Meteoritics & Planetary Science 37, 875-894 (2002)
Available online at http://www.uark.edu/meteor

Cosmic impact *versus* terrestrial origin of the Azuara structure (Spain): A review

ANGEL L. CORTÉS[1]*, ENRIQUE DÍAZ-MARTÍNEZ[2], ENRIQUE SANZ-RUBIO[2], JESÚS MARTÍNEZ-FRÍAS[2] AND CRISTINA FERNÁNDEZ[2]

[1]Departamento de Didáctica de las Ciencias Experimentales, Universidad de Zaragoza, 50009 Zaragoza, Spain
[2]Centro de Astrobiología (CSIC-INTA), Carretera de Ajalvir km 4, 28850 Torrejón de Ardoz, Madrid, Spain
*Correspondence author's e-mail address: acortes@posta.unizar.es

(Received 2001 July 30; accepted in revised form 2002 April 3)

Abstract–The Azuara structure is the largest one proposed so far in Spain as possibly related to a cosmic impact event. A review of the evidence set forward in favor of and against its cosmic origin indicates that the discussion is not yet finished. Some megascopic features (inverted stratigraphy, megabreccia, negative gravity anomalies) and shock-metamorphic effects (planar deformational features) have been described in relation with the structure, although their real significance has been questioned and is still being debated. Comparison with other similar-sized verified impacts suggests that unequivocal impactogenic features are yet to be found before the Azuara structure can be related to a cosmic impact. Until then, the Azuara structure should be considered as an unverified impact structure, and should not be included in global comprehensive maps of terrestrial impact structures.

INTRODUCTION

The recognition of large terrestrial impact craters is frequently inhibited by their erosion, deformation or burial. Most newly identified impact structures on the Earth's surface are first noted by some kind of anomalous circular or near-circular feature, such as a topographic or physiographic surface pattern, a circular region of anomalous rocks, or a circular geophysical anomaly associated with a surface or subsurface structure. These features may help in the detection of a possible meteorite impact site. However, there are many different geologic processes that may originate circular or near-circular features on the Earth's surface (volcanic processes, salt diapirism, igneous domes, *etc*.). Hence, it is only when unequivocal features such as shock-metamorphic effects (high-pressure mineral phases, diaplectic glass, planar deformational features) or shock megascopic features (shatter cones) are discovered in its rocks, that the structure is verified as related to a cosmic collision (Montanari and Koeberl, 2000). Only in such cases, when the characteristic features that are exclusive and unique to meteorite impacts are found, the structure can be considered without doubt a true meteorite impact structure.

The Azuara structure (Zaragoza province, northeast Spain; 41°12' N; 00°55' W), with a diameter of ~30 km, constitutes the largest proposed, but still unverified, meteorite impact structure in the Iberian Peninsula. After its identification as a possible impact structure (Ernstson *et al.*, 1985), a strong debate arose regarding its tectonic or impact-induced origin (Ernstson and Fiebag, 1992, 1993; Aurell *et al.*, 1993). The controversy about its origin still remains active among scientists (see, for example, Martínez-Ruíz *et al.*, 2001). The Azuara structure was initially recorded as one of the few large terrestrial impact structures (Grieve, 1987), and its location is commonly still represented in recent maps of known impact structures (Grieve *et al.*, 1995; French, 1998). However, one of the most recent reviews does not include it in the listing of terrestrial impact structures younger than 250 Ma and larger than 5 km (Montanari and Koeberl, 2000).

The purpose of this paper is twofold. Our main objective is to provide a summary and update of the evidence presented in favor and against the impact-related origin of the Azuara structure. We base this review both on published data and on our knowledge of the local and regional geology. We also present and discuss diverse debatable features that may be considered essential to resolving the controversy. Our secondary objective is to support the removal of the Azuara impact site from impact crater databases, at least until conclusive, thoroughly contrasted, and unequivocal shock-metamorphic features are found. In this direction, and however biased our approach may seem, our intention is to refute the impact hypothesis, as we consider and finally conclude that the evidence so far provided for impact metamorphism related to the Azuara structure is still inconclusive and not sufficiently convincing.

GEOLOGICAL SETTING

The Azuara structure is located ~50 km south of Zaragoza, in the northeastern border of the Iberian Range, close to the Ebro Basin (northeast Spain). The present-day observed structure of the Azuara region corresponds to a sedimentary basin infilled by Cenozoic deposits and limited by folds and thrusts involving Precambrian–Paleozoic, Mesozoic and Cenozoic rocks (Figs. 1 and 2). The Precambrian and Paleozoic series in the area exceed 7000 m in thickness (Lotze, 1961; Carls, 1975, 1977; Ferreiro *et al.*, 1991) and consist of slightly metamorphosed sedimentary rocks (shales, quartzites and occasional limestones) affected by Variscan orogeny. Triassic deposits in Germanic facies (Garrido and Villena, 1977) are more than 300 m thick in this area. The Lower and Middle Triassic sandstones, mudstones and carbonates (in Buntsandstein and Muschelkalk facies) form a single structural

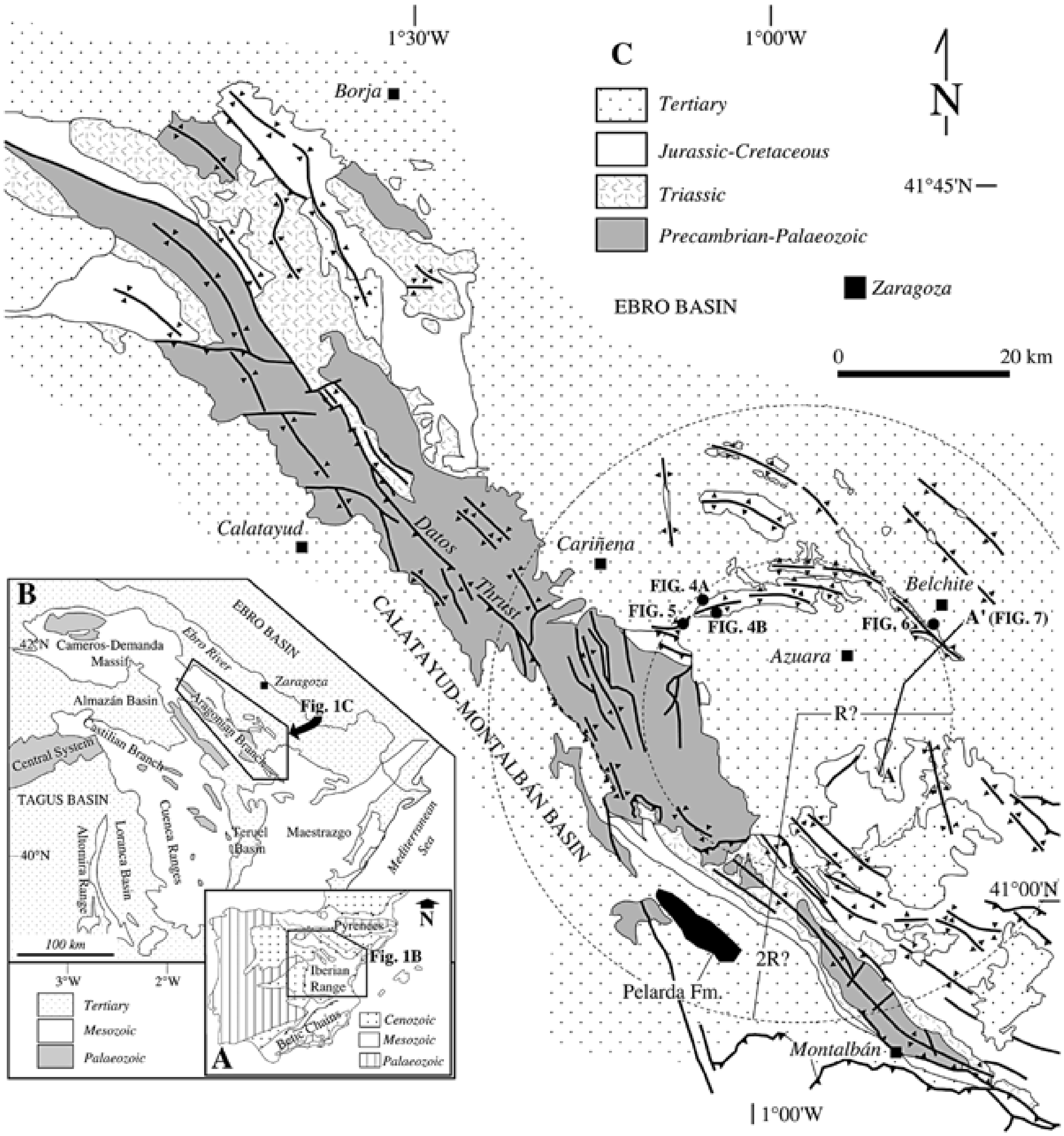

FIG. 1. (a) Location of the Azuara area within the Iberian Peninsula. (b) The Azuara structure within the geological context of the Iberian Range and Ebro Basin. (c) Geological sketch of the Azuara structure and adjacent Calatayud–Montalbán and Ebro basins (modified from Cortés and Casas, 1996). Pelarda Formation is located within the Calatayud–Montalbán Basin, south of the Azuara structure, that is encircled in the map. (R) indicates the radius of the Azuara structure suggested by Ernstson and colleagues, who indicate that ejecta and other evidences were found within a (2R) distance from the center of the structure. Location of the cross-section of Fig. 7 is shown (A–A'). Black circles indicate location of photographs (Figs. 4, 5 and 6).

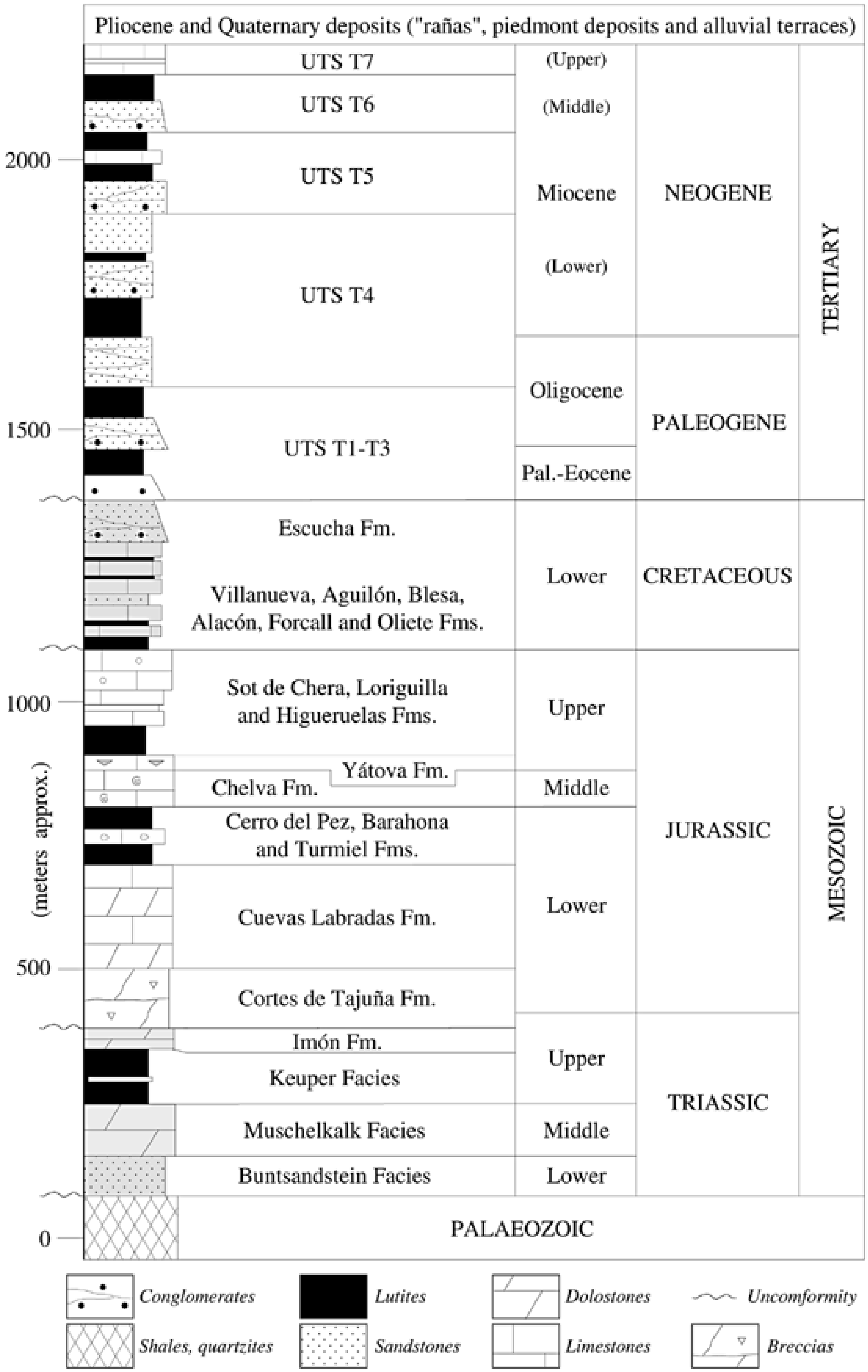

FIG. 2. Stratigraphic sequence of the Mesozoic and Cenozoic units cropping out in the studied area (approximate thickness).

unit with the Variscan basement. The Upper Triassic (Keuper facies) consists of gypsum and mudstones, and serves as a *décollement* level separating the sedimentary cover from the structural "basement" (Middle Triassic and older). The Jurassic units consist of limestones and marls, 700–800 m thick, deposited in extensive carbonate ramps and with an homogeneous distribution along the studied area (Bulard, 1972; Aurell, 1990; Salas and Casas, 1993). Lower Cretaceous deposits (Valanginian to Early Barremian) were deposited in continental environments (alluvial, deltaic and lacustrine systems) and have been related to extensional tectonics (Soria, 1997; Cortés *et al.*, 1999). Cenozoic sediments (Paleogene and Neogene) consist of continental deposits related to alluvial fans and lacustrine systems with both clastic and carbonate facies, reaching a thickness of 800 m (Pérez, 1989; Villena *et al.*, 1996).

The western border of the Azuara structure corresponds to a Paleozoic massif displaying large north–south tectonic structures involving Late Cambrian to Devonian rocks (Capote and González-Lodeiro, 1983). The main structures are east-verging thrusts and folds with steep limbs, which display a penetrative cleavage (specially axial plane cleavage in shales and siltstones) due to ductile tectonic deformation during Variscan orogeny (Ferreiro *et al.*, 1991). The southern border consists of a northwest–southeast complex antiformal structure with Paleozoic core, and which separates the Ebro Basin from the Calatayud–Montalbán Basin (Fig. 1). North of this antiform there are northwest–southeast minor folds and slightly deformed zones involving the Mesozoic cover (Cortés and Casas, 1996).

The structure of the northern border of the Azuara Basin is characterized by Mesozoic rocks along an east–west to northwest–southeast arcuate band of folds and thrusts (Figs. 1 and 3). The main structures of this northern area are symmetric gentle folds with limbs dipping <30° and asymmetric north-verging folds with near vertical forelimbs (Fig. 4a,b; Cortés and Casas, 1996). The restoration of compressional structures indicates a shortening of 12.2%, mostly related to the major anticlines (Aguilón, Belchite and Muel–Jaulín anticlines; Cortés *et al.*, 1999).

The chronology of the main contractional deformations has been established from the Tertiary syntectonic deposits

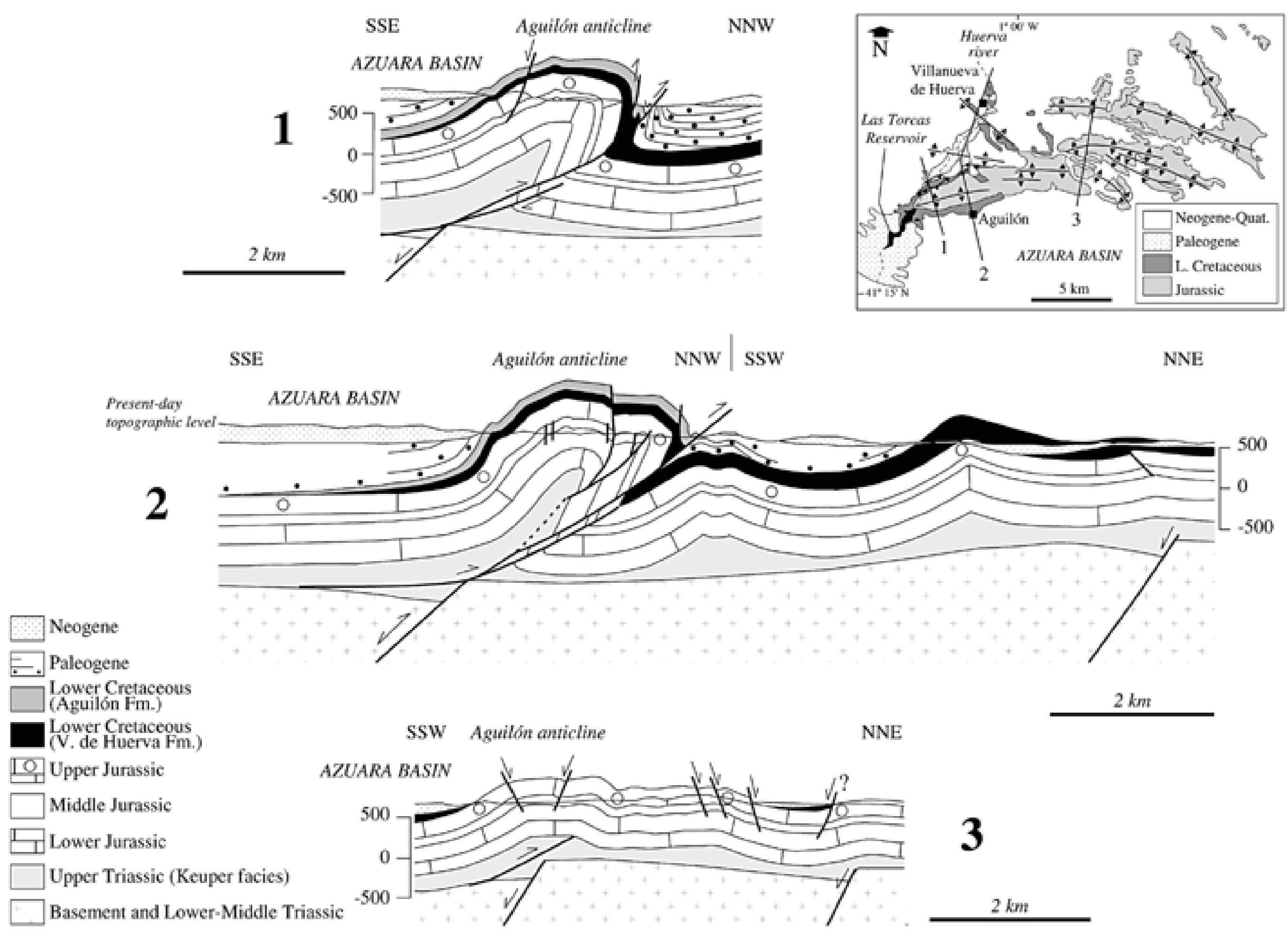

FIG. 3. Geological cross-sections through the Aguilón anticline. Traces are shown in the geological sketch.

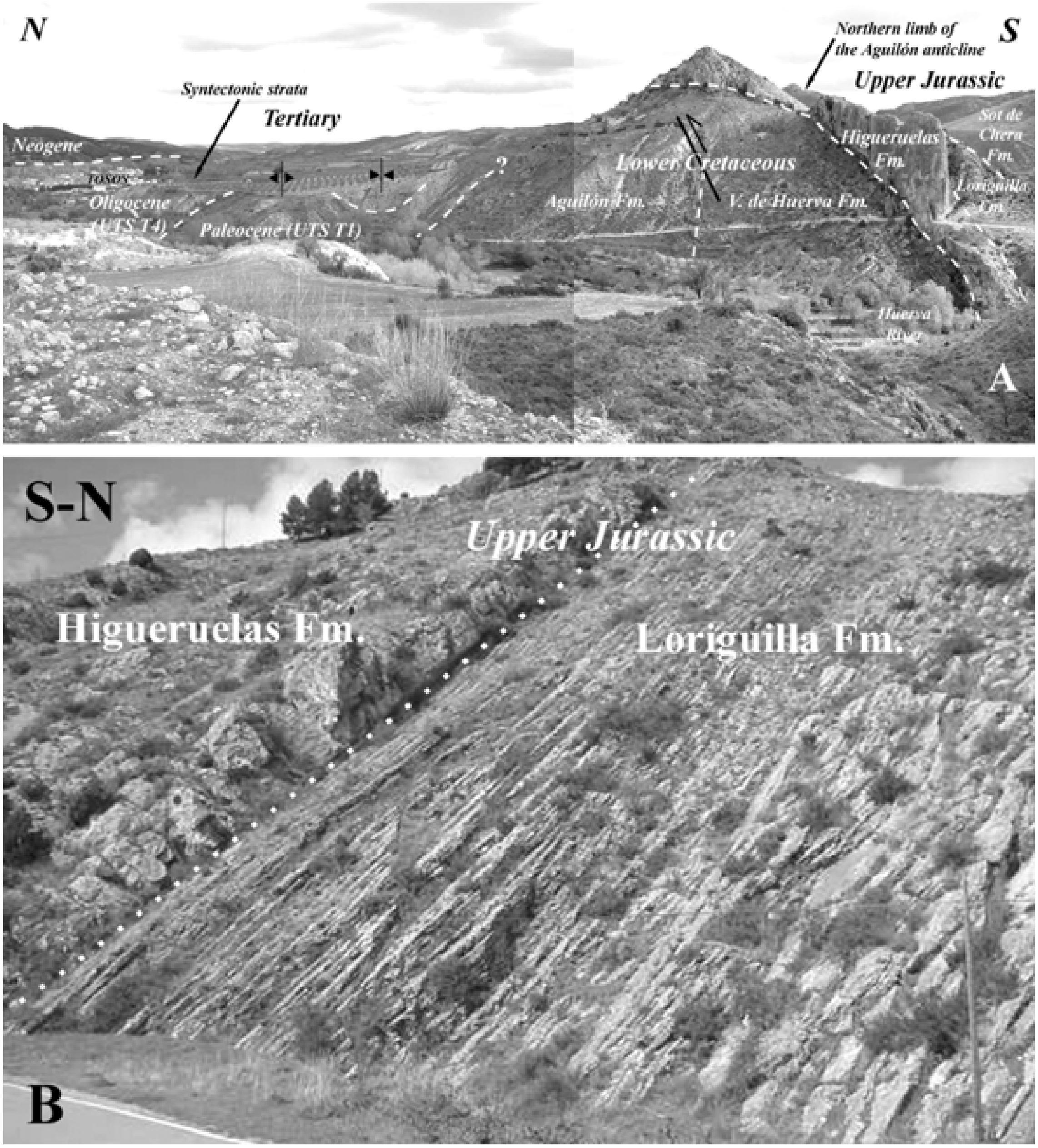

FIG. 4. (a) Panoramic view of the northern limb of the Aguilón anticline at the Huerva Valley (north of Las Torcas Reservoir). The main relationships between Jurassic, Cretaceous and Tertiary units are shown: Upper Jurassic units correspond to the vertical limb of the anticline. Lower Cretaceous units show a wedge geometry probably related to syn-sedimentary extensional processes (Cortés *et al*., 1999). Paleocene unit (T1) corresponds to the Tertiary pre-folding strata. Oligocene unit (T4) corresponds to the syn-folding growth strata. Neogene rocks are horizontal (post-folding strata) and unconformably overlying the previous Mesozoic and Tertiary folded units. (b) Upper Jurassic limestones cropping out at the southern limb of the Aguilón anticline showing a normal stratigraphic way-up (see location in Fig. 1).

associated to folds and thrusts (Pérez, 1989; Casas *et al*., 2000a). A Paleocene unit (T1) overlies the Mesozoic deposits and is unconformably overlain by folded Late Oligocene deposits (T4). This Oligocene unit (Chattian–Agenian in age) is related with the uplift of large anticlines (*e.g.*, Aguilón anticline; Fig. 4a) that became the source of clastic materials. These two units were folded together with the Mesozoic beds to form the main anticlines, displaying growth-strata geometries (Fig. 5) and syntectonic unconformities (Fig. 6). Neogene deposits within the Azuara Basin (T5, T6 and T7 units: Agenian–Vallesian in age) are horizontal or only slightly deformed, and onlap the folded structures. In contrast to the Azuara Basin, the late

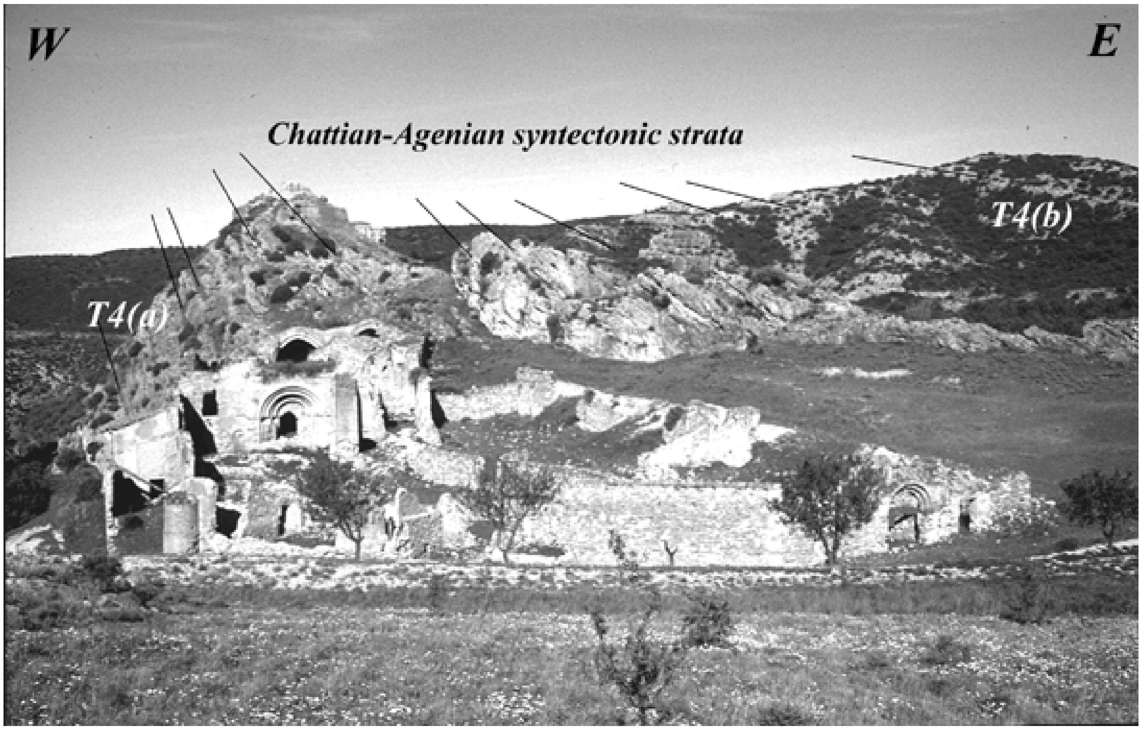

FIG. 5. Conglomerates of the unit T4 (Chattian–Agenian) cropping out at Las Torcas Reservoir area, northwestern border of the Azuara structure (approximate coordinates: 41°16.1' N, 1°6.7' W, see location in Fig. 1). The thickness of this unit reaches at least 500 m in this area. A fan-shaped bedding can be observed in this photograph. Rotation of bedding-dip to the top indicates that sedimentation was simultaneous to the uplift of the anticline.

compressional stages in this part of the Eastern Branch of the Iberian Range did affect Middle and Upper Miocene deposits in the Calatayud–Montalbán Basin (Colomer, 1987; Simón, 1989; Casas *et al.*, 2000a; Sanz-Rubio *et al.*, 2001).

THE CONTROVERSY

A research team led by K. Ernstson (University of Würzburg, Germany) proposed an impact-induced origin for the Azuara structure based on alleged evidence such as the local presence of inverted stratigraphy, megabreccias and megablocks, breccia dikes, a negative gravity anomaly, and features indicative of high-pressure and high-temperature effects (Ernstson *et al.*, 1985, 1987; Ernstson and Claudín, 1989, 1990; Mayer, 1991; Ernstson and Fiebag, 1992; Ernstson, 1994). To date, ~20 publications (including meeting abstracts and articles published both in local and international journals) and 11 unpublished works (1 Ph.D. thesis and 10 diploma theses) support the hypothesis of a cosmic impact origin for the Azuara structure.

Several lines of evidence were presented against the hypothesis of a meteorite impact (Aurell *et al.*, 1993) based on the local and regional sedimentary and structural evolution of the Azuara area within the Iberian Range and the Ebro Basin. Alternative interpretations for each of the criteria used as evidence by the group supporting the impact hypothesis are shown in Table 1. Subsequently, Cortés and Casas (1996) and Cortés *et al.* (1999) suggested that the structure of the Azuara region is consistent with north–south regional shortening during the Tertiary (Alpidic orogeny), and which controlled deformation affecting both the Variscan basement and the Mesozoic–Tertiary sedimentary cover. In these works, the Azuara structure is interpreted as a broad synclinal piggy-back Tertiary basin over an important depression of the Variscan basement (Fig. 7). The Azuara Basin is bounded by a small arcuate fold-and-thrust belt in the northern part (Belchite–Aguilón), partially controlled by inherited Mesozoic extensional faults nucleating Tertiary folds and thrusts (Cortés *et al.*, 1999), and a poorly-defined fold-and-thrust system towards the south (Casas *et al.*, 1997).

REVIEW OF FEATURES

In the next paragraphs we summarize important macroscopical and microscopical features used in the identification of terrestrial impact structures (following French, 1998) as they relate to the evidence set forward in favor and against the impact-induced origin of the Azuara structure. We also present a comparison between different criteria and lines of evidence present in the Azuara structure (Spain) and in the

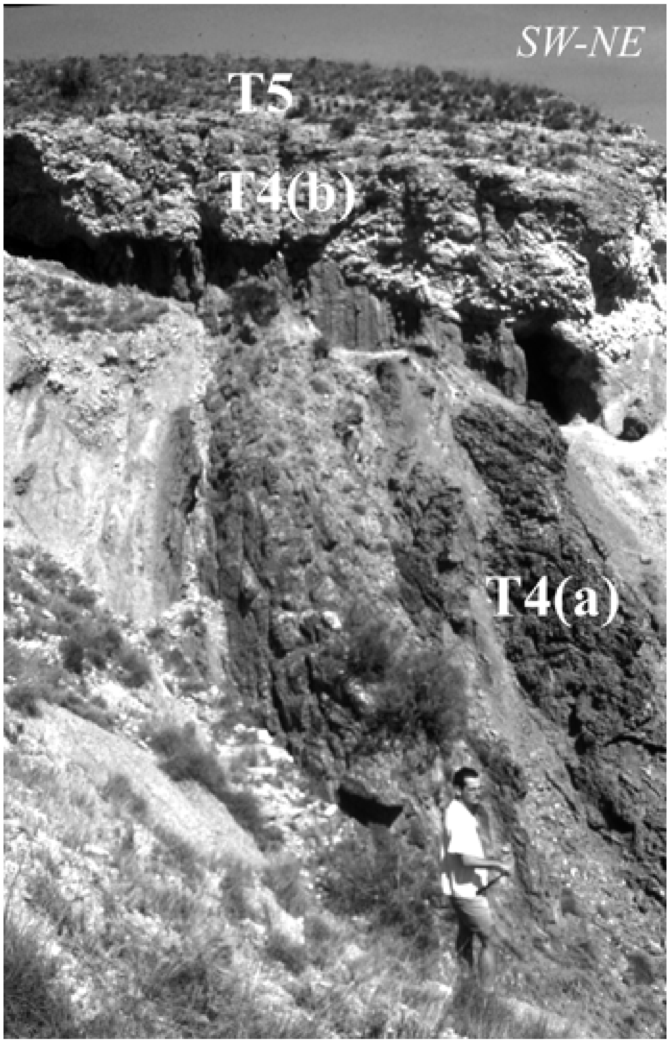

FIG. 6. Angular unconformities in the Paleogene and Neogene units close to the Belchite anticline, northeastern border of the Azuara structure (approximate coordinates: 41°17.7' N, 0°48.6' W, see location in Fig. 1). Unit T4(a) is subvertical and consists of lutites, sandstones and conglomerates with calcareous pebbles. T4(b) is dipping 15–20° northeast, unconformably overlies T4(a), and is mainly composed of conglomerates with calcareous clasts. The Neogene unit (T5) is horizontal and onlaps T4. It consists of conglomerates with siliceous pebbles. This kind of angular relationships (within Paleogene units and between Paleogene and Neogene units) is very common in several outcrops in the northern Iberian Chain.

Ries structure (Germany) (Table 1). According to Ernstson *et al.* (1985) and Ernstson and Fiebag (1992) both structures show similar features.

Surface Morphology and Geologic Structure

Surface Expression and Shape–Impact structures usually tend to present a rounded or elliptical shape due to centrifugal forces during impact explosion, in conjunction with centripetal

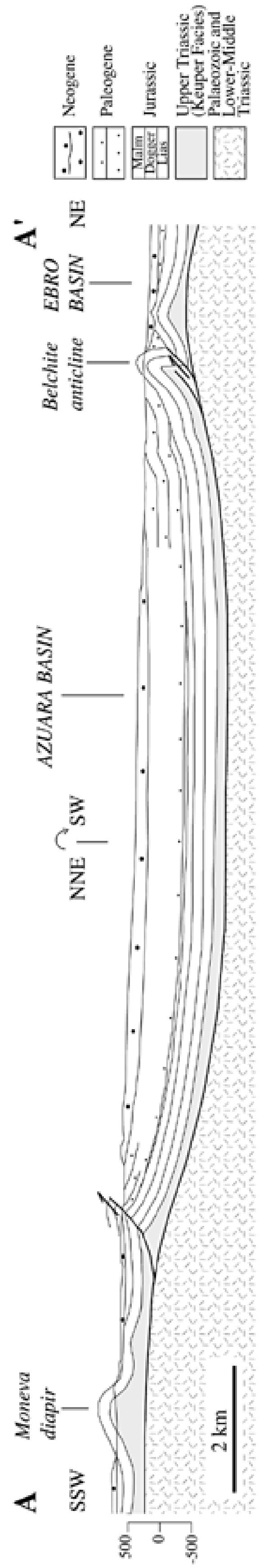

FIG. 7. Geological cross-section trough the eastern part of the Azuara structure. Location is shown in Fig. 1C (modified from Cortés and Casas, 1996).

TABLE 1. Description and interpretation of features present in the Azuara structure and in the Ries crater.*

Feature	Azuara (Spain)	Ries (Germany)
Shape of the basin	Roughly polygonal (boundary locally absent), ~30 km Ø.	Almost perfectly round, ~24 km Ø.
Central uplift	Not present.	Inner ring of crystalline basement rocks.
Drillholes	None within or outside the structure reaching any unambiguous impact-related material.	Many within and outside the structure reaching impact-related material.
		Deep drilling (Nördlingen 1973) showed a thick suevite layer 325–600 m deep.
Structural features	(A) Peripheral anticlines and intense block faulting are impact-related.	Impact-related block faulting superimposed over regional structure (Alb foreland).
	(B) All tectonic features along basin margins are due to Variscan and Alpidic orogenies.	No peripheral anticlines.
Age of the structure	(A) Eocene-Oligocene.	Middle Miocene (14–15 Ma).
	(B) Final configuration of the structure results from Alpidic orogeny (Oligocene–Miocene).	
Sedimentary fill	(A) Miocene–Pliocene post impact.	Late Miocene–Pliocene (Ries lake).
	(B) Complex syntectonic Cenozoic continental sedimentary sequence, ~800 m thick, filling in a piggy-back basin.	
Target materials	(A) Sedimentary rocks of the Ebro Basin.	Basement and sedimentary rocks of Alb foreland.
	(B) No such thing.	
Gravity anomalies	(A) Broad negative anomaly within the ring.	Conspicuous negative anomaly with respect to regional base.
	(B) Gravity data are incomplete, restricted to the interior of the basin, and not referred to regional base.	
Other geophysical studies	(A) Total magnetic field study, but no anomaly detected.	Many seismic, geoelectric and magnetic studies consistent with an impact crater interpretation.
	(B) None performed.	
Megabreccia	(A) One stratiform layer as a result of *in situ* impact-related brecciation.	Widespread within crater (megablock zone) and outside the crater (Bunte Breccia ejecta blanket).
	(B) Actually refers to regional lithostratigraphic units (Imón and Cortes de Tajuña Formations) with frequent brecciation and collapse features.	
Globular breccia	(A) Lapilli breccia found *ex situ* (not within the main ring).	No such thing.
	(B) No such thing. Actually refers to caliche-like crusts and paleosol features.	
Basal breccia	(A) Polymict breccia unconformably overlying Mesozoic and Lower Tertiary sediments.	Included with widespread ejecta (Bunte Breccia).
	(B) No such thing. Actually corresponds to Middle Miocene sedimentary conglomerates (unit T6).	

TABLE 1. *Continued*.

Feature	Azuara (Spain)	Ries (Germany)
Breccia dikes	(A) Wide variety of dikes with monomict or polymict breccias with clasts from the host rock and allochthonous components.	Wide variety, with suevite infill and shock metamorphic features clearly relating them to an impact.
	(B) No such thing related to an impact. Poor evidence provided, and ambiguous information about their location, orientation and distribution. May correspond to dikes or fracture infill related to paleosol development (some include *Microcodium*).	
Impact melting	(A) Partially melted quartz grains in dike breccias, and carbonate melt in basal breccias and dike breccias.	Widespread suevite (including a thick suevite layer 325–600 m deep), tagamite also present (Amerbach, Polsingen).
	(B) No such things. Poor evidence for melting.	
Shatter cones	(A) A few *ex situ* (Jurassic limestone debris within the main ring), but none *in situ*.	Relatively frequent, and specially in nearby (twin?) Steinheim impact crater.
	(B) No such things. Alleged identifications are really misinterpretations.	
Impact shock metamorphism	(A) Quartz with planar features and planar cleavage in polymict ejecta breccia (Pelarda Formation).	Widespread impact shock metamorphism with all different shock metamorphic stages developed.
	(B) No PDFs. Absence of any shock-metamorphic effect in all TEM-checked samples.	
Mosaicism in calcite and quartz	(A) Impact-related.	Widespread.
	(B) Due to diagenesis, tectonism or metamorphism (not impact-related).	
Kink bands in biotite	(A) Impact-related.	Frequent.
	(B) Due to Variscan deformation and metamorphism (not impact-related).	
Impact ejecta	(A) Pelarda Formation, located to the south of the structure.	Widespread impact ejecta (megablock outer ring, Bunte Breccia).
	(B) No such thing. The Pelarda Formation is a Pliocene–Pleistocene(?) alluvial fan deposit ("Raña" facies).	
Origin of basin	(A) Impact crater.	Impact crater.
	(B) Small syntectonic (piggy-back) basin formed under compression, and bounded by folds and overthrusts.	

*Where appropriate, a comparison of the two main different hypotheses proposed for the interpretation of the Azuara structure is included, (A) refers to impact hypothesis and (B) to non-impact hypothesis.

post-impact collapse and erosional processes. The shape of the Azuara sedimentary basin is not circular, but instead rather polygonal (Fig. 1). It is roughly outlined in its northern part by north to northeast-verging folded Mesozoic layers emerging from the Tertiary Ebro Basin with west–east to northwest–southeast trends, and towards the south by northeast-verging thrusts of Paleozoic and Mesozoic rocks forming part of the Eastern Iberian Range. The interior of the basin is characterized by an almost flat topographical surface with a very gentle northeast-dipping slope, in agreement with the Ebro Basin context.

According to its size, much greater than the transition diameter of terrestrial impact craters (2–4 km), the Azuara structure should correspond to a complex crater with central uplift. However, no internal relieves or outcrops can be observed towards the center of the structure that may resemble the central uplift and/or inner ring typically present in verified impact craters with similar diameter (*e.g.*, Ries crater).

Sedimentary Fill–Tertiary sediments infilling the Azuara Basin are mostly Late Oligocene to Miocene and consist of alluvial fan deposits and distally related lacustrine systems in a succession of more than 800 m in thickness which has been subdivided into five sedimentary units (Pérez, 1989; Villena *et al.*, 1996; Casas *et al.*, 2000a). The two lower units (T1 and T4) present few outcrops, and were deposited synchronously with compressive deformation (specially T4). They show growth-strata geometries related to the development of the anticlines, and are bounded by angular unconformities towards the margins of the basin (Pérez, 1989; Cortés and Casas, 1996; see Figs. 5 and 6). The existence of mammal paleontological sites within syntectonic deposits cropping out along the borders of the Azuara structure (Pérez *et al.*, 1985; Pérez, 1989) allows to date the main folding stage as Late Oligocene–Early Miocene (~23 Ma). These data are consistent with the age of folding suggested for the rest of the Iberian Chain (Villena *et al.*, 1996; Muñoz-Jiménez and Casas-Sainz, 1997; Casas *et al.*, 2000a,b). The Neogene units (T5 to T7) are post-tectonic and were deposited horizontally and unconformable over previous units. No impact-related layer such as those present in other verified impact craters has ever been identified within the Azuara structure.

Structural Features–Terrestrial impact craters exceeding 4 km in diameter generally produce allochthonous and dislocated megablocks ejected from the target during the impact process, and which can be found both within the final structure and around the crater rim. Ernstson and Fiebag (1992) reported megablocks of Paleozoic and Buntsandstein sedimentary rocks laying over Keuper marls, Paleozoic quartzites overlying Cretaceous sedimentary rocks, and large boulders of Paleozoic Armorican quartzite found along the northeastern Mesozoic border of the Azuara basin. However, no clear and precise location or convincing photographs have been provided that resemble the megablocks and tectonic structures associated with other verified impact craters. In most cases, the evidence provided to support the age of the megablock material is rather poor and based solely on facies correlation.

Other structural features, such as the peripheral arc-shaped folding affecting Mesozoic rocks along the northern margin of the structure, and the intense block faulting at the south and southwest, do not provide unequivocal evidence for the impact origin. From the point of view of impact cratering, the formation of large peripheral anticlines would be interesting. However, folding of the structure along the northern margin can be explained as the result of a non-homogeneous displacement of the Jurassic to Cenozoic cover above the regional detachment level (very common in many fold and thrust belts) and/or due to several deformation stages (Cortés and Casas, 1996). Except for the northern border, folds and thrusts surrounding the Azuara structure are not consistent with centrifuge forces inducing peripheral folding: the main folds and thrusts affecting Mesozoic and Tertiary units throughout this part of the Iberian Range are north to northeast-verging, even east-verging in Paleozoic rocks.

Intense block faulting, folding and overthrusting constitute a common feature of the Paleozoic–Mesozoic rocks of the Iberian Range. Variscan and Alpidic deformations affected with variable degrees the different Phanerozoic sedimentary units throughout the Iberian Range, resulting in complex tectonic structures. The interpretation of the structural features of the Azuara structure within their local and regional context allows to relate them with Variscan and Alpidic deformation (Viallard, 1979, 1980, 1983; Capote and González-Lodeiro, 1983; Ferreiro *et al.*, 1991; Aurell *et al.*, 1993; Cortés and Casas, 1996; Casas *et al.*, 1997, 2000a; Cortés *et al.*, 1999), rather than with an impact.

Impact Ejecta–Finding impact ejecta layers in the geological record has greatly contributed to the recognition of their source impact craters (Montanari and Koeberl, 2000). Large recent impact craters are surrounded by a deposit of debris ejected as the result of the collision and explosion. Most ejecta lie close to the crater rim, and continuous ejecta in non-oblique impacts usually extend about one crater radius from the crater rim (Melosh, 1989).

Towards the south of the Azuara structure, the clastic Pelarda Formation was interpreted as the ejecta of the Azuara impact (Ernstson and Claudín, 1990). Covering an area of roughly 30 km^2, it is basically composed of well-rounded quartzite clasts rarely exceeding 1 m in diameter, found within a muddy-sandy matrix and with an overall chaotic aspect. The origin and age of this unit still remains one of the most important debatable matters regarding the Azuara structure. Carls and Monninger (1974) described the Pelarda Formation within the Calatayud–Montalbán Basin as basically composed of Paleozoic clasts (quartzite and shale). "After the climax of alpidic movements (Late Oligocene–Early Miocene), the southeast part of the Eastern Iberian Chain was denudated to form the Peña Tajada surface. This was (locally?) covered by more than 200 m of a fluvial boulder conglomerate, the Pelarda Formation" (Carls and Monninger, 1974). These authors also reported some Buntsandstein pebbles, but did not observe limestone components. Their interpretation about the origin of this formation suggests its deposition after the Late Oligocene–Early Miocene compressional movements, unconformably overlying a Neogene erosion surface leveling the eastern Iberian Range.

Ernstson and Claudín (1990) added to the previous work the alleged identification of Buntsandstein megaclasts, a few limestone clasts, and Lower Tertiary marls admixed with the conglomerates. The Pelarda Formation is ~10 km distant from the supposed crater rim and overlies alluvial fan deposits of the adjacent Calatayud–Montalbán Basin (Fig. 1). Ernstson and Claudín (1990) and Ernstson and Fiebag (1992) pointed out that this unit is an isolated deposit located within the Calatayud–Montalbán Basin, and interpreted it as a remnant of an originally extended ejecta blanket around the Azuara structure. In addition, Ernstson and Fiebag (1992) and Claudín *et al.* (2001) described a second prominent ejecta deposit at Puerto Mínguez Pass, ~40 km to the southeast of the border of the structure. Apart from these, other similar deposits that could also be impact-induced ejecta have never been proposed elsewhere around the Azuara structure.

In contrast, the Pelarda Formation is interpreted in most of the Spanish geological literature as one of the many outcrops of Pliocene–Quaternary continental deposits frequent in central Spain in relation to local reliefs (Lendínez *et al.*, 1989; Ferreiro *et al.*, 1991; Aurell *et al.*, 1993, among others). No clear data have been provided by the authors who defend the impact origin of these deposits, and some evidences remain unexplained (*e.g.*, identification and dating of Lower Tertiary marls and Triassic megaclasts). The data provided in the aforementioned Spanish literature, together with our own field observations, support the traditional hypothesis as a remnant of Pliocene–Pleistocene alluvial deposits (locally named "Raña"). These include the existence of bedding, interbedded edaphic paleosol features, increase of grain size towards the south, conspicuous roundness of the clasts, lithofacies analysis, stratigraphic correlation of the unit, and its geomorphic location within the Calatayud–Montalbán Basin. Detailed sedimentologic and paleontologic studies of the Pelarda Formation are currently underway in order to test the hypotheses.

Striations–Rounded to subrounded striated and polished boulders and cobbles of slates, schists and quartzites were described by Ernstson and Claudín (1990) in the Pelarda Formation. Plastically deformed and fractured clasts, many of them showing rotational deformation, and multiple deformation features are also described by these authors as evidence for shock deformation (Ernstson *et al.*, 1990; Claudín *et al.*, 2001).

Striated and polished pebbles, as well as pressure solution pits, have long been known to be a common feature in conglomerate deposits affected by regional stress deformational processes (Blum, 1840; Judson and Barks, 1961; Trurnit, 1968; Campredon, 1977; Petit *et al.*, 1985; Maestro and Casas, 1995; Rodríguez-Pascua and De Vicente, 1998, among others). Their occurrence depends on factors such as lithology, grain-size ratios, interstitial water, and tectonic stress (Hossain, 1978; Sanz de Galdeano and Estévez, 1981; Schrader, 1988; Taboada, 1993). We have identified these features in carbonate clasts in both supposed pre-impact (Paleocene conglomerates close to Fonfría village) and post-impact (Middle Miocene conglomerates in Puerto Mínguez road pass; Pérez, 1989; Casas *et al.*, 2000a) sedimentary units. These features are closely related with the regional stress, as demonstrated by the study of the stratigraphic section cropping out at Puerto Mínguez (Casas *et al.*, 2000a). Here, the nearby (distant <1 km) thrusting of Cretaceous carbonates over Paleogene clastic deposits during the Miocene (Viallard, 1983; González and Guimerà, 1993; Casas *et al.*, 2000a) originated lithological changes in the source area for the Miocene conglomerates (from quartzitic to carbonate source; Pérez, 1989), and the simultaneous development of the aforementioned deformation features (polished, striated and pitted carbonate pebbles), which are common throughout the section.

Ernstson and Claudín (1990) indicate that striae directions in the sampled pebbles of the Pelarda Formation are not randomly distributed: their directional mode is northeast–southwest, "pointing to the center of the Azuara structure". In a meteorite impact, striae created by the instantaneous stress state related with the collision should be randomly distributed in the ejecta clasts (theoretically with chaotic deposition), whereas they should be approximately radial on the abraded substrate. These data reveal that striations are not related to the impact if ballistic deposition is proposed, unless a syn-depositional deformation took place. This preferential orientation of clast striations indicates that tectonic deformation affected the pebbles after their deposition, and suggests the existence of a tectonic stress regime affecting the sedimentary materials of the Pelarda Formation. The tectonic stress regime present during the Tertiary and Quaternary, with northeast–southwest maximum horizontal stress, has been inferred by several authors in the regional literature (Simón, 1986, 1989; Liesa and Simón, 1994; Cortés and Maestro, 1998, among others), coinciding with the aforementioned measurements.

Cratering and Spallation of Buntsandstein Conglomerate Clasts–Apart from the aforementioned striations and pits developed in Cenozoic conglomerate clasts, Ernstson *et al.* (1994, 1999, 2001b,c) also describe microcraters developed on the surface of quartz and quartzite pebbles and cobbles from Latest Permian–Early Triassic Buntsandstein-facies conglomerates. These authors propose this type of feature as an indicator of shock deformation in the vicinity of large impacts, in this particular case of the Azuara structure and its alleged companion, Rubielos de la Cérida structure. However, this interpretation is difficult to reconcile with the widespread distribution of these features throughout Spain and other countries in Europe (Cortés *et al.*, 2002). In particular, this type of feature is quite common throughout the Iberian Range and most areas where Buntsandstein conglomerates are present (Fig. 8). The small pits or craters are known in Spanish geology as "percussion" or "pressure-solution" marks, and are found not only along the northeastern (Aragonian) branch of the Iberian Range (García-Royo and Arche, 1987), but also along the southeastern (Castillian) branch of the Iberian Range (Trurnit, 1968; Marfil *et al.*, 1977; Ramos, 1977), even at its western end, in the eastern Segovia province (Hernando, 1980). Furthermore, they are also found in the same stratigraphic position (basal conglomerates of the Buntsandstein facies) in the Catalan Coastal Ranges (Virgili *et al.*, 1977) and in the Pyrenees (Olivé-Davo *et al.*, 1990). These features are normally

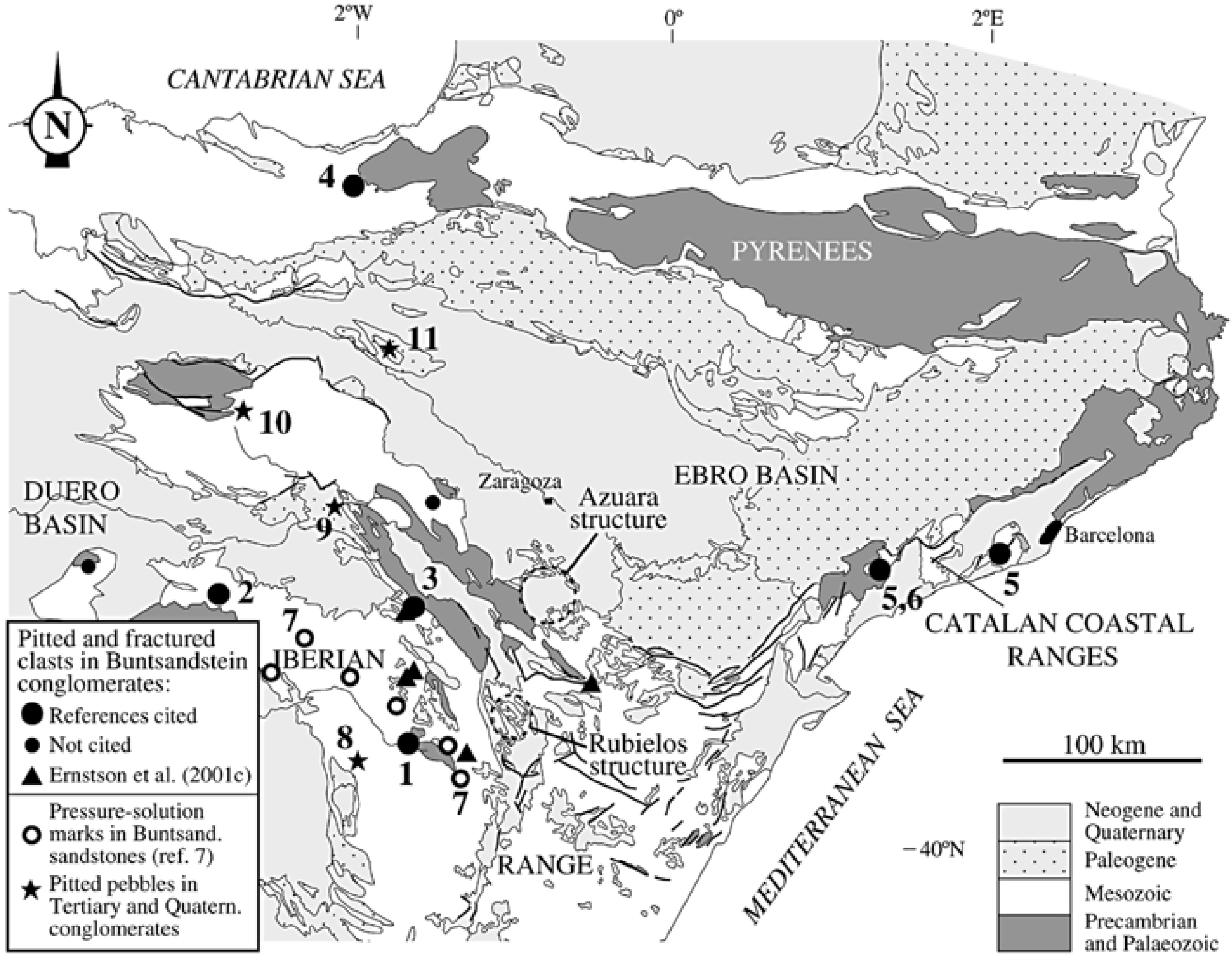

FIG. 8. Location of conglomerates exhibiting cratered and fractured clasts. Black triangles indicate outcrops studied by Ernstson *et al.* (2001c). Black circles indicate representative outcrops of Buntsandstein conglomerates studied by (1) Trurnit (1968), (2) Hernando (1980), (3) García-Royo and Arche (1987), (4) Olivé-Davo *et al.* (1990), (5) Virgili (1958) (6) Virgili *et al.* (1977). Location of other well-documented outcrops (not cited) is also shown (small black circles). White circles indicate pressure-solution marks in Buntsandstein sandstones, (7) Marfil *et al.* (1977). Stars indicate some outcrops of Tertiary and Quaternary rocks containing striated and/or pitted pebbles, (8) Rodríguez-Pascua and De Vicente (1998), (9) Maestro *et al.* (1997), (10) Casas (1992), (11) Benito and Casas (1987).

explained as resulting at contacts between clasts due to localized pressure during diagenesis and compression, both lithostatic and tectonic (see discussion in Cortés *et al.*, 2002).

Age of the Structure–Impact structures can be dated by means of radiometric dating of impact melt rocks and other impact-derived minerals and rocks directly in or around the crater. Another possibility is to date the impact ejecta based on biostratigraphic data (Montanari and Koeberl, 2000). No radiometric methods have ever been applied in order to date the Azuara structure. Also, Neogene sediments of the Azuara basin (connected to the Ebro Basin) cover almost the total surface area of the structure, and deep boreholes are absent. On the assumption that the Azuara structure constitutes an impact crater, and because the existence of impact melt or impact-derived minerals has not been shown, only biostratigraphical and lithostratigraphical methods can provide an age for the alleged related ejecta. A Late Eocene–Oligocene age was proposed for the Pelarda Formation, because the Miocene sediments within the Azuara Basin are only slightly affected by tectonism, and Eocene sediments are incorporated in the clastic Pelarda Formation and breccia dikes generated during the impact (Ernstson and Fiebag, 1992). However, the methodology used to date these Eocene sediments is not described in their work. A more precise age for the alleged impact is needed, because the inferred Late Eocene to Oligocene proposed age is broadly contemporary with the age of the two largest known impact craters of the Cenozoic Era (Popigai and Chesapeake Bay), which occurred almost synchronously at ~35.6 Ma (Koeberl *et al.*, 1996; Bottomley *et al.*, 1997). The Eocene–Oligocene transition is characterized by important long-term changes in oceanic circulation and climate (Prothero, 1993). However, vertebrate paleontological data for the units immediately below the Pelarda Formation suggest an age younger than Early Oligocene (Cuenca-Bescós, 1988; Cuenca-Bescós and Canudo, 1992). The Olalla paleontological site (MP 21 zone; Peláez-Campomanes, 1993) corresponds to the Rupelian stage (Early Oligocene), implying that the age of the Pelarda Formation is Late Oligocene or younger. According to this, a Pliocene–Pleistocene age for the Pelarda Formation cannot be excluded. We particularly favor an interpretation of this unit as a local Pliocene–Pleistocene alluvial deposit, similar to those common throughout central Spain along the major reliefs.

Shatter Cones–Rocks containing shatter cones are indicative of shock metamorphism, and provide definite evidence for a meteorite impact origin. Because the geometry and surface texture of shatter cones may sometimes be similar to other diagenetic and tectonic structures, this type of rock fractures should be carefully studied and identified. Fragments of shatter cones should not be confused with plumes developed along joint planes, nor with cone-in-cone structures and surface textures. Only a few moderately well-developed cones of Jurassic limestone have been described, found in modern fluvial debris within the Azuara structure, as described by Müller (1989), Katschorek (1990) and Mayer (1991), but no *in situ* counterparts were found. Photographs of these shatter cones have never been showed in international scientific publications.

GEOPHYSICAL CHARACTERISTICS

Previous geophysical studies have focused on gravity and magnetic signatures. No seismic profiles or deep drilling have been performed within the structure.

Gravity Anomaly

A pronounced negative gravity anomaly commonly characterizes buried impact structures, mostly due to their particular bowl or dish shape and less dense sedimentary fill. According to Ernstson and Fiebag (1992), the Azuara structure shows an overall negative anomaly, with a broad gravity minimum within the roughly ring-like border. The values of the gravity anomalies are in the same order of magnitude than those detected for similar impact structures. The gravity model shows a mass deficiency of 1.24×10^{14} kg, with the base of the fractured target rock located 4 km in depth at the centre of the Azuara structure. Nevertheless, a synclinal depression filled with Tertiary sediments would also result in the same type of anomalies (see examples in Keary and Brooks, 1991; Salas and Casas, 1993 or Casas *et al.*, 2000b). In addition, as noted by Aurell *et al.* (1993), and agreed upon by Ernstson and Fiebag (1993), the provisional Bouguer gravity map is incomplete, restricted to the interior of the structure, and not referred to any standard system. Because of this, it is hard to estimate a representative gravity field, and also hard to know whether the calculated residual anomalies have a circular or a straight pattern (Aurell *et al.*, 1993).

Magnetic Anomaly

Ernstson and Fiebag (1992) performed magnetic-field measurements and found that, similar to the magnetic expression of impacts on sedimentary targets, just the central part of the structure was void of anomalies. The magnetic anomaly map only shows the well-known south–north magnetic gradient present in the region, including a few scattered and very local anomalies with no apparent relationship to any consistent deep or shallow structure. These anomalies may also be related to minor folds involving Mesozoic rocks covered by Tertiary sediments. These folds can be laterally observed in geological maps (Lendínez *et al.*, 1989; Ferreiro *et al.*, 1991). At the outcrop scale, these folds correspond to (a) anticlines with a Triassic evaporitic core and calcareous Jurassic limbs, and (b) synclines involving Mesozoic (Jurassic and Lower Cretaceous) and Tertiary rocks. According to theoretical and practical studies on magnetism (see, for example, Keary and Brooks, 1991), these magnetic local anomalies could also be related to these folds.

ROCK TYPES

Breccias, whether parauthochtonous or allogenic, are a characteristic of many impact structures (French, 1998). Several lithic breccia generations have been described for the Paleozoic and Mesozoic of the Azuara structure by the authors defending the impact hypothesis (Ernstson *et al.*, 1985; Ernstson and Fiebag, 1992). The existence of true impact melt rocks, impact melt breccias (melt-matrix breccias), or suevitic breccias (suevites) has never been confirmed or sufficiently contrasted for the Azuara structure.

Megabreccia

A stratiform layer reaching more than 80 m in thickness located in the northeast and northwest Mesozoic part of the structure was interpreted by Ernstson and Fiebag (1992) as the result of *in situ* brecciation of the Triassic–Liassic transitional layer and/or Liassic limestone. They also indicated a contribution to this breccia of much younger (Eocene) sedimentary blocks, without providing any further detail. This breccia remains a subject of disagreement (Aurell *et al.*, 1993), because this same breccia-bearing unit crops out throughout the northeastern part of the Iberian Peninsula, in the Pyrenees,

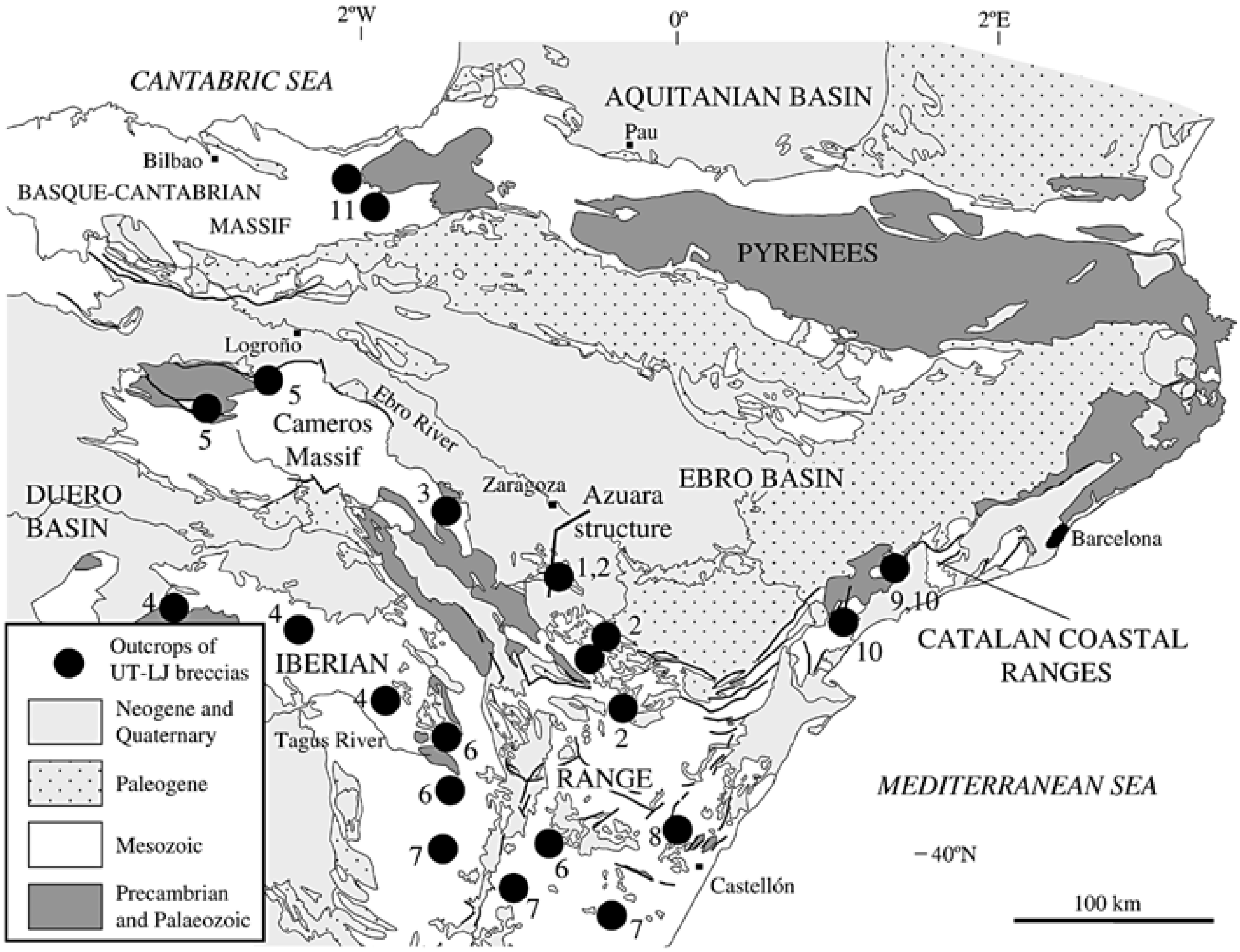

FIG. 9. Geological map of northeastern Iberian Peninsula showing the location of some reported sites within the Iberian Chain, Pyrenees and Catalan Coastal Ranges where Upper Triassic–Lower Jurassic (UT–LJ) breccias appear (black circles). Numbers close to circles indicate bibliographic references: (1) Ernstson *et al.* (1985); (2) Ferreiro *et al*. (1991); (3) San Román and Aurell (1992); (4) Goy *et al*. (1976); (5) Casas *et al.* (1995); (6) Hernández *et al*. (1985a); (7) Hernández *et al*. (1985b); (8) Canerot *et al.* (1984); (9) Giner (1978); (10) Anadón *et al*. (1987); (11) Olivé-Davo *et al.* (1990).

the Cameros and Demanda Massifs, the Iberian Range, and the Catalan Coastal Range (over 200 km from the Azuara structure, Fig. 9) towards the lower part of the Jurassic succession, and is known as the Cortes de Tajuña Formation (Goy *et al.*, 1976; Giner, 1978; Canerot *et al.*, 1984; San Román and Aurell, 1992). These authors have interpreted breccia facies within the Cortes de Tajuña Formation as the result of (1) sedimentary brecciation due to tectonic processes (San Román and Aurell, 1992) and (2) collapses related to evaporite solution (mainly anhydrite and halite, well-known in wells and occasionally at surface) below dolomitic levels (Gómez and Goy, 1999). Both processes occurred at the same time in different areas of the basin to produce the "Hettangian breccia".

Basal Breccia

Ernstson and Fiebag (1992) described a polymict and heterogeneous breccia with Paleozoic and Mesozoic components, up to 20 m thick, and unconformably overlying Mesozoic and Lower Tertiary sediments. They remarked the existence of flow textures (interpreted as carbonate melt within the breccia) and planar features in quartz grains of the matrix. Against this interpretation, Aurell *et al.* (1993) pointed out that this breccia unit corresponds to conglomerates of the Middle Miocene (unit T6). Although we have not carried out a formal detailed sedimentologic study, our observations indicate that this breccia unit may be preliminarily interpreted as fanglomerates derived from local reliefs during Miocene deformation in the Calatayud–Montalbán Basin.

Globular Breccia

A "globular breccia" was described by Ernstson and Fiebag (1992) as the result of addition of finely dispersed material in an explosion cloud. The poor basic information provided by these authors about its description and location induced Aurell *et al.* (1993) to suspect that they confused the "breccia" ("meteoritic lapilli") with a caliche-like crust. Weathering of Mesozoic carbonate rocks along the border of the central Iberian Range has been thoroughly described by Armenteros (1989). This weathering resulted in karst and paleosol development, including the generation of complex structures related with edaphic caliches and developed during the Cretaceous–Paleogene transition. Processes involved include dedolomitization, micritization and organic activity around roots, resulting in millimetric to decimetric-sized cavities filled up with different types of speleothems, detrital carbonate sediments, and terra rossa. Edaphic caliches present different microstructures, such as pedorelicts, ooids, peloids, ubiquitous *in situ Microcodium*, and root tubules. These features, described by Armenteros (1989) outside the Azuara structure, are also found in other parts of the Iberian Range in relation with the terminal Cretaceous regression (Floquet and Meléndez, 1982). Many of the features described by Ernstson and Fiebag (1992) can also be interpreted as resulting from paleosol and karst development comparing them with what Armenteros (1989) found.

Breccia Dikes

Breccia dikes are frequent features in the basement and crater walls of many complex impact structures (Lambert, 1981). This type of breccia constitutes one of the most remarkable evidence argued by the defenders of an impact hypothesis for the Azuara structure. A wide variety of dikes, usually up to 2 m wide and in some cases reaching more than 100 m in length, has been described by the Ernstson group. The dikes are described as containing monomict or polymict breccias with autochthonous and allochthonous components. Shock deformation features and carbonate melts have also been described within these breccia dikes (Ernstson and Fiebag, 1992, 1993). Breccia dikes have also been mentioned as a result of the collapse of carbonate rocks due to evaporite dissolution within the latest Triassic and earliest Jurassic units in the Iberian Range (Goy *et al.*, 1976; Giner, 1978; San Román and Aurell, 1992), as well as related to paleosol development during the Late Cretaceous and Cenozoic (Floquet and Meléndez, 1982; Armenteros, 1989), as mentioned in the previous paragraph.

Melt Rocks

Impact melt rocks are formed by cooling and crystallization of impact-generated melts. Pressures in excess of ~60 GPa induce the complete (bulk) melting of the target rocks to form impact melts (Montanari and Koeberl, 2000). The temperatures generated during the passage of shock waves in impact events are quite higher than those reached in normal crustal processes, including volcanism. In the Azuara structure, supposed melt and recrystallization products have been described admixed with shocked sandstone clasts or forming minute lens-shaped bodies within carbonate matrix in the basal breccia and breccia dikes (Fiebag, 1988; Ernstson and Fiebag, 1992, 1993). More recent works (Ernstson *et al.*, 2001a; Hradil *et al.*, 2001) report the presence of melt rocks of silicate, carbonate and phosphate composition occurring as blocks in a polymict breccia. Despite the scarce data provided and the poor location of their sampling sites, our observations at one of the outcrops mentioned by these authors (road from Barrachina to Navarrete del Río) indicates that the alleged silicate impact melt is a volcanic tuff. There is a similar volcanic tuff within the Miocene deposits of the Ebro Basin (Canudo *et al.*, 1993; Odin *et al.*, 1997), in an equivalent stratigraphic position. The surrounding polymict megabreccia is just part of a collapse structure due to dissolution of Miocene evaporites (Gutiérrez, 1999 and references therein).

With respect to recrystallization processes, previous studies on the metamorphic features in adjacent zones of the Azuara structure indicate that metamorphic recrystallization is only present in phyllosilicates of Paleozoic materials, associated with Variscan cleavage, and never above the chlorite zone (*i.e.*, low-grade metamorphism; Capote and González-Lodeiro, 1983). There is no contrasted evidence that we know of for high-temperature or high-pressure metamorphism in any place in or around the Azuara structure (Tejero, 1987; Pérez, 1989; Aurell, 1990; Soria, 1997; Gutiérrez, 1999; Sanz-Rubio, 1999, among others).

MICROSCOPIC DEFORMATION AND MELTING FEATURES

Shock metamorphic effects are considered one of the most important features to be used in the verification of terrestrial impact structures, evidently because they are distinctive and unequivocal evidence for an impact origin. The effects include microscopic planar deformational features (PDFs), optical mosaicism, changes in refractive index, birefringence and optical axis angle, isotropization (*e.g.*, diaplectic glass), and mineral phase changes (high-pressure phases, melting) (French, 1998; Montanari and Koeberl, 2000).

The existence of rocks showing evidence for shock metamorphism in the Azuara structure has been proposed by the group of K. Ernstson. Ernstson *et al.* (1985) and Ernstson and Fiebag (1992) described planar features and planar cleavage in quartz in sandstone components of the Nogueras polymict breccia (southern margin of the Azuara structure). They also found biotite grains showing kink bands within the breccia matrix (Ernstson *et al.*, 1985). Partly isotropic quartz grains (diaplectic crystals) are said to be frequently found in Azuara breccia dikes (Mayer, 1991), although completely isotropic diaplectic glass from quartz has not been observed (Ernstson and Fiebag, 1992).

Shock features were also identified within clasts from the proposed ejecta deposits: moderate shock effects, including planar elements and cleavage, mosaicism, and deformation lamellae in quartz, were described in the Pelarda Formation (Ernstson and Claudín, 1990). Multiple sets of crystallographically oriented planar elements, planar fractures, and strongly kinked micas were described by Ernstson *et al.* (1985) from quartzite clasts. In addition, Fiebag (1988) identified melt and recrystallization products and planar features in calcite. More recently, Márquez *et al.* (1995) also performed studies of planar features in clasts from this unit, agreeing with previous results of the Ernstson research group.

Some evidence can also be set off against shock metamorphism related to the Azuara structure, including alternative interpretations for the aforementioned observations and interpretations. The presence of kink bands in micas can also be the result of normal tectonic deformation linked to regional metamorphism and folding, resulting in two or three cleavage orientations, which are very common in Paleozoic rocks throughout the Iberian Range (Capote and González Lodeiro, 1983; Tejero, 1987; Ferreiro *et al.*, 1991). This is opposed to the assertion of Ernstson *et al.* (1985), who emphasize that the Paleozoic sediments of the Iberian Range lack any indication of regional metamorphism.

In addition, three samples from the Azuara and Rubielos de la Cérida structures (the latter interpreted by Ernstson *et al.* (1999, 2001a) as the possible twin crater of the Azuara structure), were studied by Langenhorst and Deutsch (1996) in order to find evidence for shock metamorphism, and gave negative results. They applied transmission electron microscopy (TEM) to study quartz grains in samples of quartzite from clasts in the Pelarda Formation and the Rubielos de la Cérida structure. Langenhorst and Deutsch (1996) remarked the absence of any shock metamorphic overprint. Under TEM, the samples revealed a large density of dislocations and many subgrain boundaries, but PDFs were absent. These samples were provided to them by K. Ernstson, who explicitly indicated that he had previously detected PDFs in each of them, and that tectonic deformation for the formation of the PDFs could very probably be excluded for all three samples provided (F. Langenhorst, pers. comm.).

Regarding the Azuara structure and its geological context, Prieto *et al.* (1995) indicated the existence of shock metamorphic effects in quartzite clasts from Buntsandstein conglomerates of the Iberian Range cropping out quite far away from the Azuara structure. This evidence for an impact was interpreted as inherited from the source area of the conglomerates, which they proposed must have included Lower Paleozoic quartzites affected by an unidentified impact.

The aforementioned optical identification of PDFs in quartzite clasts of the Pelarda Formation and Buntsandstein units cannot and should not be considered as an unambiguous or unequivocal record of shock metamorphism. Using an optical microscope, the distinction between planar features formed by shock metamorphism and those formed by normal tectonic deformation processes is not conclusive. Only TEM studies provide the definite answer for the origin of the deformation in the quartz (Bohor *et al.*, 1995; Langenhorst and Deutsch, 1996). The existence of an alternative hypothesis unrelated to impact in the interpretation of each and every other single set of evidence provided for the Azuara structure suggests that the proposed PDFs should also be considered as suspect.

Decarbonation Features

White vesicular rims were described around limestone fragments in breccia dikes (Katschorek, 1990; Ernstson and Fiebag, 1992). These rims were interpreted by these authors as a result of marginal decarbonation related to high-shock pressures (45–70 GPa). Similarly to what we argued above with respect to the proposed globular breccias and breccia dikes, paleosol and karst development result in a wide variety of features similar to those proposed, and which may have been the cause of confusion (see, for example, those described by Armenteros, 1989). In any case, as stated by Aurell *et al.* (1993), it is almost impossible to give alternative explanations to the many features proposed in support of the impact hypothesis, because description, exact location, and analysis are usually difficult to access and there are incomplete and superficial data.

GEOCHEMISTRY

Geochemical methods can provide evidence of extraterrestrial components in impact-derived melt rocks or breccias (Koeberl, 1997). This is particularly true with concentrations and interelement ratios of siderophile elements, especially the platinum group elements (PGEs), which are diagnostic and useful in order to verify the impact origin of a geologic structure. In most impact structures, impact melt rocks and impact breccias are frequently the only material in which a meteoritic component can be found (Koeberl, 1997).

Geochemical data of the rocks of the Azuara structure published by authors defending the impact hypothesis have been extremely poor (Aurell *et al.*, 1993). These only consist on the qualitative composition of the matrix of a breccia dike, and comparison of x-ray diffraction spectroscopic (XRD) and x-ray fluorescence spectroscopic (XRF) data to infer the presence of a siliceous amorphous phase (lechatelierite glass) dispersed within the breccia matrix. The description and interpretation of the geochemical data by Ernstson and Fiebag (1992) is insufficient and inappropriate for a scientific work trying to verify an impact structure. Latest works (Ernstson *et al.*, 2001a; Hradil *et al.*, 2001) do not provide any conclusive results regarding its impactogenic interpretation. To date, no more detailed geochemistry that we know of has ever been applied to rocks related to the Azuara structure in order to prove and confirm its cosmic origin.

FUTURE WORKS

Part of our ongoing research focuses on tectonic, sedimentological and paleontological evidence in both the Ebro and Calatayud–Montalbán basins in order to resolve the controversy relating the impact *vs*. tectonic origin of the Azuara structure. Immediate future work should be conducted towards: (a) the definitive interpretation and determination of the age, provenance and sedimentary environment of the Pelarda Formation, (b) searching of analogue deposits or other mesoscopic impact evidences within the distance of one crater radius from the supposed crater rim (Fig. 1), (c) searching for new microscopic evidences of shock metamorphic effects such as PDFs or isotropization, and (d) performing geochemical analyses in order to test the different hypotheses.

CONCLUSIONS

A review of the evidence set forward in favor of and against its cosmic origin indicates that the controversy on the Azuara structure (Spain) continues more than 15 years after its origin as a meteoritic impact structure was first proposed. All features used as evidence for an impact origin can also be related with other terrestrial geologic processes frequent throughout the Iberian Range (tectonic features, gravity data, breccias, pitted pebbles, *etc*.). The significance of shock-metamorphic effects (PDFs, kink-bands, diaplectic glass, melting and high-pressure minerals, *etc*.) described in relation with the structure has been questioned and is still being debated. Comparing with other similar-sized verified impact structures (*e.g.*, Ries structure), it seems obvious that many more unique impactogenic features are yet to be found before the Azuara structure can be related to a cosmic impact. Until then, the Azuara structure should be considered as an unverified impact structure, and should not be included in global comprehensive maps of terrestrial impact structures.

Acknowledgements–This work is supported by the Astrobiology Center (CSIC-INTA) of Spain, the IMPACT Program of the European Science Foundation, and Spanish D. G. E. S. projects PB-97-0997 and PB98-0503. We appreciate the help of A. M. Casas, C. L. Liesa, H. J. Mauristch and A. Pocoví for their suggestions. We also thank the comments and suggestions by M. Aurell, K. Ernstson and the associate editor to improve its content.

Editorial handing: E. Asphaug

REFERENCES

ADROVER R., FEIST M., HUGUENEY M., MEIN P. AND MOISSENET P. (1982) L'age et la mise en relief de la formation détritique culminante de la Sierra Pelarda (Province de Teruel, Espagne). *C. R. Acad. Sci. Paris* **295**, 231–236.

ANADÓN P. *ET AL*. (1987) *Mapa y memoria explicativa de la hoja 42 (Tarragona) del Mapa Geológico de España a escala 1:200,000*. IGME, Madrid, Spain. 108 pp.

ARMENTEROS I. (1989) Alteración del sustrato y encostramientos carbonáticos ligados a la discontinuidad Cretácico–Terciaria en el borde este del Sistema Ibérico central. *Studia Geologica Salmanticensia* **5**, 13–54.

AURELL M. (1990) El Jurásico superior de la Cordillera Ibérica Central (provincias de Zaragoza y Teruel). Análisis de cuenca. Ph.D. thesis, University of Zaragoza, Zaragoza, Spain. 509 pp.

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* **82**, 750–755.

BENITO G. AND CASAS A. M. (1987) Small-scale deformations in Quaternary deposits in northeastern Iberian Peninsula. *Géol. Méd.* **14**, 233–243.

BLUM R. (1840) Übber einige geologische Erscheinungen in der Nagelflue. *N. Jb. Miner.* **1840**, 525–531.

BOHOR B. F., FISLER D. K. AND GRATZ A. J. (1995) Distinguishing between shock and tectonic lamellae with the SEM (abstract). *Lunar Planet. Sci.* **26**, 145–146.

BOTTOMLEY R. J., GRIEVE R. A. F., YORK D. AND MASAITIS V. (1997) The age of the Popigai impact event and its relations to events at the Eocene/Oligocene boundary. *Nature* **388**, 365–368.

BULARD P. F. (1972) Le Jurassique moyen et supérieur de la chaîne ibérique et catalane (Espagne). Ph.D. thesis, University of Toulouse, Toulouse, France. 702 pp.

CAMPREDON R. (1977) Les déformations de conglomérats pliocene de l'Arc de Nice (chaînes subalpines méridionalles). *C. R. somm. Soc. Géol. France* **2**, 75–77.

CANEROT J., FAURE P. AND RAHAL M. (1984) Les brèches liasiques du massif du Desierto de las Palmas (Chaîne ibérique orientale-Espagne): Organisation, origine, place dans l'évolution de l'aulacogène ibérique (abstract). *Eur. Reg. Meet. Int. Assoc. Sediment., Marseille (IAS)* **5th**, 88–89.

CANUDO J. I., LAGO M., CUENCA G. AND ODIN G. S. (1993) Setting, petrology and geochemistry of a new magmatism of middle Miocene (Basin of the Ebro, Spain) (abstract). *Terra Abstracts* **5**, 528.

CAPOTE R. AND GONZÁLEZ-LODEIRO F. (1983) La estructura herciniana en los afloramientos paleozoicos de la Cordillera Ibérica. In *Geología de España. Libro Jubilar J.M. Ríos* (ed. J. A. Comba), pp. 513–528. ITGE, Madrid, Spain.

CARLS P. (1975) The Ordovician of the Eastern Iberian Chains near Fombuena and Luesma (prov. Zaragoza, Spain). *N. Jb. Geol. Palaont. Abh.* **150**, 127–146.

CARLS P. (1977) The Silurian–Devonian boundary in northeastern and central Spain. In *The Silurian–Devonian Boundary* (ed. A. Martinsson), pp. 143–158. IUGS, Stuttgart, Germany.

CARLS P. AND MONNINGER W. (1974) Ein Block-Konglomerat im Tertiär der östlichten Iberischen Ketten (Spanien). *N. Jb. Geol. Paläont. Abh.* **145**, 1–16.

CASAS A. M. (1992) *El frente norte de las Sierras de Cameros: Estructuras cabalgantes y campo de esfuerzos.* Zubía, Instituto de Estudios Riojanos, monográfico 4, Logroño, Spain. 220 pp.

CASAS A. M. *ET AL.* (1985) *Estructura y evolución mesozoico-terciaria de las Sierras de Cameros-Demanda (Cordillera Ibérica)*. Ed.

Servicio de Publicaciones de la Universidad de Zaragoza, Zaragoza, Spain. 113 pp.

CASAS A. M., CORTÉS A. L., LIESA C. L., MELÉNDEZ A. AND SORIA A. R. (1997) Estructura del borde N de la Cordillera Ibérica entre la Sierra de Arcos y el anticlinal de Montalbán. *Cuadernos de Geología Ibérica* **23**, 243–268.

CASAS A. M., CASAS A., PÉREZ A., TENA S., BARRIER L., GAPAIS D. AND NALPAS T. (2000a) Syn-tectonic sedimentation and thrust-and-fold kinematics at the intra-mountain Montalbán Basin (northern Iberian Chain, Spain). *Geodinamica Acta* **1**, 1–17.

CASAS A. M., CORTÉS A. L. AND MAESTRO A. (2000b) Intra-plate deformation and basin formation during the Tertiary at the Northern Iberian Plate: Origin and evolution of the Almazán Basin. *Tectonics* **19**, 258–289.

CLAUDÍN F., ERNSTSON K., RAMPINO M. R. AND ANGUITA F. (2001) Striae, polish, imprints, rotated fractures, and related features from clasts in the Puerto Mínguez impact ejecta (NE Spain) (abstract). In *Impact Markers in the Stratigraphic Record* (eds. F. Martínez-Ruíz, M. Ortega-Huertas and I. Palomo), pp. 15–16. 6th ESF IMPACT Workshop, Granada, Spain.

COLOMER M. (1987) Estudi geològic de la vora Sud-oest de la Fossa de Calatayud-Daroca, entre Villafeliche i Calamocha. Diploma thesis, University of Barcelona, Barcelona, Spain. 99 pp.

CORTÉS A. L. AND CASAS A. M. (1996) Deformación alpina de zócalo y cobertera en el borde norte de la Cordillera Ibérica (Cubeta de Azuara-Sierra de Herrera). *Rev. Soc. Geol. España* **9**, 51–66.

CORTÉS A. L. AND MAESTRO A. (1998) Recent intraplate stress field in the eastern Duero Basin (N Spain). *Terra Nova* **10**, 287–294.

CORTÉS A. L., LIESA C. L., SORIA A. R. AND MELÉNDEZ A. (1999) Role of the extensional structures in the location of folds and thrusts during tectonic inversion (Northern Iberian Chain, Spain). *Geodinamica Acta* **12**, 113–132.

CORTÉS A. L., DÍAZ-MARTÍNEZ E., GONZÁLEZ-CASADO J. M., AURELL M. AND CASAS-SAINZ A. M. (2002) Cratered cobbles in Triassic Buntsandstein conglomerates in northeastern Spain: An indicator of shock deformation in the vicinity of large impacts: Comment. *Geology* **30**, 91.

CUENCA-BESCÓS G. (1988) *Revision of Aragonian and Ramblian Sciuridae in the Calatayud–Montalbán Basin*. Scripta Geologica **87**, Rijksmuseum van Geologie en Mineralogie, Leiden, The Netherlands. 116 pp.

CUENCA-BESCÓS G. AND CANUDO J. I. (1992) Los Sciuridae, Rodentia, Mammalia del Oligoceno inferior de Montalbán y Olalla, Teruel, España. Discusión sobre el origen de los esciuridos. *Bol. Real. Soc. Esp. Hist. Natural (Sec. Biológica)* **87**, 155–169.

ERNSTSON K. (1994) Looking for geological catastrophes: The Azuara impact case. In *Extinción y Registro Fósil* (ed. E. Molina), pp. 31–57. Cuadernos Interdisciplinares, Universidad de Zaragoza, Zaragoza, Spain.

ERNSTSON K. AND CLAUDÍN F. (1989) Pelarda Formation (Eastern Iberian Chains, NE Spain): Continuous deposit of the Azuara impact structure (abstract). *Meteoritics* **24**, 264.

ERNSTSON K. AND CLAUDÍN F. (1990) Pelarda Formation (Eastern Iberian Chains, NE Spain): Ejecta of the Azuara impact structure. *N. Jb. Geol. Paläont. Mh.* **10**, 581–599.

ERNSTSON K. AND FIEBAG J. (1992) The Azuara impact structure (Spain): New insights from geophysical and geological investigations. *Geologische Rundschau* **81**, 403–425.

ERNSTSON K. AND FIEBAG J. (1993) The Azuara impact structure (Spain): New insights from geophysical and geological investigations—Reply. *Geologische Rundschau* **82**, 756–759.

ERNSTSON K., HAMMANN W., FIEBAG J. AND GRAUP G. (1985) Evidence of an impact origin for the Azuara structure (Spain). *Earth Planet. Sci. Lett.* **74**, 361–370.

ERNSTSON K., FELD H. AND FIEBAG J. (1987) Impact hypothesis for the Azuara structure (Spain) strengthened (abstract). *Meteoritics* **22**, 373.

ERNSTSON K., ANGUITA F. AND CLAUDÍN F. (1994) Shock cratering of conglomerate quartzite pebbles and the search for and identification of an Azuara (Spain) probable companion impact structure (abstract). *ESF Workshop, Limoges, France* **3rd**, 25.

ERNSTSON K., RAMPINO M., ANGUITA F., HILTL M. AND SIEGERT I. (1999) Shock deformation of autochthonous conglomerates near the Azuara impact structure, Spain (abstract). *Geol. Soc. Am.* **31**, 122.

ERNSTSON K., CLAUDÍN F., SCHÜSSLER U., ANGUITA F. AND ERNSTSON T. (2001a) Impact melt rocks, shock metamorphism, and structural features in the Rubielos de la Cérida structure, Spain: Evidence of a companion to the Azuara impact structure) (abstract). In *Impact Markers in the Stratigraphic Record* (eds. F. Martínez-Ruíz, M. Ortega-Huertas and I. Palomo), pp. 23–24. 6th ESF IMPACT Workshop, Granada, Spain.

ERNSTSON K., RAMPINO M. R. AND HILTL M. (2001b) Shock-induced spallation in Triassic Buntsandstein conglomerates (Spain): An impact marker in the vicinity of large impacts) (abstract). In *Impact Markers in the Stratigraphic Record* (eds. F. Martínez-Ruíz, M. Ortega-Huertas and I. Palomo), pp. 25–26. 6th ESF IMPACT Workshop, Granada, Spain.

ERNSTSON K., RAMPINO M. AND HILTL M. (2001c) Cratered cobbles in Triassic Buntsandstein conglomerates in northeastern Spain: An indicator of shock deformation in the vicinity of large impacts. *Geology* **29**, 11–14.

FERREIRO E. *ET AL.* (1991*) Mapa y memoria explicativa de la hoja 40 (Daroca) del Mapa Geológico Nacional a escala 1:200,000*. ITGE, Madrid, Spain. 239 pp.

FIEBAG J. (1988) Zur Geologie der Azuara-Struktur (NE-Spanien). Kartierung im Gebiet zwischen Herrera de los Navarros und Aladrén und süd-östlich von Almonacid de la Cuba sowie spezielle Untersuchungen der Breccien und Breccien-Gänge vor dem Hintergrund einer Impaktgenese der Azuara Struktur. Ph.D. thesis, University of Würzburg, Würzburg, Germany. 271 pp.

FLOQUET M. AND MELÉNDEZ A. (1982) Características sedimentarias y paleogeográficas de la regresión finicretácica en el sector central de la Cordillera Ibérica. *Cuadernos de Geología Ibérica* **8**, 237–257.

FRENCH B. M. (1998) *Traces of Catastrophe: A Handbook of Shock-Metamorphic Effects in Terrestrial Meteorite Impact Structures.* Lunar and Planetary Institute, Contribution no. **954**, Lunar and Planetary Institute, Houston, Texas, USA. 120 pp.

GARCÍA-ROYO J. F. C. AND ARCHE A. (1987) El Triásico de la región Nuévalos-Cubel (Zaragoza). Sedimentación en un sector del borde de cuenca del surco Molina-Valencia. *Cuadernos de Geología Ibérica* **11**, 575–605.

GARRIDO A. AND VILLENA J. (1977) El Trías germánico en España: Paleogeografía y estudio de secuencias. *Cuadernos de Geología Ibérica* **4**, 37–56.

GINER J. (1978) Origen y significado de las brechas del Lías de la Mesa de Prades (Tarragona*). Estudios Geológicos* **34**, 529–533.

GÓMEZ J. J. AND GOY A. (1999) Las unidades carbonatadas y evaporíticas del tránsito Triásico–Jurásico en la región de Lécera (Zaragoza, España). *Cuadernos de Geología Ibérica* **25**, 15–25.

GONZÁLEZ A. AND GUIMERÀ J. (1993) Sedimentación sintectónica en una cuenca transportada sobre una lámina de cabalgamiento: La cubeta terciaria de Aliaga. *Rev. Soc. Geol. España* **6**, 151–167.

GOY A., GÓMEZ J. J. AND YÉBENES A. (1976) El Jurásico de la Rama Castellana de la Cordillera Ibérica (Mitad Norte). I. Unidades litoestratigráficas. *Estudios Geológicos* **32**, 391–423.

GRIEVE R. A. F. (1987) Terrestrial impact structures. *Ann. Rev. Earth Planet. Sci.* **15**, 245–270.

GRIEVE R. A. F., RUPERT J., SMITH J. AND THERRIAULT A. (1995) The record of terrestrial impact cratering. *GSA Today* **5**, 189–196.

GUTIÉRREZ F. (1999) Fenómenos de subsidencia por disolución de formaciones evaporíticas en las fosas neógenas de Teruel y Calatayud. Ph.D. thesis, Universidad de Zaragoza, Zaragoza, Spain. 569 pp.

HERNÁNDEZ A. *ET AL.* (1985a) *Mapa y memoria explicativa de la hoja no. 47 (Teruel) del Mapa Geológico de España a escala 1:200,000*. IGME, Madrid, Spain. 192 pp.

HERNÁNDEZ A., CAPOTE R., ANADÓN P., ALONSO A., MÁS R., GÓMEZ J. J., YÉBENES A., ORTÍ F. AND DÍAZ M. (1985b) *Mapa y memoria explicativa de la hoja no. 55 (Llíria) del Mapa Geológico de España a escala 1:200,000*. IGME, Madrid, Spain. 125 pp.

HERNANDO S. (1980) Mapa geológico del Pérmico y Triásico de la región Ayllón-Atienza. *Cuadernos de Geología Ibérica* **6**, 21–54.

HOSSAIN K. M. (1978) Theoretical stress conditions in the matrix around a rigid circular inclusion and their geological implications. *Geologie en Minjbouw* **57**, 55–58.

HRADIL K., SCHÜSSLER U. AND ERNSTSON K. (2001) Silicate, phosphate and carbonate melts as indicators for an impact-related high-temperature influence on sedimentary rocks of the Rubielos de la Cérida structure, Spain (abstract). In *Impact Markers in the Stratigraphic Record* (eds. F. Martínez-Ruíz, M. Ortega-Huertas and I. Palomo), pp. 49–50. 6th ESF IMPACT Workshop, Granada, Spain.

JUDSON S. AND BARKS R. E. (1961) Microstriations on polished pebbles. *Am. J. Sci.* **259**, 371–381.

KATSCHOREK T. (1990) Geologische Untersuchungen am N-Rand der Azuara-Struktur (NE Spanien). Erläuterungen zu einer Kartierung 1:20,000 des Gebietes zwischen Fuendetodos und Belchite unter besonderer Berücksichtigung struktureller Merkmale. Diploma thesis, University of Würzburg, Würzburg, Germany. 198 pp.

KEARY P. AND BROOKS M. (1991) *An Introduction to Geophysical Exploration*. Blackwell Science, Oxford, U.K. 254 pp.

KOEBERL C. (1997) Impact cratering: The mineralogical and geochemical evidence. In *The Ames Structure and Similar Features* (eds. K. Johnson and J. Campbell), pp. 30–54. Oklahoma Geological Survey Circular **100**, Norman, Oklahoma, USA.

KOEBERL C., POAG C. W., REIMOLD W. U. AND BRANDT D. (1996) Impact origin of the Chesapeake Bay structure and the source of the North American tektites. *Science* **271**, 1263–1266.

LAMBERT P. (1981) Breccia dikes: Geological constraints on the formation of complex craters. In *Multi-Ring Basins* (eds. P. H. Schultz and R. B. Merril), pp. 59–78. Pergamon Press, New York, New York, USA.

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 (abstract). *Lunar Planet. Sci.* **27**, 725–726.

LENDÍNEZ A., RUIZ V. AND CARLS P. (1989) *Mapa y memoria explicativa de la hoja número 466 (Moyuela) del Mapa Geológico de España a escala 1:50,000*. ITGE, Madrid, Spain. 116 pp.

LIESA C. L. AND SIMÓN J. L. (1994) Fracturación a distintas escalas y campos de esfuerzos durante la tectogénesis alpina en el área de Mosqueruela (Teruel). *Estudios Geológicos* **50**, 47–57.

LOTZE F. (1961) *Das Kambrium Spanien. T1 Stratigraphie*. Akad. Wiss. Lit. Abh. Math. naturwiss., Mainz, Germany. 216 pp.

MAESTRO A. AND CASAS A. M. (1995) Fracturación y estado de esfuerzos durante la compresión terciaria en la Cuenca de Almazán (Provincias de Soria y Zaragoza). *Rev. Soc. Geol. España* **8**, 193–214.

MAESTRO A., LIESA C. L., SIMÓN J. L., CASAS A. M. AND ARLEGUI L. E. (1995) Fracturación, plegamiento y campo de esfuerzos en los conglomerados oligocenos de Gómara (Cuenca de Almazán, Soria). *Rev. Soc. Geol. España* **10**, 3–12.

MARFIL R., CRUZ B. DE LA AND PEÑA J. A. DE LA (1977) Procesos diagenéticos en las areniscas del Buntsandstein dela Cordillera Ibérica. *Cuadernos de Geología Ibérica* **4**, 411–422.

MÁRQUEZ A., GUERRERO E., MUÑOZ F. AND ANGUITA F. (1995) Pelarda Formation: A probable ejecta from Azuara structure (abstract). In *Impact Cratering and Evolution of Planet Earth* (eds. A. Montanari and R. Coccioni), p. 116. 4th ESF IMPACT Workshop, Granada, Spain.

MARTÍNEZ-RUÍZ F., ORTEGA-HUERTAS M. AND PALOMO I. (2001) *Impact Markers in the Stratigraphic Record.* 6th ESF IMPACT Workshop, Granada, Spain. 140 pp.

MAYER G. (1991) Geologische Untersuchungen am SE-Rand der Azuara-Struktur (NE Spanien). Erläuterungen zu einer geologischen Kartierung im Masstab 1:20,000 unter besonderer Berücksichtigung der Tektonischen Verhältnisse und vor dem Hintergrund einer Impaktgenese der Struktur. Diploma thesis, University of Würzburg, Würzburg, Germany. 216 pp.

MELOSH H. J. (1989) *Impact Cratering*. Oxford University Press, Oxford, U.K. 245 pp.

MONTANARI A. AND KOEBERL C. (2000) *Impact Stratigraphy. The Italian Record*. Lecture Notes in Earth Sciences **93**, Springer-Verlag, New York, New York, USA. 364 pp.

MÜLLER H. (1989) Geologische Untersuchungen am SE-Rand der Azuara-Struktur (NE Spanien). Geologische Kartierung im Masstab 1:20,000 zwischen Ventas de Muniesa und Moneva unter besonderer Berücksichtigung fazieller und struktureller Merkmale. Diploma thesis, University of Würzburg, Würzburg, Germany. 167 pp.

MUÑOZ-JIMÉNEZ A. AND CASAS-SAINZ A. M. (1997) The Rioja Trough (N Spain): Tecto-sedimentary evolution of a symmetric foreland basin. *Basin Research* **9**, 65–85.

ODIN G. S., CUENCA-BESCÓS G., CANUDO J. I., COSCA M. AND LAGO M. (1997) Biostratigraphy and geochronology of a Miocene continental volcaniclastic layer from the Ebro Basin, Spain. In *Miocene Stratigraphy; An Integrated Approach* (eds. A. Montanari, G. S. Odin and R. Coccioni), pp. 297–310. Developments in Palaeontology and Stratigraphy **15**, Elsevier, Amsterdam, The Netherlands.

OLIVÉ-DAVO A., RAMÍREZ-MERINO J. I., ALVARO-LÓPEZ M., RAMÍREZ DEL POZO J. AND AGUILAR-TOMÁS M. (1990) *Mapa y memoria explicativa de la hoja 5/12 (Bermeo/Bilbao) del Mapa Geológico Nacional a escala 1:200,000*. ITGE, Madrid, Spain. 208 pp.

PELÁEZ-CAMPOMANES P. (1993) Micromamíferos del Paleógeno continental español: Sistemática, Biocronología y Paleoecología. Ph.D. thesis, Universidad Complutense, Madrid, Spain. 385 pp.

PÉREZ A. (1989) Estratigrafía y sedimentología del Terciario del borde meridional de la Depresión del Ebro (sector riojano-aragonés) y cubetas de Muniesa y Montalbán. Ph.D. thesis, Universidad de Zaragoza, Zaragoza, Spain. 525 pp.

PÉREZ A., AZANZA B., CUENCA G., PARDO G. AND VILLENA J. (1985) Nuevos datos estratigráficos y paleontológicos sobre el Terciario del borde meridional de la depresión del Ebro (provincia de Zaragoza). *Estudios Geológicos* **41**, 405–411.

PETIT J. P., RAYNAUD S. AND CAUTRU J. P. (1985) Microtectonique cassante lors du plissement d'un conglomérat (Mio-Pliocène du Haut Atlas, Maroc). *Bull. Soc. Géol. France* **1**, 415–421.

PRIETO O., LÓPEZ I., PACHECO C. AND RAMOS S. (1995) Analysing planar features in Buntsandstein age deposits of the Iberian Chain (Spain) (abstract). In *Impact Cratering and Evolution of Planet Earth* (eds. A. Montanari and R. Coccioni), p. 136. 4th ESF Workshop, Granada, Spain.

PROTHERO D. R. (1993) *The Eocene–Oligocene Transition: Paradise Lost*. Columbia University Press, New York, New York, USA. 291 pp.

RAMOS A. (1977) El Pérmico y Triásico de la región de Molina de Aragón (Cordillera Ibérica). *Cuadernos de Geología Ibérica* **4**, 589–602.

RODRÍGUEZ-PASCUA M. A. AND DE VICENTE G. (1998) Análisis de paleoesfuerzos en cantos de depósitos conglomeráticos terciarios de la Cuenca de Zaorejas (Rama Castellana de la Cordillera Ibérica). *Rev. Soc. Geol. España* **11**, 169–180.

SALAS R. AND CASAS A. (1993) Mesozoic extensional tectonics, stratigraphy and crustal evolution during the Alpine cycle of the eastern Iberian basin. *Tectonophysics* **228**, 33–55.

SAN ROMÁN J. AND AURELL M. (1992) Paleogeographical significance of the Triassic–Jurassic unconformity in the North Iberian basin (Sierra del Moncayo, Spain). *Palaeogeography, Palaeoclimatology, Palaeoecology* **99**, 101–117.

SANZ DE GALDEANO C. AND ESTÉVEZ A. (1981) Estriaciones tectónicas en cantos de conglomerados. Su estudio en las depresiones de Granada y Guadix-Baza. *Estudios Geológicos* **37**, 227–232.

SANZ-RUBIO E. (1999) Análisis de los sistemas deposicionales carbonáticos y evaporíticos del Neógeno de la Cuenca de Calatayud (provincia de Zaragoza). Ph.D. thesis, Universidad Complutense de Madrid, Madrid, Spain. 579 pp.

SANZ-RUBIO E., DÍAZ-MARTÍNEZ E., MARTÍNEZ-FRÍAS J. AND FERNÁNDEZ-MARTÍN C. (2001) Stratigraphy of the Calatayud–Montalbán basin: Implications for the interpretation of the Azuara and Rubielos de la Cérida structures (NE Spain) (abstract). In *Impact Markers in the Stratigraphic Record* (eds. F. Martínez-Ruíz, M. Ortega-Huertas and I. Palomo), pp. 111–112. 6th ESF IMPACT Workshop, Granada, Spain.

SCHRADER F. (1988) Symmetry of pebble-deformation involving solution pits and slip-lineations in the northern alpine Molase Basin. *J. Struct. Geol.* **10**, 41–52.

SIMÓN J. L. (1986) Analysis of a gradual change in stress regime (example from the eastern Iberian Chain, Spain). *Tectonophysics* **124**, 37–53.

SIMÓN J. L. (1989) Late Cenozoic stress field and fracturing in the Iberian Chain and Ebro Basin (Spain). *J. Struct. Geol.* **11**, 285–294.

SORIA A. R. (1997) *La sedimentación en las cuencas marginales del surco Ibérico durante el Cretácico Inferior y su control tectónico*. Ed. Servicio de Publicaciones de la Universidad de Zaragoza, Zaragoza, Spain. 363 pp.

TABOADA T. (1993) Stress and strain from striated pebbles. Theoretical analysis of striations on a rigid spherical body linked to a symmetrical tensor. *J. Struct. Geol.* **15**, 1315–1330.

TEJERO R. (1987) Tectónica de los macizos paleozoicos del NE de Calatayud. Rama Aragonesa de la Cordillera Ibérica (Prov. Zaragoza). Ph.D. thesis, Universidad Complutense, Madrid, Spain. 320 pp.

TRURNIT P. (1968) Pressure solution phenomena in detrital rocks. *Sedimentary Geology* **2**, 89–114.

VIALLARD P. (1979) La Chaîne Iberique: Zone de cisaillement intra continentale pendant la tectogenèse alpine. *C. R. Acad. Sci. Paris* **289**, 65–68.

VIALLARD P. (1980) Les Iberides (Chaînes Iberique et Catalane): Interpretation de la fracturation majeure fini-oligocène. *C. R. Acad. Sci. Paris* **291**, 873–876.

VIALLARD P. (1983) Le décollement de couverture dans la chaîne Ibérique meridionale (Espagne); effect de raccourcissements diferentiels entre substratum et couverture. *Bull. Soc. Géol. France* **25**, 379–388.

VILLENA J., PARDO G., PÉREZ A., MUÑOZ-JIMÉNEZ A. AND GONZÁLEZ A. (1996) Tertiary of the Iberian margin of the Ebro Basin: Stratigraphic synthesis. In *Tertiary Basins of Spain* (eds. P. Friend and C. Dabrio), pp. 77–82. Cambridge University Press, Cambridge, U.K.

VIRGILI C. (1958) El Triásico de los Catalánides. *Bol. Inst. Geol. Minero de España* **69**, 1–856.

VIRGILI C., VÍA L., VILLALTA J. F., PARIS R., ESTEBAN M., MARZO M., COLOMBO F. AND ANADÓN P. (1977) Guía de la excursión al Triásico de la Sierra de Prades. *Cuadernos de Geología Ibérica* **4**, 527–558.