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SEQUENCES OF THE LITHOFACIES AND DEPOSITIONAL INTERVALS IN THE GODULA BEDS OF THE POLISH OUTER CARPATHIANS

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Abstract: The Markov chains procedure was applied to the study on the sequences of lithofacies and depositional intervals in the Godula Beds (Turonian–Lower Senonian) of the Flysch Carpathians. The model (depositional) and modal (a most frequent in profile) diagrams were constructed and corresponding sequences were recognized. It was found that deposition from high-density turbidity currents of variable retardation rates was the dominating mechanism whereas the low-density turbidity currents were rather rare. The newly deposited sediments were commonly eroded by the succeeding, dense currents. Deposition processes were dominated by the two clearly separated environments: channels and depositional lobes. Their systems were subjected to frequent changes due to lateral migration caused by tectonic movements (uplift of cordilleras and subsidence of sea floor) and eustatic changes of sea level.

Key words: Carpathian flysch, Markov chains, sedimentary sequences, deep-sea fans, depositional lobes, channels.

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INTRODUCTION

One of the principal study methods of flysch formations is the interpretation of sedimentary sequences, understood as the succession of deposition events of various ranks: lithofacies, sub-lithofacies and depositional intervals. Deposition events characterize specific sedimentary sub-environments or various deposition mechanisms. For channel sediments of deep-sea fans diagnostic can be the positive sequences (thickening and/or coarsening upward) whereas for lobe sediments – the negative ones (thinning and/or fining upward) (Mutti & Ricci Lucchi, 1972; Shanmugam & Moiola, 1988, 1991; Słomka, 1995; Słomka & Słomka, 1997, 1998). Deposition from turbidity currents is characterized by certain sequences of depositional intervals which reflect the decreasing dynamics of currents caused by decreasing velocity (Bouma, 1962; Lowe, 1982; Słomka, 1986).

In the thick flysch series the number of sequences can be so high that their objective analysis requires the application of mathematical methods. The effective tool for investigation of vertical succession of layers in thick flysch series (but also in the coal-bearing ones) is provided by the Markov chain procedures (Schwarzacher, 1975; Hiscot, 1980; Rolke, 1991; Kalpazidou, 1994; Kotlarczyk & Krawczyk, 1980; Krawczyk & Słomka, 1994; Le Roux, 1994). Application of the Markov chains requires the precise, unequivocal classification of sediments. The classification of deep-sea siliciclastic sediments proposed by Ghibaudo (1992) meets such requirements as it enables the description of sediments using the three hierarchic levels: lithofacies, sub-lithofacies and depositional intervals. The main advantage of this classification is the application of quantitative methods in data processing.

Markov chains procedures have been applied in the studies on the Godula Beds representing Carpathian flysch sedimentary series.

GEOLOGICAL BACKGROUND

The investigations were carried out on profiles, representing the flysch series, associated with deep-sea siliciclastic sedimentation (Godula Beds, Upper Cretaceous) of the Western Outer Carpathians.

The Godula Beds (Turonian–Lower Senonian) belong to the thickest and the most widespread formations of the Silesian unit in the Carpathians (Figs 1, 2). The Godula Beds were deposited in the Silesian basin within the shifting system of submarine fans and aprons (Słomka, 1995).

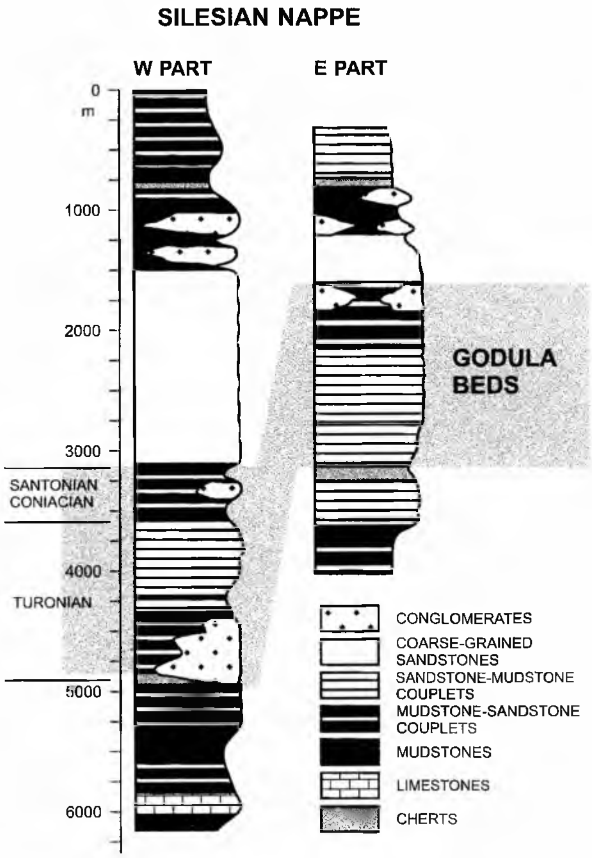


Fig. 1. Lithostratigraphy of the Godula Beds in Silesian Unit.

Deposition resulted in a "piedmont"-style lithosome extending along the toe of the northern slope of the Silesian ridge. The wedge-shaped geometry of the lithosome can be inferred from its dimensions: 250 km in length, 50 km in width and over 3000 m in thickness with a decrease northwards and eastwards.

The Godula Beds appear as a complex of glauconitic sandstones and greenish-gray shales that overlie the Lgota Beds or the Variegated Shales (locally also Ostravice Sandstone, Radiolaria Beds or Siliceous Marls) and underlie the Istebna Sandstone. Locally (mainly towards the north), the Godula Beds are replaced laterally by the Variegated Shales, which represent their dominant coeval equivalent in the Subsilesian Series, laid down on submarine ridge.

MATERIAL AND METHOD

The basic data for the reported study were thick, complete, tectonically undisturbed formation profiles. Basing upon the existing literature, the percentages of various facial types were determined and the representative numbers of profiles were selected for particular formations. All selected profiles were described in details (layer by layer), their lithofacial types and depositional intervals were identified according to classification scheme of Słomka (1995) (modified version of Ghibaudo's system, Ghibaudo, 1992; Figs 3, 4). Such detailed profiles formed the data sequences which could be analyzed with methods suitable for studies of times series (Markov chains and modal cycles).

Material for this study comes from natural outcrops. For deep-sea sediments the analysis was carried out on the sequence of over 250 lithofacies intervals and over 10000 depositional intervals derived from several, thick field profiles.

Computations were performed using a software package FACJE written especially for the purpose of this type of study (Słomka *et al.*, 1995). The package consists of two applications (MARKOV, CYCLES), each permitting for an examination of the entire section or a selected interval.

The MARKOV application allows to apply the full spectrum of Markovian procedures, including the derivation of preferred lithofacies or depositional intervals transitions. It also evaluates all procedural characteristics together with appropriate significance tests (test χ^2, test z, see Powers & Easterling, 1982). The CYCLES application allows for verification of the current presence of identified modal se-

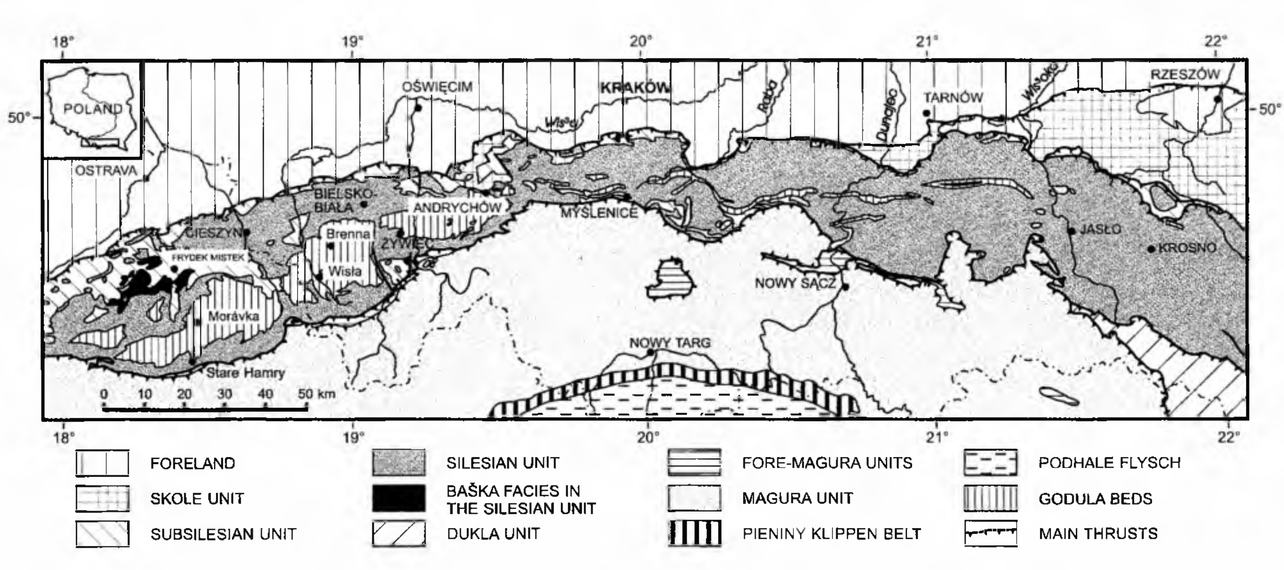


Fig. 2. Geological map of the Flysch Carpathians (simplified after Żytko *et al.*, 1988-1989) showing the outcrop belt of the Godula Beds

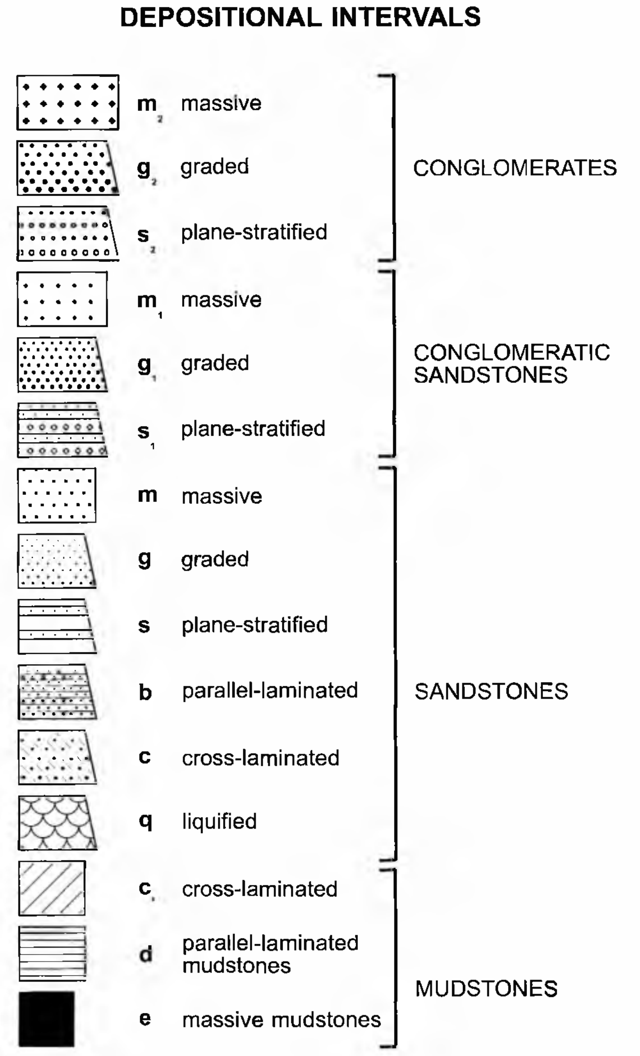


Fig. 3. Depositional intervals in Godula Beds (Ghibaudo, 1992)

quences (i.e., those with the highest occurrences) and of model sequences.

Markov chains confine numerous different parameters, among others matrices of: number of transitions, frequency of transitions, differences between the number and frequencies of observed and expected transitions; as well as successive powers of frequency transition matrices and the equilibrium vector (Schwarzacher, 1975). It was concluded that transitions of depositional intervals and lithofacies are not independent but exhibit a first-order Markov property.

The diagram represents a graphic visualisation of estimation of these matrices (Fig. 5). The diagrams of matrices of differences between number of expected and observed transitions enables the construction of a modal sequence, i.e. such that is the most common in a profile, regardless depositional implications. All the potential sequences are verified with the CYCLES software in order to eliminate the artifical sequences (e.g., two independent transitions g→b and b→c produce artificial, triple sequence g→b→c) and identify those really present in studied succesions. This may be a succession departing from that which results from deposition mechanisms as it includes various disturbing phenomena, such as erosion or interfingering of various sedimentary types. Modal sequences are, thus, a specific "photography" of a profile (Doktor *et al.*, 1997; Słomka & Słomka, 1997).

The diagram of matrices of differences between frequencies of expected and observed transitions enables also the reconstruction of a model sequence, i.e. such which shows genetic implications resulting from the nature of depositional mechanisms. A properly reconstructed model sequence eliminates effects of concealing factors, e.g. erosion. Percentage of such sequences in analyzed succession is a measure of the influence of factors disturbing the sedimentation (higher percentage – lower influence).

The degree of similarity or dissimilarity between the modal and model sequences is characteristic for a sedimentation process. If both sequences (modal and model) are similar, sedimentation was only slightly modified by incidental factors. The more they differ, the stronger is the influence of disturbing factors.

DISCUSSION

The sedimentation of the Godula Beds has lasted for some 10 M.a., and was controlled by a number of regional and local factors. The regional factors comprise eustatic, climate and plate movements. The direct local controls include the morphologies of basin floor and source areas, dimensions, composition and uplift rates of the cordilleras, and rates of sediment influx.

In the Godula Beds, a number of lithofacies sequences have been recognized, corresponding to the deposits of an inner fan (only fragmentarily preserved), middle fan, outer fan and basin plain. These deposits might have been laid down in a zone subjected to the most intense tectonic activity and, most likely, might have been cannibalized during deposition of younger members of the Silesian Series. Moreover, the slope deposits may well have been removed by erosion during a much later (Miocene) tectonism associated with nappe emplacement (Słomka, 1995).

The analysis was double-track: it contained populations of depositional intervals and lithofacies intervals. The results may characterize depositional mechanisms or subenvironments of sedimentation.

Depositional intervals

One-direction transitions are characteristic feature of a model diagram (Fig. 6); the transitions always proceed from coarse- to fine-grained sediments, thus reflecting a decrease in dynamics of gravity flows that are the major depositional mechanism (Hiscot, 1980; Kotlarczyk *et al.*, 1997; Słomka & Słomka 1997; 1998).

A modal diagram gives a completely different image (Fig. 7). The groups of intervals with diversified grain fractions may be distinguished; also there appear numerous reverse intervals, from low- to high-energy ones. The frequent repeatability of the episodes of gravel deposition ($g_1 \rightarrow g_2$) and mass deposition of sandy fraction (m→m) must be noticed.

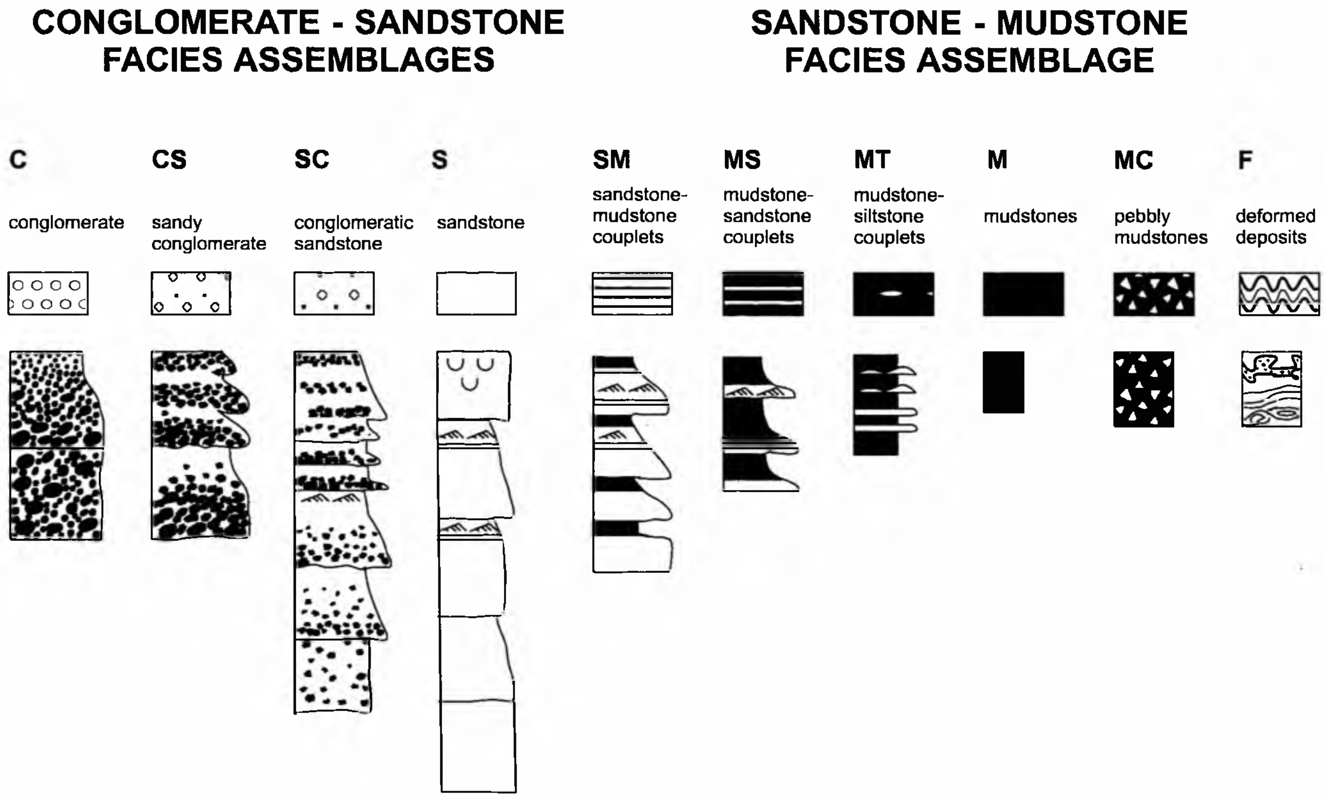


Fig. 4. Sedimentary lithofacies of the Godula Beds (Słomka, 1995)

Model (depositional) sequences, based on the model diagram, indicate the domination of sedimentation from high-density turbidity currents (Lowe, 1982), gradually depositing progressively finer material ($g_2 \rightarrow g_1 \rightarrow g \rightarrow b \rightarrow e$), often with transition to traction ($g_2 \rightarrow g_1 \rightarrow s_1$) (Fig. 6). Episodes of mass deposition with transition to traction ($m_1 \rightarrow s_1$) or deposition from low-density turbidity currents or from weak bottom currents are less frequent ($c \rightarrow e$). Finest sedimentary material was laid down by weak bottom currents not correlated to with the main deposition mechanisms.

A high amount of recognized modal sequences (Fig. 7), which are almost exclusively of two-member character demonstrates that deposition from high-density turbidity currents was a complex process controlled by the supply rate of clastic material and the relief of slope and basin floor. Usually, the very strong retardation of current velocity resulted in mass deposition (massive structure of sediment – m_1 or m intervals) or fast deposition connected with separation of coarsest material (g_1 interval). At much lower current velocity, during traction phase, the clastic material was fractionated (s_1 interval) (Lowe, 1982). The low-density turbidity currents deposited fine-grained material at much lower, gradual retardation rates (($b \rightarrow c \rightarrow e$, $b \rightarrow d \rightarrow e$, $b \rightarrow e$ or $c \rightarrow e$). Deposition from diluted tails of dense turbidity currents devoid of already sedimented coarse fractions cannot be neglected. The sedimentation process was additionally modified by intra-basinal erosion.

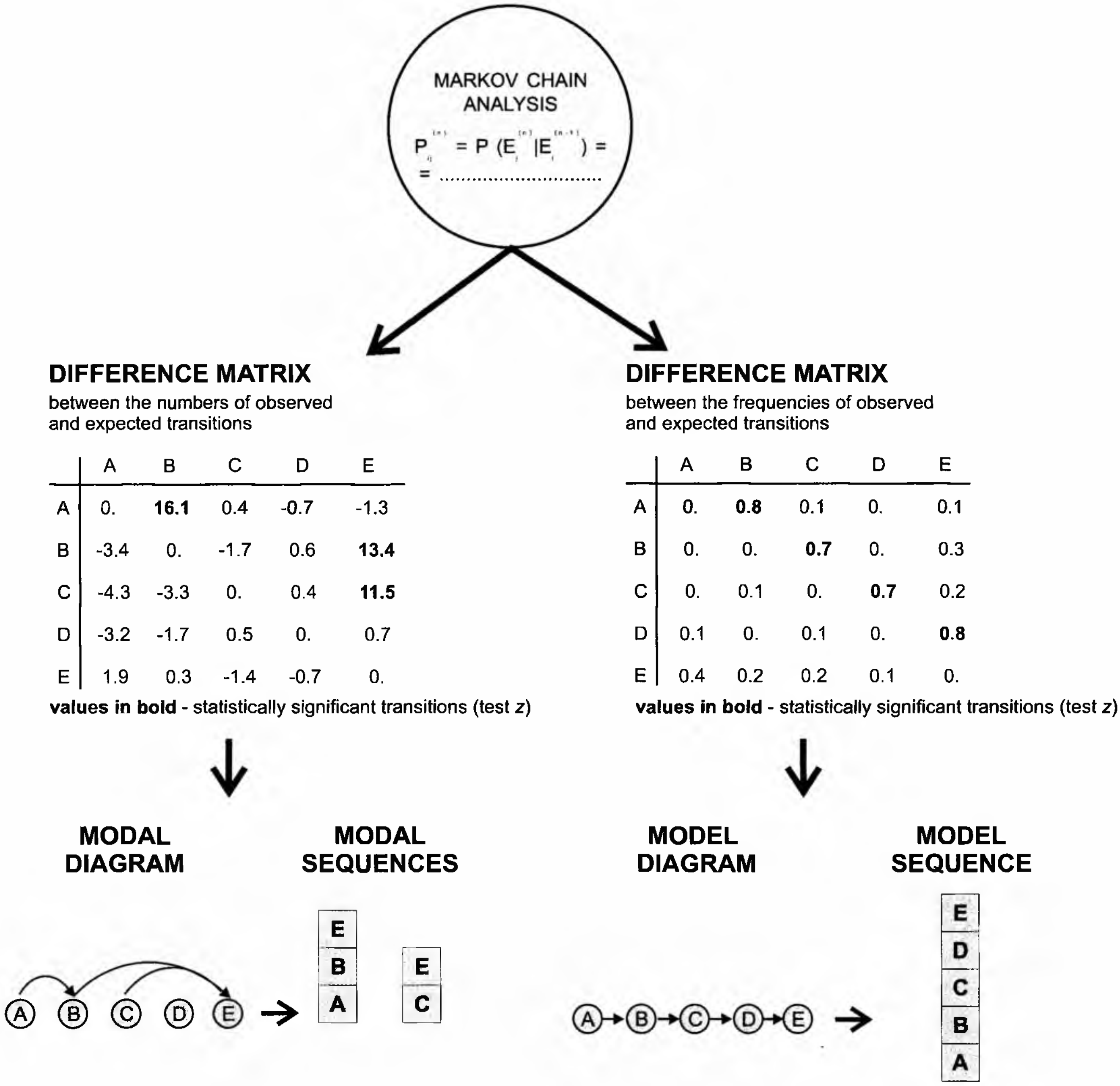
Lithofacies

The model (depositional) diagram and the sequences clearly show that the MS lithofacies tend to be preferentially overlain and rarely underlain by the SM lithofacies (Fig. 8). Such a type of vertical succession is typical of the sediments of depositional lobes (Mutti & Ricci Lucchi, 1975; Shanmugam & Moiola, 1991). The remaining, strongly significant lithofacies transitions point to the successions typical of the positive cycles attributed to the channel deposits, such as MC→C+CS→SC→S and CS→SC→S (Mutti & Ricci Lucchi, 1975; Lash, 1988; Shanmugam & Moiola, 1988).

The modal diagram represents a considerably higher number of statistically significant transitions. It is, however, an effect of processes such as erosion or migration of subenvironment which disturb normal sequence of sedimentation (Fig. 9). This fact is even more clearly visualized by the numerous short modal sequences. Such sequences demonstrate the diversified character of channel sediments controlled by their position within the middle or outer fan (Słomka, 1995) and by domination of deposition or erosion (Mutti & Normark, 1991).

CONCLUSIONS

Deposition of the Godula Beds was dominated by sand or sand-gravel, high-density turbidity currents of variable retardation rates. It is reflected by sequences which document a rapid, mass deposition ($m_1 \rightarrow s_1$, $m \rightarrow m$) or gradual



	A	B	C	D	E
A	0.	**16.1**	0.4	-0.7	-1.3
B	-3.4	0.	-1.7	0.6	**13.4**
C	-4.3	-3.3	0.	0.4	**11.5**
D	-3.2	-1.7	0.5	0.	0.7
E	1.9	0.3	-1.4	-0.7	0.

	A	B	C	D	E
A	0.	**0.8**	0.1	0.	0.1
B	0.	0.	**0.7**	0.	0.3
C	0.	0.1	0.	**0.7**	0.2
D	0.1	0.	0.1	0.	**0.8**
E	0.4	0.2	0.2	0.1	0.

Fig. 5. Method of the construction of model and modal sequences

fractionation of clastic material ($g_2 \rightarrow g_1 \rightarrow g \rightarrow b \rightarrow e$, $g_2 \rightarrow g_1 \rightarrow s_1$). During the breaks between successive flows the weak, bottom currents redistributed the finest fractions over the surrounding floor ($c \rightarrow e$). The influence of various intra-basinal factors which damaged the normal deposition mechanisms is evident. It is suggested that such factors might have included diversified morphology of basin floor, variable inclination of slope surface and variable influx rate of clastic material.

Lithofacies sequences point to the predominance of the two facial zones (sub-environments): depositional lobes (sequences: MS→SM) and channels (sequences: MC→ C+CS→SC→S and C+CS→SC→S). The strong intra-basinal erosion and channel migration resulted in rapid, vertical variability of sub-environments documented by the presence of numerous incomplete sequences. Such features significantly obliterate the natural differences in sequences typical of the two sub-environments.

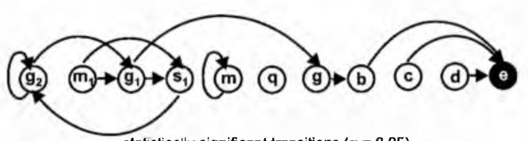
DEPOSITIONAL INTERVALS

DIFFERENCE MATRIX
between the numbers of observed and expected transitions

	g_2	m_1	g_1	s_1	m	q	g	b	c	d	e
g_2	**0.25**	-0.01	**0.40**	0.08	0.12	0.00	0.02	-0.21	-0.20	-0.05	-0.40
m_1	0.06	0.06	**0.21**	**0.22**	0.07	0.00	0.00	-0.15	-0.20	-0.15	-0.12
g_1	0.00	0.03	0.00	**0.17**	0.06	0.00	**0.56**	-0.15	-0.20	-0.15	-0.32
s_1	**0.17**	0.05	-0.02	0.11	0.01	0.06	-0.06	-0.09	-0.14	-0.05	-0.05
m	0.00	0.03	0.01	0.02	**0.20**	0.02	-0.02	-0.16	-0.17	0.05	0.03
q	0.00	-0.01	-0.02	-0.01	0.09	0.00	-0.06	-0.07	-0.20	-0.05	0.32
g	0.00	-0.01	0.02	-0.01	-0.03	0.01	-0.01	**0.25**	-0.19	0.01	-0.05
b	0.00	-0.01	-0.01	-0.01	-0.05	0.00	-0.06	-0.21	0.01	**0.03**	**0.29**
c	0.00	0.00	-0.02	-0.01	-0.05	0.00	-0.06	-0.18	-0.20	0.02	**0.50**
d	0.00	-0.01	0.00	-0.01	0.03	0.00	-0.02	0.00	-0.18	-0.05	**0.23**
e	0.00	0.00	0.01	0.00	0.02	0.00	0.04	0.20	0.16	-0.02	-0.40

values in bold - statistically significant difference ($\alpha = 0.05$)

MODEL DIAGRAM



— statistically significant transitions ($\alpha = 0.05$)

MODEL SEQUENCES

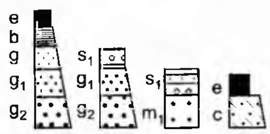


Fig. 6. Model diagram and sequences of statistically significant of depositional intervals transitions

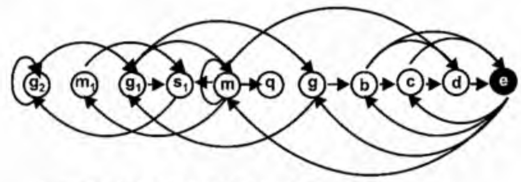
DEPOSITIONAL INTERVALS

DIFFERENCE MATRIX
between the numbers of observed and expected transitions

	g_2	m_1	g_1	s_1	m	q	g	b	c	d	e
g_2	**2.95**	0.07	**4.79**	0.93	1.39	-0.03	0.28	-2.54	-2.37	-0.56	-4.79
m_1	0.93	0.91	1.72	**2.91**	1.19	-0.04	0.05	-2.38	-3.16	-1.74	-0.38
g_1	-0.21	1.72	0.08	**3.70**	**3.36**	-0.12	**28.90**	-8.00	-10.26	-2.41	-16.74
s_1	**2.93**	0.91	-0.30	1.90	0.14	0.96	-1.01	-1.59	-2.35	-0.79	-0.78
m	-0.61	**4.19**	1.36	**3.14**	**29.38**	**2.64**	-2.95	**-24.72**	-25.58	**8.04**	5.17
q	-0.03	-0.04	-0.12	-0.04	0.64	-0.02	-0.42	-0.48	-1.38	-0.32	2.21
g	0.28	-0.95	**3.90**	-1.01	-5.95	1.58	2.50	**43.78**	-32.71	1.83	-8.20
b	-1.54	-3.38	-8.00	-3.59	-29.72	-0.48	-35.22	-128.95	**8.93**	**21.03**	**181.12**
c	-2.37	-2.16	-10.26	-3.35	-28.58	-1.38	-33.71	-107.07	-113.78	**8.98**	**293.87**
d	-0.56	-0.74	-0.41	-0.79	4.04	-0.32	-2.17	0.03	-11.02	-6.36	**18.36**
e	-1.79	-0.38	7.26	-2.78	**23.17**	-2.79	**48.80**	**232.12**	**193.87**	-28.64	-468.44

values in bold - statistically significant difference ($\alpha = 0.05$)

MODAL DIAGRAM



— statistically significant transitions ($\alpha = 0.05$)

MODAL SEQUENCES

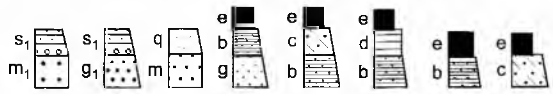


Fig. 7. Modal diagram and sequences of statistically significant of depositional intervals transitions

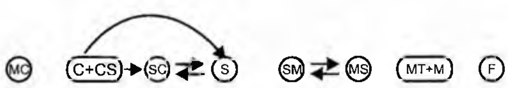
LITHOFACIES

DIFFERENCE MATRIX
between the frequencies of observed and expected transitions

	MC	C+CS	SC	S	SM	MS	MT+M	F
MC	-0.02	**0.38**	-0.22	-0.01	0.08	-0.19	-0.01	0.00
C+CS	-0.04	-0.04	**0.55**	**0.57**	-0.64	-0.38	-0.02	0.00
SC	0.02	0.02	-0.22	**0.16**	0.13	-0.10	-0.01	0.01
S	0.02	0.00	**0.16**	-0.21	0.00	0.04	0.01	0.00
SM	-0.01	-0.01	0.06	0.02	-0.32	**0.27**	0.00	0.00
MS	-0.02	-0.02	-0.08	0.00	**0.32**	-0.19	-0.01	0.00
MT+M	-0.02	-0.02	-0.12	-0.11	-0.22	0.40	-0.01	0.10
F	-0.02	-0.02	0.18	-0.11	-0.12	-0.09	0.19	0.00

values in bold - statistically significant difference ($\alpha = 0.05$)

MODEL DIAGRAM



— statistically significant transitions ($\alpha = 0.05$)

MODEL SEQUENCES

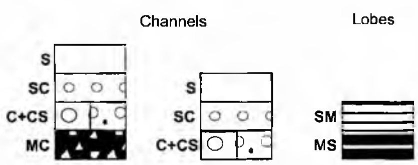


Fig. 8. Model diagram and sequences of statistically significant of lithofacies intervals

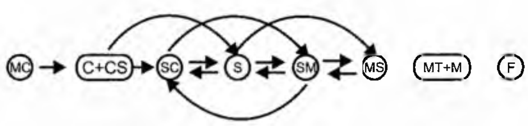
LITHOFACIES

DIFFERENCE MATRIX
between the frequencies of observed and expected transitions

	MC	C+CS	SC	S	SM	MS	MT+M	F
MC	-0.10	**1.88**	-1.12	-0.06	0.42	-0.94	-0.04	-0.02
C+CS	-0.12	-0.16	**1.66**	**1.72**	-1.90	-1.12	-0.04	-0.02
SC	0.88	0.66	-12.54	**9.13**	**7.30**	-5.53	-0.45	0.78
S	0.94	-0.88	**3.13**	11.24	**5.25**	**2.04**	0.58	-0.21
SM	-0.58	-0.90	**12.30**	**1.25**	-24.96	**13.15**	0.37	-0.32
MS	-0.94	-1.12	-3.53	0.04	**15.15**	-8.84	-0.38	-0.19
MT+M	-0.04	-0.04	-0.45	-0.42	-1.63	0.62	-0.02	0.01
F	-0.02	-0.02	0.78	-0.21	-0.32	-0.19	-0.01	0.00

values in bold - statistically significant difference ($\alpha = 0.05$)

MODAL DIAGRAM



— statistically significant transitions ($\alpha = 0.05$)

MODAL SEQUENCES

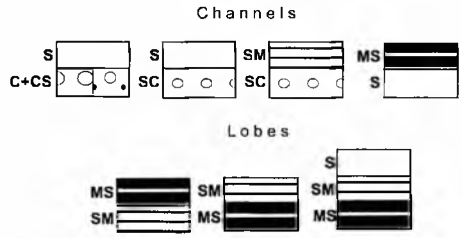


Fig. 9. Modal diagram and sequences of statistically significant of lithofacies intervals

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Streszczenie

SEKWENCJE LITOFACJI I INTERWAŁÓW DEPOZYCYJNYCH W WARSTWACH GODULSKICH KARPAT

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Celem analizy pionowego następstwa warstw jest znalezienie charakterystycznych, dobrze zdefiniowanych sekwencji. W formacjach fliszowych mogą to być sekwencje turbidytowe, kanałowe lub lobowe. Efektywnym narzędziem w badaniach sedymentologicznych tego typu sekwencji różnych warstw, w długich profilach liczących setki lub tysiące następstw są łańcuchy Markowa. Zawierają one wiele różnych procedur takich jak macierze: ilości przejść, częstości przejść, różnic między ilościami lub częstościami przejść obserwowanych i oczekiwanych, a także kolejne potęgi macierzy częstości przejść i wektor równowagi.

Procedury łańcuchów Markowa zastosowano w badaniach warstw godulskich (turon – senon dolny) reprezentujących osady Karpat fliszowych. Analizowano sekwencje ponad 250 interwałów litofacji i ponad 10 tysięcy interwałów depozycyjnych w szeregu grubych profilach terenowych. Do opisu wykorzystano klasyfikację Ghibaudo.

Jeden kierunek przejść jest charakterystyczną cechą diagramu modelowego (depozycyjnego) dla interwałów depozycyjnych; przejścia zawsze prowadzą od osadów grubo- do drobnoziarnistych, odzwierciedlając spadek dynamiki spływów grawitacyjnych, głównego mechanizmu depozycji. Diagram modalny pokazuje zupełnie odmienny obraz. Wyodrębniają się trzy grupy interwałów o zróżnicowanej frakcji, w tym także szereg przejść od interwałów niskoenergetycznych do wysokoenergetycznych. Sekwencje modelowe bazujące na diagramie modelowym wskazują na dominację sedymentacji z gęstych prądów zawiesinowych. Epizody depozycji masowej z przejściem do trakcji lub depozycji z rozcieńczonych prądów dennych są znacznie rzadsze. Wysoka liczba rozpoznanych sekwencji modalnych dwuczłonowych świadczy o tym, że depozycja osadu z gęstych prądów zawiesinowych miała złożony charakter. Najczęściej efektem bardzo szybkiego hamowania była depozycja masowa lub szybka, z rozfrakcjonowaniem najgrubszego materiału. W znacznie wolniejszym prądzie, w fazie trakcji, dochodziło do frakcyjnego rozdzielenia materiału. Z prądów o małej gęstości deponowany był drobny materiał w warunkach znacznie wolniejszego, stopniowego hamowania. Niewątpliwie duży wpływ na dominację tak krótkich sekwencji miała także wewnątrzbasenowa erozja.

Diagram modelowy i sekwencje litofacji wskazują na dominację dwóch zespołów. Jeden jednoznacznie definiuje strefę lobów depozycyjnych (sekwencje MS→SM), drugi najprawdopodobniej strefę kanałów (sekwencje: MC→C+CS→SC→S i C+CS→SC→S), ale nie można wykluczyć związku z sedymentacją nieskanalizowaną. Budowa sekwencji modelowych potwierdza pierwszą hipotezę.

Diagram modalny, znacznie bardziej złożony, oraz duża liczba różnorodnych sekwencji wskazuje na szybką i wielokrotną migrację poszczególnych stref stożków głębokomorskich. Niewątpliwie zaznacza się tutaj także pewien udział stref przejściowych między kanałami a lobami depozycyjnymi (strefy międzykanałowe i wałów).