ELSEVIER

Earth and Planetary Science Letters 148 (1997) 569–579

EPSL

Did the European dinosaurs disappear before the K–T event? Magnetostratigraphic evidence

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Received 24 October 1996; revised 25 February 1997; accepted 26 February 1997

Abstract

Debate on the non-catastrophic or catastrophic extinction of the dinosaurs by an asteroid impact, K–T event, remains a controversy and is mainly based on the interpretation of the sedimentary continental sequences in the North American Western Interior. The global aspect of this event needs to be tested in sedimentary record from all continents where continuous terrestrial deposits through the Cretaceous–Paleogene are well preserved. In the western Mediterranean realm, recognition of the Cretaceous–Paleogene boundary is limited by the lack of biostratigraphic data in the upper Cretaceous–lower Tertiary continental sedimentary sequences. New magnetostratigraphic results were obtained from the analysis of two sections in southern France and compared to previous results in northern Spain. The last occurrence of in situ dinosaurs eggshells, the only dinosaur remains found, is located in Chron 30n (southeast France) or 31n (southwest France and northern Spain). This last occurrence could demonstrate that the extinction of the European dinosaurs occurred prior to the Cretaceous–Paleogene boundary, and would therefore support the idea of a gradual or stepwise extinction unlinked to the K–T event.

Keywords: K-T boundary; terrestrial environment; dinosaurs; extinction; Southern Europe; magnetostratigraphy

1. Introduction

Evidence of a catastrophic global event at the Cretaceous–Paleogene boundary, the 'K–T event', is now irrefutable. This event is well documented by geological and geochemical features as a major impact of a large extraterrestrial body in the Carribean region [1,2]. The Chicxulub structure in northwestern Yucatan Peninsula of Mexico is believed to be the impact site [3,4]. The size of the impact crater still remains the subject of a controversy. However, the most exciting question is the exact linkage and timing between the asteroid impact and the massive biotic extinctions which characterize the Cretaceous–Paleogene boundary. In the marine environments the exact coincidence between the major features of this global event (Ir anomaly, shocked minerals, Ni-rich spinels) and extinctions of most planktonic groups is well documented all around the Earth. Recently, it has also been demonstrated that the deep-sea benthic foraminifera were also subject to dramatic faunal changes that can only be explained by a catastrophic event [5]. Meanwhile, the exact causes and timing of these marine extinctions are somewhat difficult to establish. This history is proba-

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PII S0012-821X(97)00050-2

bly complex. It seems that the effects of the 'K–T event' were not so dramatic for biotas at high latitudes [6,7]. Selective extinctions and survivals are common in marine faunas and are related to deep water depth and depositional settings (see a review in [8]). Key aspects of the environmental effects of this event will derive from the estimation of total ejecta mass and dispersal mechanisms from the bolide impact, and chemical content estimation of the volatile components. Reconstruction and analysis of the global oceanic circulation at the end of Cretaceous should also be considered for this modelling.

In the terrestrial realm, the linkage between impact and mass biotic extinctions at the K–T boundary remain unclear, due to the lack of data. Terrestrial sedimentary sections where a continuous record of late Cretaceous to early Paleogene, and the K–T boundary itself, are clearly identified, exist only in North America. Extinctions within the botanic record were recognized and often interpreted as due to global wild-fire [9,10]. However, these extinctions appears to be diachronous and function on their geographical distribution. Disappearance of the vertebrates, especially the dinosaurs, has generated much more literature and controversy. The latest North American unreworked dinosaurs bones were found 60 cm below the Ir peak at the K–T boundary in the Hell Creek Formation, eastern Montana [11]. This and previous observations were understood as a link between the extinction and the K–T event. However, the abruptness of this disappearance has generated intense debate for many years. The distribution of fossil remains in the Hell Creek Formation, which is a reference point for the study of scenarios of the extinctions, was recently re-examined and compared with expected distributions in a gradual extinction or a sudden mass extinction scheme [12]. The conclusion of this study is that there is no evidence for a catastrophic mass extinction of the dinosaurs at Hell Creek.

More investigations on continental late Cretaceous/Paleogene sections all over the world are necessary to understand how the terrestrial realm has been affected by the bolide impact. However, frequent depositional hiatuses and lateral facies changes in terrestrial sedimentary successions are a major impediment to finding suitable sections in terrestrial environments. We have undertaken a systematic investigation of numerous continental K–T sites in the western Mediterranean area. In this paper we report the results obtained in France and Spain where the last occurrence of in situ dinosaur eggshells is located in Chron C30n or C31n.

2. The Cretaceous–Paleogene boundary in southern Europe

The southern European realm is characterized by a large marine regression from late Santonian to Maastrichtian [13]. Thus thick continental sediment series were developed in southern France, north-central and northeast Spain, from the late Cretaceous to Thanetian. These sedimentary sequences are characterized by a broad variety of facies resulting from a large diversity of palaeoenvironments: fluvial, lacustrine, lagoonal, flood plain, etc. The age of these continental formations is poorly constrained by biostratigraphic datums. Ostracods, pollen, spores, molluscs, charophytes and vertebrate remains are common but their occurrence is very dependent on ecological conditions. For this reason, they are not sufficient to define a good stratigraphic framework [14,15]. Local lithostratigraphic units were defined during the last century in southeast France (i.e. Valdonnian, Fuvelian, Begudian, Rognacian and Vitrollian, see [16]). Since then these lithologic units have been widely used in southern France and northern Spain and are considered to be stages. Given the lack of good chronostratigraphic control, precise correlations with the standard marine time scale are somewhat difficult. The Cretaceous–Paleogene boundary is usually considered as occurring between the Rognacian (upper Maastrichtian?) and the Vitrollian (Danian and Selandian?). But the interval, in which this boundary is suspected to occur is most often nearly barren of fossils and is traditionally defined to lie between the last occurrence of dinosaur remains and the first well dated Tertiary marine intercalations (usually Thanetian). This interval can have a thickness of a few tens or hundreds of metres. A climatic change, expressed by the pollen distribution on the Rognac Limestone Formation (southeast France), was previously interpreted as the 'K–T' boundary [17]. However, this lithologic unit is now known to be of upper Maastrichtian age [18].

The magnetic polarity sequence of the upper Cretaceous–Paleogene has a characteristic fingerprint [19] and magnetostratigraphy is a valuable tool for resolving this problem of the recognition of the K–T boundary in European continental sections, by identification of Chron C29r in which the boundary occurs. Such successful results were obtained in North American basins [20–24]. We report here new magnetostratigraphic results obtained on the Breguere (Aix-en-Provence Basin, southeast France) and Albas (Corbières, southwest France) sections. Previous results from the Fontllonga section (Ager Basin, northern Spain) [25] will be incorporated in our discussion.

3. Magnetic results

The Breguere section is located in the Aix-en-Provence Basin which is a wide east–west trending syncline in southeast France. For over a century it has been well known for its dinosaur eggshells. The section studied is a composite of three outcrops around a large quarry (43.51°N, 5.65°E). It extends 60 m from clayey siltstones of Rognacian age (Maastrichtian?) up to the Vitrolles Limestone Formation of Vitrollian age (Danian/Selandian?). The sediments display a large range of colours, from white or pink lacustrine limestone to grey and red clayey siltstones and sandstones of flood plains and fluvial environments. In the middle of the section there is a 10 m thick conglomerate and sandstone unit, 'Le Poudingue de La Galante' Formation, in which the Cretaceous–Paleogene boundary is often considered to occur. A preliminary magnetostratigraphic study of some outcrops around about the Breguere section has already been published [26]. Unfortunately, in this study the samples were analyzed only by alternating field demagnetization. It is well known that red continental sediments have to be cleaned by thermal demagnetization in order to remove completely the secondary component of NRM, especially the component due to goethite.

The Albas section is situated in Corbières, the northeastern part of the Pyrenees (43.01°N, 2.75°E). This section unconformably overlays the Triassic basement of the 'Massif du Mouthoumet'. The lower part of the section consist of fluviatile sandstones and conglomerates containing dinosaur eggshells interbedded with red silty claystones. A lacustrine limestone occurs at the top of this formation. The upper part of the section consist of lacustrine to palustrine limestones interbedded with red silty claystones with Microcodium accumulations. The base of the Albas section is considered to be Maastrichtian in age, given the occurrence of dinosaur eggs. The palaeomagnetic sampling (85 levels over 225 m), depending of the quality of outcrops, was carried out just below a lacustrine level which contains *Aplexa prisca*, a Thanetian gasteropod. Samples were collected preferentially from fine-grained sediments (siltstones and limestones) with a portable gasoline drill and oriented with magnetic compass.

The continental Upper Cretaceous–Lower Tertiary formations in south France has been previously studied either for magnetostratigraphic, or palaeomagnetic purposes and their magnetic properties are well known [27–29]. We will not give extensive descriptions of these properties but will describe briefly the natural remanent magnetization (NRM) analysis. Goethite, which results from recent weathering, is present in most lithologies studied and can often be the main carrier of the remanence. A high coercivity component with low unblocking temperature is common in red silty claystones and pink limestones. It is easily removed by moderate thermal cleaning and is probably due to fine-grained haematite as pigment, the contribution of this component to the natural remanence is weak. Most of the lithologies display a low-coercivity mineral, which is most probably magnetite. Monitoring of initial susceptibility during thermal demagnetization showed that frequent magnetic alteration occurs after heating above 450°C.

The remanent magnetizations were measured with a three-axis RS-01 (LETI/CEA) cryogenic magnetometer which allows precise measurements on samples as weakly magnetized as 2×10^{-5} A/m. Given the common occurrence of high-coercivity minerals, thermal demagnetization was used as a routine technique to isolate the characteristic remanent magnetization (ChRM) component. The results of demagnetization were analyzed on orthogonal vector plots and the directions of the ChRM components were computed using a routine PCA technique.

For the Breguere section 37 levels were sampled with regular spacing, except in the lower part of the section where the silty claystones were difficult to collect. The NRM intensities range from 7×10^{-5} to 4.4×10^{-3} A/m. The NRM directions are largely scattered and do not display any preferential direction. All the samples were thermally demagnetized at 100°C and in 50° steps up to 450°C. The last step applied was 480°C, above this temperature the specimens became very viscous and some magnetic alteration occurred. An initial very unstable component was removed by 100°C (Fig. 1a) and is most probably carried by goethite. This component most often has a direction antiparallel to the present axial dipole field (ADF) and is probably due to chemical weathering of pre-Brunhes Chron age. A second unstable component was removed by 300–350°C, it has a direction near the present Earths' field and thus could be a viscous remanent magnetization. It could also be a secondary component acquired during diagenesis and due to fine-grained haematite with a low unblocking temperature. It was not possible to do a field test (bedding dip is less than 4°) to test these two hypotheses. The characteristic remanent magnetization (ChRM) was clearly defined above 350°C. Reliable ChRM could be computed on 33 specimens, these palaeodirections represent both normal and reversed polarities which form antipodal but not well clustered groups (Fig. 1b). Plotted against stratigraphic position, these ChRM directions defined zones of normal or reversed polarity (Fig. 2). The polarity sequence displays 5 magnetozones: 3 normal and 2 reversed zones. Two other reversed polarity zones are defined by single samples, they are represented in the polarity column by partial bars. Two gaps in the polarity sequence are due to mis-sampling in silty claystones.

The Albas section displays somewhat different magnetic properties. NRM intensities of the 85 samples analyzed range from 8.6×10^{-5} to 2.1×10^{-3} A/m. Most NRM directions were near the present

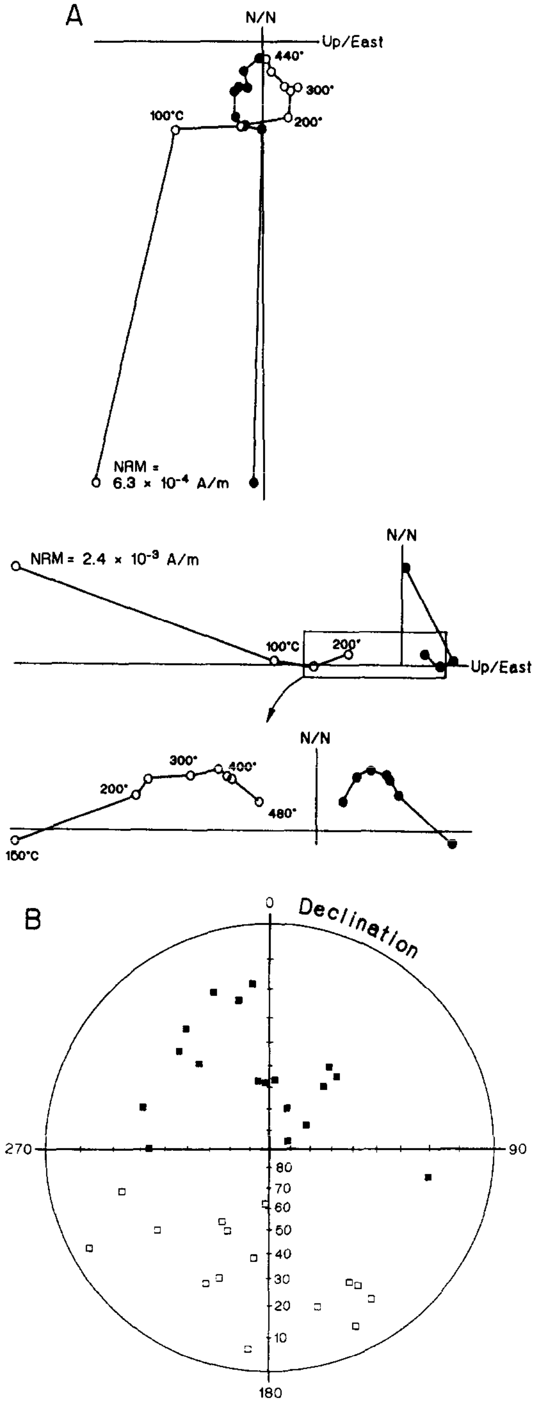

Fig. 1. (a) Typical thermal demagnetization vector diagrams from the Breguere section. Above 350°C the characteristic remanent magnetization (ChRM) of normal or reversed polarity is clearly defined. ● = projections in the horizontal plane; ○ = projections in the vertical plane. (b) Stereographic plot of the ChRM directions of the Breguere section. These palaeodirections display both normal and reversed polarities which form antipodal groups. ■ = projection of the lower hemisphere; □ = projection of the upper hemisphere.

Earths' field direction. Thermal demagnetization using temperature increments of 50°C from 100°C to 500°C was applied to all samples. An unstable component was removed by 100–150°C, its direction is the same as the present-day magnetic field and is probably due to recent weathering. The contribution of this component to the NRM is most often half of the total NRM, but this contribution could be somewhat weak (Fig. 3a). A higher-temperature component was clearly removed in the 150–450/500°C

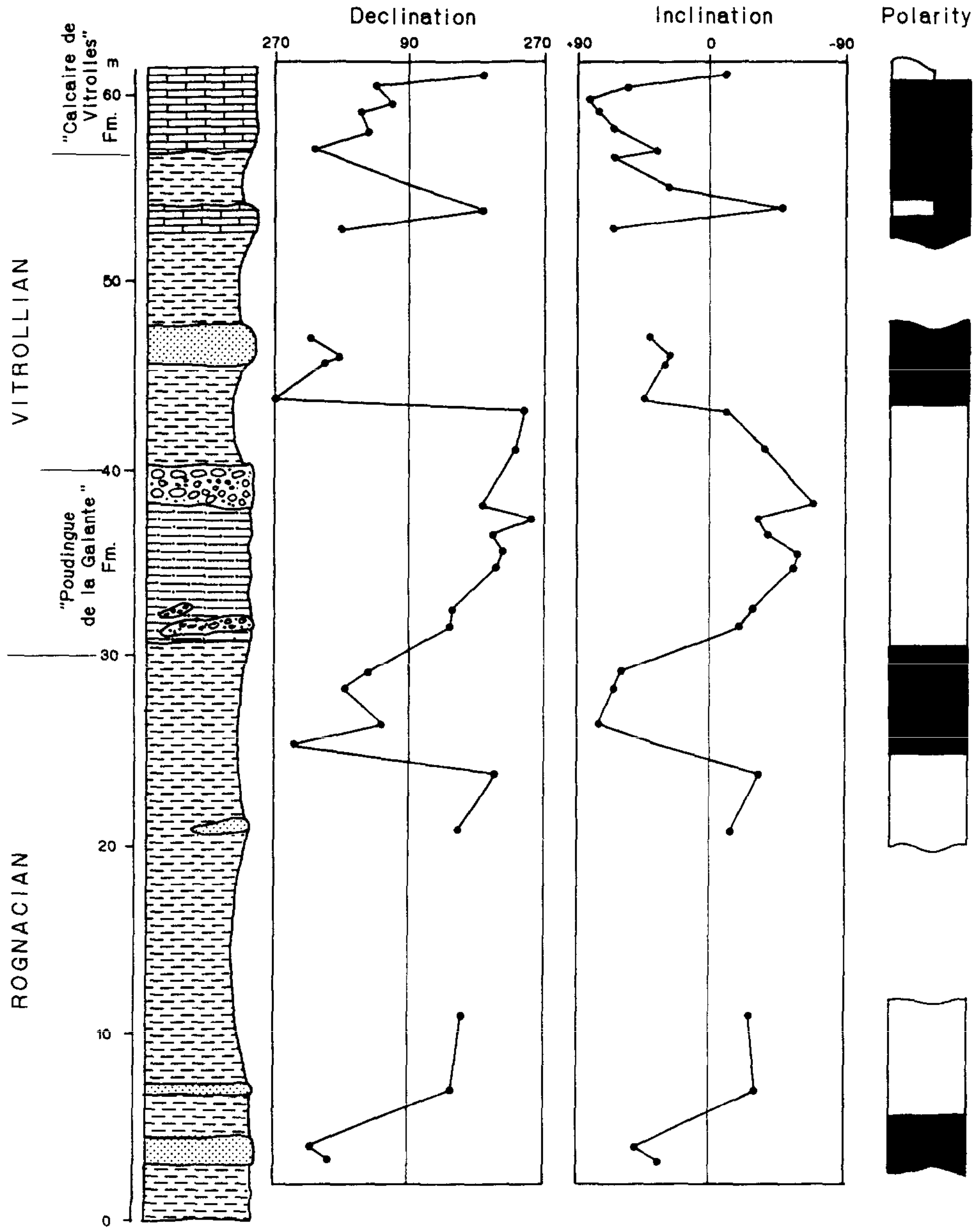

Fig. 2. Lithostratigraphy, inclinations and declinations of the ChRM directions (each data point results from a single sample at a sampling site), interpreted magnetic polarity sequence for the Breguere section (white = reversed, black = normal polarity).

range and is reasonably well characterized by regular decay towards the origin of the vector demagnetization plot (Fig. 3a). These ChRM directions were computed on 79 specimens and could be considered as reliable because most of them are of normal or reversed polarity (Fig. 3b). The stereographic plots of these directions show a poor clustering of the two groups of directions and some directions for which it is difficult to assess the polarity. This poor clustering could be due to an incomplete removal of the secondary magnetization component. Such a component is probably present in red sediments, such as a fine-grained haematite pigment which displays a low Curie temperature and thus an unblocking thermal spectrum range which overlaps with the high-temperature component. Scattered palaeomagnetic directions are also probably due to the lithologies studied, which commonly are not good recorders of a primary magnetization (i.e. fluvial sandstones). Stratigraphic plots of the palaeodirections and resulting polarity zonation is shown in Fig. 4. Polarity zone boundaries are placed midway between levels of opposite, well defined polarity. Some of the polarity zones are defined only by one or two samples, they are doubtful and thus are represented by partial bars in the polarity column. Some ChRM directions are of undetermined polarity and the related polarity column is represented by dashed lines. The proposed magnetic polarity sequence seems discontinuous, some of the gaps are due to the difficulty of collecting samples in silty claystones, especially in the upper part of the section. Another large gap in the outcrop (30 m thick) occurs in the lower part of the section. Despite numerous intermediate directions the polarity sequence is well defined in the middle part of the section, where the K–T boundary was suspected to occur.

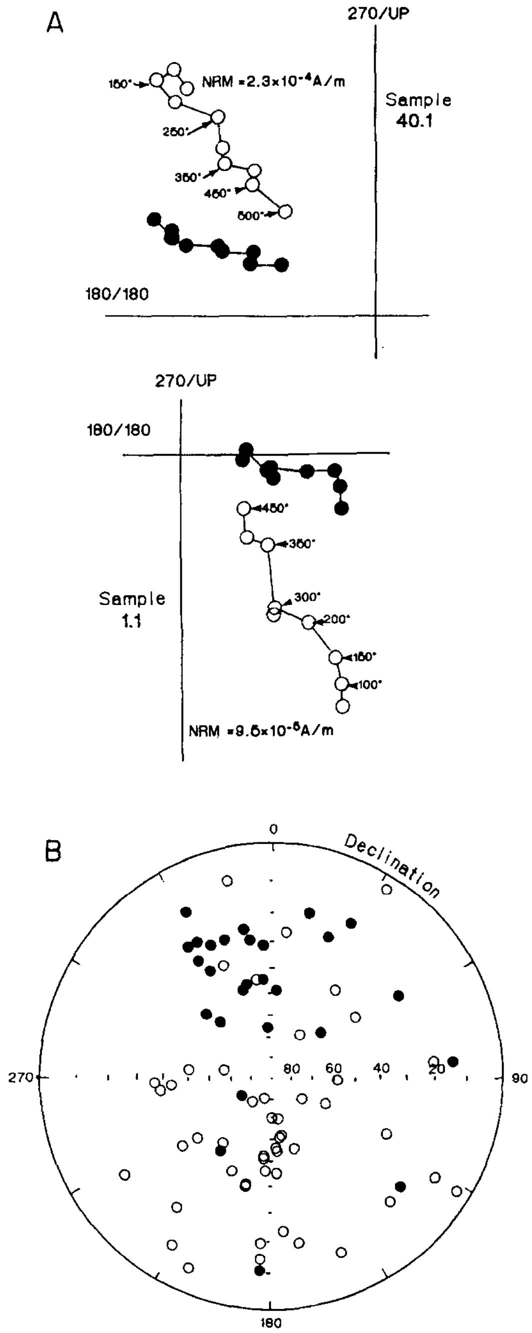

Fig. 3. (a) Thermal demagnetization vector diagrams of two representative samples from the Albas section. A stable characteristic magnetization component is removed from 150°C up to 450–500°C. ● = projections in the horizontal plane; ○ = projections in the vertical plane. (b) Stereographic plot of the ChRM directions of the Albas section. These palaeodirections are somewhat scattered but most of them display a clear normal or reversed polarity; some samples seems to be of intermediate polarity. ● = projection of the lower hemisphere; ○ = projection of the upper hemisphere.

4. Discussion

The Geomagnetic Polarity Time Scale (GPTS) displays a characteristic fingerprint around the Cretaceous–Paleogene boundary (Fig. 5). The Upper

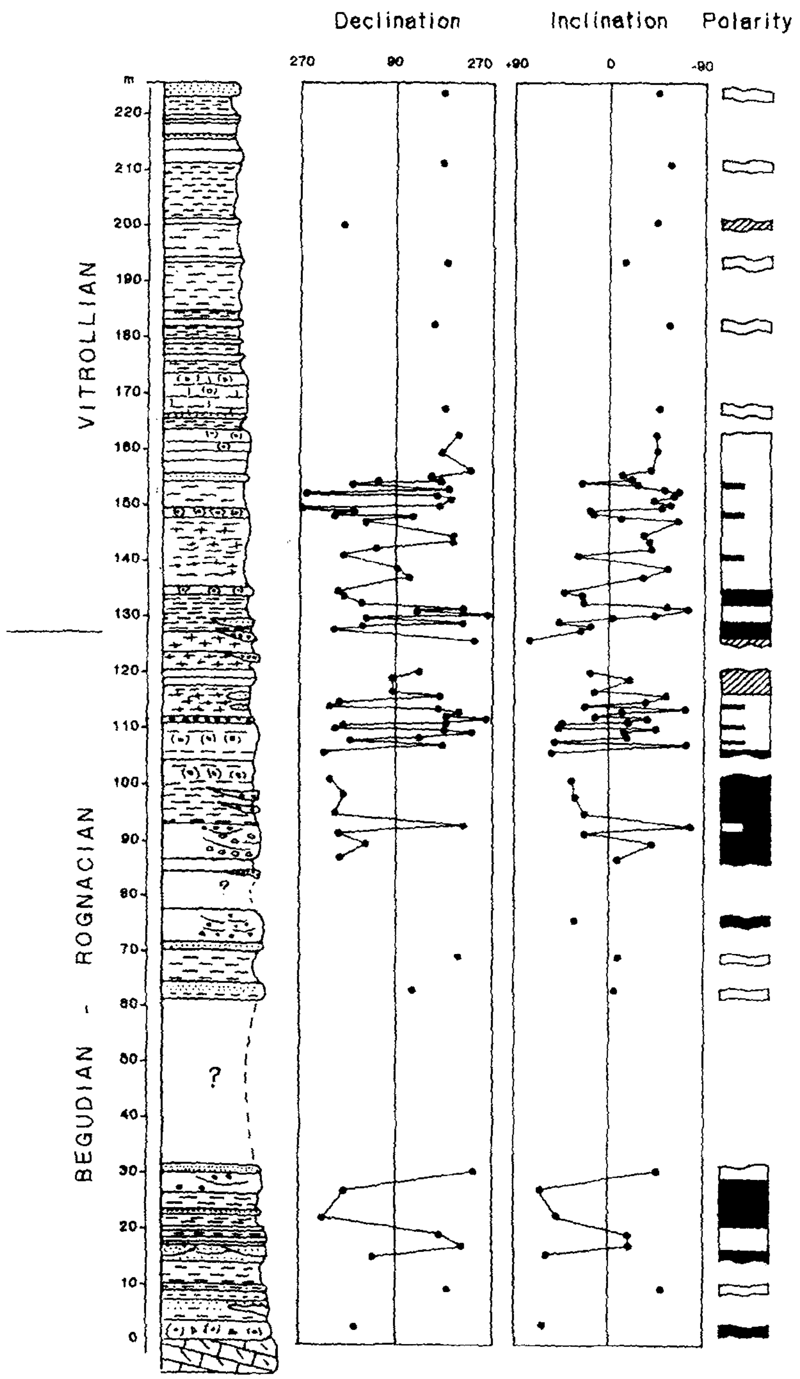

Fig. 4. Lithostratigraphy, inclinations and declinations of the ChRM directions (each data point results from a single sample at a sampling site), interpreted magnetic polarity sequence for the Albas section (white = reversed, black = normal polarity, hatched = undetermined polarity).

Maastrichtian is mostly of normal polarity (Chrons C30 and C31n), the K–T boundary occurs in Chron C29r, the basal Paleocene is mainly of normal polarity (Chrons C29n and C28n) and most of the Paleocene is of reversed polarity (middle of Chron C24r through C27r). However, the recognition of this

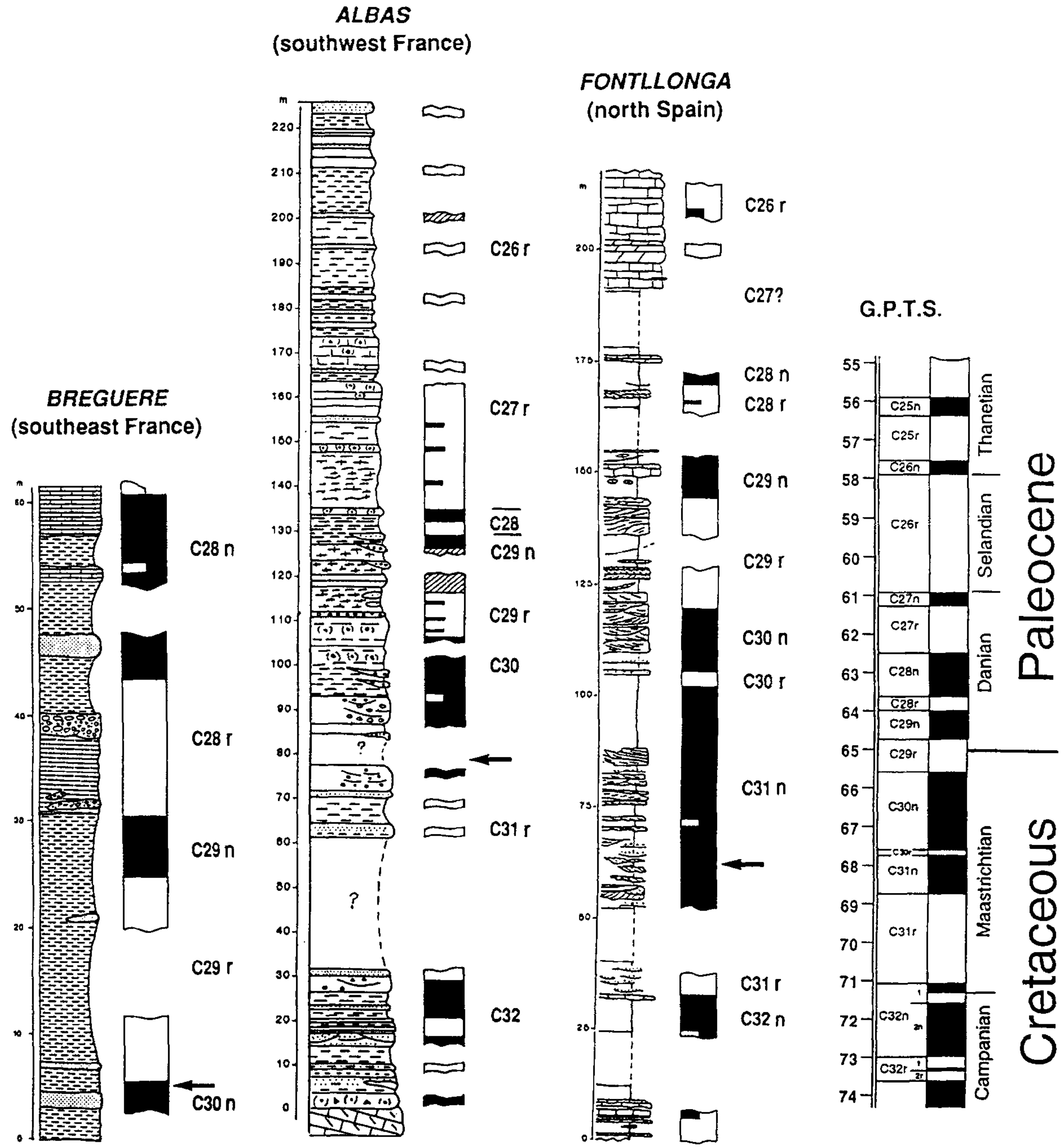

Fig. 5. Comparison of the magnetic polarity sequences of the Breguere and Albas sections (this study) with the Fontllonga section (north Spain) [22] and the Geomagnetic Polarity Time Scale [17] (white = reversed, black = normal polarity, hatched = undetermined polarity). The black arrows indicate on each section the last occurrence of dinosaur eggshells.

fingerprint in sedimentary sequences, especially from terrestrial environments, could be difficult, given the variations in sedimentation rate, and the correlations have to be constrained by some other chronostratigraphic data, especially biostratigraphy. The 1000 m thick continental series of the Aix-en-Provence Basin has already produced magnetostratigraphic results, especially from the upper Cretaceous section [28,29]. Chrons C31n and C30r were identified in the Rognac Limestone Formation, a lacustrine limestone formation outcropping 20 m below the Breguere section. At the base of this section (Fig. 5) occur the last dinosaur eggshells, which are very common in the Aix-en-Provence Basin. At the top of the section studied, above the lacustrine Vitrolles Limestone Formation a level was found containing a Danian mollusc. Given these chronostratigraphic constraints, the established polarity sequence on the Breguere section extends from the top of Chron C30n up to Chron C28n. The boundaries of Chron C29r are well defined, and this Chron represents 18 m of grey to red silty claystones.

The base of the Albas section is regionally well constrained and is of Maastrichtian age. The last dinosaur eggshells occur in the lower part of the section in a normal polarity zone. A few metres above the section is an outcrop of a marine horizon that is the regional marker of the Thanetian [13]. Considering these chronostratigraphic indications, and despite a few gaps in the polarity sequence, some correlations can be proposed with the GPTS (Fig. 5). The 'fingerprint' between the polarity sequences allows us to suggest that the section studied extends from Chron C32r to C26r. The lower boundary of Chron C29r is recognized but not the upper boundary, given the unreliability of the ChRM directions in this part of the section.

These magnetostratigraphic results allow us to propose a chronostratigraphy of the upper Maastrichtian–Thanetian continental formations in south France. The stratigraphic position of Chron C29r, in which the Cretaceous–Paleogene boundary occurs, is well defined. Thus this framework could be of great interest for finding the boundary itself and for studying how the geochemical features which characterize this event are different or similar to the other well studied terrestrial environment realms. However, at present, the most interesting result is the position of the uppermost dinosaur eggshell remains. Given the lack of any other biostratigraphic datums in the west Mediterranean realm, this position has often been considered as indicating the 'K–T' boundary. Our magnetostratigraphic results allow the assessment that this last occurrence is situated at the top of Chron C30n in the Breguere section (southeast France) and most probably in Chron C31n in the Albas section (southwest France). A previous magnetostratigraphic study of Cretaceous–Tertiary continental deposits in Spain gave similar results (Fontllonga, Province of Lerida) [25]. The palaeomagnetic study of this section provides a clear magnetic polarity sequence which extends from Chron C32r to C26r (Fig. 5), the last dinosaur eggshells occurring at the base of Chron C31n.

Does the uppermost occurrence of eggshells in the sections studied correspond to the extinction of the dinosaurs in the western Mediterranean realm? The answer to this question would generate extensive discussion. The last occurrence does not correspond to the same moment in the different realms studied: approximately 800,000 yr before the K–T boundary in southeast France, and more than 3 Myr in southwest France and northern Spain. The disappearance of eggshells could only reflect local palaeoenvironmental changes to new ecological conditions not favourable to dinosaur reproduction. However, no significant sedimentological feature suggests such environmental changes around the levels of the last occurrence of the dinosaur remains. In southeast France such an event was documented in the Rognac Limestone Formation, which was correlated with Chron C31n. In this formation a regional discontinuity characterizes a period of ferralitic weathering and was interpreted as due to a large regression, through a major change in climate and/or vegetation [18]. Data from pelagic sediments also demonstrate that the mid-Maastrichtian was a period subject to multiple climatic changes related to eustatic sea-level fluctuations [30]. Exact links between these events (climatic changes recorded in marine environments, effects on the terrestrial realm, dinosaurs eggshell disappearance/dinosaur extinction) need more regional and global data. The solution to this problem could be improved by the study of dinosaur eggshell remains themselves [31]. A geochemistry study of eggshells (clearly constrained by drinking water and food composition) was carried out in southeast France [32]. Environmental changes can be deduced from such analysis but the results are somewhat difficult to interpret. A modification of the shell chemical composition was not found, which could signify the proximity of a crisis.

What was the scenario of the dinosaurs extinction? Magnetostratigraphic data in south France and north Spain support the idea that this event probably occurred earlier in western Europe than in the North American continent. This result, which has to be confirmed in other continents, is in accordance with a gradual or stepwise extinction scenario rather than a catastrophic mass extinction. However, it does not invalidate the extraterrestrial bolide event which could have destroyed the last survivors that were dying 'naturally' in North America.

Acknowledgements

I am grateful to reviewers J.F. Lerbekmo and M. Westphal for their comments. I would like also to thank J. King for revision of the English and review of an earlier draft of this paper. ***[RV]***

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