BASIC-INTERMEDIATE IGNEOUS ROCKS FORMED BY TRANSFORMATION PROCESSES IN THE SW OF SPAIN

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Abstract: In Southwestern Spain there are various batholiths and plutons, mainly of adamellite composition, associated with basic-intermediate rocks, generally diorites and gabbros. These are all associated with epimetamorphic pelitic and carbonate rocks generally of Cambrian age.

The basic-intermediate rocks, considered by some authors to be igneous rocks of mantle provenance, constitute "shallow" masses that gradually become granitic rocks with increasing depth.

The geological field data together with the petrographic and geochemical data appear to support the existence of a relationship between the nature of the sedimentary wall rocks and the origin and diversity of the plutonic rocks.

These basic-intermediate rocks are believed to have originated from the transformation of suitable sedimentary wall rocks by granitic rocks (mainly adamellites).

The transformation by intrusive granites of pelitic sedimentary rocks produced "secondary" granitic rocks and also various quartzo-feldspathic rocks many of them wrongly interpreted as sedimentary rocks. When the granites affect marly of marly-carbonate rocks mafic minerals such as amphiboles, pyroxenes and sometimes olivines are formed. As a result, quartzo-diorites, diorites, gabbros and even some peridotites, as well as abundant granodiorites are produced.

The polyphasic character of these granitization processes have, in some cases, made basic rocks (e.g. gabbros) appear to be enclosed within granites like intrusive rocks. This caused many geologists and petrologists to interpret such rocks as later intrusive rocks from the mantle.

Key words: basic-intermediate rocks, gabbro, diorite, granite, transformation process, sedimentary wall rocks, Spain.

Introduction

In Southwestern Spain basic-intermediate rocks (gabbros--diorites) crop out (Fig. 1) and in many cases are associated with granites (mainly adamellites). They are also associated locally with carbonate rocks following ENE–WSW Hercynian structures. The wall rocks are composed of weakly metamorphosed Paleozoic sedimentary rocks that appear stratigraphically to be from Cambrian to Devonian materials. These materials are mainly lutites and greywackes with carbonate and quartzitic rocks.

The basic-intermediate rocks, which display a widespread superficial distribution, have been described and in some cases, petrologically studied, for example by Bard, 1965, 1977; Bard & Fabries, 1970; Priem et al., 1970; Vegas, 1971; Defalque et al., 1971; Saavedra, 1979; Bard & Moine, 1979; Garrote & Sanchez, 1979; Brun & Pons, 1981; Casquet, 1982; Rubio, 1982; Pons, 1983; Carnicero & Castro, 1983;

Pons & Brun, 1984; Galindo & Casquet, 1987; Gonzalo, 1987; Schermerhorn, 1987 and others, as well as the authors of the present paper.

Many workers cosidered that the basic-intermediate rocks, mainly gabbros and diorites, are of mantle provenance having no relationship to the granitic rocks that generally appear to be in contact with them. In some cases, they are related to subduction zones through which "mantle materials" emerge, e.g.: Soler, 1973; Mueller et al., 1973; Bard et al., 1973, 1974; Vegas & Muñoz, 1976; Velasco, 1976; Casquet & Velasco, 1978; Casquet, 1980.

The authors of the present work, however, consider the basic-intermediate rocks as having originated from syntectonic transformation processes of sedimentary wall rocks, mainly carbonates, by the granitic rocks: Sanchez Cela, 1971; Sanchez Cela & Aparicio, 1972; Aparicio & Sanchez Cela, 1972; Sanchez Cela y Ordoñez, 1974; Aparicio et al., 1985.

Other authors, such as Alia Medina (1963) and Casquet (1980), propose the existence of contamination processes in the formation of some small basic outcrops in Southwestern Spain.

Geological features

In general and from a field geological point of view, three outcrop-types of basic-intermediate rocks can be defined in Southwestern Spain (Aparicio et al., 1985).

1. Basic-intermediate rocks that are in contact with carbonate rocks and gradually with depth converge with granitic rocks.

2. Basic-intermediate rocks in contact with granitic rocks which do not seem to be associated with carbonate rocks.

3. Basic-intermediate rocks that are in contact with carbonate rocks which do not seem to converge with granitic rocks, or these latter rocks do not crop out.

The relative lack of basic-intermediate rocks at some points where the granitic rocks are in contact with the carbonate rocks could be related to the non-existence in some zones of
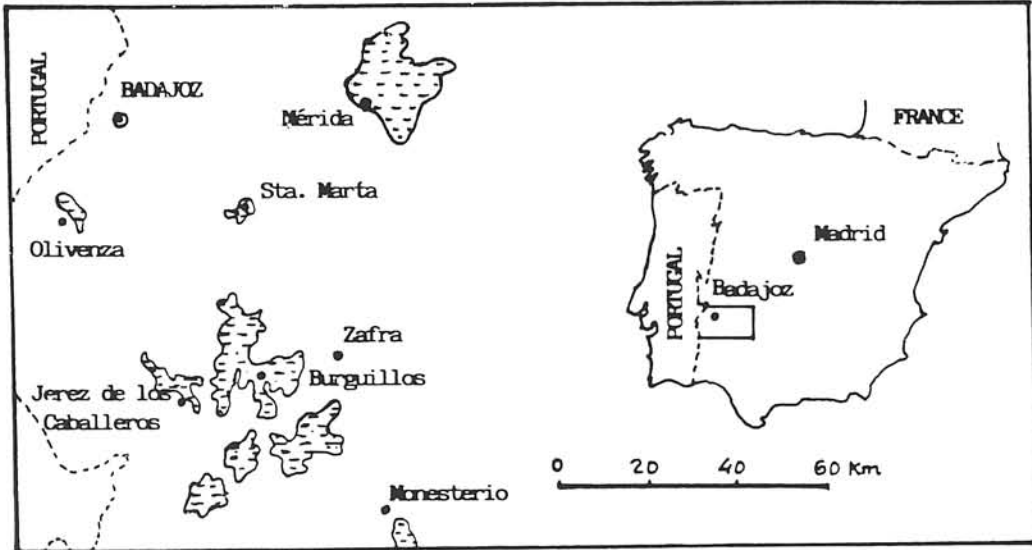

Fig. 1. Sketch map with location of the main outcrops of basic-intermediate rocks in Soutwestern Spain.
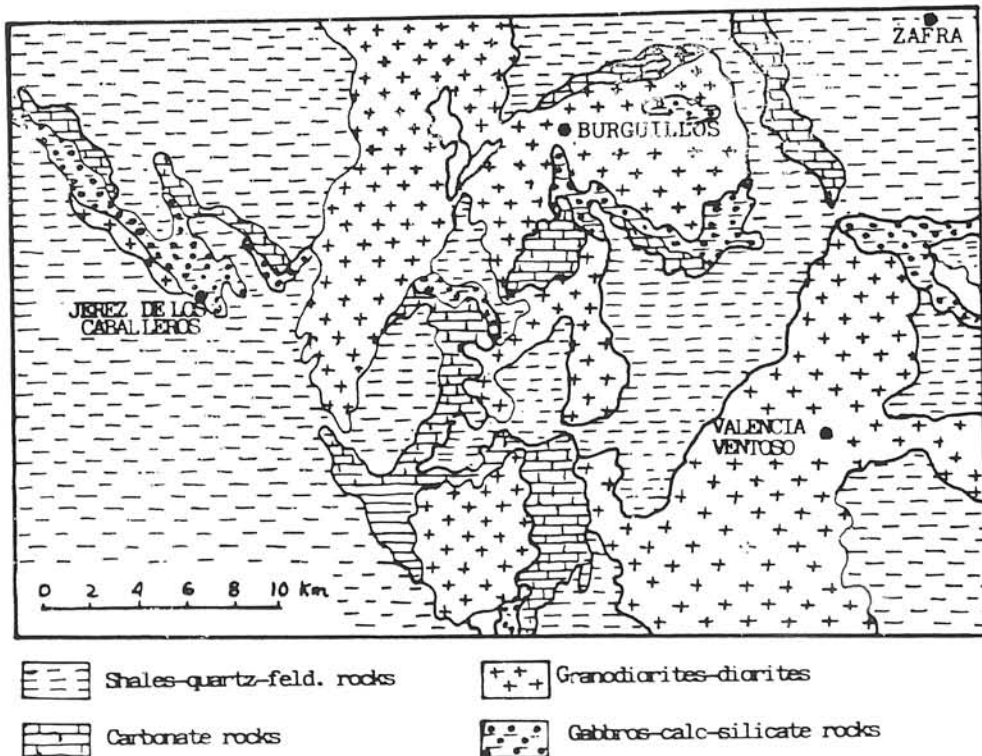

Fig. 2. Schematic map in Zafra-Burguillos zone (Badajoz. Spain).

suitable host sedimentary wall rocks (see below) or to some erosion phenomena probably induced by tectonic processes. Almost all the outcrops of the basic-intermediate rocks are affected by various tecto-petrogenetic processes that have altered the original petrogenetic-structural features of these rocks.

The first type is very frequent. Thus in the Jerez-Burguillos zone it is possible to observe, from top to bottom, the following petrological sequnce (Figs. 2, 3, and 5) (Aparicio & Sanchez Cela, 1972).

a) Carbonate rocks, composed of limestones and dolomitic limestones which are mainly atributed a Cambrian age by the presence of Archaeocyathides (Perejon, 1977).

b) Calcsilicate rocks with abundant skarn-mineralization.

c) Basic rocks mainly composed of gabbros in gradual contact-transition with the calcsilicate rocks.
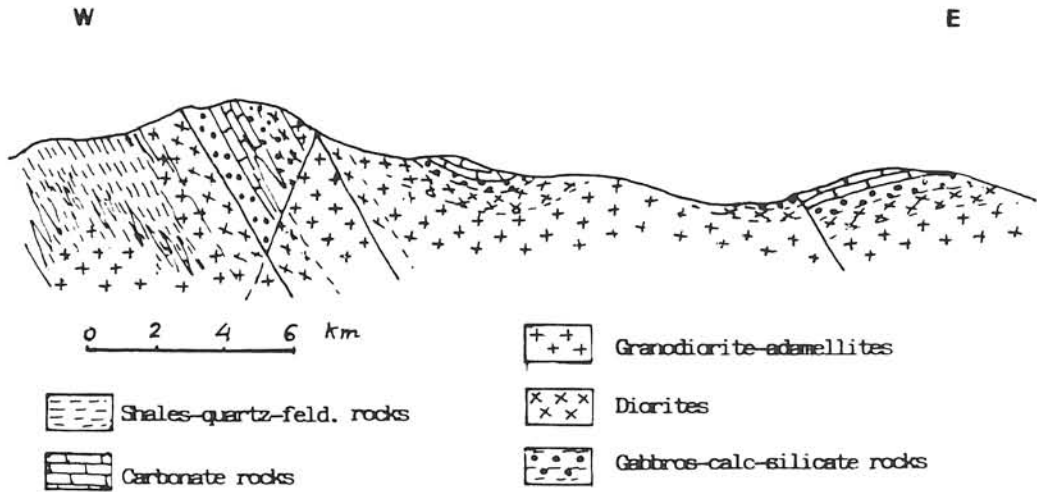

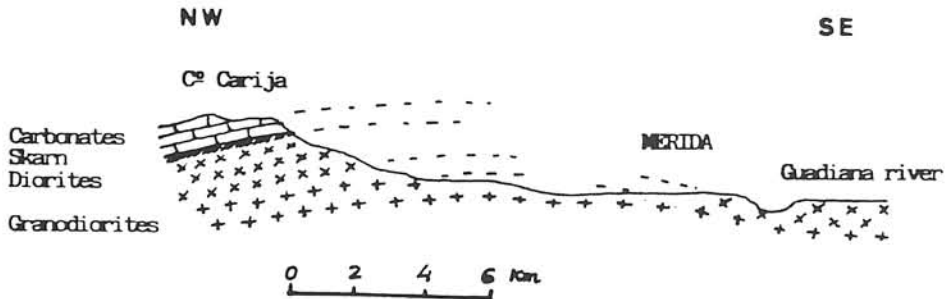**Fig. 3.** Schematic cross-section in Jerez-Burguillos zone (Badajoz. Spain).

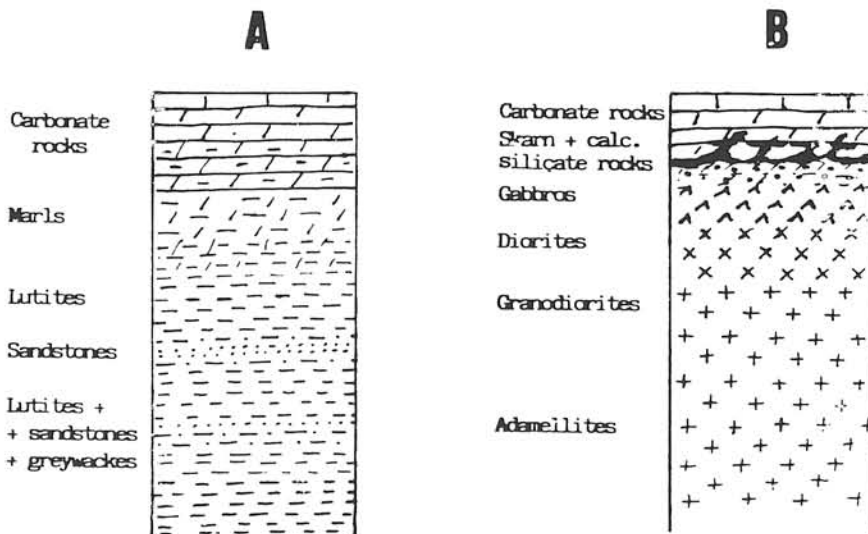**Fig. 4.** Schematic cross-section in Merida zone (Badajoz. Spain).

Fig. 5. Correlation between Cambrian sedimentary levels (A), igneous (gabbros, diorites) and metamorphic (skarn-hornfels) rocks (B) in Burguillos-Jerez zone (see Fig. 2).

d) Dioritic rocks also in gradual contact with the gabbros as well as with granodiorite.

e) Granitic rocks which range from quartzo-diorites to adamellites and constitute the main masses of plutonic rocks in almost all the igneous outcrops in Southwestern Spain.

The second type is observed, for example, in the Merida outcrop (Fig. 4) where the dioritic rocks do not appear to be related to the carbonate rocks although these sedimentary rocks do crop out in nearby zones where there is a gradual transition between basic-intermediate rocks and granitic rocks. In this zone the existence of roads, quarries and some mining facilitates the geological-petrological studies. These dioritic rocks consitute shallow outcrops that gradually converge with depth with the granitic rocks (Sanchez Cela, 1971). In this zone other geologists (Gonzalo, 1987) have interpreted the diorites as rocks of a basaltic nature and of a mantle provenance.

Locally, the basic-intermediate rocks appear isolated from the granitic ones (3rd type). It is in these places that the former are generally interpreted as proceeding from "deep zones" (mantle). There, the basic rocks, mainly gabbros, are generally in contact with the carbonate rocks, skarn and other calcsilicate rocks. These latter rocks are interpreted, by some authors, as the result of contact metamorphism associated with the intrusion of gabbros.

In some places, such as Merida (Sanchez Cela, 1971) and Burguillos (Aparicio and Sanchez Cela, 1972), the basic-intermediate rocks crop out like intrusive rocks (dykes) within granitic masses. Field observations in mines and quarries indicate that such rocks have no roots. In these zones the "dykes" are emplaced within alkaline granitic rocks of later origin.

Petrography

The basic-intermediate rocks in Southwestern Spain have been described by us in previous papers and also by other petrologists, so only a petrographic résumé is given here.

− Olivine-gabbros with coarse to fine grained textures, composed of plagioclase (60−70 An), clinopyroxene, olivine (42−63 Fo), ± orthopyroxene, hornblende, Fe-sulphur-oxides and other accessory minerals.

− Gabbros s. l., also coarse to fine grained, are formed of plagioclase (50−70 An), clinopyroxene, hornblende and biotite, with scapolite and Fe-suplhur-oxides as accessory minerals.

− Amphibole-gabbros, described as diorites and amphibolites in various papers, are generally of coarse porphyritic-poikilitic textures and formed of brown amphibole that includes plagioclase of two compositions: 67−73 An and 43−65 An, clinopyroxene and biotite. Scapolite, opaque minerals and apatite are accessory minerals. Some of these rocks can also contain green hornblende, quartz and K-feldspar.

− Diorites s. l. are the most abundant rocks (within the basic-intermediate group) in Southwestern Spain. They exhibit various textures but their mineralogical composition is quite consistent: amphibole (green hornblende), plagioclase (35−45 An), biotite and quartz; opaques, titanite, apatite and epidote are accessory minerals. Locally alkali amphibole occurs. The diorites are frequently associated in a gradual transition with granodiorites and adamellites.

Almost all the basic-intermediate rocks have generally hypidiomorphic textures but in some zones the schistosity is often present in dioritic rocks. These "gneissic diorites" are almost always associated, in gradual transition, with various metamorphic rocks of pelitic composition: schists, gneisses

and quartzo-feldspathic rocks variously interpreted as ranging from granitic to "arkosic" rocks (Sanchez Cela & Aparicio, 1982).

Geochemical features

Major elements

The analysed rocks cover several petrographic types in different outcrops where the petrographic sequences appear to be better developed (outcrop type 1, with basic-intermediate rocks in contact with carbonate and granitic rocks).

Many chemical analyses are from the previous work of Aparicio et al. (1985), where the sedimentary rocks or rocks of sedimentary origin (e.g. hornfels-skarns) were processed in the same way as the igneous plutonic rocks for the purpose of comparison.

The differentiation index (D.I.) values (Thornton and Tuttle, 1960) in relation to the different oxides of granitic, intermediate and basic rocks, as well as the wall rocks, are shown in Fig. 6. There is a linear and continous evolution between the sedimentary wall rocks and the granitic rocks with the different basic-intermediate rocks in between.

The greater part of rocks with little SiO_2 corresponds to calcsilicate rocks (skarns, diopsidites) and some gabbros. These gabbros present a greater dispersion index although they extend from the points for the calcsilicate hornfels to those of the dioritic rocks.
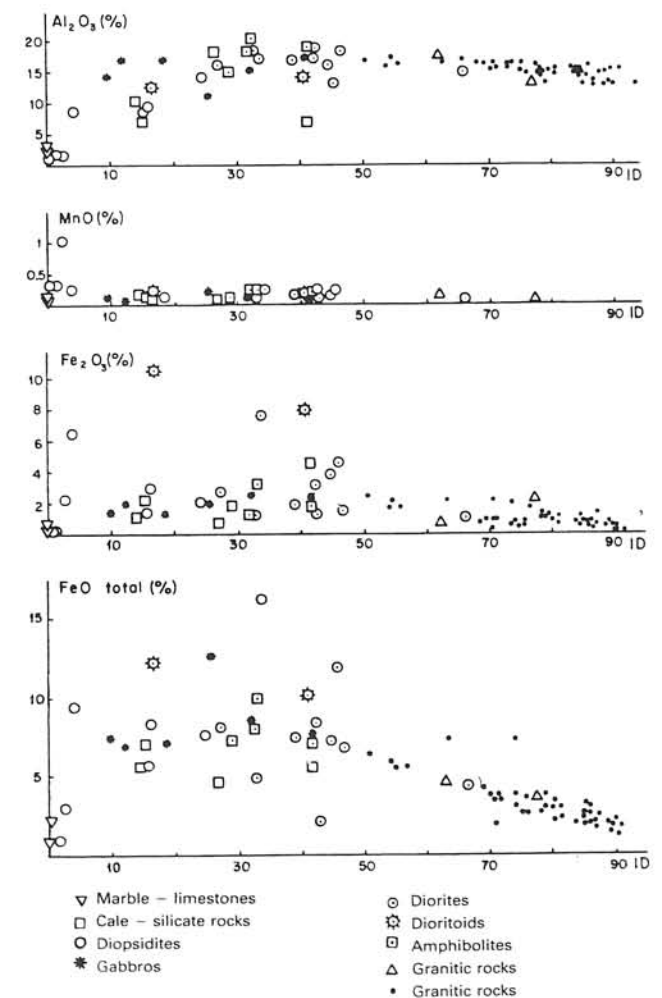
The beaviour of Al_2O_3 is uninterpretable. It presents little variation except in some calcsilicate hornfels and diopsidites where Al_2O_3 decreases as D. I. decreases. Na_2O and K_2O are, like Al_2O_3, not very expressive. Normally an increase in such oxides corresponds to a gradual increase in the D. I.. The decrease in Na_2O is established in the diorite field and subsequently it decreases in the calcsilicate hornfels (Aparicio et al., 1985).
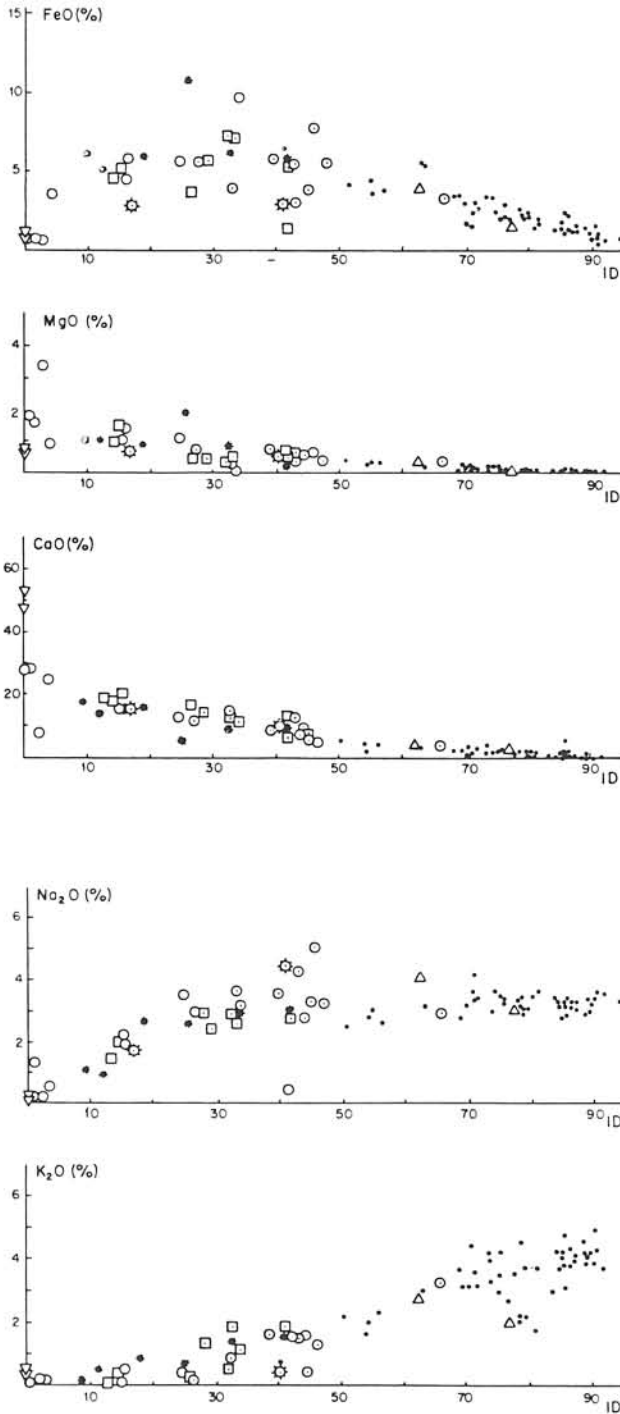

Fig. 7. AFM diagram (symbols are the same as Fig. 6).

Fig. 6. I. D. versus oxides diagram of acidic-basic and wall rocks.
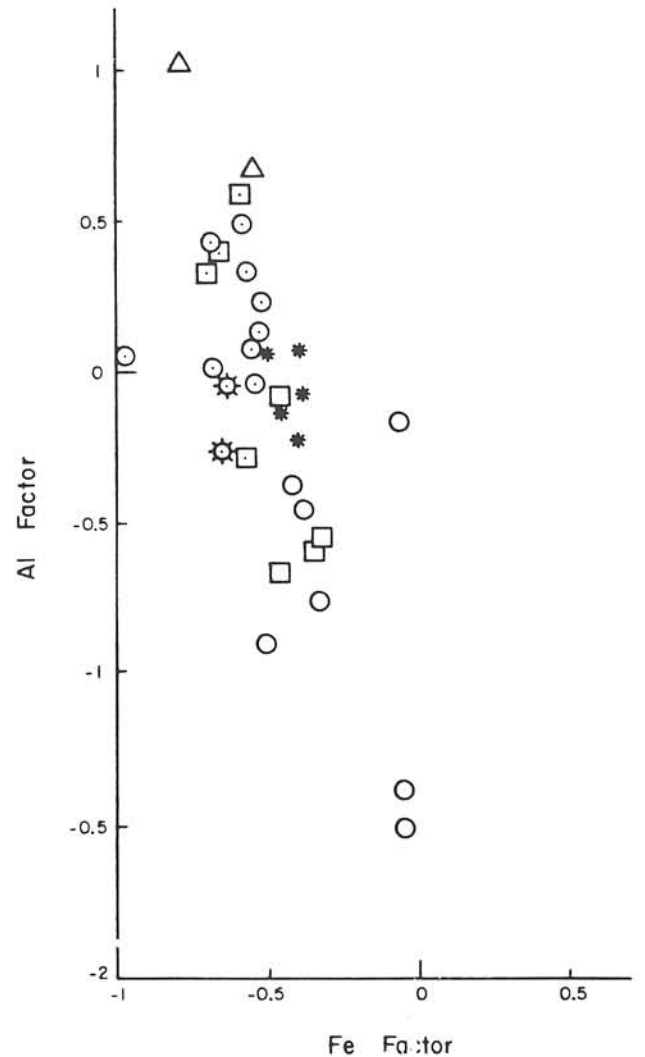
Fig. 8. Al-factor versus Fe-factor (symbols are the same as Fig. 6).
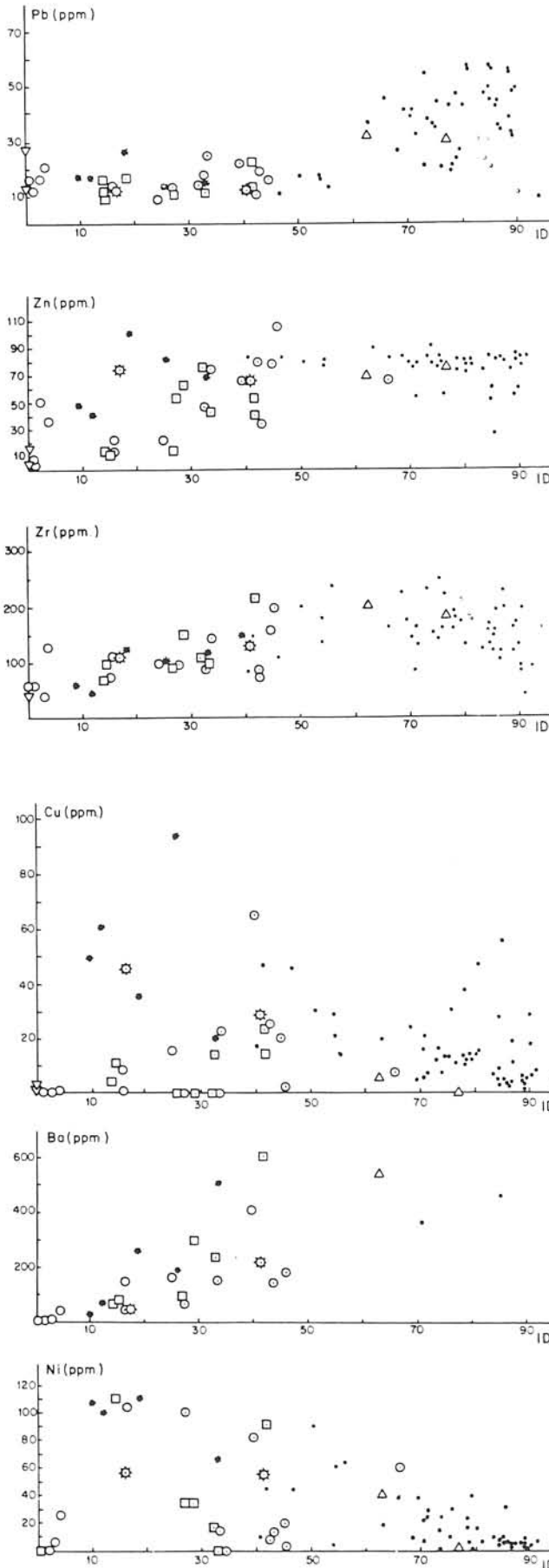
CaO and MgO exhibit a gradual decrease from the sedimentary wall rocks (carbonate rocks) to the granite. FeO evolution is generally in inverse relation to the D. I., so lower D. I. values correspond to higher FeO ones, except when the D. I. ≃ 50 where this correlation does not seem to exist. TiO₂ and MnO, due to their low percentages, are not interpretable.

The AFM diagram (Fig. 7) shows a calcalkaline trend with some inversions in the basic hornfel rocks.

The Al-factor and Fe-factor diagrams (Nesbitt & Cramer, 1981) (Fig. 8) display a continuous geochemical evolution between the sedimentary wall rocks, the basic-intermediate rocks and the granitic rocks.

Minor elements

In general, the minor elements show an analogous behaviour with the major ones. The values of these elements corresponding to D. I. values are shown for different rock types in Fig. 9.

Fig. 9. I. D. against minor elements diagram (symbols are the same as Fig. 6).

Fig. 10. Rb/K diagram (symbols are the same as Fig. 6).

b) Nature of allochthonous chemical elements deduced through petrological and chemical data.

c) The physical state of the processes of transformation and origin of the thermal energy.

d) Some mineralogical transformations in the formation of gabbro-dioritic rocks.

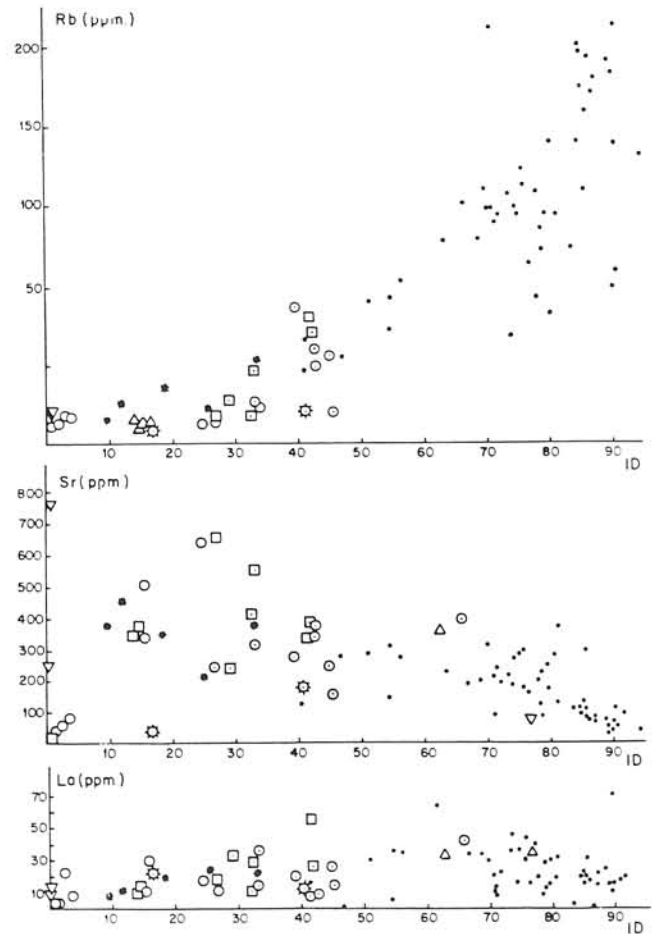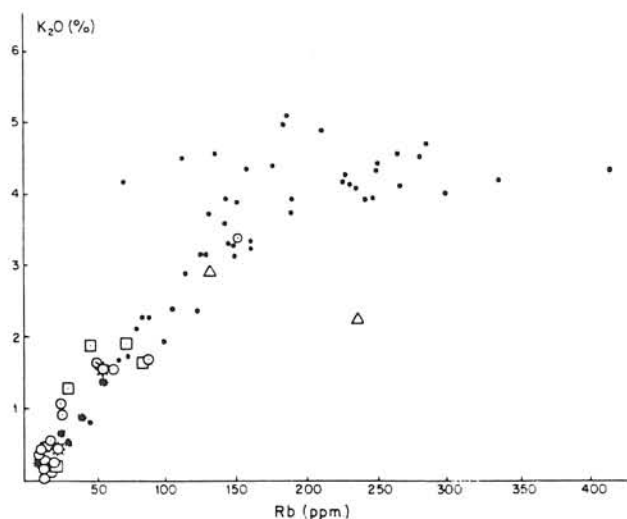## The original nature of the sedimentary wall rocks

As we have already stated, the authors of previous works (Sanchez Cela, 1971; Aparicio and Sanchez Cela, 1972; Sanchez Cela and Aparicio, 1972) have considered a certain relationship between the basic igneous rocks and the carbonate ones, constituted by limestones and dolomitic limestones, mainly of Cambrian age. These "initial deductions" were a consequence of the fact that the basic igneous rocks usually seem to be in contact with these rocks.

Subsequent stratigraphic observations at the locations of the basic igneous rocks have led us to consider the possibility that the "true sedimentary habitat", in relation to the place of emplacement of these rocks, cannot be defined exactly. Thus, subsequent stratigraphic revisions completed with some sedimentological deductions seem to indicate that as well as dolomite-limestone rocks marls are also relatively abundant in the Paleozoic sequence. Surprisingly, these materials in many cases seem to correspond to the "location" of many igneous rocks from basic to intermediate types in Southwestern Spain (Fig. 5).

From sedimentological deductions and references to the composition of the sedimentary materials in these stratigraphic levels, where they seem to be less affected by the alteration and transformation processes, (e. g. Zharkov, 1984), we can deduce that the wall materials, now associated with igneous facies, could have had a different composition in Hercynian times, for example, they were richer in solute materials. The post diagenetic petrological and tectonic processes have produced a lack of correspondence between the actual sedimentary wall materials and their original composition. Petrographic, geochemical and X-ray data indicate that the marly-evaporitic materials in the Cambrian and also in the Devonian, are formed by various illites-muscovites, chlorites, carbonates and sometimes sulphates of mainly Ca, Na, Mg and Fe. Quartz, Fe-oxides, feldspars, constitute some subordinate accessory minerals.

For this reason, in Paleozoic times, for example, in the Cambrian, the compositions of the sedimentary materials were different from the present. So, as well as carbonate components, they could have included more sulphates, chlorites and some other salts, presently altered or not recorded superficially.

The presence of salty materials is very important in the petrological transformation processes in two ways: the cations (e. g. Ca, Mg.) participating in the formation of new minerals and the anions, together with water, increasing the activity of the reactions. On the other hand, we also know that the transformation processes reach some lesser depth range in the compact carbonate rocks because of the difficulty of penetrating these materials by metasomatizing elements. Thus, the carbonate rocks seem to constitute an impermeable cover to mobile chemical elements. As a consequence, the petrological transformation-contamination processes in the lower levels

Sr shows a linear increase from granitic rocks to sedimentary wall rocks (carbonate rocks). This minor element seems to be mainly contained within plagioclase and pyroxene.

Rb displays a good linear evolution without gaps between the sedimentary wall rocks and the granitic rocks. The greater concentrations are in K-feldspar-biotite rocks. The ratio K/Rb (Fig. 10) is linear for all of the rocks, although the granitic ones exhibit a greater dispersion.

Pb, with analogous amouns in the carbonate and basic rocks, shows a greater concentration in the rocks with high D. I. values. Zn displays a wide dispersion in the basic rocks and a smaller one in the granitic rocks.

Zr displays a more linear evolution, with low values in the carbonate wall rocks and slightly higher values in the granitic rocks. Ni with high values in the carbonate rocks shows, in general, a wide dispersion. La is very constant in all petrographic types.

With respect to the mineral composition, the conclusions arrived at by Aparicio et al. (1985) from the chemical analyses of clinopyroxenes, olivines and amphiboles show a gradual transition in the element-contents among the episedimentary, basic, intermediate and acidic rocks, where the rock-mineral relationships show equilibrium conditions between them. These results represent a strong objection against the existence of two different magmas for basic-intermediate rocks and acidic rocks ("mantle" and "crustal" magmas).

Petrogenetic model

Introduction

In the formulation of our petrogenetic model, already outlined in previous papers, for example, Sanchez Cela and Aparicio (1972), we have taken field, petrographic and geochemical data into account as well as the following:

a) Nature of sedimentary wall rocks.

can be more intense because it is there that the mobile and active elements are concentrated. If, at the same time, these processes are active for a long time affecting "suitable materials" it is not very difficult to understand "where and why" they took place (Sanchez Cela, 1984).

The nature of the chemical allochthonous elements

The geochemical data (Aparicio et al., 1985) lead us to consider a unique series for the evolution of all the petrographic types of basic intermediate and acidic igneous rocks and the different metasedimentary contact metamorphic rocks. The geochemical gradation, without compositional gaps, gives support to the theory that the basic-intermediate rocks of Southwestern Spain are the result of processes of transformation (Sanchez Cela, 1971; Aparicio and Sanchez Cela, 1972; Sanchez Cela and Aparicio, 1972).

Some authors have explained the origin of calcsilicate--hornfel rocks, appearing in contact between sedimentary carbonate rocks and igneous basic rocks (gabbros), as a consequence of contact metamorphism originated in the induction of primary basic magmas of deep origin (Velasco, 1976; Casquet and Velasco, 1978; Casquet, 1980; Gonzalo, 1987, and others). Independent of the origin of the ore minerals, which these authors attribute to the same magmatic source, a view that we do not share, we believe that the skarn-calcsilicate rocks are always a consequence of an interaction between carbonate wall rocks and granitic intrusive materials either within a magmatic environment or a metasomatic one. On the other hand it is very difficult to understand how a chemical metasomatic interchange between the basic intrusive materials and the carbonate wall rocks can take place in the same ratios as the granitic ones.

Pursuing the same argument then, the skarns would, therefore, constitute the transformation fronts of such processes which have not overtaken other levels because of the isotropic behaviour of the pure carbonate rocks. These rocks seem to have acted as a "isolating cover" in relation to the infiltration-diffusion chemical process produced by the granitic materials, which acting for a long time could give rise to workable economic minerals.

In this way some authors, such as Ruiz (1976), Vazquez Guzman and Fernandez Pompa (1976), Calvo (1980), attribute the ore minerals associated with skarn rocks as originating from remobilization processes of sedimentary provenance.

The thermal energy associated with the origin and emplacement of granitic masses is the main cause of why many scattered minerals in the sedimentary materials are transformed, remobilized and concentrated in suitable upper petrological-structural environments (e.g. domed structures covered by carbonate rocks, Sanchez Cela, 1984).

The nature of allochthonous chemical matter together with the thermal energy and the main causes of the petrogenetic transformation processes can, in our opinion, be deduced from the nature of the basement rocks in Southwestern Spain. As we have already said, the field geological studies indicate that in many places a more or less continuous granitic basement exists.

On the other hand, in those zones covered by sediments or where the field geological studies do not appear to imply a granitic basement, the geophysical studies can be of great help. Geophysical transverse studies (Boloix et al., 1983; Grupo Perfiles Sísmicos, 1983; Banda, 1987) appear to confirm a thick crust where at least 30 km must be attributed to the existence of "granitic" materials, however the existence of basic-ultrabasic masses at shallow crustal levels cannot be proved either by petrological or geophysical investigations.

So, the main chemical contribution to the petrological transformation processes (origin of basic-intermediate rocks) arises from the granitic basement. These chemical granitic elements are securely related to sialic thickening phenomena that took place either in solid (metasomatic) or melting (magmatic) states.

The physical state of the process and origin of the thermal energy

We consider that estimating the temperatures reached during the petrogenetic processes, although important in distinguishing between magmatic and metasomatic processes, is not as important as discovering whether the gabbros, for example, correspond to igneous rocks from mantle provenance or whether they could have formed at shallow levels of the Crust through the transformation processes according to the model proposed here.

Although we still have no data on the thermometrical meaning of some parageneses of the basic-intermediate rocks, we can obtain some information on the thermal environment during the crystallization of the transformed pelitic rocks associated with the basic-intermediate rocks. In some zones granitic rocks exist with cordierite, sillimanite and sometimes garnets. Field-petrological studies show that these rocks belong to the same Hercynian petrogenetic episode that gave rise to the basic-intermediate rocks. Thus, at the same time as the marly-carbonate wall rocks were being transformed into various plutonic basic-intermediate rocks the associated lutitic sedimentary rocks were being converted into new granitic rocks, in many cases with "metamorphic" minerals (Sanchez Cela and Aparicio, 1982).

On the other hand, a close relationship appears to exist between the geochemical and thermal phenomena in the Earth's Crust. So the origin and later emplacement of the granitic masses in the Crust appear to be related to important phenomena that took place in the Upper Mantle, where and according to a new physical-chemical model, the denser matter is being transformed into a "granitic" one (Sanchez Cela, 1990). In this model the granitic rocks were and still are produced more or less cyclically by means of a transformation of the Upper Mantle into Crust which consequently is becoming thicker.

The transformation of Upper Mantle into Crust involves interesting geochemical, geophysical and energy phenomena that can easily be explained through the existence of polymorphic physical changes already in the Upper Mantle. These changes include the liberation and mobilization of thermal and chemical energy from the Mantle to the Crust. The "mantle granitic" elements during their upward movement can make contact with various mainly sedimentary materials, many of which are very suitable to be transformed.

Some petrogenetic considerations and mineralogical transformations

In the Cambrian sedimentary materials in Southwestern Spain, from a compositional point of view, the following sequence can be established: An upper level (relative) formed by massive limestones, dolomitic limestones and dolomites with a thickness between 50 and 300 m. An intermediate level formed by dolomitic marls and lutitic marls of variable thickness. A thick lower level formed by lutitic rocks with greater or fewer intercalations of greywackes and sandstones.

The presence of the carbonate rocks in the upper level is a very important feature in the origin and evolution of possible petrogenetic processes that could have taken place in the lower and suitable levels. These carbonate rocks act as an "impermeable cover" in the chemical-physical processes, making it possible for petrogenetic processes in lower levels (e.g. marls) to act for a longer time.

Petrologists are aware of the suitability of the carbonate--marly materials to be transformed when they are affected by active chemical elements (mainly silica) at moderate-high temperature.
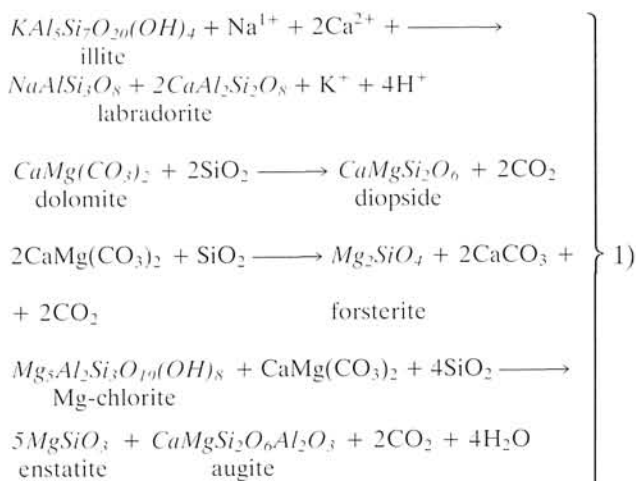
The salty materials, mainly of SO_4^{2-}, CO_3^{2-} and Cl^-, are very important in petrological processes. Because of their high solubilities in aqueous fluid they can be transported easily by static-dynamic fluids. On the other hand, the anions act as activators or buffers of the reactions, and the cations can participate in the formation of new minerals (mainly silicates). The reactions involve simple ion-exchange (e.g. alkalis) in micas and feldspars at low temperature to the formation of various ferromagnesians (e.g. amphibole, pyroxene) at higher temperatures.

From various petrographic studies of basic-intermediate rocks, mainly in zones associated with carbonate and granitic rocks, we deduced that many ferromagnesian minerals were produced by mineralogical reactions between carbonate-marly materials and granitic elements, mainly silica. So, in many basic-intermediate rocks, mainly in diorites, it is possible to deduce the existence of sedimentary restitic minerals, mainly carbonates associated in gradual zoned transition with amphibole, pyroxene and even olivine (gabbros).
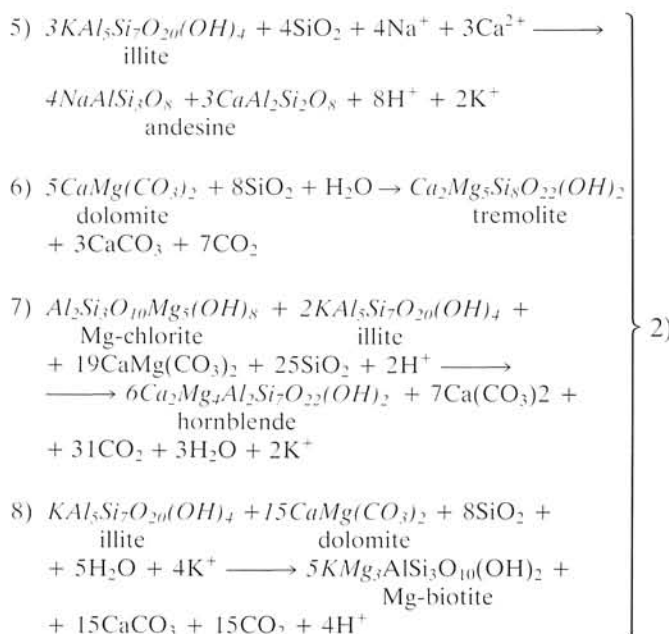
Although the petrological evolution-zonation between carbonate rocks and adamellites was, in many cases, altered by later tectonic-petrological processes, it is possible in some places (Sanchez Cela, 1971; Aparicio and Sanchez Cela, 1972) to deduce the existence of a petrological zonation between basic-intermediate rocks, carbonate-calcsilicate rocks and adamellites (Fig. 5).

From the correspondence between sedimentary rocks (mainly Cambrian) and basic-intermediate rocks together with petrographic studies we have deduced that the gabbros were produced by transformation of the carbonate-marly levels, the diorites by transformation of the marly levels and the quartzo-diorites and granodiorites by transformations of pelitic-marly levels.
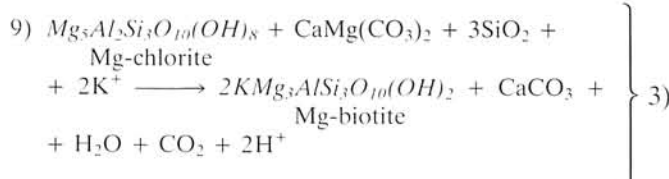
— In the origin of a gabbro formed by plagioclase (labradorite), clinopyroxene (diopside and/or augite), orthopyroxene and olivine, the following transformations can be considered:

$$KAl_5Si_7O_{20}(OH)_4 + Na^{1+} + 2Ca^{2+} + \longrightarrow$$
illite
$$NaAlSi_3O_8 + 2CaAl_2Si_2O_8 + K^+ + 4H^+$$
labradorite

$$CaMg(CO_3)_2 + 2SiO_2 \longrightarrow CaMgSi_2O_6 + 2CO_2$$
dolomite diopside

$$2CaMg(CO_3)_2 + SiO_2 \longrightarrow Mg_2SiO_4 + 2CaCO_3 + $$
$$+ 2CO_2 \qquad\qquad\qquad forsterite$$

$$Mg_5Al_2Si_3O_{10}(OH)_8 + CaMg(CO_3)_2 + 4SiO_2 \longrightarrow$$
Mg-chlorite

$$5MgSiO_3 + CaMgSi_2O_6Al_2O_3 + 2CO_2 + 4H_2O$$
enstatite augite

$$\left.\rule{0pt}{6em}\right\}\ 1)$$

— In the origin of a diorite with plagioclase (andesine), amphibole (tremolite and/or hornblende) and biotite, the following reactions are deduced:

5) $3KAl_5Si_7O_{20}(OH)_4 + 4SiO_2 + 4Na^+ + 3Ca^{2+} \longrightarrow$
illite

$4NaAlSi_3O_8 + 3CaAl_2Si_2O_8 + 8H^+ + 2K^+$
andesine

6) $5CaMg(CO_3)_2 + 8SiO_2 + H_2O \rightarrow Ca_2Mg_5Si_8O_{22}(OH)_2$
dolomite tremolite
$+ 3CaCO_3 + 7CO_2$

7) $Al_2Si_3O_{10}Mg_5(OH)_8 + 2KAl_5Si_7O_{20}(OH)_4 +$
Mg-chlorite illite
$+ 19CaMg(CO_3)_2 + 25SiO_2 + 2H^+ \longrightarrow$
$\longrightarrow 6Ca_2Mg_4Al_2Si_7O_{22}(OH)_2 + 7Ca(CO_3)2 +$
hornblende
$+ 31CO_2 + 3H_2O + 2K^+$

8) $KAl_5Si_7O_{20}(OH)_4 + 15CaMg(CO_3)_2 + 8SiO_2 +$
illite dolomite
$+ 5H_2O + 4K^+ \longrightarrow 5KMg_3AlSi_3O_{10}(OH)_2 +$
Mg-biotite
$+ 15CaCO_3 + 15CO_2 + 4H^+$

$$\left.\rule{0pt}{11em}\right\}\ 2)$$

Mg-biotite can also be produced through the following:

9) $Mg_5Al_2Si_3O_{10}(OH)_8 + CaMg(CO_3)_2 + 3SiO_2 +$
Mg-chlorite
$+ 2K^+ \longrightarrow 2KMg_3AlSi_3O_{10}(OH)_2 + CaCO_3 +$
Mg-biotite
$+ H_2O + CO_2 + 2H^+$

$$\left.\rule{0pt}{5em}\right\}\ 3)$$

Both, hornblende and biotite can be produced through the reactions:

10) $2Mg_5Al_2Si_3O_{10}(OH)_8 + KAl_5Si_7O_{20}(OH)_4 +$
Mg-chlorite illite
$+ 9CaMg(CO_3)_2 + SiO_2 \longrightarrow$
$4Ca_2Mg_4Al_2Si_7O_{22}(OH)_2 + KMg_3AlSi_3O_{10}(OH)_2 +$
hornblende Mg-biotite
$+ CaCO_3 + 17CO_2 + 5H_2O$

$$\left.\rule{0pt}{6em}\right\}\ 4)$$

4) $\begin{cases} \text{11) } KAl_5Si\text{-}O_{20}(OH)_4 + 13CaMg(CO_3)_2 + 9SiO_2 + \\ \qquad \text{illite} \\ \quad + 3H_2O + 2K^+ \longrightarrow Ca_2Mg_4Al_2Si\text{-}O_{22}(OH)_2 + \\ \qquad\qquad\qquad\qquad\qquad\qquad \text{hornblende} \\ \quad + 3KMg_3AlSi_3O_{10}(OH)_2 + 11CaCO_3 + 15CO_2 + \\ \qquad \text{Mg-biotite} \\ \quad + 2H^+ \end{cases}$
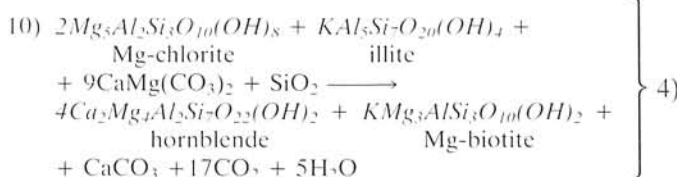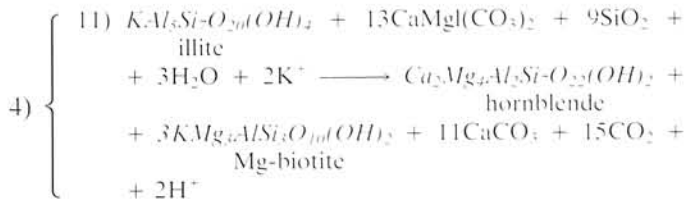
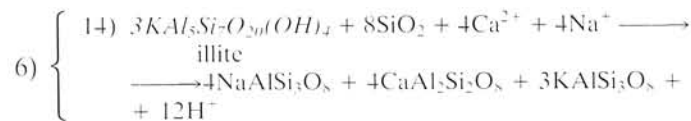— In the origin of granodiorite and quartzo-diorite that gradually evolve into diorites and adamellites, we deduce the following reactions:

5) $\begin{cases} \text{12) } 3KAl_5Si\text{-}O_{20}(OH)_4 + 8SiO_2 + 7Na^+ + 4Ca^{2+} \longrightarrow \\ \qquad \text{illite} \\ \quad \longrightarrow 7NaAlSi_3O_8 + 4CaAl_2Si_2O_8 + 12H^+ + 3K^+ \\ \qquad\qquad\qquad\qquad \text{andesine} \\ \text{13) } KAl_5Si\text{-}O_{20}(OH)_4 + 8SiO_2 + 4K^+ \rightarrow 5KAlSi_3O_8 + 4H^+ \\ \qquad \text{illite} \qquad\qquad\qquad\qquad\qquad \text{K-feldspar} \end{cases}$
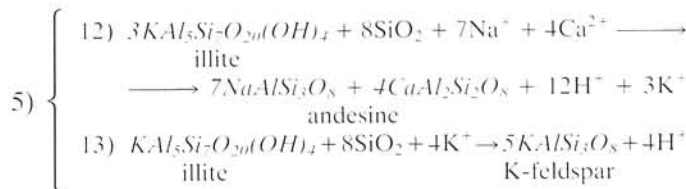
Both, plagioclase and K-feldspar can be produced by:

6) $\begin{cases} \text{14) } 3KAl_5Si\text{-}O_{20}(OH)_4 + 8SiO_2 + 4Ca^{2+} + 4Na^+ \longrightarrow \\ \qquad \text{illite} \\ \quad \longrightarrow 4NaAlSi_3O_8 + 4CaAl_2Si_2O_8 + 3KAlSi_3O_8 + \\ \quad + 12H^+ \end{cases}$

The ferromagnesian minerals, mainly biotite, could be produced by reaction number 8. The excess of SiO_2 will produce quartz.

Many of the reactions described above are controled by the cation H^+ ratio activity. Some of the cited reactions liberate H^+ which can alter the sense of the reaction and produce retrograde or break-silicate reactions. The presence of evaporites is very important since these anions (SO_4^{2-}, CO_3^{2-}) can act as buffers:

7) $\quad SO_4^{2-} + H^+ \longrightarrow HSO_4^-$; $CO_3^{2-} + H^+ \longrightarrow HCO_3^-$
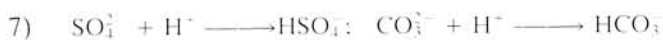
In this way the prograde reactions can continue.

Final considerations

The formation of calcsilicate rocks and skarns is generally explained by transformation-metamorphic processes that took place between intrusive granitic rocks and the carbonate wall rocks. The question is then: how can basic magmas produce the same mineralogical paragenesis as the granitic magmas in the same carbonate sedimentary wall rocks, (e.g. Archaeocyathide-Cambrian limestones)?

We fail to understand how theoretical magmas of "gabbro" and "granitic" compositions can generate analogous or equal paragenesis in the same wall rocks.

At present, we can not understand the reason why geologists postulate various petrological transformations between granitic elements and pelitic or carbonate wall rocks (e.g. various hornfelses) when the marly-evaporitic materials, present in many stratigraphic sequences as transitional materials between the carbonate and lutitic rocks, are not considered to be transformed. Yet petrologists are aware that marly-evaporitic materials can be transformed when affected by active chemical elements (e.g. silica and alkalis) at moderate-high temperature.

Geochemical diagrams and chemical mineralogy appear to demonstrate a linear evolution between the sedimentary wall rocks, basic-intermediate rocks and granitic rocks. The gradational chemical evolution could point to the existence of a relationship between the sedimentary wall rocks and the origin and the evolution of the basic-intermediate rocks. We know that the geochemical data for basic-intermediate rocks, treated in isolation from granitic rocks, could also be ineterpreted as indicating their formation by fractional crystallization of basic-intermediate magmas from a mantle provenance, but we have to take into account the field geological, petrological and geophysical data to the contrary. These data indicate that from bottom to top the thick granitic masses (mainly adamellite) gradually evolve into intermediate rocks (granodiorite-diorite), gabbros, calcsilicate rocks and carbonate sedimentary rocks all generally of Cambrian age. In such an association it is very difficult to establish a geochemical balance from adamellites to gabbros if we consider the origin of the whole of this "petrological unity" to be the fractional crystallization of basic mantle magmas.

The presence in some places of basic-intermediate rocks as "dykes" within granites, thought to be magmatic rocks originated from fractional crystallization of "mantle magmas", could, however, be formed through two or more structural-petrological transformation episodes. A first Hercynian episode when basic-intermediate rocks are produced by transformation of carbonate-marly materials (e.g. Cambrian) by intrusive adamellites that we have related to a thickening sialic phenomenon; later and related to the origin of alkaline granites and thickening sialic phenomenon, the previous basic-intermediate rocks can be affected by some distensional-compressional phenomena, as appears to occur in some rifting zones. In such dynamic zones, the basic-intermediate rocks can suffer various structural-petrological transformations, such as silicification, feldspathization, epidotization, etc. of the previous gabbros or diorites which now appear to be enclosed within the later alkaline granites.

An understanding of the physical state reached during the formation or emplacement of the gabbros and diorites in Southwestern Spain is one of the aims of petrogenesis. There is another important aim: to determine whether such rocks are from mantle provenance or, on the contrary, they were produced as a consequence of transformation of suitable carbonate-marly materials by the chemical, thermal and dynamic activity during formation and emplacement of granitic rocks in the upper levels of the Crust.

References

Alia Medina M., 1963: Rasgos estructurales de la Baja Extremadura. *Bol. R. Soc. Esp. Hist. Nat. Geol.*, 61, 247−262.

Aparicio A. & Sánchez Cela V., 1972: Origen de las rocas básicas de los alrededores de Burguillos del Cerro (Badajoz). *Bol. R. Soc. Esp. Hist. Nat. Geol.*, 70, 139−151.

Aparicio A., Garcia L. & Sanchez Cela V., 1985: Geochemical data on basic-intermediate plutonic rocks in the SW of Spain. Petrological implications. *Rev. Acad. Ciencias Zaragoza*, 40, 91-111.

Banda E., 1987: Estructura cortical del Macizo Hespérico: La aportación geofísica. In: Bea et al. (eds.): *Geología de los granitoides y rocas asociadas del Macizo Hespérico*. Rueda, Madrid; 223-231.

Bard J. P., 1965: Introduction a la Géologie de la chaine Hercynienne dans la Sierra Morena Occidentale (Espagne). Hypotheses sur les caracteres de l'evolution geotectonique de cette chain. *Rev. Geogr. Phys. Geol. dynam., Ser*, 2 (Paris), 7, 323-337.

Bard J. P., 1977: Signification tectonique des metatholeites d'affinité abyssale de la ceinture métamorphique de basse pression d'Aracena (Huelva, Espagne). *Bull. Soc. Géol. France* (Paris), 19, 385-393.

Bard J. P., Capdevila R., Matte P. & Ribeiro A., 1973: Geotectonic model for the Iberian Variscan orogen. *Nature Phys. Sci.*, 241, 50-52.

Bard J. P., Capdevila R., Matte P. & Ribeiro A., 1974: Le Precambrien de la Meseta Iberique. Precambrien des zones mobiles de l'Europe. Geol. Inst. of CSAV, Prague.

Bard J. P. & Fabries J., 1970: Aperçu pétrographique et structural sur les granitoids de la Sierra Morena Occidentale (Espagne). *Bol. Geol. Min. Esp.* (Madrid), 81, 112-127.

Bard J. P. & Moine B., 1979: Acebuches amphibolites in the Aracena Hercynian metamorphic belt (Southwest Spain). Geochemical variations and basaltic affinities. *Lithos* (Oslo), 12, 271-282.

Boloix M., Aparicio A. & Ortiz R., 1983: Una interpretación geofísica-geológica del sector SO del Hercínico Español. *V Asamblea Nac. Geodesia y Geofísica*, Madrid, 275.

Brun J. P. & Pons J., 1981: Strain patterns of pluton emplacement in a crust undergoing noncoaxial deformation Sierra Morena. Southern Spain. *J. Struct. Geol.*, 3, 219-229.

Calvo B., 1980: Estudio genético del yacimiento de magnetita pirita de Cala (Huelva). *Tecniterrae* (Madrid), 34, 5-10.

Carnicero A. & Castro A., 1983: El plutón de Higuera-Táliga y su haz de diques básicos (Badajoz, Sierra Morena occidental). *Estud. geol.* (Madrid), 39, 141-150.

Casquet C., 1980: Fenómenos de endomorfismo, metamorfismo y metasomatismo en los mármoles de Rivera de Cala (Sierra Morena). Tesis. Fac. Ciencias Univ. Complutense, Madrid, 295.

Casquet C., 1982: Metamorfismo de contacto en el borde N del plutón de Santa Olalla de Cala (Huelva-Badajoz) con especial énfasis en las rocas carbonatadas. *Rev. R. Acad. Cienc. Exac. Fis. Nat.*, 76, 333-364.

Casquet C. & Velasco F., 1978: Contribución a la geología de los skarns cálcicos en torno a Santa Olalla de Cala (Huelva-Badajoz). *Estud. geol.* (Madrid), 34, 399-405.

Defalque G., Dumont P. & Panou G., 1971: Le batholite granitique de Los Pedroches et ses minéralisations. *Bull. Soc. Belge Geol.* (Bruxelles), 51-60.

Galindo C. & Casquet C., 1987: Mineralogía y condiciones de cristalización en el complejo subvolcánico de Barcarrota (Badajoz, España). *Estud. geol.* (Madrid), 43, 169-178.

Garrote A. & Sánchez R., 1979: Granitos poscinemáticos de tendencia alcalina en Ossa Morena: el stock de la Cardenchosa (prov. de Córdoba). *Acta Geol. Hisp.* (Barcelona), 14, 90-98.

Gonzalo J. C., 1987: El plutonismo hercínico en el area de Mérida (Extremadura Central, España). In: Bea et al. (eds.): *Geología de los granitoides y rocas asociadas del Macizo Hespérico*. Rueda, Madrid, 345-355.

Mueller S., Prodehl C., Mendes A. & Sousa V., 1973: Crustal structure in the Sothwestern part of the Iberian Peninsula. *Tectonophysics* (Amsterdam), 20, 307-318.

Nesbitt H. W. & Cramer J. J., 1981: Graphical representation of mineral equilibria and material balances in igneous rocks. *Contrib. Mineral. Petrology* (Berlin-New York), 78, 136-144.

Perfiles Sísmicos Profundos, grupo de trabajo 1983: Perfiles Sísmicos Profundos en España. *Bol. Geol. Min. Esp.* (Madrid), 94, 339-347.

Perejon A., 1977: Arqueociátidos con túmulos en el Cámbrico inferior de Córdoba (Sierra Morena Oriental). *Estud. geol.* (Madrid), 33, 545-555.

Pons J., 1983: Interpretation et utilisation des diverses structures et architectures de plutons basiques et acides. Gabros et granitoides de la Sierra Morena occidentale (Espagne). *Bull. Soc. Géol. France* (Paris), 15, 349-356.

Pons J. & Brun J. P., 1984: Sur le caractere syntectonique de quelques plutons de la Sierra Morena Occidentale (Sud Ouest Espagnol). *Bol. Geol. Min. Esp.* (Madrid), 95, 26-32.

Priem B. N. A., Boelrijk N. A. I. M., Verschure R. H., Hebeda E. H. & Verdurmen E. A., 1970: Dating events of acid plutonism through the Paleozoic of the Western Iberian Peninsula. *Eclogae Geol. Helv.* (Basel), 63, 255-274.

Rubio J. L., 1982: Nota sobre las dioritas del NW de Zarza la Mayor (Cáceres). *Cuadernos Lab. Xeoloxico de Laxe*, 3, 75-84.

Ruiz Garcia C., 1976: Génesis de los depósitos de hierro del Suroeste de la provincia de Badajoz: "Mina Monchi". *Bol. Gel. Min.* (Madrid), 87, 15-32.

Saavedra J., 1979: Aspecto geológico del plutonismo geoquimicamente especializado en Extremadura (Oeste de España). *Bol. Geol. Min. Esp.* (Madrid), 90, 253-274.

Sanchez Cela V., 1971: Consideraciones petrogenéticas sobre las rocas dioríticas de la zona de Mérida. *Estud. geol.* (Madrid) 27, 305-310.

Sanchez Cela V., 1984: A structural and compositional suitable habitat in the petrological transformation processes. *Rev. Acad. Ciencias Zaragoza*, 39, 47-67.

Sanchez Cela V., 1990: Energy and geochemical-geophysical data as critical aspects of the Plate Tectonics Theory. In: "*Critical aspects of the Plate Tectonics Theory*". Theophrastus Publ., Athens, 15, 35-64.

Sanchez Cela V. & Aparicio A., 1972: Petrogénesis de las rocas básicas del SW de España. *Bol. Geol. Min. Esp.* (Madrid), 83, 402-406.

Sanchez Cela V. & Ordoñez S., 1974: Consideraciones sobre unas rocas diabasicas del SE de la provincia de Badajoz. *Bol. Geol. Min. Esp.* (Madrid), 85, 208-213.

Sanchez Cela V. & Aparicio Yague A., 1982: Feldspathic-quartz rocks of sedimentary, metamorphic and igneous facies, in relation to granitization-transformation processes in the Hercynian Massif of Spain. In: Drescher-Kaden & SS. Augustithis (eds.): *Transformist's Petrology*. Theophrastus Publ. (Athens), 189-229.

Schermerhorn J. J. G., 1987: The Hercynian gabbro-tonalite-leucogranite suite of Iberia: geochimistry and fractionation. *Geol. Rudsch.* (Stuttgart), 76, 137-145.

Soler E., 1973: L'association spilites-quartz keratophyres de Sud-Ouest de la Peninsula Iberique. *Geol. en Mijnb.* (Den Haag), 52, 277-287.

Thornton C. P. & Tuttle O. F., 1960: Chemistry of igneous rocks. I. Differentation index. *Amer. J. Sci.* (New Haven), 258, 664-684.

Vazquez Guzman F. & Fernández Pompa A., 1976: Contribución al conocimiento geológico del Suroeste de España en relación con la prospección de depósitos de magnetitas. *Mem. Inst. Geol. Min. Esp.* (Madrid), 89, 130.

Vegas R., 1971: Geología de la región comprendida entre la Sierra Morena Occidental y las Sierras del N de la Provincia de Cáceres (Extremadura, España). *Bol. Geol. Min. Esp.* (Madrid), 82, 351–358.

Vegas R. & Muñoz M., 1976: El contacto entre las zonas surportuguesas y Ossa Morena en el SW de España. Una nueva interpretación. *Com. Serv. Geol. Port.*, 60, 31–51.

Velasco F., 1976: Mineralogía y metalogenia de los skarns de Santa Olalla (Huelva). *Tesis Doctoral.*, Univ. Lejona, Bilbao, 290.

Zharkov M. A., 1984: *Paleozoic salt bearing formations of the world. Springer-Verlag*, 427.