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TO THE ORIGIN OF VARIEGATED SHALES FROM FLYSCH OF THE POLISH CARPATHIANS

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Abstract: Six facies of sediments bearing variegated shales, differing in textures and sedimentary structures, have been distinguished. The variegated shales are interpreted as deposited in bathyal to abyssal depths, below CCD, by the settling of individual particles or particle aggregates from land run-off with some lateral transfer by bottom currents and from highly dispersed turbidity currents. Subordinate to the above process was deposition from dense muddy turbidity currents, slumps and mudflows. Shale colour resulted from (1) sediment composition, (2) seafloor oxygenation, (3) frequency of event sedimentation and associated erosional effects, (4) thickness and shape of event beds, (5) degree and pattern of bioturbation.
The beginning of variegated shales sedimentation in the Carpathians, like in the Alps and the Atlantic Ocean, resulted mainly from the Cenomanian sea-level rise. Termination of this sedimentation in the Carpathians was due to the closure of connections with the open ocean.

Key words: sedimentary geology and geochemistry, sedimentology, pelagic sediments, Carpathian flysch.

Introduction

Variegated shales are characteristic components of the Carpathian flysch. The mainly reddish and greenish, muddy to clayey shales occur in flysch of the Polish Carpathians from the Cenomanian to the Upper Eocene (Książkiewicz 1962; Bieda et al. 1963; Koszarski 1963, 1967). Variegated shales of similar stratigraphic position occur in other parts of the Carpathians, as well as in the Alps and the Apennines (vide Prey 1968; Andrusov 1973; Hesse 1975; Winkler 1983; Stefanescu and Micu 1987). Variegated shales in the Polish Carpathians are chiefly carbonate-free or contain only a small amount of $CaCO_3$. However, variegated marls can also be encountered in some areas.

There is a generally accepted opinion that variegated shales represent deposits of a continuous, particle by particle fallout from the water column (background deposits – Seilacher 1981), contrary to the coarse grained deposits, recognized as redeposited by various gravity flows (catastrophic processes) from shallower, usually shelf zones (event deposits – Seilacher 1981). The variegated shales are considered to be autochthonous due to the presence of components formed *in situ* (vide Koszarski 1963; Ślączka 1963).

Detailed analyses, even at macroscopic levels, allow us to recognize a quite considerable variability in the variegated shale facies with regard to their origin. Only some of them, i. e., mainly the red shales, represent the hemipelagic deposits. The remaining ones, forming the majority of variegated shales, belong to the family of redeposited sediments.

The objective of this study is to refine assessments of variegated shales origin. Sedimentary features, colour, mineral and chemical composition of variegated shales and co-existent sediments have been described from selected outcrops of the Silesian and Magura Nappes (Fig. 1). Depositional processes and conditions of sedimentation, together with origin of colour and its changes, are interpreted.

Previous work

Variegated shales, due to their distinct colours and rich foraminifers, have been distinguished and described in many stratigraphic papers since the nineteenth century (vide Jurkiewicz 1967). A special stratigraphic significance of the variegated shales of the Carpathian flysch has been indicated by Koszarski (1963). He determined that the interval of their sedimentation was one of the three main depositional stages of the Outer Carpathian flysch. Contrary to the earlier and the latter stages, this was a stage with sedimentation in well oxygenated conditions. Gaweł (1928) was the first to describe the mineralogy and chemistry of the shales, interpreting them as sediments deposited in cool and well oxygenated water. Subsequently, Narębski (1957) briefly described chemical composition and indicated redox conditions of their sedimen-

Fig. 1. Location and simplified geological map of the Polish Carpathians. 1 – main overthrusts; 2 – boundaries of post-orogenic Neogene cover, 3 – northern border of the Tatra Mts.; 4 – sections studied (1 – Janoska stream, 2 – Jachówka, 3 – Lubomierz, 4 – Uhryń, 5 – Nowa Wieś, 6 – Bóbrka, 7 – Krosno, 8 – Czarnorzeki). TM – Tatra Mts., PF – Podhale Flysch, PKB – Pieniny Klippen Belt, MN – Magura Nappe, FMN – Fore-Magura Units, SIN – Silesian Nappe, SUN – Sub-Silesian Nappe, SKN – Skole Nappe.

tation. Koszarski (1967) interpreted depositional processes and general sedimentary conditions. In his opinion green shales are chiefly redeposited sediments, richer in organic matter than the red ones, the latter being considered pelagic. Sedimentation during periods of enhanced organic productivity and pyroclastic influx has been suggested as responsible for the development of some green shales. Andrusov (1973) described facies differentiation and stratigraphic distribution of red marls and shales (couches rouges) of the Western Carpathians and compared them to similar deposits in the Alps. He recognized these sediments as deposited in highly oxidizing conditions within areas of moderate subsidence and of a restricted supply of clastic material. Wieser (1969, 1970a, b) and Gruszczyk–Kubisz (1960) described clay minerals whereas Pelczar (1965) characterized trace elements from the variegated shales. Dominik (1977), in turn, described in his comprehensive study mineralogic and petrographic features of variegated shales of the Magura Nappe. He interpreted them as sediments of the deep-sea red clay type. He considered their distinct colours to have originated from early diagenetic processes. The green colour was interpreted as an effect of iron reduction in sediment rich in organic matter (cf. Sikora 1970).

Variegated shales have been described from many formations, both on land and on the seafloor. They are interpreted as deep-sea (hemi) pelagic sediments deposited by the settling of individual particles or particle aggregates below the CCD-level (Hesse 1975; Hoffert 1980; Dean et al. 1984; Stow et al. 1984; Jenkyns 1986). The shale colours are interpreted as resulting from chemical composition, the content of organic material and oxygenation level on the seafloor (Faupl and Sauer 1978; Potter et al. 1980; Pickering et al. 1986).

Stratigraphy

In the Polish Carpathian flysch, variegated shales occur within sedimentary sequences of all nappes (Fig. 2). They are especially wide-spread in the Lower Senonian and Upper Paleocene–Middle Eocene deposits (Książkiewicz 1962; Bieda et al. 1963; Koszarski 1963; Ślączka 1963; Sikora 1970; Morgiel and Szymakowska 1981; Oszczypko et al. 1989). The variegated shales occur as thin layers which alternate with predominantly thin beds of sandstone and siltstone (Figs. 3, 4), or in the form of packages, several metres thick, which separate complexes of sandy and normal flysch. They sporadically occur as thin intercalations within very thick bedded quartz arenites (Leszczyński 1981).

Thin bedded sandstones alternating with the variegated shales are usually entirely cross-laminated (T_c). Sometimes horizontal lamination (T_b) occurs in the lowest part of the thicker beds. Thick and very thick bedded sandstones with variegated shale intercalations are usually structureless, i. e., without lamination, and possess only normal grading, which is more or less distinct. Tops of sandstone beds alternating with variegated shales are sharp or indistinct, with transitions from sandstone to shale.

The distribution of variegated shales displays both horizontal and vertical changes. In southern and central parts of the Magura, Silesian and Skole Nappes the variegated shales are dispersed between and within complexes of sandy and normal flysch. Towards the north of these nappes, however, the variegated shales become one consistent horizon. In the Skole Nappe, thin layers of variegated shales have been treated as isochronous horizons, subdividing Senonian–Paleocene flysch of the Ropianka Formation (Kotlarczyk 1978).

In the Subsilesian Nappe and the Fore-Magura Scale, variegated shales are replaced by variegated marls (Książkiewicz 1962; Koszarski 1967).

Textures

Variegated shales are muddy and, to a lesser extent, clayey sediments. The clayey shales are denoted by shiny scratches whereas in muddy shales the scratches are dull. Clayey shales are rich in colour, i. e., brick red or sometimes green, contrary to the muddy ones which have dull colours, mainly brown red, gray green, gray, sometimes dark gray and sporadically black.

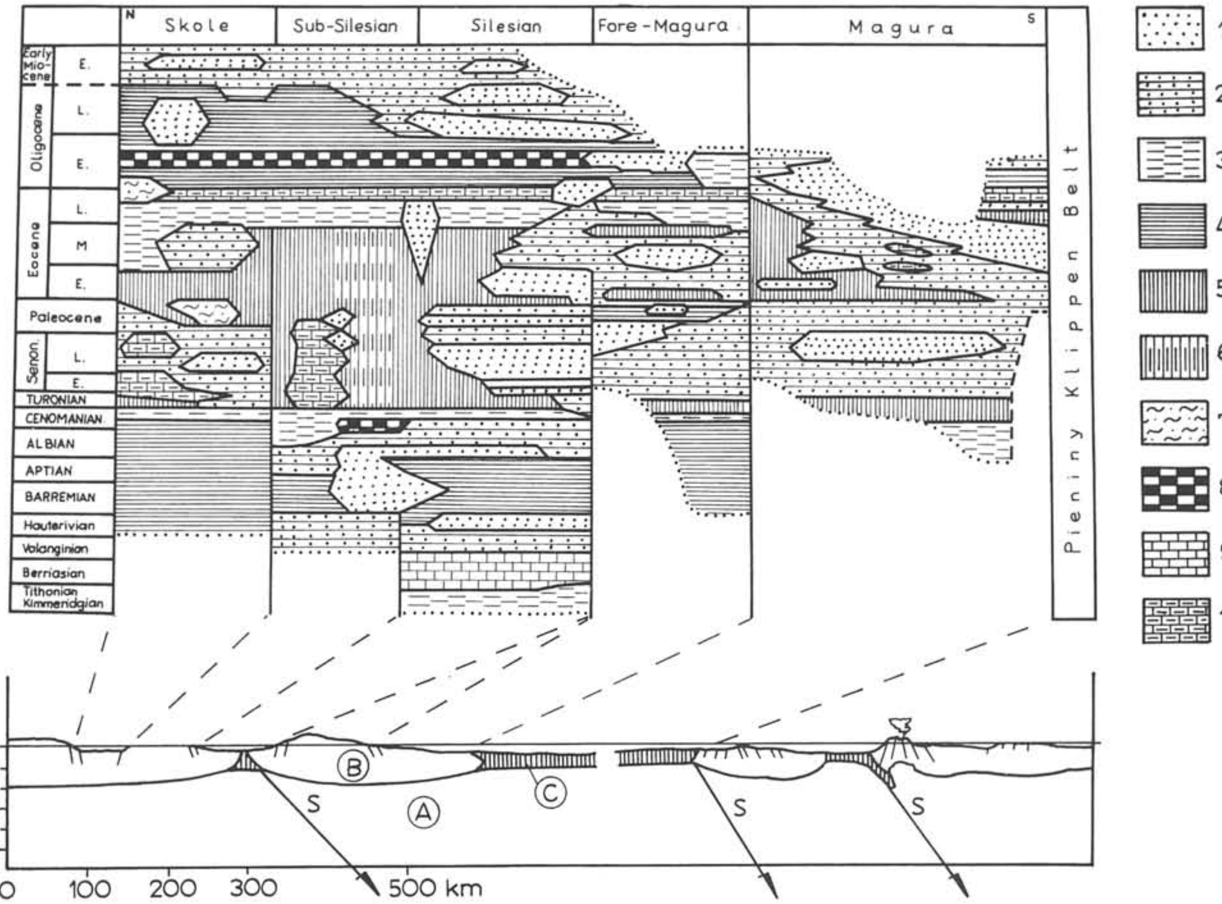

Fig. 2. Scheme of distribution of variegated shales in the Polish Carpathian Flysch (modified after Książkiewicz, in: Bieda et al. 1963, and Koszarski 1985). Palinspastic reconstructions of the Carpathian basins along the Kraków–Zakopane geotraverse (Aptian–Albian stage), based on Birkenmajer (1985) – simplified. A – mantle, B – continental crust, C – oceanic crust, S – subduction zones. 1 – thick-bedded flysch; 2 – thin- and medium-bedded flysch; 3 – shales and shaly flysch; 4 – black shales; 5 – variegated shales; 6 – variegated marls; 7 – chaotic deposits; 8 – siliceous deposits; 9 – turbiditic limestones; 10 – marls.

The macroscopic texture of the variegated shales is uniform, with rare occurrences of coarser grains, e. g., foraminifer tests and sericite flakes. Locally thick layers of red shales bear manganese micronodules. The amount of biogenic material, i. e., chiefly agglutinating foraminifers, more rarely fish teeth, does not exceed a few percent. Layers of variegated shales with loosely distributed quartz grains of sandy and fine-gravelly fraction can sporadically be encountered (cf. Koszarski 1967). Frequently the passage from red into green shale reflects an increase in silty fraction. Layers of variegated shales macroscopically uniform in texture are from a few milimetres up to a dozen centimetres thick, rarely more.

Sedimentary structures

Macroscopic structures of variegated shales are, like their textures, poorly diversified. In a cursory macroscopic observation the shales appear homogeneous, i. e., structureless. A closer examination allows one to recognize distinct or wispy laminations marked by coarser fraction or some minerals (e. g., sericite flakes, Fe hydroxides).

The microscopic structure of variegated shales is much more diversified. According to Dominik (1977) it is possible to recognize:

1. Organized, non-laminated structures – with flakes and aggregates of clay minerals showing a tendency toward parallel orientation

a) with the organization of particles changing at a distance of a few up to a dozen millimetres,

b) with constant organization at a distance of more than dozen milimetres;

2. Organized, laminated structure – with horizontal laminae of silty material;

3. Disorganized structure – with a chaotic distribution of components

a) with local organization within a chaotic background,

b) uniformly chaotic – without any clear organization on a sample scale.

According to Dominik (1977), the chaotic structure occurs only sporadically. The laminated structure is marked by silty grains of sharp-edged quartz and mica flakes.

Usually the sedimentary structures of variegated shales are accentuated by their parting (fissility) and colour changes.

This refers to the parting and colour changes controlled by the distribution of the silty material.

Silty deposits accompanying the variegated shales occur as individual laminae less than 1 *mm* thick up to layers or lenses which are several centimetres thick (Fig. 3). Their thickness does not usually exceed 3 *cm*. Both the soles and the tops of the siltstone layers are sharp. Some layers do not display any lamination while others show more or less distinct parallel and cross-lamination or convolutions.

Colour distribution

The colour of variegated shales changes according to their mineralogical and chemical composition (cf. Blatt et al. 1972; Potter et al. 1980) as well as to texture and sedimentary structures (Figs. 3, 5). The shales in contact with sandstone are usually gray, steel gray to green gray (Fig. 3 – Uhryń A). The sandstone sometimes passes directly into red shale (Fig. 4). Characteristic are colour changes around filamentous foraminifer tests or some coarser mineral grains. Changes of colour appear in the form of layers or irregular spots of variable size and shape. The spotty colour changes are frequently connected with burrows. Within red shales burrows are marked by green colouration, whereas they are gray to dark gray within green shales (Fig. 6). In the section at Bóbrka burrows appear in some places to be orange-red within green shales. In red shales exposed at Lubomierz traces resembling *Chondrites affinis* occur in the form of imprints on the shale parting surfaces without any colour change in the sediment itself.

Joint surfaces cutting variegated shales and thin sandstone bed intercalations enclosed by the variegated shales are frequently coloured in black. The shales occurring immediately below sandstone and tuffite beds are often green (Fig. 3 – Uhryń A), steel gray or sometimes black (cf. Koszarski 1965; Sikora 1970).

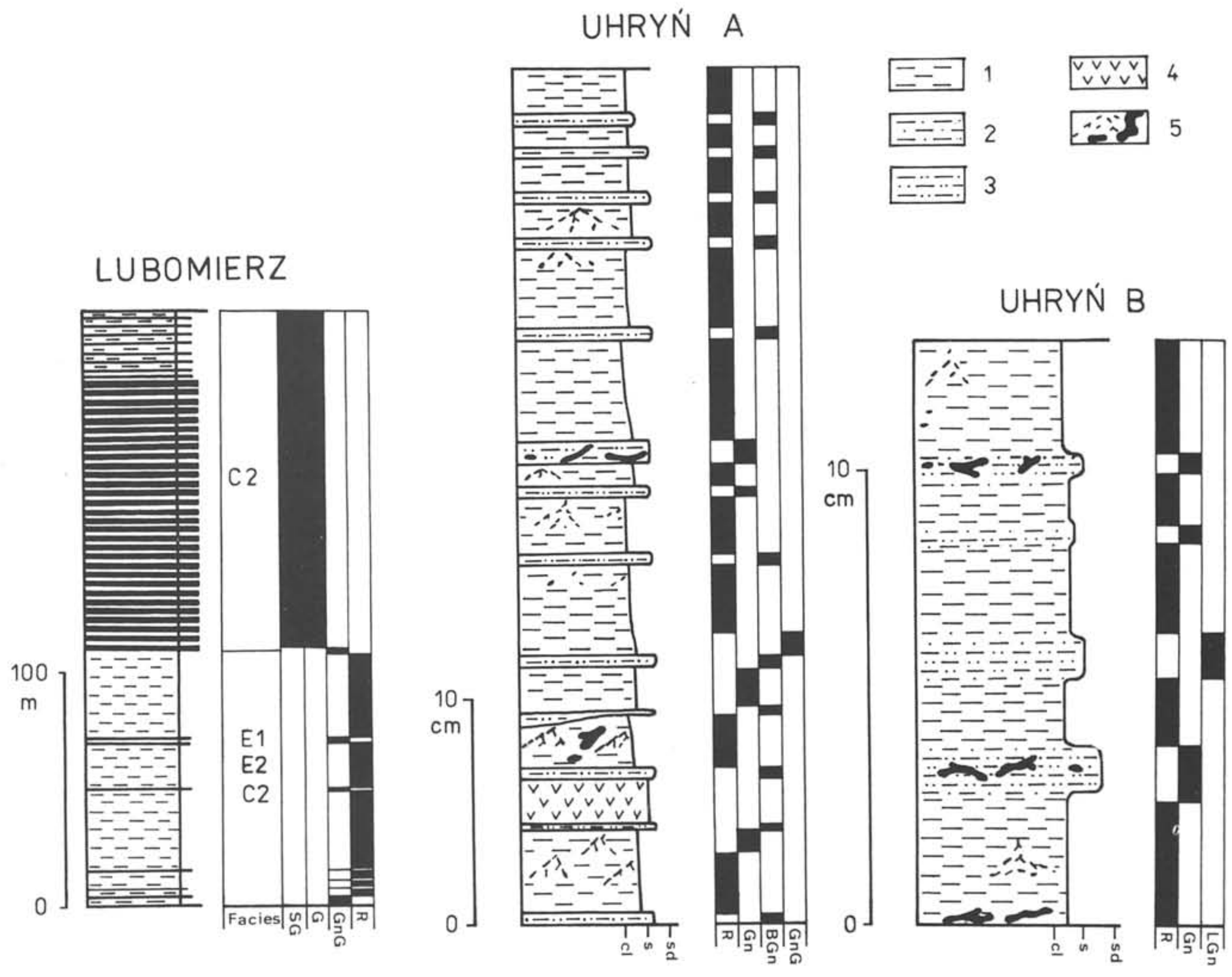

Fig. 3. Examples of the variegated shale profiles. Facies in Lubomierz according to Pickering et al. (1986).
Sediment colours: BGn – blue green, G – gray, Gn – green, GnG – green gray, LGn – light green, R – red, SG – steel gray. 1 – muddy to clayey shales; 2 – muddy siltstone; 3 – siltstone; 4 – bentonite; 5 – bioturbations. Sediments in Uhryń A represent facies II and V. In Uhryń B – facies III and V, according to the classification in this work (Fig. 7).

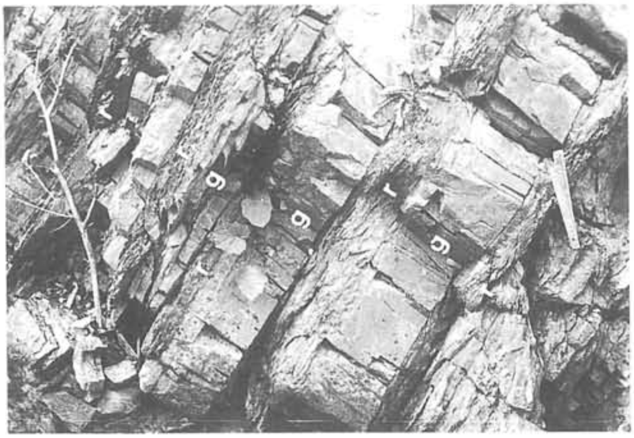

Fig. 4. Variegated shales alternating with sandstone. Facies I (see Fig. 7). Upper Paleocene/Lower Eocene, Lubomierz.

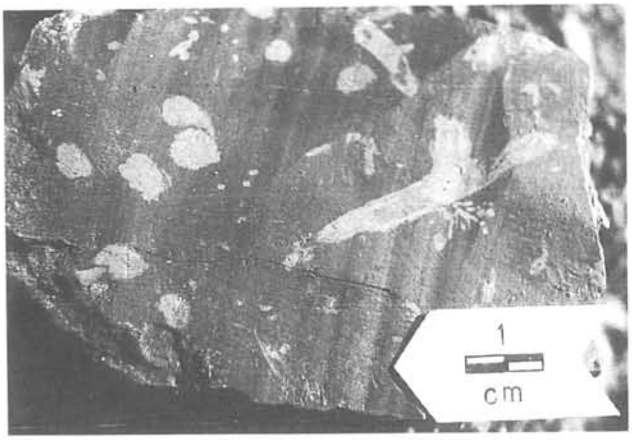

Fig. 5. Spots of burrows *(Planolites, Chondrites)* within green muddy shale. Middle Eocene, Krosno.

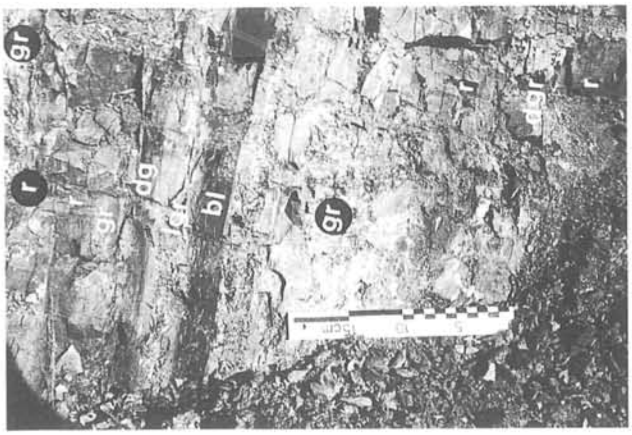

Fig. 6. Layered variegated shales.
Shale colours: bl – black, dg – dark gray, dgr – dark green, gr – green, lgr – light green, r – red. Within the black layer visible fine light spots of bioturbations. The sequences: black – light green shale and dark gray – green – red shale represent the facies IV. The other shales belong to facies V (see Fig. 7). Middle Eocene, Krosno.

Facies

The differentiation in sedimentary features of the variegated shales and accompanying sediments allows us to recognize six main facies of these deposits. The chief diagnostic, macroscopic criteria for the recognition of these facies are shown in Fig. 7. Facies I (Fig. 4) consists of sandstone-shale couplets with structures of the Bouma (1962) sequence. The sandstone/shale ratios are variable. Facies II includes siltstone-shale couplets. These are thin to medium-bedded sediments, structurally similar to those of the first facies but starting with silty fraction. The silty sediment occurs in layers or lenses. It is usually wavy and cross-laminated or convoluted, and passes upwards to parallel-laminated muddy shale. The bases of the beds are sharp and scoured (Fig. 3 – Uhryń A). Deposits of facies III are represented by indistinct layers and lenses of muddy siltstones bearing traces of lamination, with indistinct sole and top surfaces, passing both downwards and upwards into muddy and clayey shales (Fig. 3 – Uhryń B). Facies IV consists of essentially structureless silty mudstones passing upwards to muddy and clayey shales (Fig. 6). Facies V (Fig. 6), contains medium to thick intervals of poorly bedded muddy and clayey shales, analogous to those occurring in the top part of beds of facies I–IV. Facies VI includes chaotic muddy shales with irregularly dispersed coarse sand grains and sometimes shale clasts.

According to the classification scheme of the deep-water facies by Pickering et al. (1986), the above facies correspond as follows: I – C2, II – D2, III – E1.3, IV – E2.1, V – E1.2, VI – ?F2.1, A1.3.

The shaly (muddy and clayey) deposits of facies I–IV and VI display a similar tendency toward colour changes. Frequently they are exclusively green, more rarely they are exclusively red. Most commonly they are variegated: in the lower part of the sequence they are green while toward the upper one they become red. The lower parts of the shaly sequences are sometimes dark gray and pass upwards into green and then into red shale (Figs. 3, 5; cf. Koszarski and Wieser, 1960; Ślączka 1963). Proportions of particular colours in individual beds are variable. The deposits of facies V are usually red. However, sometimes they are characterized by green intercalations. The variegated shales are enclosed chiefly within facies II through V. Within beds of facies I variegated shales usually form only a thin layer at the top. This facies occurs chiefly in central parts of nappes. Shales of facies VI occur only sporadically.

Mineral and chemical composition

According to Dominik (1977), who carefully studied the variegated shales of the Magura Nappe, they chiefly comprise illite, chlorite and quartz with smaller amount of kaolinite smectite, vermiculite, mixed-layer structures, calcite, dolomite and, exceptionally, siderite. Feldspar occurs in subordinate quantities. The clay minerals are distributed zonally, parallel to the axis of the sedimentary basin. In the northern marginal zone of the nappe an increased content of kaolinite has been noted. In the central zone illite and chlorite predominante, whereas kaolinite is missing; in the southern zone illite prevails, although kaolinite and smectite also appear. All the sections show significant variations in the content of clay minerals. Similar composition has been recorded in variegated shales of flysch of the Czechoslovak

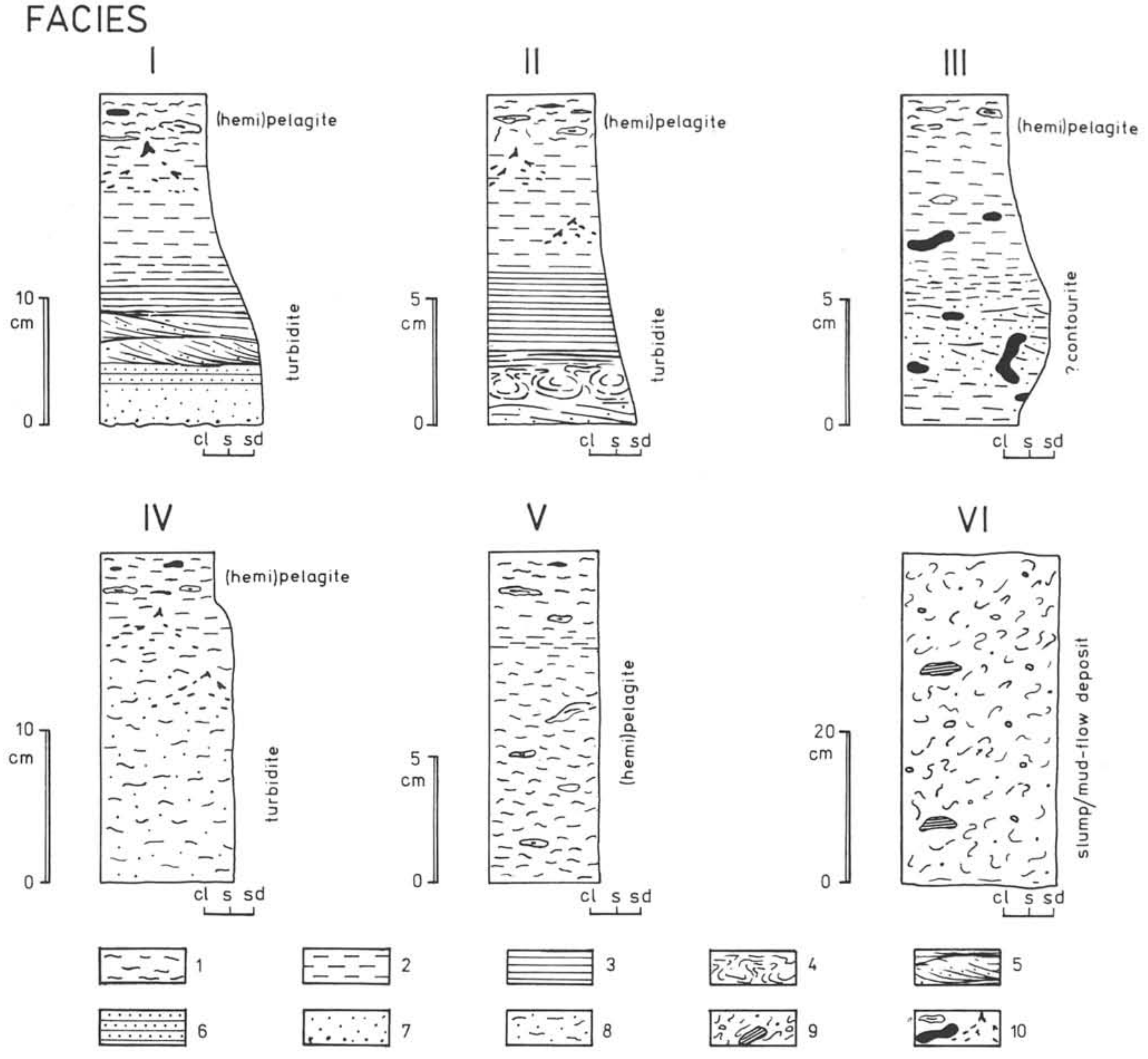

Fig. 7. Facies of variegated shales and accompanying sediments.
I – sandy to clayey turbidite/(hemi)pelagite, II – silty to clayey turbidite/(hemi)pelagite, III – contourite?/(hemi)pelagite, IV – high density muddy to clayey turbidite/(hemi)pelagite, V – (hemi)pelagite, VI – slump and mudflow deposit. 1 – muddy to clayey shale with irregular fissility; 2 – muddy to clayey shale with plane fissility; 3 – muddy shale parallel laminated (T_d); 4 – convoluted siltstone and sandstone (T_c); 5 – ripple laminated siltstone and sandstone (T_c); 6 – parallel laminated sandstone (T_b); 7 – nonlaminated sandstone (T_a); 8 – silty mudstone; 9 – chaotic muddy to clayey shale with shale clasts and coarse-sand grains; 10 – bioturbations.

Carpathians (Čičel and Ďurkovič 1965; Pícha 1969). Pícha (1969) recorded an increased amount of kaolinite only in shales of the Subsilesian (Ždánice) Nappe. A higher content of kaolinite has also been noted in red shales of the Flyschgosau in the Eastern Alps (Faupl and Sauer 1978).

According to Dominik (1977), the red shales are richer in Fe_2O_3 than are the green ones. The FeO content in both green and red shales is lower than is that of Fe_2O_3. The red shales are in general richer in iron than are the green ones. All the data resemble those recorded in variegated shales of other areas (Van Houten 1961; Friend 1966; Lajoie and Chagnon 1973; Faupl 1976; Faupl and Sauer 1978). Local concentrations of manganese oxides have been found. In red shales they occur in the form of micronodules dispersed throughout some horizons. Manganese oxides frequently impregnate sandstones occurring within sequences with variegated shales.

According to Narębski (1957), the content of organic carbon in red shales of the Polish Carpathian Flysch does not exceed 0.1%. Determinations carried out in similar deposits of other areas show that in red shales this figure reaches 0.3% (Potter et al. 1980; Thurow et al. 1988; Leszczyński, in prep.). According to Thurow et al. (1988) it may reach up to 3.0%, whereas Potter et al. (1980) maintain that it is as low as in red shales (cf. Maynard 1982).

Sedimentary environment and processes

Sedimentary features of variegated shales under study indicate that the shales are chiefly background sediments, i. e., hemipelagites and/or pelagites [(hemi)pelagites], deposited by the settling of individual particles and particle aggregates from land run-off. Homogeneous, non-laminated muddy to clayey shales (cf. Pickering et al. 1986) of facies V as well as those occurring at the tops of beds of facies I–IV have such an origin. The laminated variegated shales were deposited from low concentration, residual suspension, accompanying the bigger, sandy (facies I), silty (facies II) or muddy (facies III and IV) turbidity currents, according to the facies to which the shale belong (Tab. 1).

Table 1. Origin of facies of the variegated shales and accompanying sediments (interpretations after Pickering et al. 1986).

Facies	Genetic type of deposits	
	redopsited	background
I	sandy to muddy turbidites	present
II	silty to muddy turbidites	present
III	muddy turbidites or contourites	present
IV	high density muddy turbidites	present
V	absent	background only
VI	cohesive flow and slump deposits	absent

The laminated variegated shales of facies III may represent sediment reworked by deep-water contour currents (cf. Stow and Piper 1984). The massive muddy shales of facies IV were deposited by highly concentrated muddy turbidity currents. The chaotic variegated shales of facies VI were reworked by mudflows and slumps. The non-laminated muddy to clayey shales and some of the laminated shales contain exclusively agglutinating benthonic foraminifera of the „*Rhabdammina*" assemblage (Brouwer 1965; Olszewska 1981). This assemblage indicates sedimentation in lower bathyal to abyssal depths, below the CCD (Olszewska 1981; Koszarski 1985), and supports the deep-water origin of the sediments in which these forms occur. This suggests also that the laminated variegated shales containing foraminifera of the „*Rhabdammina*" assemblage are built up of a reworked (redeposited) deep water material. This is material eroded and picked up by the big turbidity currents from more proximal deep-water areas (cf. Hesse 1975). The variegated shales containing the *Rhabdammina* type foraminiferal assemblage resemble the deep-sea fine-grained deposits described by Hesse (1975), Dean et al. (1984), Stow and Piper (1984), Stow (1985), Pickering et al. (1986), and Jenkyns (1986). Some of the laminated variegated shales, chiefly those richer in silty fraction, contain only a poor assemblage of non-characteristic arenaceous foraminifera. The clastic material of these shales was probably redeposited from much more shallow areas, from shelf or slope. The variegated shales sporadically contain calcareous benthic foraminifera (Gasiński and Ślączka 1985). These are also redeposited from shallower zones, lying above the CCD.

The occurrence of variegated shales throughout the nappe evidences that whole areas encompassed by individual nappes must have been located entirely within abyssal to lower bathial depths. Markedly shallower (only bathial) were zones where sedimentation of variegated marls occurred, i. e., the Subsilesian Nappe and to a lesser extent the Fore-Magura Scale (Koszarski and Żytko 1965; Koszarski 1967). Differences visible in the development of variegated shales within one nappe were caused by the irregular distribution of coarse-grained material within the sedimentary basin, both in time and space. This distribution was mainly controlled by the paleogeography of sedimentary basins (Koszarski 1967; 1985). The coarse-grained material was deposited chiefly within the deepest axial parts of the basins. The amount of variegated shales is within areas of intensive coarse-grained sedimentation reduced precisely. These shales disappear or are dispersed there into many thin lenses (interlayers) which are intercalated by coarse-grained deposits (cf. Koszarski 1985).

Origin of shale colour

Background deposits within variegated shale sequences are mainly red whereas the resedimented fine-grained deposits are usually green. Dark gray colouration within series with variegated shales seems to be exclusively attributed to the resedimented deposits. However, all these colours, especially the green and red ones, may occur within both resedimented and background deposits (Fig. 8). Such colour differentiation of variegated shales suggests its depositional or diagenetic origin (cf. Van Huten 1973; Lajoie and Chagnon 1973).

According to Potter et al. (1980), the shale colour is mainly controlled by the amount of organic matter. Another important factor is the Fe^{3+}/Fe^{2+} ratio (Tomlinson 1916; McBride 1974). High ratios are associated with red colours, low ratios with green ones (Dominik 1977; Faupl and Sauer 1978; Potter et al. 1980). However, the Fe^{3+}/Fe^{2+} ratio is strongly dependent on the oxidation state of sediment, i.e., on the amount of organic matter. Even small amounts of organic matter favour the reduced form of iron (Potter et al. 1980). Thus the organic matter is to a large extent responsible for the green colours of shales. The green colour results directly from the presence of green phyllosilicates, such as illite, chlorite and, in some cases, glauconite (Blatt et al. 1972). The red colour of sediments is caused by a finely disseminated hematite which occurs as coatings, a few molecular layers thick, on top of the smectite surfaces (Degens et al. 1986). According to Berner (1981), red colours may form in sediment when all the decomposable organic matter enclosed becomes decomposed prior to burial. The lack of decomposable organic matter in sediment protects the fine-grained ferric oxide minerals, such as goethite, from reduction. Upon burial and diagenesis, the ferric oxide minerals are transformed into hematite, thus imparting a red colour to the enclosing sediment. Hematite can persist stably even in weakly reducing conditions (Garrels and Christ 1965). The early diagenetic colour of sediments can also be preserved. Green colouration will appear in sediments which are poor in organic matter and which are deposited in a weakly reducing or oxic environment. This process is due to the reduction of iron, when some organic matter escaped oxic degradation. Additional factors influencing the shale colour are grain size, mineralogy and thermal maturity of the organic matter, but these seem to be of relatively minor importance (Potter et al. 1980).

Of great importance to the origin of sediment colour is the rate of sediment accumulation. In a slowly accumulated

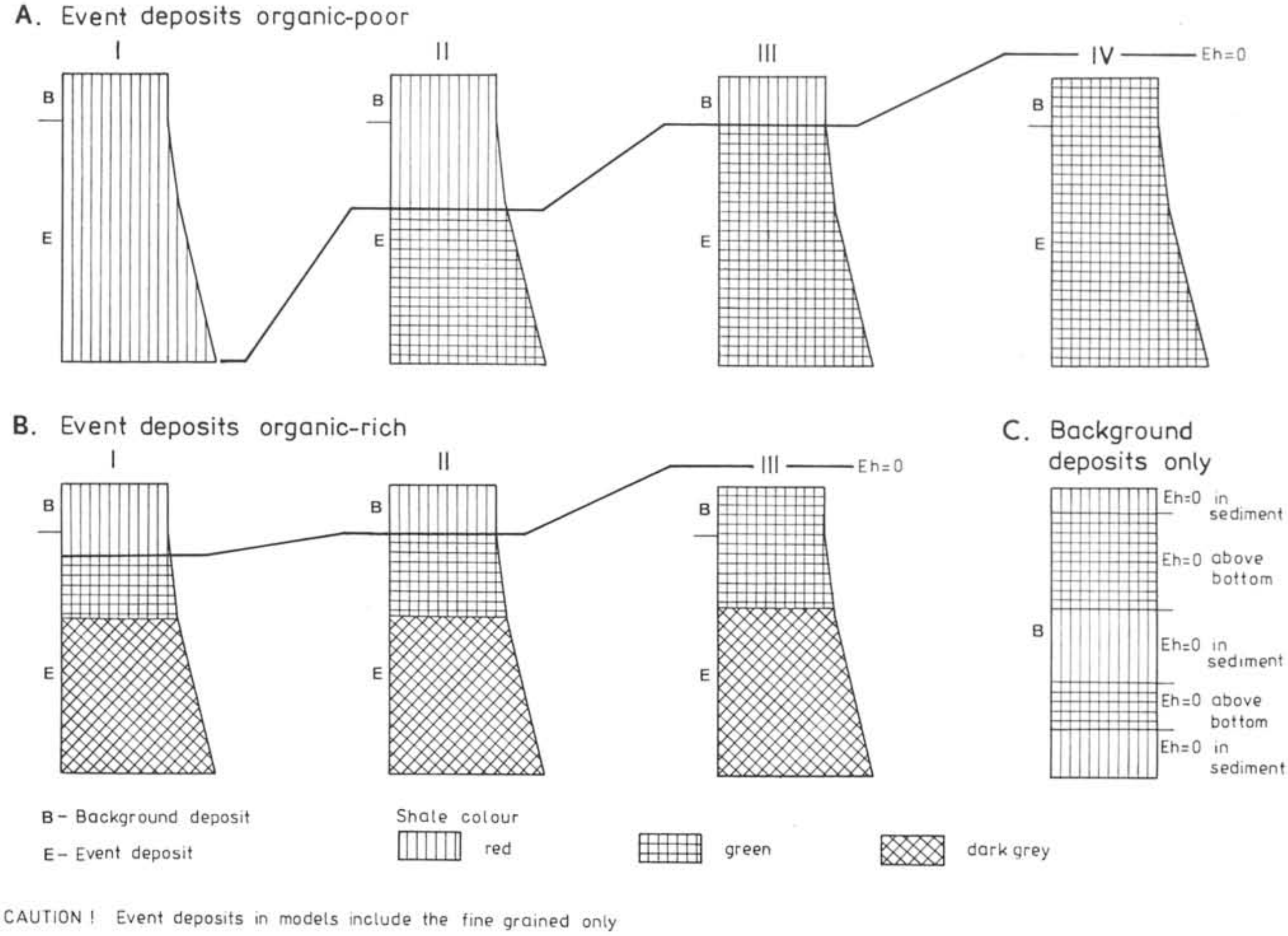

Fig. 8. Models of colour formation of variegated shales and coexistent sediments.
The interpretation of the colour sequences are based upon: (1) the positions of Eh=O-level, (2) organic content in sediment, (3) type of sedimentation. The position of Eh=O-level was strongly controlled by amount of deposited organics and by water cirulation.

sediment, such as background deposits, oxic conditions will cause reactive organic compounds to concentrate very close to the sediment-water interface (Thomson et al. 1989). As a consequence, a particularly sharp decrease in the organic carbon content of the uppermost centimetre of the sediments is observed (Jahnke et al. 1986, v. Thomson et al. 1989). At higher rates of sediment accumulation, more organic carbon escapes oxic degradation and a series of less thermodynamically favoured electron acceptors (nitrate, manganese oxyhydroxide, ferric oxyhydroxide and sulphate) is utilised successively with increasing depth (Froelich et al. 1979). The above statements are important for understanding processes which develop in the top part of a slowly accumulated sediment when it becomes quickly covered by a thick sediment bed, e.g., turbidite, as well as in the quickly accumulated bed alone. This explains one of the causes of the bedding-paralel colour changes witin the variegated shales. According to Thomson et al. (1989), the rapidly buried, non-degraded organic matter in the near-surficial part of a slowly accumulated sediment will quickly require alternatives to oxygen electron acceptors to continue bacterial remineralisation. The decreased Mn content and the low Fe content, observed just below the turbidite, are consistent with utilisation of oxyhydroxides as electron acceptors. As a result, the shales immediately underlying a turbidite unit display colours different (green) from those occurring below (red). The colouration of shales ocurring just below turbidite units, distinct from that of the deeper-lying deposits, has the character of a halo. Such halo reaches up to a few tens of centimetres (Thomson et al. 1989). Its colour depends on the chemical composition of the sediments. In series of variegated shales, the haloes are usually greenish (cf. Ślączka 1963; Koszarski 1967; Sikora 1970). The halo development has no relation to water column events and is wholly of early diagenetic origin (Thomson et al. 1989). The halo creating processes are probably responsible for the only green or gray colours of shales being densely alternated with sandstones. First of all, this refers to the sections in which the sandstone has a black colouration. Such colouration is due to impregnation by manganese oxides resulting from the halo--creating processes. A deeper erosion of the surficial, organic--bearing sediment may be responsible for the lack of a halo under the turbidite unit. This happens when the turbidite is laid down directly upon a sediment deprived of reactive organic compounds.

In addition to these halo-producing processes, the position of the Eh=O-level in the sediment-water system is also responsible for shale colour changes which are parallel to the bedding (Fig. 8; cf. Faupl and Sauer 1978). The Eh=O-level separates the zone showing reducing, anoxic conditions (Eh<O) from the oxidizing zone (Eh>O). In well oxygenated basins with a small supply of organic matter, the Eh=O-level can be placed deep in sediment. In poorly oxygenated basins it can be situated high above the bottom. The position of this level may change according to sediment accretion. Sediments accumulated above the Eh=O-level may acquire red colouration while those accumulated below become green or gray to black, according to the amount of organic matter present (Fig. 8). The above tendencies are strongly disturbed by the halo-producing processes. The Eh=O-level situated deep in sediment influence the slowly accumulating sediments, mainly the background deposits, and the rapidly accumulating sediments, mainly turbidites, differently. The former become entirely red while the colour of the latter depends upon the position of the Eh=O-level relative to its bed after the turbidite emplacement, and upon its organic content (Fig. 8). Thin turbidites in the well-oxygenated areas may occur wholly above the Eh=O-level. In such cases, not only the fine-grained turbidite becomes red but also no halo developes underneath (Fig. 3). For the sediment colour it is also significant how long it remained under oxic conditions. A short stay under oxic conditions, especially of organic rich sediments, would likely yield no change in colour.

Irregular, spotty and mottled colour changes within variegated shales are connected mainly with local concentrations of organic matter. Such colourations occur primarily within and around bioturbations. Their green and gray colours are due to enrichment in organic matter, locally lowering the redox potential of sediment (Baas and Becking et al. 1960; Thorstenson 1970; Aller 1982; Potter et al. 1980). The organic matter was left by the bioturbating animals, e.g., as burrow linings or as excrement. Green colours of bioturbations occurring within red shales suggest that these features were formed below the Eh=O-level, i.e., after the level became displaced into a higher position. It is also possible that such bioturbations were made above the Eh=O-level, but due to a considerable enrichment of the burrow infill in organic matter a part of them escaped oxidation before the Eh=O-level became displaced into a higher position. The bioturbations produced above the Eh=O-level, where all of the organic matter underwent oxic degradation, became red like the enclosing sediment. The rare occurrences of red bioturbations within green shales indicate enhanced oxidation along the burrows, in comparison with the oxidation in the enclosing sediment. Such bioturbations could have been produced below or above the Eh=O-level within the primarily empty burrows used for respiration. By means of such burrows the fresh, more highly oxygenated waters from the seafloor were conveyed to the animals and to the surrounding sediment, thus intensifying oxidation (cf. Rhoads 1974; Aller 1982). Some infaunal animals produce an oxidized layer at their feeding depth within the sediment column, owing both to the depletion of organic matter by selective feeding on fine-grained material and to irrigation of the resulting highly permeable, coarse lag layer (Rhoads 1974). Such cases can also be encountered in variegated shales.

Specific are shale colourations around some disruptions. They are most characteristic for the red shales. The colourations usually appear in the form of green haloes up to 10 *cm* thick. The connection with the shale disruptions indicate their epigenetic origin, due to a diffusional Fe reduction by the crevise water.

General conditions of variegated shale sedimentation

Variegated shales are products of an episode characterized by favourable oxygenation of the seafloor. During this episode the oxidizing conditions encompassed not only the near-bottom water but also reached deep into the sediment. However, the degree of oxygenation fluctuated with time, as denoted by some colour changes in the variegated shales (especially those within facies V). These fluctuations could have resulted mainly from the changing intensity of water circulation within the sedimentary basin and/or from variations in the supply of organic matter.

The beginning of variegated shale sedimentation in the Carpathians (Cenomanian), like in the Alps, seems to be in line with the beginning of red and variegated clay deposition in the Atlantic Ocean (e.g., Arthur 1979). Though possibly globally it was at least an Atlantic-Tethyan event, caused by a rejuvenated deep-sea circulation. The chief cause of this rejuvenation could have been a Cenomanian sea-level rise. This developed transgression resulted in a restricted supply of continental debris to the shelves (Kennett 1982), thus also lowering its supply to the deep parts of basins. The entrapment of large amounts of nutrients above the extended shelves reduced surface productivity in pelagic realms and, as a consequence, lowered organic sedimentation beneath. An important role in the rejuvenation of deep-sea circulation could also have been played by a tectonically controlled extension of connections with the open ocean.

During the Senonian and the Paleocene an increased supply of terrigenous sediments within many parts of the Carpathian area (Koszarski 1985; Stefanescu and Micu 1987) bufferred accumulation of variegated shales. This restriction seems to be clear in the light of the Cretaceous/Paleocene regression. Some reduction of water circulation due to this regression, however, may not be excluded (v. Tucholke and Vogt 1979). The eventual cessation of variegated shale sedimentation in the Carpathian area (Late Eocene) was caused by a tectonic closure of connections with the open ocean.

Conclusions

Variegated shales of the Polish Carpathian Flysch are muddy to clayey deposits occurring in six facies, each differring in texture and sedimentary structures. These facies have their equivalents among the deep-water facies of Pickering et al. (1986). The shales occur frequently in sequences with continuous passages from silty deposits, and, sometimes even from sandy deposits. Red shales, especially those occurring in thick layers, resemble pelagic clays of abyssal oceanic depths with regard to their sedimentary features, mineral composition and fossil content.

Sedimentary features of variegated shales indicate that they were formed by the settling of individual particles and particle aggregates from land run-off with some lateral transfer by weak mid- and bottom-water currents, and also from highly dispersed suspensions of turbidity currents. A small part of such shales was deposited from dense muddy turbidity currents. The shales were sporadically redeposited in slumps and mudflows. Evidence from deep-water fauna indicate that sediment of the turbiditic variegated shales was redeposited from more proximal areas of the deep-water realm.

Colours of variegated shales are nearly exclusively of early diagenetic origin and resulted from (1) the chemical and mineral composition of the sediment, (2) the oxygenation of the seafloor, (3) the frequency of turbidite sedimentation and associated erosional effects, (4) the thickness and shape of event beds, i.e., chiefly turbidites and, (5) the degree and pattern of bioturbation. Subordinate are epigenetic colourations, developed along tectonic discontinuities, mainly under reducing conditions. The layered, bedding-parallel colour changes must have developed under the control of the first four factors, whereas the spotty changes resulted directly from the last one. The last factor itself developed under strong control of the first four.

Variegated shales of the Carpathian flysch document an episode of an intensified deep-water circulation within the Tethyan and the Atlantic Oceans. This circulation sprang up mainly from the Cenomanian global sea-level rise and ceased, in the Carpathian area, in the Late Eocene due to the closure of connections with the open ocean.

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