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Upwelling regime in the Carpathian Tethys: a Jurassic-Cretaceous palaeogeographic and paleoclimatic perspective

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Jurassic and Cretaceous global palaeogeographic reconstructions show a changing configuration of mountains, land, shallow seas and deep ocean basins, and these are used as input for paleoclimatic modelling. We have generated Oxfordian-Kimmeridgian, Tithonian-Berriasian and Barremian-Hauterivian paleoclimatic maps, showing air pressure, wind directions, humidity zones and areas favourable to upwelling conditions, modelled by the PALEOCLIMATE program and plotted on the palaeogeographic background. Paleoclimate modelling suggests that prevailing Jurassic-Cretaceous winds in the northern Tethys area came from south-south-west, and may have been parallel to the Czorsztyn Ridge, uplifted as a result of extension during the Jurassic supercontinental breakup. Upwelling may have been induced at the southeastern margin of the ridge. The model is consistent with the rock records within the earliest Cretaceous deposits. The presence of phosphates and a palaeoenvironmental analysis of benthic fauna support the upwelling model.

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Key words: Tethys, Carpathians, Jurassic, Cretaceous, palaeogeography, paleoclimate, palaeoecology, upwelling.

INTRODUCTION

This paper compares a computer model with paleoclimatic indications in the rock record of the Polish Carpathians. It comprises two parts: global computer modelling maps and a case study based on field observations, faunal and facies analysis in the Pieniny Klippen Belt.

Climate modelling was introduced by Parrish (1982) and Parrish and Curtis (1982). Since then several different sophisticated computer programs have been developed (see e.g. Moore *et al*., 1992*a*, *b*, 1995; Valdes and Sellwood, 1992; Valdes, 1994; Price *et al*., 1995). We have concentrated on a single aspect of the paleoclimate — upwelling as an important cause of organic productivity. Therefore, instead of utilising the more sophisticated (and slow and expensive) general circulation model, we have used the fast, inexpensive PALEOCLIMATE software. We have focussed on the quality of the input for modelling, using the most advanced palaeogeographic maps for the Jurassic-Cretaceous of the Earth and the Tethys (see Golonka *et al*., 1994, 1996, 2000); the maps used as input by general circulation modelers (see e.g. Moore *et al*., 1995) were generalised. This study integrates modelling, palaeogeography, sedimentology and palaeontology to compare computer generated maps with the rock record.

PALEOCLIMATIC MODELLING MAPS — METHODOLOGY

The paleoclimatic modelling program is based on the methods first developed by Judy Parrish and her colleagues then at the University of Chicago (Parrish, 1982; Parrish and Curtis, 1982), later adapted by Chris Scotese (Scotese and Summerhayes, 1986) and modified by Malcolm Ross.

The PALEOCLIMATE program quantifies the Parrish approach using algorithms of the climatic control parameters. Palaeogeography, the zonal pressure system over the oceans, the thermally dominated pressure system over the continents, and seasonal shifts in pressure values are at the heart of this

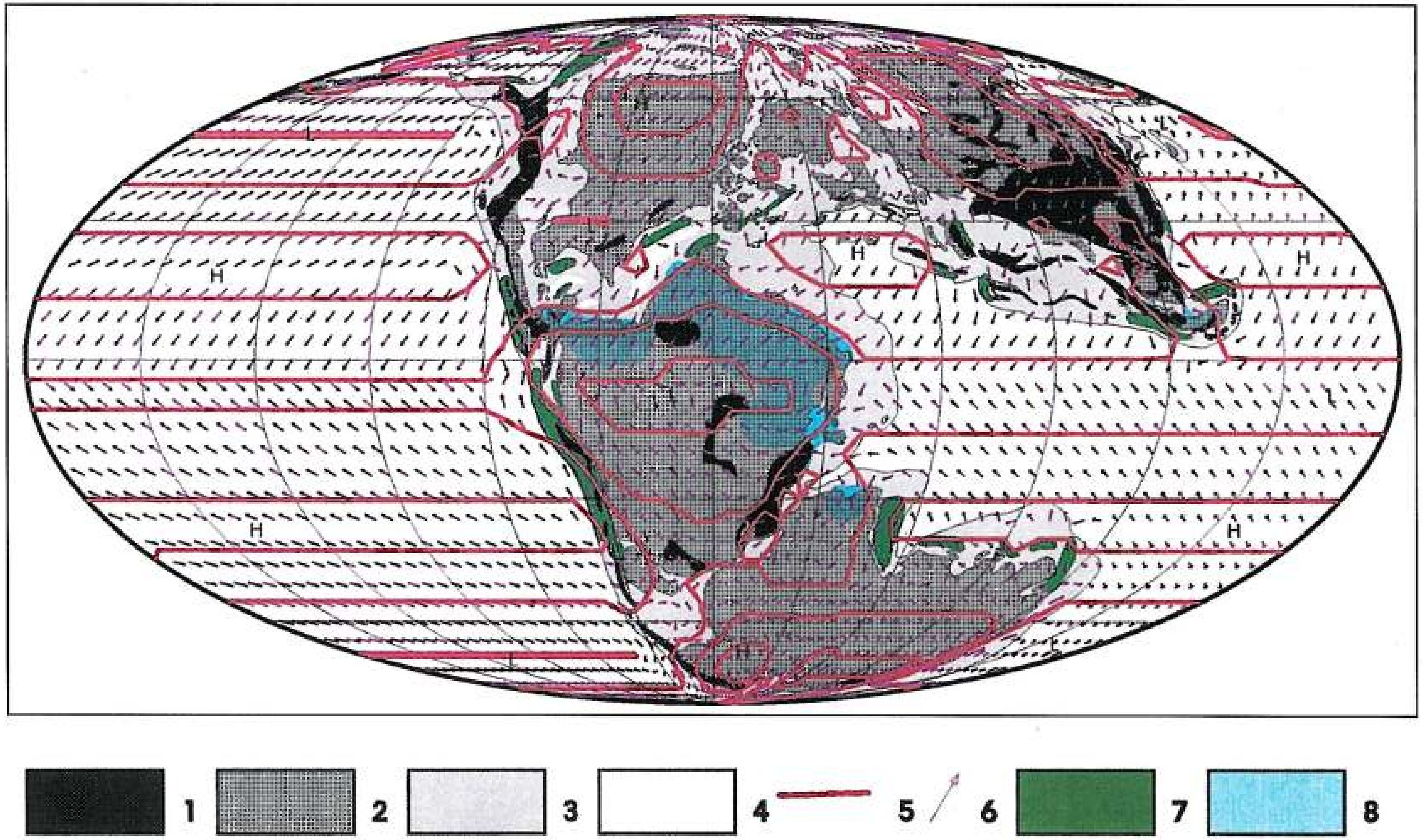

Fig. 1. Global palaeogeography and paleoclimate; Oxfordian-Kimmeridgian, Late Jurassic — 152 Ma winter Northern Hemisphere; palaeogeography based on Golonka *et al*. (1994, 1996), modified

1 — mountains, 2 — land masses, 3 — continental margins, 4 — deep water, 5 — pressure contours (H — high, L — low), 6 — wind vectors, 7 — over 70% probability of favourable conditions for coastal upwelling, 8 — over 70% probability of favourable conditions for equatorial humid environments

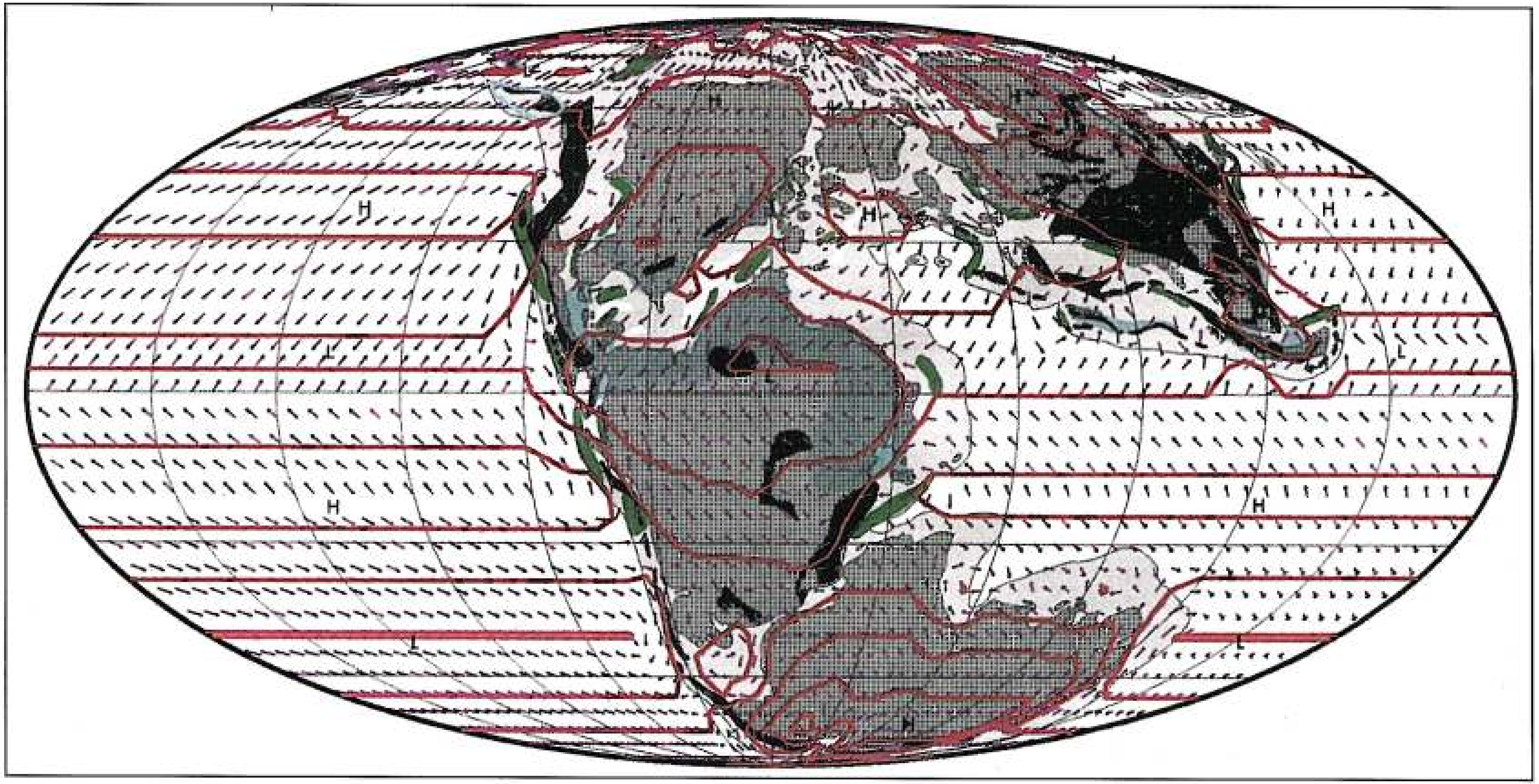

Fig. 2. Global palaeogeography and paleoclimate; Oxfordian-Kimmeridgian, Late Jurassic — 152 Ma summer Northern Hemisphere; palaeogeography based on Golonka *et al*. (1994, 1996), modified

Explanations as in Fig. 1

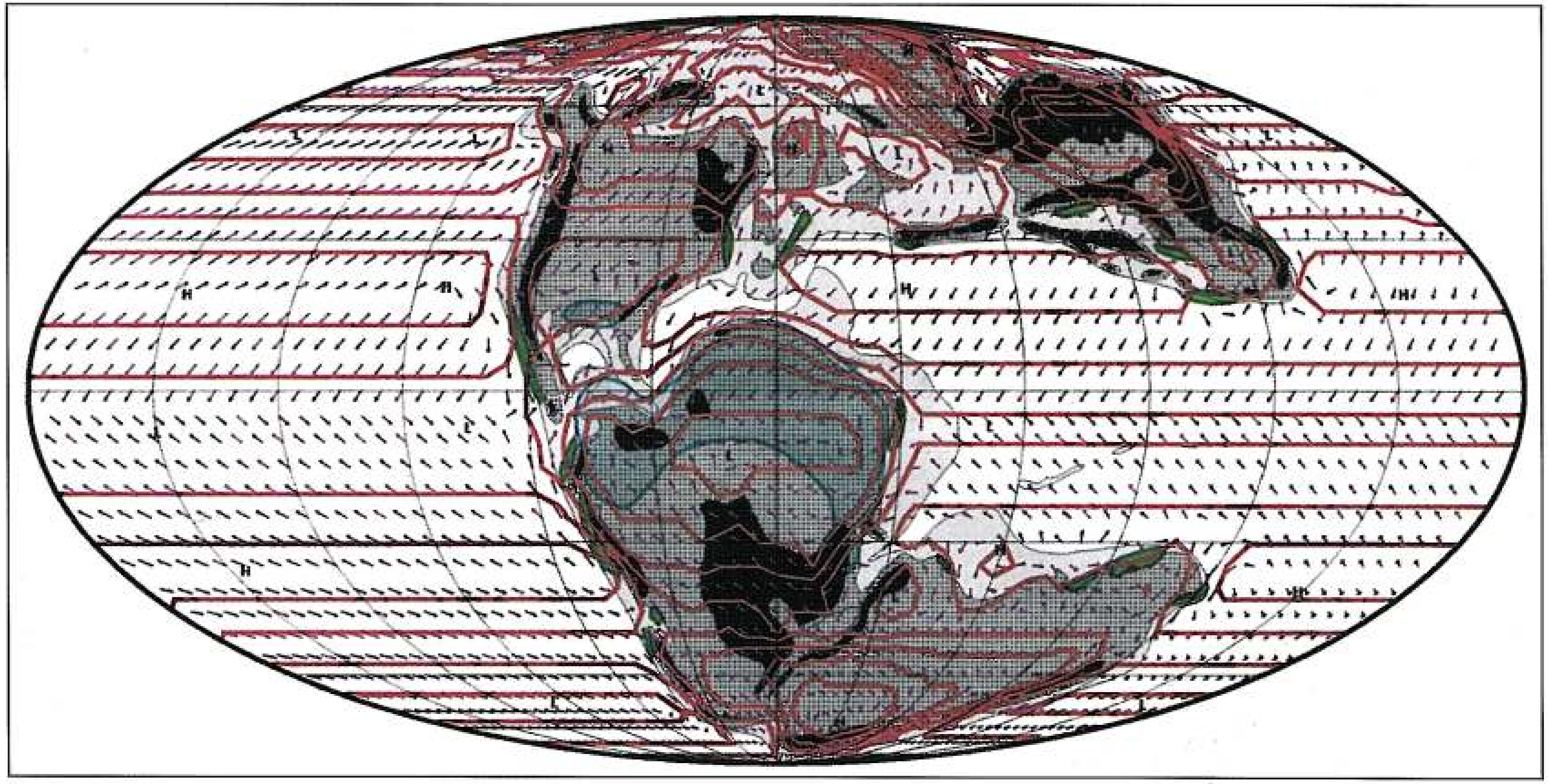

Fig. 3. Global palaeogeography and paleoclimate; Tithonian-Berriasian, Late Jurassic-Early Cretaceous — 140 Ma winter Northern Hemisphere; palaeogeography based on Golonka *et al*. (1994, 1996), modified

Explanations as in Fig. 1

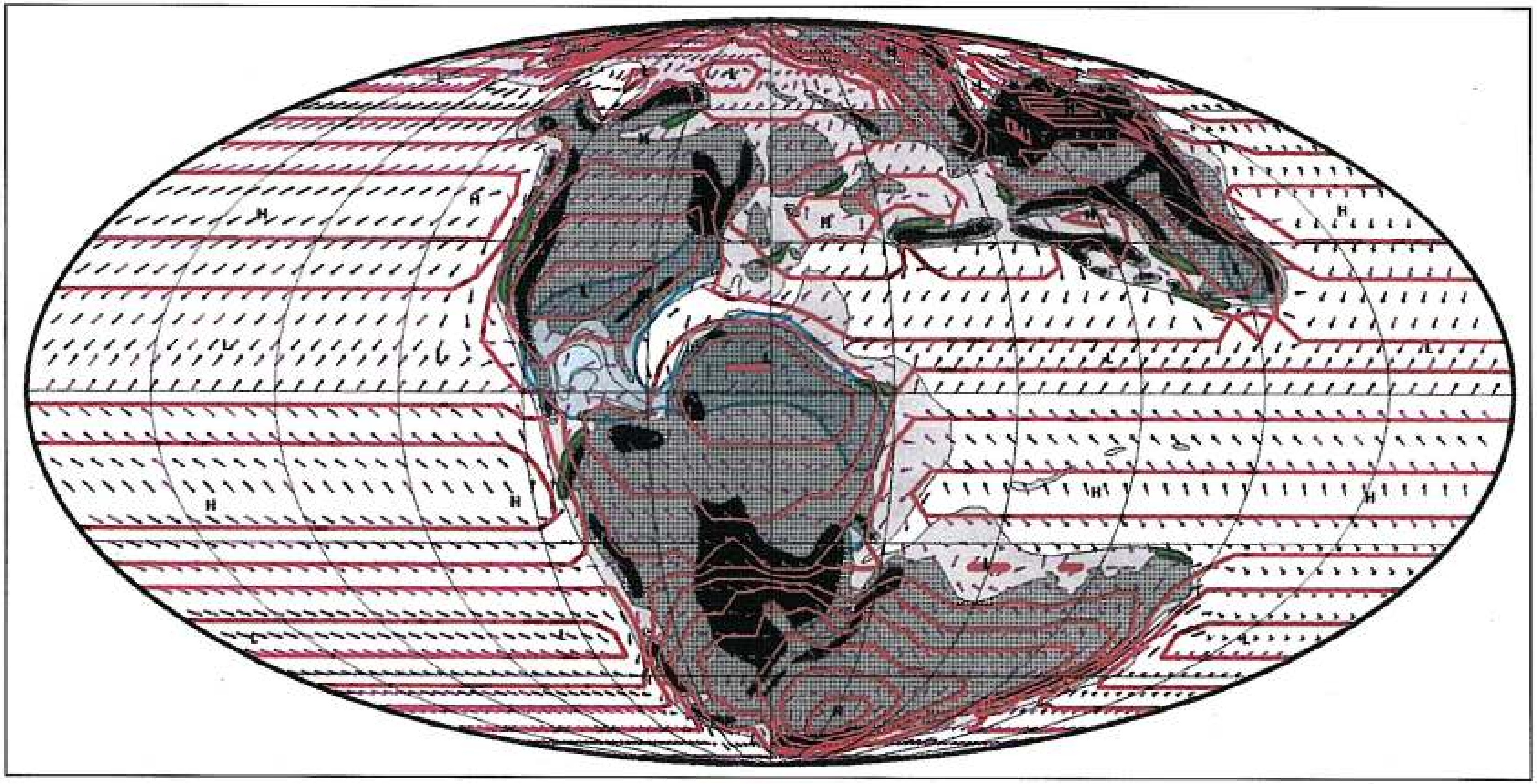

Fig. 4. Global palaeogeography and paleoclimate; Tithonian-Berriasian, Late Jurassic-Early Cretaceous — 140 Ma summer Northern Hemisphere; palaeogeography based on Golonka *et al*. (1994, 1996), modified

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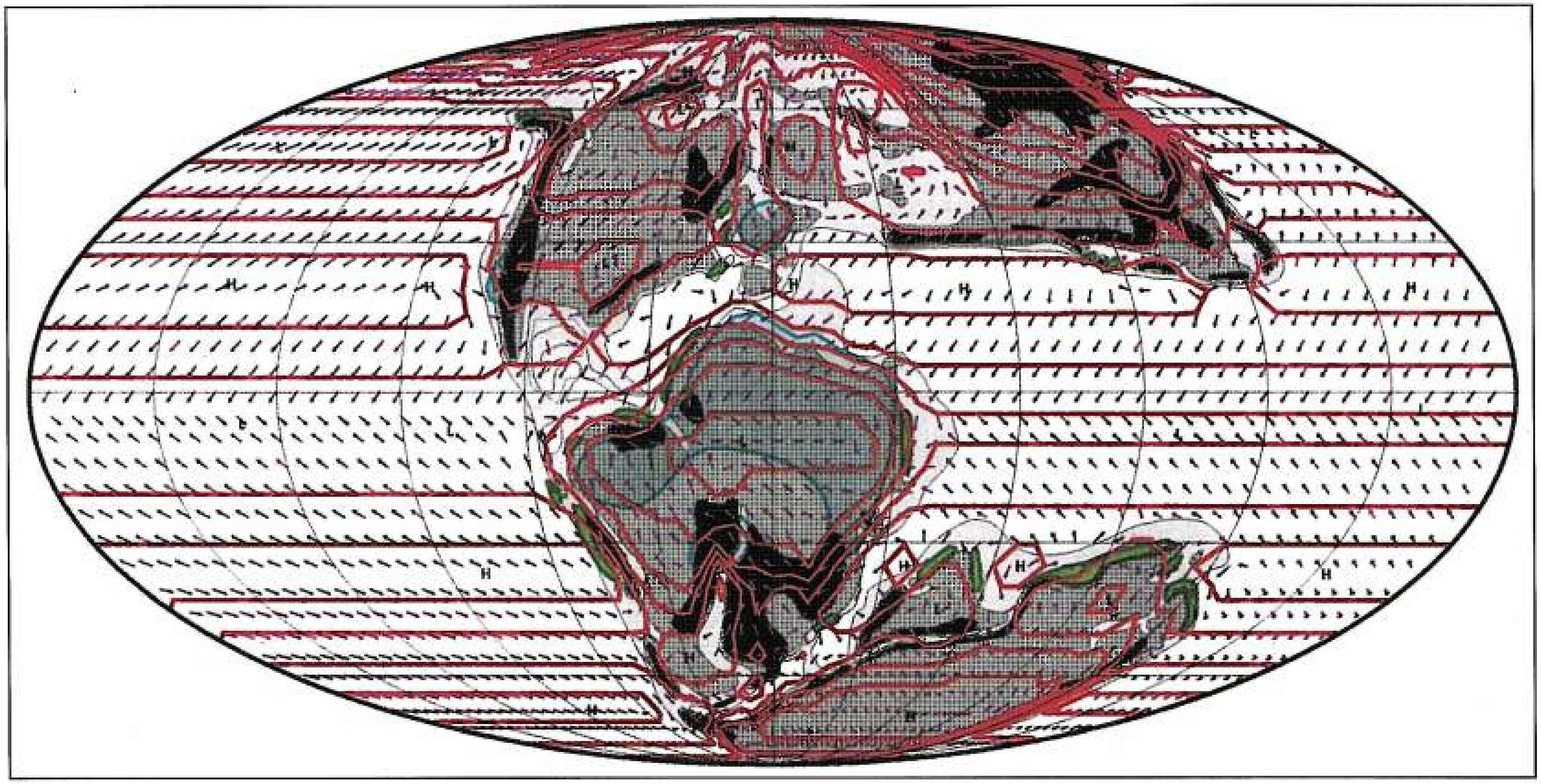

Fig. 5. Global palaeogeography and paleoclimate; Barremian-Hauterivian, Early Cretaceous — 126 Ma winter Northern Hemisphere; palaeogeography based on Golonka *et al*. (1994, 1996), modified

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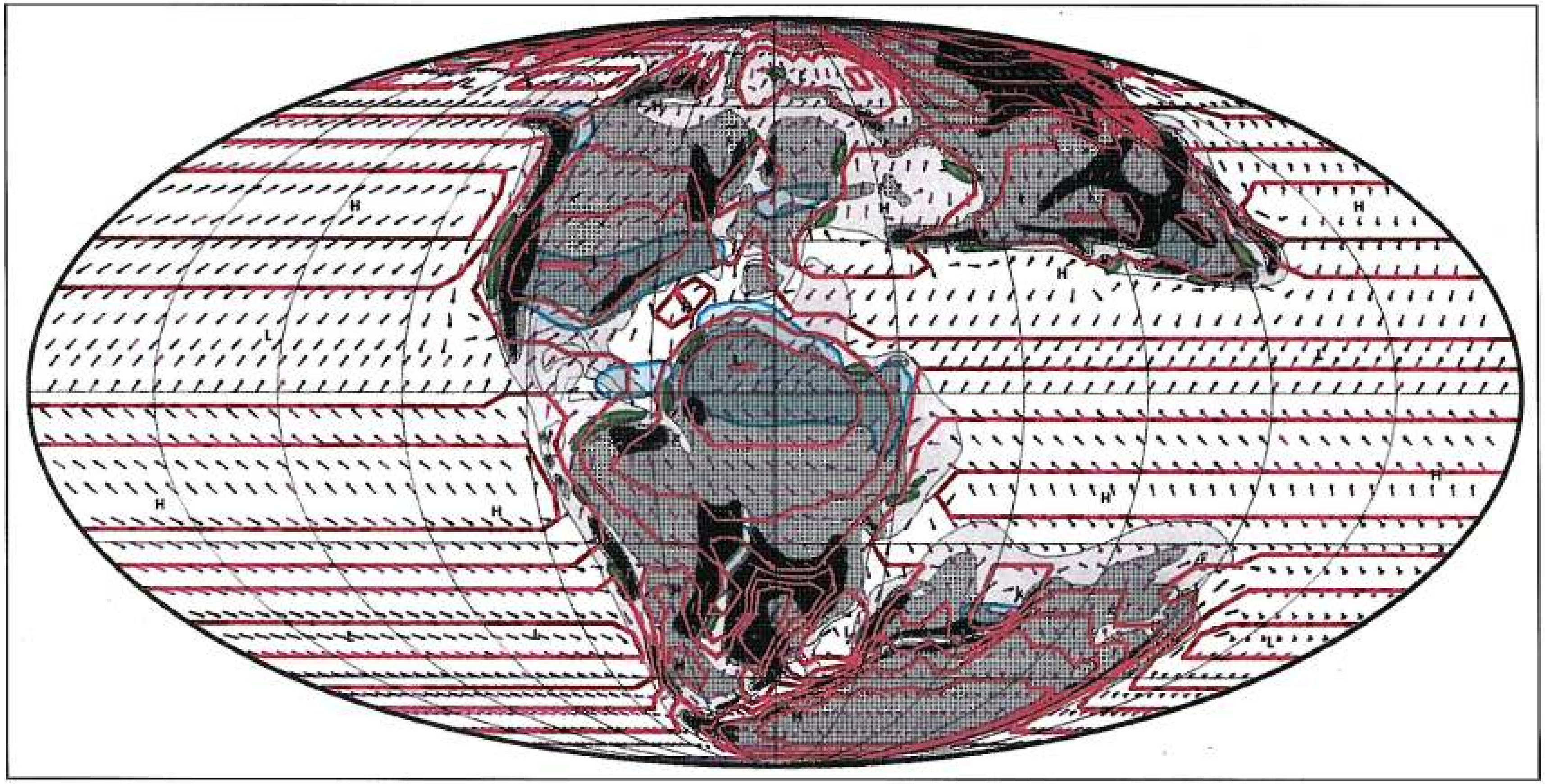

Fig. 6. Global palaeogeography and paleoclimate; Barremian-Hauterivian, Early Cretaceous — 126 Ma summer Northern Hemisphere; palaeogeography based on Golonka *et al*. (1994, 1996), modified

Explanations as in Fig. 1

computer model. The model also takes into account the effects of continentality, ocean-dominated settings, and the intensification of high-pressure cells off the coasts of continents.

Paleoclimate reads digitised palaeogeographic outlines (see Golonka, 1991; Golonka *et al*., 1994, 1996; Golonka and Gahagan, 1997; Golonka and Ford, 2000) and converts them to grid cells at the resolution specified by the user. The size of grid cells should match the resolution of the palaeogeography. For these global maps 5 degree sizes were used.

Paleoclimatic maps (Figs. 1–6) depict plate positions, palaeogeography, climate information such as relative air pressure, wind directions, humid areas, and the calculated positions of ancient upwelling systems which may correlate with hydrocarbon source rock occurrences through space and time. Because of the Coriolis force induced by the Earth's rotation, surface water moves off to the right of the wind direction in the Northern Hemisphere, and to the left in the Southern Hemisphere. This means that if winds blow parallel to the shore, the surface waters are forced to move either onshore or offshore, depending on wind direction. Where the surface waters move offshore, nutrient-rich subsurface waters well up to take their place. This process stimulates high marine productivity, which may form organic-rich muds that then may become petroleum source rocks.

Paleoclimatic information — pressure contours, wind vectors, probability of favourable conditions for coastal upwelling, and equatorial humid areas are superimposed on palaeogeographic templates. These templates illustrate the changing configuration of mountains, land, shallow seas and deep ocean basins. Generally, the individual maps illustrate the conditions present during the maximum marine transgressions of high frequency cyclicity within the Absaroka and Zuni sequences of Sloss (Golonka *et al*., 1997*a*; Golonka and Ford, 2000). Relative sea-level cyclicity (Haq *et al*., 1988), chronostratigraphy (Harland *et al*., 1990; Berggren *et al*., 1995; Gradstein *et al*., 1995; Gradstein and Ogg, 1996) and regional unconformities provide the basis to partition the higher frequency depositional cycles into subdivisions ranging from 11 to 25 Ma. The maps are named by the most representative stages within the mapped depositional cycle. The following time-slice maps were constructed:

— Oxfordian-Kimmeridgian (Figs. 1, 2) — tentative age range 166–146 Ma, begins at the Middle Bathonian unconformity and ends at the Middle Tithonian unconformity; mapped on a 152 Ma plate tectonic reconstruction;

— Tithonian-Berriasian (Figs. 3, 4) — tentative age range 146–135 Ma, begins at Middle Tithonian unconformity and ends at the Middle Valanginian unconformity; mapped on a 140 Ma plate tectonic reconstruction;

— Barremian-Hauterivian (Figs. 5, 6) — tentative age range 135–117 Ma, begins at the Middle Valanginian unconformity and ends at the Middle Aptian unconformity; mapped on a 126 Ma plate tectonic reconstruction.

We compare the computer model with paleoclimate indications found in the rock record in the Pieniny Klippen Belt in Poland.

PALAEOGEOGRAPHY OF THE NORTHERN TETHYS AND POSITION OF THE CZORSZTYN RIDGE

A detailed palaeoenvironment and lithofacies map of the northern Tethys and adjacent Europe and North Atlantic area was constructed for the Tithonian-Berriasian age slice (Fig. 7). Detailed discussion of the plate tectonics of the area and full references are given by Golonka *et al*. (2000).

The Jurassic-Early Cretaceous geodynamic evolution of the Circum-Carpathian Tethyan region reflects the plate tectonic history of the Earth during the breakup of Pangea. Triassic and Jurassic rifting resulted in the formation of oceanic basins along the northern margin of the Tethys Ocean (Fourcade *et al*., 1996). The Triassic Meliata and Triassic-Jurassic Pieniny Klippen Belt Oceans were formed in the western part of the region (Birkenmajer *et al*., 1990; Kozur, 1991; Dercourt *et al*., 1993; Channell, 1996; Channell and Kozur, 1997; Golonka *et al*., 2000). The Tauric and Greater Caucasus-Caspian Oceans were located east of the Moesian Platform (Zonenshain *et al*., 1990; Kazmin, 1991; Golonka *et al*., 2000). The Central Atlantic was in an advanced drifting stage during the Middle Late Jurassic (Golonka *et al*., 1996). Rifting continued in the North Sea and in the northern Proto-Atlantic. The progressive breakup of Pangea resulted in a system of spreading axes, transform faults, and rifts. This system connected the ocean floor spreading in the Central Atlantic and Ligurian-Piedmont Ocean to the opening of the Pieniny Klippen Belt Basin and to the rifting which continued through the Polish-Danish Graben to Mid-Norway and the Barents Sea. The oldest oceanic crust in the Ligurian-Piedmont Ocean is dated as late Middle Jurassic in the Southern Apennines and in the Western Alps (Ricou, 1996). The oldest known deposits in the basinal part of the Pieniny Klippen Belt are of Early Jurassic age (Birkenmajer, 1986). The Pieniny Klippen Belt Basin was fully opened by Middle Late Jurassic time. The basinal parts of northern Tethys are surrounded by several carbonate platforms, covering the shallow parts of the Adria, Umbria-Marche, Eastern Alpine, Inner Carpathian, and Moesian Plates. Spreading in the Ligurian-Pieniny Klippen Belt Ocean continued until the Tithonian. Major plate reorganisation took place during Tithonian time (Fig. 7). The Central Atlantic began to propagate into the area between Iberia and the New Foundland shelf (Ziegler, 1988).

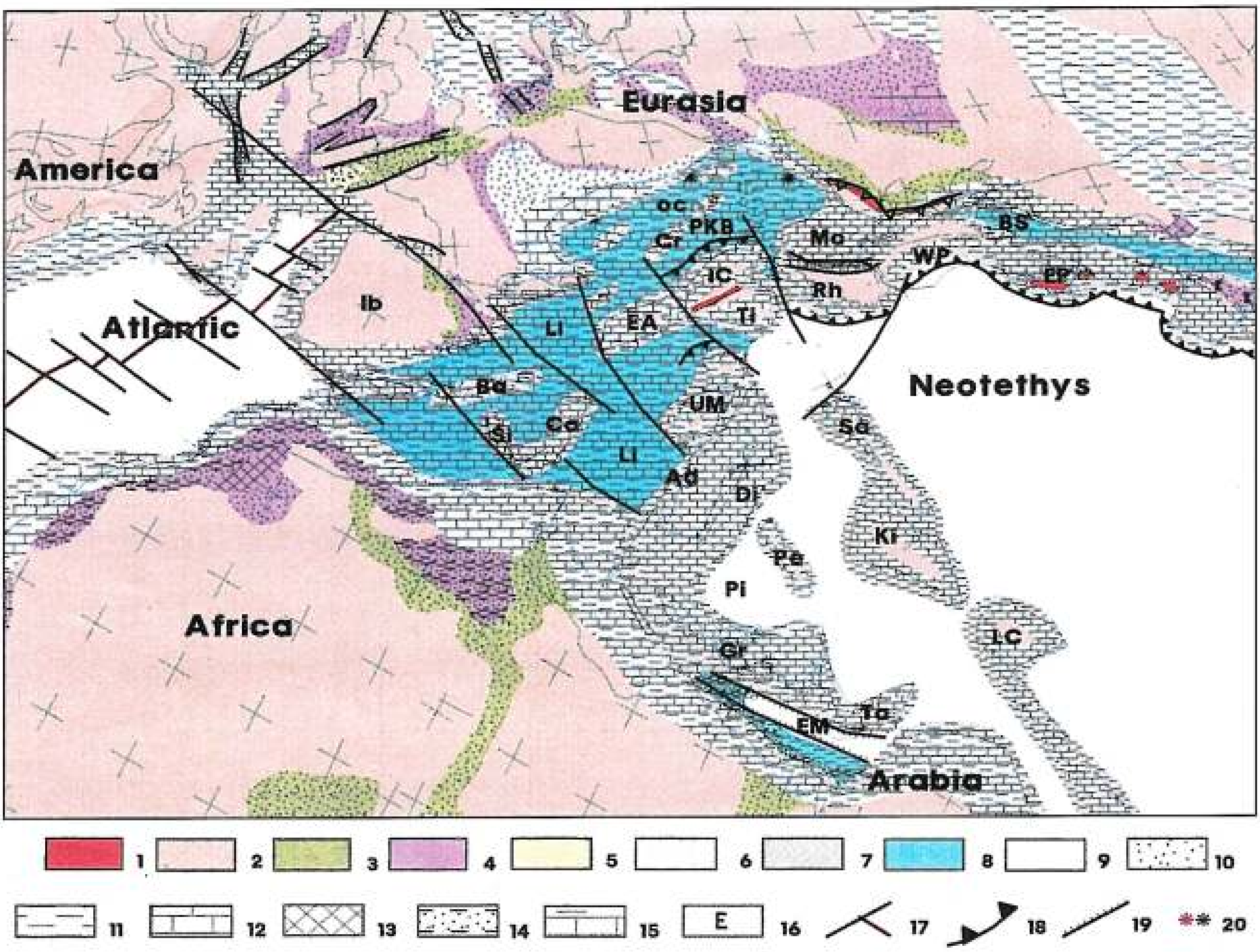

Fig. 7. Palaeoenvironment and lithofacies of the Circum-Carpathian Tethys area during Tithonian-Berriasian time (after Golonka *et al.*, 2000, modified)

Environment: 1 — mountains/highlands (active tectonically), 2 — topographic medium-low (inactive tectonically, non-deposit), 3 — terrestrial undifferentiated, 4 — coastal, transitional, marginal marine, 5 — deltaic, 6 — shallow marine, shelf, 7 — slope, 8 — deep ocean basin with sediments (continental, transitional, or oceanic crust), 9 — deep ocean basin with little to no sediments (primarily oceanic crust); **lithology**: 10 — sandstone, siltstone, 11 — shale, clay, mudstone, 12 — limestone, 13 — evaporite, 14 — interbedded or mixed sand/shale, 15 — interbedded or mixed carbonate/shale; **qualifiers**: 16 — evaporite; **tectonic elements**: 17 — oceanic spreading center and transform faults, 18 — active subduction zone, 19 — normal fault, active or significant to time, 20 — volcanoes (red — subduction related, black — extensional or hotspot related); **abbreviations of oceans and plates names**: Ib — Iberia, Li — Ligurian (Piemont) Ocean, OC — Outer Carpathian Basin (Magura and Silesian), PKB — Pieniny Klippen Belt Basin, Cr — Czorsztyn Ridge, EA — Eastern Alps, IC — Inner Carpathians (Meliata suture is located between Inner Carpathian region and Tisa), Ti — Tisa, Ba — Balearic, Si — Sicily, Ca — Calabria-Campania, UM — Umbria-Marche, Ad — Adria (Apulia), Di — Dinarides, Mo — Moesia, Rh — Rhodopes, WP — Western Pontides, EP — Eastern Pontides, BS — proto-Black Sea-Greater Caucasus Ocean, Sa — Sakariya, Ki — Kirsehir, LC — Lesser Caucasus, Pe — Pelagonian, Pi — Pindos Ocean, Gr — Greece, Ta — Taurus, EM — Eastern Mediterranean

The Ligurian-Pieniny Ocean reached its maximum width and the oceanic spreading stopped. The subduction of the Meliata-Halstatt Ocean and the collision of the Tisa Block with the Inner Carpathian terranes was concluded during the latest Late Jurassic-earliest Early Cretaceous. During the Tithonian, subduction jumped to the northern margin of the Inner Carpathian terranes and began to consume the Pieniny Klippen Belt Ocean (Birkenmajer, 1986). The Tethyan plate reorganisation resulted in extensive gravitational fault movements. Several horsts and grabens were formed, rejuvenating some older, Eo- and Meso-Cimmerian faults (Birkenmajer, 1986; Krobicki, 1996). The Outer Carpathian (Silesian and Magura) Basin had developed, with extensional volcanism (Golonka *et al.*, 2000). To the west, these troughs extended into the Valais Ocean, which entered a sea floor spreading phase (Froitzheim *et al.*, 1996), and further on into the area between Spain and France and to the Bay of Biscay (Stampfli, 1996). Eastward it was continued into the Eastern Carpathians in Ukraine and Romania (Golonka *et al.*, 2000).

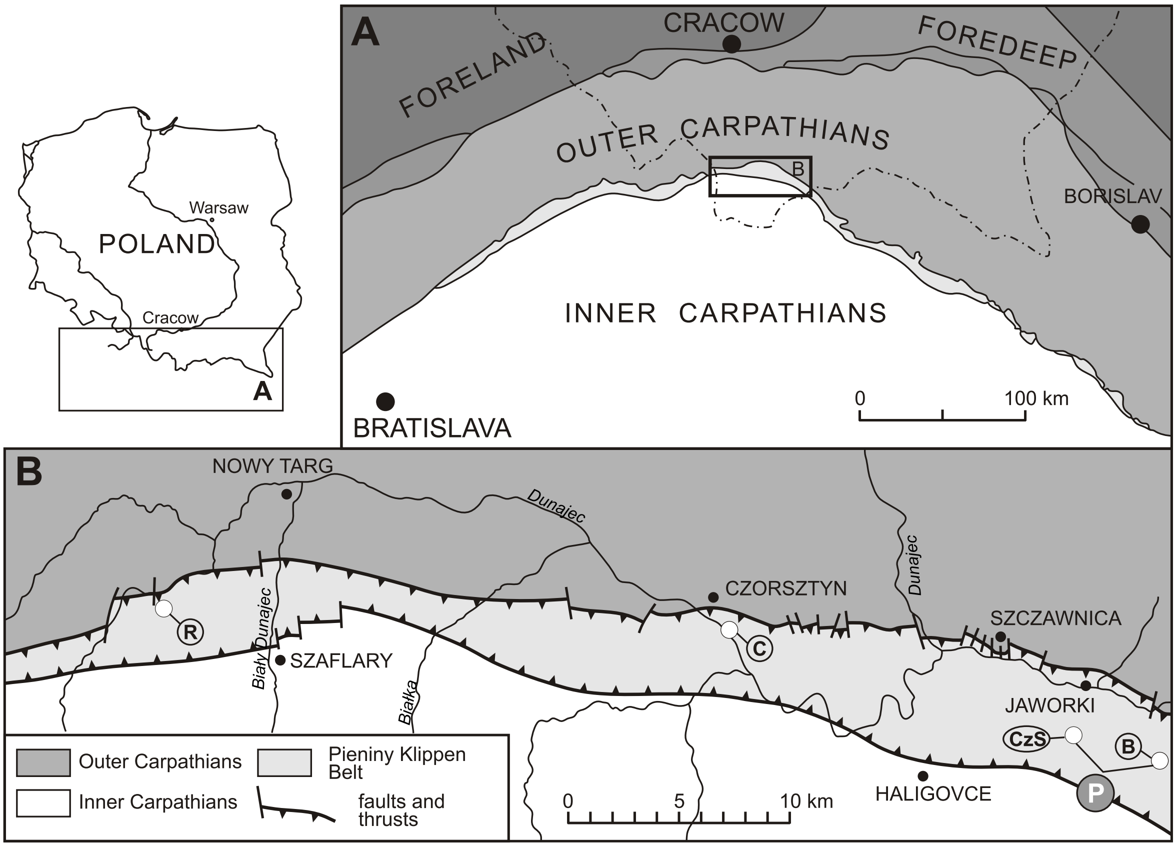

Fig. 8. **A** — location of the Pieniny Klippen Belt within the Carpathians with position of the investigated area (rectangle); **B** — location of the sections studied (mentioned in text) with Tithonian-Berriasian brachiopods and phosphates in the Pieniny Klippen Belt, Poland; sampling sites: R — Rogoźnik Klippes; C — Czorsztyn-Sobótka Klippe; phosphatic localities (P): CzS — Jaworki-Homole Gorge-Czajakowa Skała Klippe; B — Biała Woda-Brysztan

The Pieniny Klippen Belt is a narrow, elongated tectonic unit which follows the Carpathian subduction zone between the Inner and Outer Carpathians and extends from the vicinity of Vienna (Austria) through western Slovakia, Poland, eastern Slovakia and the Trans-Carpathian Ukraine to Romania (Fig. 8A). The Late Jurassic-Early Cretaceous Pieniny Klippen Belt Basin (Figs. 7, 9) is well-marked by NE–SW trending facies zones which correspond to ridges and troughs in the sea floor (from north-west to south-east: the Czorsztyn Ridge, Czorsztyn, Czertezik, Niedzica, Branisko-Pieniny and Haligovce successions and the Andrusov Exotic Ridge) (Birkenmajer, 1977, 1986, 1988) (Fig. 9).

The direction of the Czorsztyn Ridge remains somewhat speculative. Two alternative models exist in the literature on the subject:

1. A ESE–WNW orientation given for example by Michalík (1994), Vašíček *et al.* (1994), Channell and Kozur (1997).

2. A NE–SW direction (preferred in this paper), agreeing with reconstructions presented for example by Plašienka (2000, fig. 3).

A slight different “compromise” E–W position of Czorsztyn Ridge is also possible (e.g. Golonka *et al.*, 2000, fig. 5).

A NE–SW direction of the ridge is suggested by:

— the parallel direction of the major basins and ridges within the northern Carpathian realm suggested first by Książkiewicz (1960) and more recently by Burtan *et al.* (1984), Krobicki (1993), Krobicki and Słomka (1999);

— widening of the Magura and Silesian units westward (e.g. Żytko *et al.*, 1989; Kováč *et al.*, 1998; Golonka *et al.*, 2000). These units are significant in Slovakia, Czech Republic and Poland, pinching out at the Ukrainian-Romanian border;

— the mutual position of the Pieniny and Magura Basins, which relate to the breakup of Pangea. Their opening is linked to the opening of the Central Atlantic-Ligurian system (e.g. Dercourt *et al.*, 1993; Golonka *et al.*, 1994, 1996; Ricou, 1996; Kiesling *et al.*, 1999). The Atlantic-Ligurian trend is NE–SW;

— Laurasian plate rotation. The difference between the present day and palaeo-position of Laurasia (at the end of the Palaeozoic) is 43 degrees (Walker *et al.*, 1995). Laurasia rotated clockwise during Mesozoic-Cenozoic time. The trend of

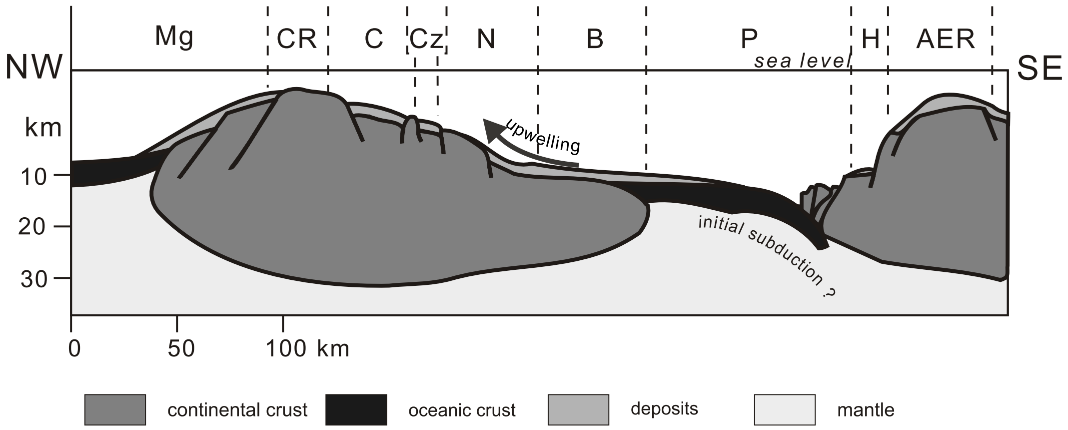

Fig. 9. Palinspastic reconstruction of the Pieniny Klippen Belt Basin during the Tithonian-Berriasian (based on Birkenmajer, 1977, 1986)

Mg — Magura Basin, Outer Carpathians, CR — Czorsztyn Ridge; successions: C — Czorsztyn, Cz — Czertezik, N — Niedzica, B — Branisko, P — Pieniny, H — Haligovce, AER — Andrusov Exotic Ridge

the Laurasian margin during the onset of Carpathian rifting is NE–SW (e.g. Kiessling *et al.*, 1999). The Czorsztyn Ridge rifted away from Laurasia in the Early Jurassic (Birkenmajer, 1986; Golonka *et al*., 2000). Its original NE–SW trend was perhaps retained until the Late Cretaceous-Paleogene basin closure;

— palaeogeographic space constraints. It is not possible to move the Inner Carpathian Block too far to the west and south (the option suggested e.g. by Michalík, 1994; Vašíček *et al*., 1994). This kind of movement would require the removal of several plates and produce severe problems in formulating a step-by-step Mesozoic-Cenozoic plate tectonic model. The plate position presented in this paper agrees with a consistent Phanerozoic global plate model (Golonka, 2000).

During the Jurassic and Cretaceous (pelagic stage C — *sensu* Birkenmajer, 1986) the submarine Czorsztyn Swell ("pelagic swell" — Mišík, 1994) was an elongated structure, nearly 500 kilometres long and some tens of kilometres wide. This swell was limited to the north-west and south-east by basins in which deep-water deposition of cherty limestones of the Maiolica *Nannoconus* facies took place (Golonka and Sikora, 1981; Wieczorek, 1988). The end-Jurassic Tethyan plate reorganisation resulted in the extensive gravitational faulting of this area (Neo-Cimmerian movements) (Birkenmajer, 1986). Effects of the Neo-Cimmerian movements are particularly well pronounced in Tithonian-Berriasian deposits (syn-sedimentary breccias, neptunian dykes, reworking of fossils, e.g. Birkenmajer, 1975; Krobicki and Słomka, 1999). Initial stages of subduction of oceanic crust under the northern, active margin of the Inner Carpathian plate along the Andrusov Exotic Ridge are related to these movements (Birkenmajer, 1986, 1988) (Fig. 9). It is also possible to envisage south-dipping subduction under the Inner Carpathian region without an acknowledgement of Andrusov Exotic Ridge existence (e.g. Plašienka, 1995). We follow Birkenmajer's model, although there are various alternative models explaining the closing of the Pieniny Klippen Belt Ocean (Ślączka and Golonka, in prep.):

1. Subduction at the northern margin of the Inner Carpathian terranes (the model preferred in this paper). The latest Cretaceous-earliest Paleocene was the time of the closure of the Pieniny Ocean and the collision of the Inner Carpathians terranes with the Czorsztyn Ridge. The subduction zone jumped from the southern margin of the Pieniny Basin to the northern margin of the Czorsztyn Ridge and began to consume the Magura Basin. The Jurassic-Early Cretaceous Magura Basin was the part of the Mesozoic Tethyan oceanic system connected with the Ligurian-Pieniny Ocean. The Silesian and other Outer Carpathian Basins developed as rifts on the European margin.

2. Subduction developed at the southern margin of the Eurasian plate. The Outer Carpathian Basin had developed as a back-arc. By Albian time, a part of the Pieniny Klippen Belt Ocean (Grajcarek-Hulina Basin) was consumed, and the new Magura Basin had developed.

3. Subduction developed at both margins of the Pieniny-Magura Basin. The Outer Carpathian realm is a combination of oceanic (part of Magura) and continental rifted basins. The rifted sub-basins, such as the Dukla, Silesian, Sub-Silesian, Skole, Tarcau, were separated by uplifted areas.

PALEOCLIMATE modelling (Figs. 1–6) suggests prevailing north-north-east Jurassic-Cretaceous wind directions in the northern Tethys area, parallel to the axis of the Czorsztyn Ridge (Figs. 14A, B). Upwelling may have been induced at the south-eastern margin of the ridge. This model is consistent with the rock record, especially from the uppermost part of the *Calpionella* limestone — type Dursztyn Limestone Formation (Sobótka Limestone Member) of the Niedzica Succession (Birkenmajer, 1986; Krobicki, 1994, 1996; Golonka and Krobicki, 1995) (Fig. 11B).

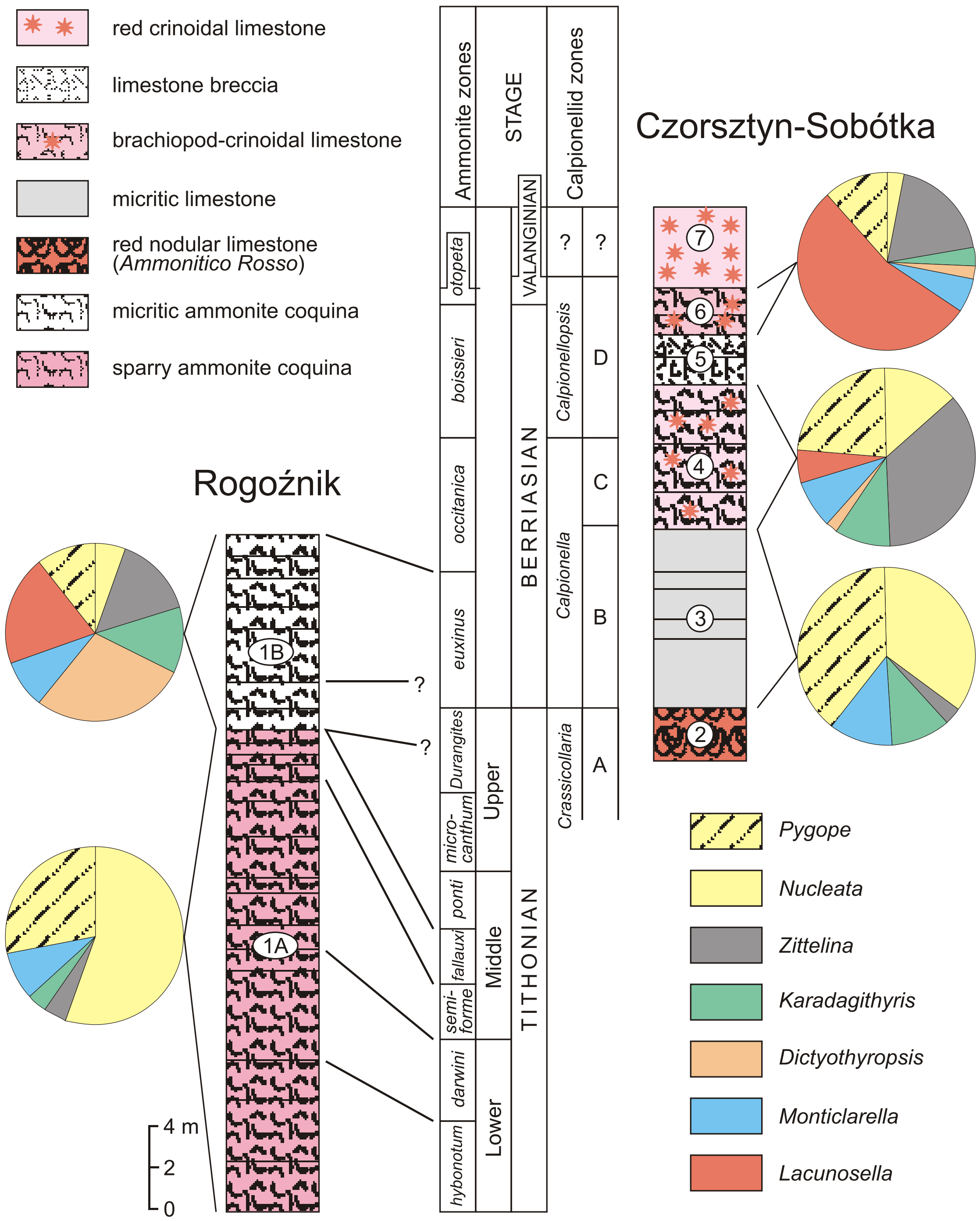

Fig. 10. Correlation of Tithonian-Berriasian deposits from Rogoźnik Klippes and Czorsztyn-Sobótka outcrops with pie charts of brachiopod assemblages (after Krobicki, 1996, modified; stratigraphy after Kutek and Wierzbowski, 1986 and Wierzbowski and Remane, 1992; lithostratigraphy after Birkenmajer, 1977)

1 — Rogoźnik Coquina Member (Dursztyn Limestone Formation): A — red sparitic coquina, B — white micritic coquina; 2 — Czorsztyn Limestone Formation; 3 — Sobótka Limestone Member (Dursztyn Limestone Formation) (white *Calpionella* limestone); 4–6 — Łysa Limestone Formation: 4 — Harbatowa Limestone Member, 5 — Walentowa Breccia Member, 6 — Kosarzyska Limestone Member; 7 — Spisz Limestone Formation

THE GLOBAL-LOCAL RELATIONS

The faunal assemblages, as well as the existence of phosphates, indicate links between sedimentation on the Czorsztyn Ridge, wind direction, water circulation and upwelling zones. The following detailed analysis of brachiopod faunas serve as a case study documenting palaeoenvironmental change connected with Neo-Cimmerian uplift of the Czorsztyn Ridge. This local uplift reflects the global trends of plate reorganisation. Simultaneously, deposition of phosphates happened as a result of palaeoceanographic changes. This case study demonstrates the validity of global paleoclimatic modelling and suggests the application of this method to the other areas of the world (see Figs. 1–6).

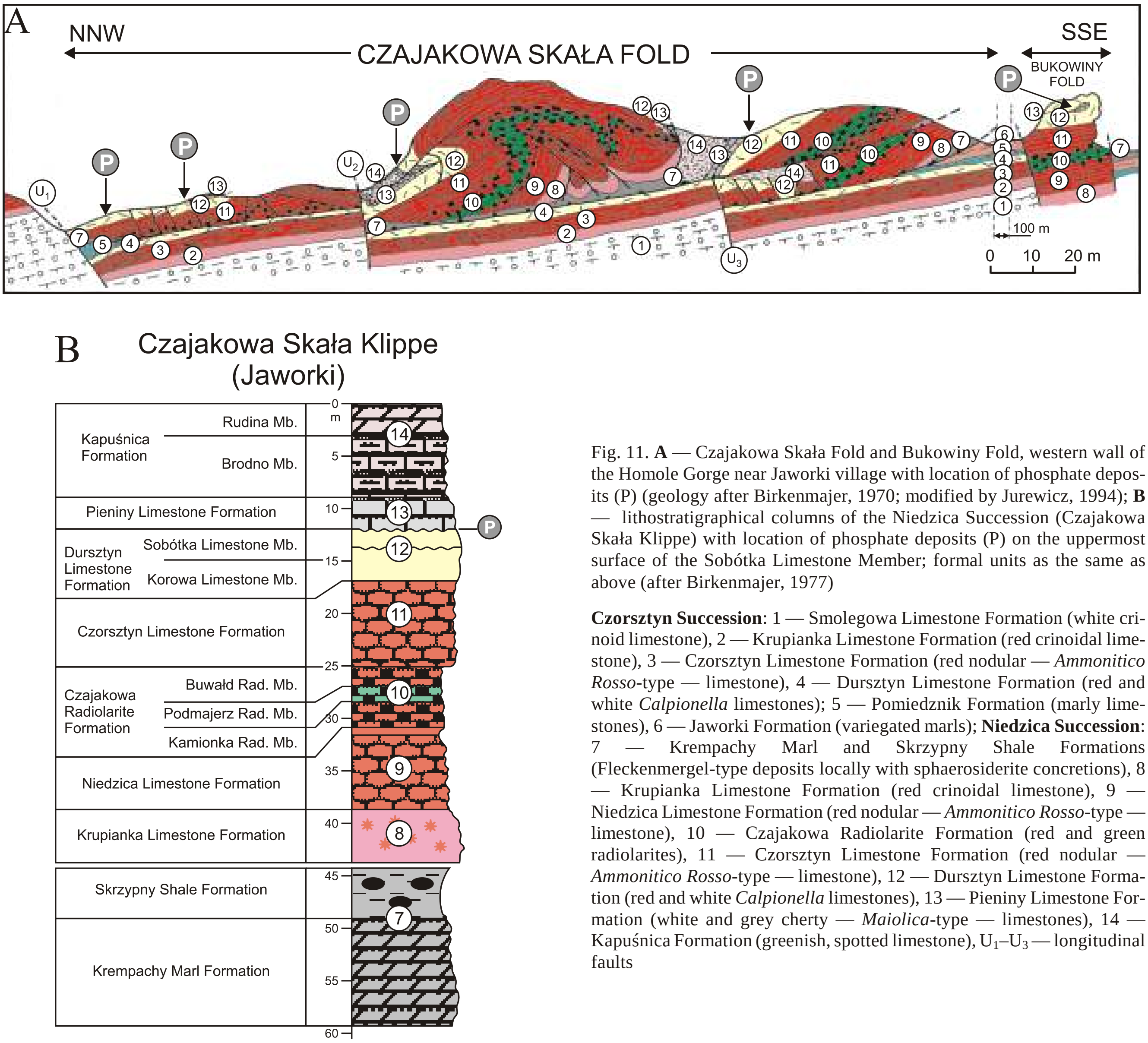

Fig. 11. **A** — Czajakowa Skała Fold and Bukowiny Fold, western wall of the Homole Gorge near Jaworki village with location of phosphate deposits (P) (geology after Birkenmajer, 1970; modified by Jurewicz, 1994); **B** — lithostratigraphical columns of the Niedzica Succession (Czajakowa Skała Klippe) with location of phosphate deposits (P) on the uppermost surface of the Sobótka Limestone Member; formal units as the same as above (after Birkenmajer, 1977)

Czorsztyn Succession: 1 — Smolegowa Limestone Formation (white crinoid limestone), 2 — Krupianka Limestone Formation (red crinoidal limestone), 3 — Czorsztyn Limestone Formation (red nodular — *Ammonitico Rosso*-type — limestone), 4 — Dursztyn Limestone Formation (red and white *Calpionella* limestones); 5 — Pomiedznik Formation (marly limestones), 6 — Jaworki Formation (variegated marls); **Niedzica Succession**: 7 — Krempachy Marl and Skrzypny Shale Formations (Fleckenmergel-type deposits locally with sphaerosiderite concretions), 8 — Krupianka Limestone Formation (red crinoidal limestone), 9 — Niedzica Limestone Formation (red nodular — *Ammonitico Rosso*-type — limestone), 10 — Czajakowa Radiolarite Formation (red and green radiolarites), 11 — Czorsztyn Limestone Formation (red nodular — *Ammonitico Rosso*-type — limestone), 12 — Dursztyn Limestone Formation (red and white *Calpionella* limestones), 13 — Pieniny Limestone Formation (white and grey cherty — *Maiolica*-type — limestones), 14 — Kapuśnica Formation (greenish, spotted limestone), U_1–U_3 — longitudinal faults

ANALYSIS OF BRACHIOPOD MATERIAL

Detailed biostratigraphic studies of Czorsztyn Succession have led to the subdivision of Tithonian and Berriasian deposits using ammonite and calpionellid zones (Kutek and Wierzbowski, 1986; Wierzbowski and Remane, 1992; Wierzbowski, 1994). The best studied sequences containing brachiopods are the Rogoźnik Klippes and the Czorsztyn-Sobótka Klippe (Fig. 8B) where successions of Tithonian and Berriasian brachiopods were studied bed-by-bed (Fig. 10). Stratigraphic ranges of the taxa are based mostly on the studies of Barczyk (1991) and Krobicki (1994). The ranges show that the taxa analysed occur in both the Tithonian and the Berriasian, suggesting that palaeoecological conditions (bathymetry, hydroenergy, and oceanic productivity) were the stimulating factors for the diversification of the brachiopod assemblages in successions and/or facies. Quantitative and qualitative changes in faunal assemblages may help determine palaeoecological conditions. These conditions depend on the palaeogeographic position of specific facies in the palinspastic reconstruction of the Pieniny Klippen Belt Basin. The dominance/presence/absence of given taxa in succeeding lithofacies has been analysed. The gradual replacement of initially dominant pygopids (*Pygope* and *Nucleata*) by rhynchonellids (*Lacunosella*) assemblages was recorded.

Lacunosella rhynchonellids commonly occur in shallow-water, reef-like, Tithonian-Berriasian and Lower Valanginian sediments (so-called Štramberk Limestones)

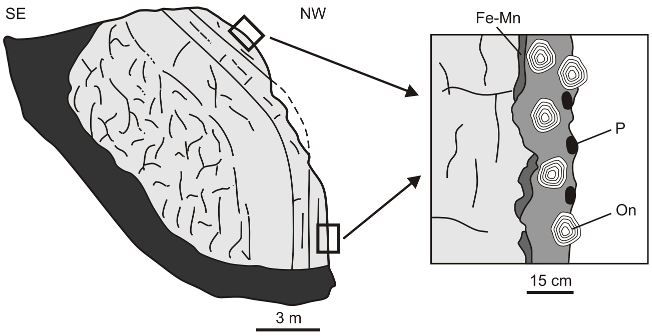

Fig. 12. Biała Woda-Brysztan section; Dursztyn Limestone Formation, Sobótka Limestone Member (Berriasian), Niedzica Succession; in enlargement: top of last bed (after Krobicki, 1993, 1994)

Fe-Mn — Fe-Mn crusts, P — phosphorites, On — phosphatic macrooncoids

(Wójcik, 1914; Książkiewicz, 1974; Nekvasilová, 1977). According to Ager (1965), these are typical sub-littoral forms.

Pygopids (the genera *Pygope* and *Nucleata*) were usually interpreted as deep-water organisms (Ager, 1965, 1976). Dieni and Middlemiss (1981) described an abundant collection of these brachiopods from the Venetian Alps, from pelagic limestones of Maiolica facies which are the facies equivalent of the cherty limestones of the Branisko-Pieniny Succession (Pieniny Limestone Formation) (Wieczorek, 1988). *Pygope*, with its deep-water preference, could be indicative rather of colder than warmer water, thus suggesting upwelling zones (*cf*. Sandy, 1991; Michalík, 1996). It has also been suggested that pygopids could also occupy shallow waters over seamounts (Ager, 1986, 1993). The Czorsztyn pelagic swell represents such a chain of seamounts. The eurybathic character of both *Pygope* and *Nucleata* suggests opportunistic, r-selected taxa (Krobicki, 1993, 1994). The domination of these brachiopods points to deeper deposition environments in which the remaining taxa were eliminated from the biocenosis.

In the Czorsztyn Succession, significant amounts of *Lacunosella* suggest a generally shallower depositional environment of the enclosing sediments in comparison with those strata in which rhynchonellids are rare or absent. On the other hand, the increasing percentage of pygopids in the studied assemblage suggests deeper environments (Fig. 10). Usually, if *Lacunosella* representatives constitute about 25% of the assemblage, both *Pygope* and *Nucleata* are subordinate and *vice versa*. Abrupt shallowing trends in sedimentary basin at the Tithonian-Berriasian boundary have been noted in various parts of the Czorsztyn Succession. This indicates that palaeoecological factors (mainly bathymetry) stimulated differentiation of the brachiopod assemblages in time and space, corresponding to a shallowing-upwards trend (Krobicki, 1994, 1996). Additionally, in the ammonite assemblage of the Lower and Middle Tithonian, nektopelagic forms prevail over nektobenthic ones, suggesting a deep-water sedimentary environment (see Cecca *et al*., 1993).

Such phenomena are the result of pronounced Neo-Cimmerian tectonic movements (Osterwald Phase — after Birkenmajer, 1958, 1975, 1986) which affected the Czorsztyn pelagic swell. These movements are expressed by facies diversification, hardgrounds and condensed beds with ferromanganese-rich crusts and/or nodules, sedimentary-stratigraphic hiatuses, sedimentary breccias, neptunian dykes and/or faunal redeposition. These processes were caused by origination and subsequent destruction of the submarine tectonic horsts attributed mainly to the Neo-Cimmerian episode of tectonic activity in the Carpathians (Birkenmajer, 1986; Krobicki, 1996; Krobicki and Słomka, 1999) (Figs. 7, 13).

PHOSPHATE DISTRIBUTION

The present paper includes data from the Jurassic/Cretaceous boundary deposits. The sequences were studied in natural outcrops of the Niedzica Succession situated in the eastern part of the Polish sector of the Pieniny Klippen Belt. The Dursztyn Limestone Formation, subdivided into the Korowa Limestone Member and the Sobótka Limestone Member (Birkenmajer, 1977), represents the Tithonian/Berriasian boundary strata of the Niedzica Succession. In the vicinity of Niedzica, the Niedzica Succession forms isolated tectonic wedges, strongly folded together with Upper Cretaceous marly deposits of the Czorsztyn Succession. East of Jaworki (Figs. 8B, 11) the Niedzica Succession occurs as a large sheet (nappe) thrust over the Czorsztyn Succession. The outcrops studied expose white, massive, micritic limestone which grades upwards into thin-bedded, micritic limestone rich in bioclasts (crinoids, brachiopods, ammonites, small gastropods) of the Sobótka Limestone Member. At the top part (in 7 exposures) of this member, a 10–20 cm thick layer composed of green micritic limestone, rich in phosphorite occurs. At this level (in all sections) large (8–10 cm across), phosphatic macrooncoids form an oncolitic pavement (see Krobicki, 1993, 1994, pl. VIII, 1996). On bedding surfaces, large ammonites (up to 30 cm in diameter) are visible. The rock is strongly fractured; Fe-Mn crusts cover the irregular surfaces of the sedimentary discontinuities (Figs. 11, 12).

DISCUSSION AND CONCLUSIONS

Paleoclimatic modelling maps for Jurassic and Cretaceous times show wind directions favourable for upwelling conditions, which existed over a long time span. The best example of such continuous conditions is the western coast of the Americas (Figs. 1–6), where upwelling happens from time to time (Parish and Curtis, 1982). Palaeozoic, Mesozoic and Cenozoic

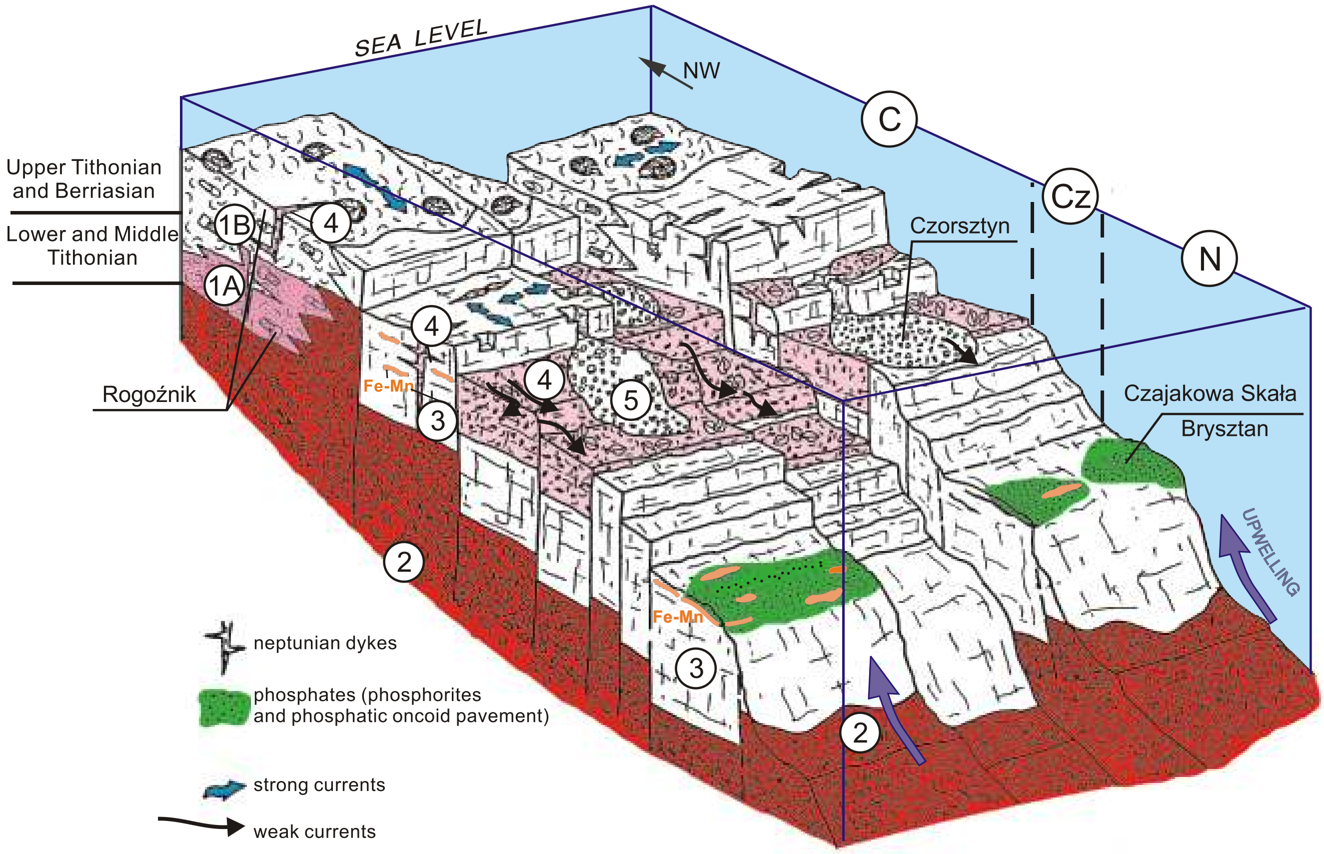

Fig. 13. Model of sedimentation on the intraoceanic Czorsztyn pelagic swell in Berriasian with effects of pronounced Neo-Cimmerian tectonic movements and upwelling currents (after Krobicki, 1996, modified)

1 — Rogoźnik Coquina Member (Dursztyn Limestone Formation): A — sparitic coquina, B — micritic coquina; 2 — Czorsztyn Limestone Formation (*Ammonitico Rosso* facies); 3 — Sobótka Limestone Member (Dursztyn Limestone Formation); 4, 5 — Łysa Limestone Formation: 4 — Harbatowa Limestone Member, 5 — Walentowa Breccia Member; successions: C — Czorsztyn, Cz — Czertezik, N — Niedzica

organic-rich deposits and associated phosphatic beds reflect the upwelling events along the coast.

The rock record from Pieniny Klippen Belt shows that upwelling happened in lowermost Cretaceous time. The inception of upwelling may be associated with the time of plate tectonic reorganisation. Tectonic movements generated shallow platforms and islands along the NE–SW trending ridges between the main part of Tethys and the Eurasian Platform. Paleoclimate modelling (Figs. 14A, B) suggests that the Jurassic-Cretaceous prevailing wind directions in the Circum-Carpathian Tethys area were north-north-east, parallel to the ridges. Upwelling may have been induced at the south-eastern margin of the ridges.

This type of oceanic circulation has been recorded in a specific association of deposits. These are, given the extremely high biological productivity associated with upwelling, mainly biogenic rocks with high contents of organic matter, silica, and phosphates in different forms, and deposits with elevated contents of some trace elements. The coincidence of these factors in a given palaeogeographical situation might help to reconstruct the palaeoceanographical conditions of a specific type of upwelling circulation.

Upwelling areas are marine regions, in which masses of cold sea waters, rich in nutrients, are lifted from ocean depths toward more shallow zones, situated most often along the continent margins. Such a nutrient-rich water circulation facilitated growth of zoo- and phytoplankton (which was, in turn, the basic food source for brachiopods — see Rudwick, 1970). Organic production at the lowest trophic level might have been very high, as it caused flourishing growth of benthic organisms along several hundreds of the kilometres-long, intraoceanic Czorsztyn pelagic swell. At the same time, at the Tithonian-Berriasian boundary, a microplankton (mainly calpionellids) explosion took place in the sedimentary basins of the Western Carpathians, triggered by palaeogeographic changes related to Neo-Cimmerian tectonics (Reháková and Michalík, 1994). The presence of phosphate-rich deposits (phosphorites and microbial phosphate structures — macrooncoids) in the Berriasian deposits of the Niedzica Succession, which in a palinspastic reconstruction represents a shelf-edge/slope boundary, supports this idea (Figs. 9, 13).

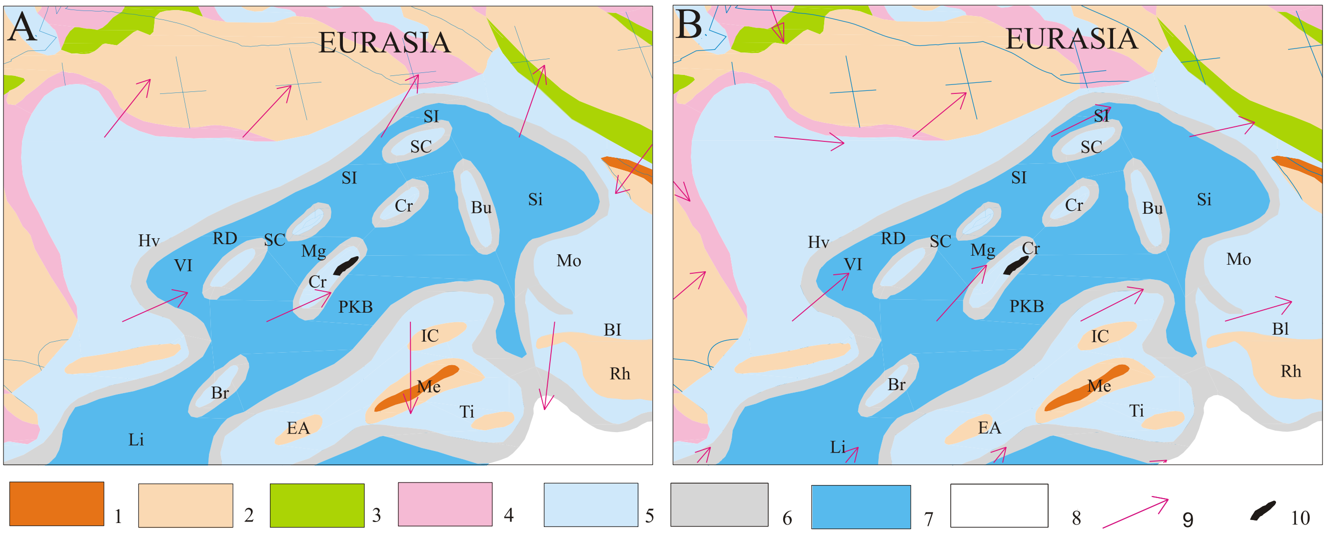

Fig. 14. Palaeoenvironments, wind direction and upwelling zones of the Carpathian area during Tithonian-Berriasian time (palaeogeography after Golonka *et al*., 2000, modified): **A** — summer Northern Hemisphere, **B** — winter Northern Hemisphere

1 — mountains/highlands (active tectonically), 2 — topographic medium-low (inactive tectonically, non-deposit), 3 — terrestrial undifferentiated, 4 — coastal, transitional, marginal marine, 5 — shallow marine, shelf, 6 — slope, 7 — deep ocean basin with sediments (continental, transitional, or oceanic crust), 8 — deep ocean basin with little to no sediments (primarily oceanic crust), 9 — wind directions, 10 — upwelling zone; **abbreviations of oceans and plates names**: Bl — Balcans, Br — Briançonnais terrane, Bu — Bucovinian terrane, Cr — Czorsztyn Ridge, EA — Eastern Alps, Hv — Helvetic zone, IC — Inner Carpathians, Li — Ligurian (Piemont) Ocean, Me — Meliata suture, Mg — Magura Basin, Mo — Moesia Plate, PKB — Pieniny Klippen Belt Basin, RD — Rheno-Danubian Basin, Rh — Rhodopes, SC — Silesian Ridge (cordillera), Si — Siret, Sl — Silesian Basin, Ti — Tisa Plate, Vl — Valais Trough

Similar phosphate sediments, known from recent and fossil sedimentary environments, suggests upwelling in such places.

Analysis of this proposed sedimentation model for the Tithonian-Berriasian carbonate rocks of the Czorsztyn pelagic swell (Fig. 13), particularly the comparison of brachiopod pie charts and phosphate distribution, suggests that the gradual tectonic uplift of the Czorsztyn Ridge, particularly in post-Tithonian time (Neo-Cimmerian movements), caused a significant shallowing over vast areas of the Czorsztyn realm. The resulting shallow, submarine ridges were parallel to wind directions and separated various zones of oceanic currents and this could have led to upwelling (Birkenmajer, 1986; Krobicki, 1993, 1994, 1996). The nutrient supply increased during the Late Jurassic Oceanic Anoxic Events and was perhaps related to volcanic activity. Mass occurrences of Tithonian and Berriasian brachiopods in the Czorsztyn Succession were probably controlled by upwelling-induced trophic relationships, which resulted in intense growth of benthic organisms. Similar effects of upwelling currents are known from modern, marine environments with this type of circulation (accumulation of turitellids in California — Allmon, 1988; brachiopod shell debris in Namibia — Hiller, 1993; e.g. also Thiel, 1978).

Upwelling currents last, as a rule, over tens to hundreds of thousands of years, as can be deduced from analysis of the Cenozoic terrains where upwelling occurred. Many facts suggest other “upwelling events" in the Pieniny Klippen Belt Basin history. This may be concluded both from Jurassic and from Cretaceous deposits (Bajocian, Valanginian and Albian/Cenomanian (?) phosphorites and/or phosphatic stromatolites) and fauna (Krobicki, 1997).

Geological observations here upheld the prediction of upwelling zones based on computer modelling generated maps. This suggests the desirability of investigating the areas where predicted upwelling and organic productivity might have contributed to the development of petroleum systems along the northern margin of the Tethys (see Golonka *et al*., 1997*b*). Computer modelling maps may help to understand the palaeoenvironment and lithofacies pattern in basinal as well as in uplifted facies in the Tethys Ocean.

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