

Magnetostratigraphy of the Jurassic/Cretaceous boundary interval in the Western Tethys and its correlations with other regions: a review

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Key words: magnetostratigraphy, Tithonian, Berriasian, Western Tethys.

Abstract. Magnetostratigraphy is an important method in regional and worldwide correlations across the Jurassic/Cretaceous boundary. The M-sequence of magnetic anomalies, embracing this boundary, provides an easily recognizable pattern which might be identified in biostratigraphically calibrated land sections. The polarity chrons between M21r and M16n are well correlated to calpionellid and calcareous nannofossil stratigraphy in the Tethyan Realm. This results in a very high precision of stratigraphic schemes of pelagic carbonates (ammonitico rosso and maiolica limestones), integrating the two groups of fossils with magnetostratigraphy. The main clusters of the reference sections are located in the Southern Alps and Apennines, but the database was recently enriched by sections from the Western Carpathians and Eastern Alps. Quite a few Jurassic/Cretaceous boundary sections with magnetostratigraphy are known in the Iberian Peninsula and south-eastern France but their importance relies on the integration of magnetostratigraphy also with the Tethyan ammonite zonation. Correlation of Boreal and Tethyan regions still remains a major problem. Just two sections with reliable correlation to the global polarity time scale are documented outside Tethys: a shallow marine to non-marine Tithonian–Berriasian–Valanginian sequence in southern England (Portland–Purbeck beds) and the marine clastic Upper Tithonian–Middle Berriasian (= Middle Volgian–lowermost Ryazanian) sequence at Nordvik Peninsula (Siberia). The Volgian/Ryazanian boundary at Nordvik seems to be located in the lower part of magnetochron M18n, while the most commonly accepted definitions of the Tethyan Jurassic/Cretaceous boundary are situated either within magnetochron M19n (A/B calpionellid zonal boundary, Durangites/Jacobi ammonite zonal boundary), or at the boundary of M19n/M18r (Jacobi/Grandis ammonite subzonal boundary).

INTRODUCTION

The worldwide definition of the Jurassic/Cretaceous boundary is still not established (*e.g.* Remane, 1991; Zakharov *et al.*, 1996; Wimbledon, 2008; Pessagno *et al.*, 2010; Wimbledon *et al.*, 2011; Michalík, Reháková, 2011). The problems in global correlation of the Jurassic/Cretaceous boundary arise primarily from:

1. Lack of any important faunal change which might be used as a biostratigraphical marker (see also Rogov *et al.*, 2010).

2. General regression and profound biogeographical provincialism, especially between ammonites of the Boreal and Tethyan Realms.

As a consequence, a variety of regional stages developed such as Tithonian and Berriasian in the Tethyan region, Bolognian, Portlandian and Purbeckian in north-western Europe, Volgian and Ryazanian in Russia and the Arctic (see *e.g.* Cope, 2008; Harding *et al.*, 2011 for review). That is also the reason why the Jurassic/Cretaceous is the only Phanerozoic system boundary not yet fixed by a GSSP. Additionally, the accuracy of numerical dating of the Jurassic/Cretaceous

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boundary, estimated as 145.5 Ma, amounts to ± 4 My (Gradstein *et al.*, 2004). This is the highest error among all system boundaries in the Phanerozoic and results from the paucity of reliable radiometric ages (Pálfy, 2008). Historically at least three definitions of the Jurassic/Cretaceous boundary are considered, tied to ammonite zonation in the Tethyan realm (Fig. 1A):

1. Base of the Jacobi ammonite Subzone, which is often (*e.g.* Gradstein *et al.*, 2004) regarded as equivalent to the boundary between calpionellid Zones A and B, correlated with the upper part of magnetosubzone M19n2n (Colloque sur la limite Jurassique-Crétacé, 1973). According to Tavera *et al.* (1994) and Pruner *et al.* (2010) the base of the Jacobi Zone must be correlated with the upper part of calpionellid Zone A and the lowermost part of magnetosubzone M19n2n.
2. Base of Grandis ammonite Subzone, in the lower part of calpionellid Zone B, almost coinciding with the base of magnetozone M18r (Colloque sur la Crétacé inférieur, 1963).
3. Boundary between Grandis and Subalpina ammonite subzones (= between Jacobi and Occitanica ammonite zones), correlated with the middle part of calpionellid Zone B and the lower part of magnetozone M17r (Hoe-demaeker, 1991; Gradstein *et al.*, 2004).

Gradstein *et al.* (2004) in their time scale accepted the first of the three options listed above, which has in fact been applied in most recent studies integrating calpionellid stratigraphy (Fig. 1B) and magnetostratigraphy in the Tethyan region (*e.g.* Houša *et al.*, 1999a, 2004; Grabowski, Pszczółkowski, 2006; Grabowski *et al.*, 2010a; Pruner *et al.*, 2010). However, recent developments in calpionellid stratigraphy seemed to question also the basic methodology in defining the A/B calpionellid zone boundary: depending on criteria, the boundary falls either in the middle part of the M19n2n magnetosubzone or slightly below the bottom of M19n1r magnetosubzone, as in the case in the Brodno section in the Western Carpathians (see Houša *et al.*, 1999a, b; Michalík *et al.*, 2009; Michalík, Reháková, 2011). Channell *et al.* (2010) suggested that the position of the Jurassic/Cretaceous boundary can be recognized by the first occurrence of the nannofossil *Nannoconus steinmannii minor*, which occurs at the base of magnetozone M18r.

Magnetostratigraphy might be used as a correlation tool between different kinds of biostratigraphical scales and distant areas or sections, and therefore its significance in the global definition of the Jurassic/Cretaceous boundary is appreciated. It works equally well in deep water, shallow water and terrestrial sediments and might be applied also in

radiometrically dated volcanic rocks. The problem of the method is that not all rocks preserve their primary magnetization (*e.g.* McCabe, Elmore, 1989) and that magnetostratigraphy must be integrated with other stratigraphical methods. The aim of this paper is to review magnetostratigraphic data from the broad Jurassic/Cretaceous boundary interval, between the magnetozones M21r (Lower Tithonian) and M16n (Upper Berriasian). An emphasis is put on the Western Tethyan sections (Fig. 2), indicating correlation possibilities with coeval sections in other palaeogeographic realms, where magnetostratigraphic calibration is available.

MAGNETIC ANOMALIES, BLOCK MODELS AND MAGNETOSTRATIGRAPHY

Marine magnetic anomalies constitute a base for the construction of a global polarity time scale (GPTS). The M-sequence of magnetic anomalies, which covers the Jurassic/Cretaceous transition, refers to anomalies older than the Cretaceous Quiet Zone (Cretaceous Normal Superchron). They are numbered from M0 (Aptian/Barremian stage boundary) to M37, which corresponds to the Upper Callovian (Opdyke, Channell, 1996). They are documented in the Pacific, Atlantic and Indian oceans, but the best record of lineation sets is derived from the Pacific. Most M anomaly models were based on the magnetic profiles from the Hawaiian spreading center (Larson, Hilde, 1975; Channell *et al.*, 1995; Gradstein *et al.*, 2004) but recently Tominaga and Sager (2010) built a new model incorporating data also from other Pacific lineation sets: Japanese and Phoenix. Its rough accordance with the linear magnetic anomalies of the Atlantic and West Australia set was tested. The model seems superior to previous ones since it takes into account subtle differences in spreading rates between the three lineation systems. Older models assumed either constant spreading rates in the Hawaiian lineations (Channell *et al.*, 1995) or accepted four intervals of constant spreading rate (Gradstein *et al.*, 2004). Assignment of numerical ages to magnetic anomalies, and hence, to magnetozones is very important. The model of Tominaga and Sager (2010) was calibrated with two dates only. These are: 155.7 Ma for the base of M26r (the $^{40}\text{Ar}/^{39}\text{Ar}$ age of celadonite from the oceanic crust of the north-western Australian margin, see Ludden, 1992) and 125.0 Ma for the base of M0r (the $^{40}\text{Ar}/^{39}\text{Ar}$ age of the MIT Guyot in the Western Pacific, *vide* Gradstein *et al.*, 2004¹). Comparison of inferred dating of magnetozones between the models of Channell *et al.* (1995), Gradstein *et al.* (2004) and Tominaga and Sager (2010) is shown in the Fig. 1A.

¹ Not Channell *et al.* (2000) as indicated in the paper of Tominaga and Sager (2010)

Stages	Calpionellid zones	First occurrence	Polarity	Numerical time scale (Ma)			Calcareous nannofossil zonation			Ammonite zonation			stratigraphic range of sections with ammonite and magnetostratigraphy	
				CENT95	GR2004	TS2010	Zone	Subzone	Zone	Subzone	Zone	Subzone		
TITHONIAN	Chit.	<i>Ch. boneti</i>	M20	143.77	146.47	146.87	NJK	NJK-A	NJK	NJK-B	NJK	NJK	Durangites	Carcabuey
				143.84	146.52	147.02								
TITHONIAN	A	<i>C. alpina</i>	M19	143.07	145.95	146.18	NJK	NJK-C	NJK	NJK-D	NJK	NJK	Durangites	Carcabuey
				141.88	144.88	145.60								
TITHONIAN	B	<i>C. elliptica</i>	M18	141.22	144.57	144.64	NJK	NJK-A	NJK	NJK-D	NJK	NJK	Durangites	Carcabuey
				141.63	144.88	145.20								
TITHONIAN	C	<i>Cs. simplex</i>	M17	138.50	142.55	142.32	NJK	NJK-2a	NJK	NK-1	NK-1	NK-1	Durangites	Carcabuey
				138.89	142.84	142.73								
TITHONIAN	D	<i>Cs. oblonga</i>	M16	137.85	142.06	141.75	NJK	NJK-2a	NJK	NK-2a	NK-2	NK-2a	Durangites	Carcabuey
				141.37	141.52	141.75								
TITHONIAN	D	<i>L. hungarica</i>	M15	136.49	141.05	139.94	NJK	NK-2a	NJK	NK-2b	NK-2b	NK-2b	Durangites	Carcabuey

Fig. 1A. Summary of bio- and magnetostratigraphic correlations across the Jurassic/Cretaceous boundary for the Mediterranean province and dating of M-sequence magnetic intervals according to different timescales: CENT95 – Channell et al. (1995); GR2004 – Gradstein et al. (2004); TS2010 – Tominaga, Sager (2010)

Three definitions (1–3) of the Jurassic/Cretaceous boundary are given: 1 – after Colloque sur la limite Jurassique–Crétacé (1973); 2 – after Colloque sur la Crétacé inférieur (1963); 3 – after Hoedemaeker (1991). More explanation and comments in the text. Correlation of calpionellid zones to magnetostratigraphic zones to magnetostratigraphy after Grabowski et al. (2010 a). Correlation of ammonite zones to magnetostratigraphy after Gradstein et al. (2004) supplemented by data of Pruner et al. (2010)

STAGES AND SUBSTAGES		Microfossil zonations published by various authors										
		Borza, 1984	Remane <i>et al.</i> , 1986	Pop, 1994a, b, 1997, 1998	Grün, Blau, 1997	Remane, 1963, 1964, 1971						
BERRIASIAN	UPPER	Calpionellopsis	Calpionellopsis	Calpionellopsis	Calpionellopsis	Calpionellopsis	Calpionellopsis	D	3			
			oblonga	oblonga	murgeanui	dadayi	murgeanui			filipescui	oblonga	2
			simplex	simplex	simplex	simplex	simplex			simplex	1	
MIDDLE	LOWER	Calpionella	Calpionella	Calpionella	Calpionella	Calpionella	Calpionella	C	B			
			elliptica	elliptica	longa	cadischiana	elliptica			elliptica	alpina	
TITHONIAN	UPPER	Crassicollaria	Crassicollaria	Crassicollaria	Crassicollaria	Crassicollaria	Crassicollaria	A	3			
			intermedia	intermedia	intermedia	intermedia	intermedia			intermedia	2	
			remanei	remanei	remanei (parvula)	remanei	remanei			remanei		1
	LOWER	"pulla-tithonica"	Praetintinnopsella	Chitinoidea	Praetintinnopsella	Chitinoidea	Chitinoidea	Chitinoidea	andrusovi	bermudezi		
			boneti	boneti	boneti	boneti	boneti	boneti			boneti	dobeni
		"malmica"										

Fig. 1B. Calpionellid zonations in the Tithonian and Berriasian, published by various authors (after Grabowski, Pszczółkowski, 2006)

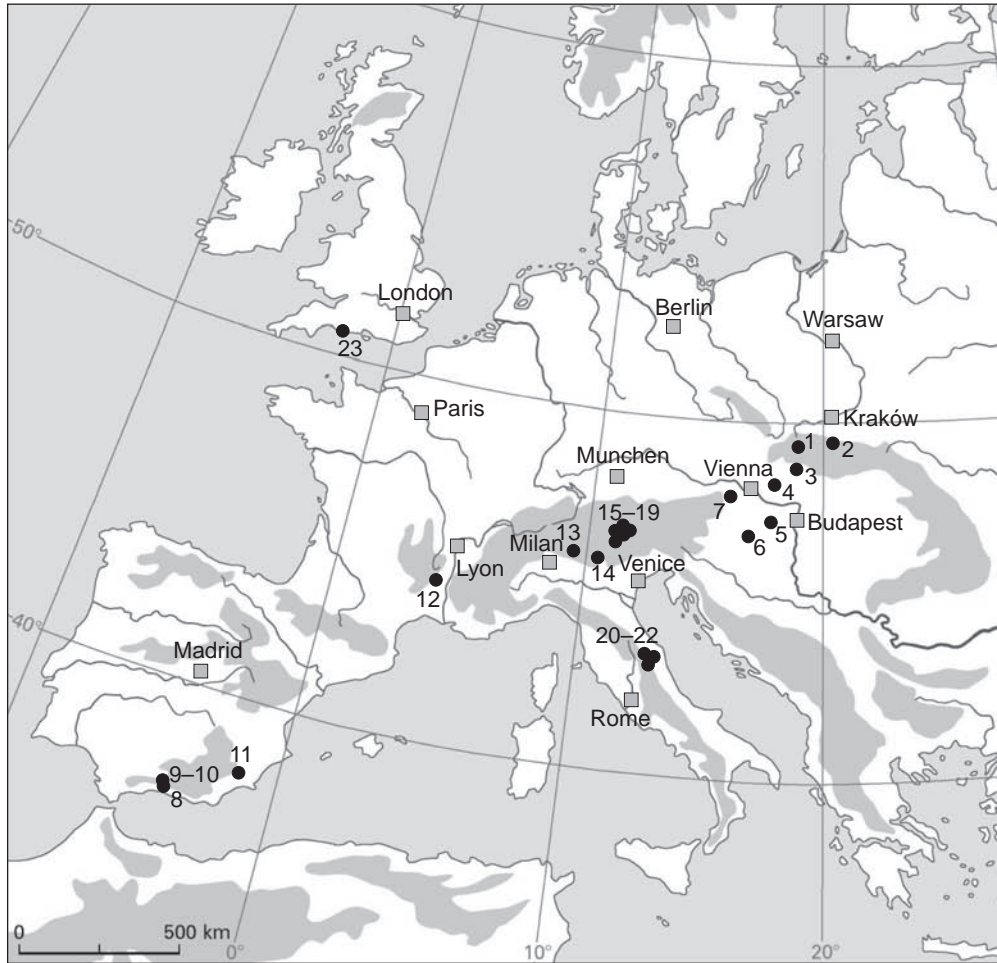


Fig. 2. Location of the magnetostratigraphically studied Jurassic/Cretaceous boundary sections in Europe

1 – Brodno; 2 – Western Tatra; 3 – Strážovce; 4 – Hlboča; 5 – Lókút; 6 – Sümeg; 7 – Nutzhof; 8 – Sierra Gorda; 9–10 – Carcabuey and Puerto Escaño; 11 – Rio Argos; 12 – Berrias; 13 – Torre de’Busi; 14 – Colme di Vignola; 15–19 – Foza, Frisoni, Xausa, Bombatierle and Mezzosilva; 20–22 – Bosso, Arcevia and Fonte Giordano; 23 – Durlston Bay.

The nomenclature of magnetostratigraphic units is not very strictly formalized. A *polarity chron* or *magnetostratigraphic unit* is defined as a time interval of constant magnetic field polarity delimited by reversals. The corresponding interval in the stratigraphic section is called a *polarity zone* or *magnetozone*. The terms *subchrons* and *subzones* are also in use but their meaning is not well constrained. Usually the term magnetozone or magnetostratigraphic unit is applied to a normal (n) or reversed (r) polarity interval which is numbered according to marine magnetic anomalies (Ogg *et al.*, 1991). For example, magnetostratigraphic unit M19r corresponds to magnetic anomaly M19, while magnetostratigraphic unit M19n – to the normal interval between anomalies M19 and M18 (Fig. 3). A magnetosubchron is defined as a short polarity interval within a magnetostratigraphic unit, like

e.g. magnetosubchron M19n1r within M19n magnetostratigraphic unit. Such a definition was applied in the present study. However some authors recommend the use of duration time as a criterion in the hierarchy of magnetostratigraphic units. According to McElhinny and McFadden (2000), the approximate duration of a magnetostratigraphic unit is 10^6 – 10^7 years, while that of a magnetosubchron is 10^5 – 10^6 years. In this case most of polarity intervals within an M-sequence (M19r, M18n *etc.*) should be defined as magnetosubchrons.

Two parallel symbols are currently used for naming the magnetostratigraphic units of an M-sequence. J.E.T. Channell (*e.g.* Opdyke, Channell, 1996; Channell *et al.*, 2010) applies the term CM. A prefix “C” is added to distinguish polarity chrons from marine magnetic anomalies. Other authors

Magnetic Polarity	Pair of linear magnetic anomalies	Magneto-zones	Magneto-subzones
	M18	M18r	
	M19	M19n	M19n1n
			M19n1r
			M19n2n
		M19r	
	M20	M20n	M20n1n
			M20n1r
			M20n2n
		M20r	

Fig. 3. Nomenclature of magnetostratigraphic units at the Jurassic/Cretaceous boundary applied in the paper

Black colour – normal polarity, white colour – reversed polarity

(*e.g.* Ogg *et al.*, 1991; Gradstein *et al.*, 2004; Pruner *et al.*, 2010) use the same terminology for magnetic anomalies and the corresponding magnetochrons (M), with the suffix *n* or *r* for polarity indication. This nomenclature is accepted also in this paper.

GLOBAL POLARITY TIME SCALE (GPTS) FOR THE JURASSIC/CRETACEOUS BOUNDARY INTERVAL AND ITS BIOSTRATIGRAPHIC CALIBRATION

The frequency of magnetic reversals is not very high in the Late Tithonian and Berriasian (*e.g.* Gradstein *et al.*, 2004; Kurazhovskii *et al.*, 2010). Some magnetozones are of almost 1 My duration (*e.g.* M20n, M19n, M17r, M16n) which is not as common in the Oxfordian–Kimmeridgian and Valanginian–Hauterivian. Moreover, magnetozones M20n and M19n reveal a characteristic pattern: they are divided in two parts by short reversed magnetosubzones (M20n1r and M19n1r) in their 50–60% and 80–90% respectively (see Fig. 1A, 3). The pattern is relatively easy to recognize in the magnetic record and, in the presence of even rough biostratigraphic markers, might usually be reliably matched with GPTS (*e.g.* Houša *et al.*, 2007). Correlation between

GPTS and biostratigraphy, especially micro- and nanofossil stratigraphy, is well established.

Correlation of calpionellid zones (*e.g.* Remane, 1986, see also Fig. 1B) to magnetozones has been achieved by integrated bio- and magnetostratigraphic studies in the Ammonitico Rosso and Maiolica formations of the Southern Alps and Apennines (Ogg, Lowrie, 1986; Channell, Grandesso, 1987; Channell *et al.*, 1987). The correlation was performed based on 5 sections in the Trento Plateau of the Southern Alps: Capriolo, Xausa, Frisoni, Valle de Mis, Quero, and a single section in the Apennines (Bosso) (Fig. 2). It is worth mentioning that the same southern Alpine sections were used to calibrate the $\delta^{13}\text{C}$ isotope curve in the Jurassic/Cretaceous boundary interval (Weissert, Channell, 1989). The correlation of calpionellid zonation to magnetostratigraphy has been positively tested and only slightly refined in numerous papers (*e.g.* Houša *et al.*, 1999a, b; Grabowski, Pszczółkowski, 2006; Houša *et al.*, 2004; Pruner *et al.*, 2010; Grabowski *et al.*, 2010a, b).

Bralower *et al.* (1989) established a correlation scheme between magneto- and nanofossil stratigraphy based on 5 land sections (Bosso and Fonte Giordano in Apennines, Foza in Southern Alps, Carcabuey in Betic Cordillera, and Berrias in south-eastern France) and one DSDP site (534A). Channell *et al.* (2010) correlated the new nanofossil zonation of Casellato (2010) with GPTS in 6 sections from the Southern Alps. The new nanofossil stratigraphy was juxtaposed also with the magnetostratigraphy of DSDP site 534A (Casellato, 2010). Integration of magnetostratigraphy with ammonite zonation is not as robust as with micro- and nanofossils. It has been reported from four land sections only (Fig. 2): the Berriasian historical type locality (Galbrun, 1985) and three sections from the Betic Cordillera of Spain (Ogg *et al.*, 1984; Pruner *et al.*, 2010). Moreover, in none of those studies were magnetostratigraphy and ammonite stratigraphy truly integrated (as is a usual case in magnetostratigraphic studies integrated with calpionellid or nanofossil stratigraphy) and there is an urgent need for modern reassessment of the stratigraphically important Lower Berriasian ammonites (Wimbledon *et al.*, 2011). Other groups of organisms were not routinely utilized in the biostratigraphic calibration of magnetostratigraphic sections. A notable exception are the summary results of DSDP sites on the Western Atlantic, where magnetostratigraphy was integrated with nanofossils, calpionellids, radiolarians, dinoflagellates and foraminifers (Initial reports of DSDP, vol. 76. www.deep-seadrilling.org). Also in the recent studies of the Brodno and Nutzhof sections (Fig. 2), magnetostratigraphy was integrated with calcareous nanofossils and dinoflagellate stratigraphy (Michalik *et al.*, 2009; Lukeneder *et al.*, 2010).

TETHYS MAGNETOSTRATIGRAPHY

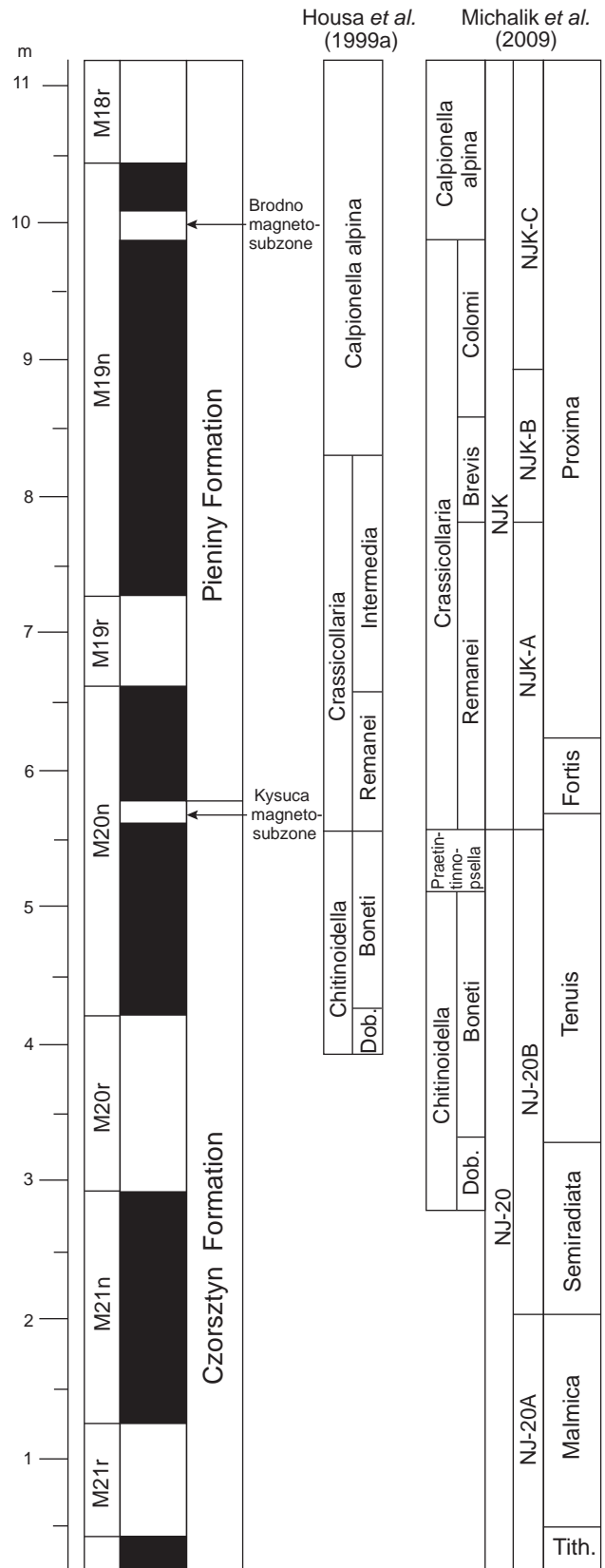
PIENINY KLIPPEN BELT

The first magnetostratigraphic results from the Jurassic/Cretaceous boundary beds from the Western Carpathians area were published by Houša *et al.* (1996a, b). These authors studied the Brodno section, near Žilina (Slovakia), situated in the Kysuca unit of the Pieniny Klippen Belt (Michalík *et al.*, 1990a). The papers (Houša *et al.*, 1996a, b) documented the 21 m long record of magnetic reversals from the top of M21r (upper part of the Lower Tithonian) to M17r (upper part of the Lower Berriasian). Three years later, new results were published from that section (Houša *et al.*, 1999a, b) based on a very high resolution of the sampling (oriented samples taken each 3–5 cm). An important achievement of the second phase of magnetostratigraphic work at Brodno was a detailed documentation of two short reversed polarity events named: (1) Kysuca magnetosubzone (M20n1r) within the middle part of M20n (55% of local thickness) and (2) Brodno magnetosubzone (M19n1r) within the upper part of M19n (82% of local thickness) – see Fig. 4. The Jurassic/Cretaceous boundary based on calpionellids (base of Calpionella Zone) was situated at 34% of the local thickness of M19n. Houša *et al.* (1999a) presented a correlation between the magnetostratigraphic results and the identified calpionellid taxa (which was lacking in older papers about the Brodno section). However, the high resolution magnetostratigraphic log published in 1999 did not embrace the higher part of the section, *i.e.* between 11.2 and 21.0 m, which corresponds to magnetozones M18r to M17r. Therefore this part of the section still awaits integrated bio- and magnetostratigraphic study. The boundary between the Czorsztyń Limestone Formation and the Pieniny Limestone Formation was situated at the top of the Kysuca magnetosubzone (at *ca.* 5.7 m of the section).

Michalík *et al.* (2009) presented a modified biostratigraphical scheme of the section (including calpionellid, calcareous dinocyst and nannofossil stratigraphy), integrated with the earlier magnetostratigraphy as well as other stratigraphical methods ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$, TOC, and CaCO_3 , and detailed microfacies and cyclic stratigraphy). The Jurassic/Cretaceous boundary was shifted higher by about 1.4 m,



Fig. 4. Magnetostratigraphy of the Brodno section (Pieniny Klippen Belt), after Houša *et al.* (1999a) and its two biostratigraphic calibrations



almost to the base of the Brodno magnetosubzone¹. The lower boundary of the Chitinoidea Zone was moved down the section and some other boundaries of calpionellid sub-zones were significantly changed (see Fig. 4). However, the frequencies of occurrence of calpionellid species for the extended Colomi Subzone were not published for the Brodno section.

Concerning the correlation of nannofossil stratigraphy to magnetostratigraphy, it should be noted that this deviates in some respects from the scheme of Bralower *et al.* (1989). In the Brodno section, zone NJ-20 terminates in the uppermost part of M20n2n and not in the middle part of M20r, as plotted by Bralower *et al.* (1989).

The mean sedimentation rate within the section was quite low (average 2.26 m/My), slightly increasing between the Czorsztyn and Pieniny Formation (Grabowski *et al.*, 2010a). This agrees with low magnetic susceptibility (MS) values (mostly below 20×10^{-6} SI, with a decreasing trend between Tithonian and Berriasian), indicating most probably a low input of detrital material towards the basin.

CENTRAL WESTERN CARPATHIANS

An extensive study of Mesozoic rocks in the Tatra Mts (Grabowski, 2000) revealed that the Tithonian–Berriasian calpionellid limestones of the Križna nappe preserved their primary magnetization. First indications about the position of the Jurassic/Cretaceous boundary were based on ammonites found in the biancone-type limestone (Lefeld, 1974). Detailed calpionellid biostratigraphy and the position of the Tithonian–Berriasian boundary were studied by Pszczółkowski (1996). A composite magnetostratigraphic section, based on four overlapping sections situated in the western part of the Križna nappe (the so-called Bobrowiec unit, see Bac, 1971), was published by Grabowski and Pszczółkowski (2006). A record of magnetic reversals was successfully revealed from M20r (uppermost Lower Tithonian) to the upper part of M16n (Upper Berriasian). The total thickness of the composite section was between 70 and 80 m. Palaeomagnetic sampling and biostratigraphic resolution was not as high as in the Brodno section, and the positions of the biostratigraphic boundaries in relation to magnetozones were determined only roughly. Nevertheless the position of the crucial biohorizons is concordant with those in the Brodno section (Fig. 5). The Jurassic/Cretaceous boundary is situated at the bottom of the Alpina Subzone, at *ca.* 40% of the thickness of magnetozones M19n. The position of the Brodno magnetosubzone is concordant with

that of the Brodno section – within the upper half of M19n. However the position of the Kysuca magnetosubzone is anomalous, within the uppermost part of M20n (Grabowski, Pszczółkowski, 2006). This was not commented on in the original paper, but subsequent inspection in the field proved that the profile is dissected by a thrust fault (Grabowski *et al.*, 2010b) and a part of the section comprising the larger part of the post-Kysuca part of M20n (M20n1n), and a bottom part of M19r, is missing. The boundary between the Jasenina Formation and the Osnica Formation is located within M19n, just below the Brodno magnetosubzone (*ca.* 0.5 m), within the lowermost Berriasian, while the Osnica/Košcieliska formation boundary is situated in the lowermost part of M16n, in the Upper Berriasian.

Within the magnetostratigraphically studied subsections in the Tatra Mts some rock magnetic analyses were performed which shed some light on the dynamics of sedimentation. Each formation within the section revealed its distinct rock magnetic signature. The Jasenina Fm., which contains a lot of clay minerals, reveals high magnetic susceptibility (between $60\text{--}150 \times 10^{-6}$ SI), abundance of hematite and relatively low sedimentation rates, close to 5 m/My. The magnetic susceptibility of Osnica Fm., which is more carbonaceous, is lower ($40\text{--}60 \times 10^{-6}$ SI) and its magnetic mineralogy is different: almost exclusively magnetite. The sedimentation rate rises to 5–10 m/Ma. The Košcieliska Marl Formation again contains a higher amount of detrital clays, as well as increasingly higher magnetic susceptibility (up to 160×10^{-6} SI), but its magnetic mineralogy remains the same as in the Osnica Fm. (Fig 6). The explanation given by Grabowski and Pszczółkowski (2006) was that the marly limestones of the Jasenina Formation sedimented during a period of low input of detrital material and low carbonate productivity. Hematite is often regarded as an indicator of low sedimentation rate (Channell *et al.*, 2000), although sometimes it is of early diagenetic nature and carries a magnetization that is *ca.* 10^5 years younger than time of sediment deposition (Channell *et al.*, 1982). The increase of sedimentation rate during the Early Berriasian was caused by increased carbonate productivity and a bloom of carbonate micro- and nannofossils. Stepwise increase of sedimentation rate in the Late Berriasian correlates with an onset of marly sedimentation which is a regional phenomenon within the basinal sections of the entire Central Western Carpathians (Vašíček *et al.*, 1994; Michalík *et al.*, 1995) and Eastern Alps (Rasser *et al.*, 2003).

The second magnetostratigraphic investigations were performed on the Strážovce section in the Strážovské Vrchy Mts in Central Slovakia (Vašíček *et al.*, 1983; Michalík *et*

¹ In the most recent paper of Michalík and Reháková (2011) the Jurassic/Cretaceous boundary in the Brodno section occurs even higher – in the middle of M19n1r (Brodno) magnetosubzone (see their fig. 7)

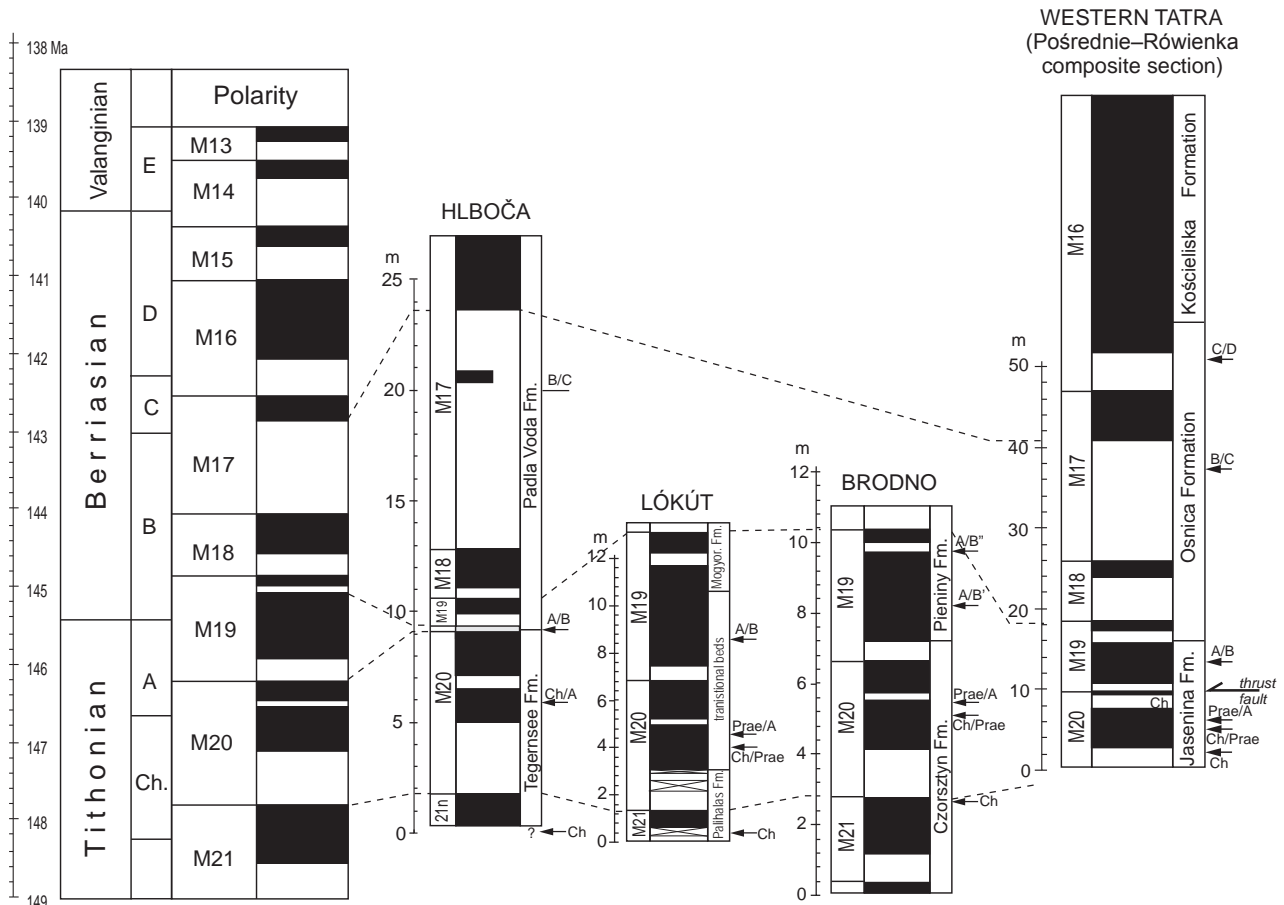


Fig. 5. Correlation of magnetostratigraphically studied Jurassic/Cretaceous boundary sections within the Carpathian domain (after Grabowski *et al.*, 2010 b, modified)

Boundaries of calpionellid zones are indicated by arrows: Ch – bottom of Chitinoidea Zone; Prae – Praetintinnopsella Zone; A, B, C and D – calpionellid zones. Within the Brodno section A/B' and A/B'' correspond to the A/B calpionellid zonal boundary as defined by Houša *et al.* (1999a) and Michalík *et al.* (2009), respectively

al., 1990c). Here, however, the strata appeared to be heavily remagnetized and not suitable for magnetostratigraphy (Grabowski *et al.*, 2009). Successful magnetostratigraphic study was performed in the Malé Karpaty Mts, located in the south-western termination of the Western Carpathian arc (Grabowski *et al.*, 2010b). The Hlboča section is situated within the Vysoká nappe, which reveals a peculiar, more shallow-water development of the Fatric domain. The Upper Jurassic (Oxfordian to Tithonian) is developed here as red nodular limestones attributed to the Tegnesee Formation, which is an equivalent of the Czorsztyn Limestone Formation. The overlying Padlá Voda Formation consists of grey, poorly or thick-bedded grey calpionellid limestones (Michalík *et al.*, 1990b). The Tithonian part of the Tegnesee Fm. revealed the presence of magnetozones from the upper part of M21n to the upper part of M20n, with the Kysuca

magnetosubzone in the middle of M20n. A significant stratigraphic gap is present at the Jurassic/Cretaceous boundary (Michalík *et al.*, 1995; Michalík, Reháková, 2011) evidenced by sedimentary breccia beds of up to 1 m thickness. The sediments comprising the upper part of the Intermedia Subzone and most of the Alpina Subzone were eroded and occur in the form of clasts. It was possible to date this gap using the magnetostratigraphic method. It appears that erosion removed the uppermost part of M20n, the entire M19r and also the pre-Brodno part of M19n, that is M19n2n (Grabowski *et al.*, 2010b), see Fig. 5. The rock magnetic properties and the state of outcrops of the Berriasian Padlá Voda Formation were not suitable for detailed magnetostratigraphy. The Berriasian limestones contained a lot of ultra-fine grained magnetite (in the superparamagnetic state) which is typically encountered in chemically remagnetized carbonates (*e.g.*

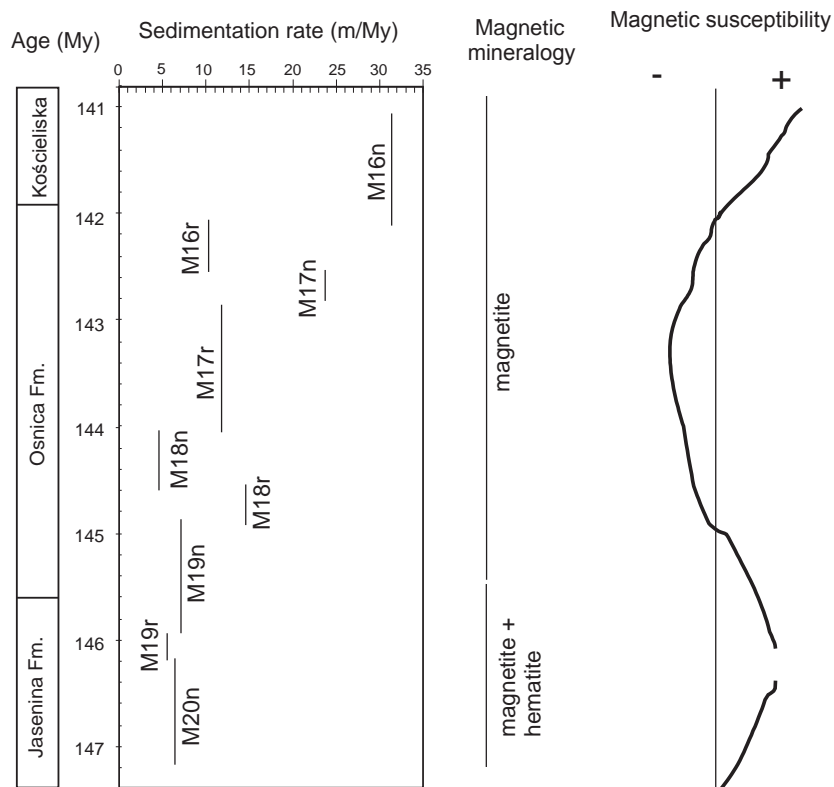


Fig. 6. Western Tatra Mts: Pośrednie-Rówienka composite section (Grabowski, Pszczółkowski, 2006)

Sedimentation rate (calculated after the timescale of Gradstein *et al.*, 2004) is plotted against lithostratigraphy, magnetic mineralogy and smoothed magnetic susceptibility curve

Jackson *et al.*, 1993; Grabowski *et al.*, 2009). Although the quality of the magnetostatigraphic results was quite poor, the presence of magnetozones from the uppermost part of M19n (M19n1n) to M17n is postulated¹. A peculiar feature of the section is an inverse pattern of MS changes across the Jurassic/Cretaceous boundary, lower MS values in the Tithonian part and higher within the Lower and Middle Berriasian. This is at odds with the common pattern where usually a decrease of MS is observed across the Jurassic/Cretaceous boundary (Houša *et al.*, 1999a, b; Houša *et al.*, 2004; Grabowski, Pszczółkowski, 2006; Pruner *et al.*, 2010; Lukeneder *et al.*, 2010; Grabowski *et al.*, 2010a).

TRANSDANUBIAN MTS

Magnetostratigraphic investigations of the Jurassic/Cretaceous boundary in the Transdanubian Mts started as early as in the Southern Alpine and Apennine sections in Italy – in

the early 1980s (Márton, 1982). The first section studied was that of Sümeg, situated close the south-eastern margin of Balaton Lake – in fact this was the first land section studied covering the interval from the Kimmeridgian to the Berriasian. The Jurassic/Cretaceous boundary occurs within a succession of white to light grey limestones of maiolica facies, dating from Tithonian to Valanginian. The 140 m thick interval of Upper Kimmeridgian–Lower Berriasian rocks was sampled there with a resolution *ca.* 1 sample per meter. Primary magnetization of dual polarity was undoubtedly revealed. Unfortunately, problems with the stratigraphic interpretation arose from two reasons:

1. Poor biostratigraphical dating of the section (just 8 biostratigraphically dated horizons) and the calpionellid zonation not fully established yet;
2. Lack of other reference land sections studied.

Therefore, although a number of reversals was documented, the section could be correlated only tentatively to the Larson and Hilde (1975) scheme of oceanic magnetic

¹ Not as high as M15r as erroneously plotted by Michalík and Reháková (2011), in their fig. 7

anomalies. The age of the Jurassic/Cretaceous boundary was put at 136.5 Ma, in the lowermost part of the M16n magnetozones. It is thus not surprising that the magnetostatigraphic data from the Sümeg section is not fully accepted at present. Nowadays only a small part of the Sümeg section is available for direct observations. Two other sections where magnetostatigraphy was done, also in the Transdanubian Mts (Borzavar and Harskut), were only briefly mentioned in a paper of Márton (1986), but without extensive biostratigraphic descriptions, only with the boundaries of the standard calpionellid zones indicated. A new magnetostatigraphic study was performed on the Lókút section (Grabowski *et al.*, 2010a). The thickness of the section amounts to 13 m. It comprises a continuous passage between Jurassic and Cretaceous rocks. The bottom part of the section is developed as multi-coloured (reddish, yellowish, white) nodular limestones of the Pálihálás Formation. Based on ammonites, the formation was assigned to the Kimmeridgian–Lower Tithonian (Vigh, 1984). The Upper Tithonian–Lower Berriasian part of the section is represented by white calpionellid limestones with cherts (Mogyorósdomb Formation). Magnetozones from the uppermost part of M21r to the bottom of M18r were identified, which indicates that the Lókút section is almost equivalent to the Brodno section (Fig. 5). The magnetic stratigraphy was calibrated on calpionellid zonation using the same samples (Grabowski *et al.*, 2010a). The Jurassic/Cretaceous boundary was established at the base of calpionellid Zone B, in magnetozones M19n at 30% of its thickness. Stepwise decrease of MS to almost negative values in the uppermost part of the section is observed indicating most probably a relative decrease of lithogenic input. The sedimentation rate reveals roughly an opposite trend, increasing from 1–3 m/My within the Tithonian to 5–7 m/My in the Berriasian. As in the sections from the Tatra Mts (see section 4.2), higher sedimentation rates are attributed to increasing productivity of calcareous micro- and nannoplankton.

EASTERN ALPS

The Nutzhof section is located in the Gresten Klippenbelt in Lower Austria, ca. 60 km ESE from Vienna (Lukeneder *et al.*, 2010) – see Fig. 2. It is now tectonically incorporated into the Rhenodanubian Flysch Zone, but the original place of deposition was a Helvetian unit, on the southern shelf of the European continent. This is the only Jurassic/Cretaceous boundary section studied magnetostatigraphically in the Eastern Alps. Its thickness is 18 m and magnetozones from M21r to M18n were documented. Beside magnetic

stratigraphy, also detailed chemostratigraphy ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$, $^{87}\text{Sr}/^{86}\text{Sr}$, TOC, S) and biostratigraphy (calpionellids, calcareous dinoflagellates, calcareous nannofossils and macrofossils: ammonoids, aptychi, belemnites *etc.*) of the deposits were studied.

The Jurassic/Cretaceous boundary, defined as the boundary between A/B calpionellid zones, falls within the Blassenstein Formation, in the pre-Brodno part of M19n (M19n2n). The lower part of the Formation (mostly Tithonian) consists of marl/limestone alternations, while the upper part of the Formation is represented by pure, grey limestones. It is characteristic that ammonitico rosso facies is not present in the Tithonian within that section. The boundary between the two parts of the Blassenstein Formation correlates with the uppermost part of the M20n2n magnetosubzone (just below the Kysuca magnetosubzone). The two parts of the Blassenstein Fm. differ distinctly in MS values. The agreement of the MS curve with the gamma log and variations of CaCO_3 content (Lukeneder *et al.*, 2010) supports the view that the MS decreasing trend across the Jurassic/Cretaceous boundary is caused by lowering input of detrital material.

Correlation of the calpionellid zonation with the magnetostatigraphy significantly deviates from a reference pattern (see Fig. 1A). The upper boundary of the Chitinoidea Zone falls as low as in the uppermost part of M20r (usually in the upper part of M20n2n, *cf.* Figs 4, 5). The Praetintinnopsella Zone embraces the boundary between M20r and M20n2n, while typically it is situated in the uppermost part of M20n2n (Michalík *et al.*, 2009; Grabowski *et al.*, 2010a). Also the position of the Jurassic/Cretaceous boundary, as well as calcareous nannofossil and dinoflagellate divisions, differs from those established in the Brodno section by the same authors (Michalík *et al.*, 2009).

The sedimentation rate in the Nutzhof section was highly variable (between 2 and 11 m/Ma – see Lukeneder *et al.*, 2010). However, it seems doubtful if the calculations reflect the real values. The positions of the two short magnetosubzones in the Nutzhof section are anomalous. The Kysuca Subzone is situated in the uppermost part of M20n which makes the post-Kysuca part of M20n zone (M20n1n) anomalously thin. Again, the Brodno magnetosubzone occurs in a quite low position within M19n, which implies an unexpectedly big thickness of magnetosubzone M19n1n. It might be only speculated that a large part of M20n1n is most probably missing and the big thickness of M19n1n might be caused either by allodapic flow (the allodapic horizons are carefully marked in the paper) or other sedimentological or diagenetic (selective remagnetization?) phenomena.

Generally the section somehow resembles the Pośrednie section from the Western Tatra Mts because of: (1) the lack of ammonitico rosso facies at its bottom (in the Tithonian) and (2) the high input of detrital material (and still low sedimentation rate) in the Tithonian.

IBERIAN PENINSULA

The first magnetostratigraphic results in Spain which approached the Jurassic/Cretaceous boundary were those of Ogg *et al.* (1984). They were obtained in the the Sub-Betic Cordillera (south-eastern Spain), which was formerly the passive margin of the Iberian Plate. Two sections, developed on submarine swells, mostly in ammonitico rosso facies, were studied magnetostratigraphically: Carcabuey and Sierra Gorda. The Sierra Gorda section, embraced sediments of *ca.* 9 m thickness, from the lowermost Kimmeridgian (Platynota ammonite Zone) to the Lower Tithonian (Admirandum/Biruncinatum Zone). Magnetozone from M21n to M25r were interpreted within the section. The second section, Carcabuey, embraced a longer interval between the uppermost Oxfordian (Planula Zone) and the Lower Berriasian (Jacobi Zone) of *ca.* 11 m thickness. The magnetozone identified were from M19n to M25 or even lower (the correlation of the Kimmeridgian/Oxfordian boundary to GPTS was still disputable). The Jurassic/Cretaceous boundary within the Carcabuey section was indicated at the Durangites/Jacobi zonal boundary which coincides with the middle part of M19n and the A/B boundary of calpionellid zones (Fig. 7). The Carcabuey section was subsequently calibrated with nannofossil stratigraphy (Bralower *et al.*, 1989).

More than 25 years later, Pruner *et al.* (2010) revisited the Sub-Betic sections, focusing on detailed (30 mm average sampling interval) magnetostratigraphic documentation of the Jurassic/Cretaceous boundary. They choosed the Puerto Escaño section (GA-7) which is 8.1 m thick and developed typically in ammonitico rosso and related facies. It is situated just a few km from the Carcabuey section, studied by Ogg *et al.* (1984). The Puerto Escaño section was carefully dated by calpionellids and ammonites, which is not possible in the Carpathian and Alpine sections. The section comprised the tintinnid zones from the Chitinoidea Zone at the bottom to the Calpionella Zone in its upper part, and from the Burckhardticeratites to the Jacobi ammonite zones (Fig. 7). Magnetozone from the top of M20r to M18n were documented, with the Kysuca and Brodno magnetosubzones situated in their "typical" positions: Kysuca at 58% thickness of M20n and Brodno at 95% thickness of M19n. The authors placed the Jurassic/Cretaceous boundary at the base of Calpionella Zone B, which falls in magnetozone M19n at 40% of its thickness. However, the boundary of the Durangites/

Jacobi ammonite zones is situated within the lowermost part of M19n. That confirms that the A/B calpionellid zonal boundary is not always coeval with the boundary between the Durangites and Jacobi zones (Tavera *et al.*, 1994) and seems to demonstrate the advantage of integrated magneto- and calpionellid stratigraphy against ammonite zonation in placing the Jurassic/Cretaceous boundary.

The sedimentation rate in the Puerto Escaño was rather low and its mean value amounted to 2.87 m/My. However the highest values of the sedimentation rate might be calculated for magnetozone M18r: 4.05 m/My, while in the underlying magnetozone it varied between 2.24 in M20n2n to 3.26 in M20n1n.

Calculated mean MS values are lower for the Berriasian than for the Upper Tithonian. Indeed a stepwise decrease of MS is observed up the section, except for a sudden increase of MS in the topmost part (M18n).

An attempt to establish a magnetostratigraphic zonation was performed in the thick Lower Cretaceous basinal section in Rio Argos, situated in the Betic Cordillera, south-eastern Spain (see Fig. 2) (Hoedemaeker *et al.*, 1998). However the section appeared to be totally remagnetized, either syn- or post-tectonically, in the Neogene. That must be considered as a great disappointment because the section was considered as a possible candidate of Jurassic/Cretaceous boundary stratotype (Zakharov *et al.*, 1996).

SOUTHERN ALPS

Since the pioneering studies on the magnetostratigraphy of the Jurassic/Cretaceous boundary in the southern Alps (see Ogg *et al.*, 1991 and references herein) new data from 7 sections were published recently by Channell *et al.* (2010). Six sections are from the Trento Plateau (Colme di Vignola, Passo Branchetto, Bombatierle, Foza, Frisoni and Sciapala), and one section is located in the Lombardian Basin (Torre de'Busi). The Trento Plateau sections are the most thoroughly studied. Especially numerous sections are located to the E and SE of Asiago town (so-called Asiago Plateau in Trentino Alps – see Ogg *et al.*, 1991 and Fig. 2, sections no. 15–19). Magnetozone from the base of M13r (Early Valanginian) to M22A (Kimmeridgian/Tithonian boundary) were reliably documented there and correlated to micro- and nannofossil zonation (Channell, Grandesso, 1987; Channell *et al.*, 1987; Bralower *et al.*, 1989; Ogg *et al.*, 1991). The Trento Plateau sections are typically bipartite, consisting of the Ammonitico Rosso Superiore in its lower (mostly Tithonian) part and the Biancone Formation in its upper (uppermost Tithonian–Berriasian) part. The conclusion of Ogg *et al.* (1991) about diachronism of these two formations was confirmed. Although Channell *et al.* (2010) did not put any sharp boundary

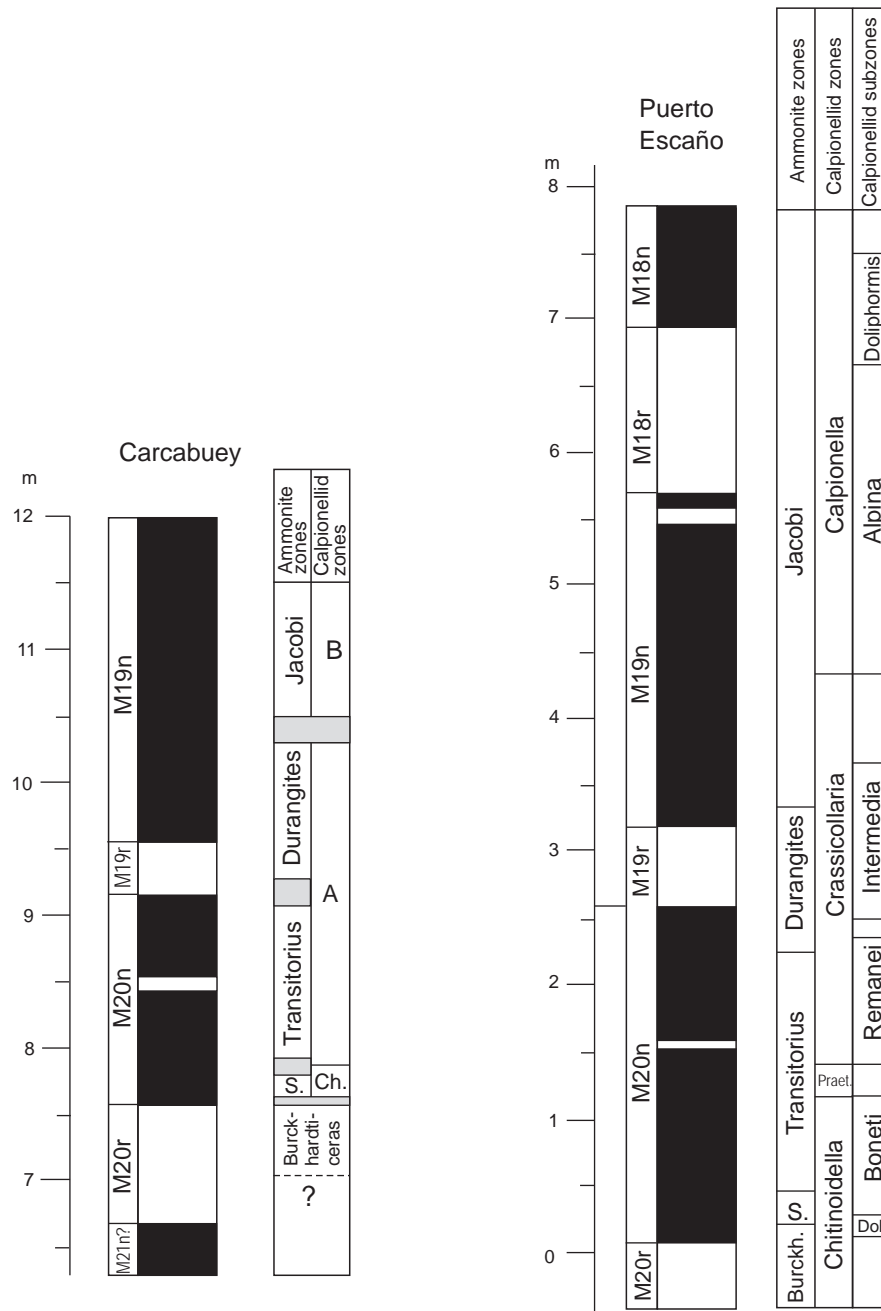


Fig. 7. Bio- and magnetostratigraphy at the Jurassic/Cretaceous boundary interval in the sections from the Sub-Betic zone of south-eastern Spain: Carcabuey (after Ogg *et al.*, 1984) and Puerto Escaño (after Pruner *et al.*, 2010)

between them, usually distinguishing a “transitional interval”, diachronism was evident even in a relatively small area like the Asiago Plateau. The “transitional interval” falls between top M20r and bottom M19n in the Foza A+ B section, within M19n in the Frisoni A section (Fig. 8), and in the top-most part of M21n in the Bombatierle section. The sections

were calibrated biostratigraphically using nannofossils only. The position of the Jurassic/Cretaceous boundary was proposed as the FO of *Nannoconus steinmannii minor* which correlates with the bottom of M18r (Channell *et al.*, 2010). (see Fig. 1A). The study of Channell *et al.* (2010) was a good opportunity to verify older magnetostratigraphic results,

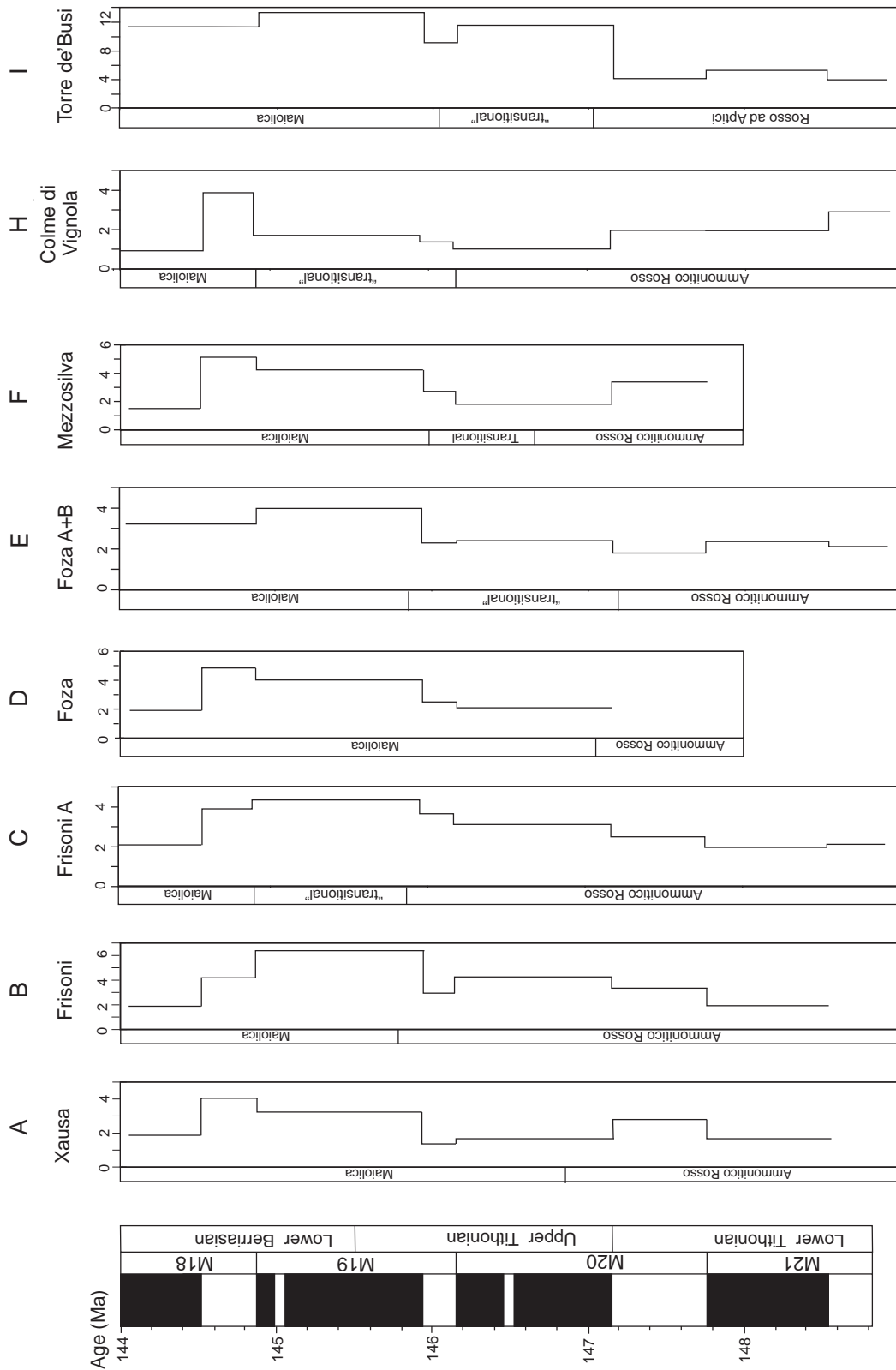


Fig. 8. Litho- and magnetostratigraphy and sedimentation rate (in m/My) in the Jurassic/Cretaceous boundary sections from the Southern Alps. Source data from: Channell and Grandesso (1987), Channell *et al.* (1987), Ogg *et al.* (1991) and Channell *et al.* (2010)

since two sections (Frisoni and Foza) studied by Channell and Grandesso (1987 – Frisoni) and Ogg (1981; Ogg *et al.*, 1991 – Foza) were restudied, although the exact location of Channell *et al.* (2010) sections was slightly different than that in older papers. The consistency of the results might be assessed by comparison of sedimentation rates, calculated for specific magnetozones from the two sets of data available for the same section, as is attempted in Fig. 8. The consistency between the old and new data for Frisoni (Fig. 8B, C) and Foza (Fig. 8D, E) is indeed very good. As the amount of data from the Asiago Plateau is significant, it may be possible to check whether any regional trends in sedimentation rate can be observed. The ammonitico rosso facies sedimented with a rate around 1–3 m/My and there is no clear trend in sedimentation rate. The bottom of M19n is usually marked by an increase in the sedimentation rate to 4–6 m/My. It is broadly related to the facies change from the ammonitico rosso to the biancone/maiolica facies. As a sharp boundary between these two formations cannot be indicated (*e.g.* Martire *et al.*, 2006), the changes in sedimentation rate are most probably not as sharp as in Fig. 8, but rather stepwise. It is remarkable that in magnetozones M18r and especially in M18n, well within the maiolica facies, the sedimentation tends to decrease in all sections. Detailed magnetic mineralogy data (even MS logs) are not available for the Southern Alpine sections, therefore it cannot be speculated about the nature of this phenomenon. Moreover, it seems that even on the scale of the Trento Plateau local sedimentary conditions varied – as can be judged from the example of the Colme di Vignola section, situated more to the west from Asiago Plateau (see Fig. 2) where the ammonitico rosso facies continues quite high stratigraphically and a major increase in sedimentation rate is observed in magnetozones M18r, with the onset of “real” maiolica, above the transitional interval (Fig. 8H). A comparison of overall sedimentation rates within the Trento Plateau with those calculated by Grabowski *et al.* (2010a) for the Lókút section in the Transdanubian Mts (Hungary), confirms the model of palaeogeographic proximity of these two regions in the Mesozoic (Vörös, Galács, 1998).

Torre de’Busi is the first magnetostatigraphically calibrated section located within the Lombardian Basin. Magnetozones between M22n and M18n were identified within the section, with both short magnetosubzones Kysuca and Brodno. It must be emphasized that these magnetosubzones were not easy to document within the more condensed sections of the Trento Plateau: both magnetosubzones were found in the Foza section only, and the Brodno magnetosubzone within Frisoni A section (Channell *et al.*, 2010). As might be expected the sedimentation rate within the Torre de’Busi section is almost twice as high as in the Trento Plateau sections: between 3 to 5 m/My in the Rosso ad Aptici

Formation and between 9 and 13 m/My in the Maiolica Formation (which corresponds to the sedimentation rates of the Jasenina and Osnica formations in the Tatra Mts – see Grabowski, Pszczółkowski, 2006). The major increase in sedimentation rate in the Torre de’Busi coincides with the onset of “transitional beds” between the Rosso ad Aptici and Maiolica formations (Fig. 8I).

The magnetostatigraphy of deposits below the Kimmeridgian/Tithonian is still to be done within both the Trento Plateau and the Lombardian Basin. In the Torre de’Busi section, it was not possible to identify reliably the bottom of M22n magnetozones (lower part of Rosso ad Aptici and upper part of Radiolariti units). In the Colme di Vignola, Foza, Sciapala and Bombatiere sections, although magnetostatigraphy was performed in the lower part of the Ammonitico Rosso Superiore, Calcare Selcifero di Fonzaso and Ammonitico Rosso Inferiore (Callovian–Kimmeridgian), it was not possible to correlate the sections with GPTS, due to very frequent polarity changes, most probably low sedimentation rates, and a still poorly defined general pattern of GPTS in this time interval, as well as a lack of reference sections with correlations between nannofossils and magnetozones (see also Channell *et al.*, 1990).

APENNINES

There are only two sections in the Apennines that cover the magnetostatigraphically documented Jurassic/Cretaceous boundary: Bosso and Arcevia (Fig. 2).

The reference Jurassic/Cretaceous boundary section is without doubt Bosso situated in the Umbria – Marche Apennines – its magnetostatigraphy was described in three independent studies (Lowrie, Channell, 1983; Houša *et al.*, 2004; Speranza *et al.*, 2005). The section constitute a part of a deep water trough located at the southern margin of the Monte Nerone pelagic carbonate platform (Houša *et al.*, 2004 and references therein). Two formations cover the Jurassic/Cretaceous boundary interval there. The first, Calcari ad Aptici (or Calcari diasprigni) is 19 m thick, and the uppermost 12 m consists of pinkish to reddish, thin-bedded cherty limestones with aptychi and *Saccocoma* (Cecca *et al.*, 1987; Speranza *et al.*, 2005). The second, Maiolica, starting from the uppermost level of red chert (Speranza *et al.*, 2005) encompasses *ca.* 80 m of white cherty limestones within the Berriasian. Magnetozones from M20n to M15n, and possibly higher were documented by Lowrie and Channell (1983), see Fig. 9. Their results were essentially confirmed by subsequent studies. The Jurassic/Cretaceous boundary was placed close to the bottom of M17r, in the uppermost part of the Alpina Subzone. The calpionellid biostratigraphy of the

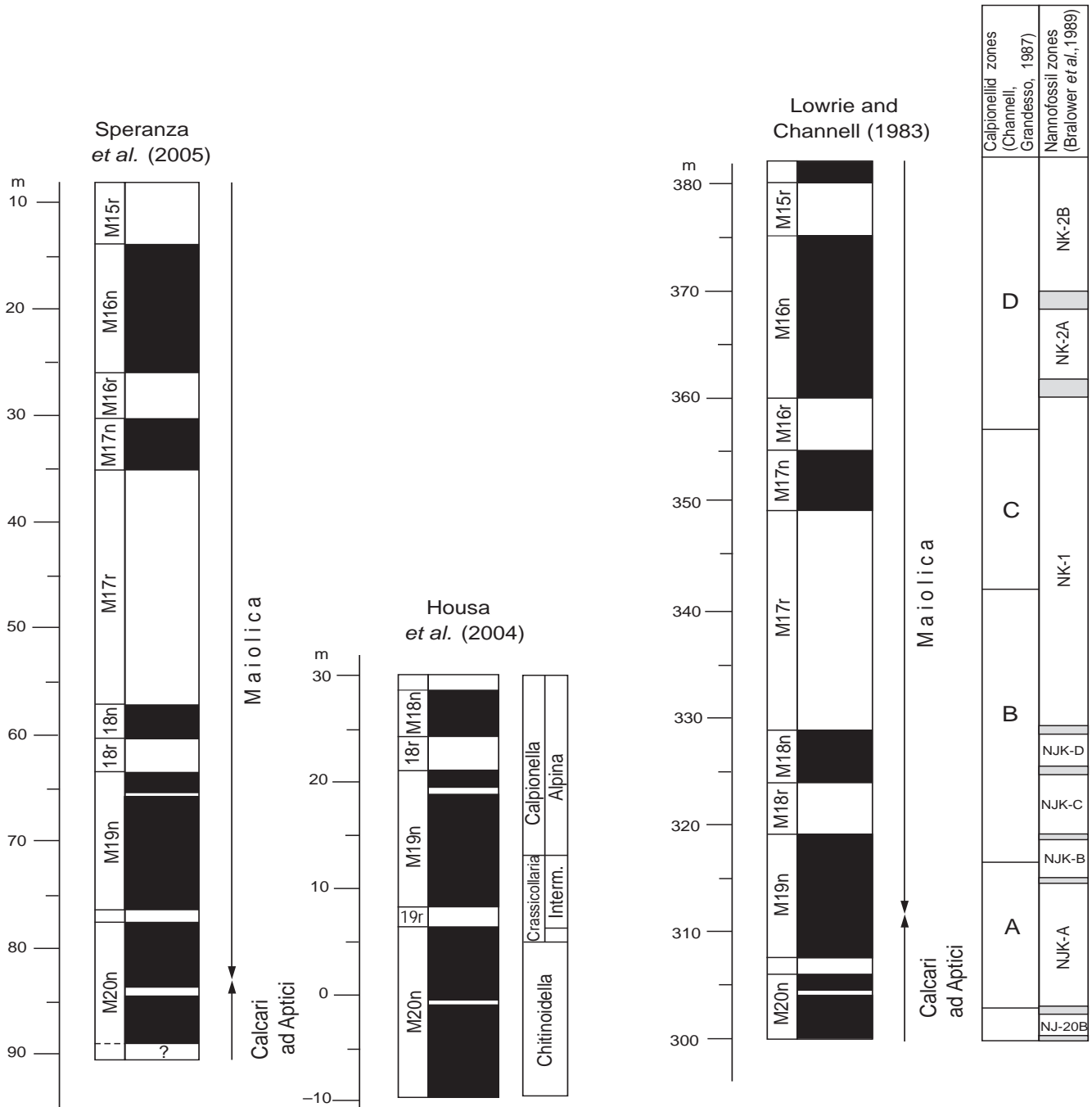


Fig. 9. Magneto- and biostratigraphy of the Bosso section (Apennines), after Lowrie and Channell (1983), Houša *et al.* (2004) and Speranza *et al.* (2005)

section was subsequently revised (see Channell, Grandesso, 1987) and a nanofossil stratigraphy established (Bralower *et al.*, 1989). Houša *et al.* (2004) put the Jurassic/Cretaceous boundary at the base of calpionellid Zone B (base of the Alpina Subzone). They focused on the lower part of the section, covering the magnetozones from M20n to the lowermost

part of M17r. Speranza *et al.* (2005) restudied the interval of Lowrie and Channell (1983), but attempted to obtain results from the older part of the Calcarei ad Aptici, sampling the beds below M20n. However, they were unable to correlate the polarity intervals to GPTS, most probably due to extreme condensation of the sediments. Both studies, Houša *et al.*

(2004) and Speranza *et al.* (2005), documented the two short magnetosubzones Brodno (M19n1r) and Kysuca (M20n1r). The latter is situated close to the boundary of the Calcari ad Aptici and Maiolica formations (Houša *et al.*, 2004; Speranza *et al.*, 2005), at the beginning of the upper half of M20n.

The characteristic feature of the Bosso section is an apparent decrease in sedimentation rate across the Jurassic/Cretaceous boundary, from 16–20 m/My in M20n1n to *ca.* 5–8 m/my in M19r, 11–12 m/My in the entire M19n, 9–10 m/My in M18r up to 6.5–7.7 m/My in M18n, which is an entirely different trend from that in sections on the Trento Plateau (see above). Decreasing trend in sedimentation rate is accompanied by a systematic decrease in magnetic susceptibility (Houša *et al.*, 2004).

The Arcevia section is situated several tens of kilometres to the east of Bosso. Magnetozones from the topmost part of M21n to M17r were reliably documented within the section. Its biostratigraphy is based only on calcareous nannofossils: biozones NJ-20B and NJ-K (Bralower *et al.*, 1989) were distinguished in the section. NJ-20B is correlated with M20r and the lower part of M20n2n while NJ-K is correlated to M20n1n–M19n1n inclusively. It differs slightly from the integrated scheme presented by Channell *et al.* (2010 – their fig. 11), where the NJ20/NJ-K zonal boundary is located within magnetozones M20r. It seems there is no biostratigraphic data from the upper part of the section.

Arcevia is claimed to be the most expanded land section documented so far between the bottom of M20n and the top of M19n (Speranza *et al.*, 2005). The Calcari ad Aptici Formation attains an apparent thickness of almost 55 m, between the uppermost part of M21n and M19n1n. It is developed atypically as fine-grained, greenish limestones with cherts. This results in a high sedimentation rate in the Upper Tithonian: almost 17 m/My in magnetozones M20n1n and M19n. It is worth noting that a large diachronism exists between the Bosso and Arcevia sections in the timing of the lower boundary of the Maiolica Formation: in the lower part of M20n1n in Bosso, and in the top of M19n1n in Arcevia (Speranza *et al.*, 2005). It is also peculiar that the base of the Maiolica Fm. is not related to an increase in sedimentation rate, as is the case with the Trento Plateau sections.

In the Fonte del Giordano section, located also in Umbria – in the Marche Apennines, a well documented magnetostatigraphy embrace magnetozones from the topmost part of M18n up to M14r, roughly attached to calpionellid and nannofossil zonation (Cirilli *et al.*, 1984; Bralower *et al.*, 1989). The Jurassic/Cretaceous boundary is situated in a gap in the section between 18 and 30 m. The normally magnetized lower part of the section might be correlated with magnetozones M20n, as it contains the lower boundary of the Crassicollaria Zone (Grabowski, Pszczółkowski, 2006; Grabowski *et al.*, 2010a).

VOCONTIAN TROUGH, SOUTH-EASTERN FRANCE

The importance of sections in the Vocontian Trough for magnetostatigraphy, like those of Sub-Betic region, relies on the co-occurrence of calpionellids and ammonites. The only section where primary magnetization was documented is the Berriasian stratotype at Berrias, at the south-eastern margin of the Massif Central (Galbrun, 1985). The section is *ca.* 25 m thick and comprises blue-gray micritic pelagic limestones. The section is well dated by ammonites and calpionellids (Le Hégarat, Remane, 1968; Le Hégarat, 1971) as well as nannofossils (Bralower *et al.*, 1989). It contains the Grandis to Boissieri ammonite zones (with ammonite subzones distinguished) and the calpionellid zones B to D. The Jurassic/Cretaceous boundary was recognized in south-eastern France at the Jacobi/Grandis zonal boundary (Le Hégarat, 1971), which corresponds to the lower (but not lowermost) part of calpionellid Zone B and almost coincides with the bottom of M18r magnetozones (Gradstein *et al.*, 2004). Magnetozones from M18r to M15r were documented in the Berrias section. The palaeomagnetic record is broken at the M17r/M17n boundary (*ca.* 2.3 m sampling gap), where slump breccia occurs. There are no palaeomagnetic results from the Jurassic/Cretaceous transition due to the very low intensities of the NRM in that interval (Galbrun, 1985). Generally, the magnetostatigraphic correlation of the section poses some problems (see also Bralower *et al.*, 1989). Magnetozones M16n contains a small reversed magnetozubzone (Ber.Z.R.3) which, until recently, was not defined in the M-sequence (Gradstein *et al.*, 2004). The most recent geomagnetic polarity time scale (Tominaga, Sager, 2010) documents a new magnetosubchron (M16n1r) which might correspond to the Ber.Z.R.3 subzone of Galbrun (1985). However the existence of another short normal polarity subzone within the interpreted M17r (Ber.SZ.N.7) has not been confirmed in any other section. The sedimentation rate within the magnetozones which are complete in this section, M16r and M16n, amounts to *ca.* 8 m/My, while in magnetozones M17n it is at least 6 m/My.

Any subsequent attempts at magnetostatigraphy in the Vocontian sections failed due to the presence of remagnetization, related either to clay mineral diagenesis (Katz *et al.*, 1998, 2000) or fluid circulation (Henry *et al.*, 2001; Kechra *et al.*, 2003). However recent activities of the Berriasian Working Group (Wimbledon *et al.*, 2011) indicate that there is still a potential for magnetostatigraphic studies in south-eastern France.

DSDP SITES

The best documentation of Jurassic/Cretaceous boundary magnetostatigraphy is derived from DSDP site 534 situated in the western part of the Atlantic Ocean, close to the

Florida coast, within the Blake–Bahama Basin (Ogg, 1983). The drilling penetrated Jurassic and Lower Cretaceous sediments from Middle to Upper Callovian up to Valanginian–Hauterivian. The Jurassic/Cretaceous transition takes place in the upper part of the red claystone of the Cat Gap Formation and a lower part of the white limestones of the Blake–Bahama Formation, being the equivalents of Ammonitico Rosso and Maiolica formations in the southern Alps and Apennines. The continuous magnetostratigraphic record embraces magnetozones from M20r up to the bottom part of M16n. The section was calibrated biostratigraphically with calpionellids (Remane, 1983) and nannofossils (Bralower *et al.*, 1989; Bornemann *et al.*, 2003). The base of B calpionellid Zone was identified within the lower part of M19n magnetozones, however it was impossible to document higher calpionellid zones (C, D, E) due to the complete absence of calpionellid associations in the Middle Berriasian – Lower Valanginian interval. A complete calcareous nannofossil zonation was applied from NJ-19A (Lower Tithonian) up to the lowermost part of NK-3 (Lower Valanginian). The boundary between the Cat Gap and Blake Bahama formations is placed either in the middle part of magnetozones M19n, just close to A/B and the NJK-B/C calpionellid and nannofossil zonal boundaries, which coincides with the Jurassic/Cretaceous boundary (Ogg, 1983; Ogg *et al.*, 1991), or in the lower part of M19r magnetozones, in the middle part of NJK-A nannofossil zone (Bornemann *et al.*, 2003). The sedimentation rate, calculated from the magnetostratigraphy, dramatically increases close to the Cat Gap/Blake Bahama formational boundary, from 8–9 m/My in magnetozones M20r–M20n to 27–31 m/My in magnetozones M19r and M19n, 17–18 m/My in M18r and M18n, and 25 m/My in M17r (Grabowski *et al.*, 2010a). The section was recently a subject of integrated palaeoenvironmental studies which included the palaeoecology of calcareous nannoplankton as well as $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotope stratigraphy (Tremolada *et al.*, 2006).

The magnetostratigraphic documentation of the Jurassic/Cretaceous boundary transition in other DSDP sites is mostly fragmentary. In neighbouring DSDP 603 site only magnetozones M16n and M15r were reported from the Berriasian, although the interpretation is very tentative (Ogg, 1987). Mostly normal magnetization (with two poorly represented reversed polarity intervals in shallow water limestones, passing upwards to clayey limestone and marlstone) from Hole 639D from the Galicia margin of the Iberian Peninsula (Ogg, 1988), was correlated to the M21n–M20n (?M19n) interval on the basis of calpionellid Zone A at the top of the section. Brown-red silty claystones at the bottom of the sedimentary sequence in ODP site 765 in the Argo abyssal plain (off north-western Australia), were correlated very roughly to M17r–M16n magnetozones (Ogg *et al.*, 1992); however more detailed biostratigraphy suggested their Tithonian age

(Kaminski *et al.*, 1992). Quite recent results from Berriasian sediments drilled in 1213B hole in Shatsky Rise (Sager *et al.*, 2005) bring evidence for the presence of M18n to M16n magnetozones in ca. 60 m of calcareous ooze with frequent chert and porcellanite intercalations. The magnetostratigraphic interpretation was performed contrary to biostratigraphic data indicating that the entire section is situated within NK-2A nannofossil Subzone (Bown, 2005) indicating Upper Berriasian only. It is worth noting that from this site useful radiometric dates (144.6 ± 0.8 Ma) were obtained which are matched with the earliest Berriasian (Mahoney *et al.*, 2005).

BOREAL AND NORTHERN EUROPEAN REALM

Ogg *et al.* (1994) correlated magnetostratigraphically the Portland–Purbeck sediments from southern England to the GPTS. The quality of their magnetostratigraphic data was much worse than that from pelagic limestones of the maiolica and ammonitico rosso type. The only biostratigraphic markers at that time, correlative with the Berriasian Stage, were miospore palynomorph assemblages from the Cinder Beds and overlying Intermarine Beds, which were dated as Late Berriasian. However, subsequent studies of palynomorphs and ostracods provided a fairly good ground for correlation with the Tithonian and Berriasian stages (Hunt, 2004; see also Wimbledon, 2008). The terrestrial to marginal-marine Purbeck Beds, investigated in the Durlston Bay section, start within M19r magnetozones and continue up to M14r magnetozones (Fig. 10A). Magnetozones M19n, where the Jurassic/Cretaceous boundary is situated in most calpionellid bearing sections (e.g. Houša *et al.*, 1999a, 2004) occurs between the *Cypris* Freestone and the Cockle Beds (see also Wimbledon, 2008). This correlation was accepted by Hoedemaeker and Hergreen (2003) and fitted in their sequence stratigraphic scheme of Tethyan–Boreal correlation. The magnetostratigraphy of the underlying shallow marine Portland Beds is more speculative due to weaker NRM intensities and a hiatus/erosion surface in the middle part of the division. The most probable correlation situates the Portland Beds between magnetozones M21r and M19r, but the reversed magnetozones are thin and based on lower quality results. As the Purbeck Formation is correlated roughly to the Boreal ammonite zonation in eastern England (Cope, 2008; Wimbledon *et al.*, 2011), the English sections can be indirectly correlated also with the Russian Upper Tithonian–Berriasian (Volgian) (e.g. Rogov, Zakharov, 2009).

Recently obtained magnetostratigraphic data from the Tithonian–Berriasian (Volgian–Ryazanian) section at Nordvik Peninsula in northern Siberia (Houša *et al.*, 2007) provide a framework for the direct correlation of the Jurassic/

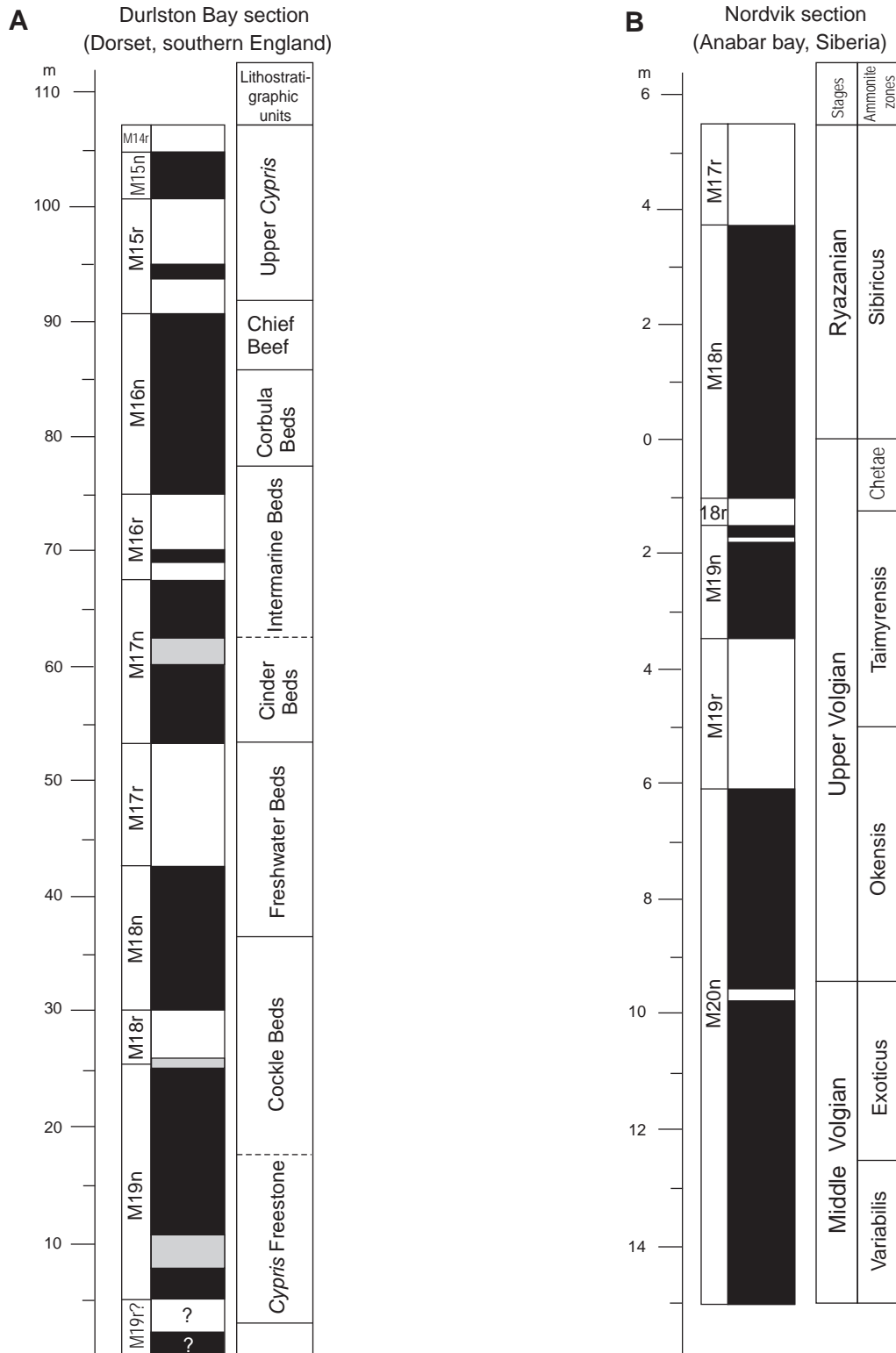


Fig. 10. Magnetostratigraphy of Jurassic/Cretaceous boundary interval outside Tethys.

A. Durlston Bay section, Purbeckian (after Ogg *et al.*, 1994). B. Nordvik section, northern Siberia (after Houša *et al.*, 2007)

Grey colour – intervals of “intermediate” polarity (not determined)

Cretaceous boundary in the Tethyan and Boreal realms. The composite section, 27 m thick, consists of marine clay and silty beds with frequent siderite nodules and pyrite occurrences (Chadima *et al.*, 2006). The interval studied magnetostratigraphically (21 m – see Fig. 10B) is dated by ammonites, from the Variabilis Zone of the Middle Volgian to the bottom of the Kochi Zone of the Lower Ryazanian. The samples for magnetostratigraphy were taken relatively densely (each 2–4 cm) in the middle part (Upper Volgian) and with a lower resolution (10 cm) in the Middle Volgian and Ryazanian. Although some horizons appeared to be remagnetized, most probably during siderite diagenesis, the bulk of sample collection revealed a double polarity component with a very steep inclination, which might be interpreted as primary. Correlation of the polarity pattern to GPTS was based on the presence of thin reversed magnetosubzones within the normal polarity intervals. They were interpreted as the Kysuca (M20n1r) and Brodno (M19n1r) magnetosubzones. Indeed their position within the normal magnetozones is identical as in the type locality Brodno (Houša *et al.*, 1999a, b). The magnetosubzone interpreted as being Brodno is situated in the topmost part of its normal magnetozones (in Brodno: at 82% local thickness of M19n). The magnetosubzone interpreted as Kysuca is situated in the upper half of the presumed M20n magnetozones, although it must be kept in mind that the bottom of this magnetozones was not documented in the Nordvik section. This interpretation is very convincing in the present state of knowledge. The Tethyan Jurassic/Cretaceous boundary (boundary between A and B calpionellid zones), located in magnetozones M19n2n, must be correlated with the Taimyrensis Zone which is situated in the upper (but not uppermost) part of the Upper Volgian (Rogov, Zakharov, 2009). The Volgian/Ryazanian boundary falls in the lower part of magnetozones M18n.

The sedimentation rate calculated for the Nordvik section from the data of Houša *et al.* (2007), seems to be quite uniform in M20n1n and M19r (*ca.* 11–12 m/My), M18n (*ca.* 9 m/My) and at least 8 m/My in M20n2n. In magnetozones M19n and M18r the sedimentation rate seems to fall dramatically to 1.5–2.0 m/My which resembles the rate from condensed ammonitico rosso sections (see above). In the lithological log of Houša *et al.* (2007 – their fig. 2) there is no indication of any sedimentation change which could justify such condensation. However it cannot be excluded that the condensation (or erosion of a part of the sediments) might be somehow related to the Mjøltnir impact event at the Barents Sea, which occurred close to the Volgian/Ryazanian boundary (Smelror *et al.*, 2001; Dypvik *et al.*, 2006; Wierzbowski *et al.*, 2011). More magnetostratigraphic studies, integrated with biostratigraphy and sedimentology is definitely required to provide a correlation of the Jurassic/Cretaceous boundary between Boreal and Tethyan realms.

CONCLUSIONS

Magnetostratigraphy should be considered as a valuable tool for regional and global correlation at the Jurassic/Cretaceous boundary interval. In the Western Tethyan Realm integration of calpionellid and magnetic stratigraphy is nowadays almost routinely applied which results in high resolution stratigraphic calibration of the sections studied. Correlation of Chitinoidea and A–D zones to magnetostratigraphy is fairly robust and has been tested in more than 20 land sections as well as some ODP and DSDP sites. Some improvement is required in estimating the real extent of calpionellid subzones relatively to GPTS, because the methodology of calpionellid zonation sometimes differs between sections and particular authors. Integration of magnetic stratigraphy with calcareous nannofossil stratigraphy is a promising option, however, from quite numerous studies it is evident that this integration still needs much refinement. The correlation of magnetostratigraphy and ammonite stratigraphy must be considered as still poorly constrained. There are just four sections when the correlation has been achieved, three of them based on work from the 1980s. In some intervals (*e.g.* between magnetozones M18n and M17n) the correlation is based on just one marine section (Berrias). In places where the sections overlap (*e.g.* between M20n and M19n), there are some important discrepancies (as in the position of the Durangites/Jacobi zonal boundary in relation to calpionellid stratigraphy and GPTS in south-eastern Spain). Important progress has been made in the magnetostratigraphical correlation of the non-marine sequences of north-western Europe and the Siberian Boreal Realm with the Tethyan Province; this however must be treated as a starting point for further testing since in both NW Europe and Siberia, results from only two magnetostratigraphically studied sections have been published.

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