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Geomagnetic polarity in the early Cretaceous and Jurassic

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Knowledge of the polarity history of the Earth's magnetic field during the Mesozoic stems primarily from oceanic (M-sequence) magnetic anomalies. Certain of these anomalies have been biostratigraphically dated from sediments immediately overlying basaltic basement at Deep Sea Drilling Project (D.S.D.P.) sites within the M-sequence. The biostratigraphic control is such that these age estimates are generally imprecise, and moreover the sediment ages represent only minimum ages for the basaltic basement itself.

Magnetostratigraphy in sedimentary land sections provides improved age estimates for magnetozones, which can then be correlated with M-sequence anomalies. Magnetostratigraphy provides not only enhanced dating of the ocean floor and resolution of the behaviour of the geomagnetic field during the Cretaceous and Jurassic oceanic 'quiet zones', but also a world-wide correlation tool for sedimentary stratigraphy.

The middle Cretaceous is characterized by a long period of normal polarity extending from the early Aptian to the early Campanian. Reversed magnetozones corresponding to oceanic anomalies M-0, M-1 and M-3 have been palaeontologically dated as early Aptian, middle Barremian and early Barremian respectively. Magnetozones corresponding to oceanic anomalies M-5 to M-15 are Hauterivian to Valanginian in age but have not been individually associated with stage boundaries, mainly due to poor biostratigraphic control in Italian pelagic limestone sections of this age. However, magnetozones corresponding to oceanic anomalies M-16 to M-22 have been individually correlated to Lower Berriasian and Tithonian palaeontological zones, and extrapolation of this correlation gives an age for anomaly M-25 close to the Oxfordian–Kimmeridgian boundary.

The Jurassic 'quiet zone' in the oceans is recognized in land sections as an extended period of predominantly normal polarity, and although poor biostratigraphic control in this interval limits our knowledge of its duration, we consider that it extended through the Oxfordian and Callovian stages. The Bathonian and older Jurassic stages are characterized by mixed polarity. A precise correspondence of magnetozones to ammonite zonations and stage boundaries is only available for the Aalenian to Pliensbachian interval, where the frequency of reversal was apparently very high.

1. Introduction

Ten years ago the range of sedimentary rocks that were sufficiently strongly magnetized for precise measurement was limited to red sandstones and siltstones. Technological advances in magnetometer design (see, for example, Goree & Fuller 1976) now allow a wide range of weakly magnetized sediments to be studied palaeomagnetically. This has spurred efforts to

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measure the record of geomagnetic reversals in palaeontologically controlled sedimentary sequences on land, in order (1) to correlate biostratigraphically dated magnetozones with oceanic magnetic anomalies to measure the age of ocean basins and calculate spreading rates, and (2) to provide a worldwide stratigraphic correlation tool, correlated with palaeontological zonations and radiometric age dates.

Much of the effort to correlate Mesozoic polarity reversals with palaeontological zonations has been focused on Italy where pelagic limestones deposited on the southern margin of the Mesozoic Tethys (Bernoulli & Jenkyns 1974; D'Argenio 1976; Channell *et al.* 1979*a*) are particularly suitable owing to their slow, constant sedimentation rates, their magnetic properties and biostratigraphic control. The slow sedimentation rates allow *patterns* of normal and reversed magnetozones to be recognized in single sections, and constant sedimentation rates decrease distortion of this pattern, facilitating correlation from section to section.

Oriented cylindrical samples are collected with a portable drill at regular stratigraphic intervals, generally 50 cm to 1 m for pelagic sediments with sedimentation rates of *ca.* 10 m Ma^{-1}, giving a time resolution of about 0.1 Ma. Partial demagnetization and rock magnetic work in the laboratory isolates the 'primary' magnetization component and gives the polarity of the geomagnetic field at the time of deposition of the sediment. The magnetozones given by the primary magnetization component can be correlated with the biostratigraphic zonation. Hence the magnetic stratigraphy can be used not only to date the ocean floor, but also to provide a worldwide linkage for diverse palaeontological zonations.

2. The Cretaceous quiet zone

The early late Cretaceous is characterized by an extended period (*ca.* 33 Ma) of normal geomagnetic polarity first recognized by Helsley & Steiner (1969) in terrestrial palaeomagnetic data. In the oceanic anomaly record, this normal polarity interval is manifest as a 'quiet zone', where anomaly amplitudes are generally subdued and nonlinear, which separates the Mesozoic (M-sequence) oceanic magnetic anomalies (Larson & Pitman 1972) from the numbered sequence of anomalies that stretches through the Cainozoic to the present (Heirtzler *et al.* 1968).

The Cretaceous 'quiet zone' is recognized in the magnetostratigraphy of several Italian land sections (figure 1). The young end of this extended period of normal geomagnetic polarity (corresponding to oceanic anomaly 34) has been located in the Lower Campanian at Gubbio in the Umbrian Apennines (Lowrie & Alvarez 1977) as well as at Cismon and other southern Alpine sections (Channell *et al.* 1979*b*; Channell & Medizza 1981). The old end of the Cretaceous 'quiet zone' (corresponding to oceanic anomaly M-0) has been located in the Lower Aptian both at Cismon (Channell *et al.* 1979*b*), and at Gorgo a Cerbara and other Umbrian sections (Lowrie *et al.* 1980*a*). These studies extended through the Barremian and identified reversed magnetozones correlated with M-1 and M-3 of the M-sequence oceanic anomalies (figure 1).

Although it is now generally accepted that the interval between the Lower Aptian and the Lower Campanian was a period of normal geomagnetic polarity, there is evidence for several short-lived reversals within the 'quiet zone' (see Lowrie *et al.* 1980*b*). The best documented are late Aptian (Lowrie *et al.* 1980*a*), late Albian and Cenomanian in age (VandenBerg &

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Wonders 1980). Although their existence should be considered tentative until duplicated in other sections, they may indicate reversals that give hitherto unrecognized, poorly lineated anomalies within the quiet zone younger than the M-sequence anomalies.

3. M-sequence oceanic magnetic anomalies

Our knowledge of the reversal history of the Earth's magnetic field during the early Cretaceous and late Jurassic is derived mainly from the M-sequence of marine magnetic anomalies. Patterns of magnetic anomalies were observed in the older parts of the Pacific (Uyeda *et al.* 1962; Hayes & Pitman 1970), but could not be correlated to the 'Keathley' sequence in the western North Atlantic (Vogt *et al.* 1971) until it was recognized that the Pacific anomalies formed near or south of the equator and hence were of opposite 'apparent' polarity (Larson & Chase 1972; Larson & Pitman 1972). Larson & Pitman (1972) assigned ages to the anomalies (and hence to the reversals that produced them) by assuming a constant spreading rate for the Pacific. Their age control points were obtained from nannofossil biostratigraphy of the oldest sediments overlying basaltic basement at three D.S.D.P. sites (100, 105, 166), which were drilled into basaltic crust at known anomalies (M-25, between M-24 and M-25, and between M-8 and M-9 respectively). Larson & Hilde (1975) revised the M-sequence by incorporating some newly identified magnetic anomalies, as well as basal sediment ages from two additional D.S.D.P. sites (303, 304) drilled on anomalies M-4 and M-9. Vogt & Einwich (1979) replotted the Larson & Hilde sequence on a Van Hinte (1976*a*, *b*) absolute timescale and were able to add several age control points from D.S.D.P. sites 417–418 (M-0), 384 (M-2) and 387 (M-15 to M-16) (see Figure 12 in Vogt & Einwich (1979)).

These estimates of basement ages are not precise owing to poor biostratigraphic control in overlying sediments. The nannofossil and foraminiferal ranges are particularly broad for the early Cretaceous – late Jurassic and, moreover, the ranges of the observed nannofossils and foraminiferans do not generally coincide. In addition, these 'basement' ages represent only minimum ages; the irregular pillow basalts may not acquire a permanent complete blanket of sediment until some significant time after their eruption. One of the aims of land-based magnetostratigraphy is to correlate magnetozones recorded in biostratigraphically controlled sections with the M-sequence oceanic anomalies, and in so doing improve the dating of both the oceanic crust and geomagnetic polarity epochs.

Recently, the M-sequence has been extended further back into the late and middle Jurassic beyond M-25 into the so-called Jurassic 'quiet zone', which has been considered by many authors (e.g. Larson & Hilde 1975) to be due to an extended period of predominantly normal geomagnetic polarity. These pre-M-25 anomalies identified in the Atlantic (Barrett & Keen 1976; Bryan *et al.* 1980) and Pacific (Cande *et al.* 1978) have subdued amplitudes and can lend themselves to various interpretations (see §5).

4. Early Cretaceous – late Jurassic magnetostratigraphy

Magnetostratigraphic studies have been carried out on lower Cretaceous – Upper Jurassic sediments in three regions: continental beds of the western United States (Jurassic only), marine sediments of the Mediterranean region, and deep-sea sediments of the North Atlantic.

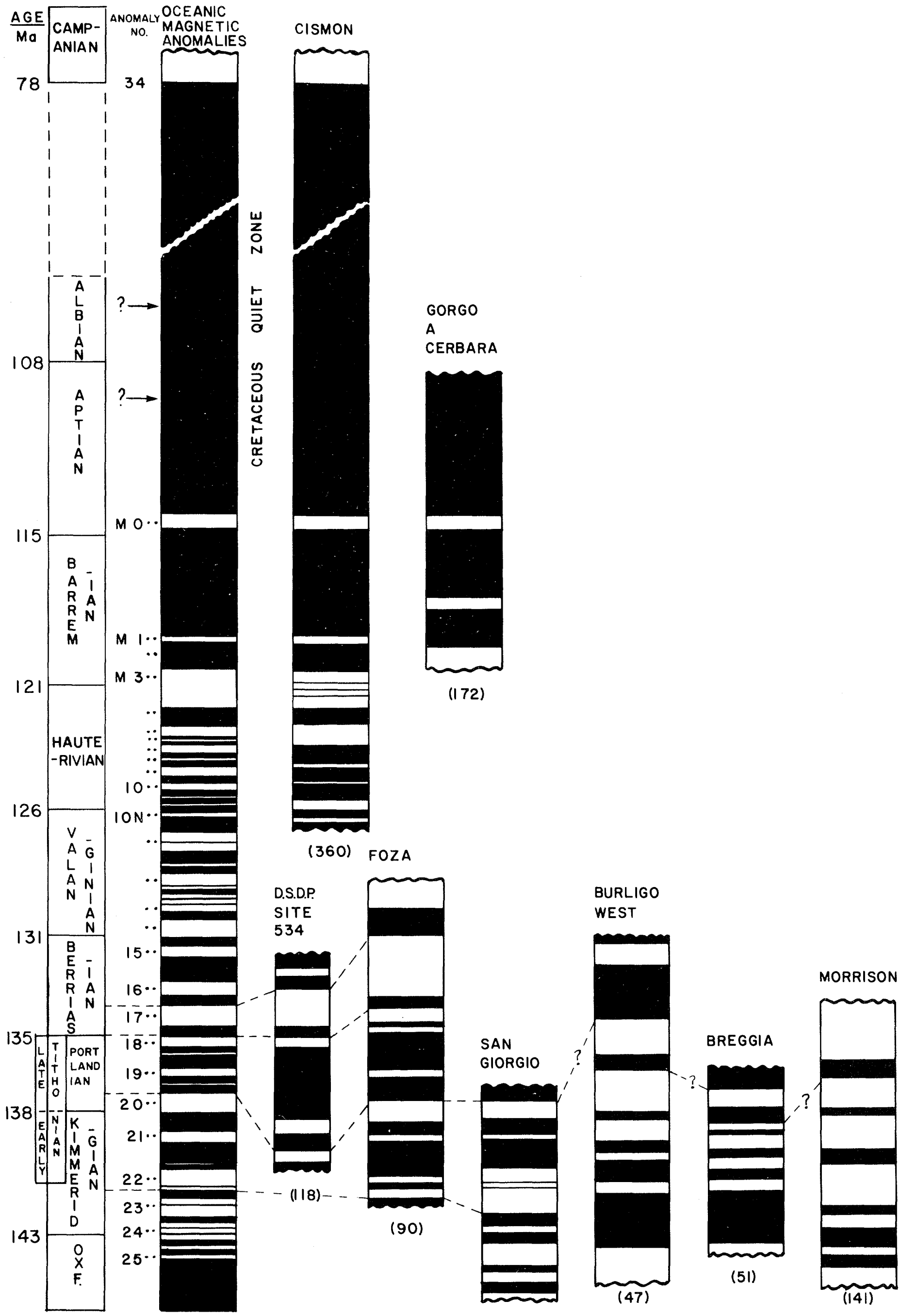

Figure 1. The M-sequence of oceanic magnetic anomalies correlated to stage boundaries in accordance with the biostratigraphic ages of magnetozones in various land-sections and at one D.S.D.P. site. The absolute ages of the stage boundaries are from Van Hinte (1976*a*, *b*). The number in parentheses beneath each column is the number of samples that define the normal (black) and reversed (white) magnetozones in each section. The six polarity stratigraphies at the base of the figure have been expanded for clarity. Dashed tie-lines indicate their true stratigraphic ranges and their correlation to the oceanic anomalies. Tie-lines are primarily biostratigraphic and secondarily magnetostratigraphic. For Burligo West, Breggia and Morrison, tie-lines cannot be drawn with confidence. These three sections are probably Kimmeridgian in age but are poorly controlled biostratigraphically.

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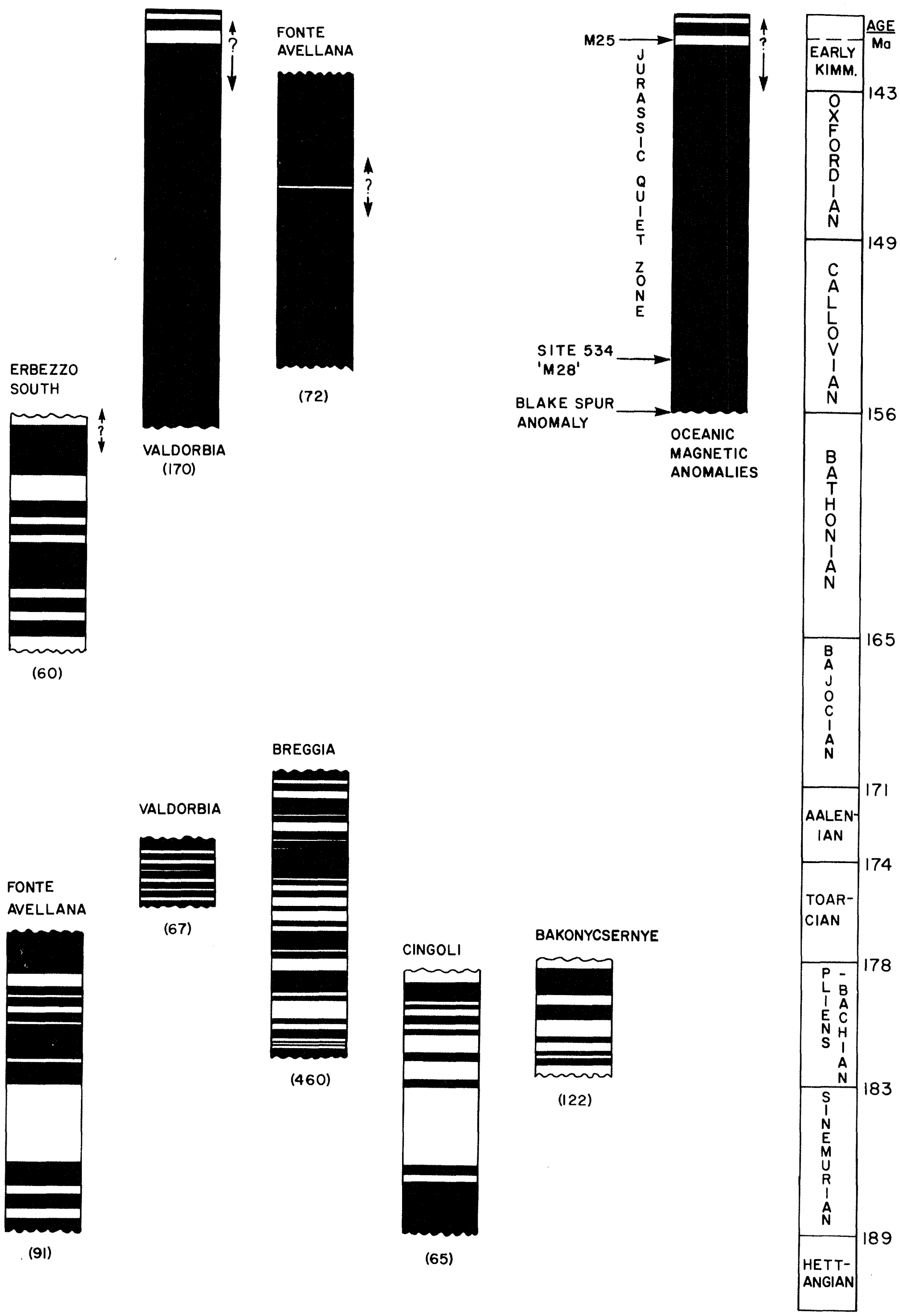

FIGURE 2. The correlation of M-25 and the Jurassic oceanic 'quiet zone' to stage boundaries in accordance with the magnetostratigraphy from two Umbrian land-sections (Valdorbia and Fonte Avellana). Six Middle and Lower Jurassic sections give a preliminary picture of the geomagnetic field in this time interval. Note the discrepancy in the age of M-25 between Valdorbia and southern Alpine sections (figure 1).

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The Jurassic continental sediments of the western United States commonly have poor biostratigraphy, and display weak, unstable or complex magnetizations. They are often stratigraphically incomplete with very variable sedimentation rates, or cover relatively short time spans, and therefore yield polarity sequences that cannot be unambiguously correlated to one another. Nevertheless, the Morrison Formation yielded a well defined polarity sequence (figure 1) that was tentatively correlated with the lower part of the M-sequence (Steiner & Helsley 1975). Poor biostratigraphic control – the age is considered Kimmeridgian to Tithonian

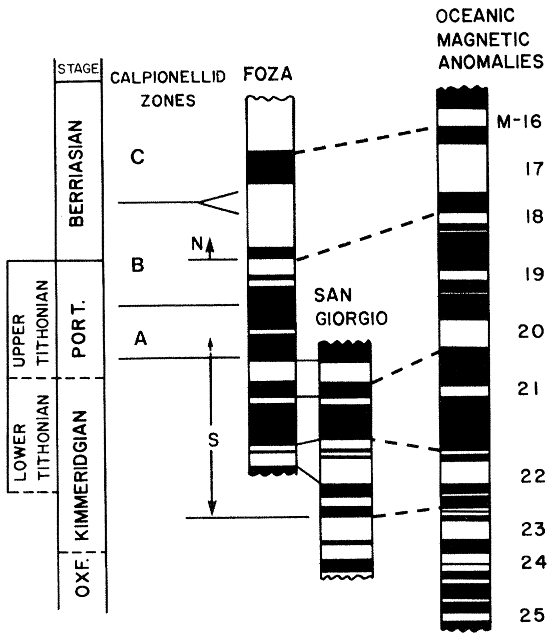

Figure 3. The polarity stratigraphy (black, normal; white, reversed) for the Foza and San Giorgio southern Alpine sections correlated with their Calpionellid Zonation (Remane 1978), to the first occurrence of abundant *Nannoconus colomi* (N) and to the occurrence of *Saccocoma* (S). These biostratigraphic correlations imply a correlation to stage boundaries. The proposed correlation of the polarity stratigraphies to the M-sequence of oceanic magnetic anomalies (Larson & Hilde 1975) is shown. (Modified after Ogg (1981).)

– and the lack of a clearly identifiable pattern of normal and reversed magnetozones do not allow a one-to-one correlation of magnetozones to other land sections or to oceanic anomalies. Steiner (1980) has summarized the available magnetostratigraphies from other Middle and Upper Jurassic terrestrial sedimentary formations in the western United States. The magnetizations are complex and magnetostratigraphies cannot be unambiguously resolved.

The pelagic carbonates of the Mediterranean region usually have better stratigraphic control and provide condensed, but fairly complete, sections covering long intervals of time. As mentioned in §2, the reversed magnetozone at the base of the Cretaceous 'quiet zone' corresponding to oceanic magnetic anomaly M-0 is dated as Lower Aptian (figure 1) both at Cismon, southern Alps (Channell *et al.* 1979*b*) and in Umbria, central Italy (Lowrie *et al.* 1980*a*). Magnetozones corresponding to oceanic anomalies M-1 to M-3 are Barremian in age in these Southern Alpine and Umbrian sections.

The Hauterivian and Valanginian stages are characterized by mixed polarity magnetozones corresponding to oceanic anomalies M-5 to M-15. These are not individually correlated to the stage boundaries or to the oceanic anomaly sequence, owing partly to poor biostratigraphic control, and partly to the lack of a readily identifiable 'fingerprint' in the pattern of magnetozones. However, in the Berriasian and Tithonian stages of the southern Alpine pelagic limestone section at Foza (Ogg 1980, 1981) a 'fingerprint' pattern of magnetozones has been recognized that closely resembles the reversal sequence given by anomalies M-16 to M-22 (figures 1 and 3). A broad reversed magnetozone in this 'fingerprint' is correlated with M-17, a prominent anomaly in the oceans. The same magnetozone is recognized at the same stratigraphic level at D.S.D.P. Site 534 (Ogg 1982), although limited core recovery impairs the recording of the entire 'fingerprint'. The biostratigraphy of the Foza section can be correlated with that at San Giorgio and these three sections (figure 1) give a good correlation of magnetozones with oceanic anomalies M-16 to M-22, which can then be correlated with stage boundaries through the biostratigraphy (figure 3). Calpionellids give the zonation in the Foza and San Giorgio sections, and the Berriasian–Tithonian boundary is marked by the sudden increase in abundance of the nannofossil *Nannoconus colomi*. The top of the reversed magnetozone corresponding to M-18 is located at the Berriasian–Tithonian boundary (figure 3). The first appearance of the pelagic crinoid *Saccocoma* places M-22 in the middle Kimmeridgian.† Other sections of equivalent age at Burligo West and Breggia (figure 1) do not yet have the biostratigraphy to make unambiguous correlations; they are considered Kimmeridgian in age. Unfortunately the Lombardian (southern Alpine) sections cannot be continued down into the Oxfordian and Callovian. The lithology becomes too siliceous and these radiolarian cherts do not give reliable magnetic data. However, by extrapolation from magnetozones equivalent to M-16 to M-22, we predict an uppermost Oxfordian age for M-25 (figures 1 and 3).

5. The Jurassic quiet zone

In the Atlantic and Pacific, as well as off Madagascar, the M-sequence of oceanic magnetic anomalies does not continue uninterrupted into the oldest (middle Jurassic) oceanic crust. M-25 is the oldest prominent anomaly; oceanic crust older than anomaly M-25 is characterized by severely subdued anomaly amplitudes and is known as the Jurassic 'quiet zone'. The anomalies in the western Atlantic Jurassic 'quiet zone' (Barrett & Keen 1976; Bryan *et al.* 1980) have amplitudes of less than 40 nT in contrast to amplitudes of over 200 nT for M-25 and younger anomalies. Although these quiet-zone anomalies are extremely weak, there is some evidence both in the Atlantic (Barrett & Keen 1976; Bryan *et al.* 1980) and in the Pacific (Cande *et al.* 1978) that they are lineated. There are various current hypotheses for the cause of the severe reduction in anomaly amplitude that characterizes the Jurassic quiet zones. The most popular are (1) constant normal geomagnetic polarity during the formation of the quiet-zone oceanic crust (see, for example, Larson & Hilde 1975) with weak lineated anomalies due to geomagnetic intensity fluctuations or basement topography; (2) increased frequency of reversal during this interval perhaps accompanied by a reduction in geomagnetic field intensity (Cande *et al.* 1978); (3) viscous remagnetization of the quiet-zone sea floor due to the particular chemistry of the basalts erupted during initial (Atlantic) rifting (Lowrie & Kent 1978).

† The Kimmeridgian stage has different meanings depending on the convention used. This paper (figures 1 and 3) employs the English convention where the Upper Kimmeridgian is equivalent to the Lower Tithonian. In the French convention the Kimmeridgian stage occurs between the Tithonian and the Oxfordian.

Magnetostratigraphy in land sections will resolve this controversy but at present the data are conflicting. Steiner (1980) has summarized evidence in North America and has concluded that although the magnetization of these sediments is complex and the data are ambiguous, there is no evidence for an extended period of normal polarity in the Jurassic.

In the Mediterranean area, the data coverage of the critical Oxfordian–Callovian stages is sparse owing to the highly siliceous nature of southern Tethyan pelagic facies of this age. The green cherts of Oxfordian and Callovian age from the southern Alps (Lombardy Basin) are very weakly magnetized and do not give reliable data (Ogg *et al.* 1981). The middle Jurassic facies in the Umbrian Apennines (Calcari Diasprigni formation) is somewhat less siliceous and two sections at Valdorbia and Fonte Avellana have given well defined magnetostratigraphies (Channell *et al.* 1980). Unfortunately the biostratigraphic control in the Calcari Diasprigni formation is poor. The first appearances of *Crassicollaria* and *Saccocoma* indicate the position of the Upper–Lower Tithonian boundary and of the middle Kimmeridgian respectively, but the Oxfordian and older middle Jurassic stages cannot be unambiguously located. Radiolarian stratigraphy of the Calcari Diasprigni formation in the Bosso section, 20 km from Valdorbia, indicates the presence of the Oxfordian and Callovian stages (Kocher 1981) and, on the basis of lithological correlation between the two sections, these stages are also present in the sampled section at Valdorbia. The magnetostratigraphy of the Calcari Diasprigni formation at Valdorbia indicates mixed polarity in the Tithonian and part of the Kimmeridgian stages. At a depth of 15 m below the first appearance of *Saccocoma*, the mixed polarity interval gives way to a broad zone of normal geomagnetic polarity (figure 2). It is probable that this well defined interval of normal polarity in the Valdorbia section extends downward from the middle Kimmeridgian into the Oxfordian and Callovian stages. An interval of normal polarity of approximately the same age, punctuated by a single short reversal, is also apparent in the Calcari Diasprigni formation at Fonte Avellana (figure 2).

In studies of shallow water marine limestones from Franconia in southern Germany, Heller (1977, 1978) has eliminated remagnetized sections in the Malm δ (late Kimmeridgian) and shown that the Malm α, β and γ (equivalent to Oxfordian and early Kimmeridgian) are normally magnetized.

On the basis of these magnetostratigraphic data, we tentatively conclude that there was an extended period of predominantly normal polarity corresponding to the middle Jurassic quiet-zone in the oceans. We cannot accurately date this normal polarity interval, but mixed polarity in Bathonian sections in the southern Alps (e.g. Erbezzo South; figure 2) and in Sicily (Catalano *et al.* 1980) limit this interval of normal polarity to the Oxfordian and Callovian stages. The age estimate for the young end of this normal polarity interval at Valdorbia is middle Kimmeridgian (figure 2), whereas our estimate from southern Alpine sections (figure 1, § 4) is uppermost Oxfordian. This discrepancy requires further work in biostratigraphically controlled sections.

D.S.D.P. Site 534 drilled to basaltic basement at anomaly 'M-28' of Bryan *et al.* (1980) within the Jurassic 'quiet zone' in the Blake–Bahama region. The oldest sediment above basement was middle to late Callovian in age (Gradstein *et al.* 1982). 'M-28' in the Blake–Bahama region is situated about 400 km landward of M-25 and about 100 km from the Blake Spur Anomaly. We therefore conclude that much of the Jurassic 'quiet zone' in the western Atlantic falls within the Callovian and Oxfordian stages, in coincidence with the normal polarity interval of this age observed in the land sections.

6. Middle and early Jurassic magnetostratigraphy

The Bathonian to Sinemurian stages are characterized by frequent geomagnetic reversals. Two studies on Bajocian–Bathonian pelagic limestones, in Sicily (Catalano *et al.* 1980) and the southern Alps (Ogg 1981), indicate several reversed-polarity zones but the condensed nature of the sections and poor biostratigraphy make correlations impossible. One Bathonian section (Erbezzo South) is shown in figure 2; the base is uppermost Bajocian but the age span and completeness of the section are uncertain.

The magnetostratigraphy of early Jurassic pelagic limestones has been studied in three Umbrian sections, at Valdorbia (Toarcian–Aalenian), Fonte Avellana (Sinemurian–Toarcian) and Cingoli (Sinemurian–Pliensbachian) (Channell *et al.* 1980). The correlation of magnetozones between sections (figure 2) remains ambiguous owing to the high reversal frequency and poor biostratigraphy. The Pliensbachian section at Bakonycsernye (Hungary) has good ammonite biostratigraphy and a well defined magnetostratigraphy (Marton *et al.* 1980) that can be correlated with that from the Pliensbachian to Lower Bajocian section at Breggia, Switzerland (Horner & Heller 1981). The magnetostratigraphy from Breggia is very well defined and closely tied to the ammonite biostratigraphy. From this study it appears that the reversal frequency was particularly high during the Pliensbachian. The Hettangian stage of the lowermost Jurassic has not yet been studied.

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