Sedimentary record of impact events in Spain

Enrique Díaz-Martínez*

Enrique Sanz-Rubio

Jesús Martínez-Frías

Centro de Astrobiología Consejo Superior de Investigaciones Científicas—Instituto Nacional de Técnica Aeroespacial, Carretera, Torrejón-Ajalvir kilómetro 4, 28850 Torrejón de Ardoz, Madrid, Spain

ABSTRACT

A review of the evidence of meteorite-impact events in the sedimentary record of Spain reveals that the only proven impact-related bed is the clay layer at the Cretaceous-Tertiary boundary (at Zumaya and Sopelana in the Bay of Biscay region, and at Caravaca, Agost, and Alamedilla in the Betic Cordilleras). Other deposits previously proposed as impact related can now be rejected, or are dubious and still debated. These include the Pelarda Formation, alleged to represent proximal ejecta from the Azuara structure; the Paleocene-Eocene boundary near Zumaya (western Pyrenees) and Alamedilla (Betic Cordillera); and the Arroyofrío Oolite Bed, which has been alleged as distal ejecta of an unknown Callovian-Oxfordian impact event. The scarcity of evidence for meteorite-impact events in the sedimentary record is possibly due to a lack of detailed studies. We propose several sedimentary units that could potentially be related to impact events, and where future research should focus.

INTRODUCTION

The sedimentary record of Spain presents evidence for at least one impact event, as well as a number of units of potential impact clastic origin (some of which are currently under investigation). In this chapter we summarize and review the information available about the sedimentary record of meteorite impacts in Spain (Fig. 1), most of it published in Spanish journals. In addition, we propose several stratigraphic units with potential for future research. In this contribution we attempt (1) to bring to the attention of the international community recent and ongoing research relating to the sedimentary record of impact events in Spain, (2) to review the current knowledge and interpretation of units previously proposed as related to impacts, and (3) to promote new research within selected units to evaluate the possibility of an impact origin.

DISTAL RECORD OF IMPACT EVENTS

The evidence from sedimentary units to be considered as distal impact ejecta may consist of geochemical anomalies of elements and isotopes (e.g., Ir, $^{187}\text{Os}/^{188}\text{Os}$), the presence of impact ejecta in the sediments (e.g., shocked minerals, microtektites, or spherules), or tsunami deposits (Montanari and Koeberl, 2000). Evidence for distal impact ejecta in the sedimentary record of Spain has been proposed in relation with the Dogger-Malm, Cretaceous-Tertiary (K-T), and Paleocene-Eocene boundaries, as discussed in the following. In brief, the only proven distal record of an impact event in Spain is found at the K-T boundary. Studies of the Paleocene-Eocene extinction event in Spanish sections have shown major changes in paleoceanographic conditions, the causes of which are still debated, but an impact origin remains only probable. Future work should

*E-mail: diazme@inta.es

Figure 1. Localities mentioned in text: 1, Alamedilla; 2, Agost; 3, Azuara and Lécera; 4, Caravaca; 5, Nazaré; 6, Osinaga and Musquiz; 7, Pozuel del Campo; 8, Ricla; 9, Sopelana; 10, Valdelacasa and Navalpino; 11, Valverde del Camino; 12, Zumaya.

focus on high-resolution studies on marine stratigraphic sections comprising critical boundaries related to major biotic and/or climatic events (e.g., Triassic-Jurassic, Paleocene-Eocene, late Eocene).

Middle-Upper Jurassic boundary

The Middle-Upper Jurassic boundary throughout many peri-Atlantic basins is associated with a stratigraphic gap spanning at least the upper Callovian–lower Oxfordian interval (three ammonite biozones), although, in places, the missing record is much longer. On a regional scale, it is normally accepted that a major tectono-eustatic event controlled this widespread stratigraphic boundary, usually including emersion and/or condensed levels (Aurell, 1991; Aurell et al., 1994). These features are recorded, among others, in the Lusitanian basin (west-central Portugal), the Iberian, Catalanian, and Cantabrian basins (northeastern and northwestern Spain), Bourgogne and the Paris basin (France), the Jura basin (Switzerland), and the Neuquén basin (Argentina).

The Dogger-Malm boundary at Ricla and Pozuel del Campo (Iberian Range; Fig. 1) presents several features that were interpreted by Meléndez et al. (1987) as related to an impact event. This hypothesis was based on the presence of conspicuous geochemical anomalies (e.g., heavy metals and platinum group elements [PGE]), volcanic and hydrothermal activity, submarine corrosion, high concentration of iron-rich

spherules, and Fe-Mn Bacterial-fungal stromatolites. According to Sepkoski (1996), the Callovian-Oxfordian interstage boundary coincides with a >20% extinction of marine fossil genera. Relatively high levels of extinction percentages are reported throughout the Middle and Upper Jurassic, although no clearly defined peak can be identified (Sepkoski, 1996). In any case, these values are higher than the percentage of extinction coinciding with other known large impact events, such as the late Eocene Chesapeake and Popigai events. No proven impact structure or impact signatures have been found at or near the Middle-Upper Jurassic boundary anywhere in the world that could be related to a large impact event (Montanari and Koeberl, 2000). Therefore, any evidence in the sedimentary record that is not unequivocal should be carefully considered before a cosmic origin is inferred.

The unit studied by Meléndez et al. (1987) is known as the Arroyofrío Oolite Bed, a thin discontinuous bed at the top of the Chelva Formation and directly below the Yátova Formation; both of these formations are shallow-marine carbonate units found at many sections throughout the eastern branch of the Iberian Range (Gómez, 1979; Aurell and Meléndez, 1990). The Arroyofrío Oolite Bed is a condensed unit, <1 m thick, consisting of wackestone and packstone with iron oolites and bioclasts. Bioclasts include ammonites, planktonic foraminifera, brachiopods, and belemnites, which were dated as mid-Callovian to early Oxfordian by Ramajo et al. (2000). Workers in Spanish basins usually interpret the Arroyofrío Oolite Bed as a result of a series of punctuated subaerial exposure and transgressive events resulting in condensed carbonate sedimentation in a shallow-marine setting near local paleogeographic highs, under the influence of local currents and regional tectonic or tectono-eustatic controls (Aurell et al., 1990, 1994; Aurell, 1991; Ramajo and Aurell, 1997; Ramajo et al., 2000).

Meléndez et al. (1987) mentioned sedimentological and biostratigraphic evidence for hardground and hiatus development, together with local (parautochthonous) resedimentation. Their studies revealed geochemical anomalies of certain siderophile elements (Fe, Mn, Ni, Co). In some cases, Pt and Ir were found in relatively high proportions. In our opinion, the high proportions of Fe + Mn/Al (indicative of hydrothermal processes), in conjunction with the evidence for submarine corrosion by acid waters, and the occasional presence of bacterial stromatolites, point the geochemical anomalies being related to shallow submarine hydrothermal vents and volcanic activity. Based on the high concentration of Ni-Fe-rich spherules found at one locality (Ricla), Meléndez et al. (1987) interpreted the volcanic and hydrothermal activity as triggered by the impact of a cosmic body. In their interpretation, the other phenomena recorded at the boundary represent the effects of such an impact. However, the evidence presented in favor of a cosmic origin for the disconformity at the Middle-Upper Jurassic boundary in the Iberian Range is not unequivocal. Discussing a recently discovered modern analogue for iron ooids and pisoids in a shallow-marine volcanic setting in Indonesia, Stures-

son et al. (2000) demonstrated that iron ooids form by chemical precipitation of cryptocrystalline iron oxyhydroxides on available grains on the seafloor, from seawater enriched with Fe, Al and Si. The enrichment can be the result of hydrothermal fluids, volcanic ash falling into shallow basins, or rapid weathering of fresh volcanic rocks. More detailed research should be carried out on the geochemistry of the spherules and PGE anomalies found within the Arroyofrío Oolite Bed before a possible cosmic origin should be considered.

K-T boundary

The Spanish sedimentary record presents good examples of continuous upper Maastrichtian sedimentary sequences, such as the sections at Agost in Alicante (Groot et al., 1989), Caravaca in Murcia, and Zumaya in the Bay of Biscay region (Smit and Romein, 1985) (Fig. 1). The Agost and Caravaca sections are in the Betic Cordillera (southeastern Spain), whereas the Bay of Biscay region includes Zumaya and other remarkable sections in Spain (Sopelana, Osinaga, Musquiz) and France (Biddart, Hendaye) (Fig. 1). Most of these sections are in pelagic to hemipelagic facies and contain rich foraminiferal and nanofossil faunas and floras, insignificant amounts of macrofossils, and little or no evidence for hardgrounds or omission surfaces (Smit, 1999). High-resolution studies resulted in a magnetostratigraphic record for the Caravaca and Agost sections, but a reliable magnetostratigraphy for the Upper Cretaceous of the Bay of Biscay region has not been established (Kate and Sprenger, 1993; Moreau et al., 1994).

Sections of the Betic Cordilleras. The Agost and Caravaca sections occur in the peri-Mediterranean Alpine orogenic belt. They are among the most complete marine sections for the K-T transition, in which the K-T boundary layer provides an excellent record of the distal ejecta facies related to the Chicxulub impact (Groot et al., 1989; Martínez-Ruiz, 1994). Marl is their main lithology of both sections, which are composed calcite, quartz, and clay minerals. A clayey 2–3-mm-thick layer appears on top of the Maastrichtian, marking the K-T boundary. It is characterized by an abrupt decrease in carbonate and by an increase in clay mineral content (Ortega-Huertas et al., 1995; Martínez-Ruiz et al., 1997). PGE anomalies and spherules are confined to the boundary layer (200–400 spherules/cm³), where spherules and smectites are the main components, and there are minor amounts of illite and kaolinite (Smit, 1990; Ortega-Huertas et al., 1995; Martínez-Ruiz et al., 1997). The composition of most of the spherules is K-feldspar and Fe-oxides, probably as a result of diagenetic alteration and replacement of precursor clinopyroxene, as interpreted from relict crystalline textures (Martínez-Ruiz et al., 1997; Smit, 1999).

The Agost section is located 1.5 km north of Agost (Alicante Province, southeastern Spain), and covers the Late Cretaceous through middle Eocene record. The K-T transition is represented by open sea deposits. The Maastrichtian record consists of light gray pelagic marls, and interbeds of calcareous

marls and scarce turbiditic calcarenite beds rich in macroforaminifera (Usera et al., 2000). The K-T boundary is represented by a dark gray, 12-cm-thick clay layer that has a red-yellowish lamina, enriched in goethite and hematite, at the base (Usera et al., 2000). This lamina contains impact evidence, such as spherules, isotopic changes, and anomalies of Ir, Co, Ni, Cr, and other elements (Martínez-Ruiz et al., 1992a, 1997). Fe-oxide spherules at Agost are more abundant than K-feldspar spherules, some of the Fe-oxide spherules showing fibroradial and dendritic textures (Martínez-Ruiz et al., 1997). The Danian record comprises mainly gray marl with some interbeds of marly limestones, but toward the top of the section, reddish colors are dominant. The sedimentary continuity of the section has been demonstrated by biostratigraphic studies (Molina et al., 1996). Several models for the extinction of planktonic foraminifera have been proposed for the K-T transition at Agost, such as an almost total catastrophic mass extinction (Smit, 1990), a gradual mass extinction (Canudo et al., 1991; Pardo et al., 1996), and a catastrophic mass extinction superposed onto a less-evident gradual trend (Molina et al., 1996).

The Caravaca section is located 4 km southwest of Caravaca (Murcia Province, southeastern Spain; Fig. 1) and constitutes one of the most complete and least disturbed K-T sections in the world (Canudo et al., 1991; MacLeod and Keller, 1991). Terminal Maastrichtian–basal Paleocene sediments at Caravaca were deposited in a middle bathyal environment (200–1000 m depth), as indicated by benthic foraminiferal assemblages (Coccioni and Galeotti, 1994). Cretaceous and Tertiary lithologies of the transition are dominantly marly. The K-T boundary clay layer is a 7–10-cm-thick dark clay-marl bed. The upper part of the boundary clay layer is disturbed, and burrows several centimeters in length have been described (Arinobu et al., 1999). A 1–2-mm-thick orange basal layer rich in goethite also has high Ir and Os concentrations, in conjunction with V, Cr, Fe, Ni, Zn, and As anomalies, and a high content of small spherules (Smit and Hertogen, 1980; Smit and Klaver, 1981; Smit, 1982; Smit and ten Kate, 1982; Smit and Romein, 1985; Schmitz, 1988; Martínez-Ruiz et al., 1992b). The spherules are mainly made of K-feldspar, 0.1–0.8 mm in diameter, and were first discovered at the K-T boundary clay of the Caravaca section by Smit and Klaver (1981). Fe-oxide spherules are rare at Caravaca (Martínez-Ruiz et al., 1997).

Kaiho and Lamolda (1999) concluded, for the Caravaca section, that most planktonic foraminifera did not survive and abruptly became extinct at the K-T boundary, on the basis of stable isotope and foraminiferal abundance determinations. In addition, Arinobu et al. (1999) carried out a study of carbon isotope stratigraphy and detected a spike of the pyrosynthetic polycyclic aromatic hydrocarbons (PAHs) at the Caravaca K-T boundary. Arinobu et al. proposed that the combustion of terrestrial organic matter in massive global fires was the most probable mechanism for the origin of these PAHs.

The Alamedilla section (Granada; Fig. 1) has been described as the closest site to the Chicxulub crater (~7000 km

away) with an undisturbed ejecta layer (Smit, 1999). Droplets recently found at Alamedilla were interpreted as altered tektites, indicating that tektites and microkrystites may occur together in the same ejecta layer (Smit, 1999).

Sections of the Bay of Biscay region. Stratigraphic sections around the Bay of Biscay region are valuable for testing hypotheses of K-T transition extinctions (Smit et al., 1987). The reasons for this are: (1) these sections are considered by micropaleontologists to be relatively complete (Smit et al., 1987), (2) they exhibit high sedimentation rates, resulting in increased resolution of the stratigraphy, (3) they were deposited in a pelagic, but nonturbiditic, environment, and (4) well-exposed outcrops along coastlines facilitate access for measuring sections and collecting samples. All the sections contain a conformable sequence of Upper Cretaceous and lower Tertiary marine strata that were deposited in the Basque-Cantabrian basin (Lamolda et al., 1981). This basin is part of the continental margin of northern Spain, and is mostly filled with Mesozoic rocks. The most striking geological feature of the region is the great thickness of its Mesozoic-Tertiary sequence, which exceeds 15 km (García-Mondéjar et al., 1985). This basin was one of several forming along the boundary of the European-Iberian plates during the Late Cretaceous (Ward, 1988). Although deposition of turbiditic sediments dominated from the Campanian to the early Maastrichtian, the reduction of siliciclastic material influx and basin-wide shallowing and regression during the late Maastrichtian resulted in limestone-marl rhythmites (Lamolda et al., 1981). Immediately following the K-T boundary, there was an even more dramatic reduction in siliciclastic influx into the basin, resulting in the deposition of pink coccolith limestones during the Danian (Ward, 1988). The most representative and most studied sections for the K-T boundary are Zumaya (Gipuzkoa Province) and Sopelana (Bizkaia Province) (Fig. 1). In addition, the nearby sections of Bidart and Hendaye (south of France) are also well-known for the K-T transition in the same region.

The Maastrichtian-Paleocene of the Zumaya section is the most thoroughly studied of the Bay of Biscay sections. It is the thickest, best exposed, and least faulted section (Ward, 1988). A continuous section from the lower Campanian to the Eocene is exposed along the coastal cliff west of Zumaya. The advantages of the Zumaya section are (Lamolda et al., 1988): (1) sedimentary continuity across the K-T boundary, (2) relative abundance of fossil remains through the Maastrichtian, (3) almost complete absence of turbidites in the purple marls and limestones of late Maastrichtian and early Paleocene ages, (4) thickness of and high sedimentation rate for the transitional beds, and (5) absence of tectonism affecting the transitional beds. The section has no boundary clay, but the boundary layer at Zumaya is pyritic, and therefore easy to recognize (Wiedemann, 1988). The uppermost part of the Maastrichtian is composed of several thin beds of green marls (1–5 cm thick), a sandy gray-brown bed, and then purple marls (Lamolda et al., 1988). The K-T boundary is marked by a single or multiple calcite vein (of supergenic nature) 2–3 cm thick, with gray dark shale interbeds. Ir anomalies and spherules interpreted as mi-

crokrystites altered to As-rich pyrite have been described from the Zumaya section (Smit, 1982; Smit and Romein, 1985; Schmitz et al., 1997) and from the Sopelana section (Rocchia et al., 1990). Above the calcite vein, 7–8 cm of dark gray shales occur, and 25 cm of gray marls forming the so-called boundary marls (Lamolda et al., 1988).

Paleocene-Eocene boundary

The largest extinction event having affected the deep-sea benthic foraminiferal fauna during the past 90 m.y. occurred in the latest Paleocene (Schmitz et al., 1997). The Zumaya section (Bay of Biscay region) also contains one of the most expanded and biostratigraphically complete Paleocene-Eocene transitions, deposited in a middle or lower bathyal environment (Pujalte et al., 1993). At Zumaya, the benthic extinction event closely coincides with deposition of a clay interval that indicates strong CaCO_3 undersaturation (Canudo et al., 1995). Approximately 15 m below the benthic extinction event, the section is dominated by gray marls that underlie a 4 m thick, mainly reddish-brown clay interval. The benthic extinction event occurs at the base of the clay interval. A transition from marls to limestone occurs above the clay interval.

High-resolution $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, calcareous nannofossil, and planktic and benthic foraminifera studies showed that, below the marl-clay transition, there is a 40–50-cm-thick interval that contains a detailed record of a gradual succession of faunal and geochemical events culminating in the benthic extinctions (Schmitz et al., 1997). There is a significant Ir anomaly (133 ppt over a background of 38 ppt) in a 1-cm-thick, gray marl layer ~40 cm below the base of the clay interval. Above the Ir anomaly, a negative gradual excursion of $\delta^{13}\text{C}$ is developed in a 40-cm-thick, glauconitic, greenish-brown marl bed. The relation of these anomalies to an impact event and its role regarding mass extinctions related to a Paleocene-Eocene (P-E) event are debatable. Schmitz et al. (1997) indicated that, if the Ir anomaly can be related to an impact event, it may not have been of any consequence for ongoing paleoceanographic changes and later mass extinctions.

Major biotic and geochemical changes have also been shown in the P-E at Alamedilla (Granada, Spain), where the transition is marked by major faunal turnover in planktic foraminifera, mass extinction in benthic foraminifera, negative $\delta^{18}\text{O}$ excursion in benthic foraminifera, negative $\delta^{13}\text{C}$ excursion in both planktic and benthic foraminifera, decrease in calcite preservation, increase in detrital flux, and changes in clay mineral composition (Lu et al., 1995). According to Montanari and Koeberl (2000), there is no relationship between the four or five impact craters known that are roughly P-E age, and the P-E benthic extinction and associated $\delta^{13}\text{C}$ shift.

PROXIMAL RECORD OF IMPACT EVENTS

The Azuara structure (41°01'N, 00°55'W, Zaragoza province, northeastern Spain), ~30 km in diameter (Fig. 2), is the

Figure 2. Geological sketch of Azuara structure and adjacent Calatayud-Montalbán and Ebro basins (modified after Cortés and Casas-Sáinz, 1996). Pelarda Formation is located to south of Azuara structure (circled in map; R). A distance of one radius from outlined structure has also been marked (2R). Fm.—Formation.

only structure on the Iberian Peninsula for which an impact origin has been formally proposed. Following its identification in the 1980s, a strong debate arose about either a tectonic or an impact-induced origin for this structure (e.g., Ernstson and Fiebag, 1992; Aurell et al., 1993). The controversy remains, although the arguments in favor of the impact hypothesis are gradually being rejected, because most of the evidence is inconclusive and allows for other interpretations. It is interesting that other meteorite-impact craters, similar in size and age to those proposed for the Azuara structure (Ries in Germany, Haughton in Canada), display numerous impact-related features (impact melts, widespread shock metamorphism) that are certainly not observed at Azuara.

The Azuara structure is located ~50 km south of Zaragoza, at the northeastern side of the Iberian Range, close to the Ebro basin (northeastern Spain; Fig. 2). The present-day structure observed in the Azuara region corresponds to a sedimentary basin filled with Tertiary deposits and delimited by folds and thrusts involving Precambrian-Paleozoic basement and Mesozoic and Cenozoic supracrustal rocks. An impact origin for the Azuara structure was interpreted from evidence such as inverted stratigraphy, occurrence of megabreccias and megablocks, breccia dikes, a negative gravity anomaly, and features alleged to be indicative of high-pressure and high-temperature effects (Ernst-

son et al., 1985, 1999; Ernstson and Claudín, 1990; Ernstson and Fiebag, 1992). Several lines of evidence based on the sedimentary and structural evolution of the Azuara area, as well as that of the Iberian Range and the Ebro basin, were presented against the hypothesis of a meteorite impact (Aurell et al., 1993), alternative interpretations being proposed for the criteria used as evidence. For example, the inverted stratigraphy is due to Cenozoic Alpine tectonism, most breccias are due to diagenetic and/or edaphic processes (evaporite dissolution with collapse of host carbonate rocks, karst and caliche development), breccia dikes are also due to karst and paleosol development on carbonates, and the negative gravity anomaly comes from an incomplete data set restricted to the interior of the Azuara sedimentary basin, and resulting from its bowl shape. In addition, Cortés and Casas-Sainz (1996) considered that the Azuara structure is consistent with a north-south regional shortening during the Tertiary that controlled deformation both in the Variscan basement and in the Mesozoic-Tertiary sedimentary cover. They interpreted the structure as a synclinal basin located over an important depression of the Hercynian basement that is bounded by a fold and thrust arc in the northern part, and a poorly defined fold system toward the south. These interpretations refute part of the evidence put forward by Ernstson's group.

Immediately after an impact event, the impact crater is surrounded by a deposit of debris ejected as the result of the collision. Most of these ejecta are close to the crater rim, and continuous ejecta normally extend about one crater radius from the crater rim, in the case of a nonoblique impact (Melosh, 1989). The only unit proposed as probable proximal ejecta related to the Azuara structure is the Pelarda Formation (Ernstson and Claudín, 1990), located ~10 km to the south of the supposed crater rim (Fig. 2), and overlying alluvial fan deposits of the adjacent Calatayud-Montalbán basin. The origin and age of this unit are debated. Although the Pelarda Formation has been traditionally interpreted as one of the frequent Pliocene-Pleistocene alluvial sedimentary cover units present throughout the area (Instituto Tecnológico Geominero de España [ITGE], 1989, 1991), Ernstson and Claudín (1990) and Ernstson and Fiebag (1992) interpreted this formation as the remnant of an originally extensive ejecta blanket around the Azuara structure. The conglomerates and diamictites of the Pelarda Formation, which has an outcrop of ~30 km², are basically composed of rounded to subrounded quartzite clasts (to 1 m in diameter) eroded from the local Paleozoic basement, embedded within a mixed clayey-silty-sandy matrix, and with apparently no internal fabric (Fig. 3B). Carls and Monninger (1974) reported some Buntsandstein pebbles, but they did not observe limestone components. However, Ernstson and Claudín (1990) added to the previous work the identification of Buntsandstein megaclasts, sporadic limestone clasts, and lower Tertiary marls as clasts within the conglomerates. Striated and polished boulders and cobbles of quartzite, schist, and slate were also described by Ernstson and Claudín (1990). Plastically deformed and fractured clasts, some of them showing rotational deformation, and multiple sets of planar deformation features in quartz were also described by Ernstson and Claudín as evidence for shock deformation and metamorphism. However, the deformational features proposed as evidence for shock metamorphism are unrelated to impact metamorphism (F. Langenhorst, personal commun., 2000; see also Langenhorst and Deutsch, 1996).

On the assumption that the Azuara structure may be an impact crater, only biostratigraphic and lithostratigraphic methods help provide an age for the alleged proximal ejecta. This is because no impact melt sheet or true suevites have ever been described for the structure, and therefore radiometric methods could not be applied. Cenozoic sediments cover almost the total surface area of the structure, and there are no deep boreholes. Ernstson and Fiebag (1992) suggested a late Eocene–Oligocene age for the Pelarda Formation because the Miocene sediments are not affected by tectonics, and Eocene sediments are incorporated into some breccia dikes. However, vertebrate paleontological data for the units immediately below the Pelarda Formation suggest an age younger than early Oligocene (Olalla paleontological site, MP 21 zone; Peláez-Campomanes, 1993). These data do not exclude a Pliocene-Pleistocene age for the Pelarda Formation, which in our opinion can also be interpreted as local Pliocene-Pleistocene alluvial deposits, which are common throughout central Spain along zones of major relief.

POTENTIAL IMPACT CLASTIC BEDS

Useful criteria for the recognition of potential impact-related units in the sedimentary record are the presence of breccia or diamictite beds as probable proximal impact ejecta, and the presence of spherules as probable distal impact ejecta. This is particularly true when these deposits coincide in time with a well-dated massive extinction event, and/or when they roughly coincide with the age of a known impact event. However, once identified, the potential of the deposit to be impact related needs to be proved with unequivocal criteria characteristic of meteorite impacts: marked geochemical anomalies and shock metamorphic features (planar deformation features, diaplectic glass, high-pressure polymorphs).

Breccia and diamictite beds are identified in the Spanish sedimentary record: our review of the literature revealed that most of them have been interpreted as the result of resedimentation related to slope and/or tectonic instability, and more rarely as glacial deposits. Many of these units are clearly related to active tectonism or eustasy, although there are some that might be impact related. For these, the evidence for a strictly terrestrial origin (i.e., unrelated to cosmic impact) is not always unequivocal: some features remain to be explained, and alternative hypotheses may relate the deposits to impact events. Following is a brief review of the principal characteristics of several units in the sedimentary record of Spain that we have identified as potential impact clastic beds. Our current research is oriented toward the verification of the terrestrial or impact origin of these strata.

Vendian-Cambrian boundary

Deep-marine breccias and olistostromes known as the Fuentes Bed (Nivel de Fuentes) in the Central Iberian Zone of the Hercynian Massif broadly coincide with the Vendian-Cambrian boundary (location 10 in Fig. 1). They have been traditionally interpreted as tectonically induced strata, within the context of the Cadomian or late Pan-African orogeny (San José, 1984). The unit is present in the Montes de Toledo and Las Hurdes (Alvarez-Nava et al., 1988; Robles and Alvarez-Nava, 1988) (Fig. 1), whereas it is absent from other areas within the Central Iberian Zone (as in southern Salamanca; Nozal and Robles, 1988). Along the northeastern flank of the Valdelacasa antiform, near its type locality (town of Fuentes) in the central Montes de Toledo, the Fuentes Bed unconformably overlies the deformed deep-marine shales and sandstones of the Late Proterozoic (Riffian) Domo Extremeño Group (Alvarez-Nava et al., 1988; Pardo and Robles, 1988; Santamaría and Remacha, 1994). To the southeast of the Valdelacasa antiform, but still within it, the Fuentes Bed overlies both the Domo Extremeño Group and a remnant of the Late Proterozoic (Vendian) Ibor Group (Santamaría and Pardo, 1994) (Figs. 3, C and D, and 4). Farther to the south of the Valdelacasa antiform, in the Villarta-Navalpino antiform, the Fuentes Bed is

Figure 3. A: Microphotograph showing general aspect of Arroyofrío Oolite Bed (Dogger-Malm boundary). Cross-polarized light. Scale bar is 1 mm. B: Paleozoic quartzite boulders at southwestern part of Pelarda Formation outcrops. C: General view of Fuentes Bed megabreccia, showing characteristic chaotic aspect. D: Carbonate and quartzite boulders of Fuentes Bed embedded in plastically deformed muddy matrix. Circled hammer for scale. E: Sandstone clast in Orea Formation diamictite in Iberian Range (east of Checa, Guadalajara Province). F: Limestone clast in Orea Formation diamictite in eastern Iberian Range (northwest of Fombuena, Zaragoza Province).

known as the Navalpino Breccia and overlies shallow-marine limestones of the Ibor Group (San José, 1984).

The Fuentes Bed was first described and defined by Moreno (1974, 1975). In the Valdelacasa antiform it is a rather continuous bed, between 200 and 300 m thick (Fig. 4). Moreno (1977) interpreted it as the result of a single event representing an isochron. However, detailed sedimentologic analysis proved that it represents a series of multiple resedimentation events (slumps, debris flows, and olistostromes), with no interbeds of

in situ (autochthonous) sedimentation separating them (Santamaría and Remacha, 1994). The size of the clasts varies from millimeter and centimeter size to blocks of several meters, and slabs of 20 to 30 m. The composition is highly polymictic, and consists of all the lithologies of the underlying Ibor and Domo Extremeño Groups, i.e., limestone, dolostone, shale, siltstone, sandstone, conglomerate, and graywacke. Thin sections reveal the complex character of the matrix, which also includes small lithic igneous clasts of probable volcanic origin, and highly

Figure 4. Schematic section of Fuentes Bed at El Membrillar (south-east Valdelacasa antiform), indicating lithostratigraphic nomenclature and approximate ages. Modified from Alvarez-Nava et al. (1988) and Santamaría and Pardo (1994). Fm.—Formation.

deformed quartz clasts, which seem to lack planar deformation features. Many terrigenous clasts display plastic deformation and partial disaggregation in the matrix, indicating their incomplete consolidation at the time of resedimentation. Carbonate clasts are thoroughly recrystallized and have been transformed to dolomite and/or magnesite during diagenesis.

Latest Ordovician

Shallow-marine, late Ashgill (Hirnantian) diamictites are present in northern Africa and western and southern Europe, along the former margin of Gondwana, and have been generally interpreted to be coeval with the north African glaciation (Fortuin 1984; Robardet and Doré, 1988). In Spain, these diamictites are known by different formation names throughout the Central Iberian Zone: *pelitas con fragmentos* (or fragment-bearing shales), Gualija Formation, Orea Formation, and Chavera Formation (Fortuin, 1984; Portero and Dabrio, 1988; Robardet and Doré, 1988). Apart from diamictites, these uppermost Ordovician units also consist of graywacke, shale, sandstone, and conglomerate, with a variable total thickness of as much as 200 m at some localities. The diamictites include reworked clasts and fossils recycled from underlying Ordovician units (e.g., quartz, limestone, shale, sandstone) (Fig. 3, E and F), and are overlain by a thin ubiquitous quartzite (García-Palacios et al., 1996).

The diamictites at most of the sections are resedimented (Portero and Dabrio, 1988). Evidence for a glacial origin is scarce and inconclusive: glacially striated clasts are extremely

rare and dubious, whereas no striated pavements or boulder pavements have ever been found. These features remain unexplained, and detailed sedimentological and geochemical studies need to be done.

Late Devonian

Shallow-marine diamictites within the Phyllite-Quartzite Group of the Iberian Pyrite Belt (South Portuguese Zone of the Hercynian Massif) are commonly interpreted as large debris flows related to tectonism (Moreno and Sáez, 1990; Moreno et al., 1995). The age of the Phyllite Quartzite Group in the South Portuguese Zone is not well defined, but it is broadly considered to be of Late Devonian age (Moreno et al., 1995). Sedimentary facies and sequences in the Phyllite Quartzite Group represent storm-dominated shallow clastic shelf deposits, interrupted toward the top by thick (to 60 m), conspicuous beds of massive diamictites. They are common throughout the Iberian Pyrite Belt, but are particularly frequent in the Valverde del Camino antiform, 40 km north of Huelva (Fig. 1). The matrix of the diamictites is abundant (80%–90%) and muddy (shaly). Clasts within the matrix consist of partially consolidated resedimented parautochthonous sandstones of variable size, normally reaching 20 cm in size. Meter-sized slumps and isolated blocks are also common.

Moreno et al. (1995) interpreted these large debris flows as having been triggered by earthquakes, and related them to tectonic instability, in particular at the beginning of the Hercynian orogeny in the region. However, mass gravity flows can also be triggered by wave loading during strong storms and tsunami events. Mass-extinction events and meteorite-impact structures are known in the Late Devonian (Sandberg et al., 2000), and therefore other possibilities should be considered in the interpretation of the Phyllite Quartzite Group.

Triassic-Jurassic boundary

In most of Spain, the Triassic-Jurassic boundary is marked by a regional erosional unconformity and/or earliest Jurassic (Hettangian) breccias (Cortes de Tajuña Formation). In some localities, the breccias are interpreted as being related to rifting and eustasy (Aurell et al., 1992; Gallego et al., 1994; Campos et al., 1996), whereas in others they are considered to be the result of collapse after evaporite dissolution (Gómez and Goy, 1998). In particular, Campos et al. (1996) described erosion of underlying Triassic units and tectonic collapse of a shallow carbonate platform of Hettangian age developed during rift extension. Gómez and Goy (1998) identified an evaporite unit (Lécera Formation) from subsurface data in eastern Spain (Fig. 1), coinciding with the Triassic-Jurassic boundary, and consisting of 100–200 m of gypsum, anhydrite, and carbonates. This unit was found to underlie, laterally grade into and replace the Cortes de Tajuña Formation in many areas.

One of the most important extinction events of the Phan-

erozoic, including 47% extinction of all known marine animal genera (Sepkoski, 1996), took place near the Triassic-Jurassic boundary. At the same time, several meteorite-impact structures of intermediate and large size are known that have Late Triassic-Early Jurassic ages (Rochechouart, Manicouagan, Lake Saint Martin, Red Wing, Obolon), and impact signatures (iridium anomaly, shocked quartz) have been found with them (Montanari and Koeberl, 2000).

Cenomanian-Turonian boundary

Possible impact ejecta have recently been found north of Nazaré (Mesozoic Lusitanian basin of Portugal; Fig. 1), near the Cenomanian-Turonian boundary, which may be related to the Tore Seamount, a possible impact structure located off the coast of Portugal (Pena dos Reis et al., 1997; Monteiro et al., 1997, 1998, 1999). It may be possible to find corresponding distal ejecta in the frequently excellent exposures of shallow- and deep-marine sequences covering this same interval (Cenomanian-Turonian boundary) in Spain. Some of the Spanish sections are already well dated on the basis of calcareous nannoflora, planktic foraminifera, and ostracod biostratigraphy (Gorostidi and Lamolda, 1991; Gil et al., 1993; Paul et al., 1994; Floquet et al., 1996). The sedimentology and sequence stratigraphy for most of these units are well known (Alonso et al., 1993; Segura et al., 1993; García-Quintana et al., 1996). During the Archaeocretacea zone of the latest Cenomanian, the same event occurred both in the Basque-Cantabrian passive margin (northern Spain) and in its Iberian hinterland (Castilian proximal ramp, central and eastern Spain), connecting the Atlantic with the Tethys, as evidenced by deposition of a thin black shale bed, formation of a glauconitic and pyritic hard-ground, low sedimentation rate, anoxia (or hypoxia), geochemical shift, and biological extinction (Floquet et al., 1996). The potential relation of these processes to a meteorite impact has not been explored. Several other intermediate-size (15–25 km in diameter) impact craters have been identified with a Cenomanian or Turonian age: Steen River (Canada), Dellen (Sweden), and Boltysh (Ukraine) (Montanari and Koeberl, 2000).

CONCLUSIONS

1. The only proven impact-related bed in the sedimentary record of Spain is the clay layer at the K-T boundary (at Zumaya and Sopelana in the Bay of Biscay region, and at Caravaca, Agost, and Alamedilla in the Betic Cordilleras).

2. Other deposits previously proposed as impact related can now be rejected, or are dubious and still debated. These include (1) the Pelarda Formation, alleged to represent proximal ejecta from the Azuara structure, (2) the Paleocene-Eocene boundary near Zumaya (western Pyrenees) and Alamedilla (Betic Cordillera), and (3) the Arroyofrío Oolite Bed, alleged to be distal ejecta of an unknown Callovian-Oxfordian impact event.

3. The scarcity of evidence for meteorite-impact events in the sedimentary record is related to the lack of detailed studies. We propose several sedimentary units that could potentially be related to impact events, and where future research should focus.

ACKNOWLEDGMENTS

This research is supported by the Spanish Center for Astrobiology (Consejo Superior de Investigaciones Científicas—Instituto Nacional de Técnica Aeroespacial). We appreciate helpful and constructive reviews of this manuscript by Bruce Simonson and Wolf Uwe Reimold, as well as comments by editor Christian Koeberl. The IMPACT program of the European Science Foundation financed the participation of Díaz-Martínez and Sanz-Rubio in Short Courses on Impact Stratigraphy and Impact Metamorphism (2000), which suggested to us the need for this review, and greatly helped the development of ideas on prospective units.

REFERENCES CITED

- Alonso, A., Floquet, M., Mas, R., and Meléndez, A., 1993, Late Cretaceous carbonate platforms: Origin and evolution, Iberian Range, Spain: *American Association of Petroleum Geologists Memoir*, v. 56, p. 297–313.
- Álvarez-Nava, H., García-Casquero, J.L., Gil-Toja, A., Hernández-Urroz, J., Lorenzo-Alvarez, S., López-Díaz, F., Mira-López, M., Monteserín, V., Nozal, F., Pardo, M.V., Picart, J., Robles, R., Santamaría, J., and Solé, F.J., 1988, Unidades litoestratigráficas de los materiales precámbrico-cámbricos en la mitad suroriental de la Zona Centro-Ibérica [abs.]: 2 Congreso Geológico de España, Granada, Actas, v. 1, p. 19–22.
- Arenillas, I., Arz, J.A., and Molina, E., 1997, El límite Cretácico/Terciario con foraminíferos planctónicos en Osinaga y Músquiz (Navarra, Pirineos): *Geogaceta*, v. 21, p. 25–28.
- Arinobu, T., Ishiwatari, R., Kaiho, K., and Lamolda, M.A., 1999, Spike of pyrosynthetic polycyclic hydrocarbons associated with an abrupt decrease in $\delta^{13}\text{C}$ of a terrestrial biomarker at the Cretaceous-Tertiary boundary at Caravaca, Spain: *Geology*, v. 27, p. 723–726.
- Arz, J.A., Canudo, J.I., and Molina, E., 1992, Estudio comparativo del Mastrichtense de Zumaya (Pirineos) y Agost (Béticas) basado en el análisis cuantitativo de los foraminíferos planctónicos [abs.]: 3 Congreso Geológico de España, Salamanca, Actas, v. 1, p. 487–491.
- Arz, J.A., Arenillas, I., López-Oliva, J.G., and Molina, E., 1998, Modelos de extinción de foraminíferos en el límite Cretácico/Terciario (K/T) de El Mulato (México) y Agost (España): *Geogaceta*, v. 23, p. 15–18.
- Aurell, M., 1991, Identification of systems tracts in low-angle carbonate ramps: Examples from the Upper Jurassic of the Iberian Chain (Spain): *Sedimentary Geology*, v. 73, p. 101–105.
- Aurell, M., and Meléndez, G., 1990, Upper Jurassic of the northeastern Iberian Chain (E Spain): A synthesis: *Publicaciones del Seminario de Paleontología de Zaragoza*, v. 2, p. 5–31.
- Aurell, M., Meléndez, A., and Meléndez, G., 1990, Caracterización de la secuencia Oxfordiense en el sector central de la Cordillera Ibérica: *Geogaceta*, v. 8, p. 73–76.
- Aurell, M., Meléndez, A., San Román, J., Guimerá, J., Roca, E., Salas, R., Alonso, A., and Mas, R., 1992, Tectónica sinsedimentaria distensiva en el límite Triásico-Jurásico en la Cordillera Ibérica: 3 Congreso Geológico de España, Salamanca, Actas, v. 1, p. 50–54.

- Aurell, M., González, A., Pérez, A., Guimerá, J., Casas, A., and Salas, R., 1993, The Azuara impact structure (Spain): New insights from geophysical and geological investigations: *Discussion: Geologische Rundschau*, v. 82, p. 750–755.
- Aurell, M., Fernández-López, S., and Meléndez, G., 1994, The Middle-Upper Jurassic oolitic ironstone level in the Iberian Range (Spain): Eustatic implications: *Geobios*, v. 17, p. 549–561.
- Baceta, J.I., Pujalte, V., Orue-Etxebarria, X., Payros, A., Apellániz, E., and Núñez-Betelu, K., 1997, El Cretácico superior y Paleógeno del País Vasco: Ciclos sedimentarios y eventos biológicos en una cuenca marina profunda: *Geogaceta*, v. 22, p. 225–231.
- Campos, S., Aurell, M., and Casas, A., 1996, Origen de las brechas de la base del Jurásico en Morata de Jalón (Zaragoza): *Geogaceta*, v. 20, p. 887–889.
- Canudo, J.I., Keller, G., and Molina, E., 1991, Cretaceous/Tertiary boundary extinction pattern and faunal turnover at Agost and Caravaca, S.E. Spain: *Marine Micropaleontology*, v. 17, p. 319–341.
- Canudo, J.I., Keller, G., Molina, E., and Ortíz, N., 1995, Planktic foraminiferal turnover and $\delta^{13}\text{C}$ isotopes across the Paleocene-Eocene transition at Caravaca and Zumaya, Spain: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 116, p. 75–100.
- Carls, P., and Monninger, W., 1974, Ein Block-Konglomerat im Tertiär der östlichen Iberischen Ketten (Spanien): *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen*, v. 145, p. 1–16.
- Coccioni, R., and Galeotti, S., 1994, K-T boundary extinction: Geologically instantaneous or gradual event? Evidence from deep sea benthic foraminifera: *Geology*, v. 22, p. 779–782.
- Cortés, A.L., and Casas-Sainz, A.M., 1996, Deformación alpina de zócalo y cobertera en el borde norte de la Cordillera Ibérica (Cubeta de Azuara-Sierra de Herrera): *Revista de la Sociedad Geológica de España*, v. 9, p. 51–66.
- Ernstson, K., and Claudin, F., 1990, Pelarda Formation (Eastern Iberian Chains, NE Spain): Ejecta of the Azuara impact structure: *Neues Jahrbuch für Geologie und Paläontologie, Monatshefte*, v. 10, p. 581–599.
- Ernstson, K., and Fiebag, J., 1992, The Azuara impact structure (Spain): New insights from geophysical and geological investigations: *Geologische Rundschau*, v. 81, p. 403–425.
- Ernstson, K., Hammann, W., Fiebag, J., and Graup, G., 1985, Evidence of an impact origin for the Azuara structure (Spain): *Earth and Planetary Science Letters*, v. 74, p. 361–370.
- Ernstson, K., Rampino, M.R., Anguita, F., Hiltl, M., and Siegert, I., 1999, Shock deformation of autochthonous conglomerates near the Azuara impact structure, Spain: *Geological Society of America Abstracts with Programs*, v. 27, no. 6, p. A122.
- Floquet, M., Mathey, B., Métais, E., Emmanuel, L., Babinot, J.-F., Magniez-Jeannin, F., and Tronchetti, G., 1996, Correlation of sedimentary events during the latest Cenomanian from the Basque Basin to the Castilian Ramp (northern Spain): *Geogaceta*, v. 20, p. 50–53.
- Fortuin, A.R., 1984, Late Ordovician glaciomarine deposits (Orea Shale) in the Sierra de Albarracín, Spain: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 48, p. 245–261.
- Gallego, R., Aurell, M., Badenas, B., Fontana, B., and Meléndez, G., 1994, Origen de las brechas de la base del Jurásico de Leizta (Cordillera Vasco-Cantábrica oriental, Navarra): *Geogaceta*, v. 15, p. 26–29.
- García-Mondéjar, J., Hines, F.M., Pujalte, V., and Reading, H.G., 1985, Sedimentation and tectonics in the western Basque-Cantabrian area (Northern Spain) during Cretaceous and Tertiary times, in Milá, M.D., and Rosell, J., eds., *Excursion Guidebook: 6th European Regional Meeting*, Lleida, Spain, p. 309–392.
- García-Palacios, A., Gutiérrez-Marco, J.C., and Herranz, P., 1996, Edad y correlación de la “Cuarcita del Criadero” y otras unidades cuarcíticas del límite Ordovícico-Silúrico en la Zona Centroibérica meridional (España y Portugal): *Geogaceta*, v. 20, p. 19–22.
- García-Quintana, A., Segura, M., García-Hidalgo, J.F., Ruiz, G., Gil, J., and Carenas, B., 1996, Discontinuidades estratigráficas y secuencias deposicionales del Cretácico medio (Albiense superior-Turonense medio) en la Cordillera Ibérica central y el Sistema Central meridional: *Geogaceta*, v. 20, p. 119–122.
- Gil, J., García, A., and Segura, M., 1993, Secuencias deposicionales del Cretácico en el flanco sur del Sistema Central: *Geogaceta*, v. 13, p. 43–45.
- Gómez, J.J., 1979, El Jurásico en facies carbonatadas del Sector Levantino de la Cordillera Ibérica: Madrid, Universidad Complutense de Madrid, Departamento de Estratigrafía, Seminarios de Estratigrafía, Monografías, v. 4, 683 p.
- Gómez, J.J., and Goy, A., 1998, Las unidades litoestratigráficas del tránsito Triásico-Jurásico en la región de Lécerca (Zaragoza): *Geogaceta*, v. 23, p. 63–66.
- Gorostidi, A., and Lamolda, M.A., 1991, El paso Cenomaniense-Turonense de Menoyo (Alava): Variaciones de la nanoflora calcárea: *Geogaceta*, v. 10, p. 54–57.
- Grieve, R.A.F., 1987, Terrestrial impact structures: *Annual Review of Earth and Planetary Sciences*, v. 15, p. 245–270.
- Groot, J.J., de Jonge, R.B.G., Langereis, C.G., ten Kate, W.G.H.Z., and Smit, J., 1989, Magnetostratigraphy of the Cretaceous-Tertiary boundary at Agost (Spain): *Earth and Planetary Science Letters*, v. 94, p. 385–397.
- Herranz, P., San José, M.A., and Vilas, L., 1977, Ensayo de correlación del Precámbrico entre los Montes de Toledo occidentales y el Valle del Matagorda: *Estudios Geológicos*, v. 33, p. 327–342.
- Instituto Tecnológico Geominero de España, 1989, Memoria Hoja número 466 (Moyuela) del Mapa Geológico de España E.: Madrid, Ministerio de Industria y Energía, Servicio de Publicaciones, 116 p., scale 1:50 000, 1 sheet.
- Instituto Tecnológico Geominero de España, 1991, Memoria Hoja número 40 (Daroca) del Mapa Geológico de España E.: Madrid, Ministerio de Industria y Energía, Servicio de Publicaciones, 239 p., scale 1:200 000, 1 sheet.
- Kaiho, K., and Lamolda, M.A., 1999, Catastrophic extinction of planktonic foraminifera at the Cretaceous-Tertiary boundary evidenced by stable isotopes and foraminiferal abundance at Caravaca, Spain: *Geology*, v. 27, p. 355–358.
- Kate, W.G.T., and Sprenger, A., 1993, Orbital cyclicity above and below the Cretaceous/Paleogene boundary at Zumaya (N Spain), Agost and Relleu: *Sedimentary Geology*, v. 87, p. 69–101.
- Lamolda, M.A., and Mao, S., 1999, The Cenomanian-Turonian boundary event and dinocyst record at Ganuza (northern Spain): *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 150, p. 65–82.
- Lamolda, M., Rodríguez-Lázaro, J., and Wiedmann, J., 1981, Field Guide: Excursions to Coniacion-Maastrichtian of Basque Cantabric Basin: Barcelona, Universidad Autónoma Barcelona, Publicaciones de Geología, v. 14, p. 1–53.
- Lamolda, M.A., Mathey, B., and Wiedmann, J., 1988, Field-guide excursion to the Cretaceous-Tertiary boundary section at Zumaya (northern Spain), in Lamolda, M.A., Kauffman, E.G., and Walliser, O.H., eds., *Paleontology and evolution: Extinction events 2nd International Conference on Global Bioevents*. Madrid, *Revista de Paleontología*, no. extraordinario, p. 141–155.
- Langenhorst, F., and Deutsch, A., 1996, The Azuara and Rubielos structures, Spain: Twin impact craters or Alpine thrust systems? TEM investigations on deformed quartz disprove shock origin [abs.]: *Lunar and Planetary Science Conference, 27th*, Houston, Texas, Lunar and Planetary Institute, v. 2, p. 725–726.
- Lu, G., Keller, G., Ortiz, N., Adatte, T., and Molina, E., 1995, Faunal isotopic and sedimentary changes at the Alamedilla section, Spain: The P-E event in the Deep Tethys Basin: *Geological Society of America Abstracts with Programs*, v. 27, no. 6, p. A405.
- Macleod, N., and Keller, G., 1991, How complete are Cretaceous/Tertiary boundary sections?: A chronostratigraphic estimate based on graphic correlation: *Geological Society of America Bulletin*, v. 103, p. 1439–1457.

- Martínez-Ruiz, F., 1994, Geoquímica y mineralogía del tránsito Cretácico-Terciario en las Cordilleras Béticas y en la Cuenca Vasco-Cantábrica. [Ph.D. thesis]: Granada, Universidad de Granada, 280 p.
- Martínez-Ruiz, F., Ortega-Huertas, M., Palomo, I., and Barbieri, M., 1992a, The geochemistry and mineralogy of the Cretaceous-Tertiary boundary at Agost (southeast Spain): *Chemical Geology*, v. 95, p. 265–281.
- Martínez-Ruiz, F., Acquafredda, P., Palomo, I., and Ortega-Huertas, M., 1992b, New data on the spherules from the Cretaceous-Tertiary boundary layer at Caravaca (SE Spain): *Geogaceta*, v. 12, p. 30–32.
- Martínez-Ruiz, F., Ortega-Huertas, M., Palomo, I., and Acquafredda, P., 1997, Quench textures in altered spherules from the Cretaceous-Tertiary boundary layer at Agost and Caravaca, SE Spain: *Sedimentary Geology*, v. 113, p. 137–147.
- Meléndez, G., Sequeiros, L., Brochwicz-Lewinski, W., Gasiewicz, A., Suffczynski, S., Szatkowski, K., Zbik, M., and Tarkowski, R., 1987, El límite Dogger-Malm en la Cordillera Ibérica: Anomalías geoquímicas y fenómenos asociados: *Geogaceta*, v. 2, p. 5–7.
- Melosh, H.J., 1989, *Impact cratering*: Oxford, Oxford University Press, 245 p.
- Molina, E., Arenillas, I., and Arz, J.A., 1996, The Cretaceous-Tertiary boundary mass extinction in planktonic foraminifera at Agost, Spain: *Revue de Micropaléontologie*, v. 39, p. 225–243.
- Montanari, A., and Koeberl, C., 2000, *Impact stratigraphy: The Italian record*: Heidelberg, Springer-Verlag, *Lecture Notes in Earth Sciences*, v. 93, 364 p.
- Monteiro, J.F., Ribeiro, A., Munha, J., Fonseca, P.E., Brandao Silva, J., Moita, C., and Galopim de Carvalho, A., 1997, Ejecta from meteorite impact near the Cenomanian-Turonian boundary found at North of Nazaré, Portugal [abs.]: *Lunar and Planetary Science Conference*, 29th, Houston, Texas, Lunar and Planetary Institute, v. 2, p. 967–968.
- Monteiro, J.F., Munha, J., and Ribeiro, A., 1998, Impact ejecta horizon near the Cenomanian-Turonian boundary north of Nazaré, Portugal [abs.]: *Meteoritics and Planetary Science*, v. 33, p. A112–A113.
- Monteiro, J.F., Ribeiro, A., and Munha, J., 1999, The Tore “sea-mount”: A possible megaimpact in the deep ocean [abs.]: *Reports on Polar Research*, v. 343, p. 64–66.
- Moreau, M.G., Cojan, I., and Ory, J., 1994, Mechanisms of remanent magnetization in marl and limestone alternations: Case study: Upper Cretaceous (Chron 31–30), Sopelana, Basque Country: *Earth and Planetary Science Letters*, v. 123, p. 15–37.
- Moreno, C., and Sáez, R., 1990, Sedimentación marina somera en el Devónico del anticlinorio de Puebla de Guzmán, Faja Pirítica Ibérica: *Geogaceta*, v. 8, p. 62–64.
- Moreno, C., Sierra, S., and Sáez, R., 1995, Mega-debris flows en el tránsito Devónico-Carbonífero de la Faja Pirítica Ibérica: *Geogaceta*, v. 17, p. 9–11.
- Moreno, F., 1974, Las formaciones anteordovícicas del anticlinal de Valdelacasa: *Boletín Geológico y Minero*, v. 85, p. 396–400.
- Moreno, F., 1975, Olistostromas, fanglomerados y slump folds: Distribución de facies en las series de tránsito Cámbrico-Precámbrico en el anticlinal de Valdelacasa (provincias de Toledo, Cáceres y Ciudad Real): *Estudios Geológicos*, v. 31, p. 249–260.
- Moreno, F., 1977, Tectónica y sedimentación de las Series de Tránsito (Precámbrico terminal) entre el anticlinal de Valdelacasa y el Valle de Alcudia: Ausencia de Cámbrico: *Studia Geologica*, v. 12, p. 123–136.
- Nozal, F., and Robles, R., 1988, Series y correlación de los materiales anteordovícicos en los Montes de Toledo y el sur de Salamanca [abs.]: 2 Congreso Geológico de España, v. 1, p. 139–143.
- Ortega-Huertas, M., Martínez-Ruiz, F., Palomo, I., and Chamley, H., 1995, Comparative mineralogical and geochemical clay sedimentation in the Betic Cordilleras and Basque-Cantabrian Basin areas at the Cretaceous-Tertiary boundary: *Sedimentary Geology*, v. 94, p. 209–227.
- Pardo, M.V., and Robles, R., 1988, La discordancia basal del Grupo Valdelacasa en el Anticlinal de Valdelacasa (sector central de los Montes de Toledo) [abs.]: 2 Congreso Geológico de España, v. 2, p. 165–168.
- Pardo, A., Ortiz, N., and Keller, G., 1996, Latest Maastrichtian and K/T boundary foraminiferal turnover and environmental changes at Agost (Spain), in MacLeod, N., and Keller, G., eds., *Cretaceous-Tertiary mass extinctions: Biotic and environmental changes*: New York, Norton and Company, p. 139–171.
- Paul, C.R.C., Mitchell, S., Lamolda, M.A., and Gorostidi, A., 1994, The Cenomanian-Turonian boundary event in northern Spain: *Geological Magazine*, v. 131, p. 801–817.
- Peláez-Campomanes, P., 1993, *Micromamíferos del Paleógeno continental español: Sistemática, biocronología y paleoecología* [Ph.D. thesis]: Madrid, Universidad Complutense de Madrid, 385 p.
- Pena dos Reis, R.P., Corrochano, A., and Armenteros, I., 1997, El paleokarst de Nazaré (Cretácico Superior de la Cuenca Lusitana, Portugal): *Geogaceta*, v. 22, p. 149–152.
- Portero, J.M., and Dabrio, C., 1988, Evolución tectosedimentaria del Ordovícico y Silúrico de los Montes de Toledo meridionales y Campo de Calatrava [abs.]: 2 Congreso Geológico de España, v. 1, p. 161–164.
- Pujalte, V., Robles, S., Robador, A., Baceta, J.L., and Orue-Etxebarria, X., 1993, Shelf-to-basin Paleocene palaeogeography and depositional sequences, western Pyrenees, north Spain: *Special Publication International Association of Sedimentologists*, v. 18, p. 369–395.
- Ramajo, J., and Aurell, M., 1997, Análisis sedimentológico de las discontinuidades y depósitos asociados del Calloviense superior-Oxfordiense medio en la Cordillera Ibérica Noroccidental: *Cuadernos de Geología Ibérica*, v. 22, p. 213–236.
- Ramajo, J., Aurell, M., Delvene, G., and Pérez-Urresti, I., 2000, El Calloviense-Oxfordiense en el sector Oliete-Torre de las Arcas (Teruel): *Geotemas*, v. 1, p. 213–216.
- Robardet, M., and Doré, F., 1988, The Late Ordovician diamictic formations from southwestern Europe: North-Gondwana glaciomarine deposits: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 66, p. 19–31.
- Robles, R., and Alvarez-Nava, H., 1988, Los materiales precámbrico-cámbricos del Domo de Las Hurdes: Existencia de tres series sedimentarias separadas por discordancias, SO de Salamanca (Zona Centro-Ibérica) [abs.]: 2 Congreso Geológico de España, v. 1, p. 185–189.
- Rocchia, R., Boclet, D., Bonté, P.H., Buffetaut, E., Orue-Etxebarria, X., and Jéhanno, C., 1990, Structure de l’anomalie en iridium à la limite Crétacé-Tertiaire du site de Sopelana (Pays Basque Espagnol): *Comptes Rendus de l’Académie des Sciences*, v. 307, p. 1217–1223.
- San José, M.A. de, 1984, Los materiales anteordovícicos del Anticlinal de Navalpino (provincias de Badajoz y Ciudad Real, España central): *Cuadernos de Geología Ibérica*, v. 9, p. 81–117.
- Sandberg, C.A., Ziegler, W., and Morrow, J.R., 2000, Late Devonian events and mass extinctions [abs.], in *Catastrophic events and mass extinctions: Impacts and beyond*: Houston, Texas, Lunar and Planetary Institute, LPI Contribution No. 1053, p. 188–189.
- Santamaría, J., and Pardo, M.V., 1994, Las Megabrechas del Membrillar y su relación con el sustrato, Precámbrico-Cámbrico de la Zona Centro-Ibérica: *Geogaceta*, v. 15, p. 10–13.
- Santamaría, J., and Remacha, E., 1994, Variaciones laterales del “Nivel de Fuentes”, Precámbrico-Cámbrico de la Zona Centro-Ibérica: *Geogaceta*, v. 15, p. 14–16.
- Schmitz, B., 1988, Origin of microlayering in worldwide distributed Ir-rich marine Cretaceous/Tertiary boundary clays: *Geology*, v. 16, p. 1068–1072.
- Schmitz, B., Asaro, F., Molina, E., Monechi, S., von Salis, K., and Speijer, R.P., 1997, High-resolution iridium, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, foraminifera and nanofossil profiles across the latest Paleocene benthic extinction event at Zumaya, Spain: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 133, p. 49–68.
- Segura, M., García-Hidalgo, J.F., Carenas, B., and García-Quintana, A., 1993, Late Cenomanian-Early Turonian platform from central eastern Iberia, Spain: *American Association of Petroleum Geologists Memoir*, v. 56, p. 283–296.

- Sepkoski, J.J., 1996, Patterns of Phanerozoic extinctions: A perspective from global data bases, *in* Walliser, O.H., ed., *Global events and event stratigraphy*: Berlin, Springer-Verlag, p. 35–52.
- Smit, J., 1982, Extinction and evolution of planktonic Foraminifera after a major impact at the Cretaceous/Tertiary boundary, *in* Silver, L.T., and Schultz, P.H., eds., *Geological implications of impacts of large asteroids and comets on the earth*: Geological Society of America Special Paper 190, p. 329–352.
- Smit, J., 1990, Meteorite impact, extinctions and the Cretaceous-Tertiary boundary: *Geologie en Mijnbouw*, v. 69, p. 187–204.
- Smit, J., 1999, The global stratigraphy of the Cretaceous-Tertiary boundary impact ejecta: *Annual Review of Earth and Planetary Science*, v. 27, p. 75–113.
- Smit, J., and Hertogen, J., 1980, An extraterrestrial event at the Cretaceous-Tertiary boundary: *Nature*, v. 285, p. 198–200.
- Smit, J., and Klaver, G., 1981, Sanidine spherules at the Cretaceous-Tertiary boundary indicate a large impact event: *Nature*, v. 292, p. 47–49.
- Smit, J., and ten Kate, W.G.H.Z., 1982, Trace element patterns at the Cretaceous-Tertiary boundary: *Consequences of a large impact*: *Cretaceous Research*, v. 3, p. 307–332.
- Smit, J., and Romein, A.J.T., 1985, A sequence of events across the Cretaceous-Tertiary boundary: *Earth and Planetary Science Letters*, v. 74, p. 155–170.
- Smit, J., Klaver, G., and Van Kempen, T.M.G., 1987, Three unusually complete Spanish sections: Caravaca, Agost, Zumaya, *in* Lamolda, M.A., and Cearreta, A., eds., *Paleontology and evolution: Extinction events (2nd International Conference on Global Bioevents)*: Bilbao, Abstracts, p. 270.
- Sturesson, U., Heikoop, J.M., and Risk, M.J., 2000, Modern and Palaeozoic iron ooids: A similar volcanic origin: *Sedimentary Geology*, v. 136, p. 137–146.
- Usera, J., Molina, E., Montoya, P., Robles, F., and Santisteban, C., 2000, Límites entre sistemas y pisos en la Provincia de Alicante, *in* Cañaveras, J.C., García del Cura, M.A., and Meléndez, A., eds., *Itinerarios geológicos por la Provincia de Alicante y limítrofes*: Alicante, Spain, Universidad de Alicante, p. 43–58.
- Ward, P.D., 1988, Maastrichtian ammonite and inoceramid ranges from Bay of Biscay Cretaceous-Tertiary boundary sections, *in* Lamolda, M.A., Kauffman, E.G., and Walliser, O.H., eds., *Paleontology and evolution: Extinction events (2nd International Conference on Global Bioevents)*: Madrid, *Revista de Paleontología*, no. extraordinario, p. 119–126.
- Wiedmann, J., 1988, The Basque coastal sections of the K/T boundary: A key to understanding “mass extinction” in the fossil record, *in* Lamolda, M.A., Kauffman, E.G., and Walliser, O.H., eds., *Paleontology and evolution: Extinction events (2nd International Conference on Global Bioevents)*: Madrid, *Revista de Paleontología*, no. extraordinario, p. 127–140.

MANUSCRIPT ACCEPTED BY THE SOCIETY MARCH 22, 2001