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ALLUVIAL-LACUSTRINE RED BEDS IN UPPER PALEOZOIC CONTINENTAL BASINS, BOHEMIAN MASSIF, CZECH REPUBLIC

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Abstract

The vertical alternation of thick red beds with coal bearing sequences in the limnic Upper Paleozoic has been often interpreted as an indication of extreme climatic changes. In the area studied grey sediments indicate a high ground water table at the time of deposition and early diagenesis. That is evidenced by lateral transitions of red to grey sediments both within individual basins as well as in the territory studied which consists of several more or less separated basins. Generally red sediments are more common near to the original basin margin or on the edges of intrabasinal basement ridges whereas contemporary grey sediments appear in central or rapidly submerging areas. The red pigmentation thus reflects sparce vegetation on elevated sites close to basin margins or ridges.

The red beds occurrence is very often used as evidence of warm arid to semiarid climate while grey-colored deposits are associated with humid periods. The customarily applied paleoclimatic indicators can be classified as follow: a) The discriminating value can be ascribed to the amount and diversity of faunal and floral remains, the presence of limestones, calcretes, evaporites, cherts, bimodal sandstones, mineralogical maturity of sandstones and conglomerates, specific sedimentary textures and diagenetic features. b) The ambiguous significance was detected in case of silicified wood, fossil weathering evidences, paleosoils, calcium sulphate or carbonate cements in sandstones. c) Arkoses, clay minerals, and kaolinized interbeds were found unreliable.

The red of studied sediments is caused by hematite pigment which was introduced partially from the source area in the form of hydrated and dehydrated iron oxide. This is indicated by variable amounts of aluminium and titanium incorporated in the hematite crystalline lattice as shown from X-ray and microprobe analyses. The decisive role of early diagenesis in conversion of hydrated oxides into hematite has been evidenced by the remanent magnetization study.

Discolored layers and green reduction spheroids occur particularly in red beds of the Stephanian C and Autunian age. While the massive hematite reduction was related to ascending or descending ground water the green spots were formed diagenetically under unique circumstances. The prerequisite of their growth was the coincidence of several factors: fluctuating temperature and migration of heavy metals (particularly vanadium and uranium), discrete sites with pH and Eh gradient within the host rock and fluctuating amounts and quality of pore solutions.

Abstrakt

Aluviálně-lakustrinní červené vrstvy ve svrchnopaleozoických kontinentálních pánvích Českého masivu

Vertikální střídání mocných, převážně červených souvrství bez uhelných slojí s uhlonosnými šedými sekvencemi v limnických pánvích je považováno za doklad hlubokých klimatických změn během svrchního paleozoika. Údaje z vrtů, výchozů a hornických prací vedou k závěru, že vznik a zachování šedých sedimentů souviselo především s vysokou hladinou podzemních vod v době jejich ukládání a následné diageneze. Dokazují to velmi často pozorované laterální přechody šedých sedimentů do sedimentů červených. Červené zbarvení je běžné v sedimentech, které se ukládaly při okrajích sedimentačního prostoru nebo na úpatí vnitropánevních elevací. Současně s nimi uložené šedé sedimenty leží pak v místech centrálních nebo asymetrických depresí. Červená pigmentace, ať již primární nebo druhotná, charakterizuje místa s omezeným vegetačním pokryvem, způsobeným sníženou hladinou podzemní vody.

Všeobecně se soudí, že červené sedimenty mohly v geologické minulosti vznikat buď za aridního nebo za teplého humidního klimatu (Van Houten 1973). Zhodnocení běžně užívaných paleoklimatických indicií ukázalo významné rozdíly mezi červenými a šedými sekvencemi. Za nepochybný doklad aridního klimatu nebo silně nerovnoměrného sezonního rozdělení srážek během ukládání červených sledů jsou považovány: nepřítomnost nebo nepatrné množství a malá druhová variabilita zbytků flory a fauny, polohy jezerních řasových a pedogenních vápenců, vrstvičky a konkrece Ca-sulfátů, silicitů, polohy bimodálních eolických pískovců, snížená mineralogická zralost pískovců a slepenců a konečně sedimentární textury ukazující na procesy typické pro aridní prostředí. Silicifikované kmeny a dřeva, různé typy zvětralin a paleopůd, stejně jako sádrovcový, barytový nebo kalcitový tmel se sice často vyskytují v červených souvrstvích, byly však zjištěny i v přechodních partiích na hranici s šedými jednotkami. Výskyt arkóz, jejich kaolinizovaných ekvivalentů, stejně jako spektrum a množství jílových minerálů v jílovcích, neodráží ve studované oblasti předpokládané paleoklimatické podmínky.

Hematit je hlavní složkou červeného pigmentu. Různá množství Al a Ti v jeho krystalové mřížce ukazují na vznik hematitu jednak z hydratovaných oxidů (zejména z goethitu), jednak z magmatického magnetitu. Rozhodující role klastického a raně diagenetického hematitu je doložena výsledky paleomagnetického studia.

Odbarvené sedimenty a redukční skvrny se vyskytují nejčastěji v červených souvrstvích stáří stefanu C a autunu. Rozsáhlé odbarvení bylo způsobeno redukčním působením podzemních vod v různých fázích diageneze. Vznik drobných sférických skvrn souvisel se specifickými raně diagenetickými procesy v porézních sedimentech vystavených subaerickým procesům. Rozhodující význam měla kolísající teplota a zvlhčení, silně proměnlivá mineralizace pórových vod, migrace a srážení iontů vanadu a uranu, podmíněné přítomností nebo vznikem center s výrazným gradientem pH a Eh vzhledem k okolnímu sedimentu.

Introduction

Red beds, continental and marine sediments of characteristic color, occur in the Bohemian Massif at various intervals throughout the Paleozoic-Tertiary stratigraphic column (Kukal 1985, Pešek-Skoček 1998). Among them, red beds filling the Upper Paleozoic limnic basins have the largest volume and areal extent. A considerable body of geological information on these red beds has been accumulated during the 1950–1990 drilling program. Data gathered in the course of extensive exploration inspired us to formulate a research project focusing on the problem of red beds origin and their paleogeography in the Bohemian Massif.

This project has been supported by the Charles University Fund, grant 133/94, and by the cooperation of numerous colleagues who contributed their findings and assistance. Special thanks go to V. Holub, V. Prouza and R. Tásler, researchers of the Czech Geological Survey, who offered valuable comments and critiques of our study.

Methods

This research is based upon a wealth of data from boreholes, outcrops and mine works documented during the geological investigations of continental basins in the Bohemian Massif. Much of the data from these investigations, spanning a period of three decades, were presented or published in various reports and papers.

From the borehole cores, stored at Geofond of the Czech Republic (state documentation center of the State Geologial Survey), rock samples were collected for laboratory analyses. The rock samples from the Boskovice Graben, given to us by L. Malý, come from now abandoned mines. The objective of the laboratory work was to quantify rock coloration, and to ascertain color-pigment morphology and its distribution. Special attention was paid to the quantitative determination of element isomorphism in the hematite lattice which was considered an important tool in detecting the pigmentation history. The dating of the magnetization, based on well known paleomagnetic Phanerozoic patterns, proved important in determining the origin of the red beds. Documentation of boreholes was used for the calculation of red beds and grey-colored sediments ratios. These ratios served as a basis for contour maps portraying fluctuating percentages of grey-colored sediments in the studied intervals of Late Namurian–Saxonian time.

Theories of red beds origin

The denomination "red beds" is synonymous with the German term "bunte Schichten" and "krasnocvety" in Russian. The term red beds, in general, denotes thick successions of sediments colored by iron oxides or hydroxides in various shades of red. In them interbeds of other colors (green, grey, violet, whitish, mottled) may occur. At least 60 % of the sediment volume should be of red color to satisfy the definition of red beds given by Hatch et al. (1965). The red pigmentation is best shown in mudstones or claystones. The pigmentation of porous sandstones and conglomerates within red beds was often altered by migrating solutions and their color may be different from the impermeable finer sediments. In addition, the fine ferric pigment in sandstones may be formed secondarily from percolating ground water after deposition. Various ferric oxides and their different aggregation yield various colors (red, violet, pink, beige etc.). Their distribution is either homogeneous or nonuniform (stained, mottled, spotted, speckled). Often sediments have lost their pigmentation and are discolored (bleached, green, yellow etc.) on a massive scale or to a limited extent. In this paper we, therefore, define red beds as successions in which more than 50 % of mudstones and claystones are either of red color or of a color which originated secondarily from red.

Textural and structural analyses, organic remains, geochemical and isotope studies, indicate that red beds originate in a variety of terrestrial and marine environments (e. g. Turner 1980, Flock 1983). The Paleozoic era is marked by extensive deposition of siliciclastic red beds in terrestrial environments (Old Red Sandstone, New Red Sandstone, Roliegendes, Buntsandstein). Many of these red beds are of the Devonian and Westphalian B-Permian age (Table 1). These red beds form either laterally continuous units or alternate with grey-colored clastic sequences. Lateral transitions between red beds and grey or discolored units are common.

Red beds have been recognized in basins of varying shape and tectogenetic type (Turner 1980). Based on climate indicators Van Houten (1973) distinguished two principal types and related criteria: 1) red beds of arid climate (lateral passing into evaporites, presence of eolian sandstones and biogenic limestones), and 2) red beds of warm humid climate (abundant flora and bioturbations, transition into coal-bearing beds). In spite of the fact that climate indicators in many red beds are poorly developed, or difficult to asses in buried successions, analysis of these indicators has been a favored method for the interpretation of red beds origin. Many red beds studies focus their attention to the geochemistry and diagenetic history of red pigmentation. While a variety of iron oxides and hydroxides occur in recent sediments and soils, hematite is the most common pigment in ancient red beds. Einsele (1992) recognizes primary red beds, pigmented by allogenic hematite, and secondary red beds, in which hematite is of authigenic origin. The primary, allogenic red beds include recycled older red beds (Johnson 1983) or sediments derived from red residual soils and laterites (Krynine 1949) formed in warm periods under low or fluctuating humidity. Hematite is generally formed not only by dehydration of ferrihydrite in a warm to tropic climate but also in a moderate climate under special circumstances (e. g. well drained soils on limestone substrate).

Table 1. Significant red bed occurrences of Late Paleozoic age in selected European and other basins

BASIN	CARBONIFEROUS										PERMIAN	
	Namurian			Westphalian				Stephanian			Early	Late
	A	B	C	A	B	C	D	A	B	C		
Europe												
Upper Silesian		◇			◇	◇	◇	←	◇	→	◇	
Flöha								←	◇	→	◆	
Zwickau					←◇	→						
Döhlen											◇	
Ibbenbühren, Ruhr						◇	◇	←	◆	→		
Saar									◇			
St. Etienne								◇	◇			
Decazeville											◆	◆
South Wales						◇	◇	←	◇	→		
Gloucester						◇	◇	←	◇	→		
Forest-of-Dean							◇					
Yorkshire						◇						
Derbyshire						←◇	→					
Doneck										◆		
Asia												
Karaganda + Ekibastuz	◇			◇								
Zanguldak					←			◇		→		
Shansi				←		◇	→					
Phong-jang				←		◇	→					
North America												
Appalachian	←◇							←	◇	→	◇	
Africa												
South Africa								←	◇	→		
Australia												
New South Wales											◇	

◇ – alternation of grey and red sediments, ◆ – distinct dominance of red and non-grey sediments, ←◇→ – red beds in several chronostratigraphic units

Sediments derived from soils or a weathering crust may contain besides hematite other ferric oxides and hydroxides (goethite, maghemite, lepidocrocite, ferrihydrite, magnetite) giving yellow or brown shades of color. Such color may be modified during diagenesis into grey-black in the reducing environment. In an oxidizing environment hematite forms and red beds will result (Van Houten 1968, 1973). In case that hematite was present in the source area the red sediment is considered primary whereas if hematite was formed by conversion of hydrated iron oxides at the site of deposition, such sediment is termed secondary (Einsele 1992). Secondary red beds may also result when hematite pigmentation originated at the expense of dark ferrous minerals or unstable rock fragments containing iron in the sediment (Walker 1967). Oxidation of authigenic ferrous minerals (esp. siderite, pyrite and chlorite) can be another source of hematite. Infiltration of hematite into a porous sediment or its precipitation from ground water might also be considered (MÜCKE-AGTHE 1988).

This review shows that red beds can have multiple origins involving a wide variety of sedimentary environments and diagenetic processes as TURNER (1980) pointed out. Therefore detailed field observation and laboratory analyses are necessary in studying each red bed occurrence.

Basin fill and sedimentary environments

The continental nature of the Upper Paleozoic sediments filling basins in the Bohemian Massif was recognized in the first half of the last century. DANEŠ (1913) compared these basins with bolsons, alluvium-floored depressions of desert regions in the American Southwest. The fifty years of exploration (1938–1988) for coal helped considerably to elucidate geologic structure of Permo-Carboniferous basins in the Czech Republic. Results of investigations published in a number of papers were recently collated by PEŠEK et al. (1998) in the paleogeographic Atlas of the Upper Paleozoic.

In analyzing the Upper Paleozoic lithologies we distinguish (Table 2) two major group of facies: a) marginal to the basin centre or subsidence axis (eluvial, deluvial, colluvial, proluvial, fluvial-braided river) and, b) basinal (alluvial plain, delta, lake or playa). The thickness and composition of individual facial types were controlled by the source area relief, type of material transport, subsidence and by the fluctuating level of perennial and/or ephemeral lakes. Independent of the axis of maximum subsidence beds of eolian sandstones and siltstones were deposited. Deposits of marginal and basinal facies occur both in grey and red colored sequences. Similar sedimentary structures can be considered evidence of similar primary depositional circumstances. The final grey or red coloration indicates either a diverse character of delivered detritus and/or a distinctly different diagenetic history. Extensive transport of weathered material in torrential currents dominated during the deposition of the red beds. In contrast, grey beds were deposited by an established river net with regular rainfalls which enhanced the vegetation cover even at higher elevations. Dark organic matter pigmented sediments form locally thick although rare units within the red bed sequences. This suggests that grey-colored units enclosed in red beds were deposited in perhumid or subaquatic environment in central or rapidly subsiding parts of the basin. Such grey-colored intercalations contain local accumulations of organic kerogen of algal or bacterial origin. The association of black mudstones with cherts, limestones and disseminated sulfides as well as increased boron content, are indicative of elevated water mineralization. The observed lateral transition of grey or black mudstones to red ones demonstrates that the initial clastic material was uniform and the different coloration was exclusively caused by diverse diagenetic processes leading to the preservation of organic pigment in grey sediments and/or to the destruction of organic matter and preservation of primary or creation of secondary ferric pigment in red beds. Red bed bodies time-equivalent to grey-colored beds are generally marginal to the depocenter. We deduce their origin is due either to a lack of organic matter or its removal by rapid oxidation. Such oxidizing circumstances characterize alluvial fans, bajadas, pediments and dominantly dry alluvial plains. By contrast, the initial identical clastic material was converted into a grey sediment containing carbonized organic matter and iron in the

Table 2. Facial classification of Upper Paleozoic sediments in area studied

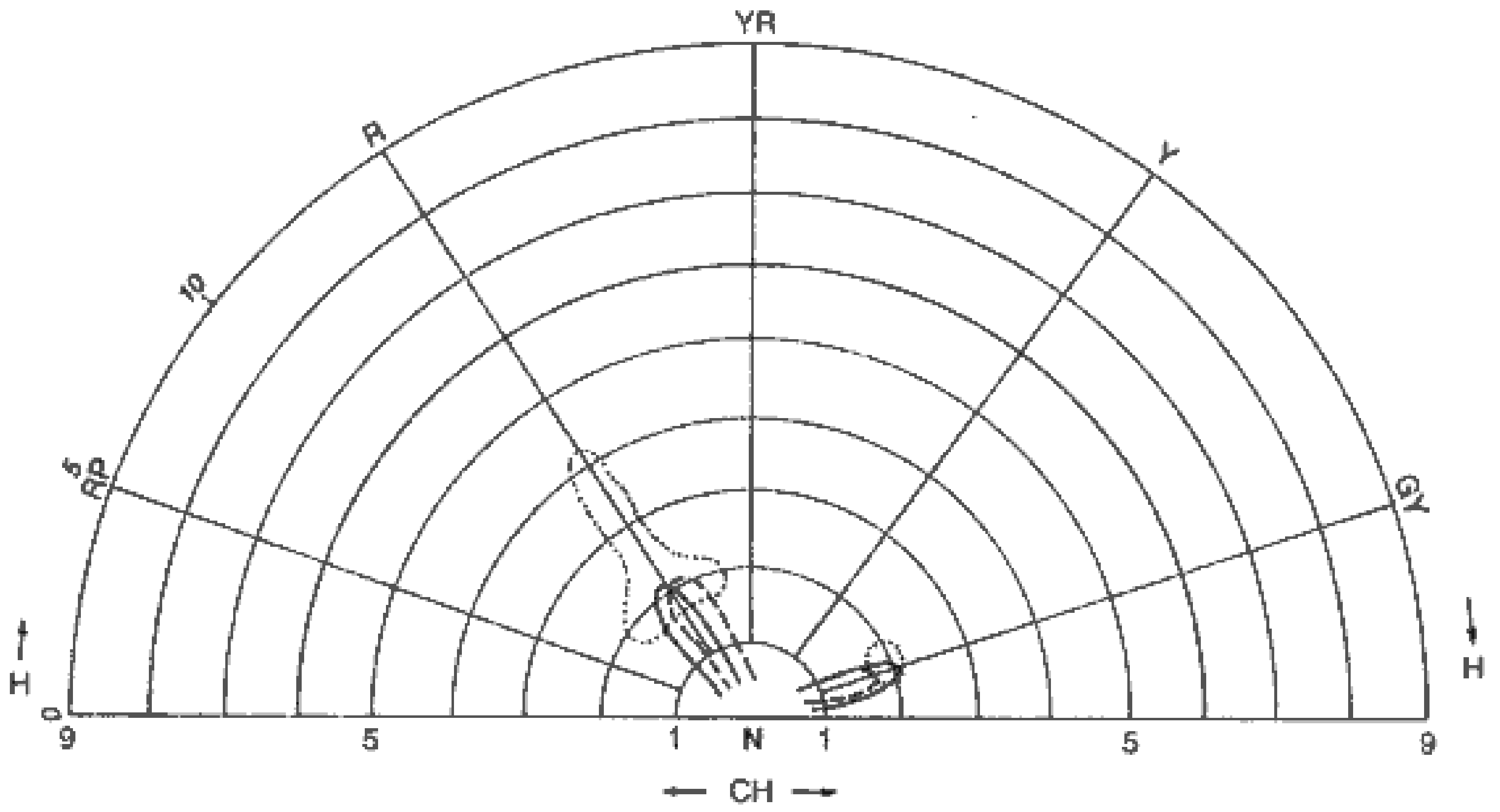
Superfacies	Environment	Sediments
marginal	eluvial, deluvial (pediment), colluvial, alluvial fan	breccias, sandstones, mudstones, variable sorting, irregular bedding
	alluvial plain of meandering river; channel bed, bars, paludal, peats, bogs; braided river	conglomerates, sandstones, fine grained sandstones, mudstones, claystones, disseminated and accumulated plant material; thick units of cross bedded conglomerates and sandstones
	ephemeral river; channel bed	sandstones and conglomerates with lenses of mudstones, variable structure and texture
	flood plain	poorly sorted mudstones and claystones, mostly structureless
basinal-terminal	lacustrine-deltaic	
	small creeks and rivers	local clastic material dominating
	large river	well seggregated lithotypes, homogenized distal clastic material, considerable thickness of sequence
	perennial lake	
	marginal	laminated or thin bedded sandstones, alternating with mud- or claystones
	profundal	black or grey laminites = euthrophic lake, variegated laminites = oligotrophic lake, chemogenic sediments
	ephemeral lake	mudstones mostly structureless, non grey mudstones with thin layers of syngenetic or diagenetic carbonates or sulfates
	desert plain	well sorted aeolian sandstones and siltstones in units of diverse thickness and extent

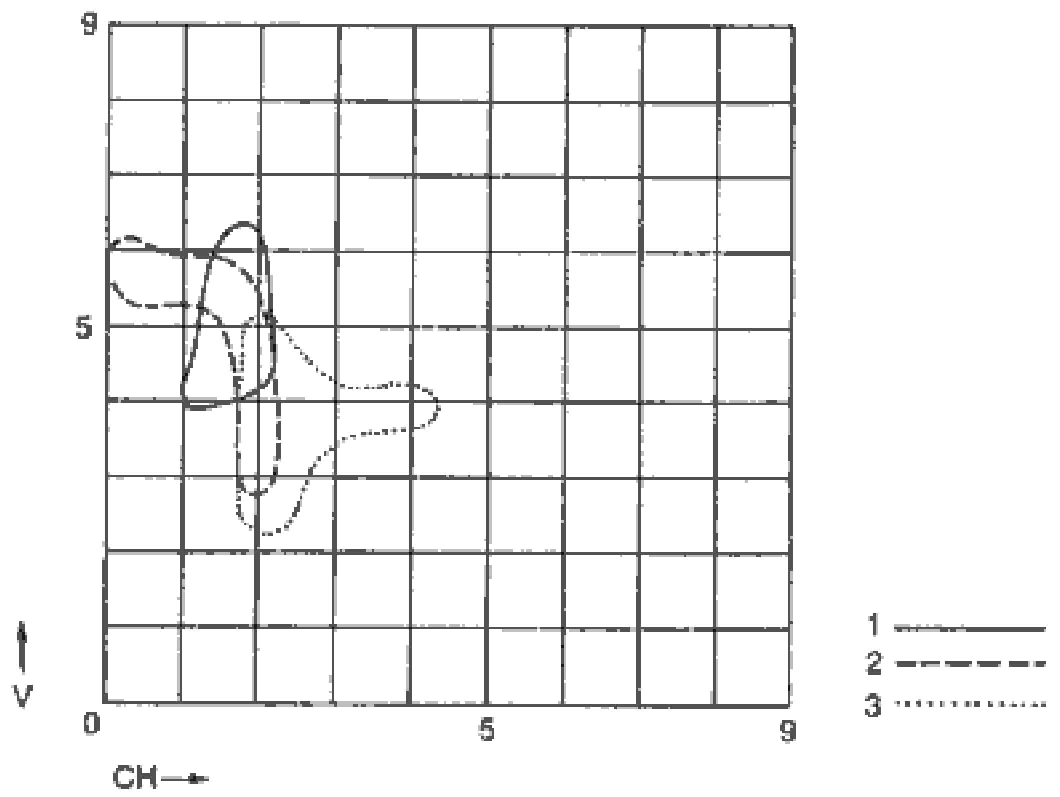
form of siderite and pyrite in perhumid or a subaquatic reducing environment which prevented destruction of the organic matter (paludal, deltaic, lacustrine, wet alluvial plain). The drab sandstones and conglomerates occurring both in red and grey complexes either did not contain a color pigment at the time of their deposition or they were deprived of it during diagenesis.

Color – pigmentation relationship

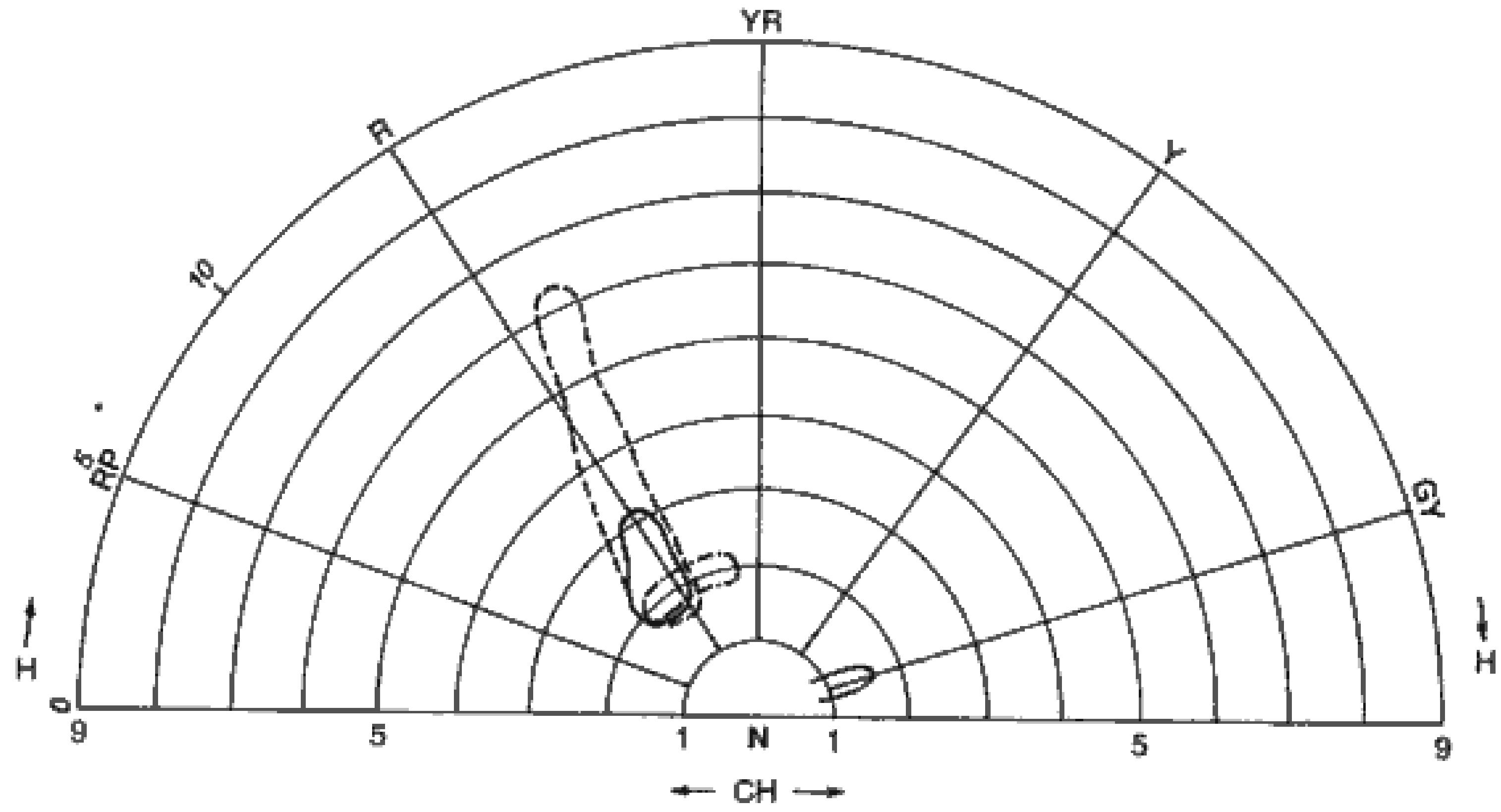
The coloration of sediments, determined from dry samples, is expressed by combined hue (H), value (V), and chroma (CH) indices according to the Munsell Atlas of colors (sine 1975). Based on the examination of 184 samples the following conclusions have been reached:

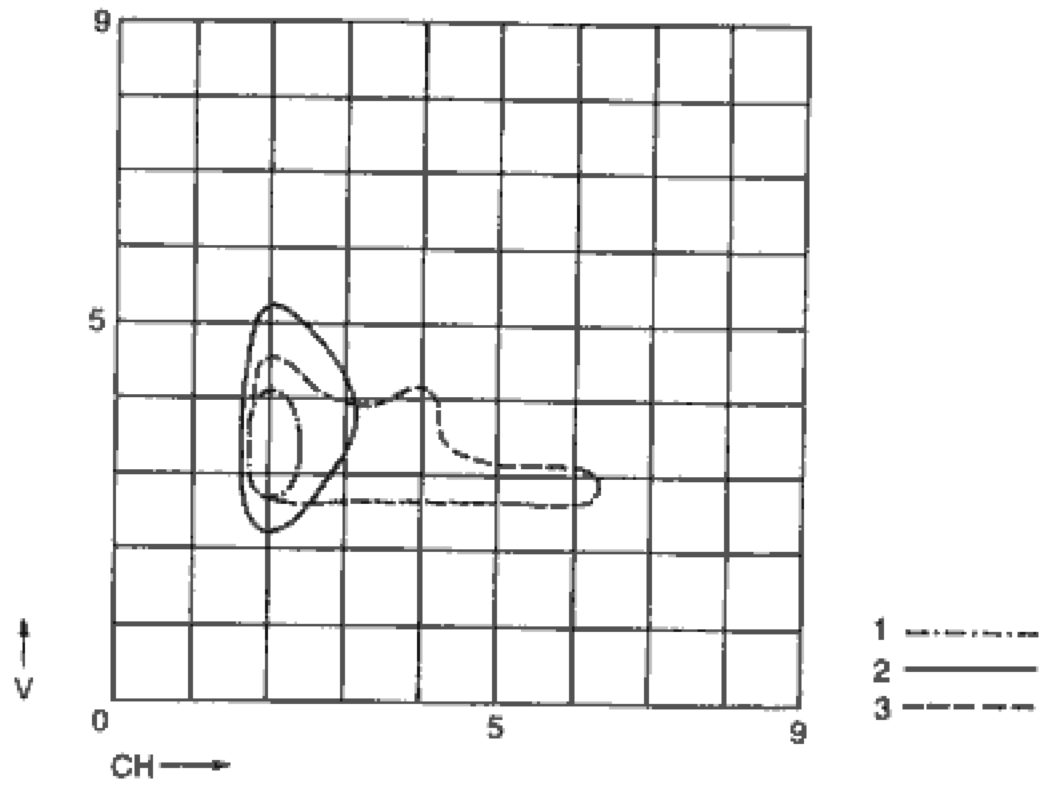
1. Value and chroma are controlled by the amount of pigmented mud fraction. Coarser sediments, therefore, display decreased value and chroma. The presence of carbonate cement may change hue, biotite admixture suppresses value, while organic matter suppresses hue.
2. Submicroscopic hematite has the most pronounced staining effect (Photo 1) controlling the variation of chroma within a narrow range of hue. A dispersion of silt sized hematite pigment is reflected by the rise of hue (above 5, shades of brownish yellow up to a color of coffee with cream, Photo 2), while the hematite agglutination results in the decrease of value (below 5, shades of purple to violet, Photo 3).
3. The mudstones of the Stephanian C and Permian exhibit high chroma and value accompanied by a wide range of hue. The mentioned parameters are measurably lower in older mudstones (Stephanian B and Westphalian) have a narrower range of coloration.
4. Regional variability in coloration, expressed by the value and chroma, is less pronounced when compared with sediments of a different age (Figs. 1–6). Noted variability of hue may be related to differing source areas and local anomalies. Examples of the regional color variation are shown in Fig. 3. A distinct difference has been especially found between the Kladno Rakovník basin and other basins concerning the Líně Formation and its equivalents.
5. Discolored spots, streaks and beds are of drab to green color shades with low value and chroma. Their chroma decreases with increasing age (Figs. 1–3). All discolored sediments are of varying chroma of green color.





1. Dry Munsell colors of mudstone samples from the Westphalian D to Cantabrian units. 1 – Plzeň Basin: Komberk Horizon (Nýřany Member); 2 – Plzeň and Mšeno-Roudnice Basins: Nýřany Member undistinguished; 3 – Intra Sudetic Basin: Svatoňovice Member. H – hue, CH – chroma, RP – red-purple, R – red, YR – yellow-red, Y – yellow, GY – green-yellow, N – neutral, V – value.





2. Dry Munsell colors of mudstone samples from the Stephanian A (Central and West Bohemia Basins) and from the Westphalian D and Stephanian A (Krkonoše Piedmont Basin). 1 and 2 – Týnec Formation: 1 – Kladno-Rakovník and Plzeň Basins, 2 – Mšeno-Roudnice Basin; 3 – Krkonoše Piedmont Basin, Kumburk Formation.

Distribution of red beds in continental basins

Sediments of red and non-grey coloration make a significant part of the strata in the Upper Paleozoic basins in the Czech Republic. Their distribution within individual lithostratigraphic units is shown in Fig. 7. Sediments filling basins in central and western Bohemia are divided into four major lithostratigraphic units. Some of these units are subdivided into members. The earliest unit (Radnice Member, Kladno Formation, Duckmantian/Bolsovian) contains varicolored breccias resting locally on weathered basement (Skoček-Holub 1968). The overlying grey sediments locally incorporate lenses of non-grey and red tuffaceous rocks or refractory claystones (Mašek 1966) associated with the Lubná coal seams and red mudstones of the Komberk Horizon at the base of the Nýřany Member (Westphalian D–Cantabrian). Aforementioned red mudstones, similar to those of the overlying Týnec Formation, grade basinward into a complex of grey sandstones and mudstones of the Nýřany Member (see page 11).

The overlying Týnec Formation (Barruelian) is the oldest laterally persistent red beds unit. Dark red, green or stained mudstones contain fossil calcrete horizons indicating an increase of aridity compared to the underlying coal bearing sequence.

The sediments of the Slaný Formation (Stephanian B) are dominated by grey mudstones with minor reddish mudstones present in the Jelenice Member. Red and non-grey mudstones are also present near the top of this formation.

The overlying Líně Formation (Stephanian C) is dominated by red (Photo 4) to violet mudstones, sandstones and conglomerates. Mudstones are characterized by the presence of green reduction spheroids up to 3 cm in diameter (Photo 5). Locally beds of grey and non-grey mudstones contain thin limestone and chert intercalations.

In the Krkonoše Piedmont and Mnichovo Hradiště Basins sandstone and conglomerate complexes incorporating non-grey mudstones form the basal Carboniferous units. The Brusnice Member of the Kumburk Formation is considered by Rieger (1968) as contemporaneous with the Svatoňovice and the Nýřany Members (Westphalian D–Cantabrian). The overlying Štikov Member (Barruelian) of the Kumburk Formation is of similar lithology. The sediments of the Syřenov Formation, (equivalent to the Jelenice Member) (Stephanian B) are dominantly non-grey. Grey mudstones and claystones are associated with coal and overlie the Black Claystone Horizon. The top of the Syřenov Formation consists of a thick succession of deposits altered by secondary oxidation. Following a hiatus the overlying thick Permian-Triassic red bed sequence contains interbeds of grey and black mudstones in addition to limestone horizons. Red mudstones of the Semily Formation and the overlying Permian formations are marked by circular green reduction spots (Table 3).

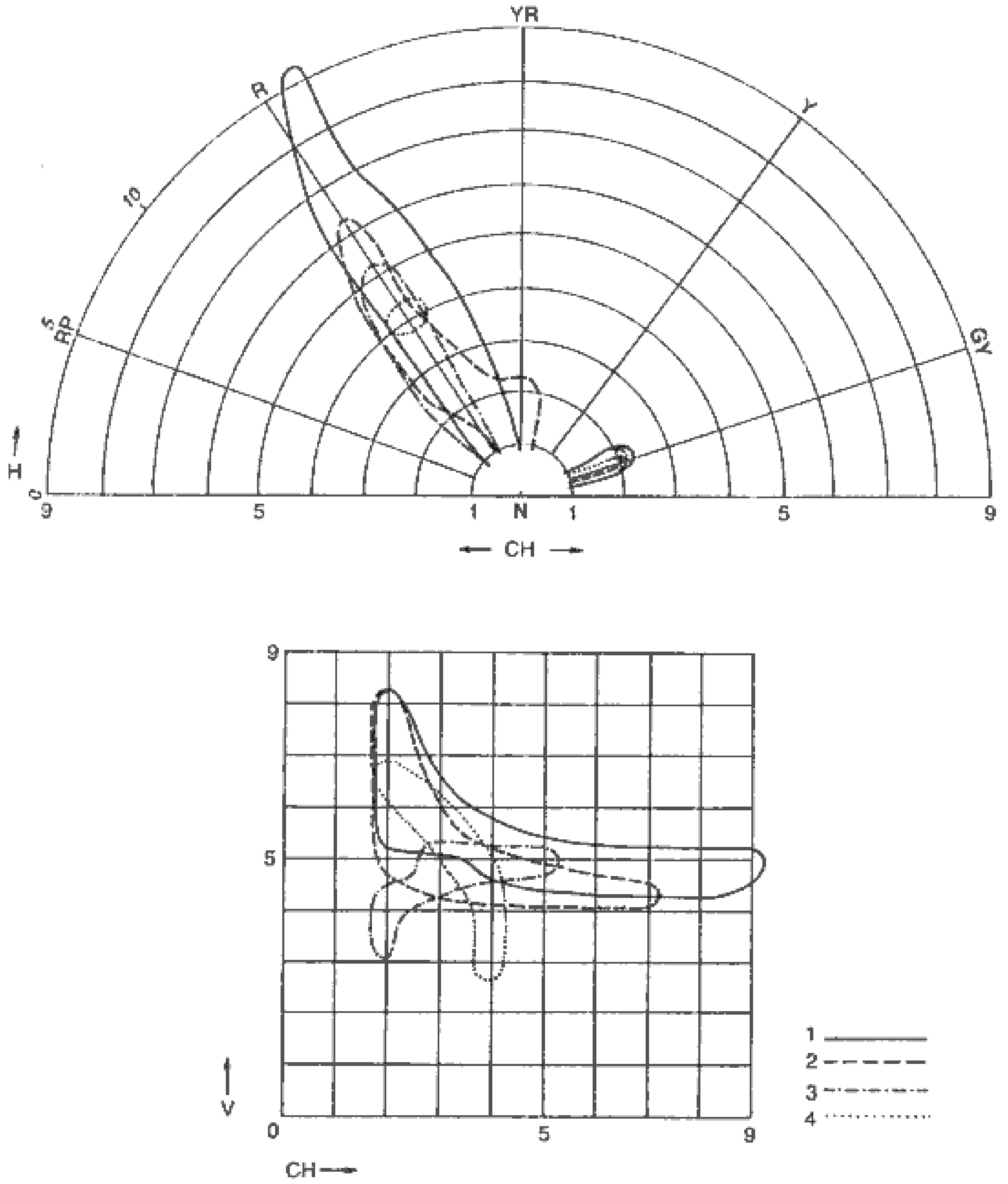
Reddish brown conglomerates including red and grey mudstone interbeds of the Blažkov Formation (Viséan-Early Namurian) were only found in the Intra Sudetic Basin near Žacléř. Sandstones and conglomerates of the Lampertice Member (Late Namurian–Duckmantian) were deposited after a hiatus in sedimentation. At the basin margin sediments of this Member are colored reddish brown to violet but grade basinward into grey, laterally extensive, coal bearing strata. The basal unit of this Member and the overlying Prkenný Důl-Žďárky Member (Duckmantian) display weathered profiles at locations where they overlap the crystalline basement. Most of the younger Petrovice Formation (Duckmantian–Bolsovian) is characterized by an increasing volume of red and non-grey mudstones containing carbonate concretions. The lateral transition of these varicolored lithologies into grey strata were alleged by Tásler et al. (1979). The Svatoňovice Member (Westphalian D–Cantabrian) consists mainly of red and non-grey mudstones and sandstones. The grey sediments occur only within the uppermost coal-bearing unit. In the succeeding Jívka Member the non-grey sediments prevail but grey units do occur in local areas together with coal.

The Permian-Triassic strata, above a major unconformity, are typical red beds similar to those in the Krkonoše Piedmont Basin. Several grey horizons of the Permian age occur in them as well. Within red beds reduction spots, eolian sediments and gypsum layers were found.

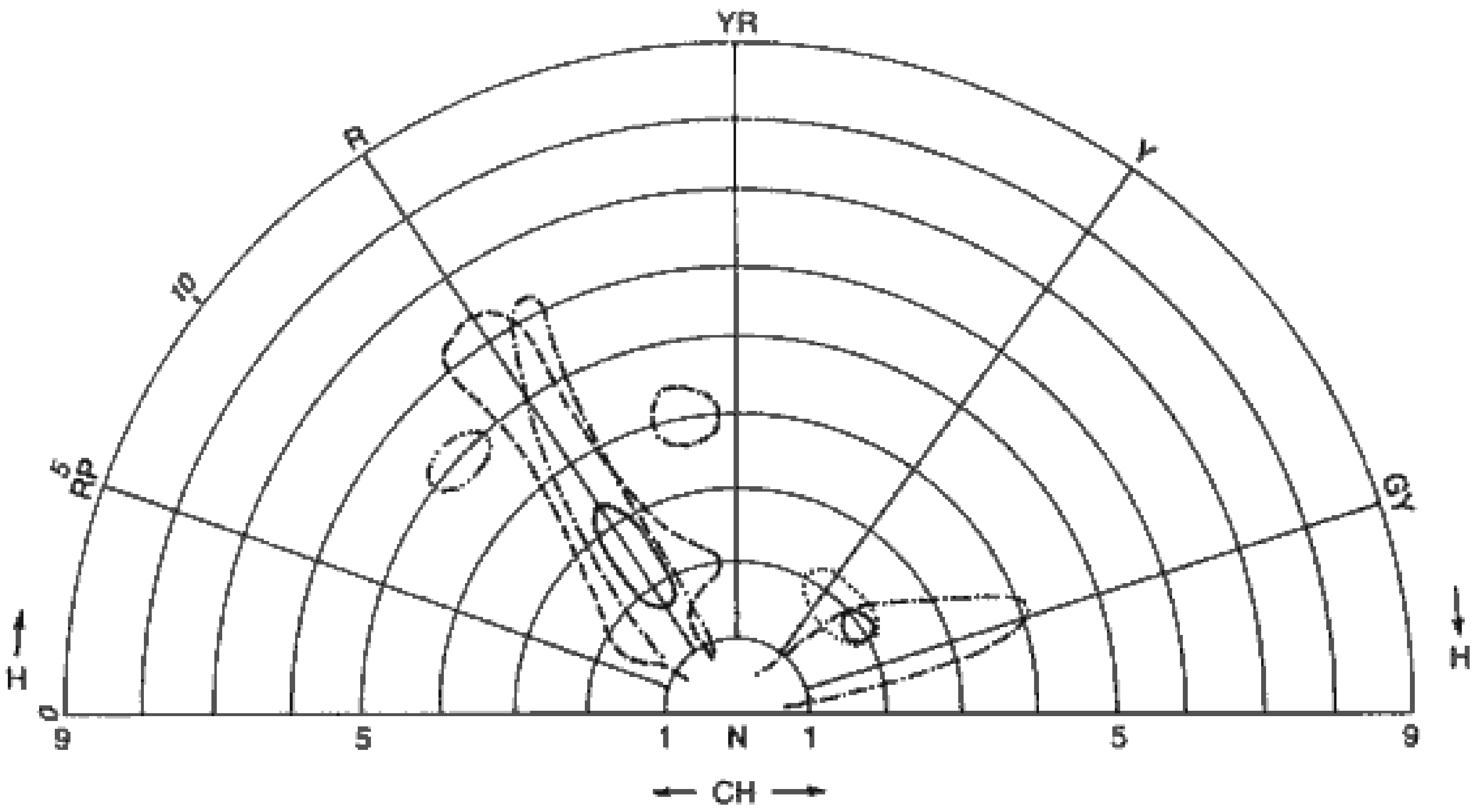
Sediments of the Blanice and Boskovice Grabens (Stephanian C–Autunian) are typical red beds incorporating grey, coal-bearing unit near the base. Subordinate interbeds of grey bituminous limestone occur in the Autunian strata. These grabens have been studied considerably less than other studied basins.

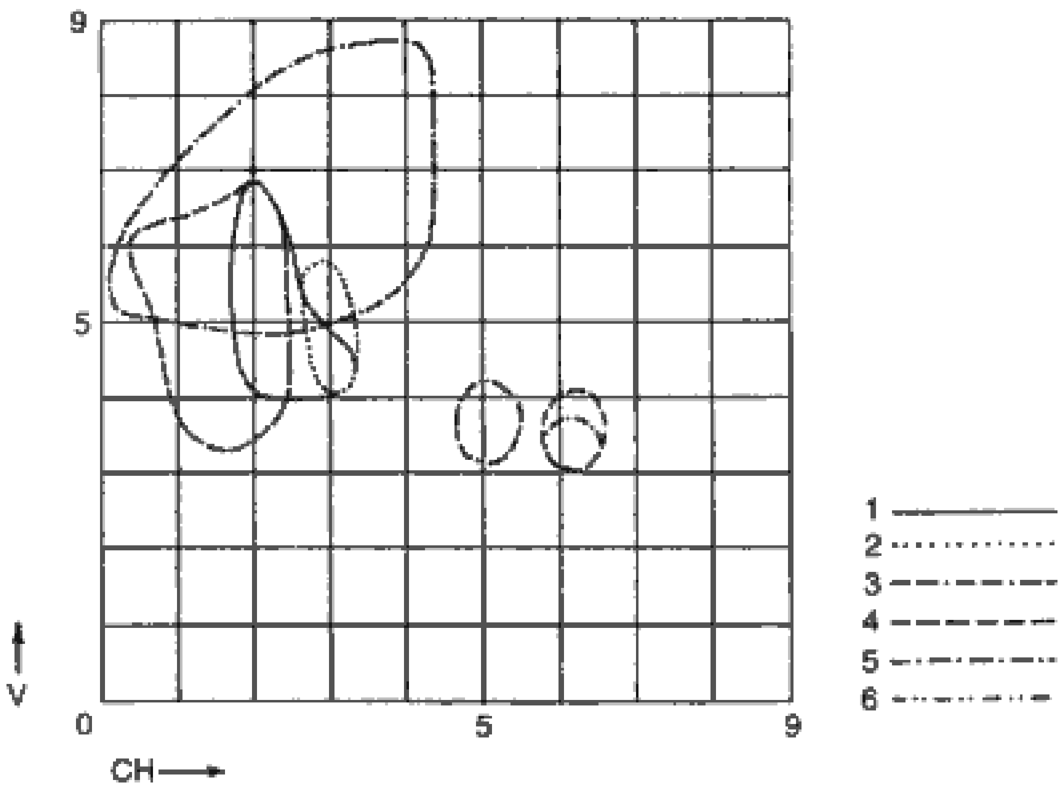
Lateral transitions of grey and non-grey sediments

The lateral sediment color changes are a common feature in the studied basins. The basic assumption involves the pre-



3. Dry Munsell colors of mudstone samples from the Stephanian C of Central Bohemia and Krkonoše Piedmont Basins and from the Autunian of the marginal area between Krkonoše Piedmont and Intra Sudetic Basins. 1 and 2 – Líně Formation: 1 – Kladno-Rakovník Basin, 2 – Mšeno-Roudnice Basin; 3 – Krkonoše Piedmont Basin Semily Formation; 4 – Vernéřovice Member, Chvaleč Formation.





4. Dry Munsell colors of mudstone samples from the Autunian and Saxonian (Trutnov Formation). 1 and 2 – marginal area between the Krkonoše Piedmont and Intra Sudetic Basins: 1 – Bečkov Member (Chvaleč Formation), 2 – Broumov Fm.; 3 – Blanice Graben (Autunian); 4–6 Krkonoše Piedmont Basin: 4 – Martínkovice Member (Broumov Fm.), 5 – Vrchlabí Fm., 6 – Trutnov Fm.

dominance of grey color in the coal-bearing formations and the mudstone dominated red beds of the barren formations. The occurrence of non-grey mudstones in coal-bearing formation is more common than the presence of grey sediments in barren units. The following examples reflect lateral changes of color observed either over a short (hundreds meters to several km) or a longer (tens to few hundreds km) distance in units of the same age.

Sediment color changes over short distance

The grey color of mudstone dominated strata (Westphalian–Cantabrian) commonly changes to non-grey to red when approaching basin margins and protruding basement structures. This change of color may suggest transport of non-grey detritus into a basin where it acquires grey-black coloration from organic matter. The occurrence of red beds marginal to a basin has been described from the Žacléř Formation of the Intra Sudetic Basin (Tásler et al. 1979). Similar transitions are also present in the overlying lithostratigraphic units (Jívka Member) and from the Rybníček Coal Horizon (Autunian).

Lateral transition of grey and non-grey mudstones in the Central and Western Bohemian basins occurs most commonly in the Nýřany Member. Here the Komberk Horizon forms a fan-shaped unit, over 60 m thick, near the margin of the Plzeň Basin (Pešek 1994). The lithology of the Komberk Horizon consists of red, green and varicolored mudstones including a brown tuffite bed (Fig. 8). Toward the basin center these sediments pass into a complex of sedimentary cycles involving beds of arkose, sandstone and grey mudstone of the Nýřany Member (Figs. 8 and 9). Šetlík (1977) pointed out that the anomalous lithology of the Komberk Horizon is further complicated by the presence of plant imprints devoid of carbonaceous matter. The mentioned author thus inferred similar conditions for the plant material fossilization as in the typical red beds of the Týnec Formation. Additional fan-shaped sedimentary aprons comprising non-grey and red sediments are a common feature of the Nýřany Member in other basins of central Bohemia. Because of the local dominance of red mudstones in the Nýřany Member, strata of this Member were erroneously lumped in the overlying Týnec Formation. In general, the color of the Nýřany coal-bearing Member progressively changes basinward into greying shades (Fig. 10).

The occurrence of red beds that onlap crystalline basement is exemplified by varicolored mudstone beds surrounding the Smečno-Velvary ridge (Pešek 1994) that separates two coal bearing areas as shown in Fig. 11. The ridge no longer controlled the red bed distribution because of burial by younger strata (Fig. 12).

Sediment color changes over long distance

A wealth of geological information, including data from 2,000 boreholes, provides a solid basis for the correlation of lithostratigraphic units in the basins studied. Considerable differences exist in the coloration of contemporaneous mudstone strata in separate basins.

Whereas the Radnice Member (Duckmantian-Bolsovian) in central and western Bohemia is dominated by grey mudstones in the time equivalent of the Intra Sudetic Basin i. e. upper part of the Petrovice Member red beds prevail.

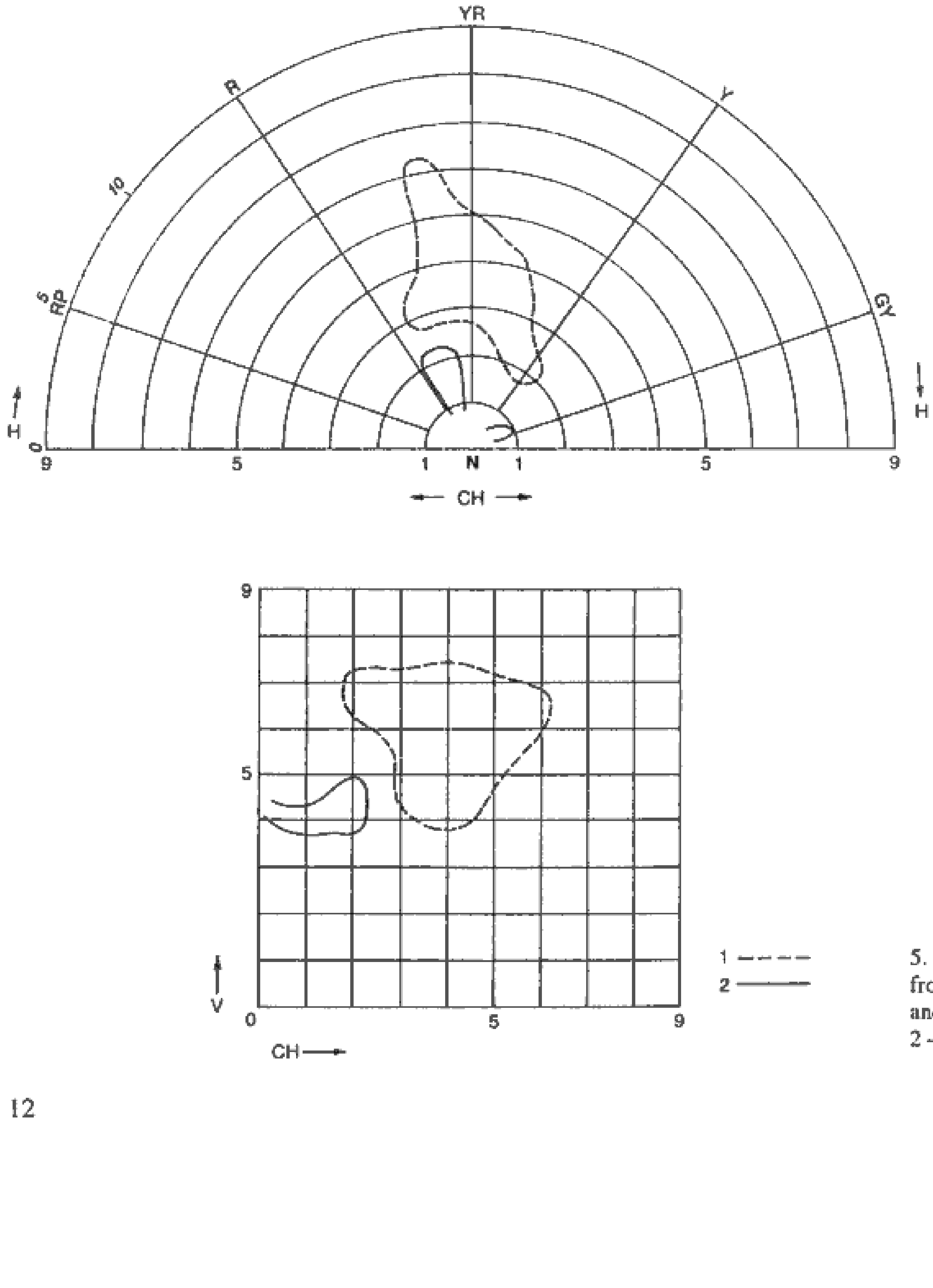
Grey mudstones and claystones dominate in the Nýřany Member (Westphalian D–Cantabrian) in central and western Bohemia while the equivalent sequence consists of red beds in the eastern part of the Mšeno-Roudnice Basin and the entire Mnichovo Hradiště, Krkonoše Piedmont and Intra Sudetic Basins (with exception of the Svatoňovice Group of Coals). Such red beds are indistinguishable from overlying units of Barruelian age.

The transition of grey mudstones into red beds is also noted in the Stephanian B. The grey color of mudstone strata of the Jelenice Member in the Plzeň Basin becomes greenish eastward i. e. in the Kladno Rakovník Basin and spotted red in the Mšeno Roudnice and Krkonoše Piedmont Basins. Red sediments of the same age dominate in the Jívka Member (excl. of the Radvanice Group of Coals) in the Intra Sudetic Basin.

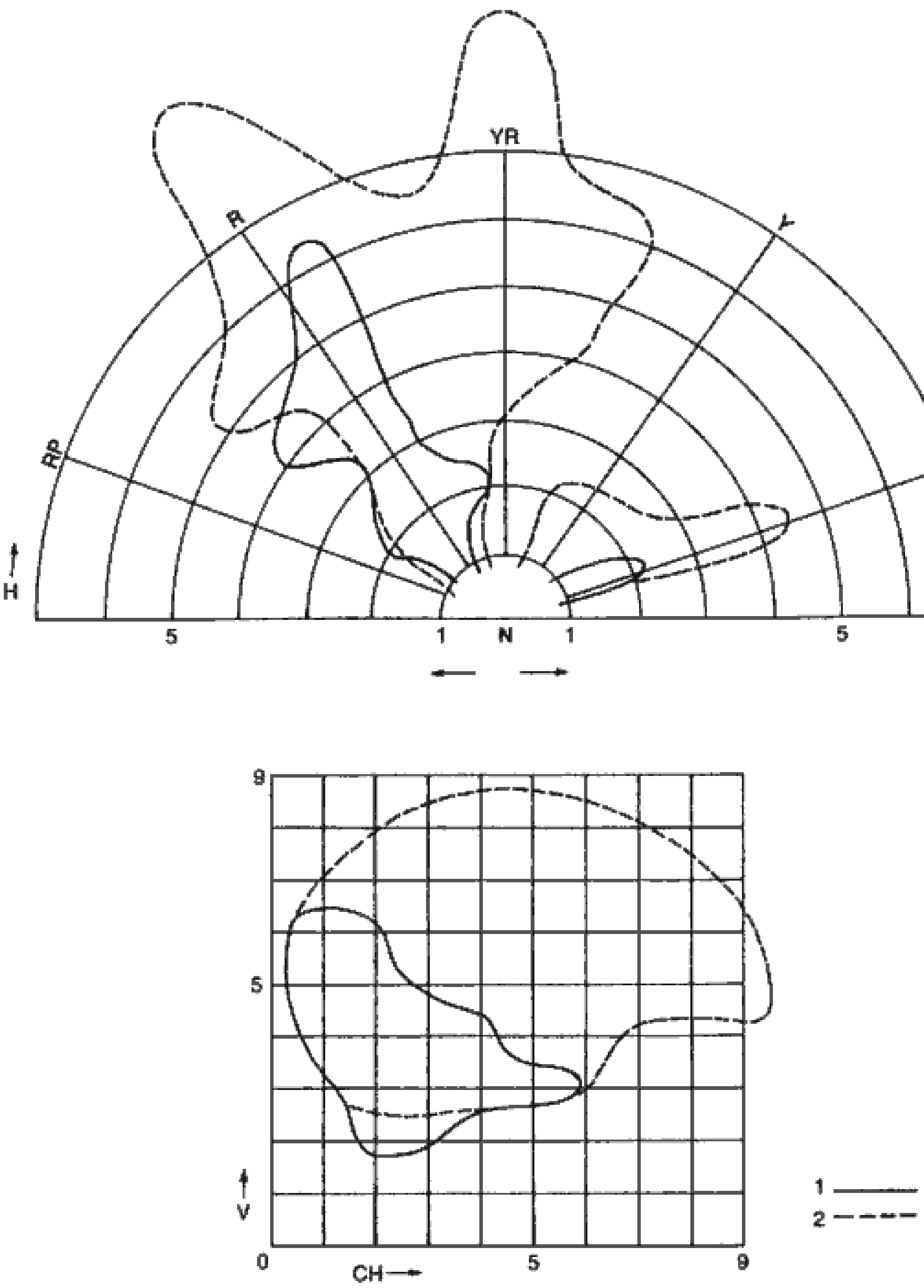
The lateral color changes, mentioned above, are difficult to explain by different microclimatic conditions. The notion that lateral changes of color in the Upper Paleozoic sediments of the Bohemian Massif are solely climate related should be, therefore, treated with caution.

Iron oxides: laboratory results

X-ray diffraction analyses show that the most common coloring pigment in the red beds is hematite (Pešek - Skoček 1998). Bouška et al. (1982) has also identified maghemite.



5. Dry Munsell colors of mudstone samples from the Stephanian C and Autunian (Blanice and Boskovice Grabens). 1 – Blanice Graben; 2 – Boskovice Graben.



6. Color clusters reflecting the age of mudstone samples. 1 – Stephanian B and older units; 2 – Stephanian C and Permian sequences.

The presence of other Fe oxides was detected only in rocks subjected to recent or subrecent weathering.

As has been stated, hematite might be derived either from the source area or it could originate secondarily in situ. In order to find evidence we investigated the range of isomorphic substitution of Fe in the hematite lattice. According to SCHWERTMANN (1993) Fe oxides present in recent soils can incorporate Al, V, Ti and other elements depending on availability and temperature. STANJEK (1995) pointed out that the elemental substitution in Fe oxides is subject to pH, Eh, presence of adsorbents, free ions, organic matter in addition to temperature. NAHON et al. (1980) described goethite from lateritic soils containing up to 30 % Al in place of Fe.

The isomorphism in hematite was determined in nine samples by X-ray diffraction. The Al content was computed according to the method used by BURNHAM (1962) and up to 2.2 % Al was found in analyzed hematite grains. Lattice parameters of hematite in a few samples suggest the presence of an ilmenite component (up to 6 %) which is in agreement with observations made by STANJEK (1995). The Al and Ti content in hematite, determined by microprobe, ranges between 0–5 % Al_2O_3 and from 0–6.15 % TiO_2 in individual grains. Compositional variations point to the multiple genesis of hematite. We suspect that, in addition to the primary and diagenetic hematite, its grains incorporating ilmenite are clasts of magmatic origin (PEŠEK-SKOČEK 1998).

The microscopy shows that the finest hematite pigment occurs in mudstones of light to dark red (5 R 6/2-). Hematite present in brown-grey, violet-grey, beige and brown sediments is seggregated in fine clusters indicating diagenetic redistribution and agglutination. Pigment morphology thus may be helpful in determining the primary or secondary hematite.

Hematite film, coating quartz grains (Photo 6) recorded in some sandstones suggests an arid environment (FOLK 1976). Rounded ferrolite grains of violet color in reflected light, found in sandstone and sandy mudstone beds, may be indicative of a ferricrust surfacing the source area or exposed contemporaneous sediments. Authigenic hematite clusters, resembling concretions, larger than clastic grains,

Table 3. Characteristic color of sediments in distinguished lithostratigraphic units

Basin/Basins	Formation	Member	Color
central and western Bohemia	Líně		mudstones mostly bright red, reduction spheroids locally common, varicololored claystones (inclusive grey ones) in lacustrine units; sandstones and conglomerates partially or dominantly red, rarely decolored (greenish-grey) or kaolinized
	Slaný	Kamenný Most	claystones varicolored – bright red, dark reddish brown, violet, greyish violet, grey; sandstones grey or uncolored
		Kounov	mudstones grey or blackish grey, exceptional red intercalation (rudka); sandstones grey or uncolored
		Ledce	mudstones grey, locally with secondary hematite pigment; sandstones grey, uncolored, locally kaolinized or pigmented with secondary hematite
		Hředle	mudstones grey or dark grey; sandstones uncolored or grey
		Mšec	claystones grey or black
		Jelenice	mudstones grey, locally greenish grey or spotted brown; sandstones grey or uncolored
	Týnec		mudstones dark reddish brown reduction spheroids extremely scarce; sandstones, conglomerates uncolored, partially reddish or greenish
	Kladno	Nýřany	mudstones mostly grey to black, locally reddish brown, scarcely violet; sandstones, conglomerates uncolored, locally greenish
		Radnice	mudstones grey to black, in upper part scarcely, in lower part often reddish brown, green, dark chocolate or stained; sandstones, conglomerates, grey, uncolored, scarcely green
Krkonoše-Piedmont and Mnichovo Hradiště	Bohdašín		sandstones, conglomerates often whitish, rarely stained, pinkish red, carmine
	Bohuslavice		mudstones deep red to carmine, uncommon reduction spheroids; sandstones, conglomerates pinkish red
	Trutnov		mudstones red to brownish red, white specks, frequent reduction spheroids; sandstones, conglomerates most frequently pale red, pink (at carbonate presence), rarely whitish
	Chotěvice		mudstones red, locally reddish violet to violet, reduction spheroids common; sandstones, conglomerates pale red
	Prosečné		mudstones red to brownish red, within Kalná Horizon grey, dark grey, violet, greenish grey, reduction spheroids frequent; sandstones uncolored or whitish
	Vrchlabí		mudstones red to reddish brown, in lacustrine units (Rudník, Háj, Kozinec) grey and dark grey, laterally passing to varicolored (mostly greenish); sandstones, arkoses uncolored, fine lacustrine sandstones pale red, reduction spheroids rare
	Semily		mudstones red to brownish red, in lacustrine sequences (Štěpanice-Čikvásky and Ploužnice) grey and varicolored (violet, brownish grey and greenish grey), reduction spheroids frequent; sandstones, conglomerates pale red
	Syřenov		mudstones grey to dark grey (locally secondary hematite pigment)
	Kumburk		mudstones reddish brown, brownish red even brown, reduction spheroids locally common; sandstones, conglomerates uncolored, exceptionally pale reddish brown
Intra Sudetic	Bohdašín		sandstones, conglomerates mostly whitish, rarely stained white, pinkish red, carmine
	Bohuslavice		mudstones deep red to carmine, reduction spheroids infrequent; sandstones, conglomerates pinkish red
	Trutnov		mudstones red to brownish red, whitish specks, reduction spheroids common; sandstones, conglomerates mostly pale red, pink (with carbonate), rarely whitish
	Broumov	Martínkovice	fine sandstones and mudstones red, in lacustrine sequences (Jetřichov, Hejtmánkovice, Vižňov) varicolored, mostly violet, greenish grey, greyish green but even grey, reduction spheroids locally frequent
		Olivětín	mudstones reddish brown, Walchia claystones grey, dark grey, greenish grey; sandstones, conglomerates uncolored, grey, rarely greenish grey; reduction spheroids frequent
		Nowa Ruda	mudstones red, brownish red, reddish brown, intercalations of varicolored mudstones and fine sandstones; reduction spheroids common

Intra Sudetic	Chvaleč	Bečkov	mudstones brownish red to reddish brown, in lacustrine sequence (Bečkov) greenish grey, greyish green and even dark grey, reduction spheroids locally common; sandstones, conglomerates greyish brown, pale reddish brown
		Vernéřovice	mudstones reddish brown, brown, in lacustrine sequence (Vernéřovice) varicolored, greenish grey, dark grey, claystones from the coalbearing horizon (Rybníček) grey, dark grey reduction spheroids locally frequent
	Odolov	Jívka	mudstones reddish brown to brownish red, in coal bearing units (Radvanice, Bystré, Vít's Mines) grey and dark grey, laterally passing to greenish grey or greyish green; sandstones uncolored or grey
		Svatoňovice	mudstones reddish brown, in coal bearing sequences grey or dark grey laterally passing to greyish violet, greenish grey and greyish green in their barren parts; sandstones and particularly arkoses are uncolored, fine sandstones are greenish grey; conglomerates reddish brown; reduction spheroids extremely rare
	Žacléř	Petrovice	mudstones mostly grey, dark grey, rarely greenish grey, in upper part mostly reddish brown; sandstones, conglomerates grey, pale grey, greenish grey, red, violetish
		Prkenný Důl-Žďárky	mudstones mostly grey, dark grey, rarely greenish and reddish brown; sandstones, conglomerates pale grey and grey
		Lampertice	mudstones grey, dark grey rarely greenish grey, reddish brown; sandstones, conglomerates grey, pale grey, rarely greenish grey and reddish
		Blażkow	mudstones reddish brown and greenish grey; sandstones, conglomerates violetish and brownish red
Blanice Graben		Chýnov	mudstones in vicinity of Český Brod bright red, greenish grey, discolored; in vicinity of České Budějovice brown, dark redish brown; sandstones, conglomerates greenish, pale reddish brown; reduction spheroids frequent
		Lhotice	mudstones mostly grey to greyish black, scarcely greenish grey; sandstones, conglomerates uncolored or pale grey
		Peklov	mudstones grey, at bottom locally dark brown to reddish brown; sandstones, conglomerates uncolored or grey
Boskovice Graben	Overlying		mudstones bright reddish brown, greenish grey; sandstones, conglomerates uncolored, pale red, at places greenish grey; reduction spheroids frequent
	Sandstone and Conglomerate + Rosice-Oslavany		mudstones dark reddish brown; coarser deposits uncolored or varicolored
	Basal		sandstones, conglomerates brownish, pale reddish brown

are probably oxidized siderite or pyrite aggregates (Photo 7). Hematitized grains of mafic minerals, retaining their original morphology, are most commonly represented by biotite flakes (Photo 8). Hematite grains with ilmenite intergrowths detected by microprobe analysis are considered weathered magmatic magnetite.

Magnetic properties

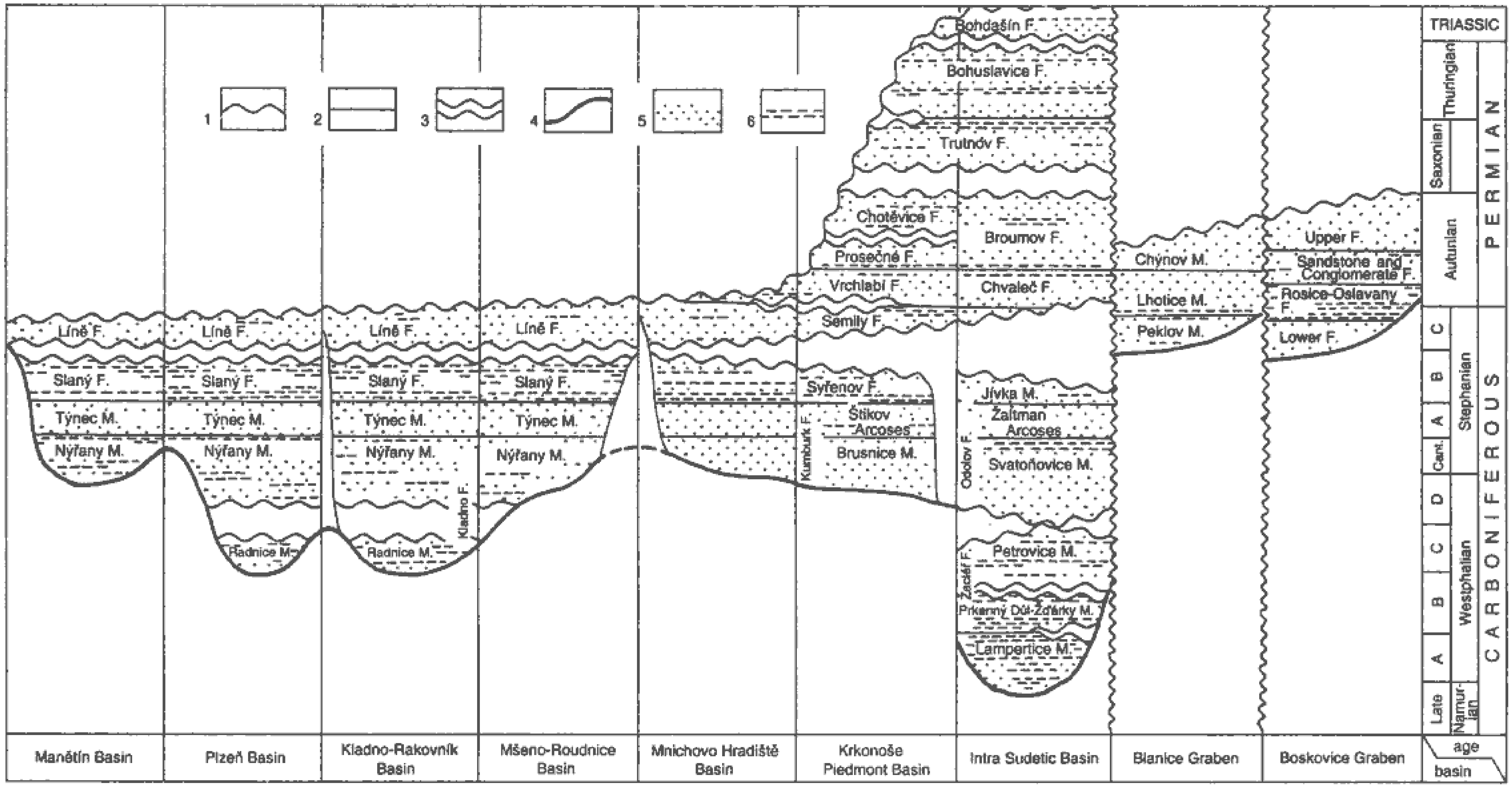
Paleomagnetic measurements of red beds in the area studied (Krs-Pruner 1995) show very low dispersal (high precision index k and low values of the half apex angle of the reliability cone at a 95 % probability level) implying a decisive role of the chemical remanent magnetization (CRM) for these strata. This CRM is caused by stable, diagenetic hematite exhibiting a low viscosity component and a wide range of temperature blocking values.

The magnetic polarity of light-reddish and grey sediments is caused by primary, detrital magnetite, syngenetic with the host rock. In addition to detrital magnetization thermoremanent magnetization was detected in tuffaceous rocks.

The study of remanent magnetization shows that hematite was the primary constituent of red mudstones or originated from hydrated Fe oxides shortly after deposition. The detrital magnetite is preserved only in grey and non-red sediments. Its absence in red beds suggests a diagenetic change of magnetite into hematite.

Geochemistry of red and grey mudstones

Statistical evaluation of analytical data from the Permo-Carboniferous sediments (Čadková 1981) yielded clarke of concentrations of essential and trace elements in various rocks. Published data and analyses accomplished in the



7. Section showing the correlation of basic lithostratigraphic units in limnic Upper Paleozoic Basins. The dominating color of sediments is shown by hachure. 1 – erosional contact; 2 – unit boundary; 3 – hiatus; 4 – Carboniferous/Permian basement; 5 – red and non-grey mudstones dominating; 6 – grey mudstones dominating.

course of our research (Pešek-Skoček 1998) support the following conclusions:

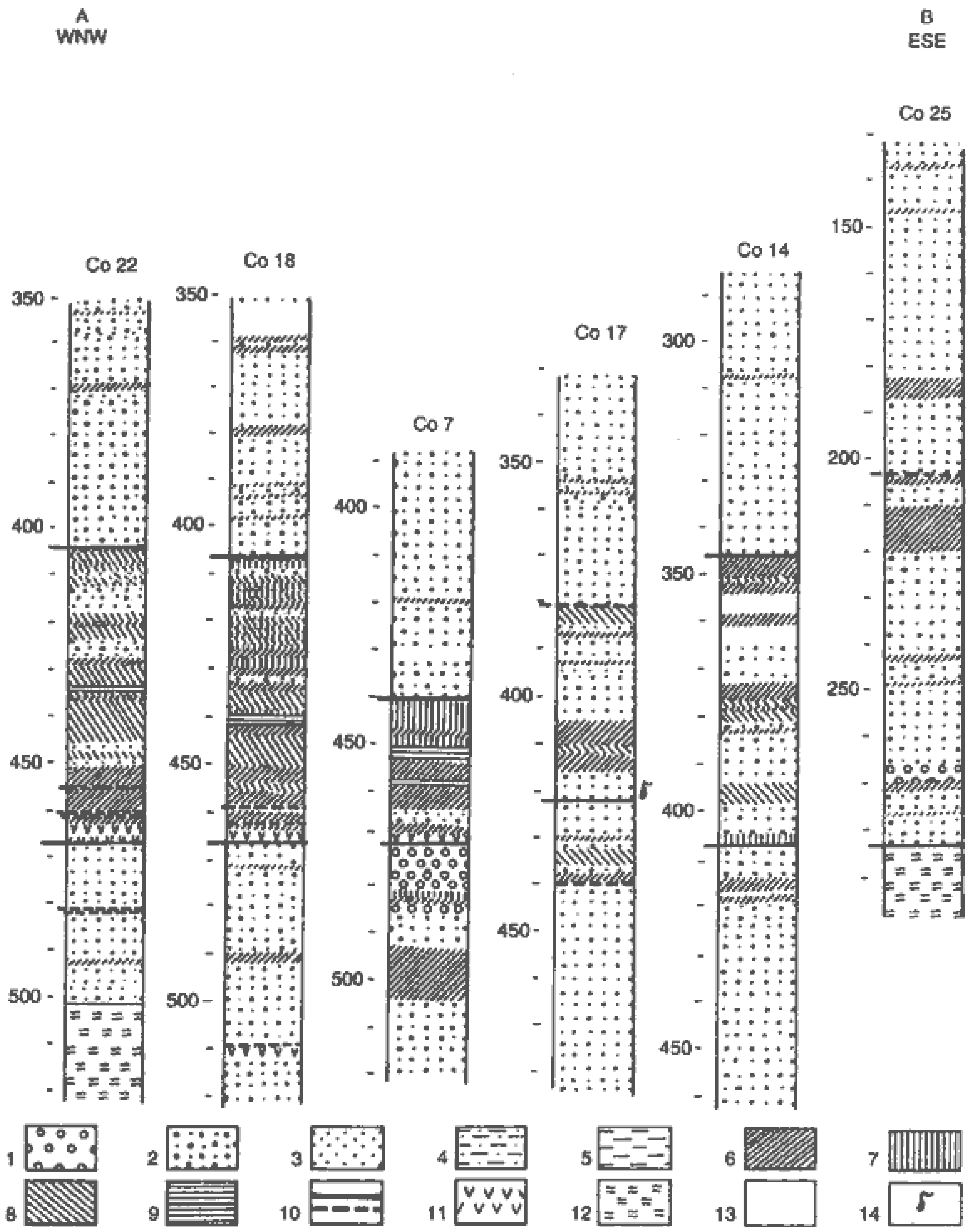
a) The largest amount of dispersed Fe (ranging 1.2–10.4 %) is present in the fine pelitic fraction regardless of its color (Fig. 13). Grey sediments usually contain similar amounts of total iron if samples are large enough and involve diagenetic ferrous minerals (siderite, pyrite). Extremely low Fe content in some grey mudstone samples may reflect either low iron content in the source rocks or a mobilization and removal of Fe. The generally lower Fe content in green and greenish-grey mudstones is a result of partial Fe removal. Figure 14 illustrates the FeO/Fe_2O_3 ratio for red mudstones (less than 0.3) and for grey mudstones (more than 1.0) with transitional values represented by greenish-grey samples.

b) The TiO_2 content (0.2–2.28 %) reaches its maximum in samples rich in iron. Samples pigmented by organic matter exhibit a high variability of the Fe/TiO_2 ratio (Fig. 14) suggesting the partial leaching of iron from some grey mudstones. A major amount of TiO_2 is present in the fine pelitic fraction as evidenced by the TiO_2–Al_2O_3 relationship and the TiO_2 independence of the SiO_2 and $CaCO_3$ contents.

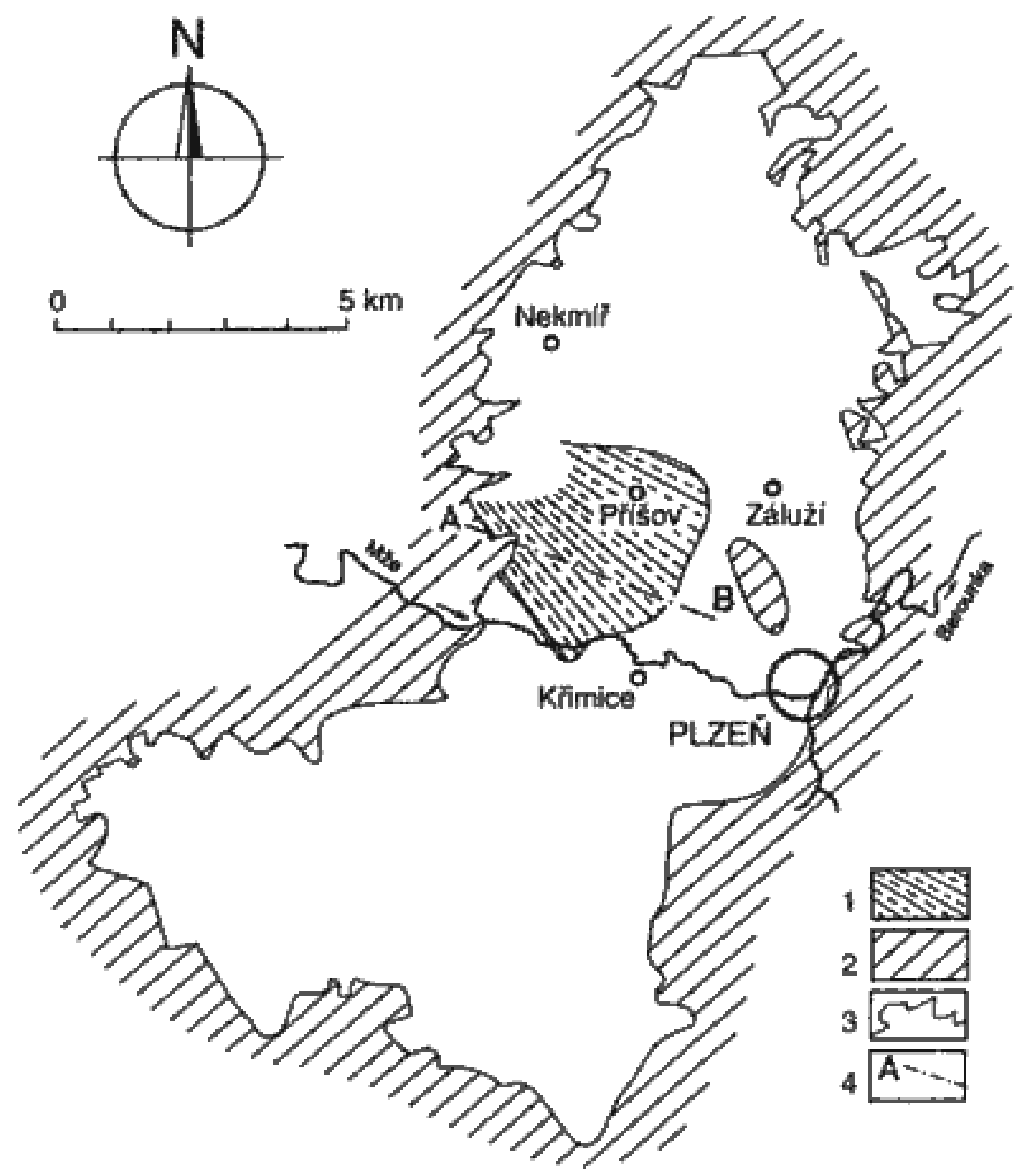
c) The geochemical maturity, expressed by the Al_2O_3/Na_2O ratio, shows a wide range of values (Fig. 15) and is explained by the interplay of a variety of sources and diagenetic processes. A high Na_2O content might reflect the presence of analcime and montmorillonite regardless of the sediment color.

d) The K_2O/Na_2O ratio above 1.0 in mudstone samples reflects the widespread occurrence of illite and mica. An exceptionally low value (less than 1.0) was found in black, bituminous mudstone from the Klobuky Horizon and in varicolored mudstones containing either analcime or montmorillonite.

e) The average boron content in red mudstones is more than 70 ppm and less than 60 ppm in grey mudstones (Bouška et al. 1975, Bouška-Pešek 1982). This relation-



8. Cross sections of the Komberk Horizon documenting the lateral transition of varicolored and grey sediments. Location of section in Fig. 9. 1 – conglomerate; 2 – arkose, feldspathic sandstone; 3 – sandstone; 4 – mudstone; 5 – claystone; 6 – grey mudstone; 7 – red mudstone; 8 – green mudstone; 9 – grey mudstone stained red and/or green (7–9 in geologic section); 10 – coal seam (*full line* workable, *dashed line* not workable); 11 – tuff, tuffite; 12 – proterozoic shale, greywacke; 13 – core missing; 14 – fault.



9. Fan like body of varicolored sediments of the Komberk Horizon in the Plzeň Basin. 1 – Komberk Horizon; 2 – Proterozoic; 3 – limit of the Carboniferous; 4 – location of the cross section (Fig. 8).

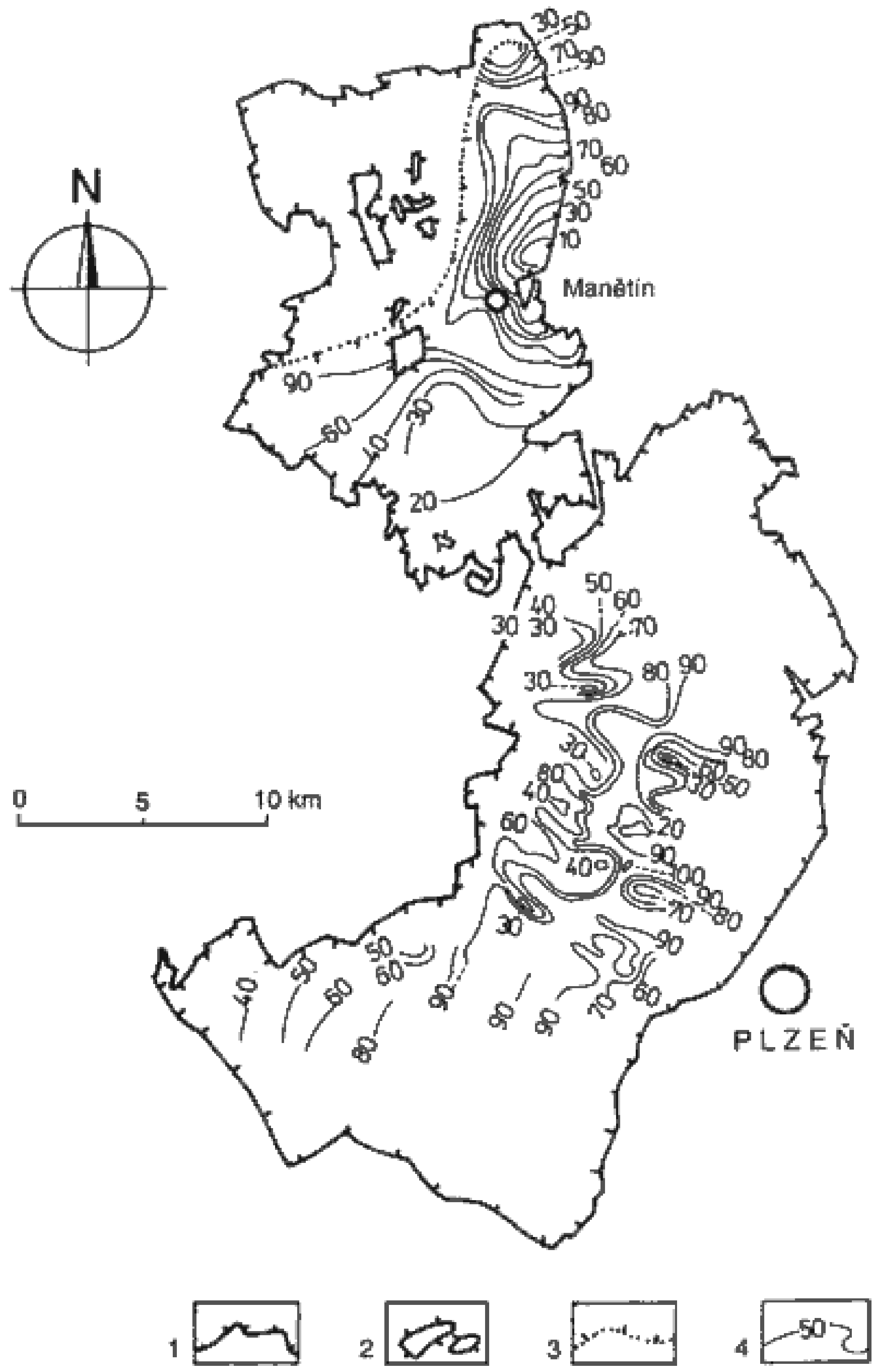
ship probably reflects the effect of mineralization by pore fluids and the fixation of boron in the illite fraction of varicolored mudstones.

f) The low content of natural radionuclides in mudstones was determined by spectroscopy (Pešek-Skoček 1998). The uranium content averages 1–5 ppm but an anomalous content (e. g. 44.7 ppm) was noted in a grey mudstone from the Klobuky Horizon (Líně Formation). Anomalous accumulations indicate diagenetic redistribution of uranium related to the presence of organic matter. The amount of thorium ranges 2–18.5 ppm, but is generally higher in grey mudstones. The rare earth elemental content, normalized with respect to the chondrite standard, shows enrichment in light elements with a low amount of europium (Bouška et al. 1982). The yttrium content averages several tens ppm.

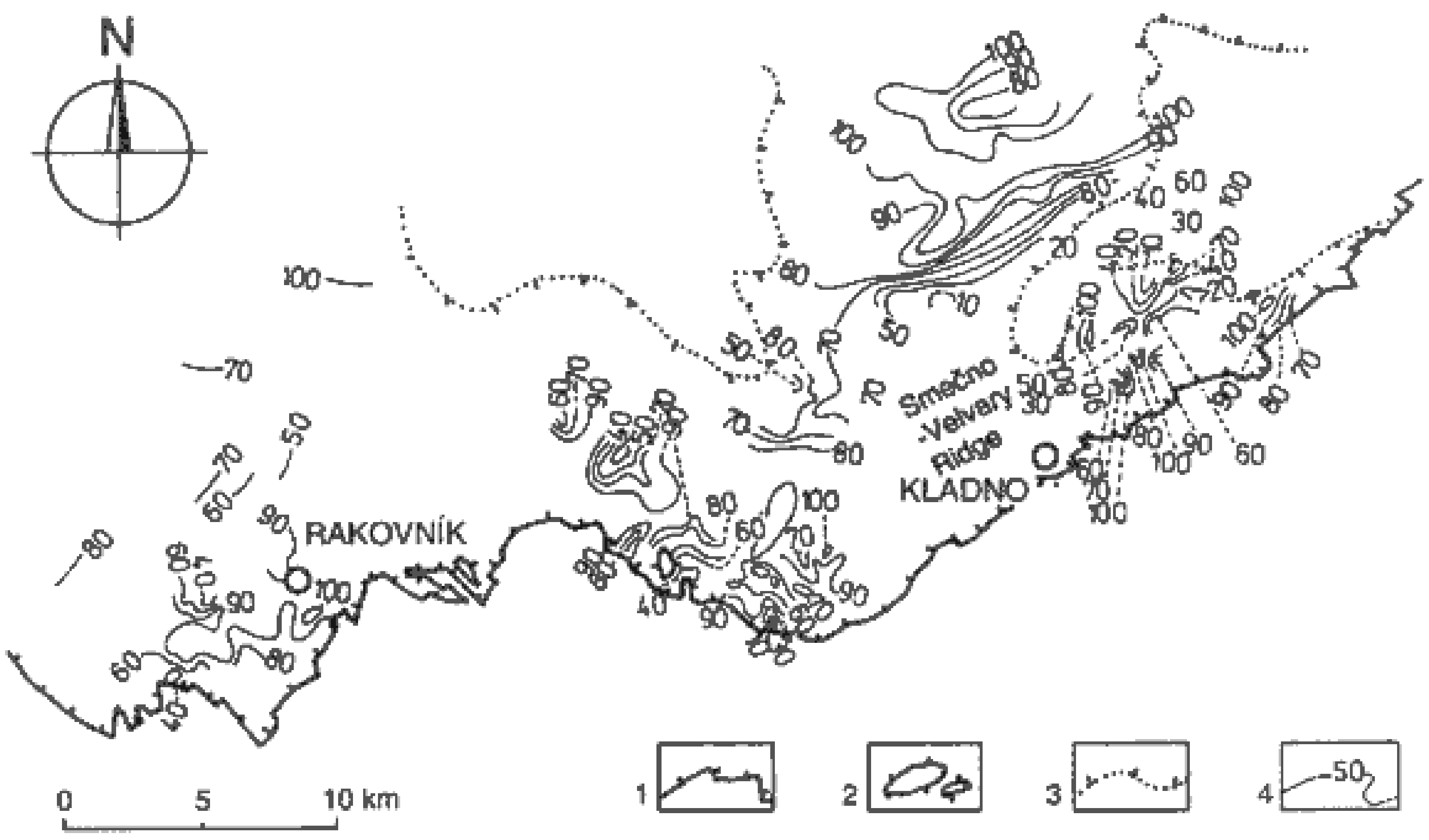
g) Trace element distribution does not depend on the mudstone color. Some elevated amounts of trace elements (Pb, Sn, Ga, Cu, Zn, Cr, Ni, V, Co, Ge, Bi, Cd, Ag, Mo) have been found in grey colored interbeds within red bed successions (Skoček 1965, 1966, Čadková 1971a, b, 1977). These anomalous occurrences were probably the result of diagenetic migration of particular elements in mineralized ground waters.

Climate indicators

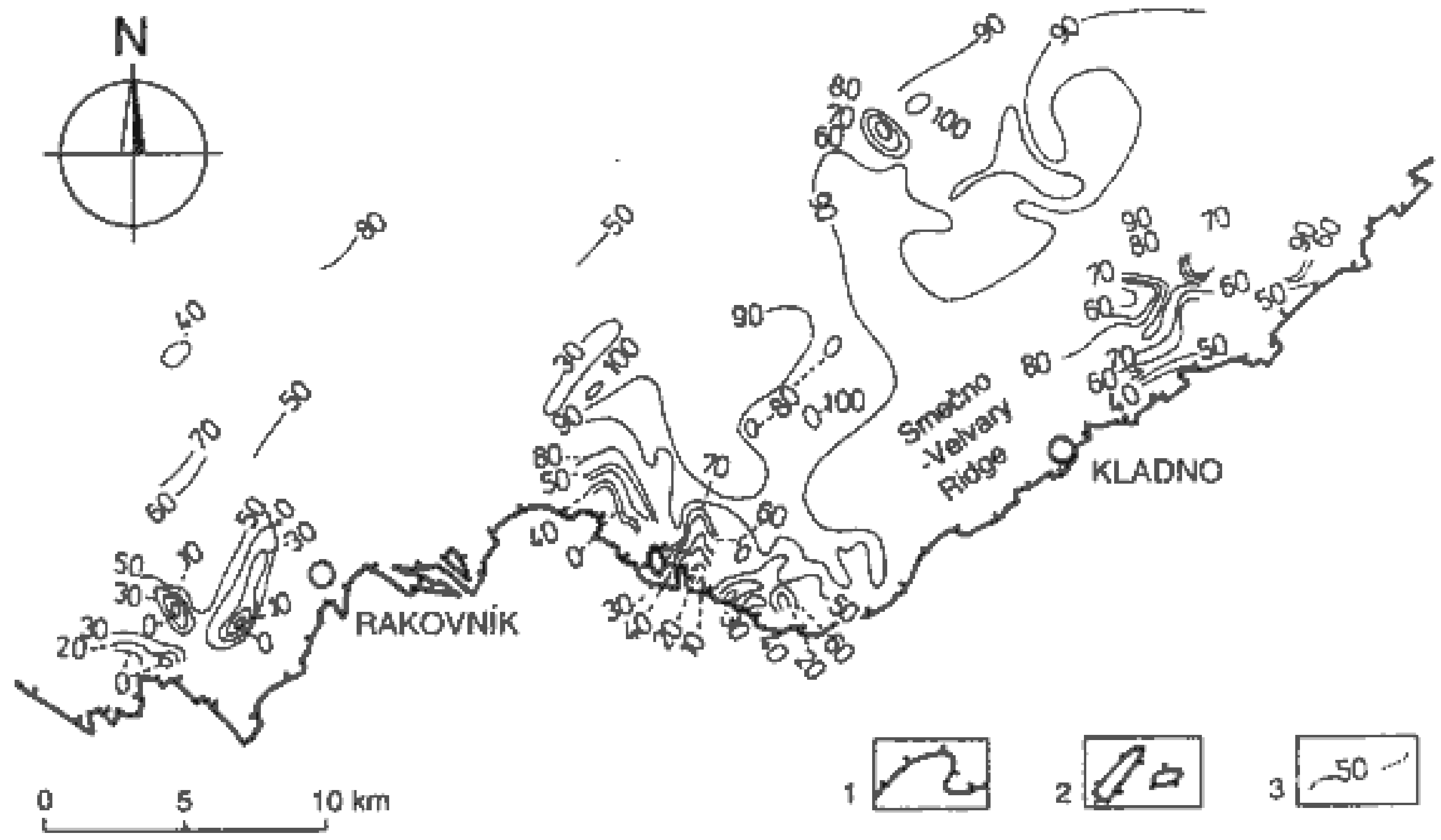
Skoček (1974) and Pešek and Skoček (1998) have revealed distinct quantitative and qualitative differences between varicolored and grey sedimentary sequences. The detailed study led to the conclusion that some commonly applied climatic indicators as arkoses, clay minerals and kaolinized rocks are unreliable in the area studied. The carbonate and sulfate cement, as well as paleosoils and silicified wood pieces are considered ambiguous. Positive differences have been found between red and grey sequences as related to: limestone occurrence, sedimentary structures, bimodal sandstones, Fe-oxide coated quartz grains, bioturbation, quality of clastic material, pedogenic carbonates, evaporites, siliceous rocks, type of volcanic material alteration, amount and diversity of floral and faunal remains.



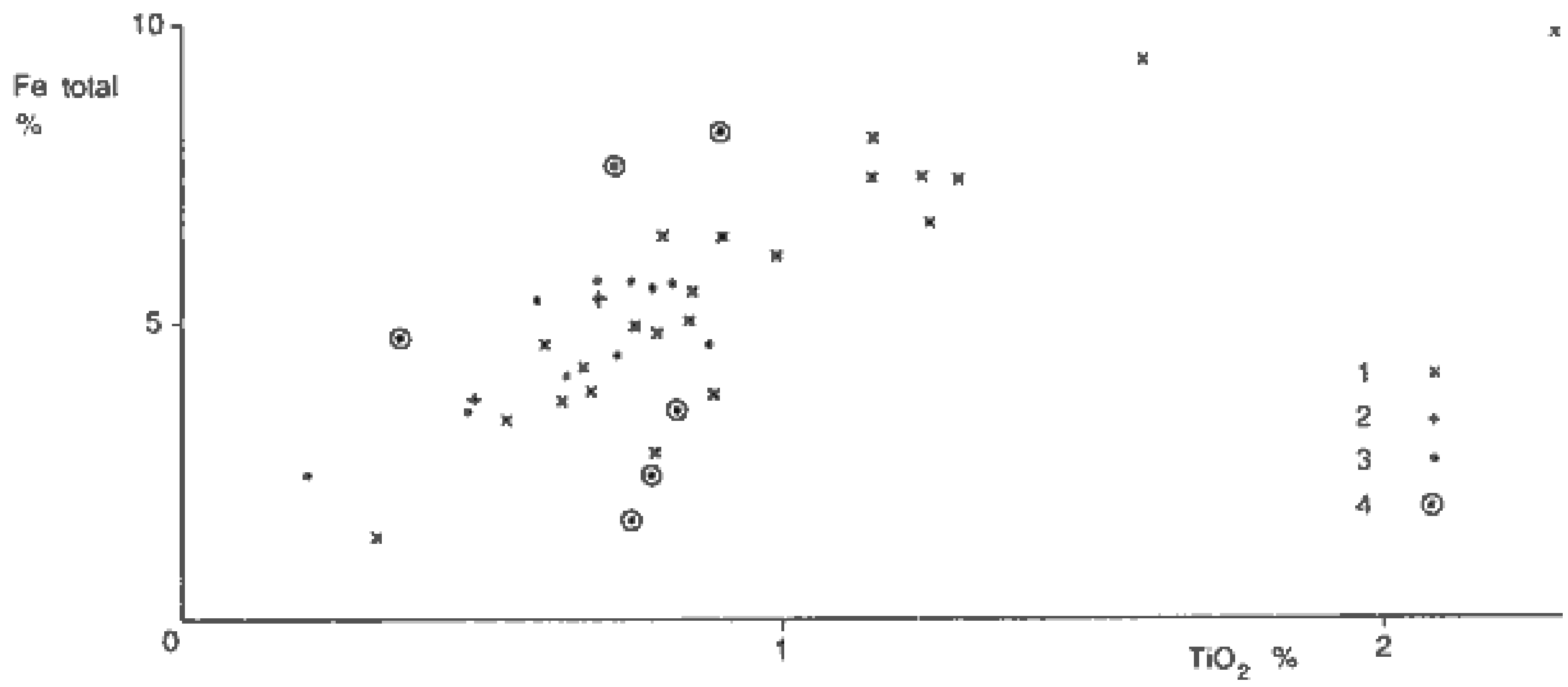
10. Contour map showing distribution of grey sediments in the Nýřany Member within Plzeň and Manětín Basins. 1 – limit of the Carboniferous; 2 – basement ridges; 3 – original outline of Nýřany Member; 4 – contours of grey sediments volume (%).



11. Contours of grey sediments percentage in the Radnice Member demonstrated in the segment of the Kladno Rakovník Basin. For explanations see Fig. 10.



12. Contours of grey sediments volume in the Nýřany Member of the Kladno-Rakovník Basin. 1 – southern limit of the basin; 2 – basement ridges; 3 – contours (%).

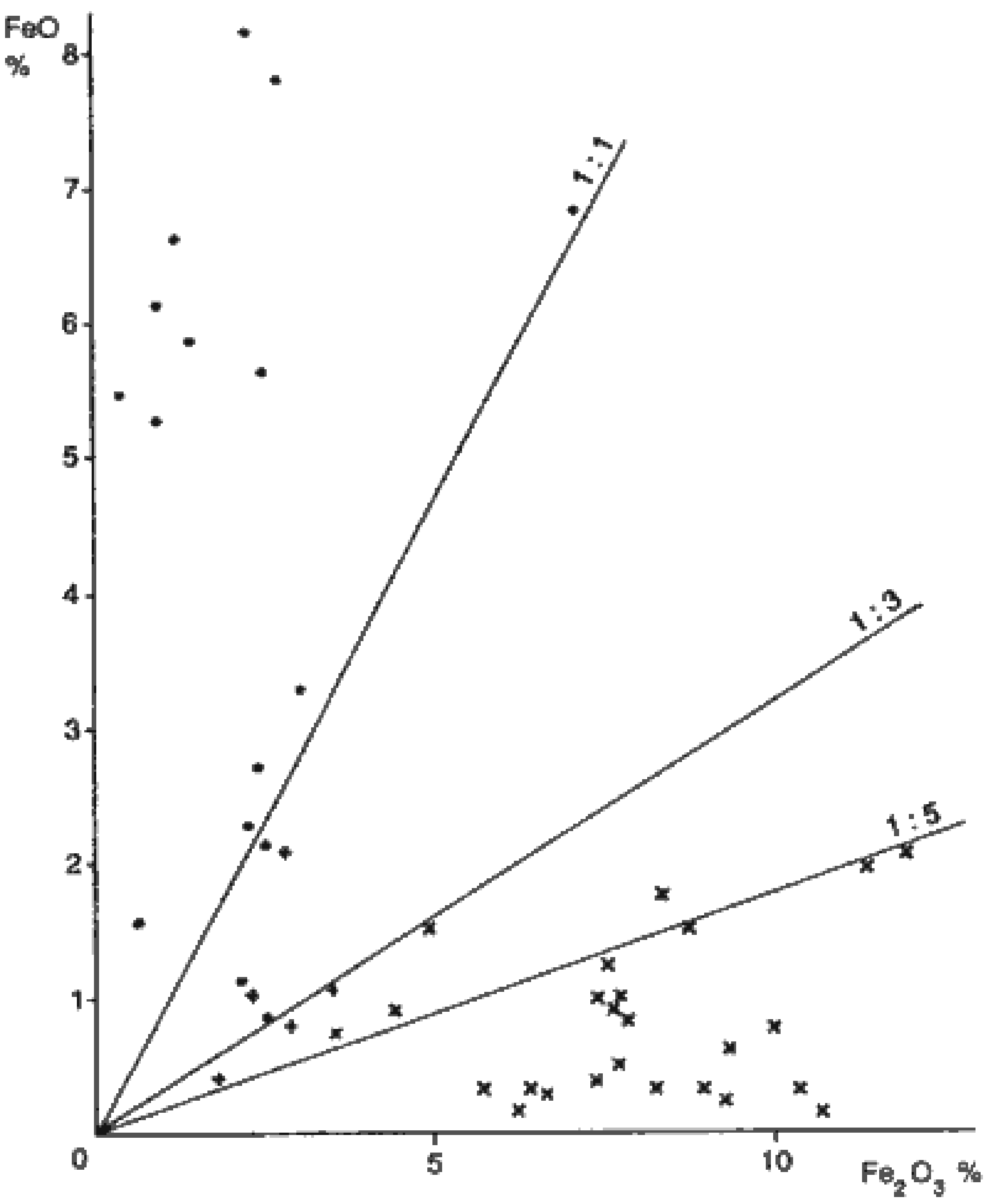


13. Relationship between total iron and TiO_2 content. Mudstone color: 1 – red; 2 – green; 3 – grey; 4 – dark grey (enriched in organic matter).

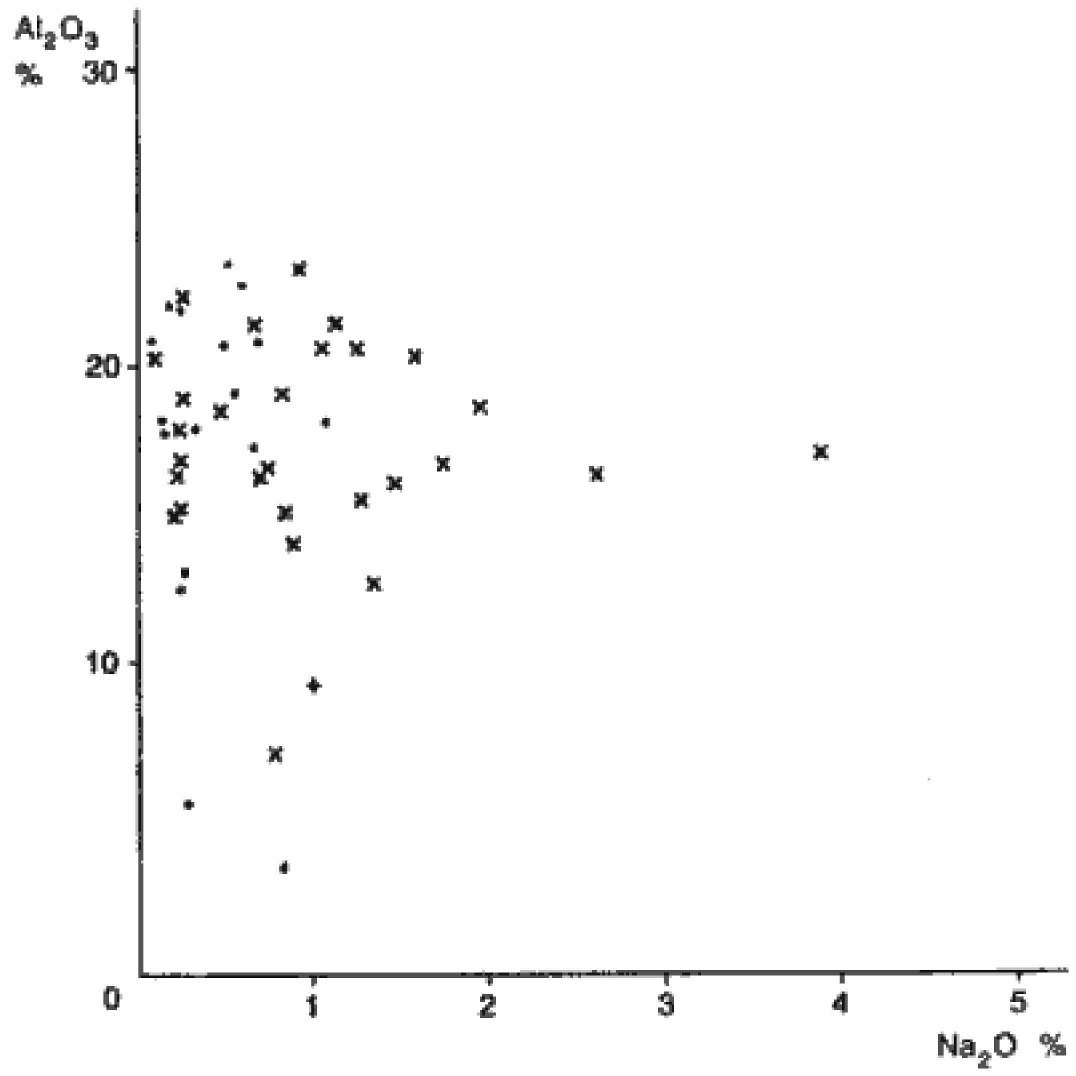
Unreliable climate indicators

Arkose of alluvial and deltaic origin is a common rock type forming sedimentary bodies of varying thicknesses as both in grey colored successions and red beds. We consider that the presence of arkose indicates a rugged relief eroded to the level of granitic plutons (Kukal 1983). The role of climate, stressed by Krynine (1949), was probably less important.

Clay minerals are represented by kaolinite, illite, chlorite, monmtmorillonite and mixed-layer minerals. Kaolinite and illite form a substantial portion of the mudstones



14. FeO/Fe_2O_3 diagram discriminating mudstone samples according to their color. Explanation of symbols see Fig. 13.



15. Al_2O_3 versus Na_2O in analyzed mudstone samples. Color symbols identical with Fig. 13.

and claystones regardless of their color. Other clay minerals occur in subordinate amounts. Local accumulations of montmorillonite and mixed-layer minerals suggest either volcanic or a pyroclastic admixture. Variations of the kaolinite between grey and varicolored mudstones are not distinct enough to determine the different character of weathered detritus at the time of its deposition. The variations of kaolinite in the studied samples reflect an in situ diagenetic changes (Füchtbauer 1988, Weaver 1989) best demonstrated in refractory clays, bentonites and tonsteins.

Kaolinization of arkoses and arkosic sandstones indicates deep, in-situ weathering probably caused by a hot, humid climate. Because kaolinized arkosic bodies occur both in red bed and grey colored sequences, it is difficult to discriminate the Upper Paleozoic kaolinization from similar weathering that may have occurred later (e. g. Kužvart-Konta 1968).

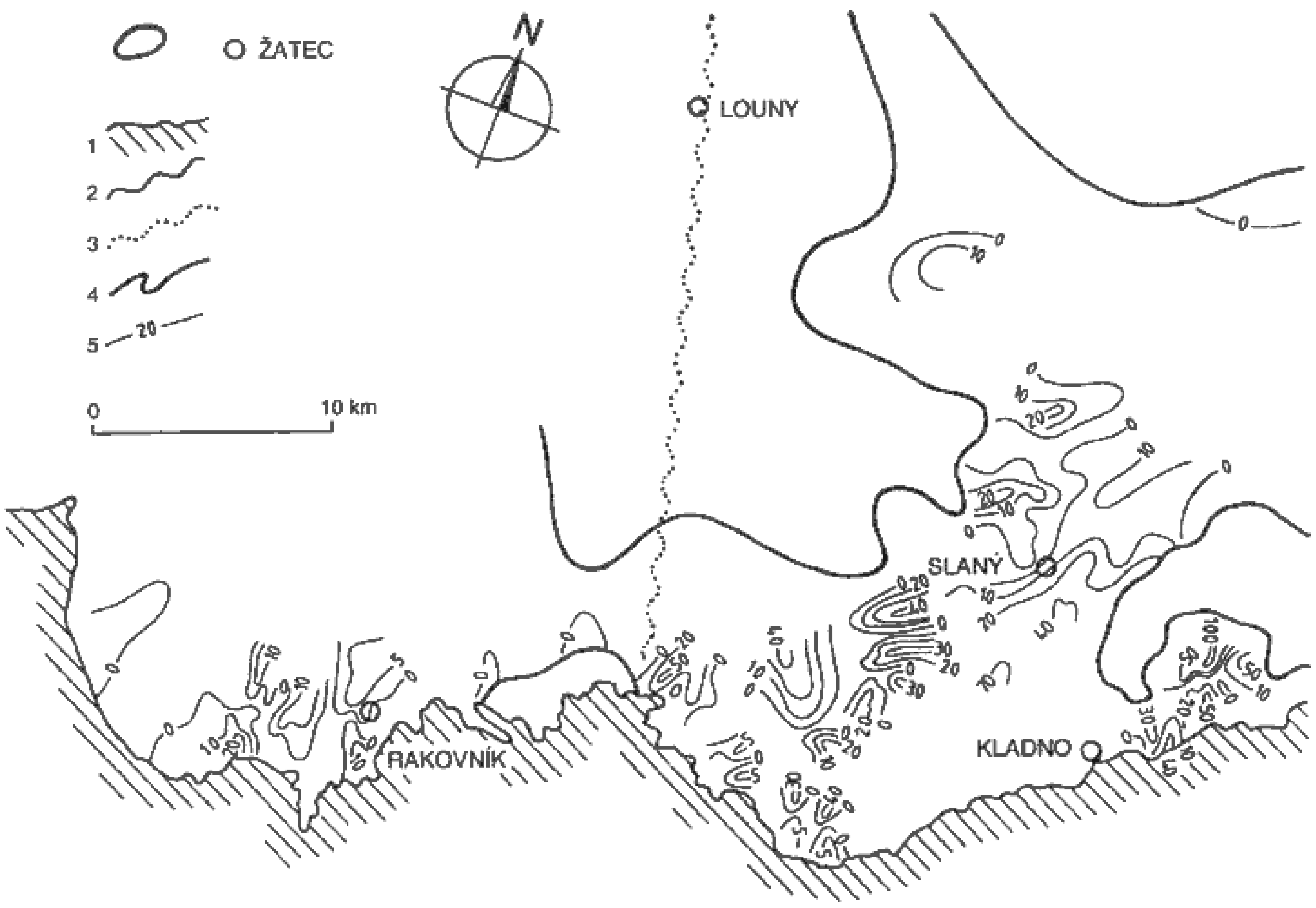
Problematic indicators

Silicified wood. Two types of silicified wood occur in the Upper Paleozoic sediments of the area studied (Skoček 1970). Logs and their fragments containing carbonized organic matter were petrified while embedded in wet sediments and wood lacking organic matter in sediments exposed to desiccation and subaerial diagenesis over long intervals. Large in situ silicified logs which occur near the contact of grey and red bed units may reflect a change of climatic conditions. A humid climate promotes the growth of trees and anoxic carbonification whereas an arid climate is condusive to silicification and is less favorable to plant growth. Clasts of silicified woods may have been reworked because of their resistance to abrasion thus their climatic significance remains ambiguous.

Weathered profiles and paleosoils are locally developed at contact between the basement and the overlying Upper Paleozoic sediments (Skoček-Holub 1968). Because of the uneven basement relief and its differing permeability, the diagenetic alteration of residual materials is highly variable. Pronounced alteration exists in permeable profiles overlain by deposits of a perhumid environment. Conversely varicolored breccias, up to 100 m thick (Fig. 16), resting on basement rocks evidence dominant mechanical weathering of exposed slopes.

Chemical weathering in a hot, humid to semiarid climate is indicated by the occurrence of lateritic to terra rosa soils. Whereas initial stages of weatherig show low concentration of hematite and the presence of sericite, illite and chlorite, advanced lateritization is characterized by the accumulation of Fe, Al, and Ti at the expense of SiO_2 and the alkali compounds. In the basins studied beds of ferruginous laterite occur at the base of grey and red units at various stratigraphic levels.

The products of fossil weathering are also found in individual sedimentary units. Their preservation and quality was primarily controlled by local geomorphology and microclimatic conditions. The weathering products in grey colored units are more variable than those occurring within red beds. From that we conclude that well drained topography was conducive for the production of ferrallitic and fersiallitic products throughout the period of basin filling. Degraded or podzolic profiles may have originated during periods of coal-bearing sedimentation which was marked by



16. Isopachous map of basal breccia, Radnice Member, Kladno Rakovník Basin. 1 – limit of the Carboniferous; 2 – limit of individualized partial areas; 3 – edge of partial area; 4 – erosional limit of the Radnice Member; 5 – isopachous line (m).

a high ground-water level and the occurrence of plant-supporting redoxomorphic soils as Besly and Fielding (1989) envisaged in England.

Carbonate and sulfate cements, including fine to coarse crystalline, pore, basal and poikilotopic types, locally occur in indurated beds or intercalations within permeable sandstones. Calcite and subordinate dolomite form cement in red beds. Calcite, ankerite and siderite are common in grey colored sediments. Ca-sulfate cements are restricted to red beds whereas some rare barite occurs in red, non colored and grey sandstones. Climatic significance of these cements is difficult to assess because their presence reflects various diagenetic processes. The coarse, poikilotopic and automorphic calcite cement, pigmented by hematite, was observed exclusively in the red bed sandstones. Similar cements were reported as characteristic of red beds by Turner (1980). Kukal (1986) considers the poikilotopic calcite cement a product of a desert environment.

The presence of sulfate cement is compatible with the regimen of an undrained basin where precipitation of sulfates from ground water occurs. However, the presence of Ca-sulfate is not definite evidence of deposition under an arid climate.

Positive climate indicators

Pedogenic carbonate concretions and crusts, forming in a warm semiarid climate (Wright - Tucker 1991) are confined in the study area to red beds. These carbonates represent either in situ calcrete accumulations or clasts derived from them. They consist of calcite, rarely dolomite with relatively low $\delta^{18}O$ which suggests organism-aided precipitation from meteoric waters at normal temperatures (Skoček 1993).

The pedogenic carbonates are irregularly distributed. They are common in the Barruelian but are more frequent in the Permian of the Sudetic basins. Their absence in the grey colored formations and grey lacustrine mudstones does not necessarily reflect specific climatic conditions as distinctly different diagenetic processes may have operated in wet local environments rich in organic matter.

Limestones form beds, up to few tens of centimeters thick, in varicolored mudstones enclosed in clastic sequences of lacustrine origin. The limestone commonly displays algal lamination, scattered ostracode tests, fish remains and rare oolite layers. The sedimentation in a lake with a fluctuating shore line is shown by the presence of mud cracks, breccias, nodular textures and evidence of secondary oxidation (hematitized pyrite and Fe-carbonate). Such limestones were never found in thick coal-bearing sequences and thus indicate periods of a warm and semiarid climate.

Siliceous rocks include: i) thin siliceous layers and chert concretions pigmented either by hematite or organic matter, and ii) silicified limestone beds with ghost oolitic (Fediuk 1956), peloidal, intraclastic or bioclastic texture. The source of SiO_2 may be ascribed to the decomposition of volcanic rocks and solutions derived from ferrallitic weathering zones. The mobilization of SiO_2 was enabled by the alkaline reaction of lake and pore waters whereas its precipitation by the occurrence of organic matter and sulfates.

The siliceous rocks form important key horizons in some lacustrine sequences of the Stephanian C and Autunian which are red beds, while these rocks are absent in the Westphalian, Barruelian, Saxonian and Lower Triassic (Skoček 1969). The absence of siliceous rocks is also noted in the grey colored sediments of the Stephanian B. It appears that among the factors controlling silica distribution and accumulation, climate played an important role.

Evaporites. The model of red beds origin in a closed desert basin (Havlena 1963) requires the presence of evaporites or evidence of their former existence. Sulfate mineralization is suggested by the presence of a silicified gypsum layer mentioned by Konta (1956). Thin dikes and sills of fibrous gypsum and anhydrite are common in the Permian sequence of the Krkonoše Piedmont Basin. Syngenetic and early diagenetic Ca-sulfates have been found by Prouza et al. (1977) in the Chotěvice Formation (Late Autunian). Calcite pseudomorphs of gypsum are known from mudstones of the Líně Formation. Isotope analyses (Skoček et al. 1977) indicate that the variation of $\delta^{34}S$ in sulfates may be related to the fluctuation of water salinity. In addition, sulfate cement is widespread in sandstones of the Semily and Vrchlabí Formations (Stephanian C–Autunian) of the Krkonoše Piedmont Basin (Skoček 1987).

The syngenetic and early diagenetic Ca-sulfate occurrences clearly indicate a warm arid climate. The absence of sulfates in the majority of red bed units studied may be related to fluctuating aridity or sulfate leaching by groundwater. Highly mineralized waters of the Permo-Carboniferous aquifers (Jetel 1974) suggest this may be the case.

Composition of coarse clastics. In general, the mineralogic composition of sandstones and conglomerates in the red-bed sequences is of a higher diversity than in the grey, coal bearing sequences. Pebbles of the Lower Paleozoic limestone were found only in red beds of the Líně Formation (Zikmundová-Holub 1965, Pešek 1996). Whereas clasts of the pedogenic carbonate and ferrolite (Photo 9) commonly occur in red-beds, they are absent in the grey-colored formations. Occurrences of these pebbles and clasts suggest short transport by ephemeral streams in a warm arid climate conducive to mechanical rather than chemical weathering.

Sedimentary textures and structures indicating an arid climate include bimodal eolian sandstones reported from the Permian red beds by Valín (1972) and Holub et al. (1981). These sandstones (Photo 10), consist of well rounded quartz grains (very coarse sand) supported by a matrix of angular very fine sand grains, and are similar to sandstones from the eolian interdune flats reported by Folk (1968).

Sedimentary structures produced by aquatic traction and gravity flows and by deposition from diluted suspension are common in red and grey-colored sequences. Structures specific to red beds include thick homogeneous beds marked by indistinct changes of silt and sand fractions which resemble the accumulation of loess. The bioturbated red-bed mudstones contain burrows of the *Palaeophycus* and *Planolites* ichnogenera (Mikuláš 1993). In contrast, and less commonly bioturbation in the grey-colored mudstones involves shallow vertical burrows or plane trails (*Sinusites*). Rare amphibian trace fossils, generally confined to the red-bed mudstone and sandstone sequences, were described from the Lower Permian strata (Mikuláš 1994). Mud cracks, desiccation fragments and mudstone breccia, in addition to raindrop imprints (Kukal 1985), are almost entirely restricted to the red-beds and testify to the aridity of the climate.

The alteration of pyroclastics yields further evidence. Secondary minerals i. e. montmorillonite, mixed-layer minerals, feldspar, analcime, quartz and carbonate indicate alkaline mineralization of basinal and pore waters during the periods of aridity and high evaporation. During humid climate periods volcanic material was altered mainly into well ordered kaolinite due to an acidic environment induced by the presence of organic matter.

Thin layers of accumulated volcanogenic biotite are restricted to red-bed sequences. These layers consist of fresh biotite flakes and booklets intergrown with kaolinite considered deflated from tuffs. Analogous layers in the grey-colored sequences were converted into the crystal kaolinite tonstein. Embedded in the red mudstone layers thin intercalations of red pod tonstein (Graupentonstein) were recognized. White pods consisting of fan-shaped kaolinite probably originated from authigenic zeolites (Skoček 1973). Similar tonstein layers from coals and grey-colored sequences are penetrated with an organic substance.

Distribution of flora and fauna in non-grey sediments

The character of flora from red bed sequences is very different than the flora from the grey-colored formations and varicolored interbeds. In the Westphalian D-Cantabrian red mudstones the flora is noted for its poor species diversity and the rare occurrence of *Lebachia* (*Walchia*). The impoverishment in floral diversity is apparent in the Barruelian and Stephanian C red beds when compared with the flora of the grey-colored sediments of the same age (Tásler et al. 1979, Šetlík 1970). This relationship suggests that the relative abundance and floral diversity was controlled by the character of the biotope rather than by the regional climate. However, the statistical difference should reflect all possible factors including the amount and distribution of annual rainfall. Increased rainfall associated with a high groundwater table is to be expected during the deposition of coal-bearing grey sequences. In contrast, a low or intermittent rainfall would be less favorable for vegetation cover during the red bed accumulations. Considering the low latitude position of the Bohemian Massif in the Late

Paleozoic (Krs-Pruner 1995) the fluctuation of annual temperatures had little impact on sediment coloration.

Fossil fauna is represented by fish, amphibian and reptile remains in addition to a large variety of invertebrates (annelid worms, coelenterates, molluscs, merostomes, ostracods, crustaceans and insects). Ichnofossils show further evidence of life during the Upper Carboniferous-Permian time (Pek-Mikuláš 1996). The faunal remains occur commonly in the grey colored units and also in grey sediments enclosed in red bed sequences. In lacustrine red mudstones fish remains (Photo 11) and insect imprints are locally common. A striking absence of fossil fauna in the Cantabrian-Barruelian interval suggests the considerable life impoverishment in the whole region. A mature drainage system established during the Stephanian B period triggered the migration of fauna to favorable environments.

Diagenetic history of basinal fill

The mechanical compaction of terrestrial sediments is very different from the compaction of subaquatic and marine deposits. A high degree of compaction occurs in fine sediments of perennial lakes which were not the typical environment where red claystones and mudstones accumulated. These were actually deposited in alluvial fans, alluvial plains and in shallow ephemeral lakes where compaction was fairly rapid due to dehydration and subsequent changes. Dehydration was accompanied by clay mineral coagulation, precipitation of authigenic minerals and cementing, therefore deposits were rapidly indurated although the porosity was not always affected. This is evidenced by pedogenic carbonate concretions embedded in mudstone which was not affected by compaction compared to the concretion. The same can be stated about mudstones in which worm burrows were only negligibly deformed. In general, the early diagenesis was marked by the transformation of hydrated Fe oxides into hematite. This process was hastened by elevated temperatures and the prevailing alkaline reaction of oxic pore water.

Quite different processes affected sediments rich in organic substance. In peats and bogs conducive for microbial processes and the destabilization of Fe minerals, siderite and pyrite were formed or iron was totally leached out. Similar processes produced siderite and pyrite concretions or layers in fine sediments of profundal areas of lakes. In shallow ephemeral lakes, characteristic of the Permian, organic substances were destroyed by oxidation with the exception of sediments of central permanently wet areas. In such environment increased water mineralization and algal activity led to the formation of limestone and chert layers in which organic matter was preserved or occasionally destroyed by subsequent oxidation. This is demonstrated by hematite replacing original bioclast coating formed of pyrite.

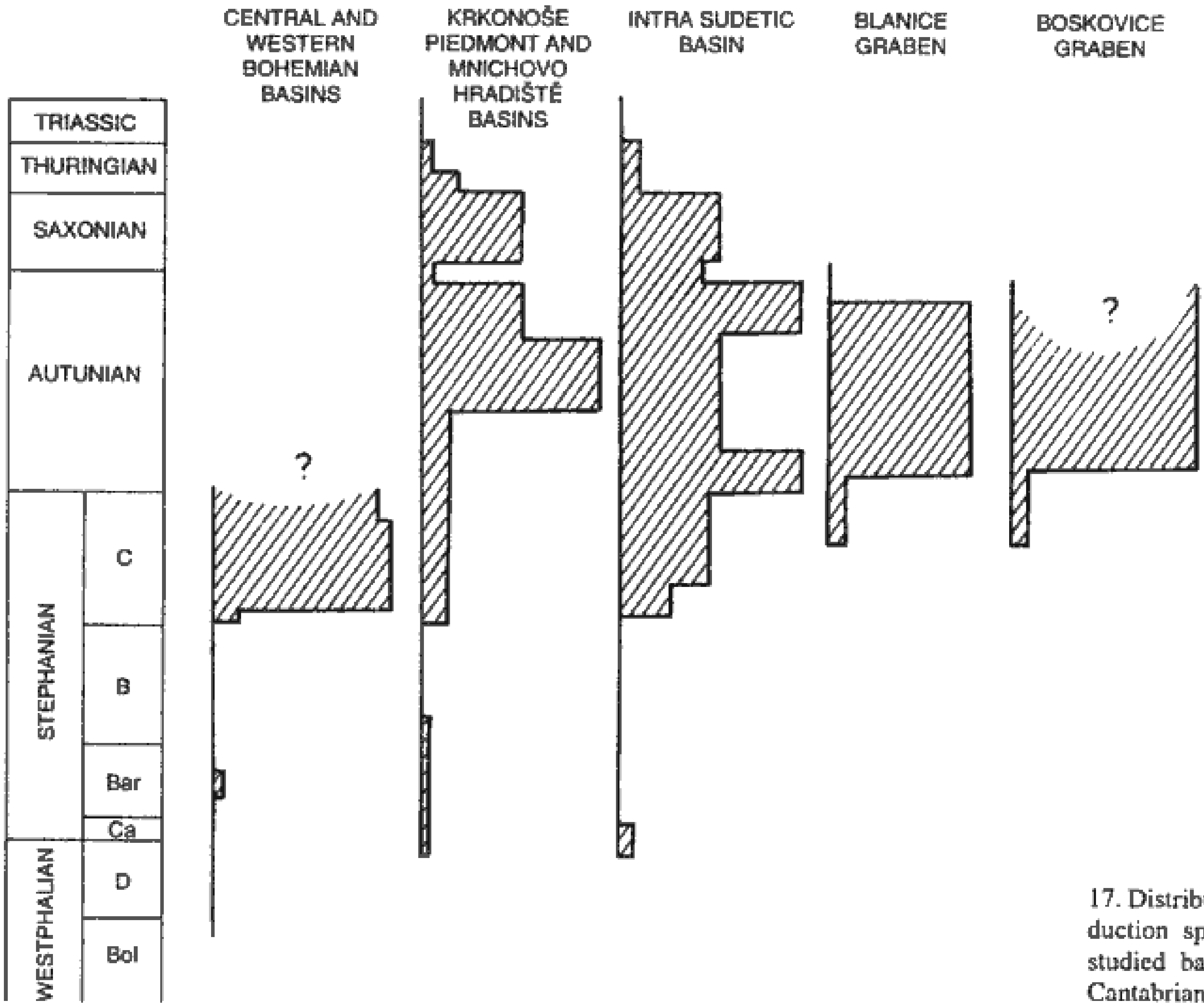
The diagenetic history of impermeable mudstones differs from the diagenesis of permeable sandstones and conglomerates. As Friend (1966) suggested, the neutral to green color of coarse fluvial sediments might be due to their position in a permanently water-saturated environment where disseminated Fe oxides, in the presence of organic matter, were subject to reduction. In contrast, hematite was stabilized at the same time in less permeable fine overbank deposits of the adjacent alluvial plain which was subject to repeated desiccation.

The diagenesis of permeable sediments in the phreatic zone was more pronounced than in impermeable mudstones and claystones. For this reason much of the diagenetic processes (kaolinization, chloritization, silicification, carbonatization, feldspatization and zeolitization) are confined to permeable sandstone units.

Indications of diagenetic changes in red mudstones and claystones include redistribution, catch crystallization and leaching of coloring pigment. Early stages involving pedogenic processes produced mottled textures (Photo 12) reflecting a partial loss of the initial homogeneous color. The pigment seggregation and growth of discolored specks was terminated in the course of early diagenesis (Richardson - Daniels 1993). Therefore mottled beds forming units up to several meters thick occur in the Carboniferous and Lower Permian and are rare or absent in Upper Permian and Triassic strata.

The decoloration in permeable sediments occurs on a variable scale. Inhomogeneous sediments are affected only within their permeable parts. The large scale regional decoloration shows the reduction effect of ground water in a lengthy time interval. Hubert (1960) and Duke (1987) consider connate waters of low redox potential a common cause of decoloration. The reducing character of such waters resulted according to Peterson (1988), Merin and Segal (1989) and Huntoon (1987), from organic substances derived from coal or oil-bearing formations. Such a relationship may be applicable to areas of our study where red beds alternate with the grey colored sequences. The occurrence of decolored sediments along fault zones and fissures indicates that reducing waters were active long after sedimentation.

Special attention was given to decolored, sharply defined circular or oval spots occurring in red sediments and volcanogenic rocks. These spots, averaging from a few mm up to 15 cm (Photo 16), occur as solitary features or in individual layers in large quantities. Because of their striking appearance the decolored spots received considerable attention in numerous papers (Keller 1926, 1929, Miller-Folk 1955, Picard 1965, Manning 1975, Durrance et al. 1978, Mykura-Hampton 1984, Daily-Augio 1990, Hofmann 1990). These spots are known under various names as reduction, radioactive and bleached spots or spheroids. In the area studied these features were described by Skoček (1962, 1967). The distribution of these decolored spots in several basins is illustrated in Fig. 17. In general, the spots are most abundant in non-bedded mudstones and sandstones of red sequences but are absent in laminated lacustrine sediments. Based on the appearance of their center the



17. Distribution and relative amount of reduction spots in red beds occurring in studied basins. Bol – Bolsovian, Ca – Cantabrian, Bar – Barruelian.

decolored spots are grouped as follows:

A. spots lacking core

B. spots with core made of:

a) black sooty substance

b) concentric or garlanded layers of black pigment

c) grey and black calcite concretions

d) dark mica flakes

e) whitish calcite crystals or concretions

Chemical and X-ray analyses of the black substance (spots sub a-c) indicate the presence of vanadium (0.40–0.20 %), uranium (0.01–1.16 %) and copper (up to 0.70 %). Spectral analyses detected anomalous concentrations of Ni, Zn, Sr and the presence of Co, Ag, Cr, Ba and P. The absence of diffraction lines for V and U minerals points to an amorphous character of the black substance. Dark calcite concretions (sub c) contain 0.01–1.64 % V and 0.003–0.63 % U. Finely crystalline vesignieite, a vanadium mineral, was found in concretions from Horní Kalná (Johan-Povondra 1987).

Black biotite flakes (sub d), in centers contain fibres of oxidized rutile and are in some cases partially bleached. This suggests that Fe^{2+} from biotite was not involved in the decoloring process. However, the catalytic effect of biotite in leaching of the hematite pigment from its proximity is indubitable.

White carbonate concretions and crystals (sub e) found in cores of spheroids are of variable size compared with the spot diameter. The shape of some crystals (Photo 13) indicates pseudomorphic calcite after gypsum.

The often reported relationship of decolored spots to organic matter has never been recognized (Photo 11). In spite of numerous papers dealing with spots many controversial views were expressed concerning their origin. Our observations lead us to conclude, in agreement with Turner (1980) and Mykura and Hampton (1984), that the spots are products of early diagenesis. This is evidenced by their relationship to diagenetic carbonate concretions and by mudstone clasts derived from sediments where decoloration was accomplished (Photo 14) prior to erosion and redeposition.

While it is possible to correlate the spots-bearing beds over tens to hundreds of meters, more distant correlation is uncertain.

The varying size and irregular distribution of decolored spots suggest the possible relationship to microorganisms present in a fresh sediment (Blodgett et al. 1993) including bacteria capable of extracting iron even from poorly soluble compounds (Boyle et al. 1977). The oxalic and citric acids, metabolic products of the *Aspergillus niger*, can bleach even a stable mineral as biotite. The decoloration could have been aided by hydrogen sulfide produced by the bacterial reduction of sulfates. Granger and Warren (1969) deny the importance of bacteria and stress instead the presence of sulfur compounds for large scale migration of iron and other elements. It is expected that intermittent wetting was a typical environment of exposed red sediments. Under such circumstances disseminated organic matter and minerals containing Fe^{2+} were oxidized by free oxygen from the atmosphere. Acid meteoric water reacted with the fine carbonate particles and also dissolved the sulfate ions. After the precipitation of carbonates the pore water again attained acid reaction. Both acid and alkaline centers were therefore created within the sediment after total water evaporation. The acid centers formed of gypsum and/or anhydrite (pH 6.6 and 6.7) and alkaline calcite or dolomite crystals and concretions (pH 9.4 and 10.4) might represent the "discrete sites" of Hofmann (1990) initiating the decoloration process. Considering the affinity between spots and accumulations of vanadium and uranium in their cores it is apparent that the iron removal was related to redistribution of these elements. The fluctuation of pH and Eh in fresh exposed sediment created an ideal circumstance for migration and precipitation of elements such as Fe, V and U. In an oxic environment vanadium is released from hydrated Fe oxides (Hallanger et al. 1991) during their conversion into hematite (Hofmann 1990). Complex vanadate anions, soluble in neutral to alkaline solutions (Fig. 18), migrate as vanadyl carbonate and precipitate as black vanadium oxide (V_2O_3) at low pH and Eh sites (Lisitzyn 1962). Such precipitate might react with Fe^{3+} as a reductant and cause iron leaching from the spot. On repeated oxidation vanadium as well as iron in the ferrous form were carried beyond the spot outline. While it is clear that the vanadium containing core determined the spot size, the nature of the initial nuclei still remains obscured. It is possible that the nucleus was formed from fragments of plant tissues, roots, bacterial colonies, biotite flakes (Photo 15), entrapped bubbles of CO_2, H_2S, CH_4. Pyrite, calcite or Ca sulfate might also serve as potential nuclei of trivalent vanadium precipitation as well.

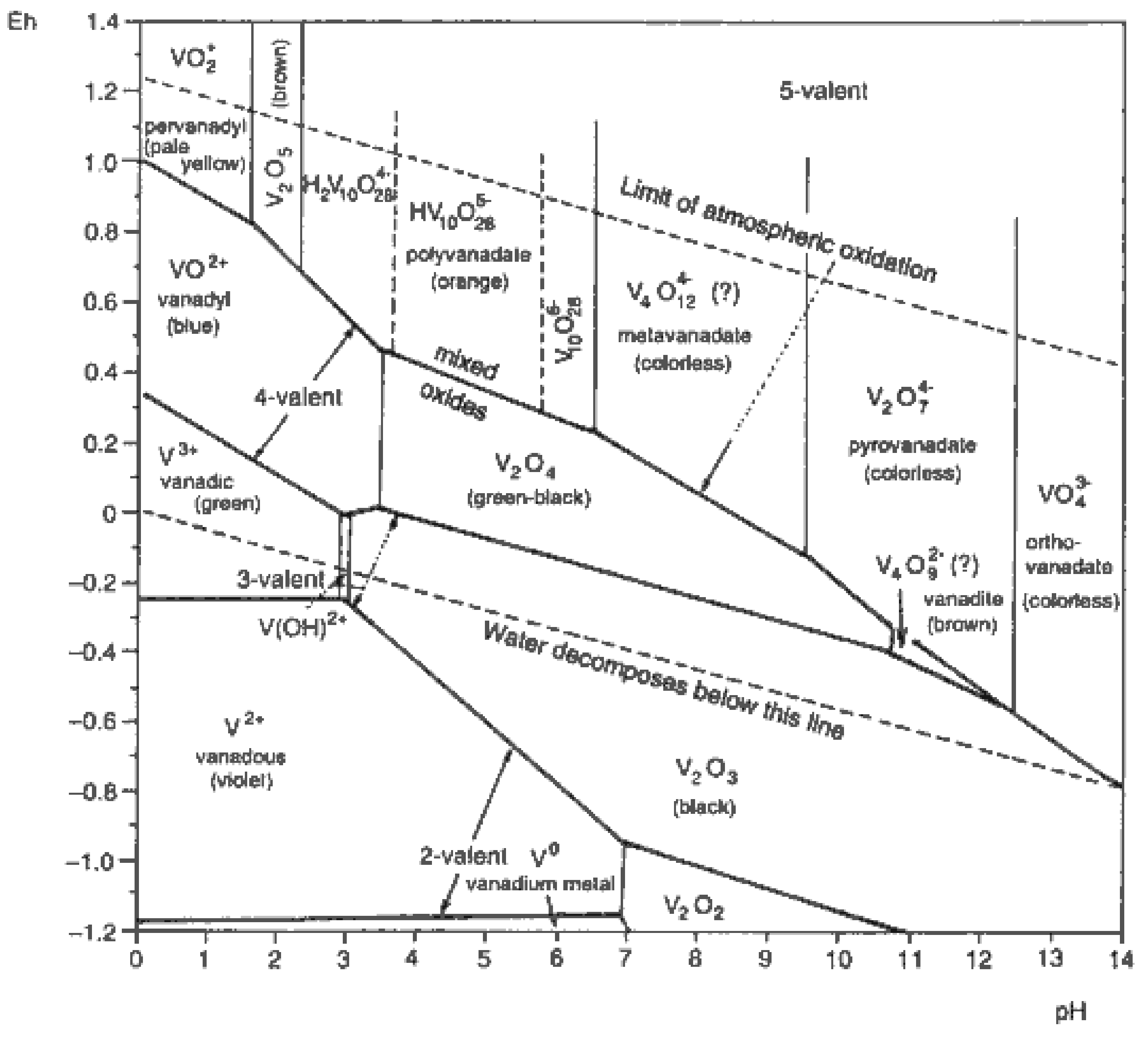
A highly oxic environment also favors the migration of uranium. In an acid setting U^{4+} reacts with Fe^{3+} as a reducing agent. The presence of dissolved carbonate leads to the formation of uranyl-carbonate complexes accompanied by the reduction of Fe^{3+} as expressed by the equation of Naumov and Mironova (1960):

$$UO_2 + Fe_2O_3 + 5HCO_3^- = \{[UO_2CO_3]^{4-}\} + 2FeCO_3 + H_2O + OH^-.$$

The uranyl ions are stable in an oxic setting where sulfur is present in the form of sulfate ions. In a reducing environment, marked by the presence of hydrogen sulfide, HS^- or S^{2-}, unstable uranyl ions yield a UO_2 precipitate. This reaction is aided by the presence Fe^{2+} and V^{3+} as Garrels and Christ (1965) pointed out.

Some authors connect the origin of spots with decomposition of pyroclastics (e. g. Hallanger et al. 1991). Beds of volcaniclastics with isometric decolored spots actually occur in the studied area (Photo 16) but a direct relationship between spots and tuffaceous sediments has not been confirmed.

Isometric decolored spots are common in rocks associated with uranium roll-type deposits where they serve as a prospecting tool (Huff-Lesure 1962). The spots indicate thus a potential for accumulation of heavy metals in favorable traps or at lithological boundaries. Such metal anomalies occur in the Intra Sudetic and Krkonoše Piedmont Basins (Tásler et al. 1979, Šolc 1964). These anomalies include Cu, Pb, Zn and uranium mineralization (Johan-Povondra 1987). The uranium mineralization is related to the proximity of coal seams or to flasers of coal matter in sandstones. Uranium is commonly associated



18. Stability of selected vanadium compounds and ions at 25 °C and 1 atmosphere total pressure (adapted from Garrels and Christ 1965).

with vanadium and other metals (BERNARD and POUBA 1986).

Conclusions

Numerous borehole data, documentation of underground coal mines and detailed geological exploration of the Upper Paleozoic continental basins have revealed the complicated relationship between red bed units and grey sequences.

The set of predominantly grey units contour maps clearly demonstrates that red and decolored sediments are preserved at the original basin margins and at the edges of intrabasinal highs whereas major parts of a sedimentary basin are filled with grey-coal bearing strata. The depicted varicolored facies distribution is typical for intervals when depocenters were occupied by sedimentary environments with high ground water level enabling the growth of a permanent vegetation cover and the large preservation of organic matter. Another configuration is characteristic for intervals when the deposition of red beds prevailed. In this case the marginal and basinal sediments are mostly red and grey deposits are restricted to areally limited permanently wet environments (e. g. peats and bogs fed mainly by ground water, profundal parts of lakes with a fluctuating water table). This clearly shows that the pigmentation itself is not unequivocally a climatic indicator. The quality of supplied clastic material from the source area was principally similar for the whole period of Upper Paleozoic sedimentation and the difference in coloration was subject to a quantitatively varying scale of oxic and anoxic diagenetic processes in individual intervals. Such intervals are defined by the presence or absence of specific features which might be considered climate indicators.

The evaluation of commonly used climate indicators suggests that they may be classified as follows:

i) a paucity and low diversity of faunal and floral remains, occurrence of limestone, calcretes, evaporites, cherts, bimodal sandstones, relatively low mineralogical maturity of sandstones and conglomerates, specific sedimentary textures and diagenetic features evidence dominating hot arid to semiarid climate.

ii) Silicified wood, fossil weathering products, paleosoils, calcium sulphate or carbonate cements in sandstones mostly indicate hot and at least semiarid climate but they occur in beds formed at the time of important climatic change.

iii) Indicators such as: arkoses, clay minerals and kaolinized interbeds were found unreliable, i. e. not reflecting primary climatic circumstances.

The alteration products of pyroclastic or volcanogenic beds distinctly differ between red and grey sequences. Montmorillonite, mixed-layer minerals, zeolites, authigenic feldspar and quartz are characteristic of the former and well ordered kaolinite for the latter.

The color parameters evaluated in 184 samples have revealed that their differences depend on several factors such as: grain size and the amount of clay fraction, sedimentary environment, age and regional peculiarities. The imprint of diagenetic processes upon the pigmentation is often obvious and microscopically recognizible. Hematite, the principal coloring pigment of red beds originated probably in the source area as well as diagenetically from hydrated iron oxides. Hematite which incorporates in its lattice up to 6 % of Al is considered a product of goethite conversion whereas an elevated amount of Ti points to a magmatic magnetite source. The evaluation of chemical remanent magnetization of red bed samples shows its origin in the early diagenetic stage. Magnetite yielding clastic remanent magnetization of grey colored sediments was mostly hematitized in red beds or was absent in the supplied detritus.

Decolored sediments originated during various stages of lithification. The early diagenetic reduction spheroids evidence a mobilization of Fe, V, U, Cu, Ni, Pb caused by temperature and moisture changes. As nuclei of the decoloration process primary (organic matter, microbial colonies, mafic minerals) or secondary inhomogenities (calcite, sulfate, sulfide) may have been engaged. Large scale decoloration was caused by ascending or descending reducing ground waters derived from layers or sequences rich in organic matter. The metal accumulations in red beds are related to grey intercalations, calcite concretions and the contacts with grey units.

The considerably different Fe_2O_3/FeO ratio identifies red, green and grey mudstones and claystones. The presence of coalified matter in some red strata suggests the secondary reddening of initially grey sediments long after their lithification. The variability of the Al_2O_3/Na_2O ratio in red mudstones reflects short transport and hence heterogeneity. The low value of this ratio is noted in mudstones containing authigenic analcime. The direct dependence between TiO_2, total Fe and Al_2O_3 reflects the presence of these elements in the fine fraction of red mudstones. The wider dispersal of total Fe versus TiO_2 values in grey mudstones compared with red equivalents is explained by a partial leaching of iron in the presence of organic matter. The slightly lower content of TiO_2 in grey mudstones is difficult to explain. A different quality of weathered clastics might be the answer. Both red and grey mudstones are rich in illite, therefore K_2O dominates over Na_2O in the majority of samples.

Trace elements in red and grey mudstones are present in minor amounts with the exception of some elements (particularly Cu, V, U) enriched in grey intercalations or coal flasers within red bed units. Red mudstones differ from grey ones in higher boron content (more than 70 ppm) evidencing an increased salinity of basinal waters.

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