Geological Quarterly, 2009, **53** (3): 363–368

SHORT COMMUNICATION

Influence of palaeoclimate and the greenhouse effect on Hettangian clay mineral assemblages (Holy Cross Mts. area, Polish Basin)

Paweł BRAŃSKI

Brański P. (2009) — Influence of palaeoclimate and the greenhouse effect on Hettangian clay mineral assemblages (Holy Cross Mts. area, Polish Basin). Geol. Quart., **53** (3): 363–368. Warszawa.

Hettangian clay mineral assemblages from the Holy Cross Mts. margin (southeastern part of the epicontinental Polish Basin) were mostly controlled by climatic conditions and weathering regime. Hettangian claystones and mudstones were deposited in continental and marine-margin palaeoenvironments in a warm climate, mostly with year-round humidity. The pronounced, long-term greenhouse conditions intensified chemical weathering in the hinterland. Reworking and redeposition of ancient sediments caused by tectonics and/or by sea-level changes and early diagenesis may have modified the clay mineral content in the earliest Hettangian. Burial diagenesis and telodiagenesis changed the clay mineral composition only locally.

Paweł Brański, Polish Geological Institute-National Research Institute, Rakowiecka 4, PL-00-975 Warszawa, Poland; e-mail: pawel.branski@pgi.gov.pl *(received: July 01, 2008; accepted: May 07, 2009).*

Key words: Hettangian, Holy Cross Mts. margin, clay mineral assemblages, palaeoclimate, greenhouse effect.

INTRODUCTION

A wide range of geochemical, sedimentological, lithological and palaeontological evidence suggests that the interval at the end of the Triassic and the beginning of the Jurassic was a time of major environmental changes. In the Late Triassic the supercontinent Pangaea began to fragment. Rifting events were accompanied by reorganization of the subsidence pattern and by basaltic volcanism that formed the largest igneous province in Phanerozoic time (Marzoli *et al*., 1999, 2004; Hames *et al*., 2000). Carbon-isotope anomalies have been reported worldwide that may indicate coeval global disturbances in biogeochemical cycles. Carbon dioxide outgassing and global warming, induced by flood basalt volcanism of the Central Atlantic Magmatic Province (CAMP), as well as a sea-level lowstand (Hallam, 1997) might have triggered the sudden release of methane hydrates and a positive feedback mechanism that in turn caused greenhouse effect, catastrophic climate change and pronounced biological turnover at the end of the Triassic (Palfy *et al*., 2000, 2001; Hesselbo *et al*., 2002, 2007; Guex *et al*., 2004). The Triassic–Jurassic boundary interval is characterized by evidence of global warming. Such evidence derives from many palaeobotanical and geochemical studies (e.g., Fowell and Olsen, 1993; McElwain *et al*., 1999; Palfy *et al*., 2001; Hesselbo *et al*., 2002; Jenkyns *et al*., 2002; Cohen and Coe, 2002, 2007), but on the other hand a “cool phase” coincident with the T–J transition was postulated by Hubbard and Boulter (2000). Changes in sea-water Os-isotope and Sr-isotope (Fig. 1) records indicate that erosion and weathering of the CAMP started soon after its emplacement (Cohen and Coe, 2002, 2007). At the beginning of the Sinemurian much of the basaltic cover had been removed by chemical weathering (Cohen and Coe, *op. cit.*). Such accelerated weathering and erosion would not have been possible without a substantial increase in rainfall. The aridity-humidity pattern is another controversial problem of Rhaetian–Hettangian time. Generally, the changes in climate-sensitive minerals, sediments and palaeosols reflect increasing humidity (e.g., Halllam, 1985; Arndorff, 1993; Ruffell *et al.*, 2002; Ahlberg *et al.*, 2003; Mørk *et al.*, 2003), but the pattern of climate change was complicated and may not have been expressed globally.

RESULTS

In the area studied (Fig. 2) clay deposits are particularly common in three formations of the Lower Jurassic: the Zagaje

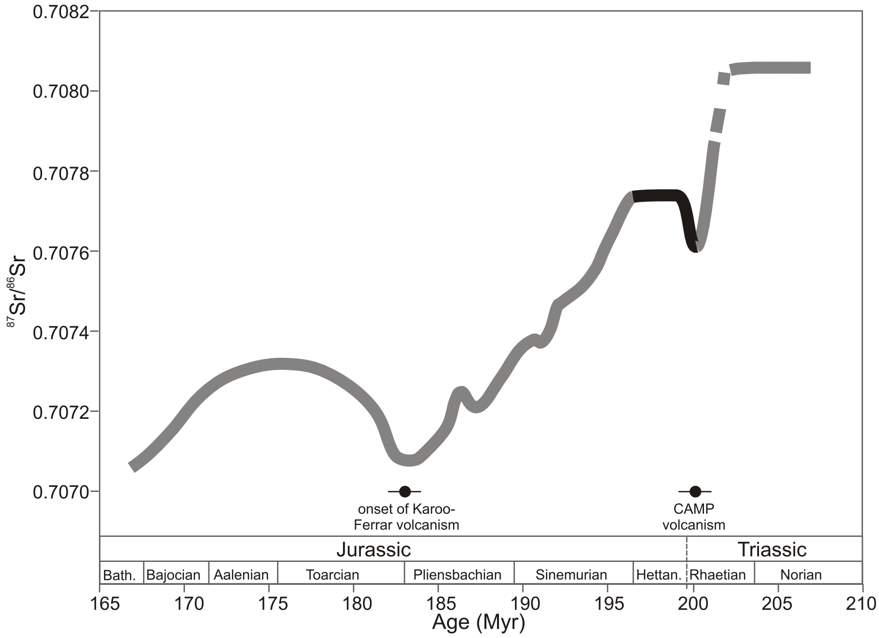

Fig. 1. Variations in the Sr-isotope composition of seawater, expressed as the $^{87}Sr/^{86}Sr$ ratio, from the latest Triassic to the Mid-Jurassic (after Cohen and Coe, 2007, simplified by the author)

Note the sudden increases of $^{87}Sr/^{86}Sr$ ratio in the latest Rhaetian and early Toarcian in response to the intensification in continental weathering followed global warming. Black line indicate the latest Rhaetian–Hettangian time interval

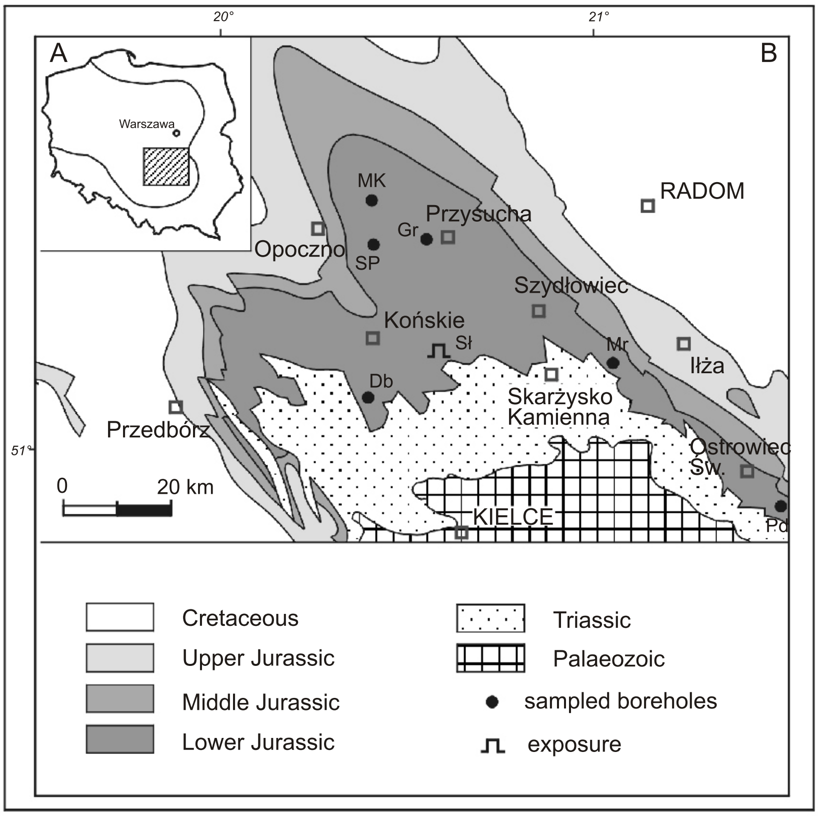

Fig. 2A — studied area and the extent of the Hettangian basin; B — location of boreholes and exposure (mentioned in text and shown on Figure 5) on a background of the simplified geological map of the Holy Cross Mts. region

Db — Dąbrówki, Gr — Gródek, MK — Mroczków–Kraszków, Mr — Mirzec, Pd — Podole, Sł — Sołtyków (Odrowąż), SP — Stare Pole

Table 1

Lithostratigraphical subdivision of the Lower Jurassic and the clay deposits content on the Holy Cross Mts. margin (based on Pieńkowski, 2004 and Kozydra, 1968)

Stage	Lithoformation	Clay deposits content [%]
Toarcian	hiatus	
	Borucice Fm.	5
	Ciechocinek Fm.	25
Pliensbachian	Drzewica Fm.	5
	Gielniw Fm.	10
Sinemurian	Ostrowiec Fm.	5

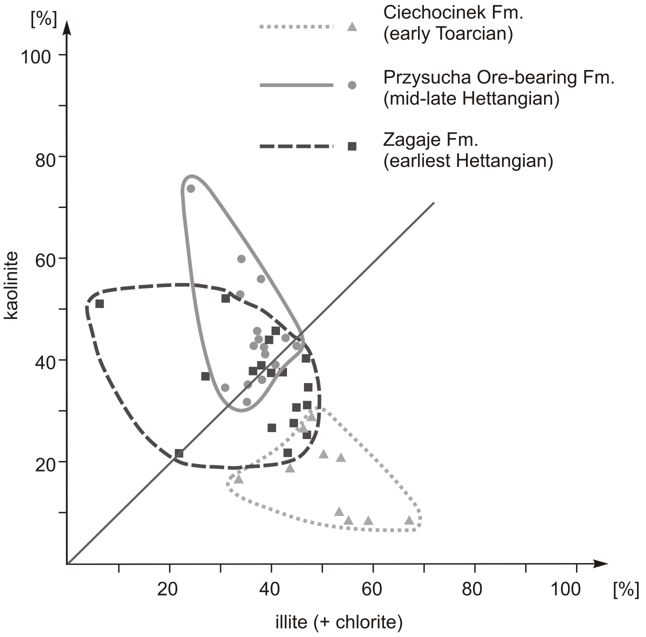

Fig. 3. Kaolinite *vs.* illite content in the claystones and mudstones of selected Lower Jurassic formations from the Holy Cross Mts. margin (on the basis of data from Kozydra, 1968 and Maliszewska, 1968)

Note the difference between Hettangian (Zagaje Fm., Przysucha Ore-bearing Fm.) and Lower Toarcian (Ciechocinek Fm.) clay mineral content

Fm., the Przysucha Ore-bearing Fm. and the Ciechocinek Fm., of Toarcian age (Table 1). In the Hettangian successions, clay mineral assemblages comprise predominantly detrital kaolinite and illite with subordinate chlorite and only trace amounts of smectite, but differences in the quantitative mineral composition are common. In many Hettangian horizons/strata very high kaolinite content was observed. The general results of the studies in 1968–2006 are given in Table 2 and illustrated in Figures 3 and 4.

The clay mineral assemblages of the alluvial-lacustrine Zagaje Fm. (earliest Hettangian) display significant variations in the kaolinite/illite (K/I) and Al_2O_3/K_2O ratio. In particular, the basal alluvial clay deposits are characterized by a predominance of kaolinite or illite that occurs in variable proportions. In many cases the original clay mineral assemblage of Zagaje Fm. was mildly to strongly transformed by early diagenetic processes in swampy environments, where significant hydrochemical and Eh–pH changes took place. Kaolinite is in general the most abundant clay mineral in the Przysucha Ore-bearing Formation (middle-late Hettangian). Clay minerals in the restricted marine (lagoonal) claystones and mudstones of Przysucha Ore-bearing Fm. show some quantitative variability. Deposition in the quiet brackish-marine environments possibly protected the detrital clay minerals from pedogenic and early diagenetic overprint.

Table 2

The main results of the clay mineral composition and Al-, K-oxides content in the Hettangian clay deposits (compiled by the author on the basis of analyses from 1968–2006)

Formation	Age	Environment	MI/Q	K**	I(Ch,I–S)**	K/ I(Ch,I–S)	Al_2O_3	K_2O	Al_2O_3/K_2O	Clay minerals assemblage	Source of data
PRZYSUCHA ORE-BEARING FM.	mid–late Hettangian	brackish-marine (lagoon, delta, embayment)	1.3	58	42	1.4	19.70	2.05	9.6	K>I>Ch (I-S)	Brański (2007)*
			1.4	60	40	1.5	25.22	2.23	11.3	K>I>Ch	Brański (1988*, 1990*, 1993*)
			–	61	39	1.6	–	–	–	K>I>Ch	Pieńkowski (1981)*
			7.3	57	43	1.3	29.85	2.45	12.2	K>I	Maliszewska (1968)
			3.6	53	47	1.1	27.21	2.77	9.8	K?I	Kozydra (1968)
ZAGAJE FM.	earliest Hettangian	continental (floodplain. lake, swamp)	1.6	58	42	1.4	26.86	2.41	12.0	K>I>Ch (I–S)	Brański (1988*, 1993*)
			–	53	47	1.1	–	–	–	K>I>Ch (I–S)	Pieńkowski (1981)*
			3.0	48	52	0.9	24.85	2.55	9.8	I?K	Maliszewska (1968)
			2.7	49	51	1.0	24.23	2.81	8.6	I = K	Kozydra (1968)

Ch — chlorite, I — illite, I–S — illite/smectite mixed-layers, K — kaolinite, MI — clay minerals, Q — quartz (and the rest of minerals); * — unpublished; ** — ΣMI = 100%

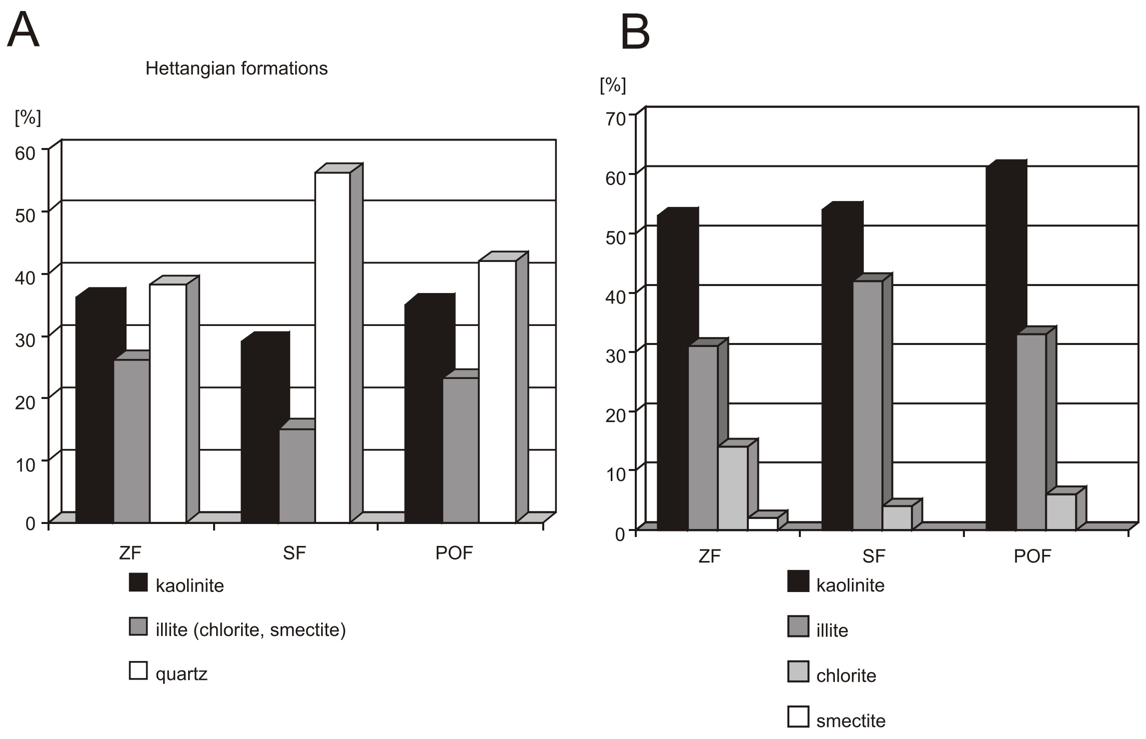

Fig. 4. Average general mineral composition (A) and clay mineral composition (B) in the claystones and mudstones from Hettangian formations (on the basis of data from Pieńkowski, 1981, 2004 and unpublished studies of the author)

POF — Przysucha Ore-bearing Fm., SF — Skłoby Fm., ZF — Zagaje Fm.

INTERPRETATION AND DISCUSSION

Detrital clay minerals are key to understanding past changes in weathering regime, because they represent the final product of the continental weathering process. Climate changes may control the clay mineral composition directly via the temperature and precipitation conditions on the continent, or indirectly via feedback mechanisms involving sea-level changes, arid episodes and sediment reworking (e.g., Singer, 1984; Chamley, 1989; Thiry, 2000; Cedric *et al.*, 2006). Clay minerals in the Hettangian claystones and mudstones of the Holy Cross Mts. area are largely detrital and show a generally weak diagenetic overprint due to moderate burial and to the fairly closed hydrological system (Brański, 2007). Telodiagenetic transformation developed only locally after the Late Cretaceous/Paleogene inversion of the Mid-Polish Trough (*cf.* Kozydra, 1968).

In the Hettangian, the area studied was located at approximately 45° palaeolatitude in a wide zone of warm-temperate climate (Chandler *et al.*, 1992; Sellwood and Valdes, 2006). The typical Hettangian clay mineral assemblage corresponds to a warm-temperate climate with year-round humidity (*cf.* Singer, 1984; Chamley, 1989; Ahlberg *et al.*, 2003) characteristic for mid latitudes. However, the abundance of detrital kaolinite in many Hettangian beds is consistent with the concept that the sediments were derived from the erosion of a “tropically” weathered cover (e.g., Wilson, 1972; Chamley, 1989; Arndorff, 1993). The extensive fluvial-lacustrine and delta-lagoonal systems acted as traps for the kaolinite formed on the hinterland. Most probably, the kaolinisation was further intensified by exchange of CO_2 with the Hettangian greenhouse atmosphere. Recent studies indicate a sudden intensification in continental weathering following a “greenhouse” effect at the Triassic–Jurassic boundary (Cohen and Coe, 2007). There is much sedimentological evidence (flooding events, storm deposits) for heavy rainfall and violent weather conditions also in the Polish Basin (Pieńkowski, 1981, 2004). Such phenomena are typical of a greenhouse effect. Generally, kaolinite is the most abundant clay mineral in the Przysucha Ore-bearing Formation (mid–late Hettangian). The tectonic quiescence and relatively low relief of the terrain, combined with “greenhouse” conditions (high temperatures and intense rainfall), would have greatly favoured chemical weathering rather than mechanical erosion. The kaolinite to illite ratio in the Przysucha Ore-bearing Formation appears to vary geographically and vertically (Fig. 5). The lateral changes (Fig. 5A) reflect the provenance and mineralogical diversity of parent rocks and soils in the source areas. A decrease in kaolinite content at the top of the Hettangian (Fig. 5B), may have been caused either by a temperature decrease and/or rainfall reduction, which followed waning of a greenhouse effect and transient sea-level fall in the latest Hettangian.

The relations between clay minerals in the Zagaje Fm. are more complicated, particularly in the lower part of the succession. The influence of the source area rocks can be observed in the different character of the basal clay assemblages, reflecting the degradation of Norian or Rhaetian deposits. These sedi-

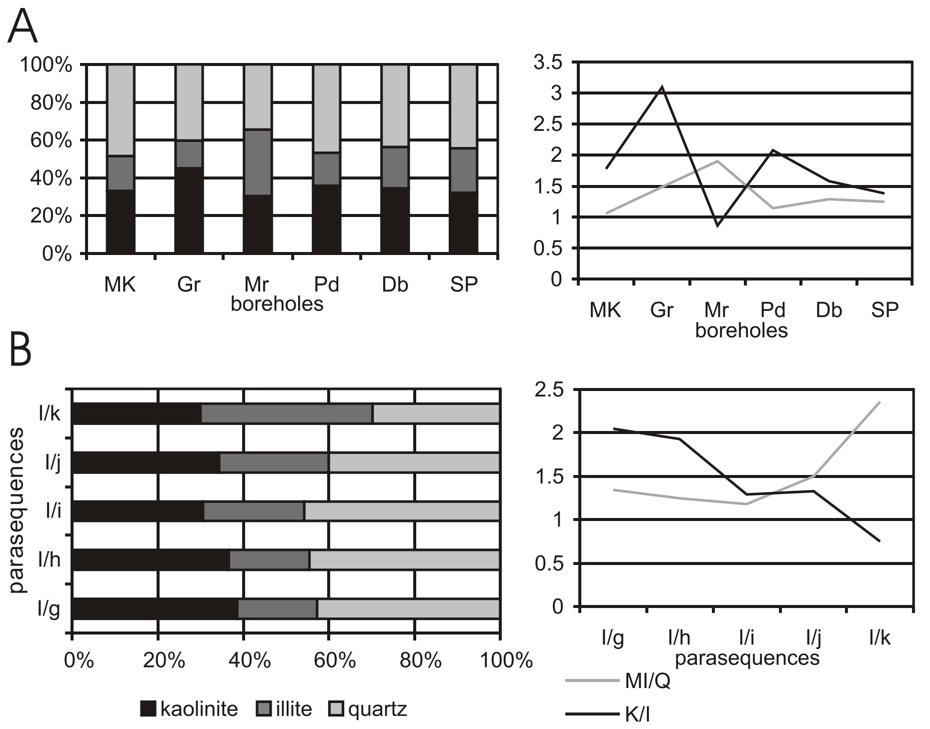

Fig. 5. Variations in the mineral composition of claystones and mudstones from the Przysucha Ore-bearing Fm. depending on: A — locality of boreholes, B — rate of deposition (based on unpublished studies of present author)

Explanations as in Figure 2 and Table 2

ments were redeposited in various amounts to produce illite or kaolinite spikes in basal beds of the Hettangian succession. Changes in the erosion rate and in consequence in the illite or kaolinite content in the the basal beds of Hettangian might have been influenced by a sea-level lowstand (Pieńkowski, 2004) and tectonic reactivation (Brański, 2006) coupled with possible arid episodes and subsequent erosion of older Norian or Rhaetian deposits. Usually, the lithological, sedimentological and mineralogical record of the lower Hettangian corresponds with generally warm and humid conditions (Gierliński *et al.*, 2003; Pieńkowski, 2004; Brański, 2007). The very minor content of smectite in the successions indicate that there were no severe seasonal aridity phases. However, one should bear in mind that the acidic conditions that characterized swampy environments in the earliest Hettangian, would lead to early diagenetic transformation of Al-smectite into kaolinite (*cf.* Saez *et al.*, 2003). Some fossils of xeromorphic plants (*Hirmeriella muensteri*) and the presence of common charcoal in the Sołtyków exposure (Reymanówna, 1991; Wcisło-Luraniec, 1991; Ziaja, 1991; Gierliński *et al.*, 2003) suggest the continuation of episodic and/or seasonal dryness, despite the stepwise rise of humidity in the transitional palaeoclimatic phase.

CONCLUSIONS

The Hettangian clay mineral composition from the Holy Cross Mts. margin was mostly controlled by greenhouse climatic conditions and intense chemical weathering.

Reworking of the ancient sediments and the early diagenesis could modify significantly the clay mineral content.

The burial diagenesis and telodiagenesis changed the clay minerals composition only in a local scale.

REFERENCES

AHLBERG A., OLSSON I. and SIMKEVICIUS P. (2003) — Triassic-Jurassic weathering and clay mineral dispersal in basement areas and sedimentary basins of southern Sweden. Sediment. Geol., **161** (1–2): 15–29.

ARNDORFF L. (1993) — Lateral relations of deltaic palaeosols from the Lower Jurassic Ronne Formation on the island of Bornholm, Denmark. Palaeogeogr., Palaeoclimat., Palaeoecol., **100** (3): 235–250.

BRAŃSKI P. (2006) — Lower Hettangian in the Holy Cross Mountains region — an example of tectonically-controlled sedimentation in the epicontinental basin of Poland. Volum. Jurassica, **4**: 80–81.

BRAŃSKI P. (2007) — Zespoły minerałów ilastych jury dolnej z południowej części epikontynentalnego basenu polskiego — wpływ paleoklimatu a inne czynniki. Tomy Jurajskie, **4**: 5–18.

CEDRIC M. J., ADATTE T. and MUTTI M. (2006) — Regional trends in clay mineral fluxes to the Queensland margin and ties to middle Miocene global cooling. Palaeogeogr., Palaeoclimat., Palaeoecol., **233** (3–4): 204–224.

CHAMLEY H. (1989) — Clay sedimentology. Springer-Verlag, Berlin.

CHANDLER M. A., RIND D. and RUEDY R. (1992) — Pangean climate during the Early Jurassic: GCM simulations and the sedimentary record of palaeoclimate. Geol. Soc. Am. Bull., **104**: 543–559.

COHEN A. S. and COE A. L. (2002) — New geochemical evidence for the onset of volcanism in the Central Atlantic magmatic province and environmental change at the Triassic–Jurassic boundary. Geology, **30**: 267–270.

COHEN A. S. and COE A. L. (2007) — The impact of the Central Atlantic Magmatic Province on climate and on the Sr- and Os-isotope evolution of seawater. Palaeogeogr., Palaeoclimat., Palaeoecol., **244**: 374–390.

FOWELL S. J. and OLSEN P. E. (1993) — Time calibration of T–J microfloral turnover, eastern North America. Tectonophysics, **222**: 361–369.

GIERLIŃSKI G., PIEŃKOWSKI G. and NIEDŹWIEDZKI G. (2004) — Tetrapod track assemblage in the Hettangian of Sołtyków, Poland, and its paleoenvironmental background. Ichnos, **11** (3/4): 195–213.

GUEX J., BARTOLINI A., ATUDOREI V. and TAYLOR D. (2004) — High-resolution ammonite and carbon isotope stratigraphy across the Triassic–Jurassic boundary at New York Canyon (Nevada). Earth Planet. Sc. Let., **225**: 29–41.

HALLAM A. (1985) — A review of Mesozoic climates. J. Geol. Soc., London, **142**: 433–445.

HALLAM A. (1997) — Estimates of the amount and rate of sea-level change across the Rhaetian–Hettangian and Pliensbachian-Toarcian boundaries (latest Triassic to early Jurassic). J. Geol. Soc., London, **154**: 773–779.

HAMES W. E., RENNE P. R. and RUPPEL C. (2000) — New evidence for geologically instantaneous emplacement of earliest Jurassic Central Atlantic magmatic province basalts on the North American margin. Geology, **28**: 859–862.

HESSELBO S. P., McROBERTS C. A. and PALFY J. (2007) — Triassic-Jurassic boundary events: problems, progress, possibilities. Palaeogeogr., Palaeoclimat., Palaeoecol., **244**: 1–10.

HESSELBO S. P., ROBINSON S. A., SURLYK F. and PIASECKI S. (2002) — Terrestrial and marine extinction at the Triassic–Jurassic boundary synchronized with major carbon-cycle perturbation: a link to initiation of massive volcanism? Geology, **30**: 251–254.

HUBBARD R. N. L. B. and BOULTER M. C. (2000) — Phytogeography and Palaeoecology in Western Europe and Eastern Greenland near the Triassic-Jurassic Boundary. Palaios, **15**: 120–131.

JENKYNS H. C., JONES C. E., GRÖCKE D. R., HESSELBO S. P. and PARKINSON D. N. (2002) — Chemostratigraphy of the Jurassic System: applications, limitations and implications for palaeoceanography. J. Geol. Soc., London, **159**: 351–378.

KOZYDRA Z. (1968) — Deposits of Lower Jurassic refractory clays in the light of the general geological structure in the northern margin of the Holy Cross Mountains (in Polish with English summary). Biul. Inst. Geol., **216**: 5–94.

MALISZEWSKA A. (1968) — Petrography of Liassic deposits in the northern margin of the Holy Cross Mountains (in Polish with English summary). Biul. Inst. Geol., **216**: 107–181.

MARZOLI A., BERTRAND H., KNIGHT K. B., CIRILLI S., BURATTI N., VERATI C., NOMADE S., RENNE P. R., YOUBI N., MARTINI R., ALLENBACH K., NEUWERTH R., RAPAILLE C., ZANINETTI L. and BELLIENI G. (2004) — Synchrony of the Central Atlantic Magmatic Province and the Triassic–Jurassic boundary climatic and biotic crisis. Geology, **32**: 973–976.

MARZOLI A., RENNE P. R., PICCIRILLO E. M., ERNESTO M., BELLIENI G. and De MIN A. (1999) — Extensive 200-million-year-old continental flood basalts of the Central Atlantic Province. Science, **284**: 616–618.

McELWAIN J. C., BEERLING D. J. and WOODWARD F. I. (1999) — Fossil plants and global warming at the Triassic-Jurassic boundary. Science, **285**: 1386–1390.

MØRK M. B. E., VIGRAN J. O., SMELROR M., FJERDINGSTADT V. and BOE R. (2003) — Mesozoic mudstone compositions and the role of kaolinite weathering — shallow cores in the Norwegian Sea (Møre to Troms). Norwegian J. Geol., **83**: 61–78.

PALFY J., DEMENY A., HAAS J., HETENYI M., ORCHARD M. J. and VETO I. (2001) — Carbon isotope anomaly and other geochemical changes at the Triassic–Jurassic boundary from a marine section in Hungary. Geology, **29**: 1047–1050.

PALFY J., MORTENSEN J. K., CARTER E. S., SMITH P. L., FRIEDMAN R. M. and TIPPER H. W. (2000) — Timing the end-Triassic mass extinction: first on land, then in the sea? Geology, **28**: 39–42.

PIEŃKOWSKI G. (1981) — Sedymentologia dolnego liasu północnego obrzeżenia Gór Świętokrzyskich. Unpubl. Ph.D. Thesis. Warsaw Univ.

PIEŃKOWSKI G. (2004) — The epicontinental Lower Jurassic of Poland. Pol. Geol. Inst. Spec. Pap., **12**.

REYMANÓWNA M. (1991) — Two conifers from the Liassic flora of Odrowąż in Poland. In: Palaeovegetational Development in Europe and Regions Relevant to its Palaeofloristic Evolution (ed. J. Kovar-Eder). Proc. Pan-European Palaeobotanical Conf., Vienna: 307–310. Naturhistorisches Museum, Wien.

RUFFELL A., McKINLEY J. M. and WORDEN R. H. (2002) — Comparison of clay mineral stratigraphy to other proxy palaeoclimate indicators in the Mesozoic of NW Europe. Phil. Trans. Royal Soc. London A, **360**: 675–693.

SAEZ A., INGLES M., CABRERA L. and De Las HERAS A. (2003) — Tectonic-palaeoenvironmental forcing of clay mineral assemblages in nonmarine settings: the Oligocene–Miocene as Pontes Basin (Spain). Sediment. Geol., **159** (3–4): 305–324.

SELLWOOD B. W. and VALDES P. J. (2006) — Mesozoic climates: general circulation models and the rock record. Sediment. Geol., **190**: 269–287.

SINGER A. (1984) — The palaeoclimatic interpretation of clay minerals in sediments — a review. Earth Sc. Rev., **21**: 251–293.

THIRY M. (2000) — Palaeoclimatic interpretation of clay minerals in marine deposits: an outlook from the continental origin. Earth Sc. Rev., **49**: 201–221.

WCISŁO-LURANIEC E. (1991) — Flora from Odrowąż in Poland — a typical Lower Liassic European flora. In: Palaeovegetational Development in Europe and Regions Relevant to its Palaeofloristic Evolution (ed. J. Kovar-Eder). Proc. Pan-European Palaeobotanical Conf., Vienna: 331–334. Naturhistorisches Museum, Wien.

WILSON M. J. (1972) — Clay mineral studies on some Carboniferous sediments in Scotland. Sediment. Geol., **8**: 137–150.

ZIAJA J. (1991) — The Lower Liassic microflora from Odrowąż in Poland. In: Palaeovegetational Development in Europe and Regions Relevant to its Palaeofloristic Evolution (ed. J. Kovar-Eder). Proc. Pan-European Palaeobotanical Conf., Vienna: 337–339. Naturhistorisches Museum, Wien.