

Rb-Sr and Sm-Nd geochronology and isotope geochemistry of Central Iberian metasedimentary rocks (Portugal)

C.C.G. Tassinari¹, J. Medina² & M.S. Pinto²

¹ Geosciences Institute, University of São Paulo / CNPq, Rua do Lago 562, CEP 05422-970, PO Box 11348, São Paulo, Brazil; ² Geosciences Department, University of Aveiro, 3810 - Aveiro, Portugal

Received 10 July 1995; accepted in revised form 29 March 1996

Key words: Central Iberian Zone (CIZ), metamorphic age, sediment provenance, Slate Greywacke Complex (CXG)

Abstract

Rb-Sr and Sm-Nd isotopic data are reported for 27 samples of fine-grained metasediments from five different localities of the Slate Greywacke Complex of the Central Iberian Zone, Portugal. Over most of the area, Rb-Sr whole-rock isotope systematics yields a 440 to 400 Ma time interval, which is considered to correspond to an important metamorphic episode.

Initial ⁸⁷Sr/⁸⁶Sr ratios of most Variscan granitoids from northern Portugal together with the Sr isotopic evolution curves for all studied metapelites, show that the latter are not suitable main sources for these granitoids.

Sm-Nd depleted-mantle model ages and whole-rock Sm-Nd isochron ages provide values of 1.35 to 1.25 Ga, which may correspond to the average age of the mantle-extraction of the sources of the sediments. These data provide evidence that metamorphism of greenschist facies does not induce Nd isotopic rehomogenization in fine-grained sediments.

The Sr and Nd isotopic signatures of the analysed metasediments ($Sr_i = 0.7090$ to 0.7170 ; and $\epsilon_{Nd}(430) = -2.6$ to -4.18) suggest derivation from young continental crust, and deposition probably in a tectonically passive setting.

Introduction

This work presents a Rb-Sr and Sm-Nd isotopic study on some pelitic and greywacke metasediments of the Slate Greywacke Complex (CXG), a sequence of pre-Ordovician rocks of uncertain stratigraphic age in western-central Portugal (Sousa & Sequeira 1993).

Considering that low-grade metamorphism of fine-grained terrigenous sediments may cause substantial exchange of Sr, and that homogenisation of initial ⁸⁷Sr/⁸⁶Sr ratios may be initiated by the metamorphism, the Rb-Sr method is potentially capable of offering geologically meaningful metamorphic age data (Bickle 1993; Dickin 1995). This fact and the age uncertainty of the CXG encouraged us to apply Rb-Sr systematics to constrain the main metamorphic episode that has affected the CXG, notwithstanding that problems may arise due to incomplete Sr isotopic homogenization in detrital minerals. In addition, to help the geological interpretation, a Rb-Sr isotopic study was also carried

out for the Caramulo granitic pluton, which is intrusive in the metasedimentary sequence.

In contrast to the Rb-Sr system, the Sm-Nd system shows no fractionation during erosion, transport and sedimentation. As shown by many authors this is due to the similar geochemical behaviour of Sm and Nd. In this paper, Sm-Nd isotopic data are used as indicator for the provenance and the depositional tectonic environment of the sediments in the study area.

Geological background and sampling sites

The study area is part of the Central Iberian Zone (CIZ) as defined by Julivert et al. (1972). This zone is regarded as the Iberian segment of the axial domain of the European Variscan fold belt, where allochthonous and autochthonous sequences have been outlined (Dallmeyer & Martinez Garcia 1990; Figure 1A). The

main aspects of the autochthonous sequences of the Central Iberian Zone are:

- a widespread occurrence of detrital metasediments (greenschist facies) of the Cambrian and/or late Proterozoic CXG sequence;
- b presence of a lower Ordovician stratigraphic unconformity over the CXG;
- c abundant Variscan granitoids showing variable and complex spatial and temporal relationships with the country rocks; some of them are more or less concordant with the Variscan structures, while others are clearly discordant;
- d metamorphic isograds are spatially related to belts of granite plutons; higher metamorphic grades are reached at deeper levels.

Figure 1B represents a simplified geological map of the study area which is bordered by the Buçaco Ordovician and post-Ordovician syncline to the west, the Arganil Ordovician syncline and the Tabua granitoid to the east, the Lousã Cenozoic basin to the south, and the Caramulo granitic pluton to the north.

Twenty seven whole-rock samples of metasediments were collected at five different localities (Figure 1B).

At each locality the metapelitic and metasilic samples were collected from the same layers, according to the recommendations of Thomaz-Filho & Lima (1981) and Mizusaki (1992). This is to guarantee as much as possible that the samples represent similar depositional conditions and an equal degree of metamorphic isotopic rehomogenization i.e. identical initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios after the metamorphic episode. The samples analysed for Sm and Nd came from only one outcrop (Raiva); they presumably represent metasediments derived from the same source.

The Raiva and Aguieira outcrops show alternating metric and centimetric beds of medium- to fine-grained sandy, and banded silty to clayey metasediments. These rocks were affected by a greenschist facies metamorphism and they exhibit a Variscan D1 slaty cleavage. Six samples (RA and RB prefixes) were collected at Raiva, and four samples (AA prefix) at Aguieira (locality descriptions in Medina & Rodriguez Alonso 1991).

The Boialvo outcrop is an old quarry in which compact organic-rich, greenschist facies metapelitic rocks show a Variscan D1 slaty cleavage. Four samples were collected (BA and BB prefixes).

The Freimoninho outcrop shows centimetre to metre-thick beds of predominantly clayey to silty metasediments alternating with beds of fine to medi-

um sandy metasediments (descriptions in Medina et al. 1989). These metasediments have also suffered a greenschist facies metamorphism and are located outside of the metamorphic aureole of the Caramulo granitic pluton mapped by Godinho (1980). A Variscan D2 crenulation cleavage is present. Five samples (FM prefix) were analysed.

Rocks from the Rio Agueda outcrop are very similar to those from Freimoninho. Metre-scale Variscan D2 folds and an axial plane foliation are visible in the outcrop. Eight samples (single-letter A, B and C prefixes) were analysed.

Six samples for Rb-Sr isotopic study of the Caramulo granitoid (Caramulo and Almjofa facies of Godinho 1980) were collected from five different outcrops (CAR prefixes).

Petrographic descriptions

The Raiva and Aguieira metasediments generally have grain sizes ≤ 0.05 mm; a few quartz grains are ≤ 0.1 mm. Mineralogically, the sediments consist mainly of quartz (< 50 vol.%) and phyllosilicates (chlorites, white micas and predominantly sericite). Opaque oxide minerals, feldspars (especially plagioclase), tourmaline, and biotite are subordinate (< 5 vol.%). The platy minerals are oriented parallel to a slaty cleavage and an oxide-rich lamination, at a low angle oblique to the stratification. Metamorphism is in the chlorite zone of the greenschist facies.

The Boialvo samples have a grain size < 0.05 mm, so that mineral identification was impossible in some cases. Only quartz and phyllosilicates could be unequivocally identified. No sedimentary structures were observed, except a thin lamination. Microscopic fractures are filled mainly with quartz, and sometimes with carbonates. Metamorphism is in the chlorite zone of the greenschist facies.

The Freimoninho samples (chlorite zone) show a grain size < 0.1 mm. Quartz (20–30 vol.%, some grains containing zircon inclusions), phyllosilicates (70–80 vol.%; chlorites, white micas and predominantly sericite), and opaques (1–2 vol.%) are predominant. The rocks always show aggregates of opaques + quartz + chlorites with a lenticular shape subparallel to the main planar structure. Stratification is well developed and marked by chlorite-rich and sometimes oxide-rich laminations alternating with quartz-rich laminations. A small-scale crenulation cleavage has affected the phyllosilicate flakes. The sampled out-

crop is about 2 km from the contact with the Caramulo granitoid, but contact-metamorphic minerals were not observed.

The grain size of Rio Agueda samples is mainly < 0.1 mm, and only some quartz, chlorite, and opaque oxide grains are larger than 0.1 mm. Phyllosilicates, mostly detrital white mica, usually compose ~ 50 vol.% of the rock, while quartz grains often make up the remaining part. Plagioclase, tourmaline, sphene and opaque minerals are subordinate (< 5 vol.%). The stratification is marked by a millimetric alternation of quartz- and phyllosilicate-rich laminations. A crenulation cleavage is present in all samples and coincides with the axial planes of minor folds. Metamorphism is in the chlorite, or possibly the biotite zone.

The Caramulo pluton is composed in general of medium- to fine-grained granites with a mineralogical composition of quartz, K-feldspar, plagioclase (albite to sodic oligoclase), muscovite, and biotite (Godinho 1980).

Analytical procedures

Rb-Sr analysis

Rubidium and Sr contents and Rb/Sr ratios were determined by X-ray fluorescence analysis on powders, using a Philips PW-1380/00 (modified) automatic spectrometer. Samples with low Rb and Sr contents (< 50 ppm) were re-analysed by isotopic dilution techniques, using ^{85}Rb and ^{84}Sr spikes. The samples were dissolved overnight with HF + HNO₃ at 65° C, and the Sr was purified using a conventional ion exchange column with AG50WX8 cation exchange resin (200–400#) as described, with some modifications, in Kawashita (1972). Strontium isotopic analysis was carried out on a fully automated VG ISOMASS 354 mass spectrometer. The Sr was loaded on a single Ta filament with phosphoric acid. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were corrected for mass fractionation by normalizing to a value of 0.1194 for $^{86}\text{Sr}/^{88}\text{Sr}$. During the period of this work, six analyses of the NBS-987 standard averaged 0.71026 ± 0.00002 (1 σ). Procedural blanks for Sr were of the order of 1 ng. The Rb-Sr ages were calculated using the decay constant $\lambda_{\text{Rb}} = 1.42 \times 10^{-11} \text{ a}^{-1}$. Errors reported here for age and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (I_{Sr}) are at the 2 σ level. Construction of isochron diagrams was based on the method of Williamson (1968).

Sm-Nd analysis

About 0.10 to 0.15 g of sample powder were used for the Sm-Nd analysis. These samples were dissolved in a mixture of HF + HNO₃ in a teflon vessel by heating at 60° C for one week. The rare earth elements (REE) were separated using cation exchange columns with AG50WX8 resin (200–400#) and elution by hydrochloric acid. Samarium and Nd were separated from each other using columns with hydrogen di-ethylhexyl phosphate (HDEHP) supported by teflon powder and elution with HCl. Samarium and Nd concentrations were determined by isotopic dilution techniques, using a mixed ^{149}Sm - ^{150}Nd spike, with a ^{150}Nd concentration of 0.0003314 mmol/g and ^{149}Sm content of 0.004575 mmol/g.

Neodymium and Sm were loaded as phosphates on two Ta side filaments and run in a triple mode with Re as the ionizing central filament, on a VG ISOMASS 354 fully automated mass spectrometer, using five collectors. The quality of the analytical measurements by isotopic dilution techniques was evaluated through a $^{142}\text{Nd}/^{144}\text{Nd}$ ratio of 1.141828, and the Nd isotopic compositions were corrected for a mass fractionation by normalizing to a value of 0.7219 for $^{146}\text{Nd}/^{144}\text{Nd}$. All Sm-Nd procedures in this work are described in detail by Sato et al. (1995).

Fourteen analyses of La Jolla and four of the BCR-1 standard yielded results around 0.511847 ± 0.000022 and 0.512662 ± 0.000027 , respectively. For the age calculations, the value of the Sm decay constant used was $6.54 \times 10^{-12} \text{ a}^{-1}$.

Results and discussion

Rb-Sr data

Table 1 presents the Rb-Sr data obtained from 27 whole-rock samples of banded metapelites and metasilts from the five localities shown in Figure 1B. Table 2 shows the Rb-Sr data obtained from six whole-rock samples of the Caramulo granite.

The Raiva samples yield a well-defined Rb-Sr isochron with an age of 434 ± 15 Ma and $I_{\text{Sr}} = 0.7120 \pm 0.0018$ (MSWD = 0.08; Figure 2). The Agueira and Boialvo whole-rock samples are plotted in a Rb-Sr diagram with the Raiva isochron for reference (Figure 3). Although the data points for both the Boialvo and the Agueira samples show some dispersion, sub-parallel alignments can be traced, that sug-

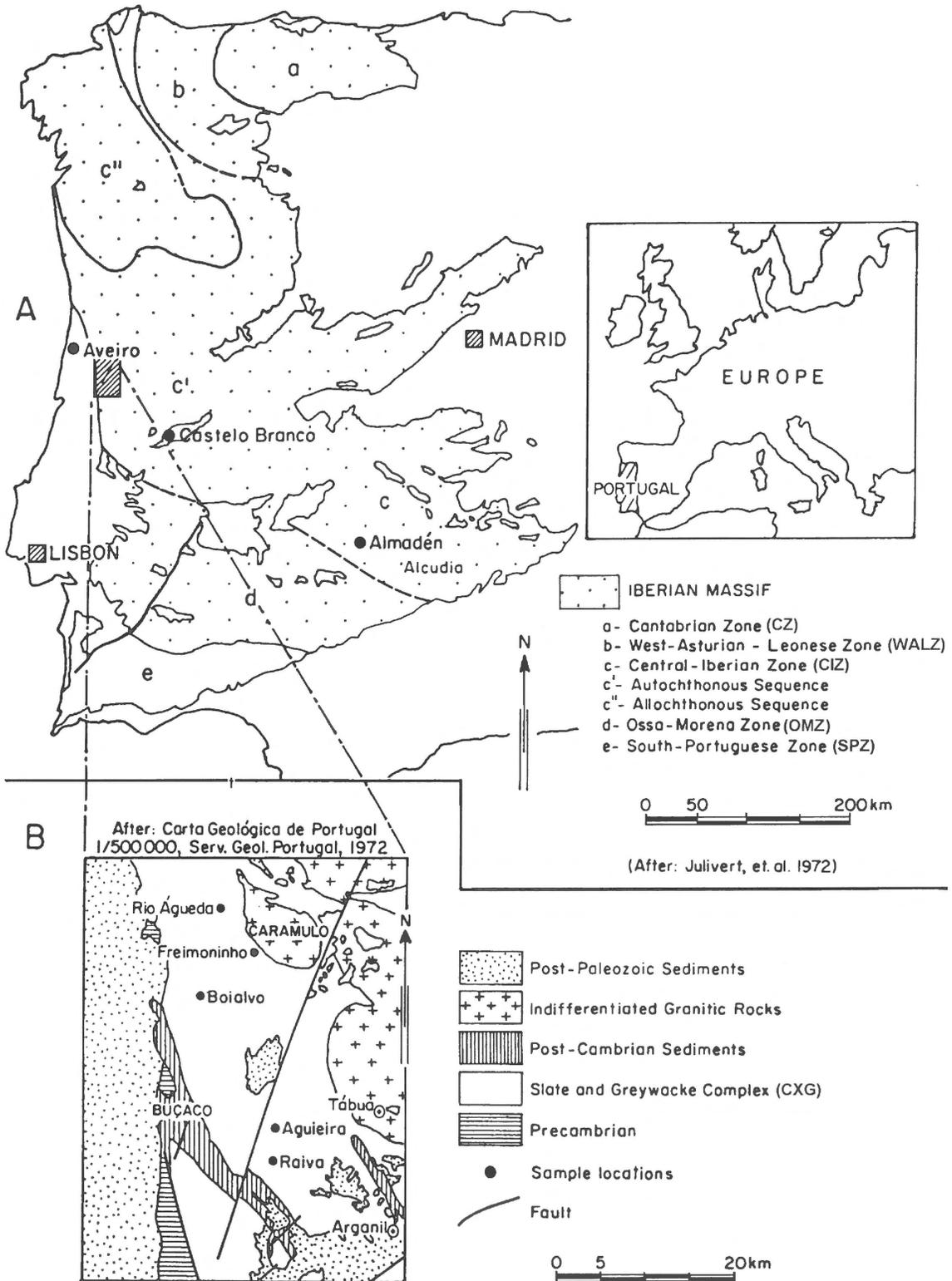


Figure 1. A – Major tectonic units of the Iberian Massif, B – Geological sketch map of the studied area and sample locations.

Table 1. Rb and Sr analytical data for metasedimentary rocks from five localities shown in Figure 1B. See text for prefixes of sample numbers

Sample	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	Error	$^{87}\text{Sr}/^{86}\text{Sr}$	Error	N° Lab.
BA-4	133.0	53.0	7.30	0.20	0.76000	0.00010	12086
BA-5	132.0	52.0	7.38	0.20	0.76077	0.00009	12087
BB-1	116.0	48.0	7.03	0.19	0.75742	0.00008	12088
BB-3	108.0	64.0	4.90	0.14	0.74629	0.00010	12089
RA-2	127.21*	41.90*	8.84	0.12	0.76696	0.00009	12076
RA-3	140.09*	37.28*	10.95	0.15	0.77992	0.00006	12077
RB-1	143.44*	37.42*	11.17	0.16	0.78085	0.00006	12078
RB-4	143.04*	32.44*	12.87	0.18	0.79150	0.00005	12079
RB-6	127.85*	45.55*	8.17	0.11	0.76237	0.00009	12080
RB-8	76.23*	44.19*	5.01	0.07	0.74297	0.00006	12081
AA-1	142.0	38.0	10.89	0.03	0.77525	0.00012	12082
AA-2	145.79*	45.46*	9.33	0.14	0.76659	0.00006	12083
AA-3	147.23*	35.66*	12.04	0.17	0.78191	0.00004	12084
AA-4	137.24*	32.23*	12.41	0.17	0.78230	0.00005	12085
A-1	106.23*	48.13*	6.42	0.09	0.75903	0.00005	12267
A-2	82.7	54.7	4.39	0.12	0.74313	0.00007	12268
A-4	135.53*	41.07*	9.61	0.13	0.77252	0.00010	12269
B-3	61.30	55.0	3.23	0.09	0.73522	0.00008	12270
B-4	116.3	63.8	5.30	0.15	0.74648	0.00009	12271
B-5	63.4	59.7	3.08	0.09	0.73495	0.00015	12272
C-2	161.1	98.1	4.77	0.13	0.74318	0.00011	12273
C-4	146.4	71.5	5.95	0.17	0.75004	0.00012	12274
FM-1	140.32*	40.54*	10.08	0.15	0.76965	0.00007	12275
FM-2-1	70.5	48.7	4.20	0.12	0.74176	0.00006	12276
FM-2-2	127.0	55.3	6.68	0.19	0.75245	0.00007	12277
FM-4	160.8	65.8	7.11	0.20	0.75334	0.00005	12278
FM-10	161.9	50.4	9.35	0.26	0.76277	0.00008	12280

* Data for Rb and Sr contents by isotope dilution.

Table 2. Rb and Sr analytical data for the Caramulo granitoid

Sample	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	Error	$^{87}\text{Sr}/^{86}\text{Sr}$	Error	N° Lab.
CAR-1	273.39*	27.60*	29.09	0.40	0.84980	0.00012	12520
CAR-3	364.54*	21.45*	50.31	0.70	0.94273	0.00016	12521
CAR-10	333.59*	55.50*	17.52	0.24	0.79448	0.00009	12523
CAR-11	301.2	62.4	14.07	0.39	0.77991	0.00008	12524
CAR-12	297.5	58.4	14.85	0.42	0.78088	0.00016	12525
CAR-13	330.8	49.9	19.34	0.54	0.79066	0.00007	12526

* Data for Rb and Sr contents by isotope dilution.

gest ages identical to the 434 Ma obtained for the Raiva samples, with the I_{Sr} value for the Boialvo samples ($I_{Sr} = 0.714$) above, and that for the Aguieira samples ($I_{Sr} = 0.709$) below that for the Raiva samples. Besides this preferred interpretation, isochron ages have been calculated of 398 ± 30 Ma ($I_{Sr} = 0.718 \pm 0.003$ and $MSWD = 0.4348$) for the Boialvo, and of 375 ± 24 Ma

($I_{Sr} = 0.717 \pm 0.003$ and $MSWD = 0.9212$) for the Aguieira metasediments. Figure 4 presents the Rb-Sr isochron diagram for the Rio Agueda samples, with an age of 404 ± 18 Ma, and an I_{Sr} of 0.7168 ± 0.0012 ($MSWD = 1.40$). One of the analytical points (sample A1) is located above the isochron, and may fall on a parallel isochron line, indicating that sample A1 was

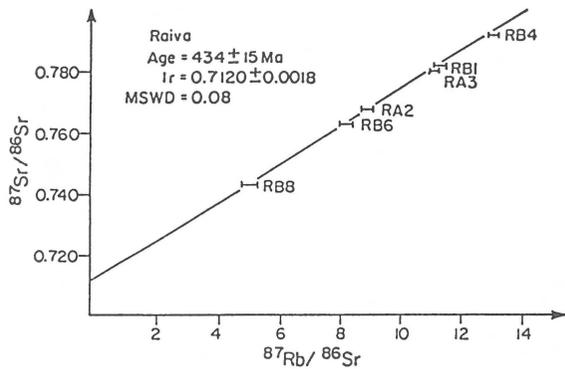


Figure 2. Whole-rock Rb-Sr isochron of metapelites from the Raiva locality.

affected by the same metamorphic event, but had a different initial Sr isotopic ratio.

However, the possibility must also be considered that the Rb-Sr isochron for the Rio Agueda samples, which contain detrital micas, represents a fictitious isochron (with slopes having no geological age significance due to incomplete Sr isotopic rehomogenization during the Variscan orogeny), similar to those obtained by Nägler (1992) and Beetsma (1995) for late Proterozoic and Paleozoic terrigenous metasediments from the Iberian Massif.

In general the incomplete Sr isotopic homogenization is demonstrated by the fact that the scatter of analytical points about the isochron is greater than that expected from analytical errors alone. This produces a broad range of Rb-Sr dates, intermediate between the age of the source rocks and the time of metamorphism.

Nevertheless, the good alignment of analytical points of the Rio Agueda samples as well as the age within the range of that of other CXG metasediments in Portugal (Raiva, Aguieira and Boialvo) indicate, in the authors' opinion, an age of 435 to 400 Ma for the important low-grade metamorphic episode in the studied area. A similar conclusion has been reached earlier by Medina et al. (1993).

The samples of metapelites from Freimoninho yield an isochron age of 327 ± 20 Ma, and an I_{Sr} of 0.7217 ± 0.0020 (MSWD = 3.14; Figure 5). This younger age for metasedimentary samples close to the contact with the Caramulo granite corresponds to the age of this granite, which is given by a six-point linear array with a slope corresponding to an age of 326 ± 12 Ma and an I_{Sr} of 0.7124 ± 0.0038 (MSWD = 6.33; Figure 6). The Caramulo granite and the Freimoninho metased-

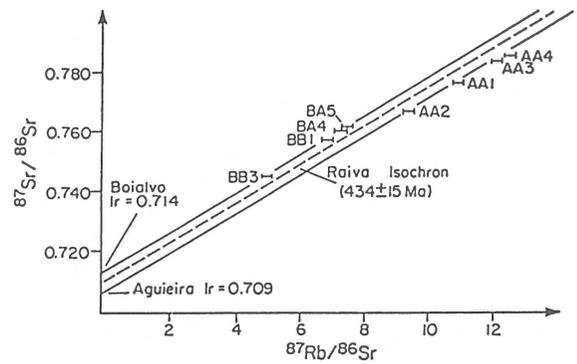


Figure 3. Plots of whole-rock Rb-Sr data for metasediments from the Boialvo and Aguieira localities.

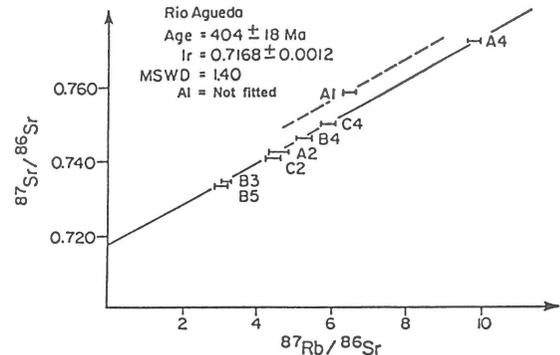


Figure 4. Whole-rock Rb-Sr isochron of metasediments from the Agueda locality.

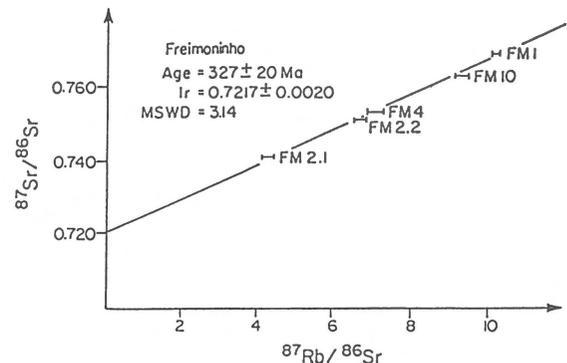


Figure 5. Whole-rock Rb-Sr isochron of metapelites from the Freimoninho locality.

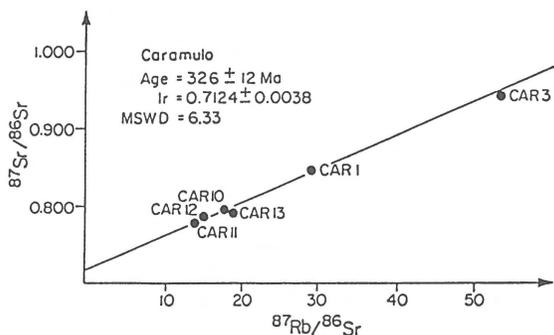


Figure 6. Whole-rock Rb-Sr isochron of the Caramulo granitoid.

imentary rocks show a similar age, but their initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios differ, probably because the interaction of magmatic fluids and the host metasedimentary rocks involved mixing of materials of different Sr isotopic compositions. According to this reasoning, the younger age of the Freimoninho metapelites relative to the age of the other metapelites may be attributed to Sr isotopic rehomogenization caused by circulation of fluids associated with the Caramulo granitic intrusion. The latter granitoid has been classified as a syn to post-orogenic Variscan F3 two-mica granite by Ferreira et al. (1987). The age of 326 Ma also agrees with the chronology of tectonic phases defined for the Central Iberian Zone by Noronha et al. (1979).

The wide range of initial Sr isotopic ratios (0.7090–0.7168) for the metasediments that escaped contact metamorphism suggests that the source areas of these sediments show differences in composition and crustal residence times.

The age of the metamorphic episode around 430 Ma in the Central Iberian Zone in Portugal is in agreement with lower intercept U-Pb zircon ages of 435 ± 5 and 459 ± 7 Ma recorded by Gebauer et al. (1989) from an argillaceous sandstone of the Montagne Noire in the southern Massif Central (France), and a paragneiss of the Moldanubian Zone in northeastern Bavaria (Germany), respectively. These U-Pb ages from metasediments of the Central European Hercynides can be explained by episodic loss of radiogenic lead during metamorphic events. In addition, Rb-Sr whole-rock isochron dating of anatectic paragneisses from the Bohemian Massif (Moldanubian region) yielded values ranging from 480 to 430 Ma (Köhler & Müller-Sohnius 1976), that were interpreted as the time of ultra-

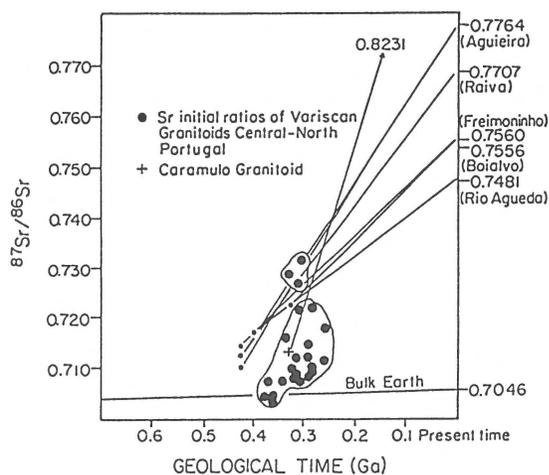


Figure 7. Sr isotope evolution diagram for studied metasediments and Variscan granitoids of central-north Portugal. Initial Sr ratios of Variscan granitoids are from: Pinto (1979), Abranches et al. (1979), Barr & Areias (1980), Pinto (1984), Priem et al. (1984), Dias (1987), Reavy (1987), Macedo (1988), Pereira (1991), Dias et al. (1993), and Dias & Leterrier (1993).

metamorphism related to the late Caledonian orogeny. According to Matte (1986), the geochronological pattern within the inner zones of the Variscan belts indicates ages within the 430–380 Ma time interval, which is considered as early Variscan. Dallmeyer & Pieren (1987) reported whole-rock $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 425 and 421 Ma for anchimetamorphic metapelites from Alcuia in the southern Central Iberian Zone (Spain), which they interpreted as corresponding to an early Silurian rifting episode. Pereira et al. (1986) reported K-Ar ages of 372 Ma and 472 Ma of biotites and muscovites from granitic intrusions in the metasediments of the Castelo Branco region (Central Iberian Zone). Based on these geochronological results and structural data, these authors concluded that the first Variscan deformation phases were active at least around 440 Ma.

Nägler et al. (1992) obtained a whole-rock Rb-Sr errorchron age of 335 ± 15 Ma for Ordovician metasediments in the Almaden syncline in the southern Central Iberian Zone of Spain. They interpreted this date as indicating the period of main folding and deepest burial of the strata in that area.

Strontium isotopic evolution curves for the CXG metasediments from the studied area and for the Caramulo and other Variscan granitoids are presented in Figure 7, which shows plots of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios versus geological time. The initial Sr ratios of the Caramulo and most other Variscan granitoids plot below the

Table 3. Sm-Nd analytical data for metasedimentary rocks from the Raiva locality

Sample	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	Age T_{DM}	$\epsilon_{Nd}(0)$	N° Lab.
RA-2	6.29	31.18	0.12272 ± 0.00012	0.51225 ± 0.00002	1328 Ma	-7.53	94
RA-3	6.59	33.81	0.11852 ± 0.00011	0.51227 ± 0.00004	1249 Ma	-7.20	95
RB-4	6.43	33.72	0.11609 ± 0.00009	0.51220 ± 0.00003	1322 Ma	-8.58	96
RB-6	6.37	31.85	0.12178 ± 0.00013	0.51227 ± 0.00004	1285 Ma	-7.14	97
RB-8	3.71	20.89	0.10808 ± 0.00001	0.51213 ± 0.00003	1316 Ma	-9.91	132

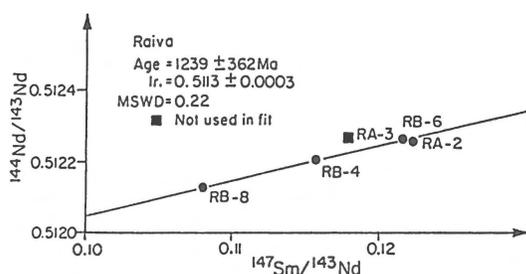


Figure 8. Whole-rock Sm-Nd errorchron of metapelites from the Raiva locality.

Sr evolution lines of the CXG metasediments. Therefore, although the granitoids yield crustal Sr isotopic signatures, they cannot have been produced exclusively by partial melting of these metasediments. The granitoids have crustal sources that may be represented by a variable mixing of continental rocks with low $^{87}\text{Sr}/^{86}\text{Sr}$ and a subordinate amount of CXG metasediments.

Sm-Nd data

The Sm-Nd results for metapelites from the Raiva locality are reported in Table 3, which also includes calculated values of ϵ_{Nd} for the present time, and Sm-Nd model ages calculated according to the depleted-mantle model of De Paolo (1981). Although all samples are from the same outcrop, the Sm-Nd data do not provide a useful whole-rock isochron age. The insufficient alignment and the spread of the analytical points may be attributed to initial heterogeneity of the Nd isotopic composition, which is common in the sedimentary environment. Four analytical points can be linked to form an ill-defined linear array with a very imprecise age of 1239 ± 362 Ma (1σ) (Figure 8).

Allègre & Rousseau (1984), Goldstein & Jacobsen (1988), McCulloch & Wasserburg (1978), Arndt & Goldstein (1987), O'Nions et al. (1983), Michard et al.

(1985), Taylor & McLennan (1985), and McLennan et al. (1989, 1990) have demonstrated that Sm and Nd are not fractionated during erosion, transport, sedimentation and diagenesis. The whole-rock Sm-Nd isochron age obtained of fine-grained metasediments may provide an estimate of the time of formation of the different protoliths. If so, this supports the view of Nägler et al. (1992), who interpreted the 1524 ± 173 Ma whole-rock Sm-Nd isochron age of Tremadocian metapelites from the Almadén syncline as the average age of mantle extraction of crustal material present in the sources of the metapelites.

The Sm-Nd depleted-mantle model ages of sedimentary or metasedimentary rocks have been considered by several authors as an approximation of the mean age of the crustal protoliths feeding the sedimentary basin (McCulloch & Wasserburg 1978; Allègre & Rousseau 1984; Goldstein et al. 1984; McLennan & Hemming 1992). Following this reasoning, the Sm-Nd depleted-mantle model ages of 1.33 to 1.25 Ga (Table 3) calculated for the CXG samples from Raiva provide an estimate of the average age of the source rocks of the CXG in the studied area.

As the CXG metapelites presumably represent mixtures of continental material from several source areas, the Sm-Nd model ages of 1.35 to 1.25 Ga, may represent an approximation of the average age of the mantle-crust differentiation episodes which produced the source rocks of the metasediments. Beetsma (1995) obtained similar Sm-Nd model ages for CXG metasediments and interpreted his results as mixing ages of older continental crust and juvenile crustal material of the Cadomian orogenic event. The Sm-Nd errorchron age around 1240 Ma may record the last Nd isotopic homogenization event, although U-Pb zircon ages for the time-period 1.5–1.2 Ga have not been reported in the European Hercynides (Gebauer et al. 1989; Gebauer & Williams 1990). It is apparent that metamorphism of greenschist facies does not cause a com-

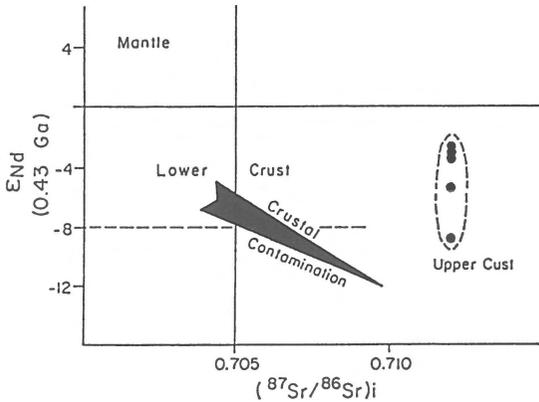


Figure 9. Plots of ϵ_{Nd} for 0.43 Ga versus Sr initial ratio of metasediments from the Raiva locality.

plete Nd isotopic rehomogenization in fine-grained sediments.

The very homogeneous Sm and Nd contents of the studied samples, with values near 6.4 ppm for Sm and a small range from 31.1 to 33.8 ppm for Nd (Table 3), are in agreement with the Nd contents reported by Nagler et al. (1992) for the Almaden metasediments, which show the typical crustal range of 30–40 ppm Nd (Taylor & McLennan 1985; Zindler & Hart 1986). The ϵ_{Nd} values calculated for the present day and for the 430 Ma metamorphic episode that has affected the CXG metasediments are in the ranges of –7.20 to –9.91 and –2.6 to –4.18, respectively, in agreement with ϵ_{Nd} values reported by Nagler et al. (1992) for Tremadocian metapelites of the Almaden region, and by Beetsma (1995) for Late Proterozoic to Cambrian metasediments in northern Portugal. According to Beetsma (1995), these ϵ_{Nd} values are indicative of an addition of juvenile magmas to pre-existent sedimentary rocks during the Cadomian orogeny.

In the ϵ_{Nd} versus $^{87}Sr/^{86}Sr$ diagram (Figure 9) the Raiva metasediments plot within the continental crust field, with most samples showing high initial Sr ratios and low negative ϵ_{Nd} values. This suggests that the sources of the sediments included differentiated granitic rocks with a short crustal life, which is in support of the interpretation of Beetsma (1995) described above.

The fractionation factor ($f^{Sm/Nd}$) between sample Sm/Nd and CHUR Sm/Nd was defined by De Paolo & Wasserburg (1976) as:

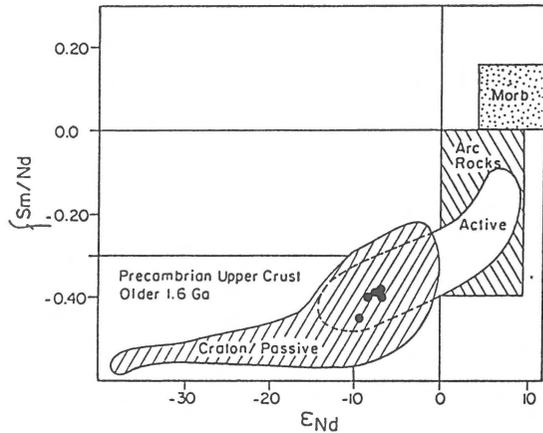


Figure 10. $f^{Sm/Nd}$ versus ϵ_{Nd} diagram for metasediments from the Raiva locality. Tectonic fields after McLennan & Hemming (1992).

$$f^{Sm/Nd} = \left[\frac{(^{147}Sm/^{144}Nd)_{sample}}{(^{147}Sm/^{144}Nd)_{CHUR}} - 1 \right]$$

where the present-day value for CHUR Sm/Nd is 0.1967. Figure 10, after McLennan & Hemming (1992), shows the $f^{Sm/Nd}$ versus ϵ_{Nd} diagram with fields for Precambrian upper crust older than 1.6 Ga, arc rocks, mid-ocean ridge basalt, and terrigenous sediments deposited in volcanically active tectonic settings and in cratonic and passive margin environments. In this diagram, the Raiva CXG metasediments plot within the superposed fields of cratonic passive and active tectonic settings, showing relatively homogeneous values for $f^{Sm/Nd}$ ratios and ϵ_{Nd} values, with ϵ_{Nd} in the range –7.20 to –9.91. This suggests the presence of a significant component of young continental crust in the sources of the metasediments, which were deposited in a tectonically passive setting. This is corroborated by stratigraphic and sedimentological observations of such features as longshore bars with typical cross-stratification, and tempestite deposits. The absence of deep-sea turbidites also suggests a stable-platform depositional environment.

Conclusions

Fine-grained CXG metasediments from four localities within the Central Iberian Zone in northern Portugal yield whole-rock Rb-Sr isochron ages of 435 to 400 Ma, which can be interpreted as the age of an

important metamorphic episode in the area. Samples of metapelites from Freimoninho locality, about 2 km from the contact with the Caramulo granitic intrusion, produce a 327 ± 20 Ma Rb-Sr isochron in agreement with the granite intrusion age of 326 ± 12 Ma.

A consideration of the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the Caramulo and other Variscan granitoids in north Portugal with reference to the Sr isotopic evolution curves for the analysed metapelitic metasediments shows that the studied metapelites are not suitable sources for the granitoids.

Sm-Nd depleted-mantle model-age calculations for metasediments of the Raiva locality provide values of 1.35 to 1.25 Ga which may be regarded to represent the average age of mantle extraction, and the crystallization ages of the source rocks of the sediments.

The Sr and Nd isotopic signatures of the Raiva metasediments agree with geological observations, suggesting that the derivation of the sediments involved mixing of continental material differentiated from the upper mantle at different times, and that the deposition of the sediments took place in a tectonically passive setting between 600 and 550 Ma.

Acknowledgements

This research is a result of the cooperation between the Geosciences Department of the University of Aveiro, Portugal, and the Geochronological Research Center of the University of São Paulo (CPGeo-USP), Brazil, where the isotopic analyses were carried out. The authors are grateful to Kei Sato, Liliane Petronilho, Ivone K. Sonoki and Helen M. Sonoki for assistance during the analytical work. Special thanks are due to Ian McReath, A.A. Soares de Andrade, Koji Kawashita, N. Clauer and an anonymous reviewer for their useful suggestions and comments. The project was funded by the Junta Nacional de Investigação Científica e Tecnologia (JNICT) of Portugal.

References

Abranches, M.C.B., M.H. Canilho & M.G.S. Canêlhas 1979 Idade absoluta pelo método Rb-Sr dos granitos do Porto e de Portalegre (nota preliminar) – *Bol. Soc. Geol. Portugal* XXI: 239–248

Allègre, C.J. & D. Rousseau 1984 The growth of the continental crust through geological time studied by Nd isotope analysis of shales – *Earth Planet. Sci. Lett.* 67: 19–34

Arndt, N.T. & S.L. Goldstein 1987 Use and abuse of crust formation ages – *Geology* 15: 893–895

Barr, S.M. & L. Areias 1980 Petrology and geochemistry of granitic intrusions in the Viana do Castelo area, northern Portugal – *Geol. Mijnbouw* 59: 273–281

Beetsma, J.J. 1995 The Late Proterozoic/Paleozoic and Hercynian crustal evolution of the Iberian Massif, N Portugal as traced by geochemistry and Sr-Nd-Pb isotope systematics of pre-Hercynian terrigenous sediments and Hercynian granitoids – PhD Thesis, Univ. of Amsterdam, 223 pp

Bickle, M.J. 1993 The ^{87}Sr evolution of the silicate sedimentary mass: metamorphic moderation and implications for global CO_2 fluxes – *Terra Abstracts, EUG VII*: 473

Carta Geológica de Portugal 1/500000 (4^a edição) 1972 Direcção Geral de Minas e Serviços Geológicos (Coordenação de Teixeira, C.), Lisboa

Dallmeyer, R.D. & E. Martínez Garcia 1990 Introduction to the Pre-Mesozoic Geology of Iberia. In: R.D. Dallmeyer & E. Martínez Garcia (eds.): *Pre-Mesozoic Geology of Iberia*. Springer-Verlag, Berlin: 3, 4

Dallmeyer, R.D. & A.P. Pieren 1987 Evidences of late Proterozoic tectonometamorphic events in SW Iberia. Significance and paleogeographic implications – *Tectonothermal Evolution of the West African Orogens and Circum-Atlantic Terrane Linkages; Nouakchott, Mauritania. Abstract IGCP Project 233, Nouakchott Meeting*: 73–76

De Paolo, D.J. 1981 Neodymium isotopes in the Colorado Front Range, and crustal-mantle evolution in the Proterozoic – *Nature* 291: 193–197

De Paolo, D.J. & G.J. Wasserburg 1976 Nd isotopic variations and petrogenetic models – *Geophys. Res. Lett.* 3: 249–252

Dias, G.T. 1987 Mineralogia e petrologia de granitos hercínicos associados a mineralizações filonianas de Sn-W (Minho, Portugal) – Unpubl. PhD Thesis, Univ. of Minho, 304 pp

Dias, G.T., J. Leterrier, N. Ferreira & J.E. Lopes Nunes 1992 Les granitoides biotitiques syn a tardi-hercyniens de Luís Alves, région de Braga (Nord Portugal). *Typologie chimico-mineralogique et implications pétrogénétiques* – *C.R. Acad. Sci. Paris* 314(II): 675–681

Dias, G.T. & J. Leterrier 1993 Cronologia e petrogénese de granitoides biotíticos tardi-hercínicos (Minho, Portugal). *Estudo isotópico Rb-Sr e Sm-Nd*. In: Fernando Noronha, M. Marques & P. Nogueira (eds.): *Memórias n.º 3. IX Semana de Geoquímica e II Congresso de Geoquímica dos Países de Língua Portuguesa*, Porto: 369–373

Dickin, A.P. 1995 *Radiogenic isotope geology*. Cambridge University Press, 452 pp

Ferreira, N., M. Iglesias, F. Noronha, E. Pereira, A. Ribeiro & M.L. Ribeiro 1987 Granitoides da Zona Centro Ibérica e seu enquadramento geodinâmico. In: F. Bea, A. Carnicero, J.C. Gonzalo, M. López Plaza & M.D. Rodríguez Alonso (eds.): *Geologia de los granitoides y rocas asociadas del Macizo Hesperico*. Editorial Rueda, Madrid: 37–51

Gebauer, D. & I.S. Williams 1990 Crust and mantle evolution of the European Hercynides – *Geol. Soc. Austr. Abstr.* 27: 38

Gebauer D., I.S. Williams, W. Compston & M. Grünenfelder 1989 The development of the central European continental crust since the early Archaean based on conventional and ion-microprobe dating of up to 3.84 b.y. old detrital zircons – *Tectonophysics* 157: 81–96

Godinho, M.M. 1980 O Plutonito do Caramulo – *Memórias e Notícias, Publ. Mus. Lab. Min. Geol. Univ. Coimbra* 89–90, 269 pp

Goldstein, S.L. & S.B. Jacobsen 1988 Nd and Sr isotopic systematics of river water suspended material: implications for crustal evolution – *Earth Planet. Sci. Lett.* 87: 249–265

- Goldstein, S.L., R.K. O'Nions & P.J. Hamilton 1984 A Sm-Nd isotopic study of atmospheric dusts and particulates from major river systems – *Earth Planet. Sci. Lett.* 70: 221–236
- Julivert, M., J.M. Fontboté, A. Ribeiro & L. Conde 1972 Mapa Tectónico de la Península Ibérica y Baleares, 1: 1000000. *Memo-ria Explicativa* (1974) – *Inst. Geol. Min. Esp.*, 113 pp
- Kawashita, K. 1972 O método Rb-Sr em rochas sedimentares – Unpubl. PhD Thesis, Univ. of São Paulo, Brazil, 111 pp
- Köhler, H. & D. Müller-Sohnius 1976 Rb-Sr Altersbestimmungen und Sr-Isotopensystematik an Gesteinen und Mineralen des Regensburger Waldes – *Fortschr. Mineral. Beih* 54: 47
- Macedo, C.A.R. 1988 Granitóides, Complexo Xisto Grauváquico e Ordovício na região entre Trancoso e Pinhel (Portugal Central) – Unpubl. PhD Thesis, Univ. of Coimbra, 432 pp
- Matte, P. 1986 Tectonics and plate tectonics model for the Variscan belt of Europe – *Tectonophysics* 126: 329–374
- McCulloch, M.T. & G.J. Wasserburg 1978 Sm-Nd and Rb-Sr chronology of continental crust formation – *Science* 200: 1003–1011
- McLennan, S.M. & S. Hemming 1992 Samarium/Neodymium elemental and isotopic systematics in sedimentary rocks – *Geochim. Cosmochim. Acta* 56: 887–898
- McLennan, S.M., M.T. McCulloch, S.R. Taylor & J.B. Maynard 1989 Effects of sedimentary sorting on neodymium isotopes in deep-sea turbidites – *Nature* 337: 547–549
- McLennan, S.M., S.R. Taylor, M.T. McCulloch & J.B. Maynard 1990 Geochemical and Nd-Sr isotopic composition of deep-sea turbidites: crustal evolution and plate tectonic associations – *Geochim. Cosmochim. Acta* 54: 2015–2050
- Medina, J. & M.D. Rodríguez Alonso 1991 O Complexo Xisto-Grauváquico (Grupo das Beiras) na região da Barragem da Aguieira – litoestratigrafia e estrutura – *Memórias e Notícias*, *Publ. Mus. Lab. Mineral. Geol. Univ. Coimbra* 112(B): 573–582
- Medina, J., M.D. Rodríguez Alonso & C.A. Bernardes 1989 Litoestratigrafia e Estrutura do Complexo Xisto-Grauváquico na região do Caramulo-Portugal – *Geociências, Rev. Univ. Aveiro* 4(1): 51–73
- Medina, J., C.C.G. Tassinari & M.S. Pinto 1993 Idade Rb-Sr no Complexo Xisto-Grauváquico na região de Mortágua (Portugal Central). In: Fernando Noronha, M. Marques & P. Nogueira (eds.): *Memórias n.º 3. IX Semana de Geoquímica e II Congresso de Geoquímica dos Países de Língua Portuguesa*, Porto: 309–403
- Michard, A., P. Gurriet, M. Soudant & F. Albarede 1985 Nd isotopes in French Phanerozoic shales: external vs. internal aspects of crustal evolution – *Geochim. Cosmochim. Acta* 49: 601–610
- Mizusaki, A.M.P. 1992 Comportamento do Rb e Sr em sedimentos recentes: implicações na datação radiométrica de rochas sedimentares – Unpubl. PhD Thesis, Univ. of São Paulo, 140 pp
- Nägler, Th.F., H-J. Schäfer & D. Gebauer 1992 A Sm-Nd isochron on pelites 1Ga in excess of their depositional age and its possible significance – *Geochim. Cosmochim. Acta* 56: 789–795
- Noronha, F., J.M.F. Ramos, J. Rebelo, A. Ribeiro & M.L. Ribeiro 1979 Essai de corrélation des phases de déformations hercyniennes dans le Nord-Ouest péninsulaire – *Bol. Soc. Geol. Portugal XXI*: 227–237
- O'Nions, R.K., P.J. Hamilton & P.J. Hooker 1983 A Nd isotope investigation of sediments related to crustal development in the British Isles – *Earth Planet. Sci. Lett.* 63: 229–240
- Pereira, A.J.S.C. 1991 Transferências de calor e ascensão crustal no segmento Tondela – Oliveira do Hospital (Portugal Central) após a implantação dos granitos sin a tardi-orogénicos – Unpubl. PhD Thesis, Univ. of Coimbra, 182 pp
- Pereira, A.J.S.C., L.C.G. Pereira & C.A.R. Macedo 1986 Os plutonitos da Zebreira (Castelo Branco): idade e enquadramento estrutural – *Memórias e Notícias*, *Publ. Mus. Mineral. Geol. Univ. Coimbra* 101: 21–31
- Pinto, M.S. 1979 Geochemistry and geochronology of granitic rocks from the Aveiro and Viseu districts (northern Portugal) – Unpubl. PhD Thesis, Univ. of Leeds, 196 pp
- Pinto, M.S. 1984 O granito gnáissico de Fânzeres (Porto-Portugal) – idade e caracterização geoquímica geral – *Memórias e Notícias*, *Publ. Mus. Lab. Mineral. Geol., Univ. Coimbra* 98: 231–242
- Priem, H.N.A., L.J.G. Schermerhorn, N.A.I.M. Boelrijk & E.H. Hebeda 1984 Rb-Sr Geochronology of Variscan granitoids in the tin-tungsten province of northern Portugal: a progress report – *Terra Cognita* 4(2): 212–213
- Reavy, R.J. 1987 An investigation into the controls of granite plutonism in the Serra da Freita region, northern Portugal – Unpubl. PhD Thesis, Univ. St. Andrews, United Kingdom, 210 pp
- Sato, K., C.C.G. Tassinari, K. Kawashita & L. Petronilho 1995 Método geocronológico Sm-Nd no IG/USP e suas aplicações – *Anais Acad. Brasileira Ciências* 67(3): 313–336
- Sousa, M.B. & A.J. Sequeira 1993 The Precambrian-Cambrian Transition of Central Iberian Zone, Portugal – *Terra Abstracts* 5(6): 8–9
- Taylor, S.R. & S.M. McLennan 1985 The Continental Crust: its composition and evolution – *Blackwell Sci. Publ. (Oxford)*, 312 pp
- Thomaz-Filho, A. & V.Q. Lima 1981 Datação radiométrica de rochas sedimentares pelíticas pelo método Rb-Sr – *Bol. Téc. Petrobrás, Rio de Janeiro* 24(2): 109–119
- Williamson, J.H. 1968 Least square fitting of a straight line – *Can. J. Physics* 46: 1845–1847
- Zindler, A. & S. Hart 1986 Chemical Geodynamics – *Ann. Rev. Earth Planet. Sci.* 14: 493–571