Earth and Planetary Science Letters, 71 (1984) 147–162
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

[3]

Jurassic magnetostratigraphy, 1. Kimmeridgian-Tithonian of Sierra Gorda and Carcabuey, southern Spain

J.G. Ogg [1,2], M.B. Steiner [1], F. Oloriz [3] and J.M. Tavera [4]

[1] *Department of Geology and Geophysics, University of Wyoming, Laramie, WY 82071 (U.S.A.)*
[2] *A-012, Scripps Institution of Oceanography, University of California at San Diego, La Jolla, CA 92093 (U.S.A.)*
[3] *Departamento de Paleontologia, Universidad de Granada, Granada (Spain)*
[4] *Departamento de Geologia General, Universidad de Granada, Granada, (Spain)*

Received December 12, 1983
Revised version received August 7, 1984

Two coeval sections of red to white ammonite-rich pelagic limestones spanning the complete Kimmeridgian and most of the Tithonian were sampled in detail. All samples were treated by progressive thermal demagnetization to remove a present field overprint. Characteristic magnetization is carried primarily by magnetite. Polarity intervals are easily identified and correlate well between the two sections. The Tithonian polarity sequence can also be correlated to sections in northern Italy. The similarity between the polarity sequence and the M-sequence of marine magnetic anomalies, coupled with the precise biostratigraphic control, allows assignment of the following ages to the M-sequence: the Late/Early Tithonian boundary is correlated to the end of M-20, the Tithonian/Kimmeridgian boundary to the end of M-23, the Late/Early Kimmeridgian boundary to the latter part of M-24, and the Kimmeridgian/Oxfordian boundary within or slightly after M-25.

The mean directions of characteristic magnetization have α_{95}'s less than 3° and demonstrate extensive differential block rotation within the Subbetic province. Paleolatitudes during the Kimmeridgian/Tithonian are in the range of 16–24°N.

1. Introduction

The sequence of linear marine magnetic anomalies is generally an accurate recorder of the changing polarity of the earth's magnetic field. Correlation to the polarity patterns in fossiliferous sediments or volcanic sequences allows assignment of ages to the formation of the seafloor crust. This has been accomplished for the Late Cretaceous and Cenozoic [1]. However, the Jurassic/Early Cretaceous M-sequence of marine magnetic anomalies [2,3] has been definitely correlated only: (1) in its earliest part, in Barremian/Aptian pelagic carbonates of Italy [4,5], and (2) in a portion of its older part, in Tithonian/early Berriasian pelagic limestones from northern Italy [6] and from Deep Sea Drilling Project Site 534 in the western Central Atlantic [7]. The bulk of the M-sequence has been assigned approximate ages by projecting constant seafloor spreading rates between or beyond a few age control points by using various absolute time scales [2,8–10]. The only age control point older than the Tithonian/Berriasian stage boundary (M-18) has been the age of basal sediments overlying basalt at DSDP Site 105, located between M-24 and M-25. However, the imprecision of the nannofossil zonation in the Jurassic has led to a continuing revision of the biostratigraphy of basal sediments at Site 105; for example, one of the lowest cores (core 37) has been dated variously as Oxfordian [11], Early Kimmeridgian [12], and Kimmeridgian [13]. As the dating of the earlier portion of the M-sequence is vital to models of the early spreading history of the Atlantic and to global seafloor spreading rates during the Late Jurassic, it is important that the

0012-821X/84/$03.00

anomaly pattern be correlated to the polarity patterns obtained from fossiliferous sediments. This paper reports the successful results from Kimmeridgian/Tithonian sediments.

There have been several previous attempts to determine polarity zonations in sedimentary sections of Late Jurassic age. However, none yielded a definite correlation with the M-sequence or an assignment of ages for a variety of reasons. Magnetostratigraphy of the Morrison Formation of North America yielded a possible correlation to M-22 through M-25 of the M-sequence [14], but the age and time span of these continental sediments has been determined only as "Upper Jurassic". Studies of Upper Jurassic carbonate sediments in Tunesia [15] and Germany [16] yielded results which could not be reliably correlated to the M-sequence. Several DSDP sites in the Atlantic have recovered Tithonian/Kimmeridgian sediments. The magnetostratigraphy of Site 534 could be correlated to M-16 through M-23 of the M-sequence [7], however the biostratigraphic ages given by different micropaleontological zonations differed considerably. Earlier studies at Site 367 [17] and Site 391 [18] used only alternating field demagnetization, which is ineffective in removing present field overprints in these red marly limestones having hematite as the magnetic carrier [7,19]. Upon thermal demagnetization, the sediments at Site 105 yielded a polarity sequence [19], but the condensed stratigraphy and poor recovery of this section did not allow correlation to the M-sequence.

Magnetostratigraphic studies in the lowermost Cretaceous and upper Tithonian have been successful in correlating the broad microfossil zonation of calpionellids to the M-sequence [6,20–22]. However, the placement of the Jurassic/Cretaceous boundary in these sections and corresponding assignment of this major period boundary to the M-sequence is very uncertain [23] and rarely corresponds to the international definition based on ammonite zones.

2. Geologic setting and stratigraphy

The Subbetic is presently a belt, 40–80 km wide, of Jurassic and Cretaceous pelagic sediments which extends 500 km across southern Spain from Cadiz to Alicante (Fig. 1). This region is interpreted as a passive margin which began active subsidence during the Carixian stage of the Early Jurassic and remained in the pelagic realm until initiation of tectonic shortening from the Eocene onwards [24]. The Prebetic region to the north continued as a shallow marine carbonate platform throughout this interval. The Subbetic is bounded to the south by the allochthonous terrains of the Betic region, which were probably emplaced during the Tertiary.

During the Jurassic, the Subbetic was divided into two submarine swells separated by a median trough which experienced local volcanic extrusions. This general topography and the irregular relief upon each swell led to considerable variation in the Jurassic facies (summarized in [25,26]). The two sections sampled for this study (Fig. 1) are interpreted to be from the summit or upper slope of small topographic highs, one on each swell [26]. The late Bathonian, Callovian and Early Oxfordian on such topographic highs is represented by very condensed sedimentation or hiatuses. Continuous pelagic sedimentation commenced in the late Early Oxfordian with red marl or gray nodular marly limestone. The Kimmeridgian is represented by a reduced-thickness, but generally continuous, section of ammonite-rich, red to pinkish gray, marly biomicritic limestone with *Saccocoma* (pelagic crinoids), calcified radiolaria, calcispheres, *Globochaete*, foraminifera, and miscellaneous shell debris. During the lithification process, differential cementation of the bioturbated sediment created a

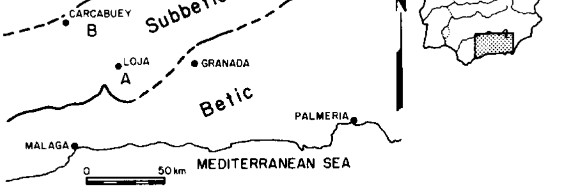

Fig. 1. Location of the magnetostratigraphic sections in the Subbetic Cordillera region of southern Spain. Section A is Sierra Gorda; Section B is Carcabuey.

nodular texture; the carbonate cement of the lime-rich nodules was preferentially derived from dissolution in adjacent zones, leaving a residual of red clay and relatively-resistant *Saccocoma* fragments which formed a matrix among the nodules [26,27]. This process is associated with the variable density of burrowing. Paleomagnetic samples are taken preferentially from the nodules. Net sedimentation rates of these sediment sections are about 75–150 cm/m.y. [26]. During the Tithonian, carbonate sedimentation increased and the lithology gradually changed to a white biomicritic limestone with calpionellids. There is another gradual transition into the light gray marls of the Berriasian.

Compression of the North Africa–Betic–Iberia region occurred during the Tertiary, with deformation of the Subbetic region peaking during the Early Miocene. The pelagic sediment series was thrust northward; in some places the detachment surface is the Triassic evaporite beds. Broad regional folding and small-scale faulting of the blocks is ubiquitous. No metamorphism is observed, but locally severe small-scale deformation exists related to the presence of thick marly facies.

The ammonite biostratigraphy in the Kimmeridgian/Tithonian of the Subbetic has recently been established in detail [28–34], based in part on the stratigraphic sections sampled in this study. Correlation to the broader calpionelled zones is possible in the Late Tithonian. Table 1 presents the ammonite zonation used for this study and its correlation to some other important biostratigraphic schemes. Placement of ammonite zone boundaries within the sampled outcrops is certain to within about 20 cm in the Kimmeridgian and about 40 cm in the Tithonian; which is equivalent to about 100,000–200,000 year precision in correlation between the sections. The small apparent hiatuses in sedimentation in each section (indicated by truncated ammonites, irregular surfaces of beds or major clay seams) commonly fall within individual ammonite zones, not at zonal boundaries; therefore we consider the maximum duration of such hiatuses to be only a fraction of an ammonite zone, or perhaps a maximum of 250,000 years for some of the levels within the Kimmeridgian. These uncertainties in placement of ammonite zone boundaries and the hiatuses, while minor in importance, are noticeable in the detailed magnetostratigraphic correlations.

The Sierra Gorda section (37.2°N, 355.9°E) is located on the eastern flank of the Sierra Gorda uplift, 1/2 km east of Cortijo del Caldador, 5 km south of Salar (45 km west of Granada). This is a natural exposure in which the beds dip 36° in the direction N38°E. This sequence of sediments was deposited on the southern swell of the Subbetic (Internal Subbetic). The regional geology of the Sierra Gorda section has been described by Linares and Vera [35] and Vera [36] (his "Corte de Venta Quesada" section). Microfacies of the units have been described by Vera et al. [25]. The Kimmeridgian/Tithonian lithostratigraphy and biostratigraphy have been studied in detail by Comas et al. [26] (their "Cardador" section). The Late Tithonian in this section is represented by red, yellow and gray marls with few indurated levels and poor exposures, and therefore was not sampled.

The Carcabuey section (37.5°N, 356.7°E) is located 4 km southwest of Carcabuey (80 km WNW of Granada), and about 50 km northwest of the Sierra Gorda section. It is a natural exposure above a small spring, and has an average dip of 25° in the direction N100°E. The regional geology of this part of the northern uplift of the Subbetic (External Subbetic) has been well studied [37–39]. The Kimmeridgian/Tithonian lithologies and biostratigraphy are described by Comas et al. [26] (their "Hornillo" section). Although the Kimmeridgian is represented by only 1.6 m of grayish red limestone, it exhibits a very detailed ammonite sequence. Sampling was continued into the lowermost Berriasian, the upper limit of the exposure. At this same outcrop, the underlying Bathonian red limestones were also sampled and are the topic of a separate report [40].

3. Laboratory procedure

The density of field sampling depended upon the estimated rate of sedimentation. In general, we collected 20 cores per ammonite zone through the uppermost Oxfordian, Kimmeridgian and Lower

TABLE 1

Comparison of ammonite zonations for Kimmeridgian/Tithonian

Stage	Calpionellid Zone	Oloriz [29] Oloriz and Tavera [30] Subbetic Zone, Spain	Sapunov [50] Bulgaria	Enay and Geyssant [51] Enay et al. [52] Southern Europe
Berriasian	B	*Berriasella (Pseudosubplanites) grandis - Berriasella jacobi*	*Protacanthodiscus chaperi* / *Transitorius*	*Berriasella (Pseudosubplanites) grandis - Berriasella jacobi*
Late Tithonian	A	*Durangites*	*Microcanthuceras Microcanthum* / *Transitorius*	*Durangites*
		Paraulacosphinctes transitorius		
	Ch	*Simplisphinctes*		*Microcanthoceras microcanthum*
Early Tithonian		*Burckhardticeras peroni*	*Parapallasiceras* ssp.	"*Micracanthoceras*" *ponti*
		Simoceras admirandum - Simolytaceras biruncinatum	*Virgatosimoceras rothpletzi*	*Semiformiceras fallauxi*
		Richterella richteri		
		Haploceras verruciferum		*Semiformiceras semiforme*
		Virgatosimoceras albertinum	*Franconites pseudojubatus*	"*Neochetoceras*" *darwini*
			Franconites vimineus	
			Subplanites schwertschlageri	
		Hybonoticeras hybonotum	*Subplanites moernscheimensis* *Hybonoticeras hybonotum*	*Hybonoticeras hybonotum*
Late Kimmeridgian		*Hybonoticeras beckeri*	*Hybonoticeras beckeri*: *Virgataxioceras setatum*	*Hybonoticeras beckeri*: *Virgataxioceras setatum*
			Hybonoticeras beckeri: *Sutneria subeumela*	*Hybonoticeras beckeri*: *Sutneria subeumela*
		Mesosimoceras cavouri	*Aspidoceras sesquinodosum*	*Aulacostephanus (Pseudomutabilis) eudoxus*
		Taramelliceras "*compsum*" (interval zone)	*Crussoliceras/Aspidoceras sesquinodosum* (interval zone)	*Aspidoceras acanthicum*
Early Kimmeridgian		*Aspidoceras uhlandi* *Idoceras balderum* (horizon)	*Crussoliceras divisum*	*Isoceras balderum* *Aspidoceras uhlandi*
		Crussoliceras divisum		*Crussoliceras divisum*
		Taramelliceras (Metahaploceras) strombecki	*Ataxioceras hypselocyclum*	*Ataxioceras hypselocyclum*
		Sutneria platynota	*Ataxioceras (Parataxioceras) desmoides*	*Sutneria platynota*
Late Oxfordian		*Idoceras planula*		

Tithonian in each section, and fewer in the Upper Tithonian at Carcabuey. Samples were trimmed to 2.5 cm cylinders.

All measurements were made on a two-axis Sct cryogenic magnetometer (noise level = 2×10^{-8} emu or 2×10^{-11} A m^2) with on-line computer data analysis. The magnetometer and demagnetization equipment (non-inductively wound furnace with separate cooling chamber and single-axis Schonsted alternating field demagnetizer) are contained within a steel-shielded room (internal field less than 1000 gammas or 1000 nT). Each sample was measured in eight orientations (90° rotations on z axis and inverted set), and the measurements averaged.

Two dozen samples were selected for pilot studies of the magnetic characteristics of the various lithologies; these underwent progressive thermal demagnetization in 40–50° increments or alternating field demagnetization at ten steps between 0 and 50 mT. Based on these pilots, the remaining samples were measured at a minimum of 4 selected demagnetization steps, which varied for each lithology and outcrop. Magnetic polarity and characteristic direction of remanent magnetization were determined for each sample individually based on its behavior during demagnetization.

4. Magnetic behavior of the lithologies

The dominant lithology in the two sections is grayish pink to light gray pelagic biomicritic limestone. The magnetic behavior is identical between the two sections and between the grayish pink and the light gray colorations. NRM intensities generally are within the 5–20 × 10^{-6} emu/cm^3 (5–20 × 10^{-3} A/m) range. With rare exception, NRM directions before bedding correction were near the present field (355° declination, 52° inclination): the Sierra Gorda NRM mean is 330 ± 30° declination, 55 ± 10° inclination; that of Carcabüey, 15 ± 15° declination, 60 ± 10° inclination (Fig. 2). Both thermal and alternating field (AF) demagne-

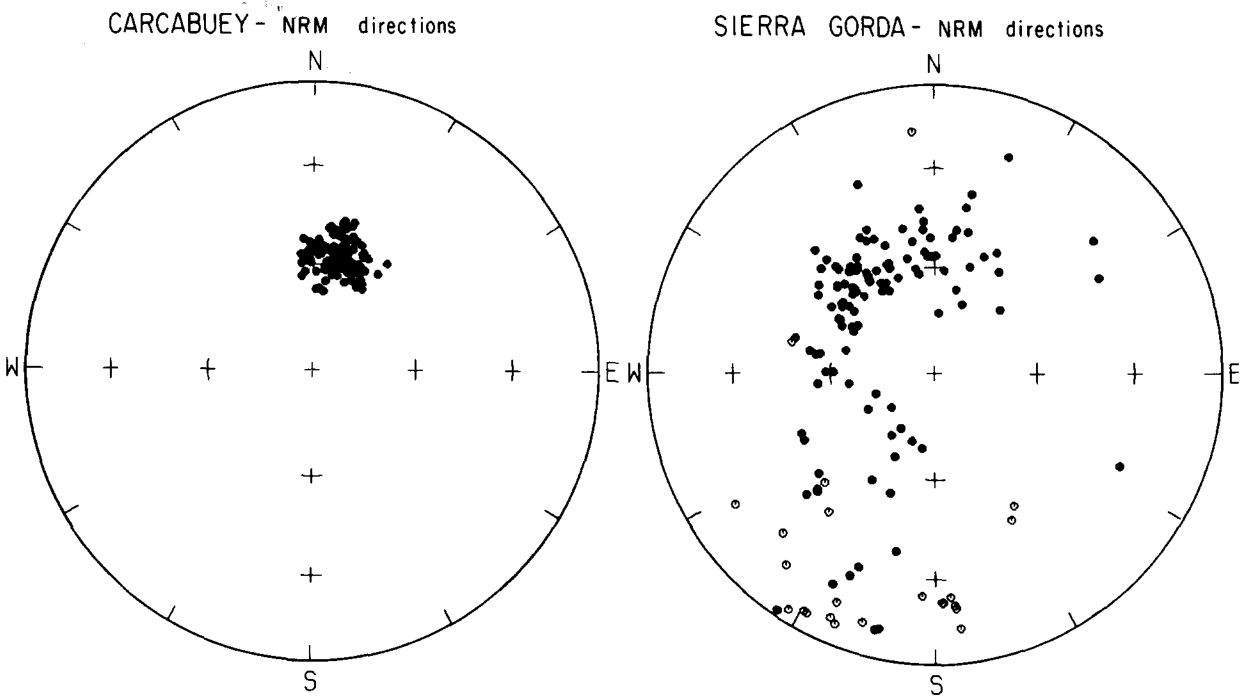

Fig. 2. NRM directions of Carcabuey and Sierra Gorda sections; equal area plot, solid symbols are lower hemisphere, open symbols are upper hemisphere.

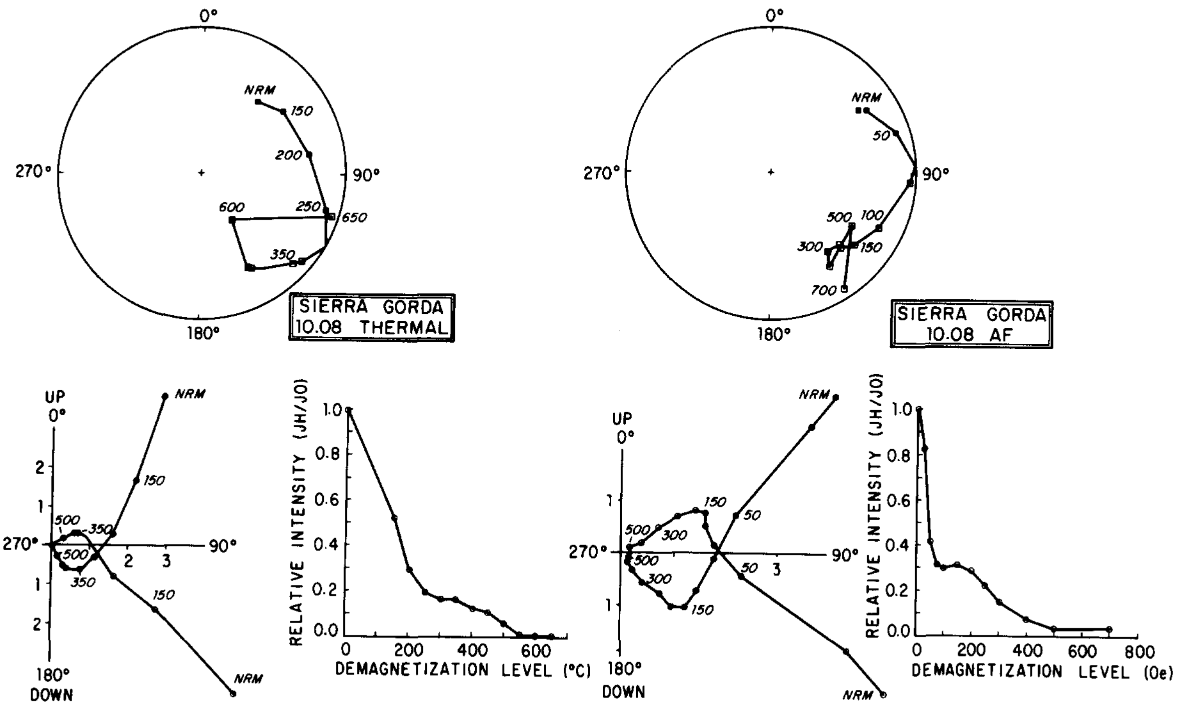

Fig. 3. Thermal demagnetization (on left) and alternating field demagnetization (on right) behavior of two specimens of a typical Tithonian sample (10.08 m in the Sierra Gorda section). Upper diagram in each set is an equal area plot of the directions during demagnetization: solid squares are on lower hemisphere, open squares are on upper hemisphere. The lower left diagram in each set is a vector demagnetization diagram: declination (solid dots) is the horizontal component of the demagnetization path; inclination (open dots) plots the angle from horizontal and the total intensity of the demagnetization path; one scale division is equal to 10^{-6} emu/cm^3 (10^{-3} A/m). Lower right diagram in each set plots the intensity at each demagnetization step relative to the intensity at NRM. Steps for the thermal demagnetization diagrams are in °C, and for the AF demagnetization diagrams in oersteds (units of 10^{-1} mT). Directions in all plots are corrected for tilt of bedding. Sample has reversed polarity upon demagnetization.

tization proved effective in removing the present field overprint. Fig. 3 shows some typical demagnetization plots. Samples with reversed characteristic directions display the reversed direction after heating to between 300° and 350°C or after AF demagnetization above 100 Oe (10 mT). Stable characteristic directions and minimum dispersion about antipodal means were attained in the 400° to 500°C interval or 200–300 Oe (20–30 mT). At 450°C, the intensities were generally in the $2–15 \times 10^{-7}$ emu/cm^3 ($2–15 \times 10^{-4}$ A/m) range with a small decrease in the more rapidly deposited Tithonian limestones. Above 500°C, the intensities fell rapidly, and directions at the 600°C step were essentially random. This was also the case upon AF demagnetization above 500 Oe (50 mT) for several samples. From this behavior we conclude that magnetite is the principal carrier of the characteristic direction, and that the NRM is dominated by a viscous present field magnetization. For batch demagnetization, the Sierra Gorda samples were treated with 100 Oe (10 mT) then progressively demagnetized in 50° steps from 100° to 550°C, the Carcabuey samples were heated in 50° steps from 350° to 500°C.

The uppermost Oxfordian and lower Kimmeridgian in the Sierra Gorda section is a light tannish gray nodular marly limestone. NRM intensities were $10–20 \times 10^{-6}$ emu/cm^3 ($10–20 \times 10^{-3}$ A/m), and NRM directions before bedding correction centered about 280° declination, 50° inclination (after bedding, 330° declination, 45° inclination) with no indication of a polarity pattern. Thermal demagnetization was effective in

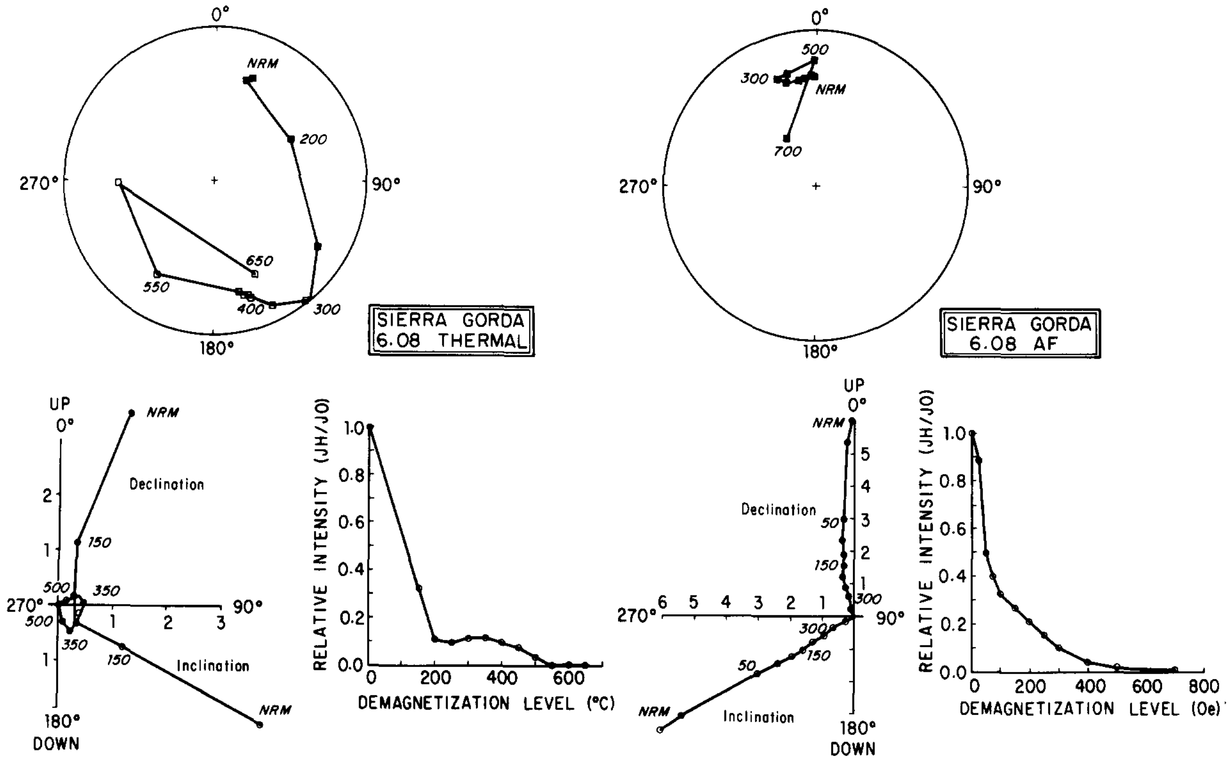

Fig. 4. Thermal demagnetization (right side) and alternating field demagnetization (left side) behavior of two specimens of a typical Kimmeridgian sample (6.08 m in the Sierra Gorda section). Diagrams are explained in the caption of Fig. 3. Sample has reversed polarity upon demagnetization.

removing the overprint, and each sample was given six thermal steps between 200° and 550°C (Fig. 4). Above 500°C, there was another sharp drop in intensity and a dramatic increase in dispersion.

The Middle to Upper Oxfordian at Sierra Gorda is a light gray nodular marly limestone with a yellow or pink tint and the Middle Callovian is a yellowish limestone. NRM intensities were moderately high ($5-10 \times 10^{-5}$ emu/cm^3 or 10^{-2} A/m), and average NRM directions before bedding correction were an unusual 200° declination, −15° to +20° inclination (180° declination, 10° to 50° inclination, after bedding correction). Neither thermal nor AF demagnetization had any affect upon this peculiar direction, even though the intensities decreased. This Callovian/Oxfordian section was deemed unsatisfactory for magnetostratigraphy.

As a result of the poor Oxfordian exposure at Carcabuey and poor magnetic properties of the rocks below the uppermost Oxfordian at Sierra Gorda, polarity zonations were obtained only for the uppermost Oxfordian through Tithonian stages.

5. Magnetostratigraphy

The excellent separation of the antipodal directions made polarity determination very simple (Fig. 5). Stratigraphic plots of the characteristic direction of magnetization (usually either the 450° or 500°C step) and polarity interpretation for the Sierra Gorda and Carcabuey sections are shown in Figs. 6 and 7 respectively. Polarity zones on single samples are shown in two cases, though the validity of such short intervals is open to question. Gaps in sampling or intervals within which polarity is indeterminant are cross-hatched.

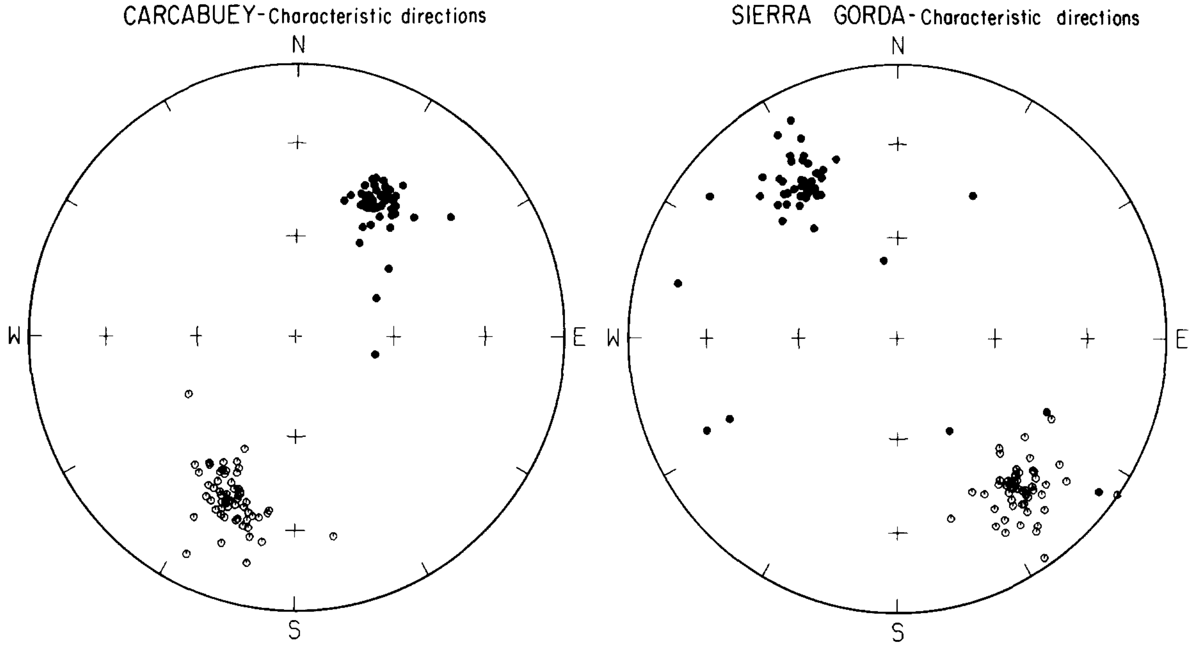

Fig. 5. Characteristic directions of magnetization for the Carcabuey and Sierra Gorda section: thermal demagnetization 450°C (except for a few at 500°C); equal area plot (solid symbols are on lower hemisphere, open symbols are upper hemisphere).

Intermediate directions were rarely observed. The sampling density is such that any polarity interval of 100,000 year duration or longer should have been recorded by at least two samples. The possible minor hiatuses in sedimentation (indicated in Figs. 6 and 7) may have caused slightly longer gaps in the record. We are confident, however, that the results of each section reveal all polarity episodes greater than 200,000 year duration through the Kimmeridgian and Early Tithonian. The only exceptions are (1) the lowest ammonite zones (*S. Platynota* and *T. (M.) strombecki*) of the Kimmeridgian where the sequence appears to be thinner than normal and therefore the sample density is sparse relative to the time represented, and (2) near the base of the lowest Tithonian ammonite zone (*H. hybonotum*) where an erosion surface in each section may have eliminated a significant portion of that zone. This may explain the slight discrepancy in the fine-scale correlation at this time, as discussed below. It is noteworthy that nearly all the polarity changes occur within beds, not at bedding planes or minor hiatuses.

6. Correlation of polarity intervals

Fig. 8 shows the biostratigraphic-magnetostratigraphic correlations between the two sections, and the correlations to polarity columns from Tithonian-Berriasian sediments of northern Italy [6] and to the marine magnetic anomaly "M-sequence" [2]. In this correlation diagram, the relatively thin Kimmeridgian portion of both Spanish sections has been linearly expanded in order to show polarity intervals more clearly and to better approximate the relative duration of the Kimmeridgian with respect to the Tithonian for ease in visually comparing the polarity patterns to the M-sequence.

There is a relatively good match between the polarity zonations of the two sections. The few exceptions are (1) a short normal polarity interval at the *M. cavouri / H. beckeri* ammonite zone boundary (middle Late Kimmeridgian) which is recorded at Carcabuey, but lacking in the Sierra Gorda section, (2) the reversed polarity interval of the *R. richteri* ammonite zone (middle Early Tithonian) which was present in the Sierra Gorda

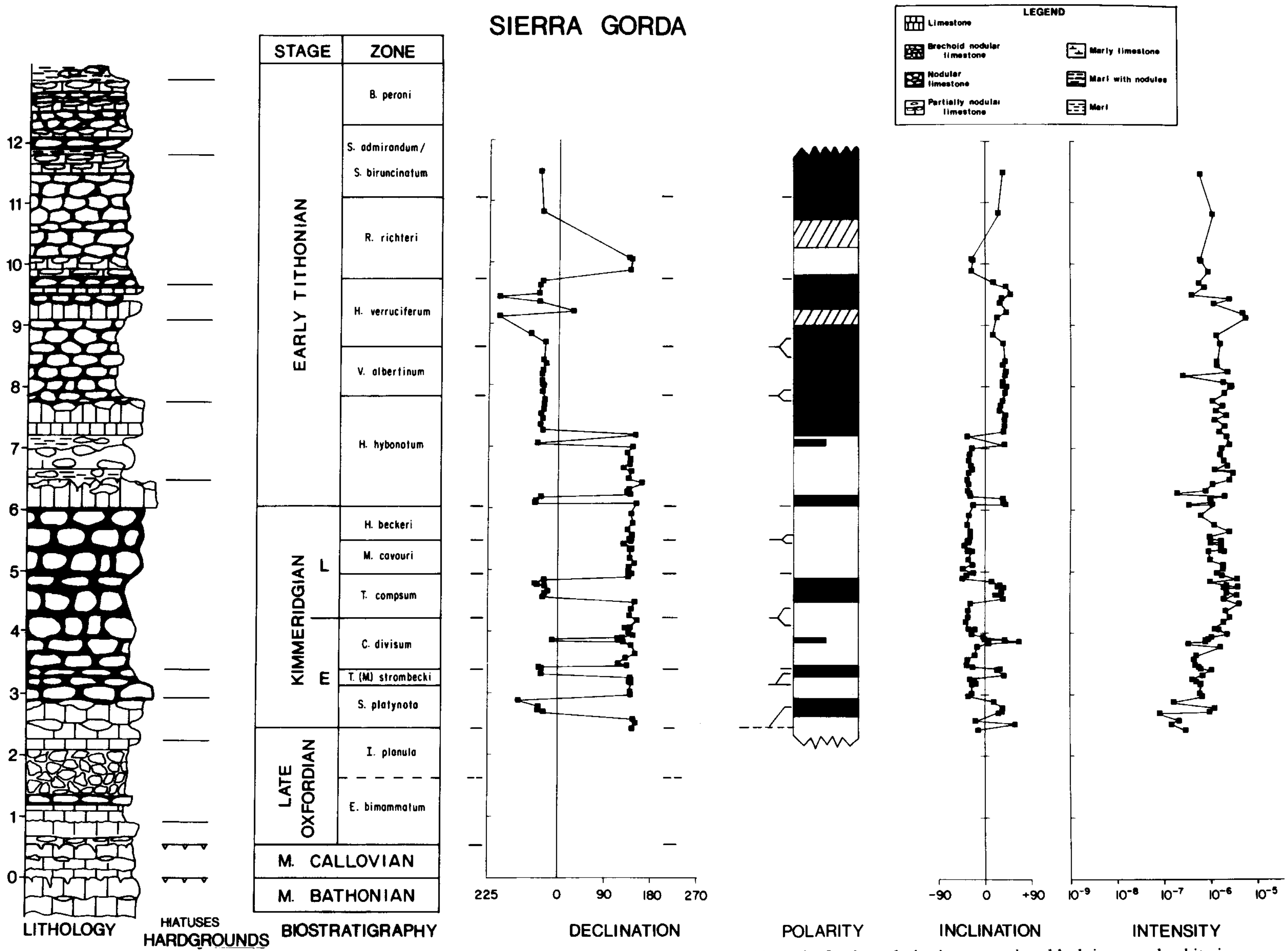

Fig. 6. Characteristic directions of magnetization for the Sierra Gorda samples plotted on a stratigraphic scale. In the polarity interpretation, black is normal, white is reversed polarity, and hachured is indeterminate or unsampled; a possible polarity interval indicated by only a single sample is drawn as a partial bar.

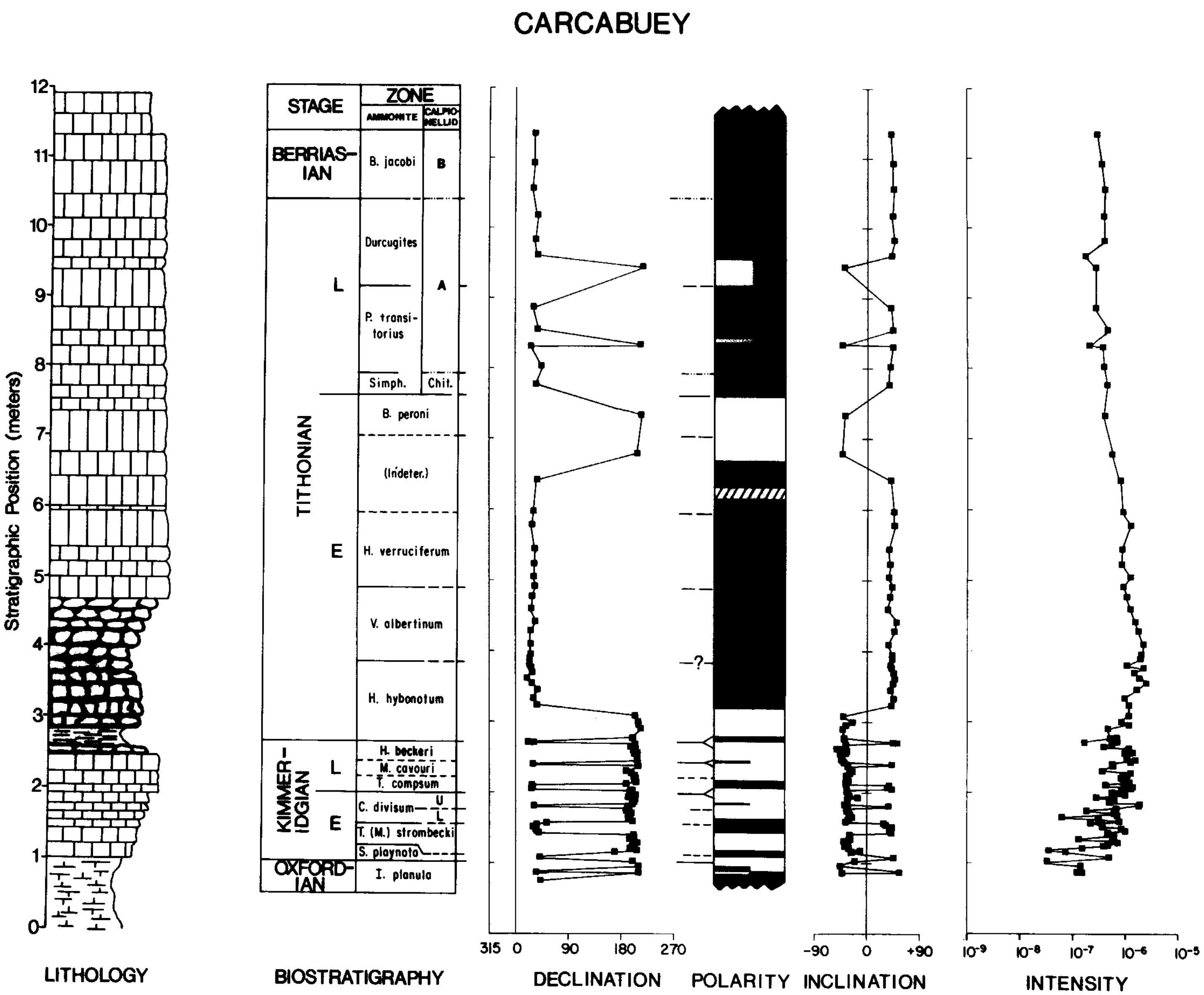

Fig. 7. Characteristic directions of magnetization for the Carcabuey samples plotted on a stratigraphic scale. Black is normal polarity, white is reversed, hachured is indeterminate or unsampled, partial bars are single sample polarity intervals.

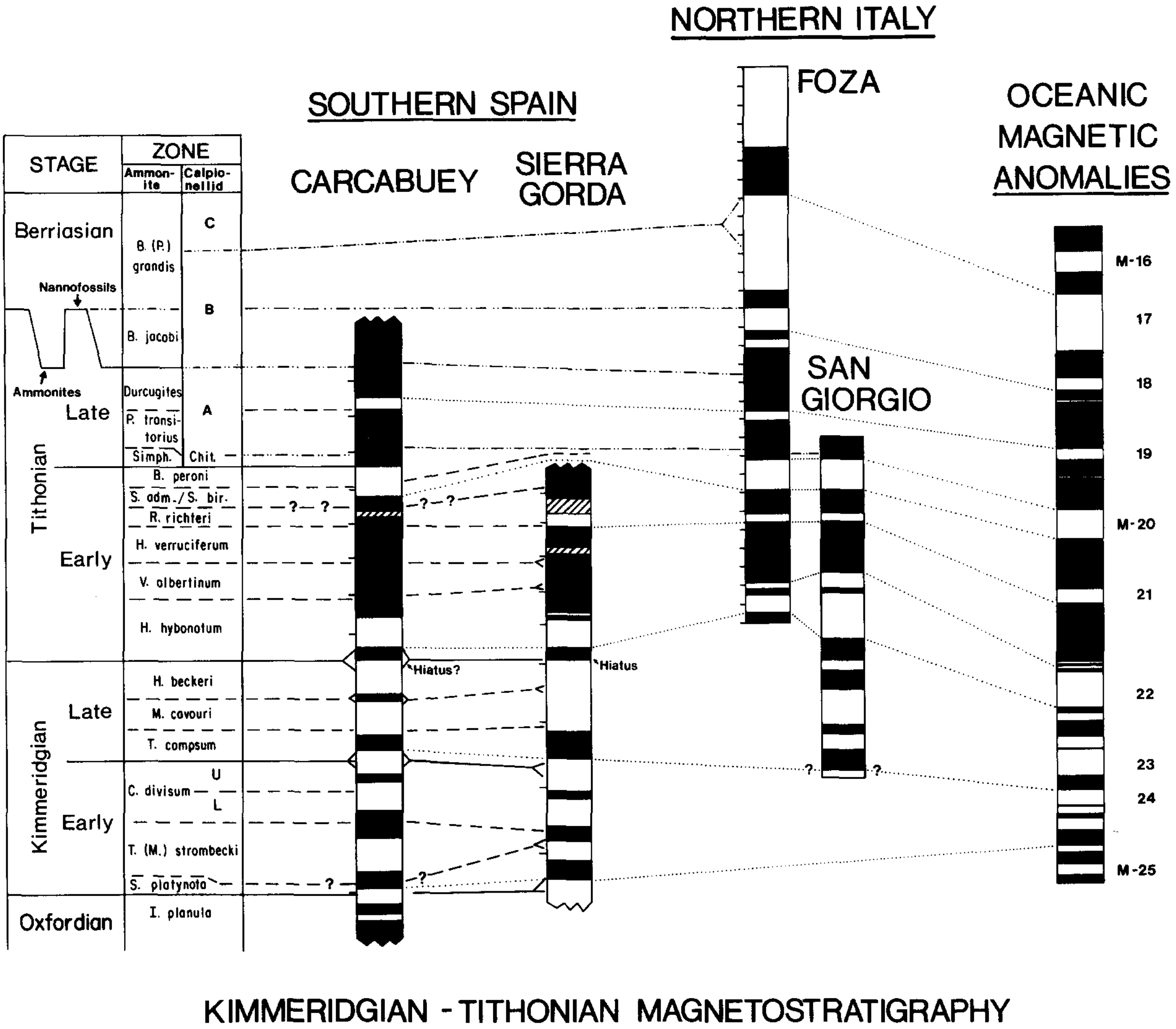

Fig. 8. Correlation of the Spanish magnetostratigraphy with the magnetostratigraphy from northern Italy [6] and the M-sequence of marine magnetic anomalies [2]. Black is normal polarity; white is reversed. Single sample polarity intervals are represented by a full bar, in contrast to Figs. 6 and 7. Solid tie lines are ammonite zone boundaries (uncertainties indicated by a bracket); dot-dash tie lines are calpionellid standard zone boundaries or nannofossil events (sudden increase in abundance of *Nannoconus colomii*); dotted lines are the proposed correlation of polarity intervals. For this diagram, the Kimmeridgian portion of each Spanish section has been linearly expanded relative to the Tithonian portion (expansion factor of 3.5 for Carcabuey and 2.4 for Sierra Gorda). Meter intervals are denoted by the scale on each polarity column.

section, but absent or not sampled in the Carcabuey section (where the *R. richteri* ammonite zone itself has not been identified) and (3) the polarity correlation of the *T. (M.) strombecki–S. platynota–I. planula* interval at the base of the sections.

The two northern Italian magnetic polarity columns are "type" sections used for magnetostratigraphic correlation of pelagic sediment outcrops in the Trento Plateau region of the Southern Alps [6]. These lack ammonite zonation, so the biostratigraphic correlation is based on microfossils (calpionellid zones, *Saccocoma*, *Protogloberinae*). The correlation of the Tithonian (using calpionellid zone boundaries for tie lines) between Spain and northern Italy is fairly good. The correlation in the Kimmeridgian is less reliable, probably because of less continuous sedimentation in the Italian sections (as indicated by rapid changes in facies [27]). A particular problem is that the basal Tithonian in the Spanish sections has a short normal polarity interval, whereas the Italian section and M-sequence (normal interval between M-22 and M-23) has a much longer zone of normal polarity split by a short reversed event (though this was often lacking in other sections of the Trento Plateau region [6]). Hiatuses in the Spanish sections may have omitted much of this normal polarity zone.

The proposed correlation to the marine magnetic anomaly M-sequence is based on the combined Spanish and Italian data. It is important to note that the M-sequence is a model drawn assuming a constant spreading rate in the Pacific [2] and the Spanish sections are drawn on stratigraphic scales with only a linear change of scale to partially adjust the thickness of the Kimmeridgian portion of the section to the Tithonian portion. The correlation to M-17 through M-22 is uniquely determined by the patterns of long and short polarity intervals. The pattern of the M-sequence between M-22 and M-25 lacks a distinctive "fingerprint", therefore the correlation for the Kimmeridgian is based in part by counting downwards the major normal and reversed polarity intervals below M-22. The long normal interval between M-22 and M-23 correlates to the shorter normal interval at the base of the Tithonian in the Spanish sections. The predominantly reversed polarity of the M-23 and M-24 interval is matched by a similar zone in the Spanish sections with the normal intervals between M-23 and M-24 corresponding to the relatively long normal in the *T. compsum* zone. A problem arises between M-24 and M-25 which Larson and Hilde [2] modeled as alternating short normal and reversed polarity intervals. The *T. (M.) strombecki–S. platynota* ammonite zones in both land sections include a fairly large reversed interval. This discrepancy may be the result of the extreme thinness of the *S. platynota* ammonite zone here and the resulting relatively low density of samples per unit of time. It is also possible that the width of the reversed episodes between M-24 and M-25 may have been modeled too narrowly. We suggest that M-25 corresponds to a reversed polarity zone crossing or slightly below the Oxfordian/Kimmeridgian boundary; there will remain some uncertainty until the magnetostratigraphy of the Late Oxfordian is known. Detailed analysis of two expanded sections of the *T. (M.) strombecki–S. platynota–I. planula* interval are underway.

7. Discussion

7.1. Jurassic/Cretaceous boundary

The magnetic polarity pattern presented here is from rocks which have a well-developed Kimmeridgian/Tithonian ammonite zonation. This zonation has been developed by Oloriz and Tavera [28–34]. The correlation to other biostratigraphic zonation schemes is presented in Table 1; this will no doubt be refined in future years by using the magnetic polarity scale as a common standard.

There is one point on which the Oloriz-Tavera zonation scheme differs from some other time scales, namely in the placement of the Jurassic/Cretaceous (Tithonian/Berriasian) boundary. Oloriz and Tavera [33], following the decision of the 1973 Colloque [41], place the Jurassic/Cretaceous boundary at the base of a combined *B. (P.) grandis–B. jacobi* ammonite zone; this boundary, which is the time of greatest change in the Tithonian ammonite assemblages, thus coincides with the Calpionellid Zone A to B transition. Other schemes place the boundary between separate *B. (P.) grandis* and *B. jacobi* ammonite zones (e.g. Allemann et al. [42] in their biostratigraphic study of the Berriasian of the eastern Subbetic). This alternate boundary falls near the middle of Calpionellid Zone B [43,44] and is similar to the definition of the base of the Berriasian stage in France [45]. Because the Tithonian stage does not have a type section, the Tithonian/Berriasian boundary has been a topic of considerable debate among paleontologists (e.g. [41,45] and the international colloquium in Budapest in 1984). The sudden abundance of the nannofossil *Nannoconus* *colomii* appears to coincide with the top of the *B. jacobi* ammonite zone, and this nannofossil event was proposed by Thierstein [46] as a more useful global definition of the Cretaceous/Jurassic boundary. This nannofossil-defined boundary was used for the northern Italian sections shown in Fig. 8 ([6]; see discussion in [7]). Eventually, a more detailed magnetic polarity time scale will provide the most precise global definition of the boundary [23].

7.2. *Precision of the magnetic time scale*

The biostratigraphic correlation to the magnetic polarity intervals has two main sources of uncertainty. The first is a relative uncertainty in placement of the ammonite zone boundaries caused both by the fossil record of the evolution of the species and especially by the identification of assemblages within each bed. By necessity, such an assemblage is obtained from the average of several centimeters. The uncertainty is shown in Figs. 6 and 7 by brackets at the ends of the correlation lines. The second source of imprecision is the small delay in the setting of magnetization within the sediment. Magnetization carried by magnetite is thought to be fixed during early dewatering of the sediment [47]. The time lag between the setting of the magnetic polarity zones to the deposition of the ammonite zones is probably an insignificant fraction of the time represented by an ammonite zone (perhaps up to 10% in the Kimmeridgian). Probably, when a polarity sequence is determined for a Kimmeridgian section with rapid sedimentation, the assignment of polarity boundaries will move upward very slightly relative to the biostratigraphic boundaries.

7.3. *Mean directions*

The low dispersion of the antipodal characteristic directions and the large sample sets allowed determination of very precise mean directions of magnetization (Table 2). Means were calculated with and without points lying two standard deviations away from the mean. These were quite similar and Table 2 reports the selected data. Because of the abundant faulting and thrusting within the Subbetic, the different rotations of the regions since the end of the Jurassic are interesting, but have no significance for the motion of the Iberian plate or Subbetic block at all. The average paleolatitude of the region during the Late Jurassic is about 20°N. There is a noticeable difference between the mean Kimmeridgian and Tithonian directions in each section. At first glance, one might think that this suggests northward motion of the Subbetic block between these times, or a clockwise rotation. However, it is apparent that the difference between the Kimmeridgian and Tithonian in each case is a difference between the mean normal and reversed directions. The validity of

TABLE 2

Summary of magnetization results

	D (°)	*I* (°)	*N*	*K*	α_{95} (°)	Paleo-latitude	Paleo-longitude	*Dp*	*Dm*
Sierra Gorda									
Normal	327.1	33.2	41	55.57	3.02	118.6°W	55.4°N	1.95	3.43
Reversed	140.4	−27.6	56	30.20	3.52	116.4°W	48.3°N	2.09	3.84
Mean	323.2	30.0	97	34.66	2.47	117.1°W	51.3°N	1.52	2.74
Tithonian	324.4	32.5	43	79.49	2.46	116.3°W	53.2°N	1.57	2.78
Kimmeridgian	322.2	27.9	54	24.60	3.98	117.6°W	49.8°N	2.38	4.36
Carcabuey									
Normal	32.3	41.7	48	150.78	1.68	102.4°E	59.4°N	1.26	2.06
Reversed	201.6	−35.2	57	68.60	2.29	123.5°E	63.9°N	1.53	2.64
Mean	26.3	38.3	105	66.42	1.70	113.4°E	62.3°N	1.20	2.02
Tithonian	30.4	41.6	48	160.09	1.63	104.5°E	60.7°N	1.22	1.99
Kimmeridgian	23.0	35.5	57	56.32	2.53	121.0°E	63.1°N	1.69	2.93

this has been further substantiated by calculating the mean of normal and reversed data from individual stages. Whether this difference between normal and reversed means is the result of incomplete cleaning or asymmetry in the normal and reversed field is unclear, however it is in the sense that would be expected from incomplete cleaning of present-day overprint. These results indicate that a computed pole with low error limits does not necessarily imply that that pole is accurate; it is important to evaluate the normal and reversed directions independently.

8. Conclusions

A magnetic polarity pattern for the Kimmeridgian and Tithonian has been duplicated in two pelagic sediment sections having precise ammonite zonation. The polarity pattern shows excellent correlation to the magnetostratigraphy of Tithonian pelagic limestone sections of northern Italy. Correlation to the marine magnetic anomaly M-sequence allows assignment of biostratigraphic ages to anomalies M-17 through M-24 and an approximate age to M-25. The Jurassic/Cretaceous boundary as defined by the 1973 Colloque [41] occurs in the middle of the normal polarity interval between M-19 and M-18; the Late/Early Tithonian boundary is at the end of M-20; the Tithonian/Kimmeridgian boundary is in the latest part of M-23; the Late/Early Kimmeridgian boundary is in the middle of the younger half of M-24; and the Kimmeridgian/Oxfordian boundary is either within or slightly younger than M-25. Further subdivision by individual ammonite zones is diagrammed in Fig. 8. These sections thus provide a precise dating for the Kimmeridgian/Tithonian portion of the magnetic polarity time scale.

Acknowledgements

The magnetostratigraphic research is part of a larger study funded by NSF grants EAR-8107739 and EAR-8206263. We express our appreciation to Prof. J.M. Vera and to H. Wilke (Departamentos de Estratigraphia and Paleontologia of the Universidad de Granada) for bringing us together, our research assistant, Beverly DeVore, for helping with the thousands of measurements, and to Juan Antonio Ortiz Molero of Salar, Espana, for his hospitality and help, and for permission to drill on his property at Sierra Gorda. An early manuscript was reviewed by Dr. E.L. Winterer and two anonymous reviewers.

References

1 W. Lowrie and W. Alvarez, One hundred million years of geomagnetic polarity history, Geology 9, 392–397, 1981.
2 R.L. Larson and T.W.C. Hilde, A revised time scale of magnetic reversals for the Early Cretaceous, Late Jurassic, J. Geophys. Res. 80, 2586–2594, 1975.
3 S.C. Cande, R.L. Larson and J.L. LaBrecque, Magnetic lineations in the Pacific Jurassic quiet zone, Earth Planet. Sci. Lett. 41, 434–441, 1978.
4 J.E.T. Channell, W. Lowrie and R. Medizza, Middle and Early Cretaceous magnetic stratigraphy from the Cismon section, Northern Italy, Earth Planet. Sci. Lett. 42, 153–166, 1979.
5 W. Lowrie, W. Alvarez, I. Premoli-Silva and S. Monecki, Lower Cretaceous magnetic stratigraphy in Umbrian pelagic carbonate rocks, Geophys. J.R. Astron. Soc. 60, 263–281, 1980.
6 J.G. Ogg, Sedimentology and paleomagnetic studies of Jurassic pelagic limestones: "Ammonitico Rosso" facies, 204 pp., Ph.D. Thesis, Scripps Institution of Oceanography, University of California at San Diego, 1981.
7 J.G. Ogg, Magnetostratigraphy of Upper Jurassic and lowest Cretaceous sediments, Deep Sea Project Site 534, western North Atlantic, Init. Rep. DSDP 76, 685–697, 1983.
8 P.R. Vogt and A.M. Einwich, Magnetic anomalies and sea floor spreading in the Western North Atlantic, and a revised calibration of the Keathley (M) geomagnetic reversal chronology, Init. Rep. DSDP 43, 857–876, 1979.
9 W.B. Harland, A.V. Cox, P.G. Llewellyn, C.A.G. Pickton, A.G. Smith and R. Walters, A Geologic Time Scale, 132 pp., Cambridge University Press, Cambridge, 1982.
10 Shipboard Scientific Party, Site 534: Blake-Bahama Basin, Init. Rep. DSDP 76, 141–340, 1983.
11 H.R. Thierstein, Calcareous nannoplankton biostratigraphy at the Jurassic-Cretaceous boundary, in: Colloque sur la Limite Jurassique-Crétacé, Lyon-Neuchâtel 1973, Mém. Bur. Rech. Géol. Min. 86, 84–94, 1975.
12 F.W. Wind, Western North Atlantic Upper Jurassic calcareous nannofossil biostratigraphy, Init. Rep. DSDP 44, 761–771, 1978.
13 F.M. Gradstein, Peleoecology and stratigraphy of Jurassic abyssal foraminifera in the Blake-Bahama Basin, Deep Sea Drilling Project Site 534, Init. Rep. DSDP 76, 537–559, 1983.

14 M.B. Steiner and C.E. Helsley, Reversal pattern and apparent polar wander for the Late Jurassic, Geol. Soc. Am. Bull. 86, 1537–1543, 1975.
15 A.E.M. Nairn, T.J. Schmitt and M.E. Smithwick, A palaeomagnetic study of the Upper Mesozoic succession in Northern Tunisia, Geophys. J.R. Astron. Soc. 65, 1–18, 1981.
16 F. Heller, Rockmagnetic studies of Upper Jurassic limestones from Southern Germany, J. Geophys. 44, 525–543, 1978.
17 D.V. Kent and L. Ping Tsai, Paleomagnetism and rock magnetism of Upper Jurassic limestone and basalt from Site 367, Init. Rep. DSDP 41, 995–1002, 1978.
18 B.H. Keating and C.E. Helsley, Paleomagnetic results from DSDP Hole 391C and the magnetostratigraphy of Cretaceous sediments from the Atlantic Ocean floor, Init. Rep. DSDP 44, 523–528, 1978.
19 M.B. Steiner, Magnetization of Jurassic red deep-sea sediments in the Atlantic (DSDP Site 105), Earth Planet. Sci. Lett. 35, 205–214, 1977.
20 E. Mårton, Late Jurassic/Early Cretaceous magnetic stratigraphy from the Sumeg section, Hungary, Each Planet. Sci. Lett. 57, 182–190, 1982.
21 W. Lowrie and J.E.T. Channell, Magnetostratigraphy of the Jurassic-Cretaceous boundary in the Maiolica limestone (Umbria, Italy), Geology 12, 44–47, 1984.
22 S. Cirilli, P. Mårton, and L. Vigliotti, Implications of a combined biostratigraphic and palaeomagnetic study of the Umbrian Maiolica formation (in press).
23 J.G. Ogg, Comment on "Magnetostratigraphy of the Jurassic-Cretaceous boundary in the Maiolica limestone (Umbria, Italy)", Geology (in press).
24 M. Garcia-Hernandez, A.C. Lopez-Garrido, P. Rivas, C. Sanz de Galdeano and J.A. Vera, Mesozoic palaeogeographic evolution of the external zones of the Betic Cordillera, Geol. Mijnb. 59, 155–168, 1980.
25 J.A. Vera et al., Las Microfacies del Jurasico y Cretacico de las Zonas Externas de las Cordilleras Beticas, 83 pp., Universidad de Granada, Granada, 1979.
26 M.C. Comas, F. Oloriz and J.M. Tavera, The red nodular limestones "Ammonitico Rosso" and associated facies: a key for settling slopes or swell areas in the Subbetic Upper Jurassic submarine topography (Southern Spain), in: Rosso Ammonitico Symposium Proceedings, A. Farinacci and S. Elmi, eds., pp. 113–136, Edizioni Techoscienza, Rome, 1981.
27 J.G. Ogg, Middle and Upper Jurassic sedimentation history of the Trento Plateau (Northern Italy), in: Rosso Ammonitico Symposium Proceedings, A. Farinacci and S. Elmi, eds., pp. 479–503, Edizioni Techoscienza, Rome, 1981.
28 F. Oloriz, Kimmeridgiense-Tithonico Inferior and el Sector Central de las Cordilleras Beticas (Zona Subbetica), Paleontologia, Bioestratigraphia, Tesis Doctorales, Univ. Granada 184, 758 pp., Universidad de Granada, Granada, 1978.
29 F. Oloriz and J.M. Tavera, El transito Tithonico inferior-Tithonico superior en las Cordilleras Beticas (Zona Subbetica), Tecniterra 29, 6–15, 1979.
30 F. Oloriz, El Kimmeridgense en la Zona Subbetica, Cuad. Geol. Univ. Granada 10, 475–488, 1981.
31 F. Oloriz and J.M. Tavera, El Tithonico en la Zona Subbetica, Cuad. Geol. Univ. Granada 10, 489–508. 1981.
32 F. Oloriz and J.M. Tavera, El Jurasico Superior en el sector central de la Zona Subbetica. Introduccion al conocimiento de las facies. Indices y correlaciones, Real Academia de Ciencias Exactos, Fisicas y Naturales, segunda parte, 207–239, 1981.
33 F. Oloriz and J.M. Tavera, Stratigraphische Position der Kalke von Stramberg (CSSR)-Uberarbeitung der jungsten Hypothesen, Neues Jahrb. Geol. Palaontol. Monatsh. 1982, 41–49, 1982.
34 F. Oloriz and J.M. Tavera, Correlation of the Tithonian in the central sector of the Betic Cordilleras (Spain) in the light of recent studies, Bull. Acad. Polonaise Sci., Ser. Sci. Terre, 30, 146–156, 1982.
35 A. Linares and J.A. Vera, Precisiones estratigraficas sobre la serie Mesozoica de Sierra Gorda (Cordilleras Beticas), Estud. Geol. 22, 65–69, 1965.
36 J.A. Vera, Estudio geologico de la Zona Subbetica en la transversal de Loja y sectores adjacentes, Mem. Inst. Geol. Min. 72, 1–192, 1969.
37 J.E. Comas and C. Felgueroso, Hoja 989 (Lucena), Mapa Geol. Espana 1:50.000 (1ª serie), Inst. Geol. Min. Espana, Madrid, 1963.
38 P. Rivas, Estudio Geologico de la Region de Carcabuey, Tesis Lic., Fac. Ciencias, Granada, 1969 (unpublished).
39 J.L. Ruiz Lopez, Geologia Estructural de la Sierra de Cabra, Tesis Lic., Fac. Ciencias, Granada, 1969 (unpublished)
40 M.B. Steiner, J.G. Ogg and J. Sandoval, Jurassic magnetostratigraphy, 3. Bajocian-Bathonian of the Subbetics, Southern Spain (in preparation)
41 Colloque sur le Crétacé inférieur, Lyon 1963, Mém. Bur. Rech. Géol. Min., 34, 840 pp., 1965.
42 F. Allemann, W. Grun and J. Wiedmann, The Berriasian of Caravaca (prov. of Murcia) in the Subbetic Zone of Spain and its importance for defining this stage and the Jurassic-Cretaceous boundary, in: Colloque sur la Limite Jurassique-Crétacé, Lyon-Neuchâtel 1973, Mém. Bur. Rech. Géol. Min. 86, 14–22, 1975.
43 J. Remane, Calpionellids, in: Introduction to Marine Micropaleontology, B.U. Haq and A. Boersma, eds., pp. 161–170, Elsevier, New York, N.Y., 1978.
44 J. Remane, Calpionellids and the Jurassic/Cretaceous boundary at Deep Sea Drilling Project Site 534, western North Atlantic Ocean, Init. Rep. DSDP 76, 561–567, 1983.
45 Colloque sur la Limite Jurassique-Crétacé, Lyon-Neuchâtel 1973, Mém. Bur. Rech. Géol. Min. 86, 393 pp., 1975.
46 H.R. Thierstein, Lower Cretaceous calcareous nannoplanktonic biostratigraphy, Abh. Geol. Bundesanst. (Wien) 29, 3–52, 1973.
47 K.L. Verosub, Depositional and post-depositional processes in the magnetization of sediments, Rev. Geophys. Space Phys. 15, 129–143, 1977.
48 I.G. Sapunov, Ammonite stratigraphy of the Upper Jurassic in Bulgaria, III. Kimmeridgian: substages, zones and sub-

zones; IV. Tithonian: substages, zones and subzones, Geol. Balcanica 1-8, 43–64, 1977.

49 R. Enay and J.R. Geyssant, Faunes tithoniques des chaines betiques (Espagne meridionale), Colloque sur le Limite Jurassique-Crétacé, Lyon-Neuchâtel 1973, Mém. Bur. Rech. Géol. Min., 86, 39–55, 1975.

50 R. Enay, H. Tintant, and M. Riout, Les zones du jurassique en France, Kimmeridgian, C.R. Somm. Sc. Soc. Géol. Fr. 6, 22–23, 1971.