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Kaolinite peaks in early Toarcian profiles from the Polish Basin – an inferred record of global warming

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In lower Toarcian clay deposits (Ciechocinek Fm., VIII depositional sequence of the Lower Jurassic) from three boreholes from the Polish Basin, illite-dominated sedimentation representing the lower part of studied interval was interrupted by enhanced kaolinite input. Levels of high kaolinite/illite ratio at the VIIIb/VIIIc parasequence boundary suggest strong continental weathering in a humid-subtropical to tropical climate related to the phase of the early Toarcian global warming recorded at the top of the *tenuicostatum* Zone and correlated with isotope curves from a number of European sections. Kaolinite enrichment may be locally enhanced by reworking of pre-Jurassic kaolinitic rocks and differential settling. Diagenetic processes were not sufficient enough to transform the initial kaolinite, but may have altered smectite and mixed-layers into illite and/or chlorite.

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Key words: lower Toarcian, Ciechocinek Fm., Polish Basin, kaolinite content, palaeoclimate, global warming.

INTRODUCTION

The early Toarcian (Early Jurassic, ~183 Ma ago) was a critical time in Earth history, characterized by pronounced negative carbon isotope excursion (CIE) recorded in marine organic matter, marine carbonate and terrestrial wood (e.g., Hesselbo *et al*., 2000, 2007; Schouten *et al*., 2000; Röhl *et al*., 2001; Jenkyns *et al*., 2002; Kemp *et al*., 2005; Hermoso *et al*., 2009) as well as perturbations to other isotopic systems. The disruptions were associated with an oceanic anoxic event – the Toarcian OAE (Jenkyns, 1988), a pronounced transgression (Hallam, 1997, 2001), carbon production crises (e.g., Mattioli *et al*., 2004, 2009; Tremolada *et al*., 2005), an increase in atmospheric CO_2 content, global greenhouse warming (Bailey *et al*., 2003; Cohen *et al*., 2004; McElwain *et al*., 2005; Hesselbo *et al*., 2007), and a second-order global mass extinction (e.g., Little and Benton, 1995; Pálfy and Smith, 2000; Wignall *et al*., 2005). Brief but extreme climatic events spanning mainly the *tenuicostatum-falciferum* biochronozonal transition were related to massive injections of isotopically light carbon most probably from oceanic methane hydrate and/or intense volcanic degassing in the Karoo-Ferrar large igneous province of southern Gondwana (Hesselbo *et al*., 2000, 2007; Pálfy and Smith, 2000; Kemp *et al*., 2005; Suan *et al*., 2008). Some authors point to thermal metamorphism of organic-rich deposits (McElwain *et al*., 2005; Svensen *et al*., 2007), changes in palaeoceanography (Bailey *et al*., 2003; van de Schootbrugge *et al*., 2005; Wignall *et al*., 2005) or extensive biomass burning (Finkelstein *et al*., 2006) as a main reason. The substantial increase in global temperature (McArthur *et al*., 2000; Bailey *et al*., 2003; Rosales *et al*., 2004; Suan *et al*., 2008) and abundant rainfall caused a substantial increase in continental weathering and in sediment supply (Bailey *et al*., 2003; Cohen *et al*., 2004, 2007; Hesselbo *et al*., 2007).

Marine clays represent a final product of the continental weathering process and may reveal global climatic fluctuations. Clay mineralogy has been successfully used in palaeoclimate interpretations especially of Mesozoic rocks (e.g., Singer, 1984; Chamley, 1989; Ruffell *et al*., 2002; Ahlberg *et al*., 2003; Deconinck *et al*., 2003; Schnyder *et al*., 2006; Raucsik and Varga, 2008; Godet *et al*., 2008; Dera *et al*., 2009; Hesselbo *et al*., 2009). Recently, the present author used clay minerals in Hettangian palaeoclimate interpretation (Brański, 2009). The present paper comprises the results of clay mineralogical research into lower Toarcian successions in two boreholes (Brody-Lubienia BL-1 and Suliszowice 38 BN; Fig. 1) from the southern marginal part of the Polish Basin and additionally of the Mechowo IG 1 borehole in its central part (Pomerania region).

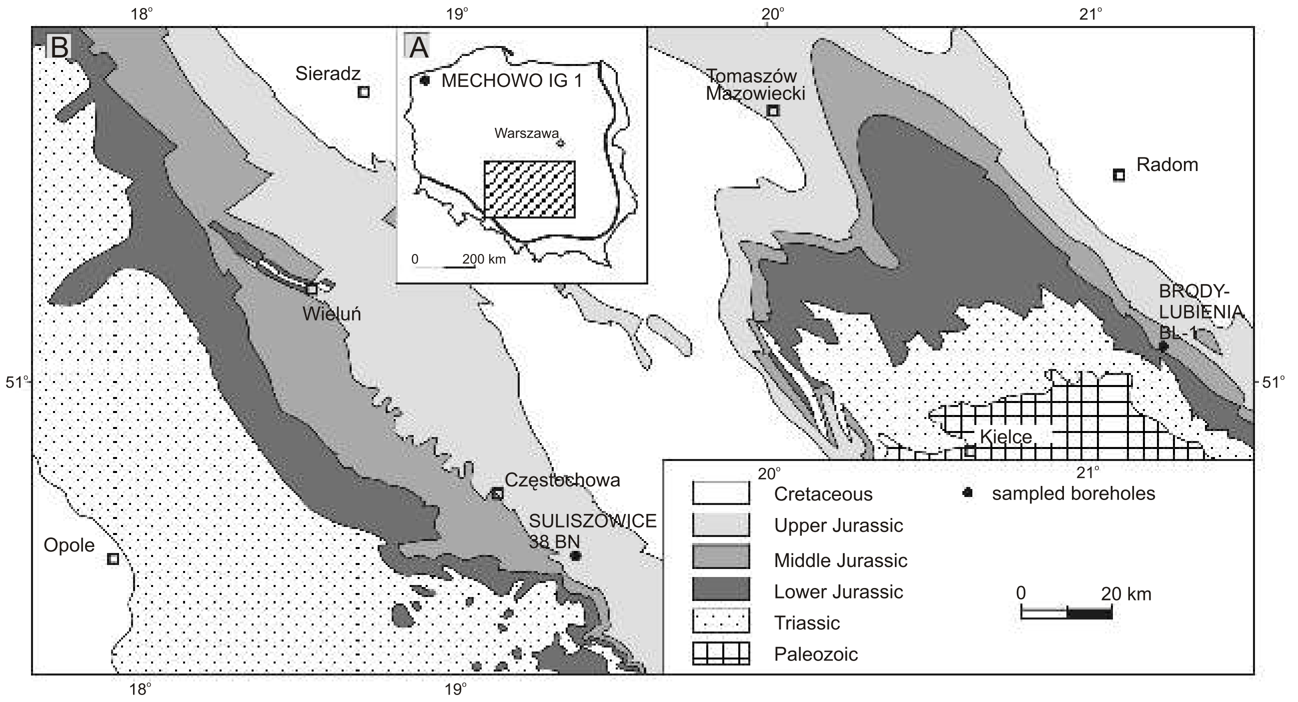


Fig. 1. Location of boreholes examined

A – area shown on Figure 1B and the extent of the Toarcian basin in Poland (after Pieńkowski, 2004); **B** – geological sketch map of Southern Poland without Cenozoic deposits (after Dadlez *et al*., 2000, simplified)

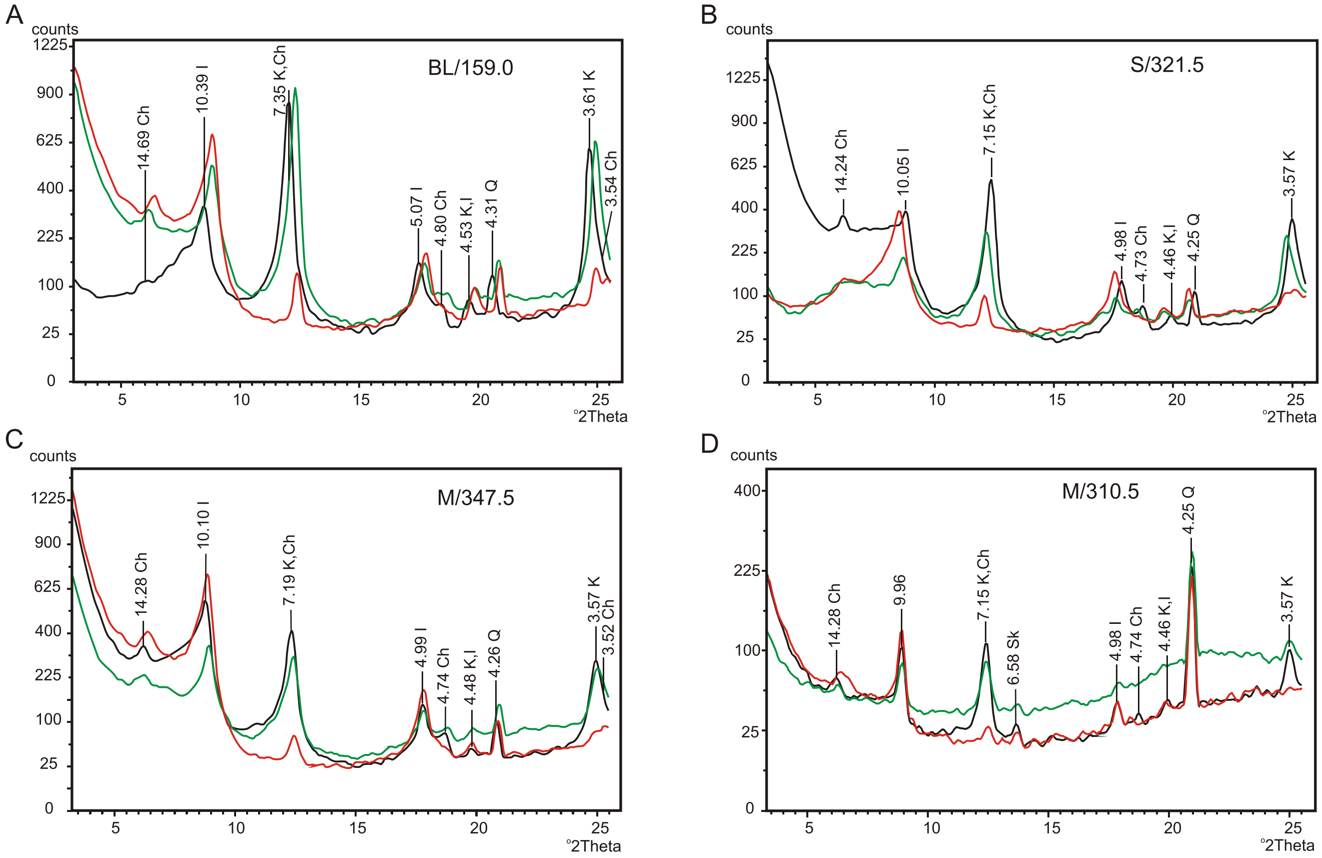


Fig. 2. Selected X-ray diagrams of lower Toarcian samples (<0.002 mm fraction) (carried out by W. Narkiewicz)

A – kaolinite-dominated claystone with very subordinate illite and only trace amount of chlorite (Brody-Lubienia borehole, depth 159.0 m); **B** – kaolinite-dominated claystone with subordinate illite and chlorite (Suliszowice borehole, depth 321.5 m); **C** – kaolinite-dominated claystone with subordinate illite and chlorite (Mechowo borehole, depth 347.5 m); **D** – illite-dominated mudstone with minor amount of kaolinite and very subordinate chlorite (Mechowo borehole, depth 310.5 m); black line – air-dried sample, green line – glycolated sample, red line – heated sample (550°C)

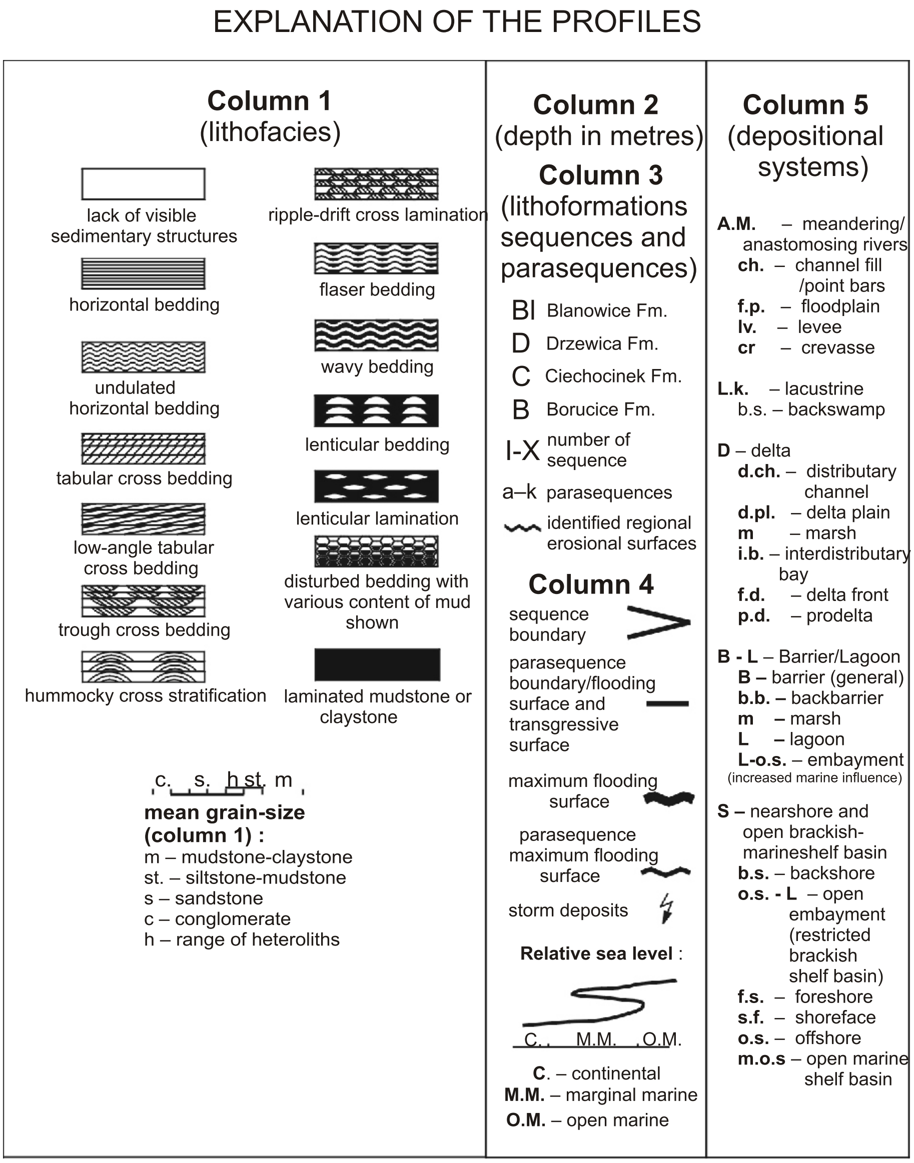


Fig. 3. Explanations for the sedimentological profiles on Figures 4, 5 and 6 (after Pieńkowski, 2004, modified)

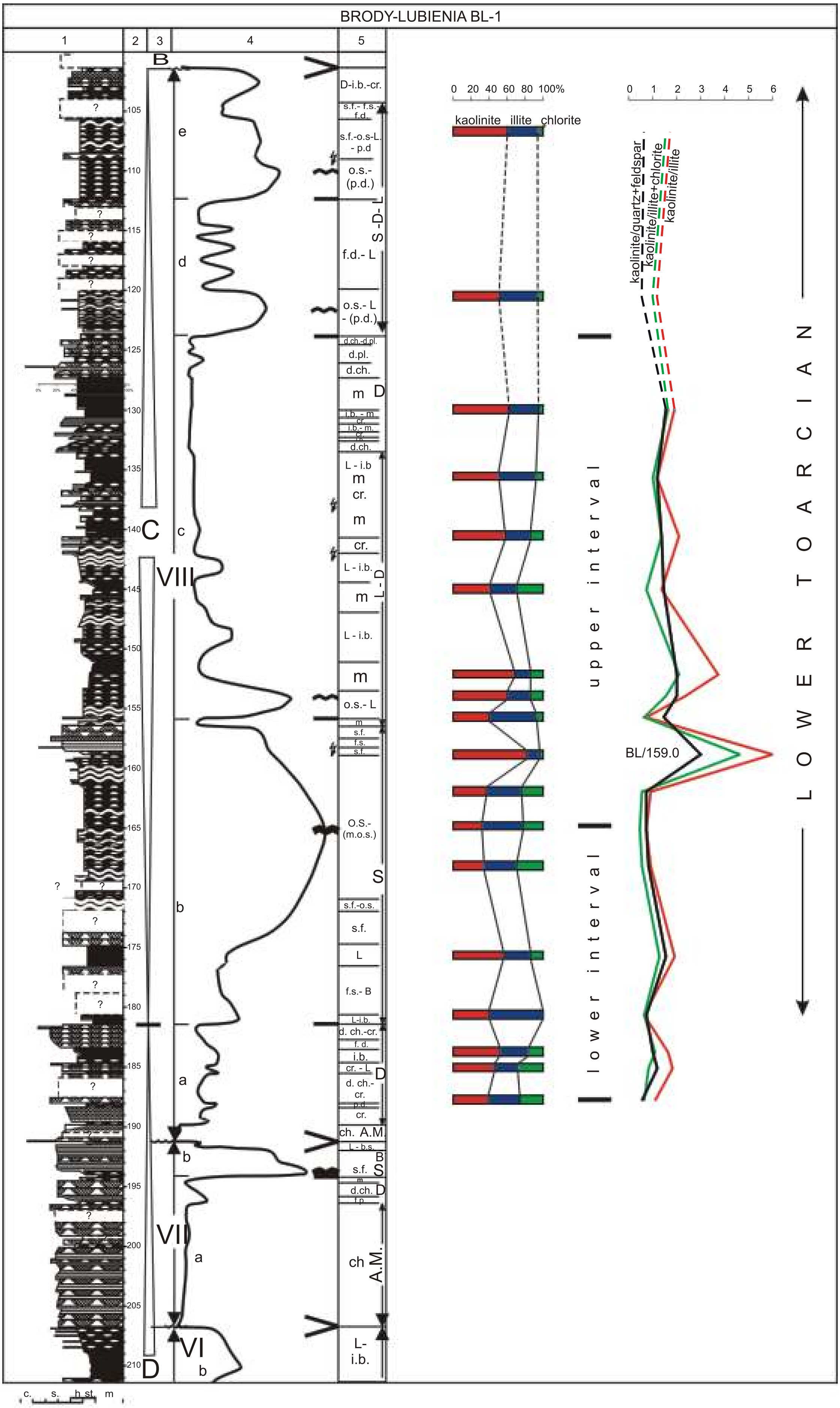
MATERIAL AND METHODS

In the present study 64 samples from clay-rich lower Toarcian beds were examined using X-ray diffraction (*Phillips PW* diffractometer with CuKa radiation) in the laboratory of the Polish Geological Institute – National Research Institute. The analyses ran on untreated, glycolated and heated samples of the <2 μm fraction (Fig. 2). Clay mineral identification was made according to the procedure of Moore and Reynolds (1997). Afterwards, the present author calculated the indices: kaolinite/illite (K/I), kaolinite/illite+chlorite (K/I+Ch) and kaolinite/quartz+feldspar (K/Q+F). SEM analyses were also performed.

RESULTS

According to Pieńkowski (2004), greenish-grey mudstones, claystones and heterolithic deposits of the Ciechocinek Fm. (lower Toarcian – VIII depositional sequence) were developed in a large, shallow, brackish-marine embayment and in lagoons (see for details Figs. 3–6).

Previous mineralogical analyses lower Toarcian claystone and mudstones performed on bulk rock samples only from Southern Poland showed a distinct predominance illite over kaolinite (Kozydra, 1968; Maliszewska, 1968; Leonowicz, 2005). They were briefly summarized by the present author (Brański, 2007).


BRODY-LUBIENIA BL-1
1
2
3
4
5
B
C
D
VIII
VII
VI
a
b
c
d
e
D-i.b.-cr.
s.f.- f.s.
f.d.
s.f.-o.s-L.
- p.d
o.s.-
(p.d.)
S -D- L
f.d.- L
o.s.- L
- (p.d.)
d.ch.-d.pl.
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m D
L - i.b
m
cr.
L - i.b.
L - D
o.s.- L
O.S.-
(m.o.s.)
S
s.f.-o.s.
s.f.
L
f.s.- B
L-i.b.
d. ch.-cr.
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cr. - L
d. ch.-
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195
200
205
210
?
0 20 40 60 80 100%
kaolinite illite chlorite
0 1 2 3 4 5 6
kaolinite/quartz+feldspar
kaolinite/illite+chlorite
kaolinite/illite
BL/159.0
upper interval
lower interval
LOWER TOARCIAN
c. s. h st. m

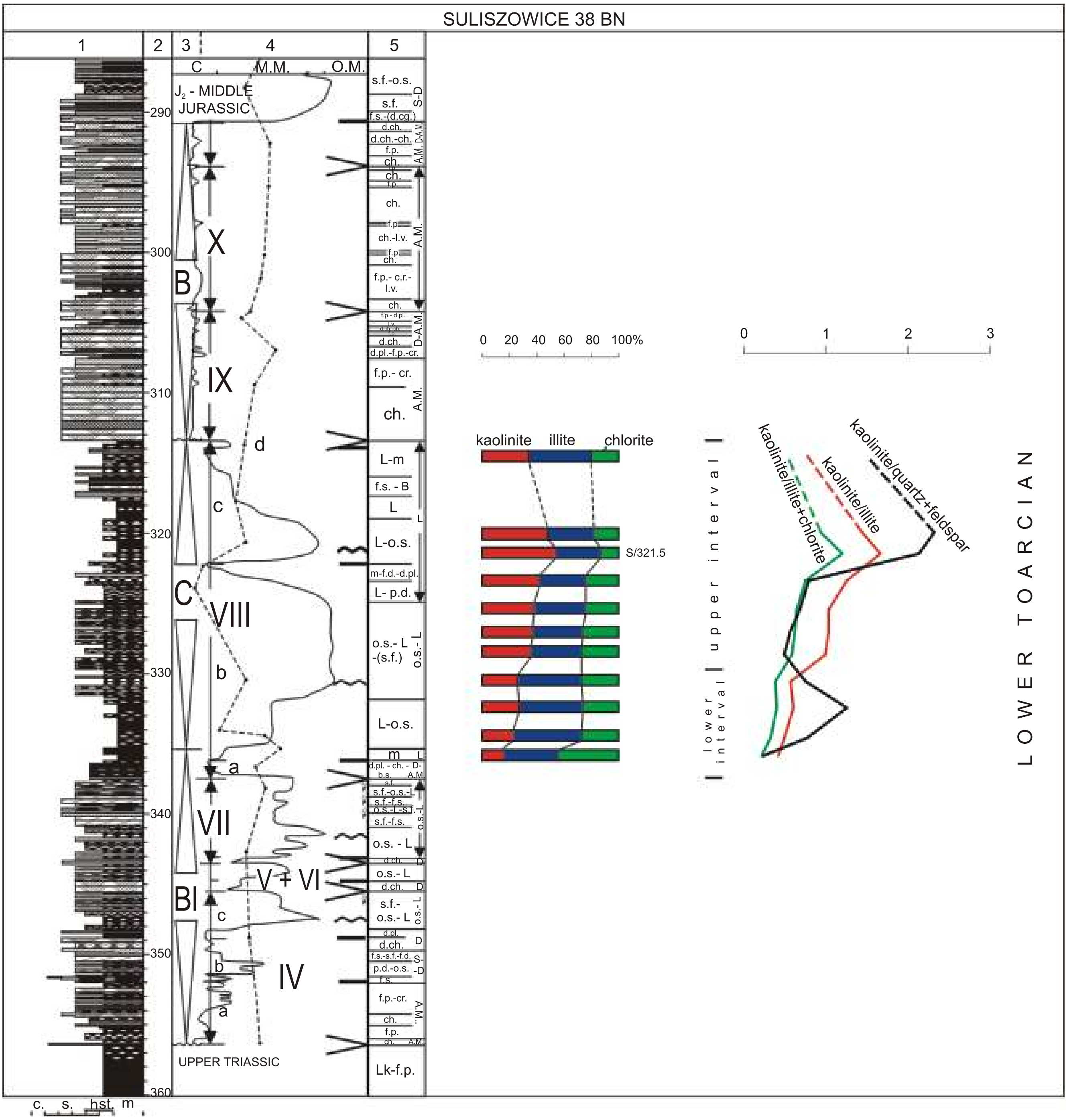


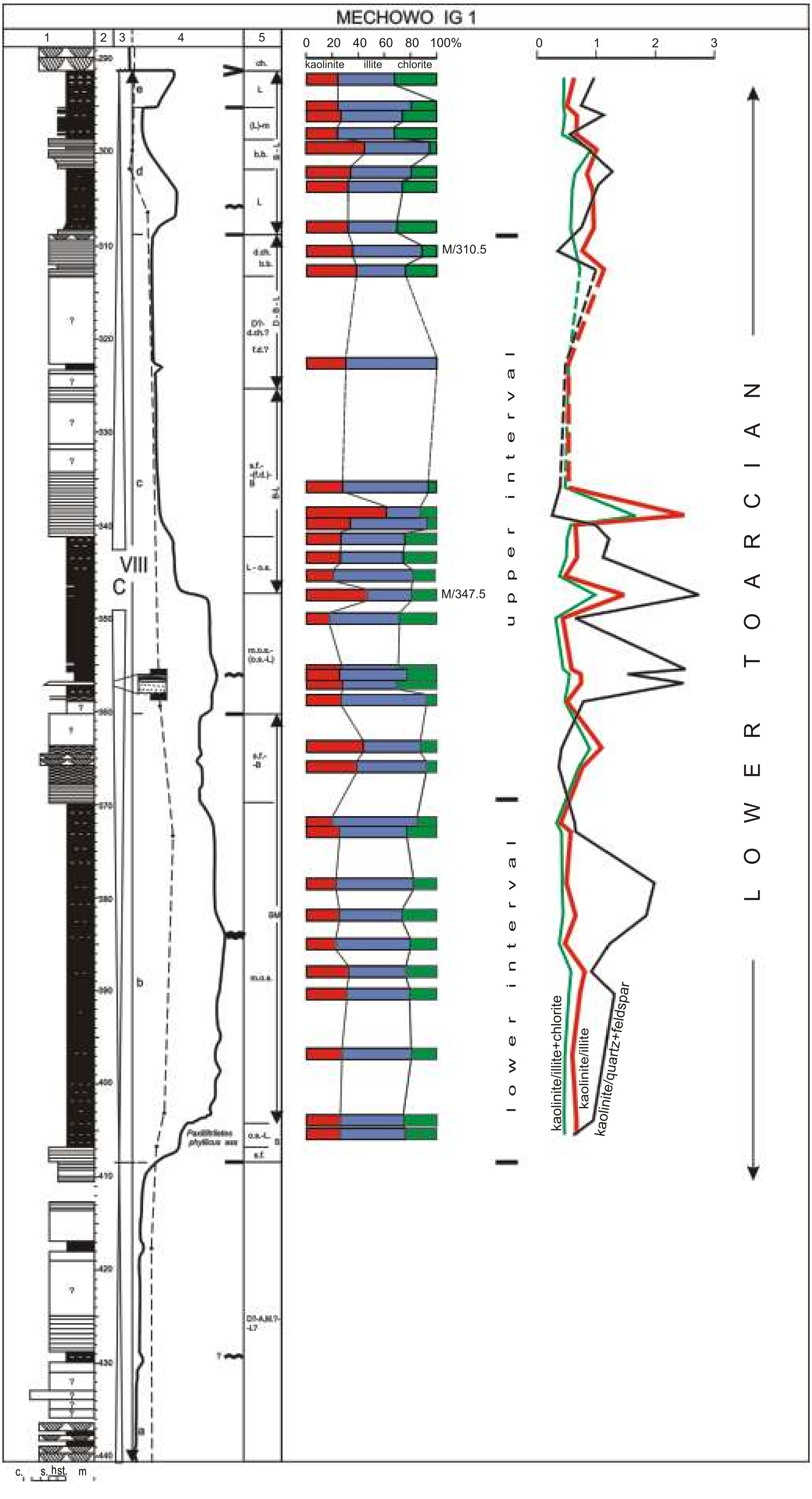
Fig. 5. Lower Toarcian clay mineral composition and mineralogical indices from the Suliszowice borehole (with detailed sedimentological profile after Pieñkowski, 2004)

Note the gradual increase in kaolinite content but well expressed kaolinite maximum above the VIIIb–VIIIc parasequence boundary; for explanations see Figure 3

←

Fig. 4. Lower Toarcian clay mineral composition and mineralogical indices from the Brody-Lubienia borehole (with detailed sedimentological profile after Pieñkowski, 2004)

Note a kaolinite spike at 159.0 m suggesting extreme continental weathering in a humid-subtropical to tropical climate (most probably related to the onset of the main phase of early Toarcian global warming); for explanations see Figure 3


MECHOWO IG 1
1
2
3
4
5
290
300
310
320
330
340
350
360
370
380
390
400
410
420
430
440
e
d
c
b
a
VIII
C
ch.
L
(L)-m
b.b.
L
d.dh.
b.s.
D?-d.dh.?
f.d.?
s.f.-(f.d.)-B
L - o.s.
m.o.s.-(o.s.-L)
s.f.-B
m.o.s.
o.s.-L
s.f.
D?-A,M.?-L?
Paxillitriletes phyllicus acs
0 20 40 60 80 100%
kaolinite illite chlorite
M/310.5
M/347.5
0 1 2 3
upper interval
lower interval
kaolinite/illite+chlorite
kaolinite/illite
kaolinite/quartz+feldspar
LOWER TOARCIAN
c. s. hst. m

The clay fraction of recently examined samples comprises kaolinite (16–82%), illite (14–70%) and chlorite (0–44%). Smectite was almost never observed. The section corresponding to the VIIIb and VIIIc parasequences was especially examined (Figs. 3–6). The age of parasequence VIIIb represents the *tenuicostatum* Zone, and parasequence VIIIc is roughly comprised of *falciferum* Zone deposits (Pieńkowski, 2004). It should be noticed that a difference in clay mineral distribution occurs between the lower interval of the sections (approximately from the sequence boundary located at the Pliensbachian/Toarcian boundary to the maximum flooding surface) and the upper interval (up to the VIIIc/VIIId parasequence boundary; Figs. 4–7; Table 1). In the lower interval the average kaolinite amounts are minor (~23% in Suliszowice and ~ 26% in Mechowo to ~43% in Brody-Lubienia) while those of illite are major (between 38 and 53%). In the upper interval kaolinite becomes dominant (on average 33% in Mechowo and 41% in Suliszowice to ~56% in Brody-Lubienia) by comparison with illite (50 and 37%, and 31%, respectively). The content of chlorite is considerable and ranges from 13–19% (in Brody-Lubienia) and 17–21 (in Mechowo) to 22–31% (in Suliszowice).

At the base of the upper interval in Brody-Lubienia profile there is a surge of kaolinite (up to 82%) offset by a significant depletion of illite (~14%) and chlorite (~4%; Fig. 2A). The kaolinite spike at 159.0 m is very well marked in the curves of the kaolinite/illite and kaolinite/illite+chlorite ratios (Fig. 4). The abundance of fine-grained degraded kaolinite is shown also via SEM observations (Fig. 8A and B). In the Suliszowice section, the kaolinite content increases more gradually from the base of Ciechocinek Fm. to the lower part of the parasequence VIIIc (Fig. 5). The kaolinite maximum, though, (Fig. 2B) is well expressed in the curves of the all mineralogical indices. In Mechowo borehole a few cyclic variations at the 10–20 m scale in kaolinite/illite ratios are observed, but the most distinct increase in kaolinite content is seen in the lower part of the parasequence VIIIc (Figs. 2C and 6). It is noteworthy that, in all sections, the interval with the highest kaolinite content is represented mostly by open embayment deposits punctuated by prograding nearshore sediments (Pieńkowski, 2004).

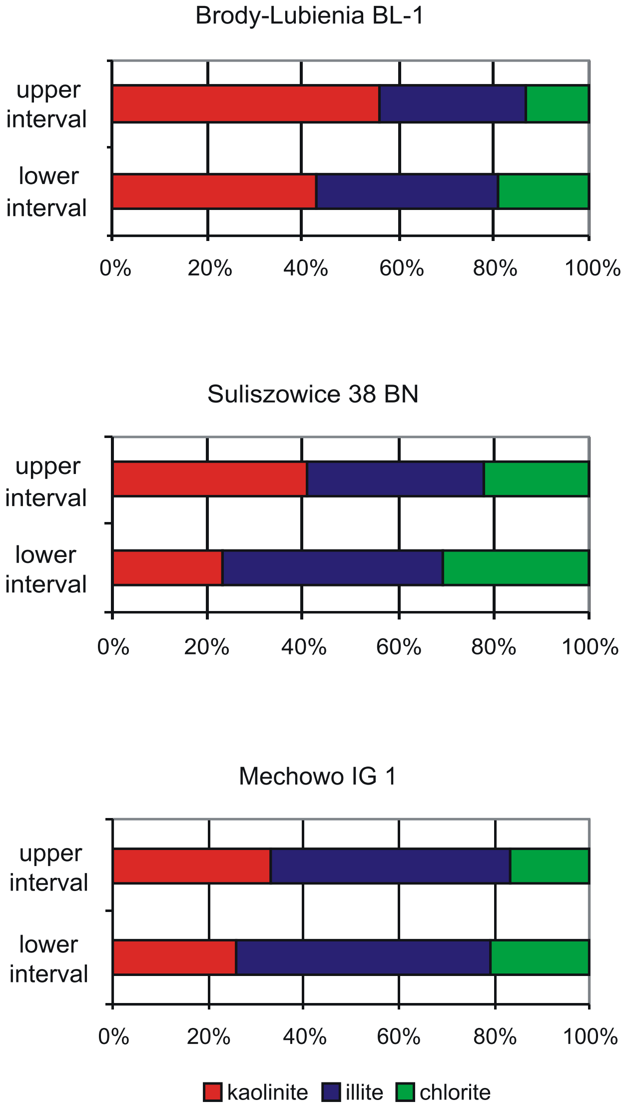


Fig. 7. Average clay mineral compositions in the early Toarcian claystones and mudstones from lower and upper intervals in the boreholes studied

Note the enhanced kaolinite enrichment in the Brody-Lubienia borehole and the predominance of kaolinite in the upper interval of all studied sections; for "lower" and "upper" intervals see Figures 4–6 and explanations in text

INTERPRETATION AND DISCUSSION

The author focuses on kaolinite content because of its strong climatic dependence and significant resistance under moderate diagenetic conditions. Kaolinite typically dominates in mature soils that develop as a result of intense chemical weathering in a tropical or humid-subtropical climate. The detrital clay mineral suites in the Toarcian mudstone and shale samples show a weak diagenetic overprint due to low (Suliszowice) or moderate (Brody-Lubienia, Mechowo) burial and to closed diagenetic systems (Brański, 2008). The burial diagenesis was never strong enough to transform the initial kaolinite into illite and/or chlorite, but part of the illite and chlorite may have come from transformation of smectite (*cf.* Dera *et al.*, 2009).

In the most cases isotope and micropalaeontological data from the *tenuicostatum* Zone suggest moderate climate control (e.g., Suan *et al.*, 2008; Mattioli *et al.*, 2008), although there is a distinct negative C-isotope excursion correlated with a positive O-isotope excursion, that record a short-lived warming just at the Pliensbachian–Toarcian boundary (Hesselbo *et al.*, 2007;

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Fig. 6. Lower Toarcian clay mineral composition and mineralogical indices from the Mechowo borehole (with detailed sedimentological profile after Pieńkowski, 2004)

Note a few kaolinite pulses in the upper interval of the lower Toarcian; for explanations see Figure 3

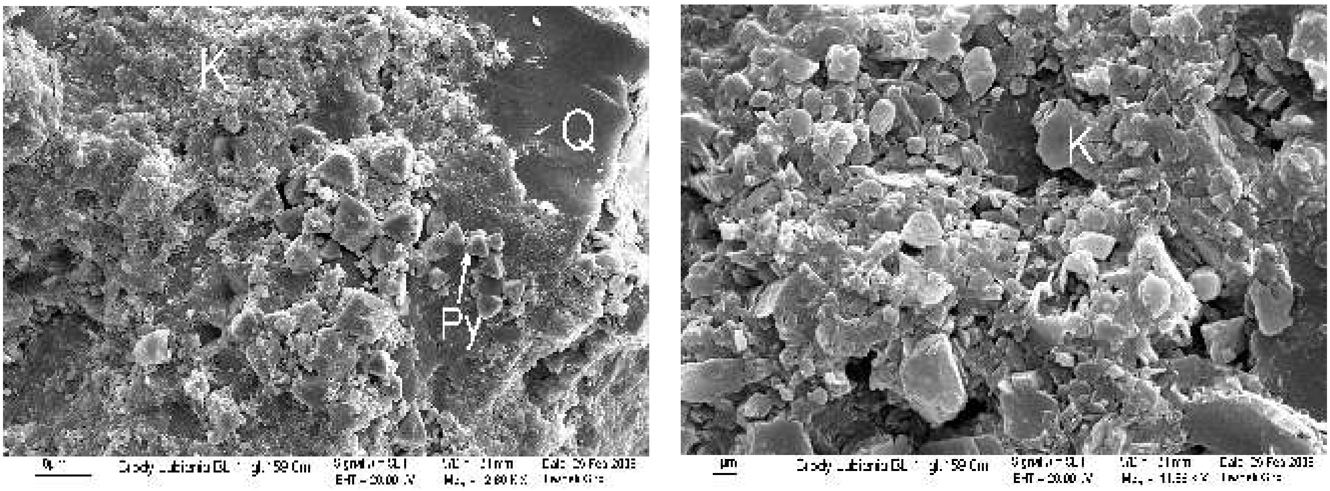

Fig. 8. SEM images of kaolinite clay specimen from the Brody-Lubienia BL-1 borehole, depth 159.0 m (taken by L. Giro)

Note very fine (0.2–2.0 µm) degraded kaolinite plates and crystals of pyrite; K – kaolinite, Q – quartz, Py – pyrite

Suan *et al.*, 2008). The moderate climate coincides with the higher illite and chlorite content in the lower interval studied due to prevention from extended hydrolysis. In the upper part of the lower Toarcian interval kaolinite becomes the dominant clay mineral, suggesting mostly warm and humid climate conditions (Figs. 4–7; Table 1).

In the Brody-Lubienia borehole initially illite-rich sedimentation was interrupted by a sudden amplified kaolinite input at the top of the VIIIb parasequence (Figs. 2A, 4 and 8). A more gradual mineralogical change was also recorded in Suliszowice borehole (Fig. 5). In the Mechowo borehole the kaolinite increase is oscillatory (Fig. 6). In this part of the Ciechocinek Fm. one may observe deposits representing a conspicuous shallowing event marked in the whole basin (Figs. 4–6), that was connected with a decrease in the basin depth as a result of enhanced continental weathering and sediment supply (Pieńkowski, 2004; Cohen *et al.*, 2004; Pieńkowski and Schudack, 2008). It is compatible with the idea (Hesselbo *et al.*, 2007), that the shallowing event at the *tenuicostatum-falciferum* biochronozonal transition may be linked with early Toarcian global greenhouse warming, but may misleadingly simulate the effects of sea level fall. The new data presented in this paper are also consistent with the results of most recent clay mineral studies on Toarcian deposits from other parts of Europe (*cf.* Raucsik and Varga, 2008; Dera *et al.*, 2009). Levels of the high (up to 6.0!) kaolinite/illite ratio at the VIIIb/VIIIc parasequence boundary interval (Fig. 4) suggest extreme continental weathering in a humid-subtropical to tropical climate related to the onset of the main phase of global warming that was recorded in Europe on many isotope curves at the top of the *tenuicostatum* Zone. In the more densely sampled Mechowo borehole we may suspect the effects of brief palaeoclimatic fluctuations (Fig. 6) that most probably correspond to Milankovitch cycles. The evolution of kaolinite content in the deposits may correspond to these short-term climate variations because the formation of kaolinite on continents and its deposition in marine sediments seems to have been almost contemporaneous during the Early Jurassic (Dera *et al.*, 2009). Kaolinite enrichment may be locally enhanced by erosion and reworking of pre-Jurassic kaolinitic rocks and proximal deposi-

Table 1

Average clay mineral composition and mineralogical indices in the early Toarcian claystones and mudstones from studied boreholes

Profile		Composition and indices					
		K [%]	I [%]	Ch [%]	K/I	K/I+Ch	K/Q+F
Brody-Lubienia BL-1	upper interval	56	31	13	2.25	1.58	1.65
	lower interval	43	38	19	1.24	0.79	0.86
Suliszowice 38 BN	upper interval	41	37	22	1.14	0.73	1.19
	lower interval	23	46	31	0.49	0.30	0.73
Mechowo IG 1	upper interval	33	50	17	0.74	0.54	1.03
	lower interval	26	53	21	0.51	0.36	1.03

K – kaolinite, I – illite, Ch – chlorite, Q – quartz, F – feldspar; for “lower” and “upper” intervals see Figures 4–6 and explanations in text tion of kaolinite due to differential settling in shallow marine environments surrounded by continents. Some decrease of kaolinite relative to the illite content above the kaolinitic interval discussed may reflect an interruption in the weathering cycle or a change in the source of clay minerals as a result of erosion. Alternatively it may reflect hot but less humid climatic conditions that may have slowed chemical weathering.

CONCLUSIONS

Distinct changes in the clay mineral contents in the Brody-Lubienia, Suliszowice and Mechowo boreholes reflect marked climatic change during the early Toarcian. Other factors (provenance, differential settling and diagenetic transformation of smectites) may, though, cloud the palaeoclimate signal. However, an increase in kaolinite content is inferred to be a direct result of amplified chemical weathering even though part of kaolinite was derived from older sedimentary rocks. Kaolinite abundance at the VIIIb/VIIIc parasequence boundary reflects an increase in temperature and especially in year-round rainfall related to the onset of the early Toarcian global warming that was recorded at the top of the *tenuicostatum* Zone on isotope curves in other European sections. The kaolinite pulses in the upper interval of the lower Toarcian (Mechowo borehole) were possibly controlled by astronomically forced changes in climate, superimposed upon longer-term global warming.

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REFERENCES

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

BAILEY T. R., ROSENTHAL Y., McARTHUR J. M., van de SCHOOTBRUGGE B. and THIRLWALL M. F. (2003) – Paleoceanographic changes of the Late Pliensbachian–Early Toarcian interval: a possible link to the genesis of an Oceanic Anoxic Event. Earth Planet. Sc. Lett., **212**: 307–320.

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

BRAŃSKI P. (2008) – Górnotriasowe i dolnojurajskie iły kaolinitowe – studium genezy i kierunki poszukiwań, etap II (unpubl. manuscript). Centr. Arch. Geol. Państw. Inst. Geol. Warszawa.

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

CHAMLEY H. (1989) – Clay Sedimentology. Springer Verlag, Berlin.

COHEN A. S., COE A. L., HARDING S. M. and SCHWARK L. (2004) – Osmium isotope evidence for the regulation of atmospheric CO_2 by continental weathering. Geology, **32**: 157–160.

COHEN A. S., COE A. L. and KEMP D. B. (2007) – The late Paleocene–early Eocene and Toarcian (Early Jurassic) carbon-isotope excursions: a comparison of their timescales and associated environmental changes, causes and consequences. J. Geol. Soc., London, **164**: 1093–1108.

DADLEZ R., MAREK S. and POKORSKI J., eds. (2000) – Mapa geologiczna Polski bez utworów kenozoiku. Państw. Inst. Geol., Warszawa.

DECONINCK J.-F., HESSELBO S. P., DEBUISSER N., AVERBUCH O., BAUDIN F. and BESSA J. (2003) – Environmental controls on clay mineralogy of an Early Jurassic mudrock (Blue Lias Formation, southern England). Internat. J. Earth Sc., **92**: 255–266.

DERA G., PELLENARD P., NEIGE P., DECONINCK J.-F., PUCEAT E. and DOMMERGUES J.-L. (2009) – Distribution of clay minerals in Early Jurassic Peritethyan seas: palaeoclimatic significance inferred from multiproxy comparisons. Palaeogeogr. Palaeoclimat. Palaeoecol., **271**: 39–51.

FINKELSTEIN D. B., PRATT L. M. and BRASSELL S. C. (2006) – Can biomass burning produce a globally significant carbon-isotope excursion in the sedimentary record? Earth Planet. Sc. Lett., **250**: 501–510.

GODET A., BODIN S., ADATTE T. and FÖLLMI K. B. (2008) – Platform-induced clay-mineral fractionation along a northern Tethyan basin-platform transect: implications for the interpretation of Early Cretaceous climate change (Late Hauterivian–Early Aptian). Cretaceous Res., **29**: 830–847.

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.

HALLAM A. (2001) – A review of the broad pattern of Jurassic sea-level changes and their possible causes in the light of current knowledge. Palaeogeogr. Palaeoclimat. Palaeoecol., **167**: 23–37.

HERMOSO M., LE CALLONEC L., MINOLETTI F., RENARD M. and HESSELBO S. P. (2009) – Expression of the Early Toarcian negative carbon-isotope excursion in separated carbonate microfractions (Jurassic, Paris Basin). Earth Planet. Sc. Lett., **277**: 194–203.

HESSELBO S. P., DECONINCK J.-F., HUGGETT J. M. and MORGANS-BELL H. S. (2009) – Late Jurassic palaeoclimatic change from clay mineralogy and gamma-ray spectrometry of the Kimmeridge Clay, Dorset, UK. J. Geol. Soc., London, **166**: 1123–1133.

HESSELBO S. P., GRÖCKE D. R., JENKYNS H. C., BJERRUM C. J., FARRIMOND P., BELL H. S. M. and GREEN O. R. (2000) – Massive dissociation of gas hydrate during a Jurassic oceanic anoxic event. Nature, **406**: 392–395.

HESSELBO S. P., JENKYNS H. C., DUARTE L.V. and OLIVEIRA L. C. V. (2007) – Carbon-isotope record of the Early Jurassic (Toarcian) Oceanic Anoxic Event from fossil wood and marine carbonate (Lusitanian Basin, Portugal). Earth Planet. Sc. Lett., **253**: 455–470.

JENKYNS H. C. (1988) – The Early Toarcian (Jurassic) Anoxic Event: stratigraphic, sedimentary and geochemical evidence. Am. J. Sc., **288**: 101–151.

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.

KEMP D. B., COE A. L., COHEN A. S. and SCHWARK L. (2005) – Astronomical pacing of methane release in the Early Jurassic period. Nature, **437**: 396–399.

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

LEONOWICZ P. (2005) – The Ciechocinek Formation (Lower Jurassic) of SW Poland: petrology of green clastic rocks. Geol. Quart., **49** (3): 317–330.

LITTLE C. T. S. and BENTON M. J. (1995) – Early Jurassic mass extinction: a global long-term event. Geology, **23**: 495–498.

(TEOFILAK-) 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.

MATTIOLI E., PITTET B., BUCEFALO PALLIANI L., RÖHL H. J., SCHMID-RÖHL A. and MORETTINI E. (2004) – Phytoplankton evidence for the timing and correlation of palaeoceanographical changes during the early Toarcian oceanic anoxic event (Early Jurassic). J. Geol. Soc. London, **161**: 685–693.

MATTIOLI E., PITTET B., PETITPIERRE L. and MAILLIOT S. (2009) – Dramatic decrease of pelagic carbonate production by nannoplankton across the Early Toarcian anoxic event (T-OAE). Glob. Planet. Change, **65**: 134–145.

MATTIOLI E., PITTET B., SUAN G. and MAILLIOT S. (2008) – Calcareous nannoplankton changes across the early Toarcian oceanic anoxic event in the western Tethys. Paleoceanography, **23**, PA3208, doi: 10.1029/2007PA001435

McARTHUR J. M., DONOVAN D. T., THIRLWALL M. F., FOUKE B. W. and MATTEY D. (2000) – Strontium isotope profile of the early Toarcian (Jurassic) oceanic anoxic event, the duration of ammonite biozones, and belemnite palaeotemperatures. Earth Planet. Sc. Lett., **179**: 269–285.

McELWAIN J. C., WADE-MURPHY J. and HESSELBO S. P. (2005) – Changes in carbon dioxide during an oceanic anoxic event linked to intrusion into Gondwana coals. Nature, **435**: 479–482.

MOORE D. M. and REYNOLDS R. C. (1997) – X-ray diffraction and the identification and analysis of clay minerals. Oxford University Press, New York.

PÁLFY J. and SMITH P. L. (2000) – Synchrony between Early Jurassic extinction, oceanic anoxic events, and the Karoo–Ferrar flood basalt volcanism. Geology, **28**: 747–750.

PIEŃKOWSKI G. (2004) – The epicontinental Lower Jurassic of Poland. Pol. Geol. Inst. Spec. Pap., **12**: 1–154.

PIEŃKOWSKI G. and SCHUDACK M. E. (co-ordinators) (2008) – Jurassic. In: The Geology of Central Europe, **2**: Mesozoic and Cenozoic (ed. T. McCann): 823–922. Geol. Soc., London.

RAUCSIK B. and VARGA A. (2008) – Climato-environmental controls on clay mineralogy of the Hettangian-Bajocian successions of the Mecsek Mountains, Hungary: an evidence for extreme continental weathering during the early Toarcian oceanic anoxic event. Palaeogeogr. Palaeoclimat. Palaeoecol., **265**: 1–13.

RÖHL H. J., SCHMID-RÖHL A., OSCHMANN W., FRIMMEL A. and SCHWARK L. (2001) – The Posidonia Shale (Lower Toarcian) of SW-Germany: an oxygen-depleted ecosystem controlled by sea level and palaeoclimate. Palaeogeogr. Palaeoclimat. Palaeoecol., **165**: 27–52.

ROSALES I., QUESADA S. and ROBLES S. (2004) – Paleotemperature variations of Early Jurassic seawater recorded in geochemical trends of belemnites from the Basque-Cantabrian basin, northern Spain. Palaeogeogr. Palaeoclimat. Palaeoecol., **203**: 253–275.

RUFFELL A., Mc KINLEY 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. R. Soc. Lond. A, **360**: 675–693.

SCHNYDER J., RUFFELL A., DECONINCK J.-F. and BAUDIN F. (2006) – Conjunctive use of spectral gamma-ray logs and clay mineralogy in defining late Jurassic–early Cretaceous palaeoclimate change (Dorset, U.K.). Palaeogeogr. Palaeoclimat. Palaeoecol., **229**: 303–320.

SCHOUTEN S., KAAM-PETERS M. E., RIJPSTRA I., SCHOELL M. and SINNIGHE DAMSTE J. S. (2000) – Effects of an oceanic anoxic event on the stable carbon isotopic composition of early Toarcian carbon. Am. J. Sc., **300**: 1 –22.

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

SUAN G., MATTIOLI E., PITTET B., MAILLIOT S. and LÉCUYER C. (2008) – Evidence for major environmental perturbation prior to and during the Toarcian (Early Jurassic) oceanic anoxic event from the Lusitanian Basin, Portugal. Paleooceanography, **23**, PA1202, doi: 10.1029/2007PA001459

SVENSEN H., PLANKE S., CHEVALLIER L., MALTHE-SØRENSEN A., CORFU F. and JAMTVEIT B. (2007) – Hydrotermal venting of greenhouse gases triggering Early Jurassic global warming. Earth Planet. Sc. Lett., **256**: 554–566.

TREMOLADA F., van de SCHOOTBRUGGE B. and ERBA E. (2005) – Early Jurassic schizosphaerellid crisis in Cantabria, Spain: implications for calcification rates and phytoplankton evolution across the Toarcian oceanic anoxic event. Paleooceanography, **20**, PA2011, doi: 10.1029/2004PA001120

Van de SCHOOTBRUGGE B., McARTHUR J. M., BAILEY T. R., ROSENTHAL Y., WRIGHT J. D. and MILLER K. G. (2005) – Toarcian oceanic anoxic event: an assessment of global causes using belemnite C isotope records. Paleooceanography, **20**, PA3008, doi: 10.1029/2004PA001102

WIGNALL P. B., NEWTON R. J. and LITTLE C. T. S. (2005) – The timing of paleoenvironmental change and cause-and-effect relationships during the Early Jurassic mass extinction in Europe. Am. J. Sc., **305**: 1014–1032.