Geological Quarterly, 2005, **49** (3): 317–330

The Ciechocinek Formation (Lower Jurassic) of SW Poland: petrology of green clastic rocks

Paulina LEONOWICZ

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

The Lower Jurassic Ciechocinek Formation from the Częstochowa-Wieluń region of SW Poland comprises greenish-grey muds and silts as well as poorly consolidated mudstones and siltstones with lenticular intercalations of fine-grained sands, sandstones and siderites. Analysis of a mineral composition indicates that the detrital material was derived mainly from the weathering of metamorphic and sedimentary rocks of the eastern Sudetes with their foreland and of the Upper Silesia area, and that this material underwent repeated redeposition. The Fe-rich chlorites which give the green colour to the mudstones of the Ciechocinek Formation are most probably early diagenetic minerals, genetically linked with the deposition in a brackish sedimentary basin.

Paulina Leonowicz, Institute of Geology, University of Warsaw, Żwirki i Wigury 93, PL-02-089 Warszawa, Poland, e-mail: Paulina.Leonowicz@uw.edu.pl (received: June 8, 2004; accepted: March 3, 2005).

Key words: Lower Jurassic, Cracow-Silesian Upland, provenance, petrology, sandstones, mudstones.

INTRODUCTION

The Ciechocinek Formation (Pieńkowski, 2004), earlier known as the Lower Łysiec, Gryfice, Ciechocinek or Estheria beds, represents a very characteristic mud-silt succession in the Lower Jurassic epicontinental succession of Poland (Fig. 1). Despite changes in thickness and some facies variability it forms a relatively constant unit, which can be traced and correlated over the entire Polish Lowlands due to its characteristic green colour. For this reason the Ciechocinek Formation is used as a reference horizon in correlations of the upper part of the Lower Jurassic succession of Poland.

The most important studies of the petrology of the Lower Jurassic deposits of Poland were by Teofilak-Maliszewska (Teofilak, 1966; Teofilak-Maliszewska, 1967, 1968; Maliszewska, 1997). These studies were based on deep boreholes from the Polish Lowlands and from the northern Mesozoic Margin of the Holy Cross Mts. The results suggest that the Ciechocinek Formation has a similar mineral composition across Poland; however, analysis of heavy minerals distinguished different source areas supplying material to the Polish Basin (Teofilak, 1966).

This paper deals with the Ciechocinek Formation deposits exposed in the Cracow-Silesian Upland, between Częstochowa and Wieluń (Fig. 2). Its main purpose is recognition of the provenance of clastic material in these rocks, based on their mineral composition, and investigation of the origin of the characteristic green colour of the mudstones, generally considered as the characteristic feature of the Ciechocinek Formation. Current knowledge of source areas, which supplied detrital material to this part of basin is based mainly on general palaeogeographical reconstructions (Deczkowski and Franczyk, 1988; Deczkowski, 1997; Pieńkowski, 2004). Previous sedimentological studies of this unit (Leonowicz, 2002, unpubl.) did not satisfactorily indicate palaeocurrent directions responsible for the sediment supply. This was because of insufficient exposures and the poor preservation of cores on the one hand, and the generally reworked character of the Ciechocinek Formation deposits on the other. Thus petrological studies may help further constrain source areas, presently based only on palaeogeographical interpretations.

STRATIGRAPHY AND GENERAL DESCRIPTION OF THE CIECHOCINEK FORMATION

The Ciechocinek Formation is composed of muds and silts as well as poorly consolidated mudstones and siltstones with

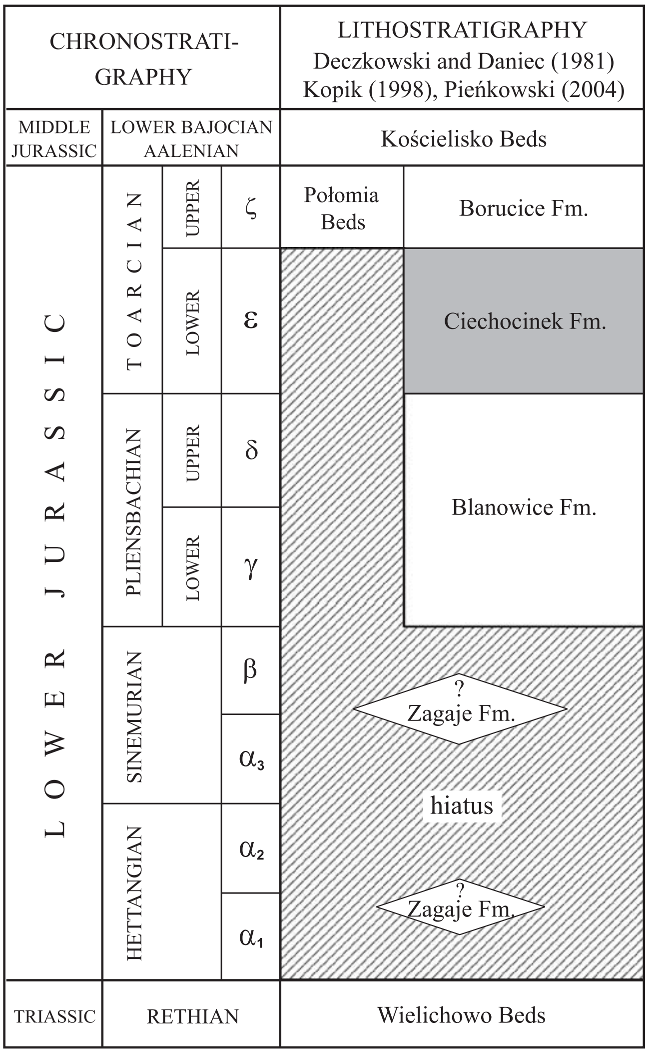

Fig. 1. Lithostratigraphy of the Lower Jurassic in the Cracow-Silesian region

lenses and subordinate intercalations of fine-grained sands and sandstones (Fig. 3). Sandy lenses and intercalations are typically 1 mm to less than 20 cm thick and they rarely reach several metres. Diagenetic siderite intercalations and concretions, less than 20 cm thick, as well as pyrite concretions are also present. The muddy-silty character of the Ciechocinek Formation is clearly different from that of the under- and overlying sand-dominated units, which in the Cracow-Silesian area are referred to the Blanowice and Borucice formations, respectively (Kopik, 1998; Pieńkowski, 2004) (Fig. 3). However, locally the boundaries between these units can be difficult to determine.

Deposits of the Ciechocinek Formation are largely of brackish-marine origin (Pieńkowski, 2004). They were deposited in an epicontinental sedimentary basin of Poland, which constituted the eastern arm of the Mid-European Basin (Fig. 4). From the north, east, south-east and south-west the Polish Basin was surrounded by land areas, which supplied, according to Teofilak-Maliszewska (Teofilak, 1966), detrital material to the Lower Jurassic deposits. Deposition of the Ciechocinek Formation represented the most widespread Early Jurassic brackish-marine sedimentation in Poland. Dadlez (1969) and Pieńkowski (2004) noted a link with the early Toarcian marine transgression, which was pronounced throughout the European Basin. Pieńkowski (*op. cit.*) stated that deposition took place in a large, shallow, brackish embayment — at a maximum some 35 m deep — with some deltaic facies in marginal parts; only in Pomerania a somewhat deeper, nearly wholly marine facies occurred. According to the Pieńkowski (2004), maximum flooding in the Polish Basin occurred as two phases and the maximum flooding surfaces may be dated at the *tenuicostatum* and *falciferum* zones. However, the biostratigraphy of the Lower Jurassic in Poland is mostly of relatively low resolution, because of the paucity of stratigraphically indicative faunas. For a long time the main tool in age determinations were macrospores. Based on them the age of the Ciechocinek Formation was determined as Toarcian (Marcinkiewicz, 1957, 1960, 1964, 1971). At present the most precise dating of the Ciechocinek Formation, based on the presence of the dinoflagellate cyst *Luehndea spinosa*, points to a late Pliensbachian–early Toarcian age (*margaritatus–tenuicostatum* zones) (Barski and Leonowicz, 2002). This was determined for deposits from the Częstochowa-Wieluń area and concerns only the lower part of the profile. The upper

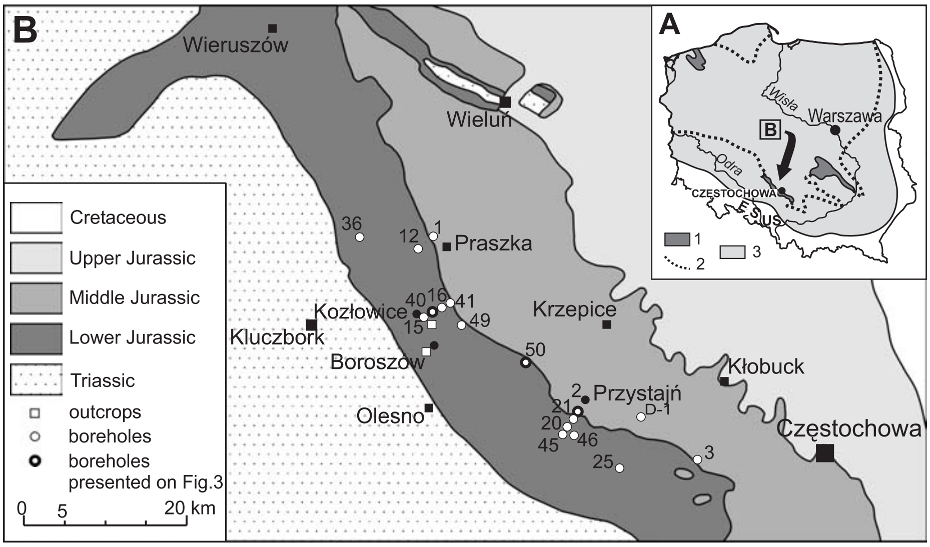

Fig. 2. A — Lower Jurassic in Poland (without Carpathians): 1 — at the surface or under the thin Quaternary cover, 2 — present-day extent of deposits, 3 — maximum extent of sedimentary basin in Early Toarcian (after Dadlez, 1973 and Pieńkowski, 2004, simplified), land areas: ES — eastern Sudetes, US — Upper Silesia; B — location of investigated profiles on a geological sketch-map of the Częstochowa-Wieluń region

Boreholes: 1 — Praszka 1, 2 — Przystajń 2, 3 — Wręczyca 3, 12 — Nowa Wieś 12, 15 — Gorzów Śląski 15, 16 — Gorzów Śląski 16, 20 — Przystajń 20, 21 — Przystajń 21, 25 — Przystajń 25, 36 — Pogorzałki 36, 40 — Pawłowice 40, 41 — Jastrzygowice 41, 45 — Bór Zajaciński 45, 46 — Dąbrowa 46, 49 — Skrońsko 49, 50 — Wichrów 50, D-1 — Dankowice IG 1

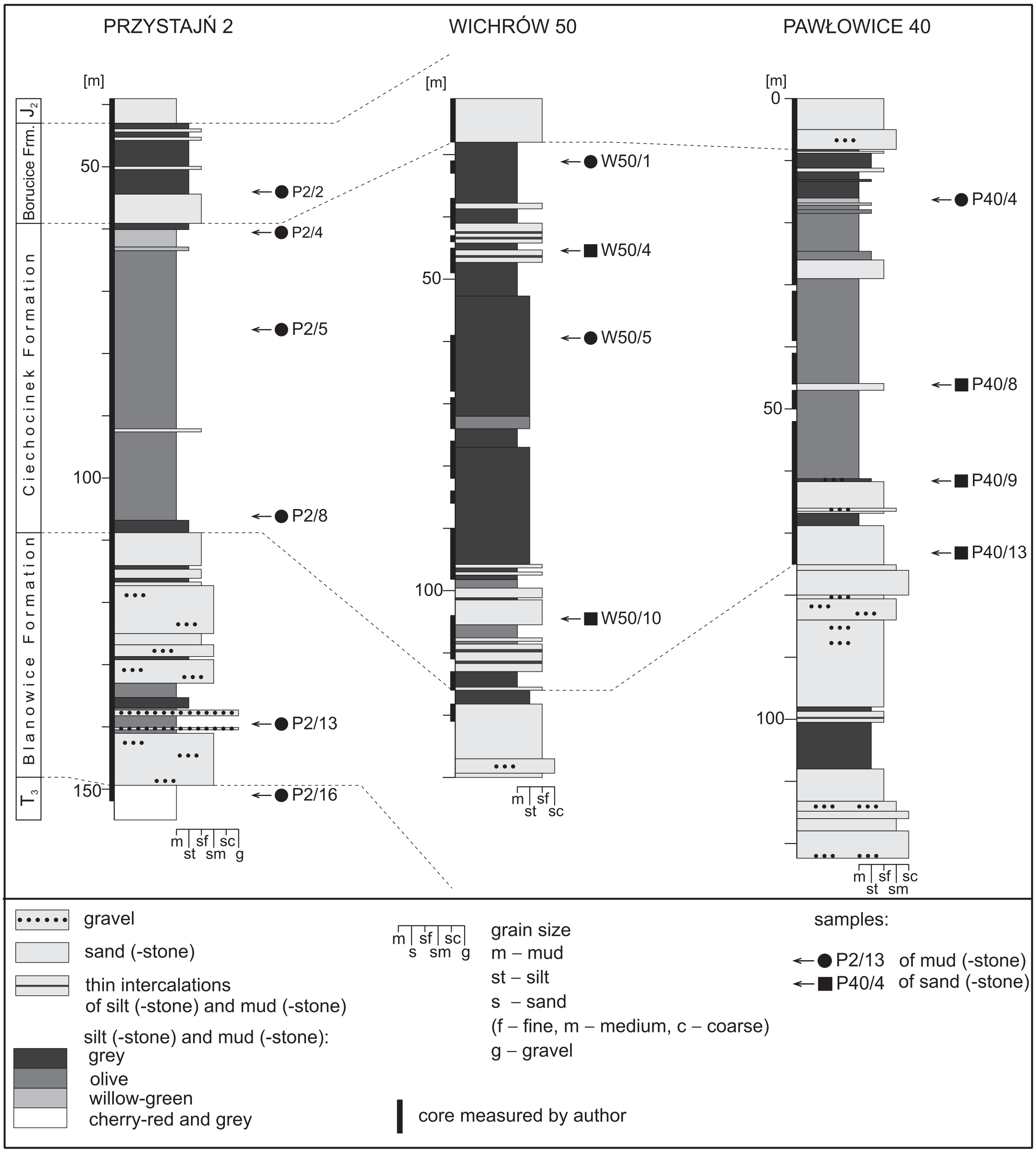

Fig. 3. Lithology of the Lower Jurassic deposits in the Częstochowa-Wieluń region exemplified by selected profiles (location on Fig. 2B)

Location of analysed samples and simplified lithostratigraphical division are marked (Ciechocinek Formation includes here deposits of uncertain lithostratigraphical position, marking transition between continental and marine environments); lacking parts of cores completed after Kieżel (1990, unpubl.)

part is devoid of dinoflagellate cysts (Barski, pers. comm.), suggesting change in the sedimentary environment. Pieńkowski (*op. cit.*) suggested that the Ciechocinek Formation may by placed within the lower Toarcian based on a sequence stratigraphy correlation.

If the Ciechocinek Formation really originated during the *tenuicostatum* and *falciferum* zones, as Pieńkowski indicated, the upper part of green mudstone facies may represent a brackish-marine counterpart of the early Toarcian bituminous shales, known from profiles in deeper parts of the European Basin (Jenkyns, 1988; Graciansky *et al.*, 1998). Black shales from West Europe are usually correlated with the maximum of Toarcian transgression (Graciansky *et al.*, 1998); however, in the German Basin, neighbouring with Polish Basin, they mark a lowstand of sea level (Röhl *et al.*, 2001), perhaps connected with a 3rd-order regressive episode.

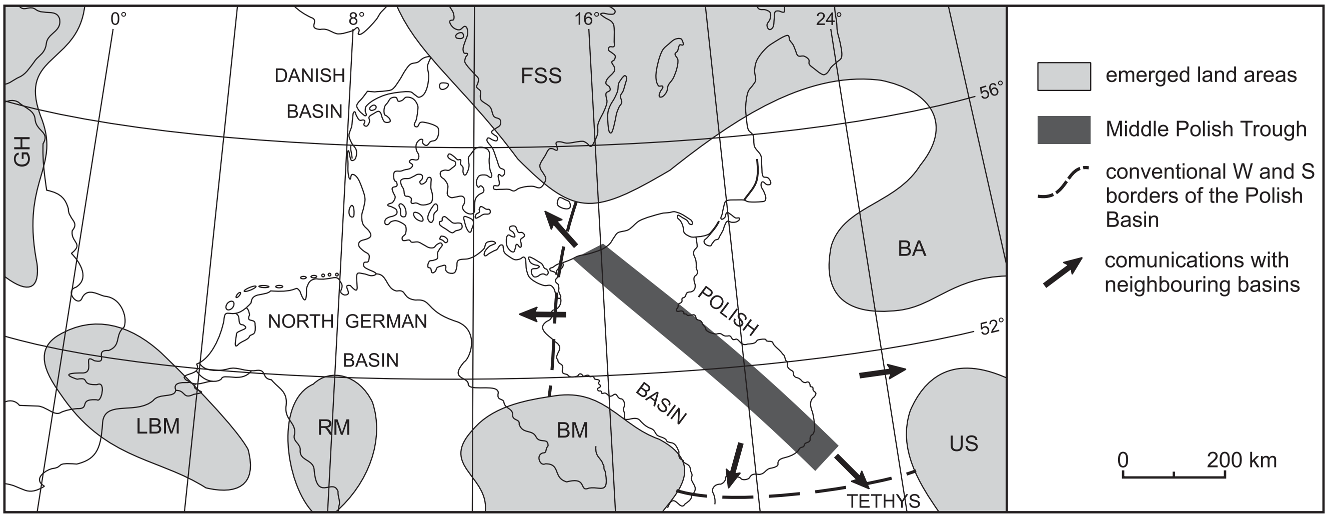

Fig. 4. Polish Basin as a part of Mid-European Basin in the Early Jurassic time (after Dadlez, 1989, with changes)

BM — Bohemian Massif, BA — Belarussian Anteclise, FSS — Fennoscandian Shield, GH — Grampian High, LBM — London-Brabant Massif, RM — Rhenish Massif, US — Ukrainian Shield

MATERIALS AND METHODS

Fieldwork included measuring and sampling of successions in two exposures in clay-pits of the “Cerpol-Kozłowice” Enterprise in Kozłowice and in the “Boroszów” Brickyard in Boroszów, as well as analysis of 17 boreholes, drilled by the Polish Geological Institute in the Lubliniec-Wieruszów area (Fig. 2). As some cores were not complete, descriptions made by Kieżel (1990, unpubl.) were used during measuring and drawing of borehole profiles for reconstruction of a detailed lithological succession.

Samples of muds were examined by X-ray diffraction (XRD) and scanning electron microscope (SEM). They were selected in order to determine whether there was any lateral and vertical variations in mineral composition of the Ciechocinek Formation muds; how they differ from deposits of other lithostratigraphic units of Early Jurassic age; and whether there was any relation between the mineral composition and colour of the muds. Initial bulk-rock XRD analysis was carried out on 22 non-oriented samples, collected from different parts of the Przystajń 2 core (Fig. 3) as well as from outcrops in Kozłowice and Boroszów and 6 other cores taken from different parts of the area investigated (Wręczyca 3, Nowa Wieś 12, Gorzów Śląski 16, Pawłowice 40, Bór Zajaciński 45, Wichrów 50). For further investigations 3 samples were selected, taking into account the mineral composition and colour of the mud. The clay fraction (<2 µm) was separated from them by a standard sedimentation method and oriented slides were prepared. These were analysed in air-dried conditions, after ethylene glycol treatment and heating for 3.5 hours at *ca*. 490°C. Samples were analysed with a step size of 0.04° 2θ and 4 s counting time on a *DRON 2.0* diffractometer, using Co-Kα radiation and a Fe-filter.

Nine of the XRD-analysed samples, representing different colour varieties of the muds, were examined by SEM. The chemical composition of the minerals was determined using an electron microprobe equipped with an energy dispersive system (EDS). Analyses were carried out on a *Tesla BS 301* scanning electron microscope and on a *Philips XL 20* scanning electron microscope integrated with an *EDAX Dx4i* system.

In order to recognize the provenance of the silt- and sand-grade detrital material, samples from different parts of the Ciechocinek Formation profile were selected (Fig. 3). As some parts of cores were strongly crushed and weathered and, additionally, sandy intercalations are infrequent in the Ciechocinek Formation as a rule, the number of samples was restricted. Polished thin sections were prepared from the set of selected samples for detailed petrographic study. Analyses by polarizing microscope included: quantitative analysis of the grain framework, recognition of lithic fragments and of the assemblage of heavy minerals.

21 thin sections of sandstones and sandy siltstones were analysed applying the criteria of Basu *et al.* (1975). Thin sections were point-counted and 300 grains were determined in each sample. Heavy minerals were determined in 5 sand samples from the Kozłowice exposure. These samples had been earlier sieved to separate particular fractions. Determinations were made for grains from the 0.125–0.1 mm fraction, which represented the most diverse assemblage of heavy minerals. The heavy mineral grains were separated by gravity-settling through bromoform. Microscope slides were analysed by polarizing microscope. 600 grains were determined in each slide.

OBSERVATIONS AND RESULTS

MUDS AND MUDSTONES

Muds and mudstones are the most common deposits of the Ciechocinek Formation. They are olive, willow-green, light or dark grey in colour. In some cases the presence of iron compounds renders them rusty, brown, pink or cherry-red. They often contain an admixture of micas and fine plant debris, which are commonly concentrated on parting planes. Larger, several cm-long wood fragments were also found in the muds. Muds and mudstones consist mainly of clay-sized particles with some admixture of silt; sandy muds and mudstones are also encountered, whereas pure clays and claystones, without admixtures of other fractions are rare. Mudstones are typically poorly consolidated; when immersed in water they undergo disintegration, swell and become plastic. The only exceptions are consolidated, heavy sideritic mudstones, brown or cherry-red in colour, which form intercalations and lenses in muds and sands. The grey and green muds do not alter their colour during weathering. The colour of green muds becomes in some cases more intense, and on parting planes of grey muds an olive shade often appears.

Analysis of lithological profiles showed that the most common colour within the Ciechocinek Formation muds is olive (Fig. 3). Grey muds form only subordinate intercalations within the olive muds; the thickest packets of grey deposits appear in the lowermost and uppermost parts of profiles. The only exception is in the Wichrów 50 borehole, where grey muds dominate. Willow-green deposits occur only in the uppermost part of the Ciechocinek Formation profile.

XRD AND SEM OBSERVATIONS RESULTS

XRD analysis of muds from the Ciechocinek Formation indicates that they comprise illite, kaolinite, chlorite, mica and — in some samples — irregular illite-smectite (I/S) mixed-layer minerals (Figs. 5 and 6). Besides these, all samples indicate the presence of significant amounts of quartz and sporadically K-feldspar.

Mica occurs mainly in the >2 μm fraction and is often macroscopically visible in the form of light coloured flakes. I/S mixed-layers are quite abundant in some samples, which results in clay swelling. The lack of well-shaped diffraction peaks (Figs. 5 and 6) indicates that they comprise irregular mixed-layers. Chlorite, like the mica, is partly present in >2 μm fraction, as shown by a decrease in the intensity and widening of its reflections on diffractograms of the <2 μm fraction. The coarse-grained fraction comprises most probably detrital and post-biotite chlorite, which can be observed macroscopically and in thin sections of sandstones and siltstones. The fine-grained chlorite, visible on diffractograms of the clay fraction (Fig. 6), probably corresponds to the green clay matrix

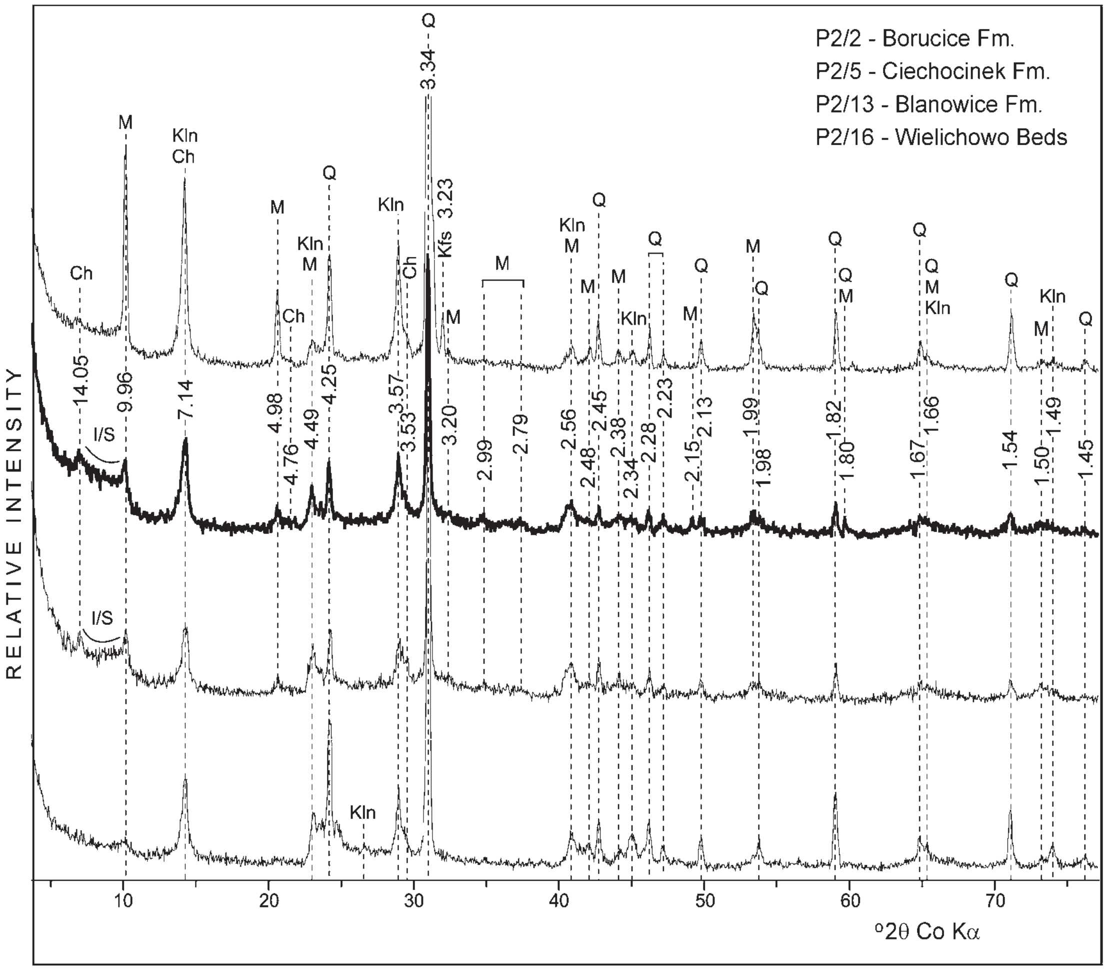

Fig. 5. X-ray diffraction patterns of muds from different lithostratigraphic units of Upper Triassic and Lower Jurassic from Przystajń 2 borehole; air dried whole-rock samples, non-oriented aggregates

Kln — kaolinite, Ch — chlorite, M — mica and illite, I/S — illite/smectite mixed-layer minerals, Q — quartz, Kfs — K-feldspar

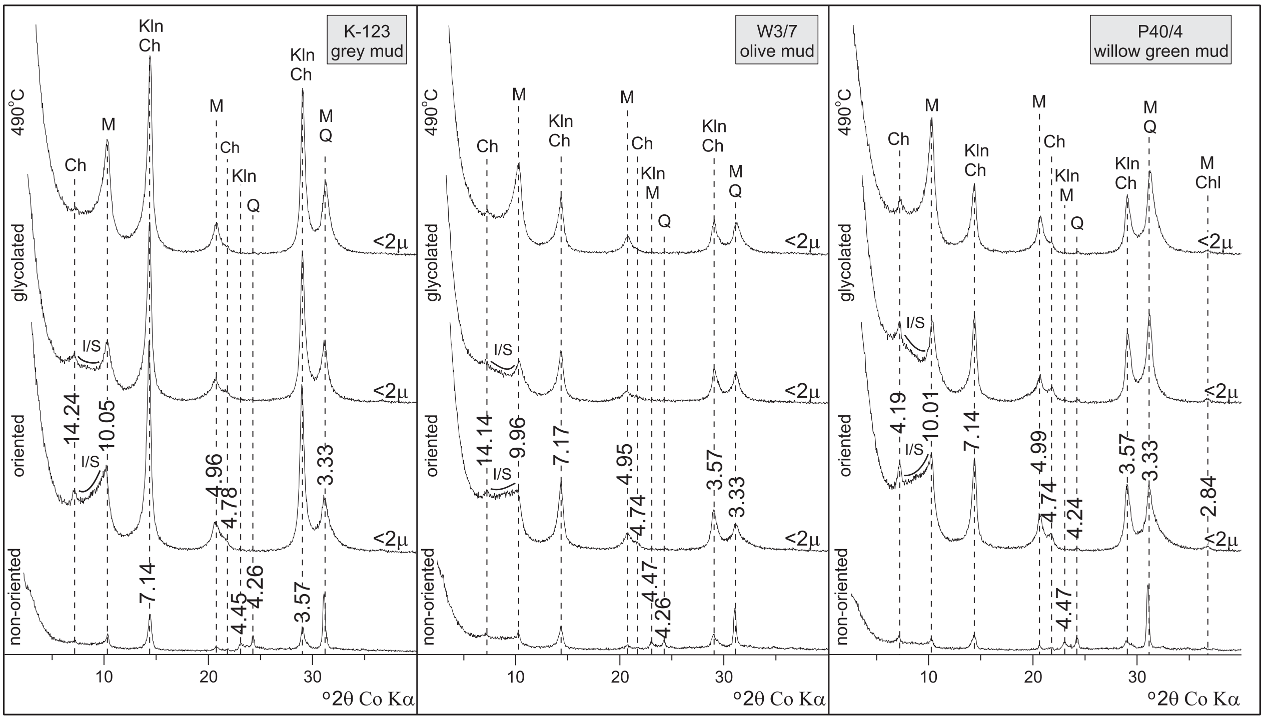

Fig. 6. X-ray diffraction patterns of three colour varieties of muds from the Ciechocinek Formation

K-123 — Kozłowice outcrop, W3/7 — Wręczyca 3 borehole, P40/4 — Pawłowice 40 borehole; for other symbols see Figure 5

which can be observed in thin sections of some willow-green siltstones (see: sandstone and siltstone characteristics). The decrease in the intensity of its reflections after heating indicates that it is probably a Fe-chlorite, less resistant to higher temperatures than the Mg-chlorite.

Although the percentage contents of particular clay minerals were not determined, X-ray diffraction analysis showed some differences in the mineral composition of the three characteristic colour varieties of muds from the Ciechocinek Formation (Fig. 6). Grey muds are the only variety in which the mixed-layer minerals are not always present; they also contain much less chlorite than the olive and willow-green varieties. The olive and willow-green muds have a similar composition; the only difference visible on diffractograms is the higher content of chlorites in the latter case.

Analyses of muds from different lithostratigraphic units of Upper Triassic and Lower Jurassic from Przystajń 2 borehole, carried out for comparison, indicated that they significantly differ in their mineral composition (Fig. 5). However, in all the samples, excluding sample P2/16 from the Triassic Wielichowo Beds, the presence of chlorite was observed. The sample of mud from the Blanowice Formation (P2/13) was collected from an olive-coloured lithologic variety uncommon for this unit, as muds of this formation are usually grey and chlorite-poor (Śnieżek, 1986); it, however, shows that in places chlorite is also present in deposits underlying the Ciechocinek Formation.

SEM observations indicate that particles of detrital origin are the main constituents of the Ciechocinek Formation muds. They include flakes of clay minerals, reaching from a fraction to several μm in size (Fig. 7A) and much rarer quartz grains (Fig. 7B). Single, large, automorphic flakes (30–100 μm) of chemical composition similar to that of the Fe-mica, are also present (Fig. 7C). Muds typically have a well-ordered fabric, arising from the parallel orientation of clay flakes (Fig. 7D). Most probably this is an effect of compaction of the deposits, rather then a primary fabric resulting from the quiet deposition of particles from suspension.

Ciechocinek Formation muds contain also authigenic clay minerals. They occur in the form of automorphic crystals (Fig. 7E) and finely-crystalline aggregates growing on detrital grains (Fig. 7F), as well as growth zones attached to existing detrital flakes. Reliable determination of the chemical composition of these minerals, using the electron microprobe, was impossible due to the small size of crystals. Some mud samples indicate the presence of framboids and individual octahedral pyrite crystals, reaching several μm in size. Structures resulting from pyrite dissolution as well as numerous traces of chemical corrosion on surfaces of detrital clay particles were also observed.

SAND (-STONES) AND SILT (-STONES)

The Ciechocinek Formation typically comprises fine-and very fine-grained sands and poorly consolidated quartz sandstones as well as silt and siltstone intercalations. The sands and sandstones are pale grey to white, in some cases also grey-yellow, rusty or willow-green in colour. Besides quartz, macroscopically visible detrital constituents commonly include white mica, rarely a greenish flaky mineral — probably chlorite and

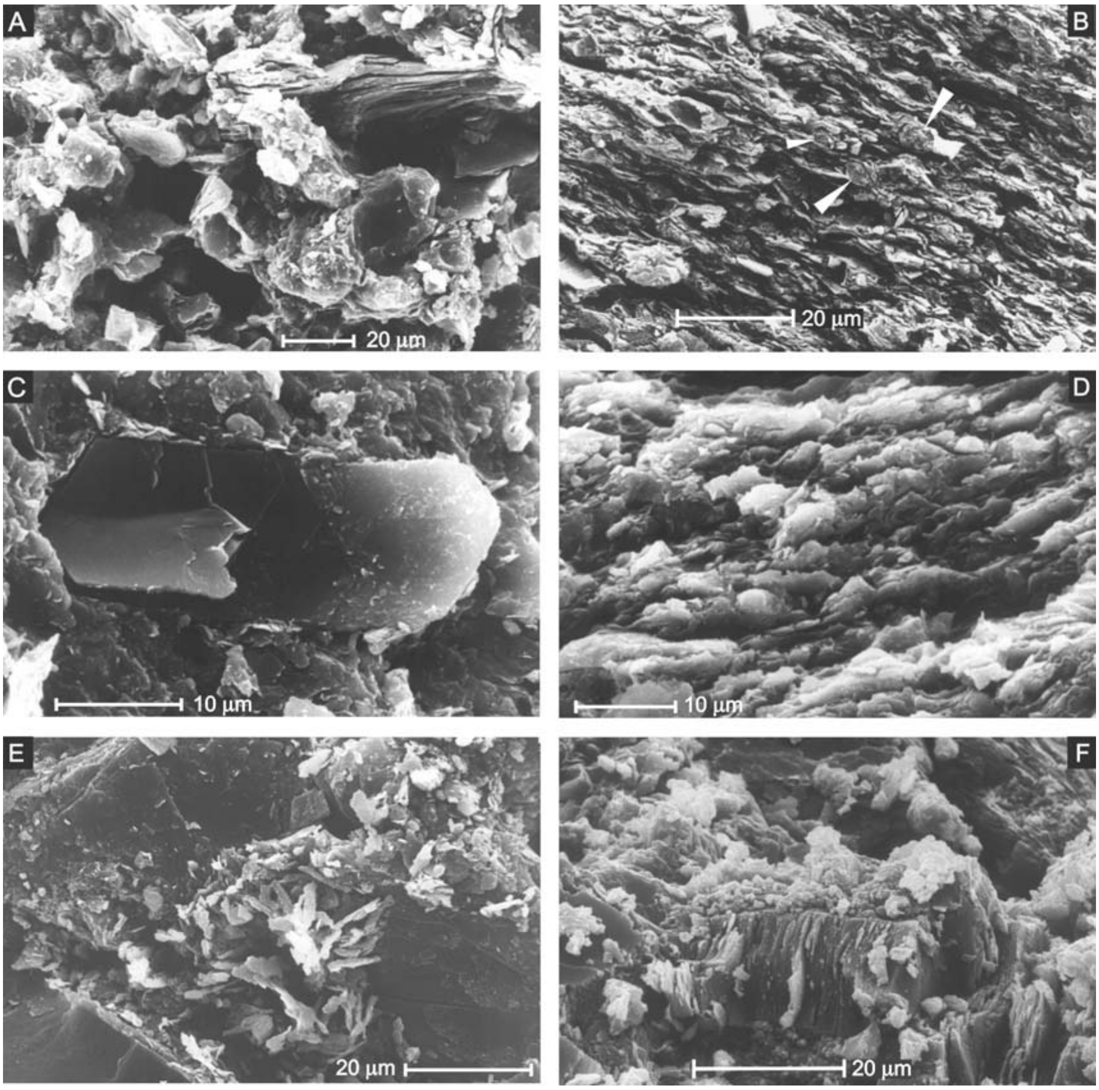

Fig. 7. SEM photomicrographs of muds and mudstones of the Ciechocinek Formation

A — detrital flakes of clay minerals (Nowa Wieś 12 borehole); **B** — quartz grains (arrows) surrounded by clay flakes, well-ordered fabric of mud is visible (Gorzów Śląski 16 borehole); **C** — large automorphic flake of Fe-mica (Przystajń 2 borehole); **D** — well-ordered fabric of mud arising from the parallel superposition of clay flakes (Nowa Wieś 12 borehole); **E** — automorphic crystals of unidentified autigenic clay minerals (Bór Zajaciński 45 borehole); **F** — fine-crystalline aggregates of unidentified autigenic clay minerals growing on detrital grains (Przystajń 25 borehole)

kaolinite grains. Plant debris is common, randomly distributed in the deposit or concentrated with mica flakes on lamination planes. Larger wood fragments, several cm long, are also moderately frequent. Thin sandstone lenses and intercalations are more consolidated. Intercalations of brown and cherry-red ferruginous and sideritic sandstones are strongly consolidated regardless of their thickness. Sands and sandstones often contain considerable admixtures of silt and clay, therefore an entire spectrum of mixed deposits can be observed: sands–silty sands–sandy silts–silts. Sporadic intercalations of medium- and coarse-grained sands can be observed in the lower part of the Ciechocinek Formation and in the transition zone with the Blanowice Formation.

Silts and poorly consolidated siltstones macroscopically resemble muds and mudstones. They are olive, willow-green as well as pale and dark grey in colour. They comprise silt-sized quartz grains and variable contents of clay-sized material; they can also contain an admixture of fine sand. Other detrital constituents include white mica flakes; plant debris is also common. Siltstones are commonly sideritized. Sideritic siltstones are strongly consolidated, heavy, pale grey, grey-yellow or brown in colour; their weathered surfaces are commonly rusty, cherry-red or pink.

Microscopic analysis of the grain framework indicated that sandstones of the Ciechocinek Formation represent quartz arenites and subarkoses (*sensu* Pettijohn *et al.*, 1973). The matrix content varies from 0 to 11% of the bulk volume. Siltstones and sandy siltstones have a similar composition of the grain framework. The matrix content reaches 14%, but may be higher in reality because of the poor consolidation of the rocks and the formation of secondary porosity during thin section preparation. Thus, most probably some of these deposits should be referred to quartz wackes and arkosic wackes.

The main component of the grain framework is quartz (Fig. 8A), the content of which varies from 76–94% in sandstones and 70–88% in siltstones. Therefore the deposit can be considered as mineralogically mature. Quartz crystals contain numerous zircon and mica inclusions and are frequently corroded. Quartz overgrowths *in situ* are commonly observed (Fig. 8B). Inherited quartz overgrowths on polycyclic quartz grains, developed due to weathering of earlier sandstones, are less common. In all samples analysed quartz occurs as both monocrystalline (Q_m) and polycrystalline (Q_p) grains (Fig. 8B, C). The latter consists of 2–3 ($Q_{2–3}$) as well as more than 3 ($Q_{>3}$) crystal units per grain. Quartz Q_m predominates, but the content of quartz Q_p is also high and varies from 14–36% in sandstones to 9–23% in siltstones. The large content of grains $Q_{>3}$ is noteworthy; this grains reach up to 35% of all polycrystalline grains. Observation of the undulosity in monocrystalline quartz grains indicates a prevalence of non-undulatory quartz grains (Q_{nu}). The content of undulatory (Q_u) quartz grains is 17–42% in sandstones and 23–37% in siltstones.

Other detrital constituents occurring in analysed sandstones and siltstones include: feldspars, common micas, heavy minerals including opaque minerals and lithic clasts. Feldspars (Fig. 8E) represented by the alkali group are often strongly corroded or kaolinized. Muscovite is the most common type of mica (Fig. 8F); larger quantities of usually chloritized biotite occur only in some samples. Rare flakes of green chlorite were also encountered. The large content of flaky minerals in the siltstones is notable; they reach 18% of all grains. The lithic clasts include fragments of sedimentary rocks, mainly cherts (Fig. 8A), less common siltstones, mudstones, quartz sandstones and marls, as well as metamorphic rocks: quartzites, mica schists (Fig. 8F) and quartz-mica schists. Fragments of igneous rocks are sporadic.

The assemblage of heavy minerals determined in several samples is constant and restricted almost exclusively to minerals most resistant to weathering (Fig. 9A). It includes zircon, rutile, staurolite and tourmaline; garnets are also common. Most minerals occur as several morphological types, differing in the degree of breakage and roundness of grains (Fig. 9B–G). The most common are euhedral forms (zircon, rutile, tourmaline), angular fragments (rutile, garnet, staurolite) and well-rounded oval grains (zircon, rutile, garnet, tourmaline). Two samples revealed also a moderately high content of flaky minerals: chlorite and biotite. Sporadical well-rounded grains of green hornblende, apatite, disthene, epidote as well as one pyroxene grain were observed.

Three types of grain-to-grain bonds occur in the sandstones and siltstones of the Ciechocinek Formation analysed: clay, quartz and sideritic. A clay bond is developed as a very fine-grained mixture of clay minerals, regarded as a matrix, or as well-developed vermicular aggregates and "booklets" of neoformed kaolinite crystals (Fig. 8E). In one sample of willow-green sandy siltstone (Skrońsko 49 borehole) the presence of authigenic "green grains" (Odin, 1988; Chamley, 1989) was noted. The bond of this siltstone mainly comprises a finely crystalline green clayey mass. The composition of this mass is microscopically unrecognisable; however, it probably corresponds to a fine-grained Fe-chlorite, visible on diffractograms of the clay fraction of the muds. A quartz cement occurs at con-

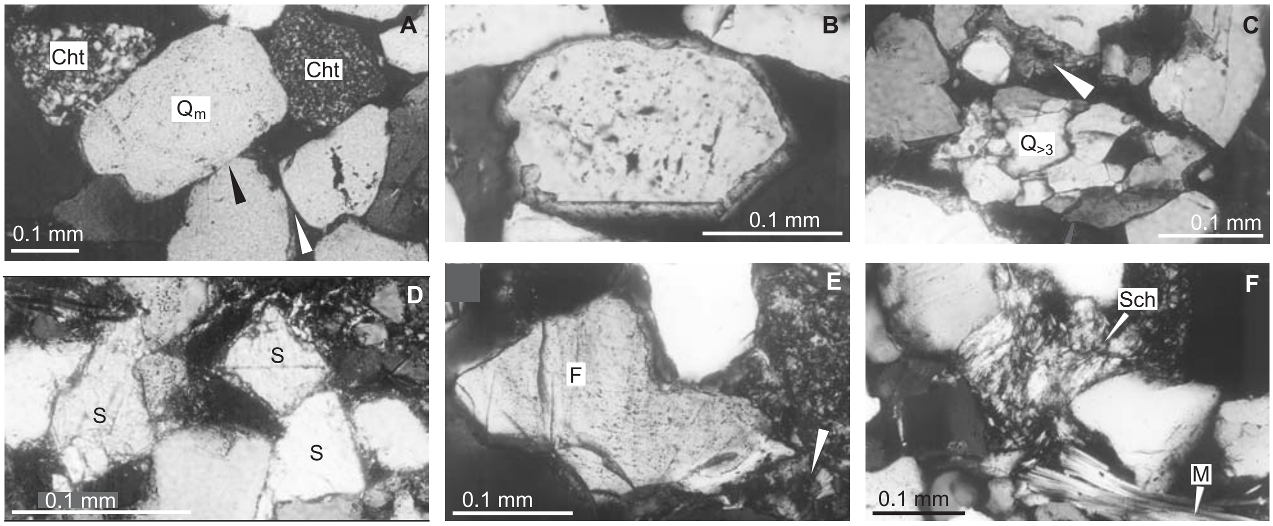

Fig. 8. Sands and sandstones of the Ciechocinek Formation

A — common constituents of quartz arenites: monocrystalline quartz grains (Q_m) and chert fragments (Cht); quartz cement occurs at the contact of detrital grains (black arrow) and as overgrowths (white arrow); **B** — monocrystalline quartz grain with quartz overgrowths *in situ*; **C** — polycrystalline quartz grain consisting of more than 3 crystal units per grain ($Q_{>3}$); quartz cement developed as connected overgrowths is visible (arrow); **D** — sideritic cement (S) developed as single rhombohedral crystals; **E** — K-feldspar grain (F) and neogenic kaolinite "booklets" (arrow); **F** — fragment of mica schist (Sch) and muscovite flake (M); crossed nicols

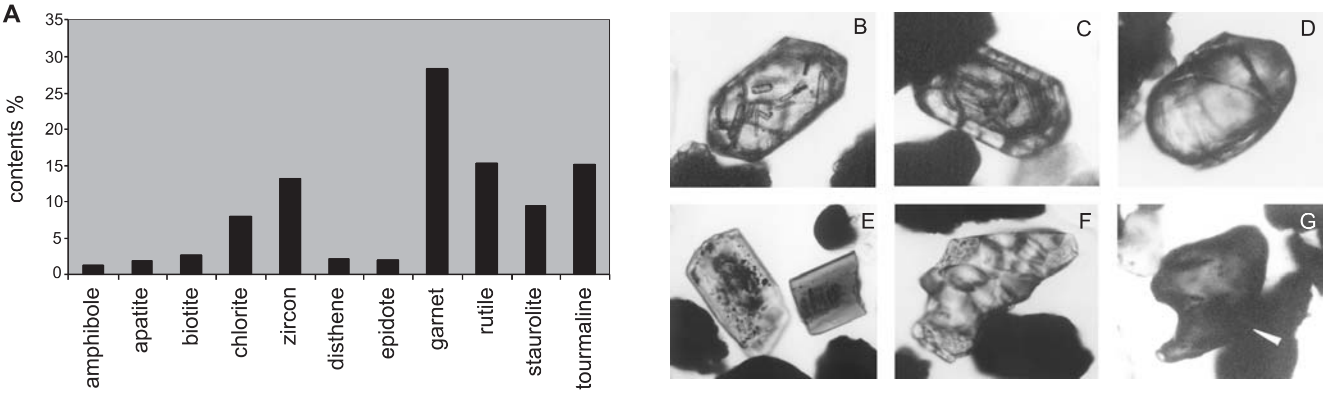

Fig. 9. Heavy minerals from sands of the Ciechocinek Formation (Kozłowice outcrop)

A — frequency distribution of heavy minerals; **B**–**G** — morphological types of heavy minerals: **B**, **C** — euhedral crystals of zircon; **D** — well-rounded oval grain of zircon; **E** — fragments of euhedral tourmaline crystals; **F** — angular fragment of staurolite; **G** — well-rounded grain of rutile; grains of 0.125–0.1 mm fraction; one nicol

tacts between quartz grains or as quartz overgrowths (Fig. 8A, C) and is very common in the rocks analysed. A sideritic cement is best developed, occurring as fine, xenomorphic crystals or well-developed rhombohedrons (Fig. 8D). It forms a basal or pore-filling cement, occurs as individual crystals in other cements, or as a replacive cement.

INTERPRETATION OF RESULTS

ORIGIN OF MUD (-STONES)

Muds of the Ciechocinek Formation have a generally common mineral composition. Similar compositions can be observed in deposits within different sedimentary basins. SEM observations indicate that most of components are of detrital origin. Studies on recent and ancient mud deposits, both of marine and freshwater origin, indicate that clay minerals supplied by rivers to sedimentary basins do not undergo significant transformations at the land-sea or land-lake boundary, and the composition of the resulting deposits depends mainly on the mineral composition of rocks and soils in the hinterland and on the distance from the river mouth (Chamley, 1989). Thus the composition of clay suite of the Ciechocinek Formation muds should largely reflect the mineral composition of the source rocks.

The co-occurrence in the muds analysed of kaolinite and minerals less resistant to chemical weathering, such as chlorite and particularly biotite, indicates that the source area was varied in terms of hypergenic processes and in the type of exposed and eroded rocks. Kaolinite, which forms in continental, intertropical environments due to the chemical weathering of different igneous, metamorphic and sedimentary rocks (Chamley, 1989; McBride, 1994), must have been washed out from kaolinitic or lateritic blankets developed on older rocks of the basement. Illite and chlorite are mostly components of detrital origin, derived from the physical weathering of crystalline and sedimentary rocks exposed on the land (Chamley, 1989). If the products of physical weathering of the parent rocks did not undergo prolonged chemical weathering, but were transported directly to the sedimentary basin, only those minerals least resistant to chemical transformation, such as ferromagnesian minerals and feldspars, may have undergone hydrolysis, kaolinization and chloritization. The remaining ones, i.e. micas, quartz and chlorite, would have been transported to the sedimentary basin as largely unweathered particles. Partial hydrolysis of micas and illite would have resulted in the formation of mixed-layer illite-smectite minerals.

Some clay minerals, forming automorphic crystals, growth zones and aggregates growing on detrital flakes, originated during diagenesis. The lack of information about their chemical composition makes their identification difficult but most probably they represent early diagenetic chlorites and/or illite, or mixed-layer minerals, formed by weathering of muds in subaerial conditions.

GREENISH COLOUR OF MUD (-STONES)

The origin of the characteristic greenish colour of the Ciechocinek Formation muds, considered as a diagnostic feature of this unit (Pieńkowski, 2004), is still in dispute issue. Teofilak-Maliszewska (1967, 1968) and Jurkiewiczowa (1967) concluded that the green colour is linked with enrichment of illite in ferrous iron. Such an interpretation is possible; however, it is difficult to accept the view of Jurkiewiczowa (*op. cit.*) that an Fe-rich illite formed as a result of kaolinite transformation associated with slow sedimentation rates in a brackish-marine environment. As previously mentioned, clay minerals do not undergo significant transformations at a river/sea boundary, and most post-depositional modifications are caused by diagenetic processes, linked with deeper burial of the sediment. During these transformations, kaolinite can be either stable or it can undergo recrystallization or disintegration, but alteration to illite has not been observed (Chamley, 1989).

The mineralogical compositions detailed above indicate that the origin of the green colour of the Ciechocinek Formation muds is connected with the presence of iron-rich chlorites. This assumption is supported by a correspondences of chlorite content with colour in the muds. The Fe-chlorite is most common in willow-green muds and least common in grey muds, although its precise percentage content has not been determined. The origin of the greenish colour may also be connected with the presence of Fe^{+2} oxides and hydroxides. These, however, are compounds usually associated with reducing environments, and they are sensitive to changes in the oxygen level within the sediment. With the introduction of oxygen the Fe^{+2} compounds rapidly convert into the Fe^{+3} compounds. Meanwhile, increased weathering of the green muds has led to an intensification of their colour, rather than to transformation into a red or rusty colour. This feature excludes the presence of significant amounts of Fe^{+2} compounds.

Therefore, understanding the origin of this specific colour requires understanding the origin of the chlorite. As shown by microscopic observations and XRD analyses, chlorites from the Ciechocinek Formation muds can be of both diagenetic and detrital origin. The source of detrital chlorite may be low-grade metamorphic rocks, i.e. chlorite-mica schists or mafic rocks metamorphosed under greenschist facies conditions. If the entire chlorite was of detrital origin, then it should be assumed that its abundance in a certain interval of time would be linked with a change in the source area or with a change in the weathering process on the adjacent land. The first assumption is highly improbable, because chlorite occurs also in muds representing other lithostratigraphic units: the Upper Triassic Zbąszynek Beds (Śnieżek, 1986) as well as the Lower Jurassic Blanowice and Borucice Formations (Fig. 5). It indicates that the source area did not change significantly during the Late Triassic to Early Jurassic interval. The second assumption, which explains the mass occurrence of chlorite by a change in the sedimentary environment within the receiving basin and of the weathering process in the source area, is more probable. As deposits devoid of chlorite are rich in kaolinite, it may be assumed that they underwent longer and more intense weathering in a continental environment. Deposition of the detrital material, supplied directly from eroded source rocks, in a permanent basin could protect minerals less resistant to weathering, such as chlorite, from chemical transformations. Therefore a change in the sedimentary environment from continental into marine could result in the formation of the distinctive mudrocks of the Ciechocinek Formation. However, it is difficult so to explain the lateral changes in colour observed in these deposits, particularly if they take place over small distances and without distinct changes in the sedimentary environment. Thus, it becomes most probable that the greenish colour is linked with the presence of authigenic minerals.

Diagenetic chlorites may form in deep burial conditions, at temperatures above 80°C, or in shallow burial conditions, at the expense of volcanic rock debris and Fe-Mg minerals, e.g. biotite (Burley *et al.*, 1985; Tilley and Longstaffe, 1989; McKay *et al.*, 1995). They may also form as a result of syndepositional and early diagenetic reactions which take place close to the sediment/water interface, as in the case of chamosite and berthierine associated with oolitic ironstones (Odin, 1988; Velde, 1989; Aagaard *et al.*, 2000). It is quite possible that the finely crystalline chlorite visible on diffractograms of the <2 μm fraction is of diagenetic origin. Because the depth of burial of Lower Jurassic deposits, estimated from the original thickness of Mesozoic deposits in the Cracow-Częstochowa Monocline (Sokołowski, 1973; Deczkowski and Franczyk, 1988; Dayczak-Calikowska and Moryc, 1988; Niemczycka and Brochwicz-Lewiński, 1988; Marek, 1988; Jaskowiak-Schoeneichowa and Krassowska, 1988), is between 500–900 m, and the main diagenetic transformations of clay minerals (assuming a normal geothermal gradient *ca.* 30°C/km), take place at burial depths exceeding 2 km (Chamley, 1989), it should be expected that analysed rocks are only slightly affected by such diagenetic processes. A generally weak diagenetic modification is supported by the presence of irregular mixed-layer minerals. Therefore this finely crystalline chlorite must have arisen as an early diagenetic mineral. This seems to be confirmed by the presence of microscopically identified "green grains", showing that authigenesis of clay minerals took place in the Ciechocinek Formation muds.

Odin (1988) distinguished four types of iron-rich green clay granules and associated facies, differing in geochemical parameters and bathymetric distribution. These are: verdine and ironstone facies — both linked with the shallow-marine environment and glaucony and celadonite-bearing facies, considered as open marine deposits. Ferrous chlorite (chamosite) and berthierine — which is considered to be the precursor of the former — are characteristic components of the ironstone facies (Odin *op. cit.*). They form at low Eh conditions, in an open reducing environment; therefore they usually occur in muddy deposits, which inhibit easy oxidation. Ironstone deposits are often associated with siderite (Odin, 1988; Harder, 1989). Chamosite and berthierine granules are almost entirely absent from recent deposits; therefore some aspects of their genesis are still controversial. In spite of differences in geochemical conditions responsible for verdine and ironstone formation, Odin (*op. cit.*) suggests that modern depositional environments which include the verdine facies may represent analogues for the ancient ironstone palaeoenvironment, as both facies are shallow-marine and a limiting factor for their development is the availability of iron. Green granules of the verdine facies, composed of ferric clay minerals — odinite and phyllite C — were reported from many recent sediment bodies, located on the shelves of the W and E Atlantic, New Caledonia, Mayotte and Sarawak (Odin, 1988; Chamley, 1989). Their occurrence is restricted to intertropical regions and the vicinity of river mouths. Analyses of ancient ironstone deposits as well as experimental data support such an environmental interpretation. They have been variously attributed to deposition in a warm, humid climate, in brackish-marine environments of lagoons, embayments, estuaries, low-energy deltas and near sandwave fields or barrier islands, where a concentration of iron supplied from land took place and reducing conditions in the sediment, resulting from decomposition of organic matter, favoured the precipitation of these minerals (Odin, 1988; Harder, 1989; McKay *et al.*, 1995).

Oolitic ironstones occur widely in the Lower Jurassic deposits of central and northern Europe (Hallam, 1975). Chamosite ooids have also been reported from cements in sandstones of the Ciechocinek Formation from W Poland and Pomerania (Teofilak-Maliszewska, 1967). Thus, it is very probable that greenish muds of the Ciechocinek Formation, containing Fe-chlorites — most likely early diagenetic — and common sideritic mineralization, represent the ironstone facies, although not completely developed. The sedimentary environment of their deposition, described by Pieńkowski (2004) as a large, shallow, brackish marine embayment is typical of this facies. As mentioned above, the limiting factor for development of ferrous chlorites is the concentration of iron. Changes in Fe content and salinity, resulting from a variable influx of fresh water from the land, are a common feature in nearshore environments and may well explain lateral changes in the colour of the Ciechocinek Formation muds. The most favourable conditions for the formation of green grains prevailed during the last stage of the marine transgression and resulted in the deposition of willow-green muds, in the uppermost part of the Ciechocinek Formation.

Besides chlorites and iron oxides, the colour of muds may also be affected by dispersed organic matter and pyrite, which give grey and black shades. Small quantities of pyrite observed in the SEM and its lack in some samples of the grey mud indicate that it is not significant mineral as far as concerns origin of the colour. Most probably, the presence of organic matter, which can be observed both macro- and microscopically in the Ciechocinek Formation, is more important. Analysis of results of investigations performed on different shales and mudstones indicated (Potter *et al.*, 1980) that green, olive and grey deposits are typically characterised by a similar content of bivalent iron, but differ in the content of dispersed organic matter. It is therefore possible that larger concentrations of organic matter are partly responsible for the grey colour of muds, particularly those containing chlorite.

PROVENANCE OF CLASTIC MATERIAL IN SAND (-STONES) AND SILT (-STONES)

Investigations of modern and ancient sand deposits indicate that sands derived from the weathering of plutonic and metamorphic rocks, displaying various degree of alteration, are characterized by a different percentage content of different quartz grain types (Basu *et al.*, 1975). According to criteria presented by Basu *et al.* (*op.cit.*) and Tortosa *et al.* (1991), the character of quartz grains of sandstones and siltstones from the Ciechocinek Formation indicate that they are sourced from medium to high grade metamorphic as well as plutonic rocks (Fig. 10). However, this interpretation should be corrected to take into account the fine-grained fraction and the mineralogical maturity of the deposits analysed, because the criteria applied were established for medium-grained, first-cycle sands. Undulatory (Q_u) and polycrystalline (Q_p) quartz grains are less resistant to weathering and recrystallisation (Basu *et al.*, 1975), and their content decreases with a decrease in grain size and with the compositional maturity of the deposit. The fine fraction and maturity of the deposits analysed indicate that the primary content of Q_u and Q_p quartz grains, including $Q_{>3}$, was higher, therefore the presence of low grade metamorphic rocks in the source area was also very probable.

The assemblage of heavy minerals and lithic clasts supplies additional evidence of the presence of metamorphic rocks (including those of low grade) in the source area. The presence of minerals such as staurolite, garnet, disthene, chlorite and epidote, as well as fragments of metamorphic rocks, including mica- and quartz-mica schists indicates that source rocks were mainly of metamorphic origin. Detrital chlorite is evidence of the presence of low-grade metamorphic rocks in the source area. The presence of igneous rocks in the source area is indicated by rare fragments of volcanic rocks.

The high mineralogical maturity of the deposits, including that of the heavy mineral assemblage, as well as the presence of fragments of clastic rocks and inherited quartz overgrowths on polycyclic quartz grains suggest redeposition of the clastic material, which probably underwent several sedimentary cycles. It was repeatedly enriched in fresh material derived directly from the source rocks, as shown by the presence of different morphological types of heavy minerals and the occurrence of

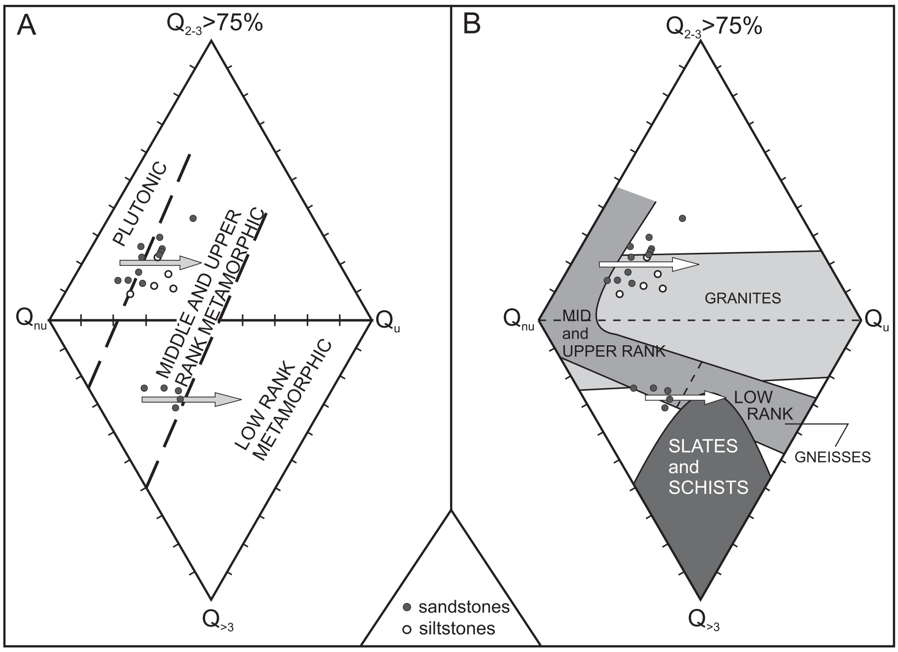

Fig. 10. Plot of nature of quartz population in analysed sandstones and sandy siltstones of the Ciechocinek Formation with provenance interpretation after: A — Basu *et al.* (1975) and B — Tortosa *et al.* (1991)

Arrows point at the supposed approximate position of the primary deposit (see text); Q_u — undulatory quartz, Q_{nu} — non-undulatory quartz, Q_{2-3} — polycrystalline quartz grains consisting of 2–3 crystal units per grain, $Q_{>3}$ — polycrystalline quartz grains consisting of more than 3 crystal units per grain easy-weatherable biotite. The enrichment in fragments of biogenic and chemical sedimentary rocks — marls and cherts — is also linked with later redeposition stages.

CONCLUSIONS

Most of the material forming the Ciechocinek Formation is of detrital origin. Petrological analyses indicate that the sources of detrital material forming both the sandstones and muds of the Ciechocinek Formation were mainly metamorphic rocks of various metamorphic grades and sedimentary rocks. The contribution of igneous rocks was smaller.

During Early Jurassic time the land adjacent to the part of the sedimentary basin analysed comprised the eastern Sudetes and their foreland, as well as the Upper Silesia area (Fig. 2A). Weathering of metamorphic rocks of the Eastern Sudetes Block, including gneisses, mica and chlorite schists, phyllites, amphibolites and migmatites, could have supplied most of the detrital constituents comprising the preserved deposits of the Ciechocinek Formation. This is in concordance with the interpretation of Teofilak-Maliszewska (Teofilak, 1966), who recognised the Sudetes and their foreland as the source area for the Lower Jurassic deposits in the Fore-Sudetic Monocline, neighbouring the Cracow-Częstochowa Monocline. The common occurrence of lithic fragments of sedimentary rocks in sandstones and siltstones and features pointing to the recurrent redeposition of deposits are noteworthy. It seems that direct supply from exposures of metamorphic rocks was accompanied by simultaneous weathering of sedimentary rocks, comprising detrital material of metamorphic parentage. Besides the Eastern Sudetes Block, flysch series of the Culm Zone (Moravo-Silesian Structure) and clastic rocks of the Upper Silesian Basin could have provided the detrital material for this part of the sedimentary basin.

Redeposition stages of the clastic material forming deposits of the Ciechocinek Formation were probably linked with the Late Triassic–Early Jurassic interval of continental sedimentation in the Cracow-Częstochowa Monocline. In the latter period, thick kaolinite blankets could have formed in the Cracow-Częstochowa area in warm climatic conditions (Pieńkowski, 1988). Processes of erosion and redeposition of the Upper Triassic Zbąszynek and Wielichowo beds caused the incorporation of their constituents, mainly kaolinite, first into the Blanowice Formation deposits and then also into the Ciechocinek Formation deposits, where they accompany detrital illite and chlorite. The mechanism of washing out weathering covers in the Hettangian–Pliensbachian time was described by e.g. Śnieżek (1986) and Pieńkowski (1988, 1997, 2004).

The green colour of the Ciechocinek Formation muds is caused by the presence of Fe-rich chlorites. Most probably these are early diagenetic minerals, which can be referred to the ironstone facies. They formed in a brackish-marine, shallow-water sedimentary basin (Pieńkowski, 2004). Changes of salinity and Fe content in marginal parts of this basin resulted from variable influx of fresh water and caused lateral changes of colour within the Ciechocinek Formation muds.

Acknowledgements. I would like to thank A. Świerczewska for help with the petrological analyses, E. Słaby for heavy mineral determinations, G. Kaproń for XRD analyses and E. Dubińska for help in their interpretation. I extend my gratitude to P. Roniewicz for reading the manuscript and for making valuable remarks. I am also indebted by A. Maliszewska and G. Pieńkowski for constructive comments on the manuscript. The Management of the Polish Geological Institute in Warsaw allowed free access and permission to sample the core material and the Management of the "Cerpol - Kozłowice" Enterprise and the "Boroszów" Brickyard allowed fieldwork at their sites. This paper is a part of a Ph. D. thesis finished in 2002 and financed by the Institute of Geology, Department of Geology, University of Warsaw.

REFERENCES

AAGAARD P., JAHREN J. S., HARSTAD A. O., NILSEN O. and RAMM M. (2000) — Formation of grain-coating chlorite in sandstones. Laboratory synthesized vs. natural occurences. Clay Miner., **35** (1): 261–269.

BARSKI M. and LEONOWICZ P. (2002) — Cysty Dinoflagellata z odsłonięć liasu w Kozłowicach i Boroszowie (Wyżyna Woźnicko-Wieluńska). Prz. Geol., **50** (5): 411–414.

BASU A., YOUNG S. W., SUTTNER L. J., JAMES W. C. and MACK G. H. (1975) — Re-evaluation of the use of undulatory extinction and polycrystallinity in detrital quartz for provenance interpretation. J. Sedim. Petrol., **45** (4): 873–882.

BURLEY S. D., KANTOROWICZ J. D. and WAUGH B. (1985) — Clastic diagenesis. In: Sedimentology. Recent Developments and Applied Aspects (eds. P. J. Brenchley and B. P. J. Williams). Blackwell Sc. Publ. Oxford.

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

DADLEZ R. (1969) — Stratigraphy of the Lias in Western Poland (in Polish with English summary). Pr. Inst. Geol., **57**.

DADLEZ R. (1973) — Jura dolna. In: Budowa geologiczna Polski, tom I . Stratygrafia, cz. 2. Mezozoik: 196–236. Wyd. Geol. Warszawa.

DADLEZ R. (1989) — Epicontinental Permian and Mesozoic basins in Poland (in Polish with English summary). Kwart. Geol., **33** (2): 175–198.

DAYCZAK-CALIKOWSKA K. and MORYC W. (1988) — Evolution of sedimentary basin and palaeotectonics of the Middle Jurassic in Poland (in Polish with English summary). Kwart. Geol., **32** (1): 117–136.

DE GRACIANSKY P. C., DARDEAU G., DOMMERGUES J. L., DURLET C., MARCHAND D., DUMONT T., HESSELBO S. P., JACQUIN T., GOGGIN V., MEISTER C., MOUTERDE R., REY J. and VAIL P. R. (1998) — Ammonite biostratigraphic correlation and Early Jurassic sequence stratigraphy in France: comparison with some U.K. sections. In: Mesozoic and Cenozoic Sequence Stratigraphy of European Basin (eds. P. C. de Graciansky *et al.*). Soc. Econ. Paleont. Miner. Sp. Publ., **60**: 583–622.

DECZKOWSKI Z. (1997) — Jura dolna: Sedymentacja, paleogeografia i paleotektonika. In: Epikontynentalny perm i mezozoik w Polsce (eds. S. Marek and M. Pajchlowa). Pr. Państw. Inst. Geol., **153**: 208–217.

DECZKOWSKI Z. and DANIEC J. (1981) — Rudy żelaza. In: Surowce mineralne województwa częstochowskiego. Wyd. Geol. Warszawa.

DECZKOWSKI Z. and FRANCZYK M. (1988) — Palaeothickness, lithofacies and palaeotectonics of the Norian and Rhaetian in Polish Lowland (in Polish with English summary). Kwart. Geol.**,** **32** (1): 105–116.

HALLAM A. (1975) — Jurassic Environments. Cambridge Univ. Press.

HARDER H. (1989) — Mineral genesis in ironstones: a model based upon laboratory experiments and petrographic observations. In: Phanerozoic Ironstones (eds. T. P. Young and W. E. G. Taylor). Geol. Soc. Spec. Publ., **46**: 9–18.

JASKOWIAK-SCHOENEICHOWA M. and KRASSOWSKA A. (1988) — Palaeothickness, lithofacies and palaeotectonic of the epicontinental Upper Cretaceous in Poland (in Polish with English summary). Kwart. Geol., **32** (1): 177–198.

JENKYNS H. C. (1988) — The Early Toarcian (Jurassic) anoxic event: stratigraphic, sedimentary and geochemical evidence. Am. J. Sc., **288** (2): 101–151.

JURKIEWICZOWA I. (1967) — The Lias of the Western part of the Mesozoic Zone surrounding the Świętokrzyskie (Holy Cross) Mountains and its correlation with the Lias of the Cracow — Wieluń Range (in Polish with English summary). Biul. Państw. Inst. Geol., **200** (2): 5–32.

KOPIK J. (1998) — Lower and Middle Jurassic of the north-eastern margin of the Upper Silesian Coal Basin (in Polish with English summary). Biul. Państw. Inst. Geol., **378**: 67–129.

MALISZEWSKA A. (1997) — Jura dolna: charakterystyka petrograficzna. In: Epikontynentalny perm i mezozoik w Polsce (eds. S. Marek and M. Pajchlowa). Pr. Państw. Inst. Geol., **153**: 206–208.

MARCINKIEWICZ T. (1957) — Megaspores of the Lias from Praszka, Zawiercie and Święty Krzyż Mountains (in Polish with English summary). Kwart. Geol., **1** (2): 299–302.

MARCINKIEWICZ T. (1960) — Megaspore analysis of Jurassic sediments near Gorzów Śląski–Praszka (Cracow–Wieluń region) (in Polish with English summary). Kwart. Geol., **4** (3): 713–733.

MARCINKIEWICZ T. (1964) — The stratigraphy of the Lower Jurassic in the Mechowo IG I borehole on the basis of megaspore research (in Polish with English summary). Biul. Inst. Geol., **189** (12): 57–60.

MARCINKIEWICZ T. (1971) — The stratigraphy of the Rhaetian and Lias in Poland based on megaspore investigations (in Polish with English summary). Pr. Inst. Geol., **65**.

MAREK S. (1988) — Palaeothickness, facies and palaeotectonic maps of the epicontinental Permian and Mesozoic in Poland (in Polish with English summary). Kwart. Geol., **32** (1): 1–14.

McBRIDE M. B. (1994) — Environmental Chemistry of Soils. Oxford Univ. Press.

McKAY J. L., LONGSTAFFE F. J. and PLINT A. G. (1995) — Early diagenesis and relationship to depositional environment and relative sea-level fluctuations (Upper Cretaceous Marshybank Formation, Alberta and British Columbia). Sedimentology, **42**: 161–190.

NIEMCZYCKA T. and BROCHWICZ-LEWIŃSKI W. (1988) — Evolution of the Upper Jurassic sedimentary basin in the Polish Lowland (in Polish with English summary). Kwart. Geol., **32** (1): 137–156.

ODIN G. S. ed. (1988) — Green Marine Clays. Developments in Sedimentology, **45**. Elsevier. Amsterdam.

PETTIJOHN F. J., POTTER P. E. and SIEVER R. (1973) — Sand and Sandstone. Springer-Verlag. Berlin.

PIEŃKOWSKI G. (1988) — Facies analysis of the Upper Triassic and Liassic of the Cracow-Wieluń Upland and prospects for occurence of clay deposits (in Polish with English summary). Prz. Geol., **36** (8): 494–456.

PIEŃKOWSKI G. (1997) — The Lower Jurassic: Sequence stratigraphy and sedimentology (in Polish with English summary) In: Epikontynentalny perm i mezozoik w Polsce (eds. S. Marek and M. Pajchlowa). Pr. Państw. Inst. Geol., **153**: 217–235.

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

POTTER P. E., MAYNARD J. B. and PRYOR W. A. (1980) — Sedimentology of Shale. Study Guide and Reference Source. Springer-Verlag.

RÖHL H. J., SCHMID-RÖHL A., OSCHMANN W., FRIMMEL A. and SCHWARK L. (2001) — Erratum to: "The Posidonia Shale (Lower Toarcian) of SW-Germany: an oxygen-depleted ecosystem controlled by sea level and palaeoclimate". Palaeogeogr., Palaeoclimat., Palaeoecol., **169** (3–4): 273–299.

SOKOŁOWSKI S. ed. (1973) — Budowa geologiczna Polski, tom I. Stratygrafia, cz. 2, Mezozoik. Wyd. Geol

ŚNIEŻEK P. (1986) — Upper Rhaetian and Lower Jurassic clayey sediments near Lubliniec and Wieruszów (in Polish with English summary). Arch. Mineral., **41** (1): 135–143.

TEOFILAK A. (1966) — Liassic Heavy Minerals and their Origin. Bull. Acad. Pol. Sc. Ser. Sc. Geol. Geogr., **14** (1): 17–21.

TEOFILAK-MALISZEWSKA A. (1967) — Petrografia osadów liasu na Niżu Polskim. Biul. Inst. Geol., **207**: 67–144.

TEOFILAK-MALISZEWSKA A. (1968) — The petrography of the Liassic deposits in the Polish Lowland area (in Polish with English summary). Biul. Inst. Geol., **216**: 107–190.

TILLEY B. J. and LONGSTAFFE F. J. (1989) — Diagenesis and isotopic evolution of porewaters in the Alberta Deep Basin: The Falher Member and Cadomin Formation. Geochim. Cosmochim. Acta, **53** (10): 2529–2546.

TORTOSA A., PALOMARES M. and ARRIBAS J. (1991) — Quartz grain types in Holocene deposits from the Spanish Central System: some problems in provenance analysis. In: Developments in Sedimentary Provenance Studies (eds. A. C. Morton, S. P. Todd and P. D. W. Haughton). Geol. Soc. Spec. Publ., **57**: 47–54.

VELDE B. (1989) — Phyllosilicate formation in berthierine peloids and iron oolites. In: Phanerozoic Ironstones (eds. T. P. Young and W. E. G. Taylor). Geol. Soc. Spec. Publ., **46**: 3–8