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Palaeontology, sedimentology, and biostratigraphy of a fossiliferous outcrop of the Early Miocene Querales Formation, Falcón Basin, Venezuela

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Abstract The top of the Querales Formation is well exposed at the Quebrada Corralito section, 17 m thick, in northern Venezuela. The section, dominated by siliciclastic accumulations of fine-grained sediments, preserves one cycle of transgressive–regressive phases of the deltaic environments facing the marine platform. An X-ray analysis revealed kaolinite as the main clay mineral. The age ranges from late Early Miocene to early Middle Miocene—zones N8 to N9, Late Burdigalian to Langhian. The section shows low biodiversity, including eleven macroinvertebrate taxa and two ichnotaxa; at its base, it contains mostly plant debris and amber from the continent, thus revealing a continental source near the littoral zone. Its middle portion preserves macroinvertebrates from the littoral zone, but also including the cephalopod *Aturia* sp., transported by a hydraulic flow to an area of greater depth; these macroinvertebrates are absent from overlying sections, at a time in which the basin was flooded most. The X-ray diffraction on six rock samples revealed mainly the presence of quartz with calcite, subordinated plagioclase and traces of potassium feldspar. Other minerals that compose this stratigraphic section are pyrite, dolomite and siderite, but they are disseminated in a siltstone. The section is dominated by mudstone sediments. The succession is kaolinite in the most pure fraction, and in lesser proportion smectite and illite; the stratified illite–smectite, chlorite and chlorite–smectite are present in low quantity. The mineralogical components of a molluscan valve were also examined, showing abundant pyrite, and moderate amounts of siderite and dolomite. In a part of the section, we recorded a rich assemblage of calcareous microfossils with foraminifers, nannofossils and marine ostracods. In the

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foraminiferal assemblage, 99 % correspond to planktonic forms. Most macroinvertebrates from benthonic assemblages suggest that they may have inhabited a near-shore marine environment, and sporadically experienced storm transport to deeper, shelf waters.

Keywords Calcareous microfossils · Fossil macroinvertebrates · Amber · Neogene · Urumaco · Falcón Basin

Introduction

The Falcón Basin in northwestern Venezuela is an area of importance for the oil industry (e.g. González de Juana 1937, 1938; Wheeler 1963; González de Juana et al. 1980; Díaz de Gamero 1989) and is also known for a sedimentary sequence extending for most of the Neogene that preserves a diverse extinct fauna of evolutionary and biogeographic significance (e.g. Jung 1965; Sánchez-Villagra et al. 2010; Smith et al. 2010). The study of marine microfossils and macroinvertebrates in this area is potentially relevant to address several issues, including changes of marine communities in the neotropics (Hendy 2013), the evolution of the Caribbean Sea (Sánchez-Villagra et al. 2010), and changes of the fluvial systems in the northern portion of the continent (e.g. Díaz de Gamero 1996; Johnson et al. 2009; Aguilera et al. 2013). The 'Urumaco Trough', in western Falcon State, is an area of accumulation of thousands of metres of sediments which document changes in continental and marine deposits going back to the Eocene. Changes in the sedimentary succession mainly occurred in connection with the uplift of the Andes and the interactions of the southern boundary of the Caribbean plate with the South American plate. Among the Neogene units is the Querales Formation, towards the base of the Urumaco sequence (Quiroz and Jaramillo 2010).

The Querales Formation (Hodson 1926), with the type locality in the southwest of Sabaneta, represents a geological unit from the "*surco de Urumaco*" which consists mainly of large accumulations of laminated black clay–shales and silty shales, interbedded siltstone and to a lesser extent, by thin layers of fine sandstones (Díaz de Gamero 1989; Hambalek et al. 1994). A few microfossils from the Querales Formation have been reported (Gamero and Díaz de Gamero 1963; Díaz de Gamero 1977; Lorente 1986; Wozniak and Wozniak 1987), but the formation has not been studied in depth thus far. Here, we present a detailed palaeontological, sedimentological, and biostratigraphical study from the uppermost Querales Formation.

The studied site of the Querales Formation is located close to the road between Urumaco and Pedregal towns (Fig. 1). It is a succession of 17 m of a siliciclastic sequence with fine sandstones, laminated siltstones and massive to laminated dark shales. The site preserves a fossil assemblage with a low diversity of microfossils, macroinvertebrates, and other plant materials and ichnofossils. Most fossils are found in facies of the lower segment of the section. This new locality of 100 m of exposure along the quarry is named "*Quebrada Corralito*", abbreviated 'QC' (Fig. 1). The complete Querales formation outcropping nearby along the Caduce river has a total thickness of 320 m (Quiroz and Jaramillo 2010). Here, we study the uppermost 17 m of the formation and we characterize sedimentologically and palaeontologically the deposits exposed at QC, and provide a biostratigraphic and palaeoenvironmental interpretation. These results are then discussed in the context of geological, palaeoenvironmental and palaeogeographical change in the Neogene Falcón Basin.

Geological framework

Querales Formation

The Querales Formation was originally defined by Hodson (1926, p. 174) as "Querales Shales", in Quebrada Querales, western tributary of Mitare River, Southwest of Sabaneta town, Falcón State. There have been nomenclatural and stratigraphical disagreements about the Querales Formation. Several authors include this unit as a lower portion of the Socorro Formation (Senn 1935; Liddle 1946; Gamero and Díaz de Gamero 1963). The top of the Querales Formation presents a transitional change into the Socorro Formation. Stainforth (1962) sub-divided the Querales Formation into two members: the lower Las Pilas Member, mainly composed of grey shales that crop-out in western Falcón Basin; and the upper Las Lomas Member, mainly composed by sandstones that crop-out in north eastern Falcón Basin. According to Díaz de Gamero et al. (1988) and Díaz de Gamero (1989), the Querales Formation extends all over the northern part of Falcón State and it is equivalent to the Las Pilas Member of Stainforth (1962). It is composed of more than 90 % dark-coloured shales with intercalations of fine-grained sandstones in packages up to 4 m thick, intensely burrowed, sparse and thin marlstone and limestone levels with mollusc shells. The shales become thicker upwards in and they yield concretions, ferruginous nodules and micro- and macrofossils. The one to four-metre-thick, fine-grained sandstones are locally silty and occasionally calcareous. They also show high degree of bioturbation that obliterates all previous sedimentary structures.

An earliest Middle Miocene age has been suggested for the Querales Formation (Wheeler 1963; González de Juana

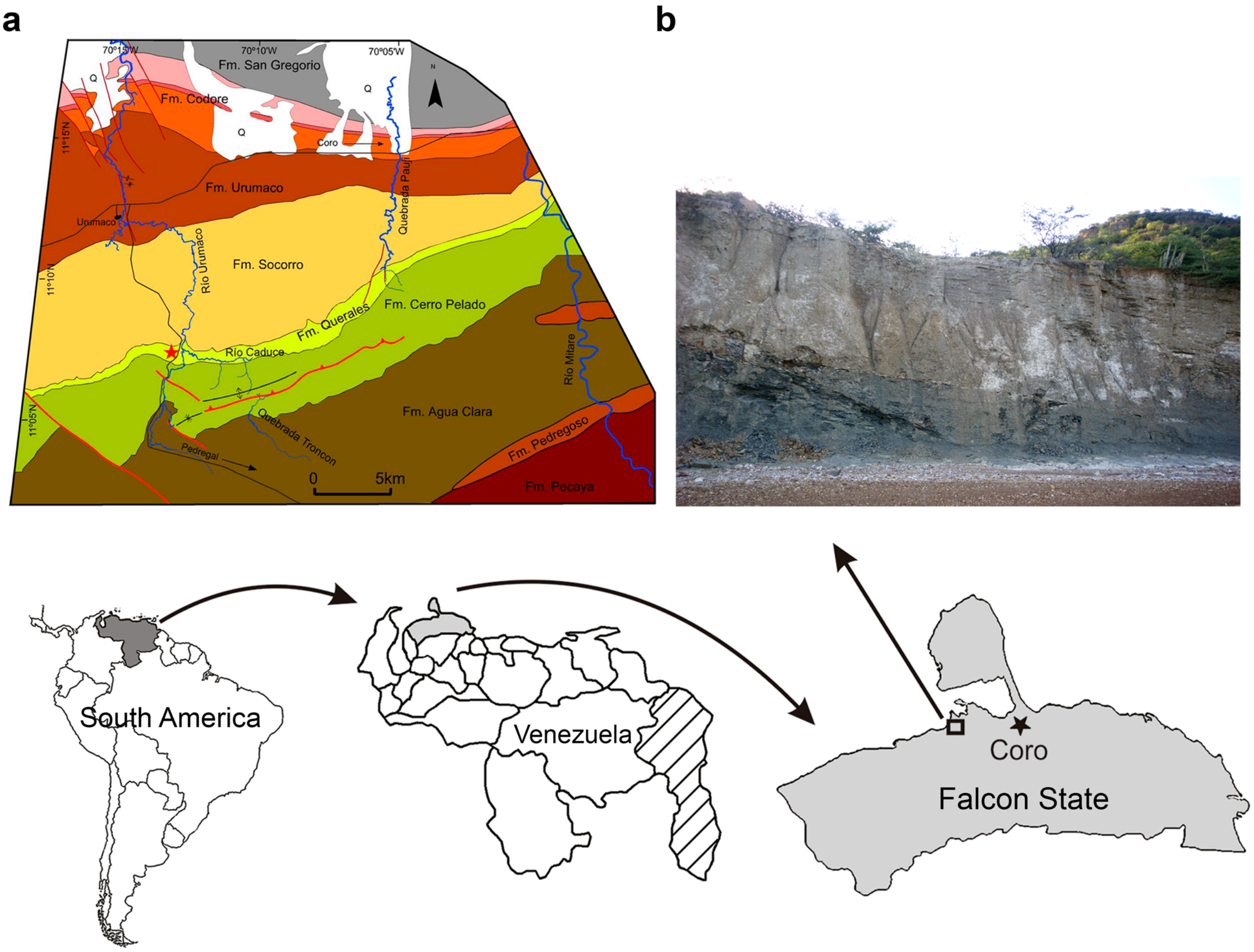


Fig. 1 **a** Geographical setting of “Quebrada Corralito” (QC) quarry of the Querales Formation, Falcon Basin, northwestern Venezuela. Examined site is indicated with a *star*; *GPS* 11°07.180 N–70°13.092 W. **b** General view of the outcrop analysed. Geologic map after Quiroz and Jaramillo (2010)

et al. 1980; perhaps, even latest Early Miocene, Díaz de Gamero 1989). Wheeler (1963) stated that the unit preserves the transgressive phase where deep marine sediments deposited in the western Falcón Basin. Díaz de Gamero (1989) hypothesized fluvio-deltaic to deltaic–marine conditions, while Quiroz and Jaramillo (2010) suggest shallow-marine, open sea conditions, typical of a prodeltaic/offshore-shelf environment. The deposits of the Querales Formation and those of the Cantaure Formation (exposed in the Paraguaná Peninsula, Jung 1965), may be partly correlatable and/or laterally equivalent (Hunter and Bartok 1974; Díaz de Gamero 1989).

Palaeontology of Querales Formation

Lorente (1986) studied palynomorphs from the Querales Formation and reported abundant *Polypodiisporites usmensis*, *Polypodiisporites* spp., and *Mauritiidites franciscoi*, and sparse occurrences of *Malvacipolloides maristellae*, *Retitricolporites*? *irregularis*, and *Psilamonocolpites medius.* Díaz de Gamero et al. (1988) recovered the planktonic foraminifers *Globorotalia praemenardii*, *G. foshi peripheroronda*, *G. continuosa*, *Orbulina* spp. among an abundant and highly diverse assemblage, bearing also *Praeorbulina* sp., *Globigerinoides* sp., *Globigerina* sp. and *Globoquadrina* sp. They also recorded some benthonic foraminifers and the calcareous nannofossils *Coccolithus pelagicus*, *Discoaster* spp., *Helicosphaera ampliaperta*, *Reticulofenestra* spp. and *Sphenolithus heteromorphus*.

There is extensive illustrated bibliographical information on Early Neogene molluscs in northwestern Venezuela and adjacent areas (e.g. Rutsch 1930, 1934; Senn 1935; González de Juana 1937; Miller and Thompson 1937; Ingram 1947; Weisbord 1962, 1964a, b; Jung 1965, 1966a, b; Gibson-Smith and Gibson-Smith 1974, 1983; Wesselingh et al. 2006; Landau and Marques da Silva 2010;

Hendy et al. 2015), but hardly any for the Querales Formation, in which only the presence of molluscs has been reported. Hodson (1926) reported turritelids from this stratigraphic unit (cf. also Hodson et al. 1927; Hodson and Hodson 1931). Quiroz and Jaramillo (2010) recognized the presence of ichnofossils in the sandstone beds at the top of the sequences, including *Thalassinoides* and *Planolites*.

Materials and methods

We conducted sedimentological and palaeontological analyses of a detailed profile scale 1:25 at the "Quebrada Corralito" (QC) section, GPS: 11°07.180°N–70°13.092 W. We collected six fresh-rock samples for X-ray and microfossil analysis (Fig. 2).

For the sedimentological analysis, X-ray diffraction (XRD) was carried out on fine screen-washed sample material (<20 μm), measured with a PANalytical X'Pert PRO diffractometer, with Cu lamp ($k = 1.5403$ Å) operated at 40 mÅ and 40 kV at the Centro de Investigaciones Geológicas (CIG). The samples were measured from 2° to 40° 2, with a scan speed of 0.04°/s and a time per step of 0.50 s.

For calcareous microfossil analysis (foraminifera and ostracods), 0.2 kg of rock was smashed on an iron mortar, set to boiling point in a jar with tap water and 20 ml of hydrogen peroxide at 100 % volume, and then washed on a 64 μm sieve. Almost 99 % of the original rock was lost after washing it, and the remaining was picked under a stereo microscope. The recovered foraminifers are plotted in a Range Chart (Table 1). Planktonic foraminifers were photographed under the SEM of the Electron Microscopy Service of the Museo de La Plata, Argentina.

Calcareous nannofossil samples were prepared for study in a petrographic microscope with polarized light at a magnification of 1200×, using the standard gravity settling technique of Bramlette and Sullivan (1961). Some drops of Sodium-hexametaphosphate were added to the jar, so the clays could be deflocculated. Different time intervals (2, 10 and 45 min) of sediment deposition in the jar were controlled to concentrate the nannofossil content. Their relative abundances are plotted in a Range Chart (Table 1).

Macroinvertebrates were studied under light microscope and photographed using a digital camera. Measurements were taken according to Stanley (1970) using 0–150 mm digital calliper. Abbreviations used are L = length; H = height; W = width.

Abbreviations used in the text are: AMU-PI/MF/PB (AMU = Alcaldía del Municipio de Urumaco, PI = Colección de Paleontología Invertebrados; MF = Colección de Micropaleontología and PB = Colección Paleobotánica) Museo Paleontológico de Urumaco, Falcón State, República Bolivariana de Venezuela. NMB (Naturhistorisches Museum Basel), Switzerland.

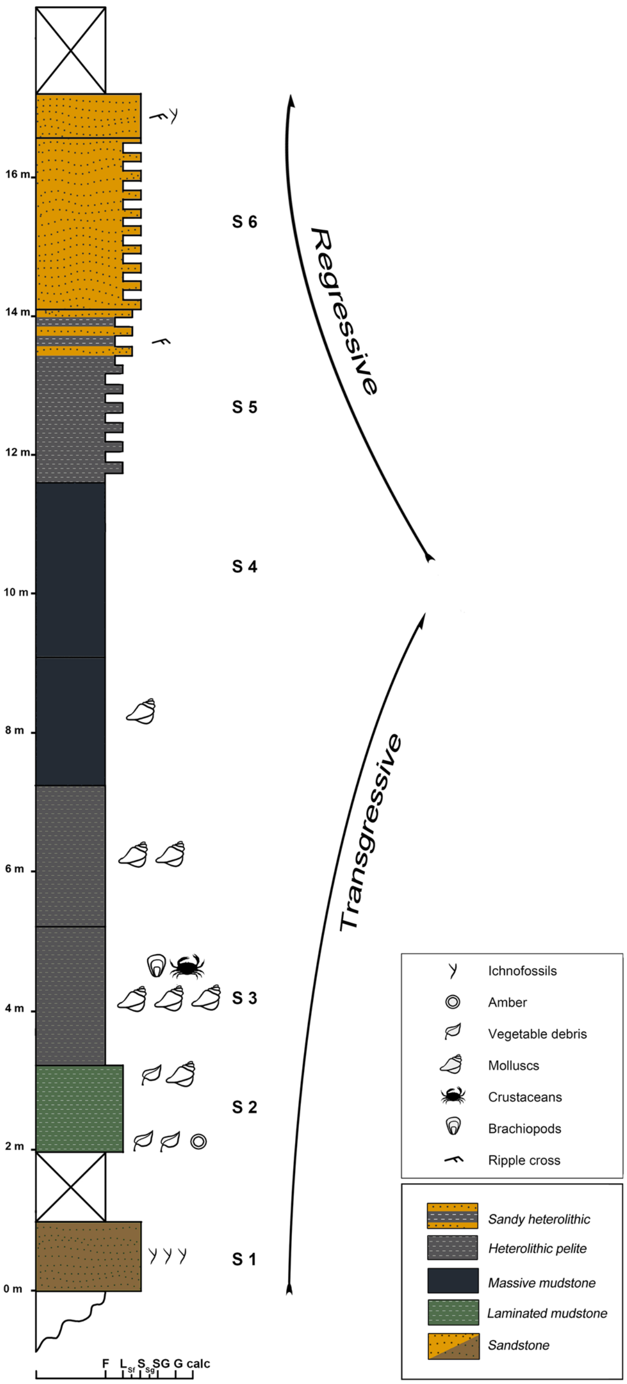


Fig. 2 Section logged in (QC) and stratigraphic location of the samples used for analysis of x-ray and microfossils, the levels with macrofossils are indicated with *drawings in the column*, and overall transgressive/regressive trend, denoted by *arrows*

Table 1 Range charts for foraminifers, calcareous nannoplankton and ostracod families at Quebrada Corralito quarry

Sample	Abundance	Planktonic							Benthonic	
		Globigerina praebulloides	*Globorotalia archaeomenardi*	*Praeorbulina glomerosa*	*Globoquadrina dehiscens*	*Globigerinoides trilobus trilobus*	*Globigerinoides trilobus immaturus*	*Globigerinoides obliquus obliquus*	*Rosalina californica*	Unidentified agglutinated
S6	Barren									R
S5	R									F
S4	F									F
S3	V	R	R	V	C	V	V	F	F	
S2	Barren									
S1	R									R

Sample	Abundance	*Calcidiscus leptoporus*	*Catinaster calyculus*	*Coccolithus pelagicus*	*Discoaster deflandrei*	*Discoaster exilis*	*Helicosphaera ampliaperta*	*Helicosphaera obliqua*	*Scyphos-phaera apsteinii*	*Sphenolithus moriformis*	*Tho-racosphaera heimii*	*Tri-quetrorhabdus rugosus*
S6	Barren											
S5	Barren											
S4	Barren											
S3	R	R	R	R	R	R	R	R	R	R	R	R
S2	Barren											
S1	Barren											

R rare, *F* frequent, *C* common, *A* abundant, *V* very abundant

Results

Sedimentology

The sediments of the QC are dominated by mudstones and blue–black shales, with low levels of highly bioturbated sandstones arranged in the base and the top of the section. These beds show massive to laminated levels with macroinvertebrates, microfossils and plant debris, with a layer containing small nodules of amber (Fig. 2). The QC section has a thickness of 17 m, and it is dominated by siliciclastic materials.

To better characterize the sedimentology and palaeontology of the studied section, we defined six lithofacies within it (Fig. 3; Table 2). The top of the section is covered by vegetation.

Rx analysis of the sediments

The X-ray diffraction provided information on lithological composition. This analysis was conducted on six rock samples (S) from the stratigraphic column representing the six facies described above (Fig. 2). The diffractogram of total rock (Table 3a) revealed mainly the presence of quartz (Qz) with calcite (Ca), subordinated plagioclase (Pl) and traces of potassium feldspar (Fsp). Other minerals that compose this stratigraphic section are the pyrite (Py), dolomite (D) and siderite (S), but they are disseminated in a siltstone.

The section is dominated by mudstone sediments; the X-ray analysis indicated that the main clay mineral is kaolinite (Table 3b). The succession is kaolinite (K) in the most pure fraction, and in lesser proportion smectite (Sm) and illite (I), the stratified illite–smectite (IS), chlorite (C) and chlorite–smectite (CS) are present in low quantity. The mineralogical component of a molluscan valve was also examined, showing abundant pyrite, and moderate amounts of siderite and dolomite.

Calcareous microfossils

Samples S2 and S6 are barren of microfossils. In samples S1, S4 and S5 only rare to few, poorly preserved, agglutinated foraminifera of the genus *Ammobaculites* were recovered. Sample S3, in contrast, yielded a rich assemblage of calcareous microfossils where foraminifers, calcareous nannofossils and marine ostracods were recovered.

Regarding the very abundant foraminifera assemblage, 99 % correspond to planktonic forms. The preservation varies from very good to poor, with frequent pyritization. This assemblage [AMU-MF-002] is composed of the planktonic species *Globigerina praebulloides*, *Globigerinoides obliquus obliquus*, *Globigerinoides trilobus immaturus*, *Globigerinoides trilobus trilobus*, *Globoquadrina dehiscens*, *Globorotalia archaeomenardi*, *Praeorbulina glomerosa*, and the benthonic *Rosalina californica* (Fig. 4; Table 1). The marine ostracods are represented by five species of the Cytherellidae and Cytheridae [AMU-MF-004].

Fig. 3 a Massive mudstone (Fm), showing the conchoidal and ▶ irregular fracture of the massive material; **b** Laminated and bioclastic mudstone (Fl), the *arrow* indicates the observed parallel lamination; **c** Laminated mudstone with plant debris (Ll), showing lamination and fragmentation; **d** Heterolithic lutite (pelite) (Htp); **e** Heterolithic facies (Hta), sandstones with trough cross-bedding, and thin levels of mudstones interbedded in strata thickening upwards; **f** Sandstone (Sm), amalgamated sandstone levels with signs of bioturbation (*arrowed*)

The calcareous nannofossil assemblage [AMU-MF-001] is of very low abundance (0.026 specimens per field of view) and the specimens have strong signs of etching and overgrowth. In some cases, it was impossible to determine them at species level. However, the assemblage has a high biodiversity index, due to the recognition of 19 species that are represented in almost the same relative abundance (Fig. 5; Table 1). These are the heterococcoliths *Calcidiscus leptoporus*, *Coccolithus miopelagicus*, *C. pelagicus*, *Helicosphaera ampliaperta*, *H. obliqua*, *Reticulofenestra haqii*, *R. pseudoumbilicus*, the nannoliths *Discoaster deflandrei*, *D. druggii*, *D. exilis*, *D. formosus*, *D. sanmiguelensis*, *Discoaster* sp. indet., cf. *Catinaster calyculus*, *Scyphosphaera apsteinii*, *Sphenolithus heteromorphus*, *S. moriformis*, *Triquetrorhabdulus rugosus*, and the thoracospherid *Thoracosphaera heimii* (Electronic Supplementary Material 1).

Fossil macroinvertebrates

Three layers containing macroinvertebrates were recognized at the QC (Fig. 2). In the lower one (S2), a low-diversity association of molluscs, crab fragments and one brachiopod was recovered; whereas in the upper layers, the association was composed only by sparse bivalves and gastropods. In the three layers, specimens are enclosed in a massive matrix, with complete valves and in some cases in butterfly position. In almost all cases, the fossil macroinvertebrates are represented by complete specimens that lack signals of interactions with epibiotic organisms (bioeroders and/or encrusters) and without any marked taphonomical alteration. The specimens are usually well preserved and articulated, being mostly casts and moulds, and occasionally presenting pyrite-coated surfaces (S4).

We identified eleven molluscan taxa, after comparative work at the **NMB** collection: Bivalves, *Anadara* sp. [AMU-PI-001], *Trachycardium* sp. [AMU-PI-002], *Cyclinella* cf.

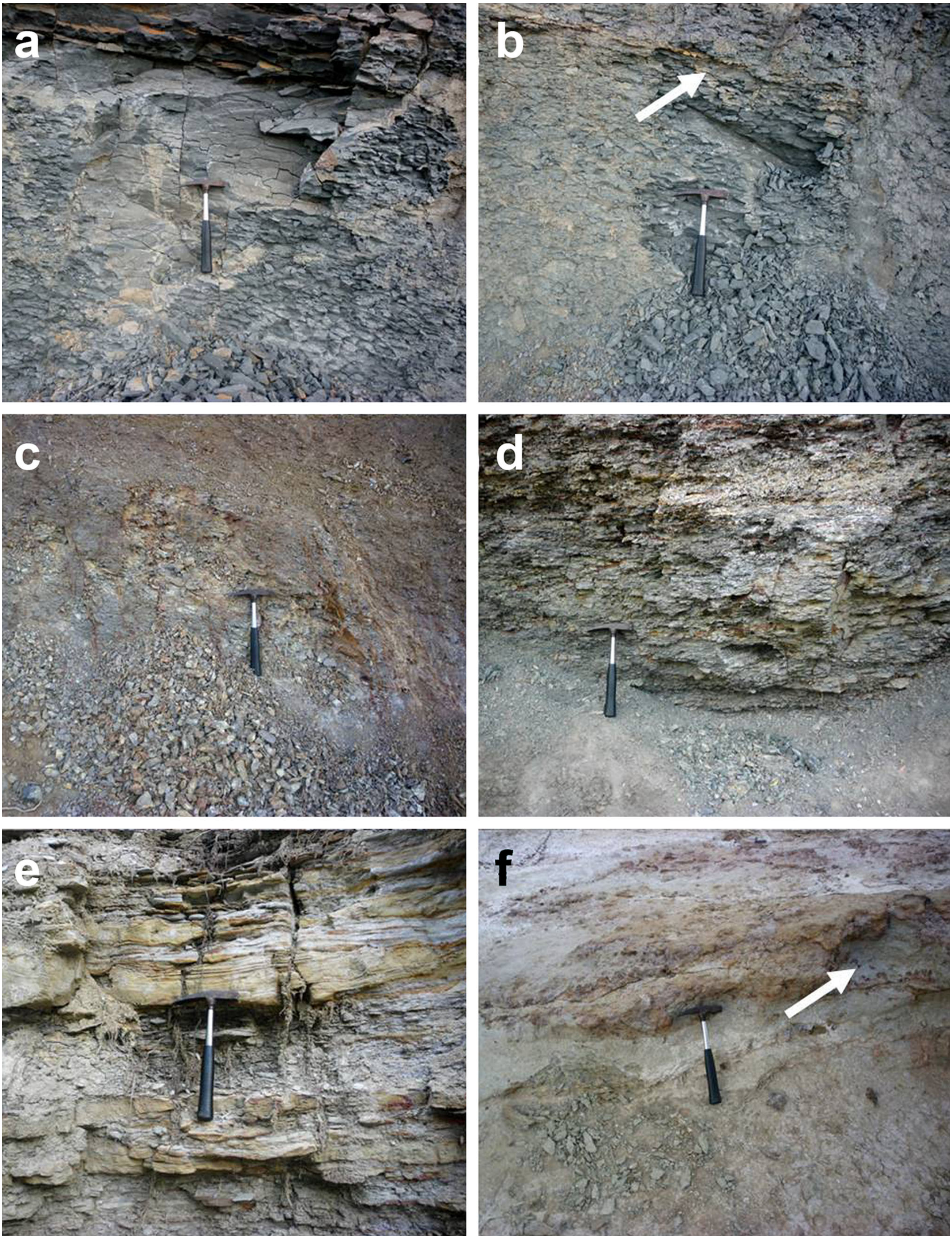

a
b
c
d
e
f

Table 2 Lithofacies at the "Quebrada Corralito" section of the Querales Formation

Facies	Lithology	Description	Bioturbation	Depositional interpretation
Fm	Massive mudstone	Black–blue colour. Pyrite disseminated widely; few bioclasts. *Aturia* sp. and few microfossils	Absent	Fine-grained material decantation. Low energy deposition dominated by low energy, in an anoxic environment. *Offshore* (inner to outer platform)
Fl	Laminated and bioclastic mudstone	Dark grey colour, abundant bioclasts, macroinvertebrates and microinvertebrates. Scarce presence of mudstone fraction. Transitional passage	Absent	Fine-grained material decantation and traction transport to a low energy environment which generated the accumulation of bioclasts. *Shoreface* to *Offshore* (inner platform)
Ll	Laminated mudstone with plant debris	Brown–green colour. Plant debris and amber nodules. Transitional passage	Absent	Deposition via decanting in low-mid energy environment. "*Shoreface*" environment
Htp	Heterolithic pelite	Dark grey colour, layered pelites alternate with thin layers of fine-grained sandstones and light-coloured limestones. Heterolithic levels are lenticular and are combined with flow ripple laminations. Inverse grading	Scarce	Decantation predominates over traction transport. *Offshore* transition to low *Shoreface*
Hta	Sandy heterolithic levels	Dark grey, layer laminated shales alternate with thin layers of fine and mid-grained sandstones, light yellow in colour, with trough cross-bedding. Flaser bedding, in which cross-laminated sand contains mud streaks. Strata thickening upwards	Scarce, small burrows of cf. *Skolithos* isp.	Tractive process predominates over decantation process. Action of orbital flows in subaqueous environments, Lower to middle *Shoreface*
Sm	Sandstone	Fine and mid-grained sandstones, brown–yellow in colour, with massive structure. Amalgamated sandstone levels with iron oxide specks	Abundant, *Thalassinoides* isp. and *Planolites* isp.	Tractive deposits of mid to high energy that lost their primary mechanical structure by synmixis and bioturbation process. Well-oxygenated substrate. High *Shoreface*

Table 3 (a) Mineral rock components for the six samples of the section "Quebrada Corralito". (b) Percentages (%) of clay minerals estimated for the samples representing the six facies of the "*Quebrada Corralito*"

S	Q	Fsp	Pl	Ca	D	S	Py	Ms
(a)								
6	VA	T	VR	VR	T	0	0	R
5	VA	T	VR	T	VR	0	T	R
4	VA	T	VR	T	VR	VR	VR	M
3	VA	T	R	VR	0	VR	VR	M
2	VA	T	R	VR	0	T	0	R
1	VA	T	VR	VR	0	0	0	VR

S	Sm	C	IS	CS	I	K
(b)						
6	20	5	15	T	10	50
5	20	5	10	T	25	40
4	15	5	10	T	25	45
3	25	T	10	0	25	40
2	15	T	10	0	30	45
1	30	T	10	T	10	50

Notice the abundance of Qz. Categories: *VA* very abundant (>50 %), *A* abundant (between 30 and 50 %), *M* moderate (between 15 and 30 %), *R* rare (between 5 and 15 %), *VR* very rare (between 1 and 5 %), *T* traces (<1 %). *Qz* quartz, *Fsp*: feldspar, *Pl* plagioclase, *Ca* calcite, *D* dolomite, *S* siderite, *Py* pyrite, *Ms* mudstone, *T* traces (<1 %). Notice the abundance of K, and the presence of I in the middle portion of the section. *Sm* smectite, *C* chlorite, *IS* illite–smectite, *CS* chlorite–smectite, *I* illite, *K* kaolinite

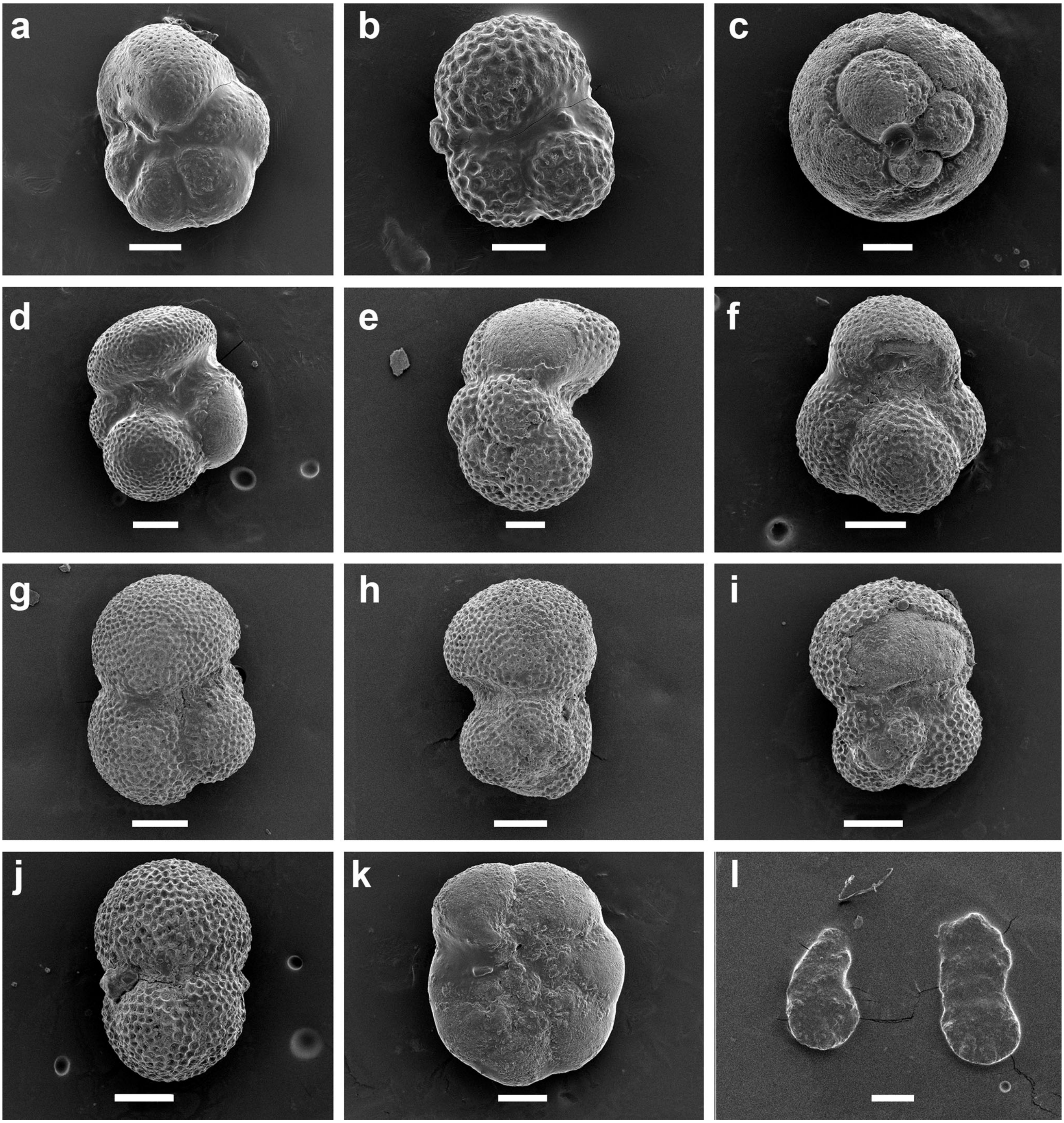


Fig. 4 Foraminifers recovered at Quebrada Corralito. (**a**–**k**, sample S3; **l**, sample S4). **a** *Globorotalia archaeomenardi* Bolli; **b**, *Globigerina praebulloides* Blow; **c,** *Praeorbulina glomerosa* (Blow); **d**, **e** *Globoquadrina dehiscens* (Chapman, Parr & Collins), apertural and side view; **f** *Globigerinoides obliquus obliquus* Bolli; **g**, **h** *Globigerinoides trilobus trilobus* (Reuss), apertural and side view; **i**, **j** *Globigerinoides trilobus immaturus* Bolli, spiral and side view; **k** *Rosalina californica* (Cushman); **l** *Ammobaculites* sp. *Scale bar* **a**, **b**, **e**, **k** = 50 μm; **c**, **d**, **f**, **g**, **h**, **i**, **j** = 100 μm; **l** = 200 μm

cyclica [AMU-PI-003]; *Psammacoma* cf. *falconensis* [AMU-PI-004], *Tellina* sp. [AMU-PI-005], Veneridae indet.1 [AMU-PI-006], Veneridae indet.2 [AMU-PI-007], the gastropods *'Turritella'* cf. *matarucana* [AMU-PI-008], *Oliva* sp. [AMU-PI-009], *Natica* sp. [AMU-PI-010] and one nautiloid fragment of *Aturia* sp. (see Klug and Etter 2012, Fig. 4.12; cf. also Miller and Thompson 1937, pls. 8–10; Jung 1966b, pls. 1–2). The other macroinvertebrates recovered correspond to small and fragmentary valves of the brachiopod *Glottidia* sp. [AMU-PI-011] (Fig. 6) and carapace and pincer fragments of crabs (Fig. 7) referred to the Plagusiidae, Callianassidae of the genus *Neocallichirus* and Calappidae (Electronic Supplementary Material).

Fossil plants

One layer (S2) containing plant debris was recorded in the lower section of the stratigraphic column (Fig. 2). In this layer, corresponding with facies Ll, there is a dense accumulation of non-identifiable and charcoalized plant debris. In this bed, we also found small nodules of amber of dark brown colouration, translucid and lacking visible organisms inside (Fig. 6). This record of amber from Venezuela is one of the few from this part of the world together with the reports from Colombia (only copal), Peru, and Brazil and the well-known Dominican Republic one (Antoine et al. 2006; Feist et al. 2007; Hinojosa-Díaz and Engel 2007; Pereira et al. 2009; Judson 2010). Karsten (1851) mentioned the finding of amber in the Falcón Basin, from an imprecise area and unknown Formation. Karsten (1851, p. 445) reported amber in a geologic formation with coal (‘Zur tertiären Formation gehören Paraguaná, der grösste Theil des nördlichen Coro, soweit es das Gebiet zwischen den älteren Inselbergen ausfüllt (eine Kohlenformation in der sich Bernstein findet’)). The second reference to amber, from the same publication, concerns La Mesa, close to Carora, Lara State, south of the Baragua River. He mentioned abundant fragments of amber, in different sizes, underlying a coal layer and also isolated in the sand of the river, and stated that there are excellent and well-preserved fragments of yellow and light-brown amber with wasps and bees embedded inside.

Fig. 5 Some calcareous nannofossils recovered at Quebrada Corralito. All specimens from sample S3. **a**, **b** *Coccolithus miopelagicus* Bukry, 1971, emend. Wise, 1973; **c** *Coccolithus pelagicus* (Wallich, 1877) Schiller, 1930; **d** *Reticulofenestra pseudoumbilicus* (Gartner, 1967) Gartner, 1969; **e** *Helicosphaera obliqua* Bramlette & Wilcoxon, 1967; **f–h** *Discoaster exilis* Martini & Bramlette, 1963; **i**, **j** *Discoaster formosus* Martini & Worsley, 1971; **k**, **l**, *Discoaster sanmiguelensis* Bukry, 1981; **m**, **n** *Discoaster druggii* Bramlette & Wilcoxon, 1967; **o**, **p** cf. *Catinaster calyculus* Martini & Bramlette, 1963; **q–s** *Sphenolithus heteromorphus* Deflandre, 1953; **t**, **u** *Sphenolithus moriformis* (Brönnimann & Stradner, 1960) Bramlette & Wilcoxon, 1967; **v** *Thoracosphaera heimii* (Lohmann, 1919) Kamptner, 1941; **w** *Watznaueria barnesae* (Black in Black & Barnes, 1959) Perch-Nielsen, 1968, Cretaceous reworked heterococcolith; **x** *Micrantholithus flos* Deflandre in Deflandre & Fert, 1954, Paleogene reworked nannolith. *Scale bar* 2 μm

Discussion

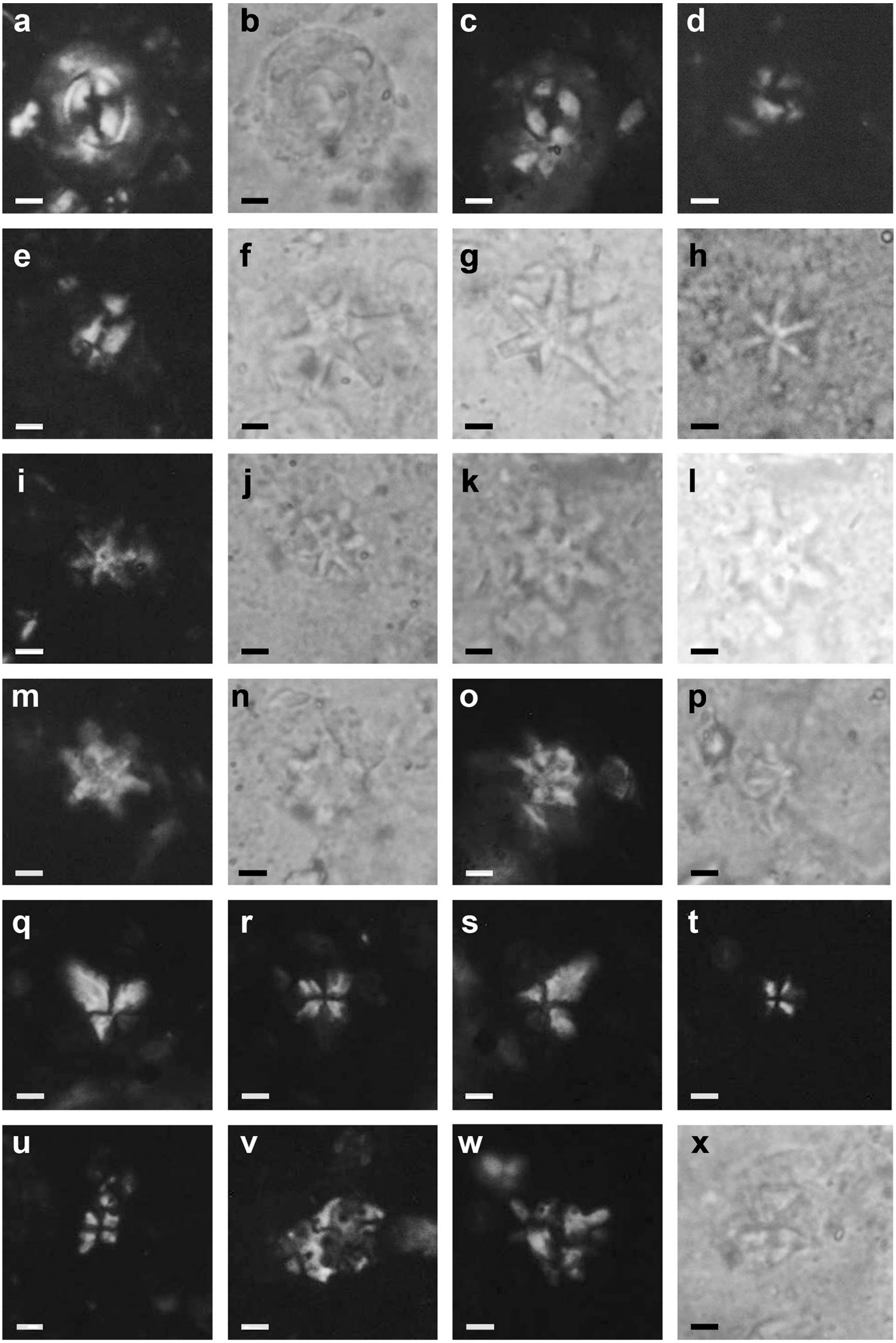
Sedimentology

In accordance to previous characterizations of the Querales Formation (Hodson 1926), the type section is dominated by siliciclastic accumulations of fine-grained sediments originated from a transgressive–regressive event. The Quebrada Corralito (QC) section represents a complete relative sea-level cycle, located at the top of the unit. The geographic and stratigraphic position of the QC section indicates that this is the last phase of accumulation of the Querales Formation in the area.

The QC section starts at the base with a prominent bed of massive sandstones (F-Sm) which were probably deposited in coastal areas with influence from waves (lower to middle shoreface). The ichnofossils *Thalassinoides* and *Planolites* indicate an environment of high productivity and with well-oxygenated sediments (Buatois and Mángano 2011). In these facies, we identified *Thalassinoides* isp. and *Planolites* isp. Above this psammitic layer, in a transitional passage, the laminated mudstone (F-Ll) preserves plant debris and nodules of amber; the latter having been transported by currents that originated in the continent and which entered a low-mid energy environment (shoreface). In this distal setting of low energy, the environment was little affected by water currents, as in deltaic fronts in which plant remains and resin accumulate (Grimaldi 1996).

This gradual change from a coastal environment to a relatively deeper one (shoreface to offshore) is reflected in the overlying facies (Fl and Fm), respectively. We recorded the largest concentration of macroinvertebrates of the section in Fl, that is characteristic of littoral environments, and in the fine-grained matrix of the massive layer we recorded few fossils of pelagic organisms. The fossils found in the upper levels of the section, together with the sedimentological and mineralogical features recorded, suggest that the studied section represents times of maximal flooding of the basin. This middle segment of the stratigraphic column is mostly non-fossiliferous, yielding only a fragmentary specimen of the nautiloid *Aturia* sp. These homogenous levels with little clastic components have been deposited mainly via decantation in the inner and outer platform (offshore). The geochemical analysis supports the hypothesis of accumulation via decantation in an inner platform, with the presence of pyrite in facies Fl and Fm (S3 and S4) and the replacement of the original shells of invertebrates. These facies were formed in a reductive environment, which facilitated the formation of ion sulphur characteristic of anoxic conditions in the sediment found below the line of compensation of calcium carbonate.

In the upper part of the section, the facies change gradually from (Fm) to (Htp) and (Hta). This gradual change is characterized by an increase in the grain size towards the top, all lacking organic remains. In this portion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of the section, the depositional conditions suggest that the process of lowering of the sea level (regression) was coupled with an increase of clastic materials and the presence of thin sandstone layers with trough cross-bedding, instead of laminated shales. The increase of transported material together with the decrease in deposition of sediments by decantation suggests the change from an offshore transition to low shoreface environment.

Calcareous microfossils

According to the recovered calcareous microfossils in the QC, it is possible to identify two different marine environments along the succession. The lower and upper levels (samples S1–S2 and S4–S6) represent shallow, marginal-marine environments, where planktonic foraminifera and calcareous nannofossils are absent, and only rare agglutinated benthonic foraminifera of the genus *Ammobaculites* were recorded (Fig. 4). The species of the genus *Ammobaculites* are infaunal detritivores that frequently dominate brackish marshes, lagoons and other marginal-marine temperate to tropical environments (Murray 1991, 2006).

The middle part of the succession (sample S3) is interpreted as an outer shelf marine environment (over 200 m deep) on the basis of the high proportion of planktonic foraminifera against benthonic ones, and the occurrence of a poorly preserved but diverse calcareous nannofossil assemblage. Pyrite granules and pyritization observed in some calcareous microfossil specimens, together with the strong dissolution that affected the poorly preserved calcareous nannofossil assemblage, suggest deep marine waters with very low energy and anoxic/dysoxic conditions near the sea floor. The ostracods, as the molluscs, were probably transported from coastal areas.

The calcareous microfossils also allowed to establish a reliable age for this locality on the basis of the assemblage recovered in sample S3. Both planktonic foraminifera and the calcareous nannofossils suggest a late Early Miocene to early Middle Miocene age. The most abundant species of planktonic foraminifera are those of the genus *Globigerinoides*, a widely observed characteristic of the planktonic foraminiferal assemblages that occur after the Oligocene/Miocene boundary (Bolli and Saunders 1985). On the basis of the biostratigraphic ranges of the planktonic foraminifers found in this section (Electronic Supplementary Material, Planktonic Foraminiferal Zones), the assemblage is interpreted to fall into the Zones N8–N9 of Berggren and van Couvering (1974). The recovered calcareous nannofossil assemblage is consistent with the planktonic foraminifer's age interpretation. The marker species *Helicosphaera ampliaperta*, *Discoaster exilis*, *Sphenolithus moriformis* and *Triquetrorhabdulus rugosus* suggest an assignation to the Zones CN3–CN4 of Okada and Bukry (1980) for the assemblage (Electronic Supplementary Material, Calcareous Nannofossil Zones). Díaz de Gamero et al. (1988) also interpreted the same age for the Querales Formation in its type area, based on a more diverse assemblage of planktonic foraminifera.

Fig. 6 Examples of the macroinvertebrate record and of amber from ▶ Quebrada Corralito, Querales Formation. Mollusc bivalves; **a** *Anadara* sp. [AMU-PI-001] (*left valve*); **b** *Trachycardium* sp. [AMU-PI-002] (*right valve*, internal mould); **c** *Cyclinella* cf. *cyclica* (Guppy, 1866) [AMU-PI-003] (*left valve*, internal mould); **d** *Psammacoma* cf. *falconensis* (H.Hodson, 1931) [AMU-PI-004] (*right valve*, steinkern); **e** *Tellina* sp. [AMU-PI-005] (*right valve*, steinkern); **f** Veneridae indet.1 [AMU-PI-006] (*left valve*, internal mould); **g** Veneridae indet.2 [AMU-PI-007] (*right valve*). Gastropods; **h** *'Turritella'* cf. *matarucana* F.Hodson, 1926 [AMU-PI-008] (steinkern with shell remains); **i** *Oliva* sp. [AMU-PI-009] (steinkern); **j** *Natica* sp. [AMU-PI-010] (steinkern with shell remains). Cephalopod; **k** *Aturia* sp (lateral view of broken phragmocone, suture partly visible). Linguliform brachiopod; **l** *Glottidia* sp. [AMU-PI-011] (pair of divergent internal septa just discernible through semi-translucent shell); **m** Amber nodule [AMU-PB-1]. *Scale bar* **l** = 0.5 cm; **a**, **e**, **i**, **j**, **k**, **m** = 1 cm; **b**, **c**, **d**, **f**, **g**, **h** = 2 cm

Macroinvertebrates

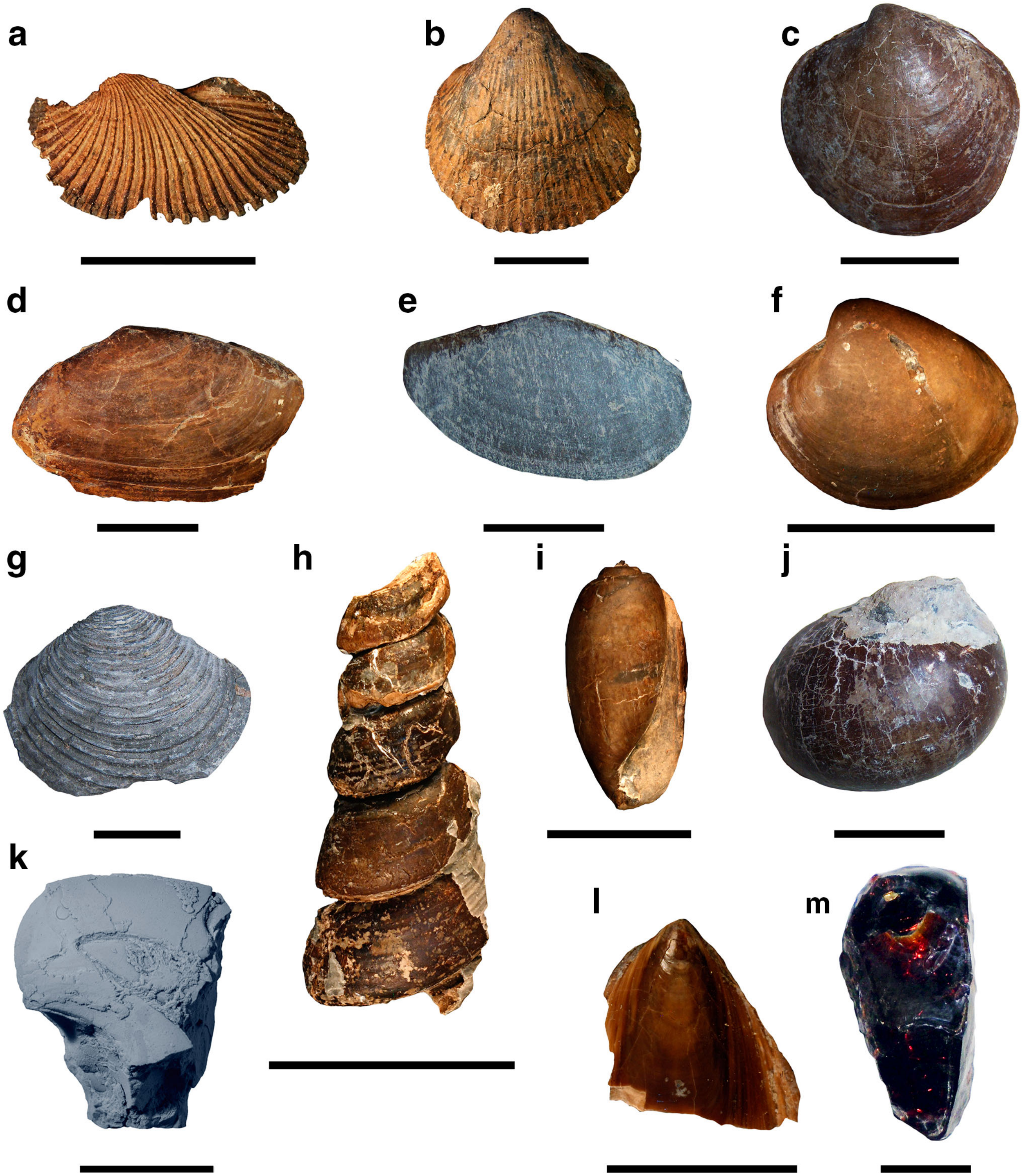
There is a low-diversity association of macroinvertebrates that yielded only eleven taxa and two ichnotaxa, corresponding mainly to a littoral marine fauna. The assemblage found in this site corresponds to a heterogeneous palaeoenvironment, with a mixture of species characterized by different ecological features, occurring in a chaotic arrangement in a small segment of the Quebrada Corralito section. Based on comparison with extant close relatives of the recorded taxa (Stanley 1970), the taxa represent different guilds (Aberhan 1994; Brenchley and Harper 1998 del Río et al. 2001; Lazo et al. 2005).

Endobenthonic: with shallow infaunal forms, including shallow-burrowing suspension feeders (*Glottidia* sp., *Trachycardium* sp., *Anadara* sp., *Cyclinella* cf. *cyclica*, Veneridae indet.1 and Veneridae indet.2); deep-burrowing suspension/detritus feeders (*Psammacoma* cf. *falconensis*, *Tellina* sp.); and deep-burrowing deposit feeders (Callianassidae).

Epibenthonic: including mobile carnivores (*Oliva* sp., *Natica* sp., Calappidae, and ?Plagusiidae), and a mobile epi-to semi-infaunal suspension/detritus feeder or browser ('*Turritella*' cf. *matarucana*; Allmon 1988).

Nekto-benthonic: with a single representative of scavengers (*Aturia* sp.).

The great majority of the macroinvertebrate taxa sampled were deposited in an environment untypical for the palaeoecology of the groups they represent. The sampled bivalves inhabit in near-shore (littoral) zones of warm seas with normal salinity, in areas with sandy and granular sediments, especially the species capable of burrowing



themselves relatively deep and which feed by filtering using their syphons. All the bivalves were preserved with their shells in external view, and in some cases, with both valves joined by the ligament in “butterfly” pattern, typical of a post-mortem deposition after a rapid and short-distance transportation from the original living area. The gastropods are also organisms that inhabit granular and soft sediments on the sea floor. The same is valid for the sampled crustaceans, especially the callianasid, which build deep gallery systems in sandy sediments, lining them

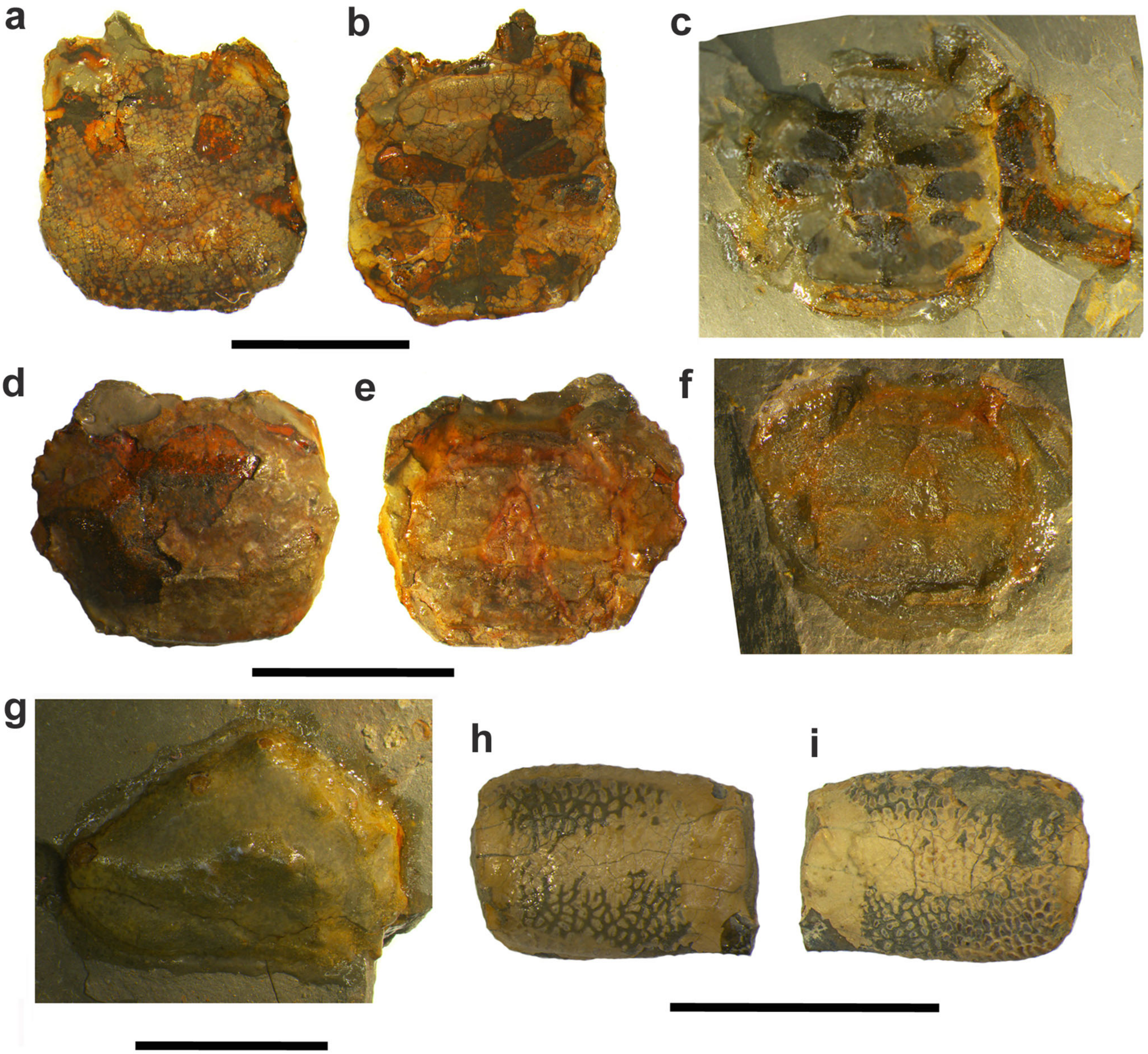


Fig. 7 Crustaceans from Quebrada Corralito, Querales Formation. Decapods; **a–f** ?Plagusiidae (**a** dorsal, **b** ventral, **c** in situ mould of carapace, **d** dorsal, **e** ventral, **f** in situ mould of carapace), **g** Calappidae in situ; **h–i** *Neocallichirus* (outer and inner lateral views of cheliped). *Scale bar* 1 cm

with mudstone pellets to avoid the collapse of the galleries due to movement and erosion produced by waves. Finding these fossils in a mudstone matrix suggests that they have been transported, with a change in the abundance and preservation of remains, which decreases from the Fl facies to the Fm facies, in which almost no macroinvertebrates have been recorded. Only the occurrence of *Aturia* sp. represents an organism which inhabited the area where the sediments were deposited, as this taxon had nekto-benthonic habits.

The fossil macroinvertebrates consist only of individual specimens, with no records of interactions with epibionts and bioeroders, most of the preserved forms being burrowers. This may be explained by sporadic and sudden storms, which resulted in scour and transport of bioclastic materials from the littoral zone to deeper areas of the marine platform. The evidence provided by scattered, disarticulated, very fragile, single valves of linguloid brachiopods is also compatible with a brief, storm-derived, transport from a shallower, subtropical, environmental setting although some extant species may inhabit up to greater, bathyal, depths (Emig et al. 1978; Emig 1986, 1997).

Interpretation of depositional environments

The fine-grained sediments of the Quebrada Corralito section resulted from a transgressive–regressive event in a deltaic system which came into contact with a carbonate platform and generated the resulting deposits. This combination of the two systems helps to explain the recorded mixture of fossil organisms and the differences between the upper and lower facies of the upper Querales Formation. The kind of preservation of both macroinvertebrates and microinvertebrates suggests that transport over long distances was not involved, as is clear, for example, in the case of the microfossils from S3. The deposition of sediments started in a deltaic system which faced a marine front, with the subsequent mixed accumulation of organisms. Plant debris and amber were transported from the continent and mixed with marine elements. The palaeontological and sedimentological changes recorded in the section relate to transgressive–regressive phases along it.

Conclusions

1. The studied section shares many features and overall the same kind of depositional environment with the type section of the Querales Formation.
2. Low faunal diversity is present in the section, the base of which mostly contains plant debris and amber from the continent, indicating a continental source near the littoral zone. Whereas the middle portion preserves macroinvertebrates from the littoral zone, transported by a hydraulic flow to an area of greater depth, macroinvertebrates are absent from overlying sections, at a time in which the basin was flooded most.
3. The age the of upper Querales Formation can range from late Early Miocene to early Middle Miocene (zones N8 to N9, late Burdigalian to Langhian).
4. The Quebrada Corralito section preserves one cycle of transgressive–regressive phases of the deltaic environments facing the marine platform.

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