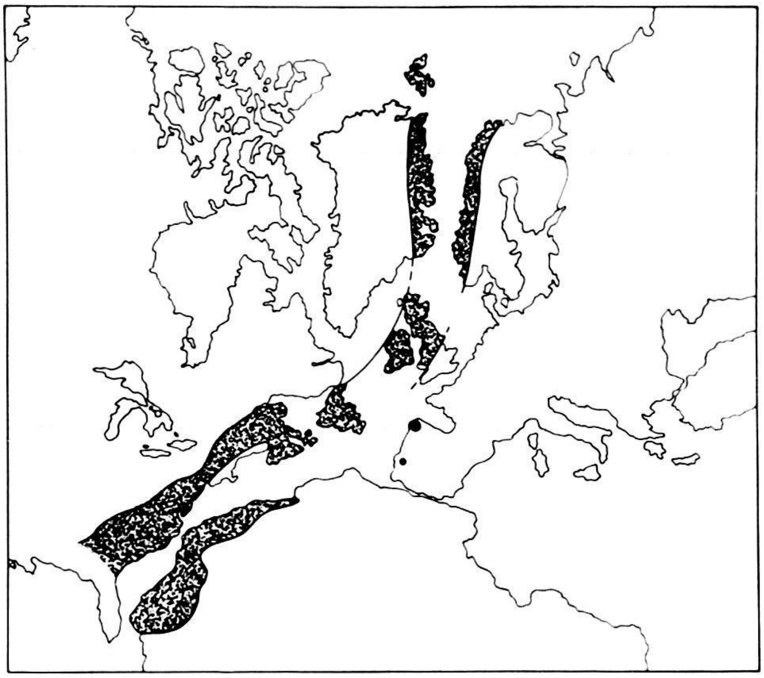

Fig. 7. Pre-drift reconstruction of the Northern Atlantic (simplified after HURLEY, 1968), showing the areas of Upper Ordovician acid plutonism in the western Iberian Peninsula (black dots) in relation to the Caledonian mobile belt (dark grey).

pattern of events is suggested by preliminary data of current investigations in the Caledonides of northern Norway by the Amsterdam Laboratory for Isotope Geology (unpublished). It may thus be postulated that the Upper Ordovician plutonic event in the western Iberian Peninsula was contemporaneous with the post-orogenic uplift of the Caledonian mobile belt to the West.

Taking into account the 35° clockwise rotation of the Iberian Peninsula required for pre-drift reconstruction (e.g., VAN DER VOO, 1969), the zone of Upper Ordovician acid plutonic rocks in north-western Spain could be expected to continue in Brittany (cf. Fig. 7). This region is likewise situated outside the Caledonian fold belt, and only some epeirogenic movements did occur in Caledonian time. However, only a few data of 460–470 million years have been reported from Brittany (LEUTWEIN et al., 1968). On the other hand, abundant data, both in Brittany (LEUTWEIN et al.) and southern England (e.g., ADAMS, 1967), reflect wide-spread granite emplacements and metamorphism around 600 million years ago, the "Cadomian orogeny". According to LEUTWEIN et al., the data of 460–470 million years in Brittany (recording granite emplacements and, allegedly, greisenization with tin-tungsten mineralization) should represent "Late Cadomian" phenomena.

Whether Late Cadomian or not, the 430–460 million years old acid plutonism in the western Iberian Peninsula has some special characteristics. The invading magmas were mainly granodioritic to granitic in composition, but minor amounts of peralkaline magmas have also intruded: in western Galicia, astrophyllite-bearing riebeckite-aegirine granites (FLOOR, 1966-a. 1966-b; DEN TEX & FLOOR, 1966), in Alto Alentejo, riebeckite-aegirine granites to syenites and, subordinately, even nepheline- or sodalite-bearing syenites (TEIXEIRA & TORRE DE ASSUNÇÃO, 1957, 1958).

FLOOR's (1966-b) studies in south-western Galicia show that per-alkaline granites were the latest intrusions, separated from the earlier ascent of granodioritic to granitic magmas by intrusion of basic dykes. In Alto Alentejo the per-alkaline magmas likewise have intruded into gabbroic masses themselves intruding Upper Cambrian limestones (TEIXEIRA & TORRE DE ASSUNÇÃO, 1957, 1958).

Intrusion of per-alkaline granitic and syenitic magmas is generally restricted to stable continental areas characterized tectonically by simple fracturing. However, such conditions seem difficult to fit in the structural regime prevailing in the western Iberian Peninsula during Upper Ordovician time, as in many areas of Portugal and western Spain there is ample evidence for continuous marine (geosynclinal) sedimentation through the Ordovician, Silurian and Lower Devonian. Only some oscillations of epeirogenic nature can be deduced from the sedimentary column. One might speculate that the granitic, per-alkaline granitic and syenitic magmas ascended along faults in geanticlines or relatively stable blocks. In this respect it might be of significance that in western Galicia the characteristic basal quartzites of the Ordovician are conspicuously absent, though little is known as yet regarding the occurrence of other post-Cambrian Paleozoic deposits (P. FLOOR, private communication). According to TEIXEIRA & TORRE DE ASSUNÇÃO (1957), the post-Cambrian sedimentation in the Elvas-Alter Pedroso area should start with Silurian, Ordovician being absent; the recent edition of the CARTA GEOLOGICA DE PORTUGAL (1968), on the other hand, shows bands of Ordovician rocks in this region. Clearly, more field data and detailed geological research are required before the mechanism of this plutonism in western Galicia and southern Portugal can be understood.

Acknowledgments

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APPENDIX

Nature and locations of samples analysed

(a) Hercynian "younger" granites in Portugal (Fig. 1)

61 Gu 3	Coarsely porphyritic biotite granite. Casal Cinza, 8.5 km E of Guarda, on road from Guarda to Rochoso.
65 Gu 5	Coarsely porphyritic two-mica granite from the "Dão Granitic Complex" (DE BOORDER, 1965). About 6 km SE of Sernancelhe, roughly 10 km NW of Trancoso.

61 Mar 4A	Coarsely porphyritic biotite granite from the "Amarante Granite" (MAIJER, 1965). Serra do Marão, in the Rio Marão, about 6 km E of Amarante.
61 Ber 2	Biotite granite. Island of Berlenga.

(b) Hercynian "younger" granites in western Galicia (Fig. 2)

61 Cor 7	Biotite granite from the "Granito de Traba" (PARGA PONDAL, 1956, 1963). Harbour entrance of Camelle.
67 Cor 34	Muscovite-quartz porphyry. Erbo de Arriba.

(c) Hercynian "older" granites in central and northern Portugal (Fig. 1)

65 Gu 6	Faintly gneissose two-mica albite granite from the "Sernancelhe Granite" (DE BOORDER, 1965). About 4.3 km SE of Sernancelhe, roughly 13.6 km NW of Trancoso.
65 Gu 7	Porphyritic two-mica granite from the "Granito de grão médio" (CÂNDIDO DE MEDEIROS, 1961). About 0.6 km N 58 W of Povoa de Concelho, at 6 km ESE of Trancoso.
61 Op 1	Two-mica albite granite from the "Granito de Porto". Oporto.

(d) Hercynian "older" granites, except the gneissic granites, in western Galicia (Fig. 2)

61 Cor 10	Sillimanite-bearing two-mica granite, an anatectic granite rich in inclusions of sillimanite rock. About 8 km NNE of Co. Finisterre, 1 km W of Pta. Sardiñeiro.
61 Cor 11	Porphyritic biotite granite from the "Finisterre Granite" (WOENSDRECHT, 1966). About 500 m N of Co. Finisterre.
61 Cor 12	Gneissose two-mica albite granite from the "Muros Granite". About 1 km SW of Muros, on road to Corcubión.
61 Cor 15	Gneissose two-mica granite from the "Cotro de Eiras Granite", Vilarinho.
61 Cor 16	Porphyritic biotite granite. About 2 km NE of Suevos.
61 Cor 17	Two-mica granite from the "La Ruña Granite" (WOENSDRECHT, 1966). Mazaricos, about 3 km N of Fornis.

(e) Hercynian gneissic granites in western Galicia (Fig. 2)

68 Cor 35	Two-mica gneissic granite. Carril.
68 Cor 58	Idem. Sampling site close to 68 Cor 35.
68 Cor 59	Idem. Cabo Silleiro.
68 Cor 60	Idem. Lage.

(f) Pre-Hercynian granite-gneisses in western Galicia (Fig. 2)

61 Cor 20	Astrophyllite-bearing riebeckite granite-gneiss from the "Riebeckite Gneiss of the Galiñeiro type" (FLOOR, 1966-b). On the coast about 0.5 km S of La Guia, Vigo.
61 Cor 21	Biotite granite-gneiss from the "Biotite Orthogneisses" (FLOOR, 1966-b). About 0.5 km W of Rebullón, E of Vigo.
66 Cor 22	Biotite augengranite-gneiss. About 6 km NW of Boiro.
66 Cor 23	Muscovite-garnet granite-gneiss. About 3 km SW of Pazos.
67 Cor 27	Two-mica augengranite-gneiss. About 10 km NE of Mellid.
67 Cor 28	Biotite granite-gneiss. About 6 km N of Boimorto.
67 Cor 29	Biotite granite-gneiss. About 4 km NW of Curtis.
67 Cor 30	Two-mica granite-gneiss. About 3 km W of Mellid.
67 Cor 31	Biotite augengranite-gneiss. About 6 km S of Mellid.
67 Cor 32	Two-mica granite-gneiss. About 3 km ENE of Silleda.
67 Cor 33	Biotite granite-gneiss. About 10 km N of Lalín.
67 Cor 36	Two-mica granite-gneiss. Carril.
67 Cor 37	Biotite augengranite-gneiss. About 4 km SW of Mellid.
68 Cor 44	Garnet-epidote-muscovite granite-gneiss. On road from Puenteceso to Silvarredonda, at km 15.5.
68 Cor 45	Two-mica granite-gneiss. Allones.
68 Cor 48	Astrophyllite-bearing aegirine-riebeckite granite-gneiss (cf. 61 Cor 20). Vilaverde, Zamanes.

68 Cor 51	Riebeckite-aegirine granite-gneiss (cf. 61 Cor 20). Vilaverde, Zamanes.
68 Cor 53	Two-mica granite-gneiss. Malpica.
68 Cor 55	Biotite granite-gneiss. Allones.
68 Cor 56	Biotite granite-gneiss (cf. 61 Cor 21). Madroa, E of Vigo.
68 Cor 57	Biotite granite-gneiss (cf. 61 Cor 21). On road from Puxeiros to Mos, at km 5.

(g) Pre-Hercynian granite-gneisses, syenite-gneisses and gneissose syenites in the Elvas-Portalegre area, Alto Alentejo, southern Portugal (Fig. 3)

66 Porta 1	Gneissose riebeckite- and aegirine-bearing syenite from the "Syenite hyperalcalin sodique" (Teixeira & Torre de Assunção, 1957, 1958). Summit of hill immediately N of Alter Pedroso.
66 Porta 2	Gneissose riebeckite-aegirine syenite (cf. 66 Porta 1). N of Alter Pedroso.
66 Porta 3	Aegirine granite-gneiss from the "Orthogneiss hyperalcalin quartzifère de Cevadais" (Teixeira & Torre de Assunção, 1958). Immediately E of Cevadais.
66 Porta 4	Mylonitic and porphyritic muscovite-chlorite granite-gneiss from the "Granito alcalino, porphyróide, de grão grosseiro, tectonizado, ante-hercinico" (Fernandes, 1961). Immediately NW of Portalegre.
68 Porta 8	Gneissose riebeckite-aegirine syenite (cf. 66 Porta 1). Alter Pedroso.
68 Porta 9	Idem. About 600 m SE of Cevadais.
68 Porta 10	Gneissose biotite syenite. About 350 m ESE of Cevadais.
68 Porta 11	Sodalite syenite from the "Ouguellite, syenite à néphéline et sodalite" (Teixeira & Torre de Assunção, 1958). About 1.5 km ESE of Cevadais.

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