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Geochemical characterization of sedimentary basins by statistical analysis: The Mio-Pliocene sequences of the Vera Basin, SE Spain

Angel Sánchez Bellón[a], Christine Mosser[b], Claude Roquin[b], Eduardo Sebastián Pardo[c]

[a] *Universidad de Cádiz, Departamento de Estructura y Propriedades de los Materiales, Apartado 40, 11510 Puerto Real (Cádiz), Spain*
[b] *Centre de Géochimie de la Surface, CNRS, 1 Rue Blessig, F-67084 Strasbourg Cedex, France*
[c] *Departamento de Mineralogía y Petrología de la Universidad de Granada, Avenida Fuentenueva s/n, 18002 Granada, Spain*

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Abstract

The origin and history of sedimentary rocks can be deciphered from the trace elements in their clay minerals. The inheritance from weathering profiles is detected by the analogy in trace-element amounts of the < 2-μm fractions of the sediments and the presumed parent rocks. The paleoenvironmental conditions are printed in the clay fraction by specific elements like B or by anomalous amount associations of elements not related with parent rocks. The geochemical environment during the deposit of Mio-Pliocene sediments of the Vera Basin (SE Spain) and the influence of their parent source rocks were studied by statistical analysis of the chemical composition of the < 2-μm fraction of these sediments and the bulk samples of their surrounding parent rocks.

Principal components analysis (PCA) was used to find the relationships among the chemical elements, the minerals and the parent rocks, and to select the most discriminating elements. Sr, Ni, Cr, Cu, Co, V, Sc and Zn appeared so to be representative of the clay fractions and the parent rocks, and were therefore selected to obtain information about the parent rocks of the sediments. A hierarchical ascending classification (HAC) was performed with these elements, it regroups samples with similar geochemical characteristics. Graphical comparison of mean geochemical composition among HAC groups provided a better identification of inherited similarities between some sediments and the parent rocks. Most of the clay minerals in the sediments appeared so to have been formed by weathering of the metamorphic basement. Only one laminite sample from Cuevas de Almanzora section in the north of the basin was identified as formed by weathering of volcanic rocks. Volcanic weathering fluids enriched some clays from the Coscojar, Garrapancho and Garrucha sections in Sr. Some Cu and Zn enrichments acquired during early diagenesis are also evidenced by graphic comparisons.

B and Mg contents were used to indicate paleoenvironments. They distinguished two different sedimentary environments, separated by a paleogeographical high situated at the site of Garrapancho Hill. Higher B contents in the southern part of the basin indicate a more marine environment than in the north composed of several subbasins with different salinities correlated with varying inputs of fresh water. The Mg contents are always higher in the north, suggesting a more confined environment. The sediments in the south were deposited in higher-energy environments as shown by the presence of olistostromes whereas in the north marls and clayey laminites suggest a calmer and more monotonous environment.

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1. Introduction

The Vera Basin, located in SE Spain about 60 km NE of Almeria, is one of the intermontane basins of the eastern Betiques Cordilleras (Fig. 1). These basins are enclosed between basement blocks that were raised during the compressive episode of the African–European collision at the end of the Serravallian (Miocene). The Vera Basin is connected towards the SW with the Sor-

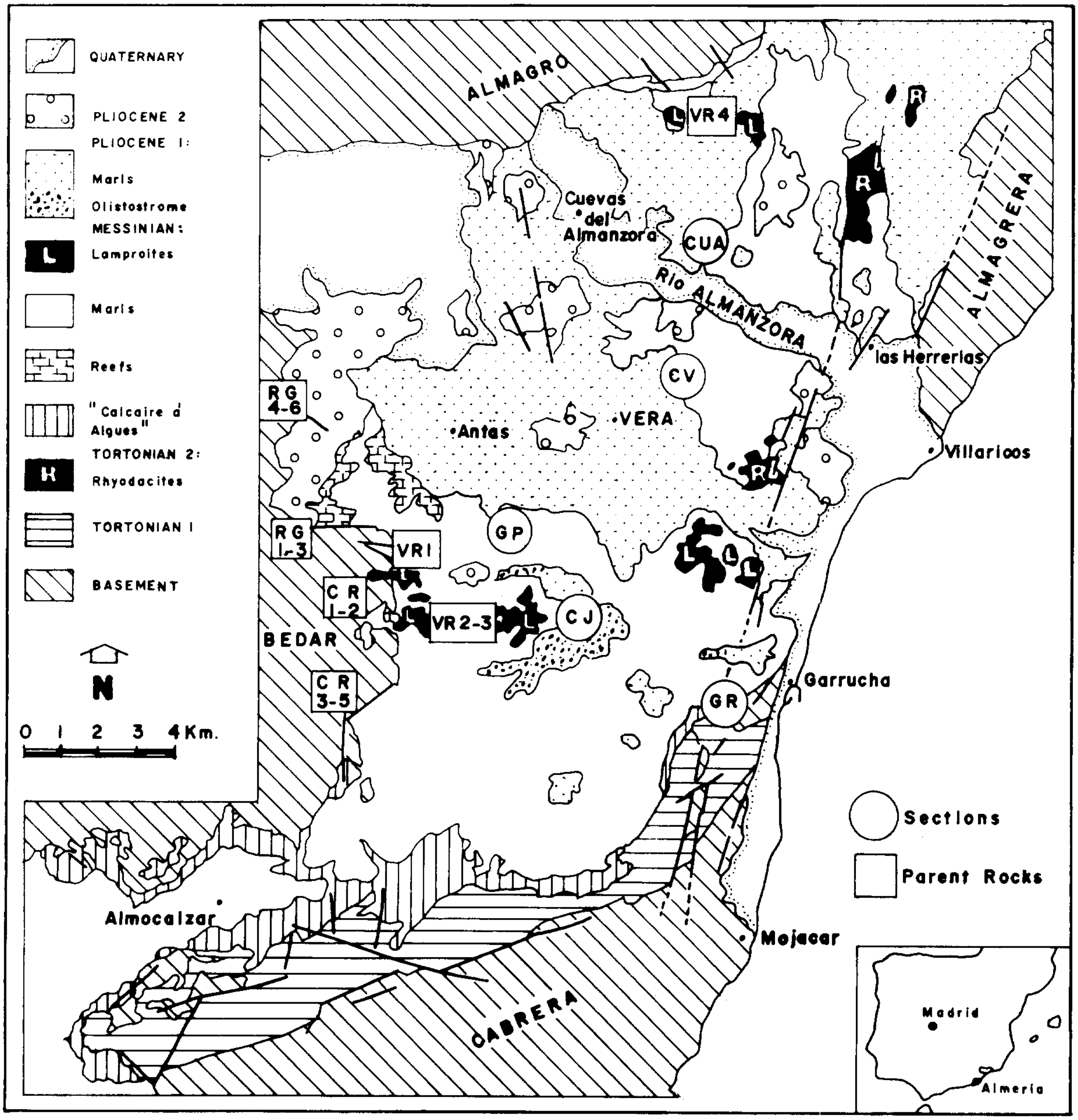

Fig. 1. Geological map of the Vera Basin and locations of the studied sections and parent rocks. [Taken from Ott d'Estevou et al. (1990), modified.]

bas Basin, through the Almocaizar Ridge, and towards the NE with the Lorca depression by the Pulpi Corridor. The eastern part of the Vera Basin is open towards the Mediterranean Sea between Mojacar and Villaricos. The basement of the basin is composed of metamorphic rocks of the external zones of the Betiques Cordilleras, which forms the surrounding mountains. To the south, at Sierra Cabrera, are rocks from the middle and upper units of the Alpujarride Complex; to the north is the Sierra Almagro, containing material of the lower unit of the same complex (previously the Ballabona–Cucharon Complex); and to the east and west are the Sierras of Bedar and Almagrera, which consist of rocks of the Nevado–Filabride Complex (Fig. 1).

The age of the sediments filling the basin ranges from Burdigalien (Miocene) to the present. They are essentially marine, with intercalations of continental material. Völk and Rondeel (1964) differentiated an older and a younger Neogene in the Vera Basin. The Mio-Pliocene boundary was the subject of controversy. Montenat et al. (1976), González Donoso and Serrano (1977), Carrasco et al. (1979), and Ott d'Estevou et al. (1990) interpret the boundary as lying within a continuous marine sequence; Cita et al. (1980), Geerlings et al. (1980), and Barragán Bazán (1987) believe that sedimentation was interrupted by a period of predominantly lacustrine sedimentation.

The aim of the geochemical study presented here is to characterize the geochemical environment during sedimentation, to trace the influence of the parent source rocks on the sediments, and to determine if the marine sedimentation was interrupted during the Mio-Pliocene transition period. The clay fraction of the sediments was selected for analysis for its ability to reflect the trace-element pattern of its parent rocks, and to retain the trace elements acquired during sedimentation (Mosser, 1980; Mosser et al., 1991). The chemical analyses were interpreted by different statistical methods.

2. Geological setting

The Vera Basin is surrounded by several transverse faults. In the eastern part of the basin the faults form the tectonic corridor of Palomares (Fig. 1). The basement is composed of piled-up sheets. According to their degree of metamorphism they are classified into the following three lithological units (Aldaya et al., 1979; Fontboté, 1983): the Nevado–Filabride, Alpujarride and Malaguide complexes. The Nevado–Filabride Complex is formed of piled-up sheets, each one containing the following three lithological formations: (1) the Nevada Formation of graphitic mica-schists with garnets, and of quartzites and gneiss with tourmaline; (2) the Tahal Formation of albitic mica-schists; (3) the Las Casas Formation of marble with basic intrusions. The Alpujarride Complex consists of a lower unit, previously named Ballabona Cucharon Complex (Egeler and Simon, 1969), made up of schists, phyllites, gypsum layers and carbonaceous formations, and by an upper unit composed of grey schists, purple phyllites and quartzites, with dolomites at the top. The Malaguide Complex comprises rocks of low metamorphic grade (sandstones, limestones, schists, pelites and dolomites). The Malaguide Complex is present in the Vera Basin, but only in small and isolated outcrops that are always related to tectonic features (Sierra Cabrera and Sierra Almagro).

The Neogene deposits in the Vera Basin were usually differentiated into an older and a younger Neogene (Völk and Rondeel, 1964; Völk, 1966), depending on the absence or the presence of detrital material of Nevado–Filabride origin. The deposits older than middle Miocene, which are always highly tectonized and poorly preserved, are found in proximity to basement outcrops. The upper Miocene and the Pliocene, however, are more abundant and better preserved. Two volcanic episodes occurred during the late Miocene. One episode is of rhyodacitic character. The other is lamprophyric, and gives rise to volcanic rocks interstratified with the Messinian turbidites. These rocks are ultra potassic lamprophyres, and are known as "verites".

Between the lower Messinian and the Pliocene are marly sediments that are usually unconformable on the lower Messinian. On the borders of the basin they interfinger with the olistostrome deposits near the top of the series. In the centre of the basin there are no olistostromes. Olistostromes in the south contain numerous gypsum pebbles and blocks, whereas in the north they are not observed.

Different interpretations have been given for the Mio-Pliocene boundary. Montenat et al. (1976) have carefully studied the Cuevas de Almanzora section (CUA on Figs. 1 and 2). Taking the micropaleontological results as well as the absence of evaporitic deposits into account, they demonstrated continuity of marine sedimentation at the Mio-Pliocene boundary. They described in that section, from the upper Tortonian until the lower Pliocene, a continuous succession of planktonic *Foraminifera*. Montenat et al. (1976) believed that their succession demonstrated an uninterrupted connection with the Atlantic Ocean. This conflicts with the theory of a generalized regression in the Mediterranean Basin during the Messinian. A similar idea is maintained by González Donoso and Serrano (1977), Carrasco et al. (1979), and Ott d'Estevou et al. (1990). All these authors interpreted the presence of ostracodes (indicators of brackish waters) in the laminites near the Mio-Pliocene boundary as the result of transport by turbidity currents or as an adaptation to marine conditions.

On the other hand, Cita et al. (1980) believe that the ostracode association of the *Cyprideis* genus is in situ. For them it is an indication of brackish environments like those described to explain the Italian "lago-mare" facies, occurring between the Messinian and the marine lower Pli-

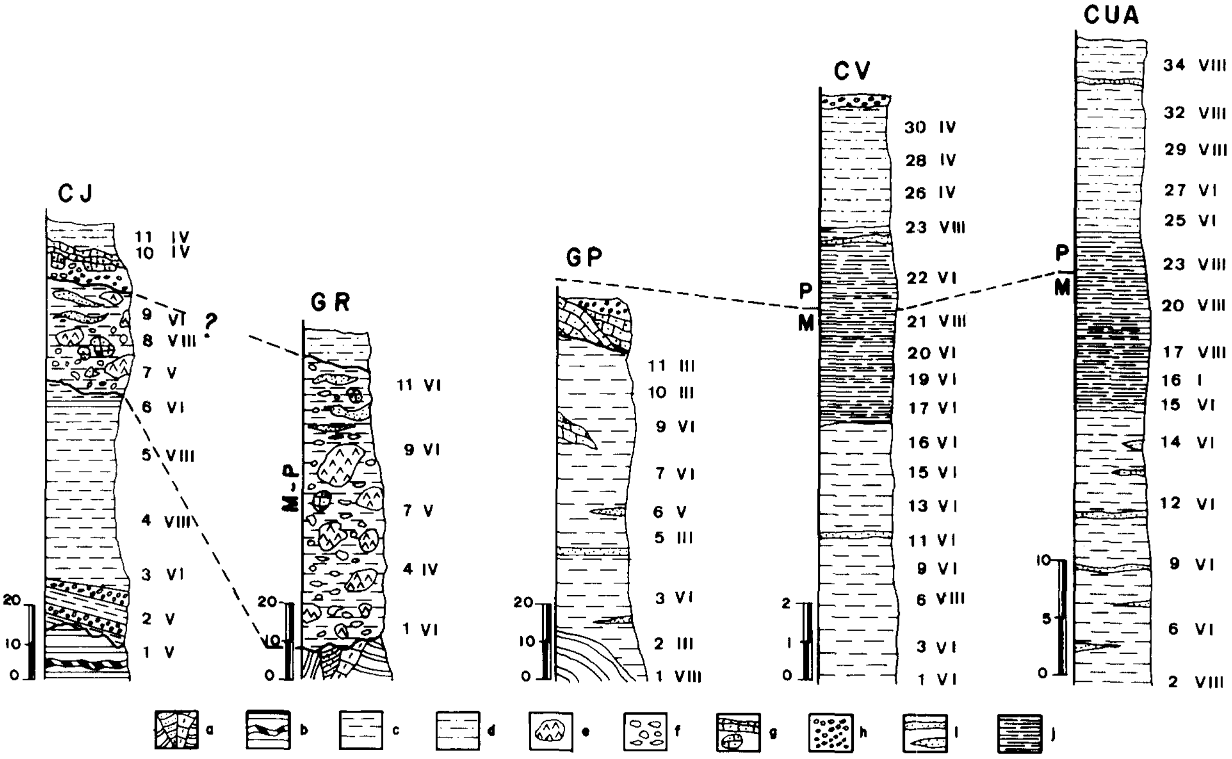

Fig. 2. Description of the sampled sections. Names of sections: *CJ*=Coscojar; GP=Garrapancho; *GR*=Garrucha; *CV*=Canada de Vera; *CUA*=Cuevas de Almanzora. Names of facies: *a*=very tectonised, early Neogene; *b*=turbidite with intercalation of verites; *c*=marls; *d*=silty marls; *e*=gypsum; *f*=turbidite pebbles; *g*=reef limestone; *h*=conglomerate; *i*=sandstone; *j*=laminites. Number of the samples=1, 2, ... Number of the HAC group of the sample=I, ..., VIII; *M-P*=Mio-Pliocene boundary.

ocene. Geerlings et al. (1980) found non-reworked charophyte algae, with preserved oogones, indicating lacustrine sedimentation. Consequently, they also believed that there was an interruption of the marine sedimentation. Barragán Bazán (1987) was of the same opinion, placing his reliance on the stratigraphic relations of the olistostrome sets of the southwest of the basin. Finally, Benson and Rackic El Bied (1991) revealed a new problem. They attributed a Messinian age to sediments considered until then to be of early Pliocene age. For them the Mio-Pliocene boundary is represented by the unconformity between the Cuevas and the Espiritu Santo formations described by Völk and Rondeel (1964).

3. Methods

15 parent rocks were sampled (Fig. 1) from the Nevada Formation of graphitic mica-schists with garnets (samples RG*2*, RG*4*, CR*1*), the Tahal Formation of albitic mica-schists (samples CR*2*, CR*3*, CR*4*, CR*5*, RG*1*, RG*3*, RG*5*, RG*6*) and the lamprophyric volcanic rocks known as "verites" (samples VR*1*, VR*2*, VR*3*, VR*4*)

57 samples from the sediments studied here come from five sections representing three different situations. In the south of the basin [Garruch (GR) and Coscojar (CJ) sections, Fig. 1] are marls deposited directly on paleorelief. Deposited unconformably on top of these marls are olistostromes, rich in gypsum blocks and pebbles, travertines, and turbidites derived from older units (Fig. 2). The sections in the centre of the basin [Garrapancho (GP), Fig. 1] consist of monotonous successions of marls capped with reef deposits. Finally, in the north, the Canada de Vera (CV) and Cuevas de Almanzora (CUA) sections contain marls, Messinian laminites and Pliocene marly silts (Fig. 2).

The mineralogical analysis of each bulk sample collected was made by X-ray diffraction (XRD) on an unoriented powder preparation. Semi-quantitative estimation of the amounts of the different minerals present in the sample was made by measurement of the diffraction peak surface and by using the reflecting powers corrected for an automatic slit in the diffractometer, according to Schultz (1964) and Barahona Fernández (1974).

Extraction of the <2-μm fraction from sediment samples was carried out by decantation and centrifugation after careful crushing in distilled water. Some samples were treated with H_2O_2 to remove the organic mater. For decarbonation we used acetic acid. Clay minerals within the <2-μm fraction were identified by XRD on oriented preparations on a glass slide in a 20°C normal state, after saturation with ethylene glycol, with dimethyl sulphoxide, and after heating at 550°C for 1.5 hr. The relative abundance of different clay minerals was estimated by the method utilized for the bulk sample.

To confirm the presence of minerals difficult to determine by other means and to determine the chemical composition of the various mineralogical phases, we used transmission electron microscopy (TEM) and scanning electron microscopy (SEM) (Zeiss® EM *10*C and Zeiss® DSM *950*, respectively). This was achieved by analysis of X-ray dispersive energy (EDS) with a Kevex® *8000* (López Galindo et al., 1989).

Chemical analysis was undertaken on the <2-μm fraction of the different sampled sections, as well as on the bulk of the unweathered supposed parent rocks. The major and minor elements were analyzed by spark emission spectrometry (for Si, Al, Mg, Ca, Fe, Mn, Ti), flame emission spectrometry (for Na, K), and ICP emission spectrometry (for P, Sr, Ba, V, Ni, Co, Cr, Zn, Cu, Sc, Zr, Y) following the method described by Samuel et al. (1985). B was analyzed by inductively coupled plasma–mass spectrometry (ICP–MS). Samples were dried at 110°C prior to analysis. Weight loss on ignition (LOI) was measured after 3-hr calcination at 1000° C. Major-element results are given in oxide percent with an analytical relative error of $\pm 2\%$. Trace-element contents are given in ppm metal with an analytical error of $\pm 10\%$.

Chemical analyses for the whole rocks and for <2-μm fractions were analyzed statistically [i.e. means, standard deviations, correlation coefficients, principal components analysis (PCA), and hierarchical ascending classification (HAC)]. The computer programs utilized for PCA and HAC are those edited respectively by SAS (1988) and ADADD (Benzecri, 1973; Lebart et al., 1982; Benzecri and Benzecri, 1984). Variables are centered and standardized. HAC groups together samples according to the Euclidean distances between the samples in the chemical vector space determined by analyzed elements.

4. Results and discussion

4.1. Mineralogy

The supposed parent rocks belong to the metamorphic basement and to the lava flows of the studied region. All the metamorphic rocks are albitic schists with quartz, muscovite, chlorite, rutile and zircon. They differ one from the other by their amounts of muscovite, chlorite, and particularly by the presence (RG*2*, RG*4*, CR*1*) or the absence (CR*2*, CR*3*, CR*4*, CR*5*, RG*1*, RG*3*, RG, RG*6*) of garnets. The volcanic rocks are composed of volcanic glass (30–50%), phlogopite (40% for RV*1*, RV*3*, RV*4*; 10% for RV*2*) and augitic pyroxene (30% for RV*2* and as a minor phase for the others). Apatite, rutile and muscovite can sometimes be found in low amounts. These volcanic rocks also contain variable amounts of carbonates that were incorporated during deposition.

The studied sedimentary sequences contain phyllosilicates, calcite, dolomite, quartz and feldspars. Gypsum, opal-Ct and goethite are present in minor proportions. Rutile and zeolites are locally present in some sections.

The five studied sections (Fig. 2) can be regrouped into two zones according to mineralogical composition. Those from the south, Garrucha (GR) and Coscojar (CJ) contain zeolites in the sandstone levels that are interbedded on top of the olistostromes. The zeolites, of clinoptilolite type, resemble the zeolites of the turbidites beneath the marly series. Zeolites are absent in the northern zone. The southern sediments are also richer in gypsum. This mineral (6–15%) is present in the numerous pebbles of the olistostromes. The samples from the north of the basin contain more phyllosilicates (40%) than those farther south (31–38%). The amounts of carbonates (35–45%), quartz (12%) and feldspars (5%) are the same for all the five sections, as well as accessory minerals, such as opal-CT and goethite, which are present in all outcrops.

The clay minerals of the studied sediments consist of smectite, illite, interstratified illite–smectite, kaolinite, chlorite and paragonite. Palygorskites are also present in the GP, CV and CUA sections, the three northern sections, and represent ~30% of the <2-μm fraction. The palygorskite amounts increase slightly towards the top of GP, and towards the middle of CV and CUA. The southern sections (GR and CJ) do not contain palygorskite; but the amounts of illite (38%) and smectite (67%) are greater than in the northern sections (25% illite and 43% smectite on average). Kaolinite and chlorite are present in low amounts within all the sections where traces of paragonite have been detected.

4.2. Geochemistry

The parent rocks (Table 1) can first be distinguished by the SiO_2 contents. The volcanic rocks contain the lowest SiO_2 (55%), and the metamorphic rock are divided into two groups. One metamorphic group contains the schists (RG samples), from near Garrapancho (SiO_2 65%), and the other group contains the more acidic schists (CR samples) from near Coscojar (SiO_2 80%). The Garrapancho schists are also richer in Al_2O_3, Fe_2O_3 and K_2O, as well as in Ba, V, Sc and Y than the schists of Coscojar. The volcanic rocks contain the greatest amounts in MgO, CaO, TiO_2, Na_2O, K_2O, P_2O_5, Sr, Ba, Ni, Co, Cu and Zr. High Mn concentrations are present in the garnet schists.

The sediments (Table 1) show only minor geochemical variations and these are related to the sedimentary facies or to the age of the deposits. The differences in geochemistry are rather functions of the geographical position of the sediments in the basin.

Table 1
Chemical analysis of representative samples from the different studied sections and the parent rocks: RG (graphitic mica-schists with garnets), VR (lamprophiric volcanic rocks); and CR (albitic mica-schists)

Sample No.	(wt%)										(ppm)													
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	TiO_2	Na_2O	K_2O	P_2O_5	LOI	Sr	Ba	V	Ni	Co	Cr	Zn	Cu	Sc	Y	Zr	Mn	B
CUA *9*	53.5	16.8	7.5	3.3	2.6	0.69	1.46	3.34	1.38	8.0	176	278	152	57	19	118	146	30	15	25	132	212	161
CUA *32*	58.2	17.3	5.8	3.7	1.8	0.73	1.09	3.38	1.18	7.1	206	307	142	32	10	115	146	53	16	25	155	165	167
CJ *3*	55.4	17.8	8.6	2.9	1.4	0.78	1.29	3.07	1.15	6.9	602	313	180	77	8	125	204	89	13	20	120	119	242
GP *2*	54.2	21.8	6.7	2.7	0.7	0.92	1.03	4.38	0.43	6.3	172	568	162	50	15	125	232	271	18	27	150	216	155
GR *4*	56.4	24.2	5.3	2.3	0.5	0.95	1.31	4.51	0.28	5.1	215	604	166	68	12	130	472	35	19	28	164	157	155
CV *15*	55.7	18.1	7.2	3.6	1.4	0.76	1.28	3.49	0.92	7.0	146	266	165	51	19	129	150	32	16	22	114	193	191
CV *21*	54.7	17.4	7.8	4.0	1.1	0.72	2.82	3.25	2.24	6.4	146	216	155	69	12	168	161	36	16	20	112	150	194
RG *4*	64.4	16.7	6.2	1.1	1.0	0.89	0.99	4.64	0.27	2.7	90	540	121	29	8	86	49	9	15	33	324	688	
VR *2*	57.9	11.1	4.0	4.3	5.1	1.36	2.62	3.99	0.74	7.3	412	1,473	102	245	18	769	71	32	12	22	722	461	
CR *2*	79.6	9.7	2.9	0.4	0.5	0.58	3.44	0.67	0.11	1.3	79	86	55	16	3	47	24	7	6	16	343	60	

LOI = loss on ignition.

4.3. General geochemical features

The geochemical characteristics of the sediments are best determined by statistical analysis. The general features displayed by PCA are presented for the parent rocks (Fig. 3A) and for the sediments (Fig. 3B). On these three-dimensional diagrams, the elements are plotted in the space of the three first factors (*F*1, *F*2, *F*3) which yield 84% of the variance of the system for the parent rocks, and only 51% for the sedimentary rocks. This indicates that the geochemical features of the parent rocks are related to only a few major characteristics, in contrast to those of the sedimentary rocks.

For the parent rocks (Fig. 3A), all the elements have positive *F*1-values except Si. This major differentiation is mainly due to the strong con-

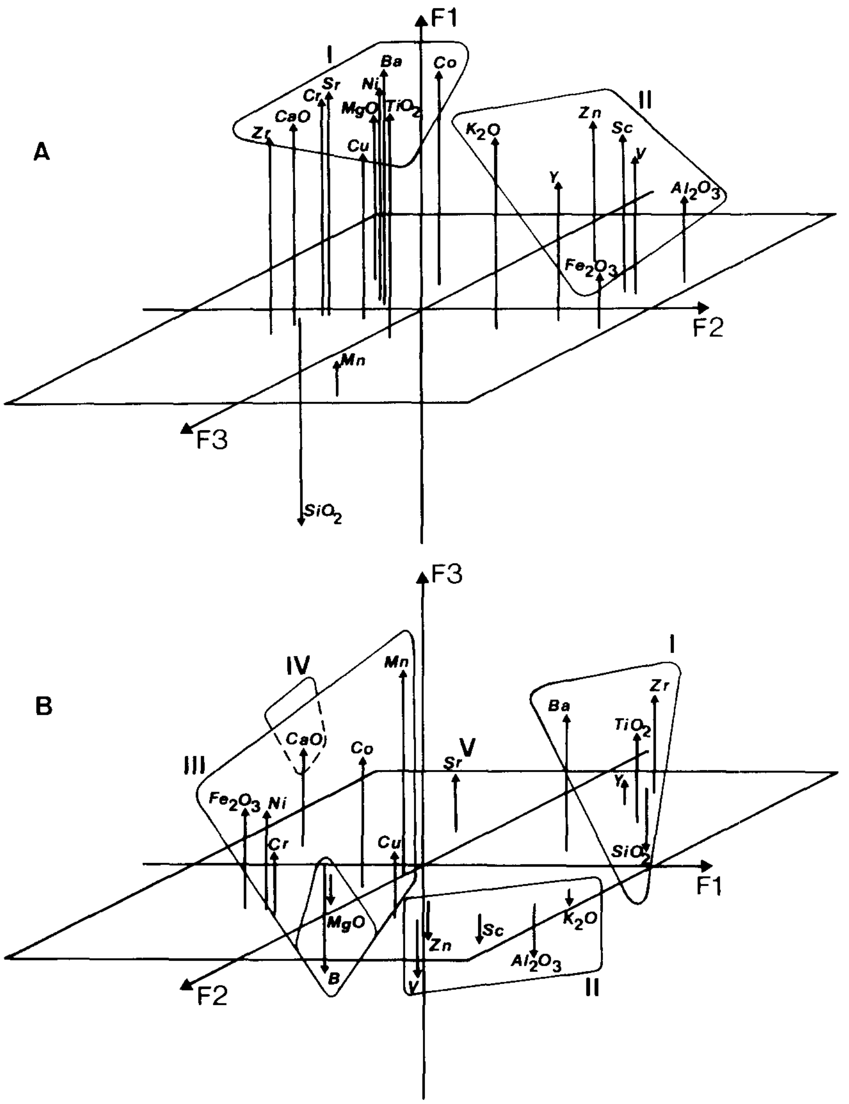

Fig. 3. Principal components analysis performed on: (A) parent rocks; and (B) <2-μm fraction of the sediment. Three-dimensional plotting of the elements.

trast in quartz contents between the basic volcanic facies (verites) and the more acidic metamorphic rocks. The elements with positive *F*1 are divided into two units by factor *F*2: Mg, Ca, Ti, Sr, Ba, Cr, Ni, Co, Cu and Zr, with negative *F*2-values, are designated as group I (Fig. 3A); and Al, Fe, K, V, Sc, Zn and Y, with positive *F*2-values, are designated as group II (Fig. 3A). The *F*3 factor introduces slight differences, especially for the positive *F*2 group; K, Y and Fe have positive *F*3-values; Al, V, Sc and Zn have negative *F*3-values. The *F*3 factor represents mainly a strong positive correlation with Mn. The position of the elements, interpreted with the aid of PCA and with the samples distributed in the space of the three first factors, shows two main groups; group I with elements characteristic of the volcanic rocks, and group II with elements characteristic of the metamorphic rocks.

For the sedimentary rocks (Fig. 3B) the positions of the elements in PCA were also determined by the minerals wherein they are mainly located. Five groups have been distinguished:

Group I, with Ba, Ti, Zr, Y and Si, linked with feldspars, quartz and heavy minerals, which are inherited minerals, shows positive *F*1, *F*3, and negative *F*2 factors;

Group II, with Al, K, Sc, V and Zn, related to inherited clays, illite–muscovites and kaolinites, and formed under weathering processes, displays positive *F*1, *F*2, and negative *F*3 factors;

Group III, with Fe, Ni, Co, Cr, Mn, Mg and B linked with smectite, interstratified illite–smectite (I–S), and palygorskites which are transformed or neoformed in the depositional environment, shows negative *F*1 and positive *F*2 factors. The negative *F*3 factor differentiates Mg and B from the other elements. Mg and B are good indicators of the sedimentary environments;

Group IV, with Ca, represents essentially the carbonates and the gypsum, which are also characteristic of the sedimentary environment; this group has negative *F*1 and *F*2, but positive *F*3 factors;

Group V, with Sr half way between the feldspars (Ba) and the carbonates and gypsum (Ca), shows negative *F*1, *F*2, and positive *F*3 factors.

These results can be summarized as follows. Positive *F*1-values characterize the heritage and negative *F*1-values characterize the remobilizations. Elements linked with the clay minerals have positive *F*2 and those linked with the non-clayey minerals (i.e. quartz, carbonates, gypsum) have negative *F*2.

4.4. Relationship between the parent rocks and the sediments

The influence of the parent-rock chemistry on the sediments was determined by an automatic sample classification called HAC, which regroups the sediment samples with those of the parent rocks. As part of the clay minerals of the sediments which were formed by weathering, this procedure is justified by the results of Mosser (1980) and Mosser et al. (1991), which show that clays preserve the geochemical fingerprint of the parent rocks from which they are formed. The classification was performed with trace elements selected according to the following two criteria:

(1) elements representative of the clay fraction (in sediments PCA, elements with positive *F*2);

(2) elements that are the most representative of the parent rocks (in parent rocks PCA, elements with negative *F*2-values for the volcanic rocks and positive *F*2-values for the metamorphic rocks).

The selected trace elements used for HAC analysis are thus: Sr, Ni, Cr, Cu, Co, V, Sc and Zn. The samples are regrouped into eight major classes by HAC analysis. Classes *1*, *2* and *7* contain almost exclusively parent-rock samples, the sediments being regrouped into the five other classes (Fig. 4).

Class *1* contains all the volcanic rocks together with one sediment sample from the section at Cuevas de Almanzora (CUA*16*). Class *2* corresponds to the schists from south of Garrapancho Hill, whereas in class *7* are only the schists from the north of the basin.

The other classes contain the <2-μm fraction from the sediments. Their distribution over the classes is essentially a function of their geographic position (Fig. 2). The stratigraphic po-

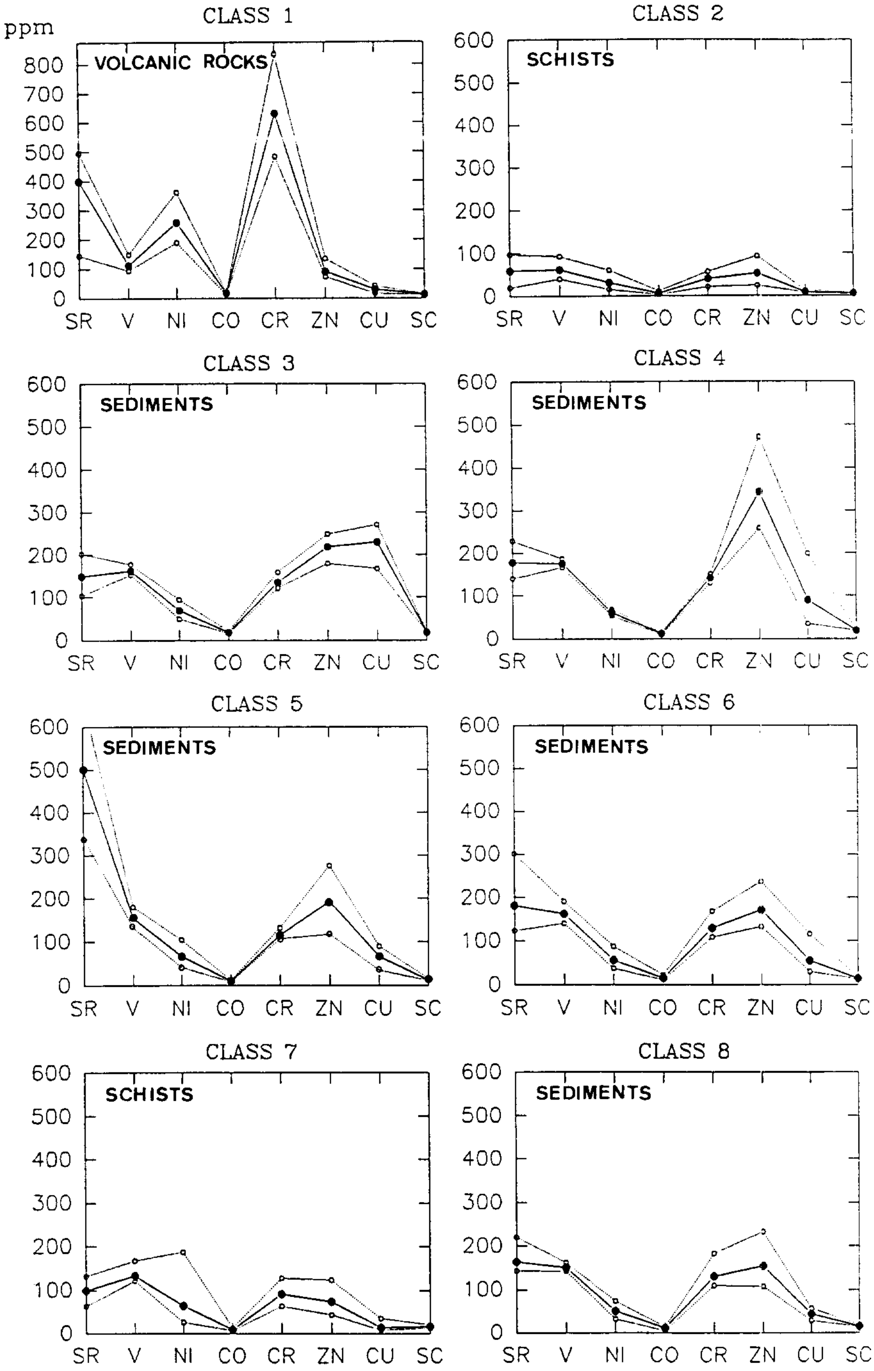

Fig. 4. Mean, maxima and minima for Sr, V, Ni, Co, Cr, Zn, Cu and Sc of the eight HAC groups.

sition of the samples introduces only small differences in the manner in which the samples are regrouped. Class *3* contains samples from section GP exclusively. Classes *6* and *8* are dominated by samples from the northern sections of the basin (CV and CUA). Samples from class *5*, except GP*6*, come from sections CJ and GR situated south of GP. Class *4*, finally, contains the samples from the top of sections CJ and CV.

HAC results show that, except for one sample in class *1*, there are no sediment samples grouped with parent-rock samples. Therefore, we can conclude that the influence of the sedimentary environment modifies the geochemical composition of the samples. Nevertheless, relationships between the parent rocks and the sediments can be found by comparing the mean of each element of the HAC classes containing only sediment samples with those of the HAC classes containing the different parent rocks. For this purpose geochemical profiles of sample groups were represented by the mean, maximum and minimum values of the selected elements (Fig. 4).

The volcanic rocks (class *1*) are clearly distinct from the metamorphic ones (classes *2* and *7*). Nearly all the elements, and in particular Sr, Ni and Cr, are in greater amounts in class *1*. Patterns in the two schist groups, classes *2* and *7*, resemble each other, and only Cr is present in significantly greater amounts in class *7* (schists from the northern part of the basin).

For the sediments (classes *3–6* and *8*), most of the mean values are very similar (Fig. 4), and present close analogies with those of the metamorphic rocks (classes *2* and *7*). However, each sediment class presents specific characteristics. The dispersion of values for both Sr and Cu differentiates class *6* from class *8*. For class *3* the Cu amounts are ~200 ppm higher than in classes *5*, *6* and *8*, whereas the Zn values are ~200 ppm lower than in class *4* and the Sr values ~350 ppm lower than in class *5*.

The high Sr values of class-*5* samples (GP*6*, CJ*1*, -*3*, -*7* and GR*7*) can be linked to the high Sr values (400 ppm) of the "verites". Outcrops of weathered "verites" are very close to the location of these samples which could so be considered as volcanic weathering products transported to the sedimentary basin. In this case, according to Mosser (1980), we should also have nearly the same high Cr and Ni amounts for class *5* as for the volcanic rocks (class *1*), which is however not the case here. A better explanation argues for a relation between the samples of class *5* and the "verites", only through the solutions which weathered the volcanics. In fact, Mosser (1980) noticed that during the weathering process, Cr and Ni of the basic rocks were conserved by the weathering clays, whereas Sr was depleted in these minerals relative to the parent rocks and was partly exported into solution. It can be concluded that for the Vera Basin only the dissolved phase transported by the fluids issuing from the weathering mantle of the "verites" contributed to the geochemical signature of the samples in class *5*, which were collected on the eastern side of these volcanic outcrops, and very close to them.

Class *1* (volcanic rocks) contains one <2-μm fraction (CUA*16*) from the CUA section. This fraction can be considered as a weathering clay derived from volcanic rocks rich in Cr (484 ppm) and Ni (292 ppm), but depleted in Sr (145 ppm for CUA*16* vs. a mean content of 400 ppm for the volcanic rocks).

The higher levels of Cu for class *3* (230 ppm) and Zn for class *4* (340 ppm), compared with Cu (50 ppm) and Zn (150 ppm) in classes *6* and *8*, cannot be explained as an inheritance from the parent rocks. Neither the volcanic rocks (30 ppm Cu, 90 ppm Zn) nor the metamorphic rocks (10 ppm Cu, 60 ppm Zn) are rich enough in these two elements for that. The only explanation which satisfies us, but cannot be proven is related with their bond with organic matter (Krauskopf, 1956; Gulbrandsen, 1966; Cook, 1972; Tardy, 1975). These elements, necessary for the life of planktonic microorganisms (Warren et al., 1952; Krauskopf, 1955), are returned after death and during early diagenesis into the environment and incorporated into the clay fraction.

4.5. Depositional environment

A major contrast can be noticed between sediment samples located in the northern and southern parts of the basin separated by the Garrapancho Hills. Zeolites and gypsum pebbles are present only in the olistostromic sediments of the southern part of the basin, while palygorskites (Mg clays) are present only in the clay fractions of the northern part of the basin where the smectites are also richer in Mg. B also distinguishes the north from the south; it is more concentrated and more variable in the south. We will consider successively B and Mg variations in the south and the north domains.

B in clay minerals is considered by many authors as a good marine fingerprint (Goldschmidt and Peters, 1932; Degens et al., 1958; Frederickson and Reynolds, 1960; Harder, 1970; Mosser, 1980) and Mg linked to palygorskites as a confining indicator (Millot 1964). Mg and B are considered as good indicators of the sedimentary environment and the variations of their contents were studied together on sedimentary logs (Fig. 5). B is here considered as a marine fingerprint, and Mg as a confining indicator.

In the south, from bottom to top, section CJ presents successively: sandy and illite-rich turbidites (140 ppm B in the <2-μm fractions) cut by a surface showing paleorelief; smectitic marls (<2-μm fraction B amounts decreasing from 280 to 226 ppm); an olistostrome (<2-μm fraction B amounts decreasing from 204 to 143 ppm); and finally, a marly level (166–198 ppm B in the <2-μm fraction). The sandy turbidites with low B concentrations represent coastal sediments reworked into the marine environment. After the erosive episode forming the paleorelief, marly marine sedimentation began. This was characterized by high B contents which decreased towards the top of the section, indicating progressively less marine conditions. After the olistostromic episode the sediments were again under marine influence. The evaporitic minerals, like gypsum present in the olistostromes, are interpreted as reworked material.

In section GR, also situated in the southern domain, there are only olistostromic episodes. B contents decrease from 182 to 144 ppm, which is interpreted as a decreasing marine influence similar to the olistostromic part of CJ.

The decrease of B amounts in these two southern sections is interpreted as a mixing effect of continental and marine sediments. This hypothesis is strengthened by the highly significative negative correlation at a probability level of 0.99, observed over the whole basin, between B and the elements characteristic of heavy minerals coming from the continent (B–Ti$=-0.32$; B–Ba$=-0.49$; B–Zr$=-0.35$). The presence of olistostromes suggests that continental material was eroded and included in the sediments during a transgressive episode. That idea is in good accord with the idea of a more open system in the south as suggested by the Mg concentrations which are lower in the south than in the north.

In the north, the three studied sections are essentially marly. CV and CUA begin with argillaceous marls, followed by marls with more clayey laminites, and end with more sandy marls. GP is exclusively formed with marls. These sedimentation characteristics in the north indicate calmer and more monotonous environments than in the south.

GP and CUA (Fig. 5) contain relatively low and more or less constant amounts of B (150–160 ppm), but MgO varies between 2% and 4%. The CV section has higher and more variable B concentrations (165–205 ppm), and MgO that varies between 3% and 4.3%. These three sections contain illite in similar amounts (~23–26%). Consequently, the greater B amounts in section CV can only be attributed to a more marine or saline character of these sediments. It must be noted that the B concentrations increase from bottom to top of the zone with laminites giving these latter an increasing marine or saline character, whereas the overlying and more sandy marls, with lower B values, present these features with less strength.

The increase in Mg is interpreted as the result of a confinement (or restriction) of the basin. Variations in Mg indicate variations in this confinement; variable degrees in confinement can range from marine environments like CV, to less

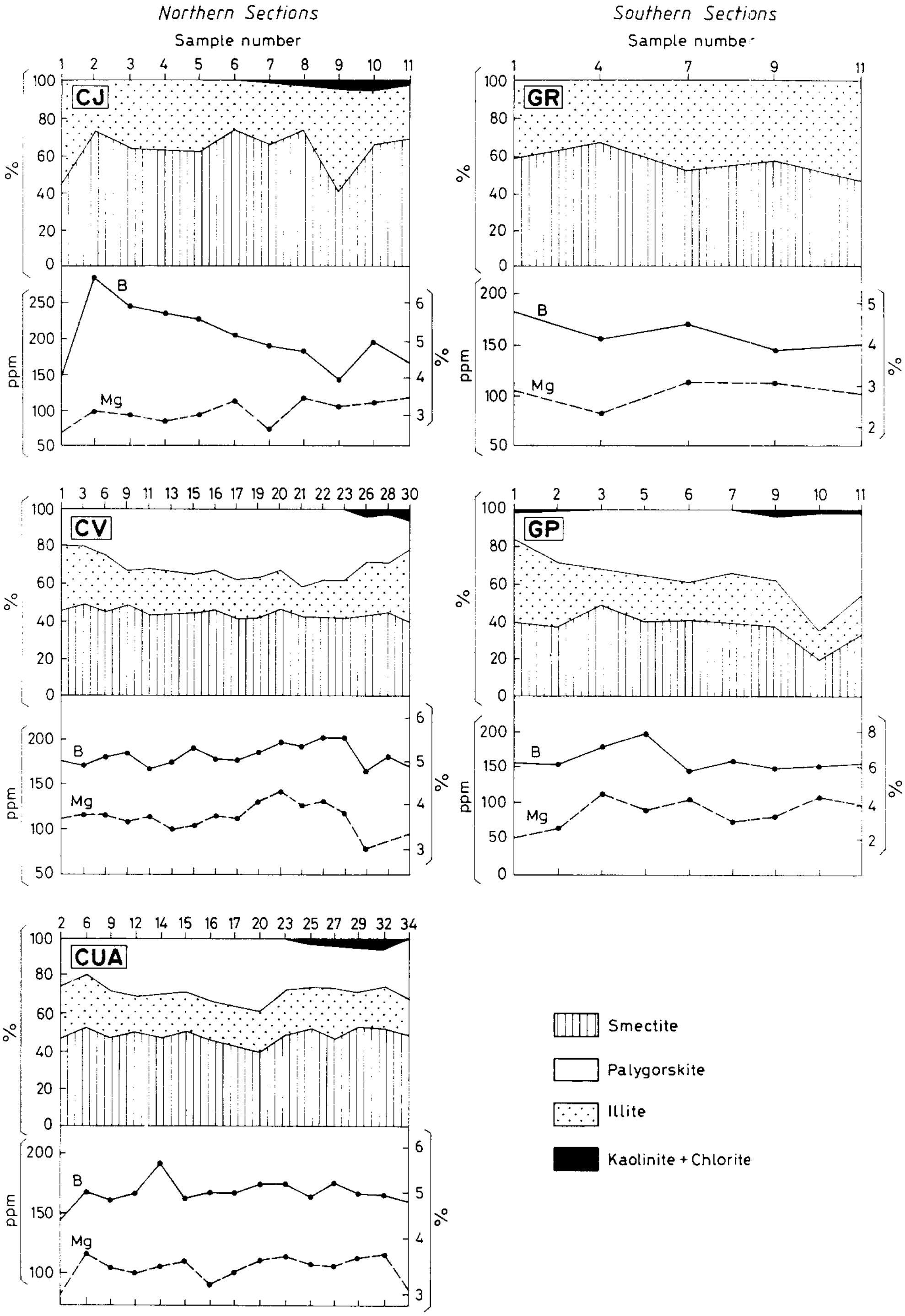

Fig. 5. Clay composition and MgO and B amounts of each sample in each studied section. Names of sections: *CJ*=Coscojar; *CV*=Canada de Vera; *CUA*=Cuevas de Almanzora; *GP*=Garrapancho; *GR*=Garrucha.

marine environments, as seen in CUA and GP samples.

Mg increases jointly with B in the laminite part of the CV section. This is indicative of the increasing confinement of a marine environment which becomes increasingly saline. Decreased Mg and B in the overlying marls are indicative of a less confined environment characterized by greater inputs of fresh water.

The characteristics of these northern sections suggest calm sedimentation with restricted water circulation, where confinement could allow the neoformation of palygorskites. This confinement operates in environments of varying salinity depending on the importance of freshwater inputs. It can be concluded that freshwater input was more important for GP and CUA, where B amounts are lower, than for CV. Nevertheless, we could not find any geochemical evidence for a completely freshwater environment where carophyte algae could develop. It seems more reasonable to postulate the possibility of an adaptation of these algae to a more marine environment, which would explain their "in situ" position in the CUA section, as described by Geerlings et al. (1980).

5. Conclusions

The statistical geochemical study shows that almost every sediment sample has a genetic relationship with the schists of the basement. The influence of the volcanic rocks is very localized and can be discerned by two geochemical features of the clays; either they are rich in Cr and Ni but depleted in Sr, or they have high Sr amounts and rather low Cr and Ni contents. The first ones are inherited from the volcanic weathering profiles, the second are sedimentary clays enriched in Sr derived from the weathering solutions which percolated through volcanic rocks.

The mineralogy and geochemistry of the <2-μm fractions of the sediments characterize the following two different sedimentary environments: the environment south of Garrapancho Hill (sections GR and CJ) and the environment north of Garrapancho Hill (GP, CV and CUA sections). Zeolites and abundant gypsum pebbles are only present in the south as reworked material in the olistostromes; in the north, smectites are richer in Mg, and palygorskites are present. The two environments are also geochemically different with respect to B and Mg. In the south, the higher B levels characterize a more marine environment, and the lower Mg levels are indicative of a less confined environment. In the north, the Mg concentrations are always greater, and thus suggest a more confined environment. It is also noted that this confinement occurred in environments with both low and high B concentrations.

These differences are good evidence for the existence of two different kinds of sedimentary environments, separated by a paleogeographical barrier situated near Garrapancho Hill. In the southern part of the basin, there was an energetic environment where rising sea level led to the formation of significant olistostromes. In the northern part of the basin, there were perimarine environments, which were calmer and more restricted, and where confinements took place with different salinities depending on the input of fresh water coming from the continent.

Although the controversy concerning the continuity of marine sedimentation in the north of the Vera Basin cannot be definitely solved, we have found no evidence of any geochemical freshwater environment in the northern region of the basin. It seems, on the contrary, that the sedimentary environment, although it may resemble saline lakes was compartmentalized perimarine, with variable degrees of salinity.

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