ANNALES SOCIETATIS GEOLOGORUM POLONIAE
ROCZNIK POLSKIEGO TOWARZYSTWA GEOLOGICZNEGO

v. 51—1/2: 3—44 Kraków 1981

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A REVISION OF THE FLUXOTURBIDITE CONCEPT BASED ON TYPE EXAMPLES IN THE POLISH CARPATHIAN FLYSCH

(Pl. I—VI and 15 Figs.)

Rewizja pojęcia fluksoturbidyt, w oparciu o przykłady z polskich Karpat fliszowych

(Pl. I—VI i 15 fig.)

Andrzej Ślączka, Sam Thompson III: A revision of the fluxoturbidite concept based on type examples in the Polish Carpathian Flysch. *Ann. Soc. Geol. Poloniae*, 51—1/2: 3—44, 1981. Kraków.

Abstract: A fluxoturbidite is redefined as the depositional product of composite sediment, gravity flow, with a gravity grain flow (or related type) in the lower part and a turbidity flow in the upper part. A model of a complete fluxoturbidite (FT) bed is constructed; it consists of a 5 m composite bed of conglomerate and sandstone with a thin mudstone at the top. The lower (F) part is generally massive (internal lamination is absent) with coarser grains dispersed among the finer; the transport mechanism is considered to be a grain flow, although some zones may be produced by liquefied sediment flow. The upper (T) part is essentially a Bouma sequence (Ta to Te), and represents deposition from a turbidity flow.

Fluxoturbidites form significantly coarser parts of submarine canyon-fan depositional systems than normal turbidites, and may extend into distal parts of the fan. Fluxoturbidites generally are cleaner sandstones and conglomerates, and constitute better reservoir objectives in petroleum exploration than normal turbidites which generally are muddy.

Key words: fluxoturbidite, fluxoturbidite model, gravity flow, flysch, Carpathians

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manuscript received: May 1980 accepted, July, 1980

Treść: Badania typowych osadów fluksoturbidytowych polskich Karpat fliszowych wskazują, że tworzenie się ławic fluksoturbidytowych było wynikiem złożonego procesu sedymentacyjnego rozpoczynającego się potokami piaszczystymi, a kończącego się normalnymi prądami zawiesinowymi. Zaproponowany został koncepcyjny model pełnego fluksoturbidytu. Osady fluksoturbidytowe są charakterystyczne dla proksymalnych części stożków podmorskich, a niekiedy budują prawie całe stożki turbidytowe.

INTRODUCTION

After the concept of fluxoturbidite was introduced by Dżułyński, Książkiewicz, and Kuenen (1959), many workers recognized deposits of a similar type associated with normal turbidites in several deep-marine basins around the world. In general, fluxoturbidites are characterized by thick beds (several meters) of sandstone and conglomerate that tend to be nongraded and lacking in internal stratification (at least in the lower part), in contrast to the normal turbidites that are graded and contain a sequence of internal layers defined in the model of Bouma (1962).

For many units of flysch in the Carpathian Mountains of Poland, Dżułyński and others (1959) listed several different examples of fluxoturbidites. The mechanism of sedimentary transport was inferred to be intermediate between submarine slumping-sliding and turbidity flow, but several processes were implied. The fluxoturbidites in the Istebna Beds were described in detail by Unrug (1963), and the sedimentary processes were interpreted; that paper remains one of the best documentations of the fluxoturbidite concept in the type area.

Some geologists, for example Walker (1967, 1970), recommend that the term "fluxoturbidite" should be abandoned and that the concept be incorporated into "proximal turbidite". Not all agree, for example Schlager W. and Schlager M. (1973); and some would keep the term but modify the concept of the sedimentary mechanism, for example Carter (1975). In this paper, we will review these concepts and problems, and propose revisions.

In addition to the significance of fluxoturbidites in sedimentology, we are also concerned with their importance in the exploration and development of petroleum resources in deep-marine basins. The reservoir quality of the cleaner sandstones and conglomerates in fluxoturbidites tends to be much better than that of normal turbidites. In Poland, the fluxoturbidite reservoirs have produced up to 3,900 barrels of oil per day, averaging 300 to 400 barrels per day, whereas those in normal turbidites usually produce 10 barrels per day or less. Contrasting rates of petroleum production also are reported in other basins. We plan to discuss this subject further in a subsequent paper.

At Ślączka's invitation, Thompson made three vacation trips to Poland to see with him several of the typical examples of fluxoturbidites in the Carpathian Flysch. Based on the first two reconnaissance trips in 1972 and 1973, a preliminary model for fluxoturbidites was presented at the International Congress of Sedimentology in Nice (Ślączka and Thompson, 1975). During the third trip in 1977, the key exposures were described in detail and the improved model of the present paper was developed.

We are indebted to many geologists whose work and guidance have facilitated our study of fluxoturbidites. Only a few of them are mentioned specifically in this brief paper. Expecially we are grateful to S. Dżułyński and R. Unrug for their stimulating discussions and their suggestions for improving the first draft of the manuscript. We regret the passing of Ph. H. Kuenen, who was one of the greatest advocates of the fluxoturbidite concept.

REGIONAL SETTING

The Alpine-Carpathian mountain chain passes through the southernmost part of Poland. As is characteristic of the rest of the chain, the tectonic style of the Polish Carpathian Mountains consists of nappe structures (Fig. 1) developed during Early to Middle Miocene time. From south to north the main nappes in the outer part of the Polish Carpathians are: Magura, Silesian, sub-Silesian, and Skole.

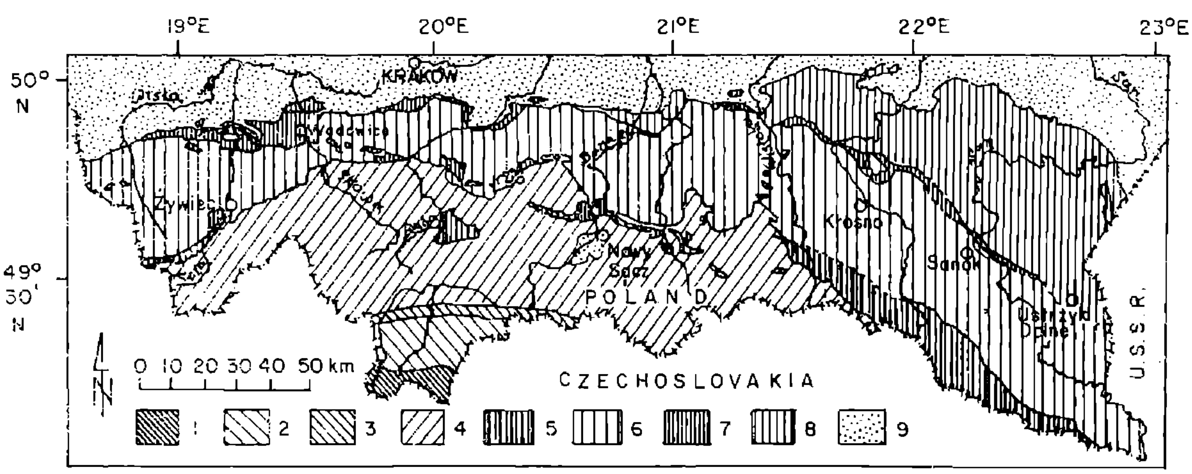
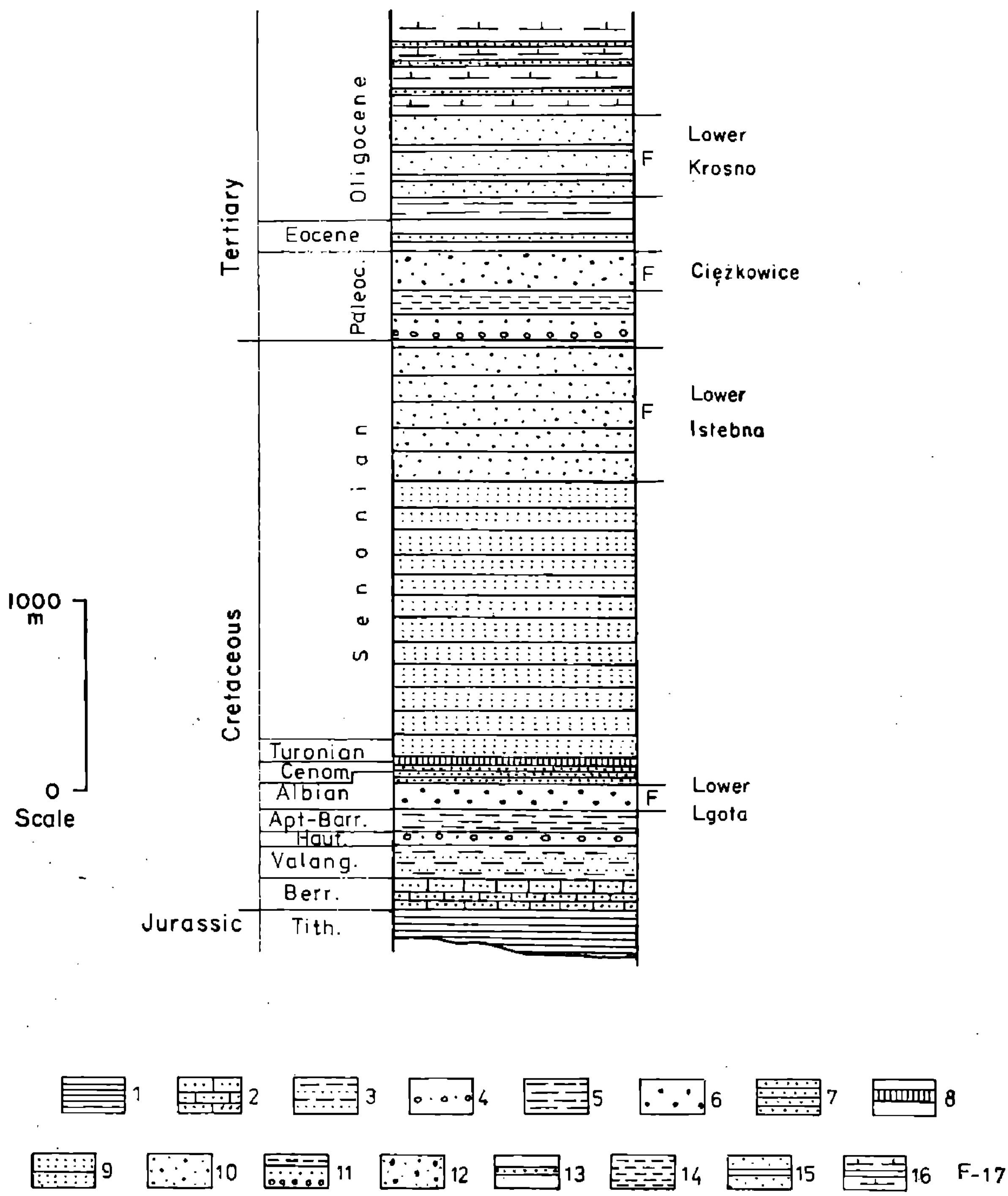


Fig. 1. Tectonic sketch map of the Carpathian Mountains in the southern part of Poland. Tectonic units are: 1 — Tatra, 2 — Podhale Flysch, 3 — Pieniny klippen belt, 4 — Magura nappe, 5 — Fore-Magura nappe (Dukla), 6 — Silesian nappe, 7 — sub-Silesian nappe, 8 — Skole nappe, 9 — Miocene and younger foreland beds. (Modified from Książkiewicz, 1962)

Fig. 1. Szkic tektoniczny Karpat: 1 — Tatry, 2 — Flisz podhalański, 3 — Pieniński Pas Skałkowy, 4 — Płaszczowina magurska, 5 — Jednostka przedmagurska i dukielska, 6 — Płaszczowina śląska, 7 — Jednostka podśląska, 8 — Płaszczowina skolska, 9 — Przedgórze Karpat. (W oparciu o pracę Książkiewicz 1962)

The Outer Carpathians are built of flysch sequences totaling nearly 6000 m in thickness and ranging in age from latest Jurassic to Early Miocene. Paleobathymetric depths generally range from 200 to 600 m (Książkiewicz, 1975). These sequences consist of normal turbidites, fluxoturbidites, and other deep-marine deposits (Fig. 2). Three flysch formations with abundant fluxoturbidites are the Lower Istebna Beds (Upper Senonian) (Fig. 3a, b), Ciężkowice Sandstone (Paleocene-Lower Eocene) (Fig. 4), and Krosno Beds (Oligocene).

More detailed treatment of the geology of the Polish Carpathian Mountains is given by Książkiewicz (1962, 1963, 1968) and others.



ORIGINAL CONCEPT OF FLUXOTURBIDITE

Although the term f l u x o t u r b i d i t e was first published by Kuenen (1958, p. 332), the original definition of the concept is given by Dżułyński, Książkiewicz, and Kuenen (1959, p. 1114):

"A different type of sedimentation is encountered amidst normal turbidites in many places. In this type the grain size is large and the beds tend to be less muddy. The bedding is thick and rather irregular, and the shales between are silty to sandy and thin or even absent. Current sole markings are scarce, load casting is more common, and coarse current bedding of somewhat variable direction is encountered. Indications of slumping are found, and grading is absent, repetitive, irregular, or even inverted, and irregular lenses of coarser grain occur inside the beds. These sandstones may occur as large lenses between normal flysch or shales. In other cases the material or the direction of supply contrast with those of the normal surrounding flysch of the same age".

"Because characteristics of deposition from turbidity currents appear to be mixed with evidence for sliding, we prefer to call this kind of bed a «fluxoturbidite»".

"We suggest that the cause for this abnormal type of flysch can be either a deepening of the basin and steepening of the slope, or a quickening of the supply, or a change in position of the supply, for instance the building of a new delta".

"But whatever the cause, the mode of transportation has changed. Instead of a well-mixed turbulent turbidity current carrying almost

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Fig. 2. Schematic stratigraphic column of the Silesian nappe. Sedimentary units are: 1 — Lower Cieszyn Beds, 2 — Cieszyn Limestones, 3 — Upper Cieszyn Beds, 4 — Grodischt Beds, 5 — Wierzowice Shales, 6 — Lower Lgota Beds, 7 — Upper Lgota Beds, 8 — radiolarite beds (and red mudstones), 9 — Godula Beds, 10 — Lower Istebna Beds, 11 — Upper Istebna Beds, 12 — Ciężkowice Sandstones, 13 — Hieroglyphic Beds, 14 — Menilite Beds, 15 — Krosno Beds — thick sandstones, 16 — Krosno Beds — thinner sandstones and mudstones, 17 — Units containing fluxoturbidites

Fig. 2. Schematyczna kolumna stratygraficzna jednostki śląskiej. 1 — Łupki cieszyńskie dolne, 2 — Wapienie cieszyńskie, 3 — Warstwy cieszyńskie górne, 4 — Warstwy grodziskie, 5 — Łupki wierzowskie, 6 — Warstwy lgockie dolne, 7 — Warstwy lgockie górne, 8 — Warstwy radiolarytowe z czerwonymi łupkami, 9 — Warstwy godulskie, 10 — Warstwy istebniańskie dolne, 11 — Warstwy istebniańskie górne, 12 — Piaskowce ciężkowickie, 13 — Warstwy hieroglifowe, 14 — Warstwy menilitowe, 15 — Warstwy krośnieńskie — litofacja gruboławicowych piaskowców, 16 — Warstwy krośnieńskie — litofacja piaskowców średnio- i cienkoławicowych oraz łupków, 17 — Odcinki profilu zawierające fluksoturbidyty

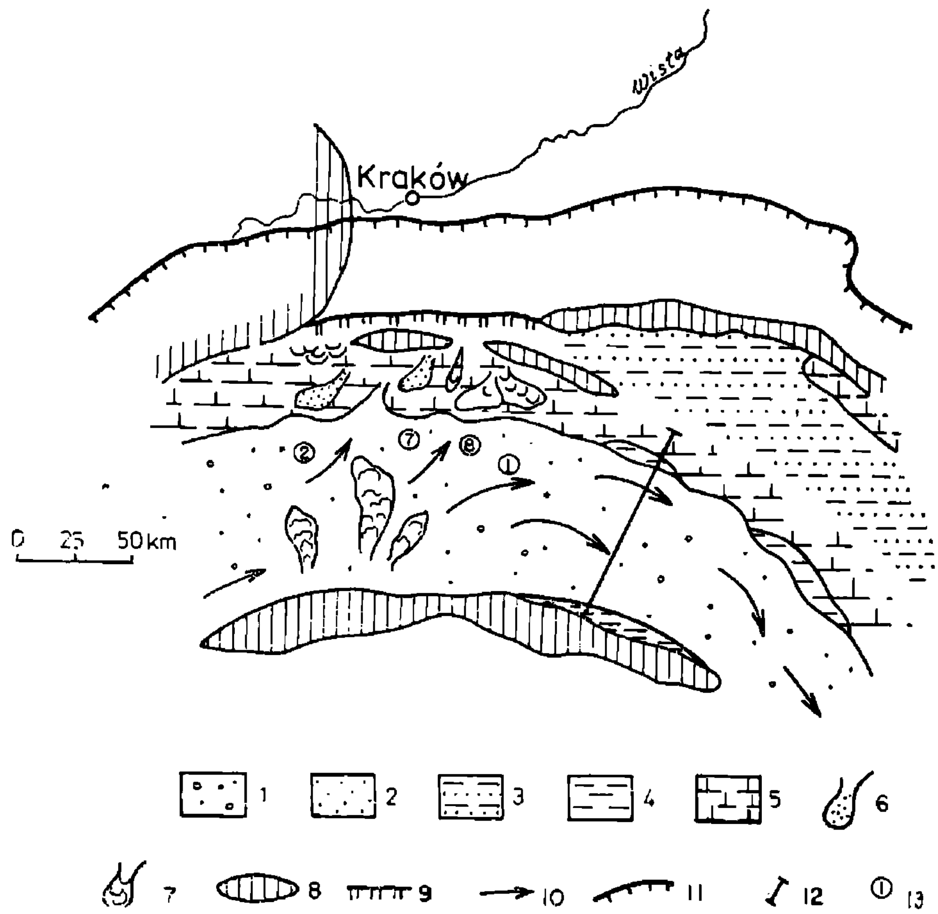

Fig. 3a. Paleogeographic map of the Lower Istebna Beds (Upper Senonian). Symbols are: 1 — sandstone and conglomerate (turbidites and fluxoturbidites), 2 — sandstone, 3 — sandstone and mudstone, 4 — red mudstone, 5 — calcareous red mudstone, 6 — submarine fan, 7 — submarine mudflow, 8 — positive elements, 9 — northern border of geocyncline, 10 — paleocurrent directions, 11 — present northern limit of Carpathian Mountains, 12 — location of Fig. 3b, 13 — locality numbers from Fig. 5. (Palinspastic reconstruction modified from Książkiewicz, 1962, sheet 7)

Fig. 3a. Szkic paleogeograficzny basenu Karpat fliszowych w czasie sedymentacji warstw istebniańskich dolnych (senon górny). 1 — Piaskowce i zlepieńce (turbidyty i fluksoturbidyty), 2 — Piaskowce, 3 — Piaskowce i mułowce, 4 — Pstre łupki, 5 — Pstre margle, 6 — Podmorskie stożki, 7 — Spływy mułowcowe, 8 — Obszary wypiętrzone, kordyliery, 9 — Północna granica geosynkliny, 10 — Kierunki paleotransportu, 11 — Współczesna granica północna orogenu karpackiego, 12 — Położenie fig. 3b, 13 — Numeracja opisywanych odsłonięć, patrz fig. 5 (rekonstrukcja oparta na Książkiewicz 1962, częściowo zmieniona)

the entire load in suspension, one can imagine a turbidity current in which most of the sand and gravel moves in a watery slide along the base. The current is too poor in clay to raise this load in suspension, and the slope is too steep for the load to come to rest until it has spread out in a layer".

"A true turbidity current can be likened to a dry avalanche, and a normal slump is the equivalent of a wet avalanche remaining in contact with the ground. We believe that an intermediate type of

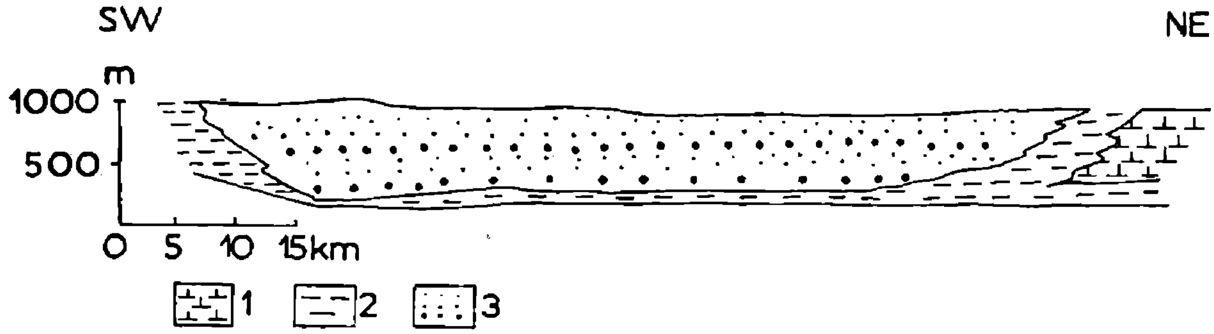

Fig. 3b. Paleogeographic cross section of the Lower Istebna Beds in the Silesian Basin. Symbols are: 1 — calcareous mudstone facies, 2 — mudstone and shaly facies, 3 — sandstone — conglomerate facies (turbidites and fluxoturbidites). Note that the sandstone-conglomerate facies contact with the mudstone and shaly facies without an intervening sandstone ("distal") facies

Fig. 3b. Przekrój paleogeograficzny (schematyczny) warstw istebniańskich dolnych. 1 — Facja marglista, 2 — Facja łupkowa i mułowcowa, 3 — Facja piaskowcowo-zlepieńcowa (turbidyty i fluksoturbidyty). Zwraca uwagę bezpośredni kontakt lateralny facji piaskowcowo-zlepieńcowej z facją mułowcowo-łupkową, a brak dystalnej facji piaskowcowej

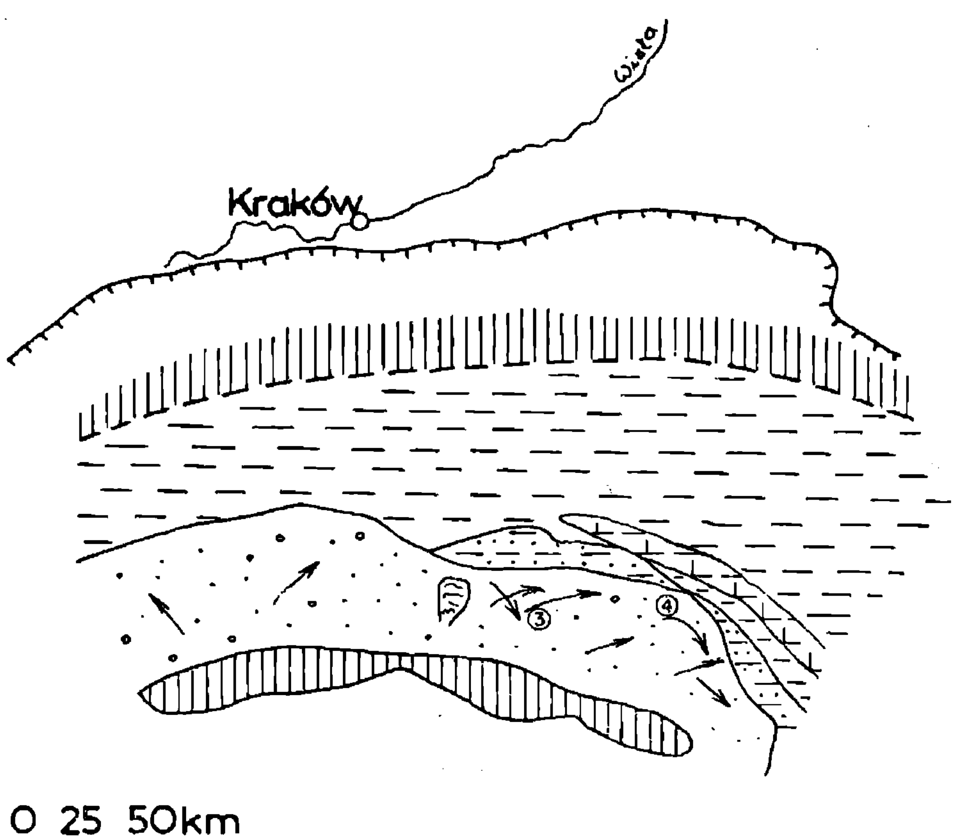

Fig. 4. Paleogeographic map of the Ciężkowice Sandstones (Upper Paleocene to Lower Eocene). Symbols are same as for Fig. 3a. (Palinspastic reconstruction modified from Książkiewicz, 1962, sheet 9)

Fig. 4. Szkic paleogeograficzny basenu Karpat fliszowych w czasie sedymentacji piaskowców ciężkowickich. Objaśnienia jak w fig. 3b. (rekonstrukcja oparta na Książkiewicz 1962, częściowo zmieniona)

movement is also possible and suggest that the resulting deposit be called a fluxoturbidite".

The first quoted paragraph above describes so clearly what a fluxoturbidite looks like that no illustration is needed to visualize it; however, the "indications of slumping" are not clear. Nevertheless, with this description many subsequent workers have been able to recognize fluxoturbidite in other deep-marine basins.

The other quoted paragraphs discuss the processes that produce fluxoturbidites. That discussion was adequate for its time, but considering more recent advances in sedimentology some parts are now out dated. In the same paper (p. 1095), they used the term "slumping" in a general sense approximately synonymous with "submarine sliding", and considered "subaqueous mudflows" as "slumps" and mud "slides". These imprecise usages have caused some communication problems with subsequent workers.

Some additional remarks may help in understanding their conceptual framework. In that paper, they were discussing mainly turbidites in flysch, paleogeography, and paleocurrent directions; the fluxoturbidite discussion was only a minor subject. Indeed, they noted that the most important type of flysch consists of normal turbidites, and the abnormal, subordinate type called "fluxoturbidite" comprises only 15% of the thickness and less of the areal extent of the Carpathian Flysch. Apparently "slump" deposits were considered as comprising an even less common type of abnormal flysch. That usage of "fluxoturbidite" as a type of flysch, rather than as only an individual deposit in a flysch sequence, has also caused problems.

These few problems with the original concept result from the lack of an explicit definition. Although the general description of a fluxoturbidite bed is adequate for recognition, specific descriptions and illustrations of type examples are needed to determine the range of diagnostic characteristics so that a model and a more rigorous definition may be formulated.

TYPE EXAMPLES

Dżułyński and others (1959, p. 1095) listed the Ciężkowice Sandstone, the Istebna Beds, and the lower part of the Lgota Sandstone as containing the most representative examples of fluxoturbidites. They also listed the Grodischt Sandstone, Pasierbiec Sandstone, lower part of the Krosno Beds, and some parts of the Magura Sandstone as intermediates between examples of turbidites and fluxoturbidites. They did not describe or illustrate details of sedimentary structures at specific localities.

Unrug (1963) provided the first detailed sedimentologic analysis of typical examples of fluxoturbidites in his paper on the Istebna Beds; he presented several line drawings and photographs of the sedimentary structures. He summarized (p. 86):

"Fluxoturbidite deposits are characterized by lenticular shapes of beds, coarseness of detrital material, great thickness of beds, low pelite content, prevalence of symmetrical, multiple, and discontinuous grading over other types of bedding, and occurrence of non-graded beds, traces of strong erosion, lack of sole markings, and poor development of pelitic sediments. Occurrence of armored shale balls arranged in regular layers parallel to the bedding planes within sandstone beds points out to the transition of sand flows into turbidity currents".

He introduced (p. 64) the concept that fluxoturbidites are the deposits of "sand flows", but also considered the process as an intermediate type of mass movement between true slumps and turbidity currents after Dżułyński and others (1959). Later (Unrug, 1965) he added the observations that Polish fluxoturbidites are formed during times of rapidly rising cordilleras both on the margins and within the geosynclinal troughs, that steep slopes on the flanks of the cordilleras provided the setting for the initiation of the sand flows, and that fluxoturbidites may be distributed in submarine fans extending across the basin; that is, they are not only confined to the "proximal" parts of fans.

DISCUSSIONS OF LOCALITIES

From the many localities where fluxoturbidites have been identified by M. Książkiewicz and others working the Polish Carpathian Flysch, we have chosen some of the better exposed ones in the stratigraphic units listed by Dżułyński and others (1959) as type examples (see location map, Fig. 5, and Table 1). Instead of the Lgota Beds, we have chosen the lower part of the Krosno Beds as it is a thicker and more widely exposed unit with many good examples of fluxoturbidites (Dżułyński and Ślączka, 1959), and the dominance of sandstone provides a contrast with the Istebna Beds and Ciężkowice Sandstone which are more conglomeratic. In addition to the representative stratigraphic distribution, we have also attempted to space the localities geographically, and provide the distribution of fluxoturbidites within the submarine canyon-fan systems.

For the examples, we are presenting columnar sections of the sequences of sedimentary structures, cross sections of the bedding relationships, and photographs of significant features. Because our work

Table 1. Main type examples of fluxoturbidites (see locality numbers on Fig. 5)

Loc. No.	Name	Stratigraphic Unit	Remarks
1	Rożnów ("Rawsh-noove") 65 km SE of Kraków, near Rożnów Lake	Lower Istebna Beds Upper Cretaceous, Senonian	Principal type example of fluxoturbidite. Zones of gravel segregations and mudstone clasts die out laterally within grain-flow deposits, which are gradational with overlying turbidites. Good exposure in quarry.
2	Mucharz ("Mu-házgh") 40 km SW of Kraków, on Skawa River	Lower Istebna Beds Upper Cretaceous, Senonian	Channel deposits of conglomerate; sandstones from margin "slumped" (by fall or slide) into flows. Good exposure in stream cut.
3	Ciężkowice ("Chairn-skow-véet-sah") 80 km SE of Kraków	Ciężkowice Sandstone Paleocene to Lower Eocene	Zones of gravel segregations above dispersed gravels in grain-flow deposits. Channels with trough laminae; some horizontal lamination. Fair to good exposure in park.
4	Odrzykoń ("Awd-gée-cawn") 145 km SE of Kraków	Ciężkowice Sandstone Paleocene to Lower Eocene	Zones of gravel segregations up to 20 cm thick. Fair exposure at castle.
5	Koniaków ("Cawn-ee-ák-ov") 85 km SW of Kraków	Krosno Beds Lower Oligocene	Grain-flow deposit gradationally overlain by complete turbidite sequence. Good exposure in quarry.
6	Polana ("Poh-láhn-ah") 175 km SE of Kraków	Krosno Beds Lower Oligocene	Massive (debris?) flow deposit is gradational with overlying turbidite. Good to fair exposure in quarry.

is of a reconnaissance nature, only macroscopic observations generally were made; more detailed sedimentological investigations could provide additional documentation.

Descriptions and interpretations of the turbidites encountered in these sections follow the Ta to Te model of Bouma (1962). Grain-flow deposits (Middleton and Southard, 1977, p. 8.4—8.6) are recognized as conglomerates or sandstones that are associated with turbidites, but are generally without grading, internal stratification, or a mud matrix.

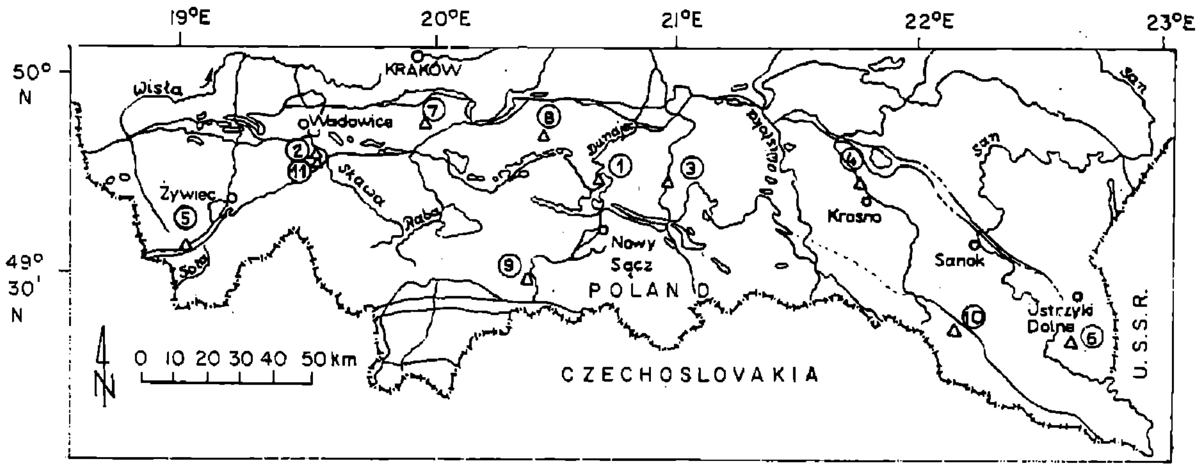

Fig. 5. Location map of type examples of fluxoturbidites. Locality numbers, 1 — Rożnów, 2 — Mucharz, 3 — Ciężkowice, 4 — Odrzykoń, 5 — Koniaków, 6 — Polana, 7 — Borzęta, 8 — Muchówka, 9 — Tylmanowa, 10 — Komańcza, 11 — Śleszowice

Fig. 5. Mapa lokalizacji opisywanych fluksoturbidytów. 1 — Rożnów, 2 — Mucharz, 3 — Ciężkowice, 4 — Odrzykoń, 5 — Koniaków, 6 — Polana, 7 — Borzęta, 8 — Muchówka, 9 — Tylmanowa, 10 — Komańcza, 11 — Śleszowice

Bedding and lamination description follows the system of Campbell (1967). Interpretation of horizontal, current-ripple, and trough lamination produced by migrating bed forms is based on Harms (1975).

Rożnów (Loc. 1; Fig. 6; Pl. I; Pl. II, Fig. 1)

S. Dżułyński informed us that the Rożnów locality is the principal type example where the fluxoturbidite concept was originally developed. Unrug (1963) described and illustrated many of the sedimentary features. This long abandoned quarry near Rożnów Lake contains some of the best exposure of fluxoturbidites seen in our study.

Two thick beds (Fig. 6a, 0.00 to 2.73 m and 2.73 to 6.47 m) contain grain-flow deposits (F) with zones of mudstone clasts and segregations of gravel, and upward transitions into turbidites (Ta to Tc). On the basis of such observations, we will propose later that a fluxoturbidite be considered as a composite bed of a grain-flow or related deposit and a turbidity-current deposit.

In the grain-flow deposits, pebbles of igneous or metamorphic rock generally are dispersed evenly through the sand matrix, but locally they may be found in clast-supported clusters. Mudstone clasts sank within each flow to form a zone on top of a surface of density contrast, in some cases marked by the transitional contact of sandstone above

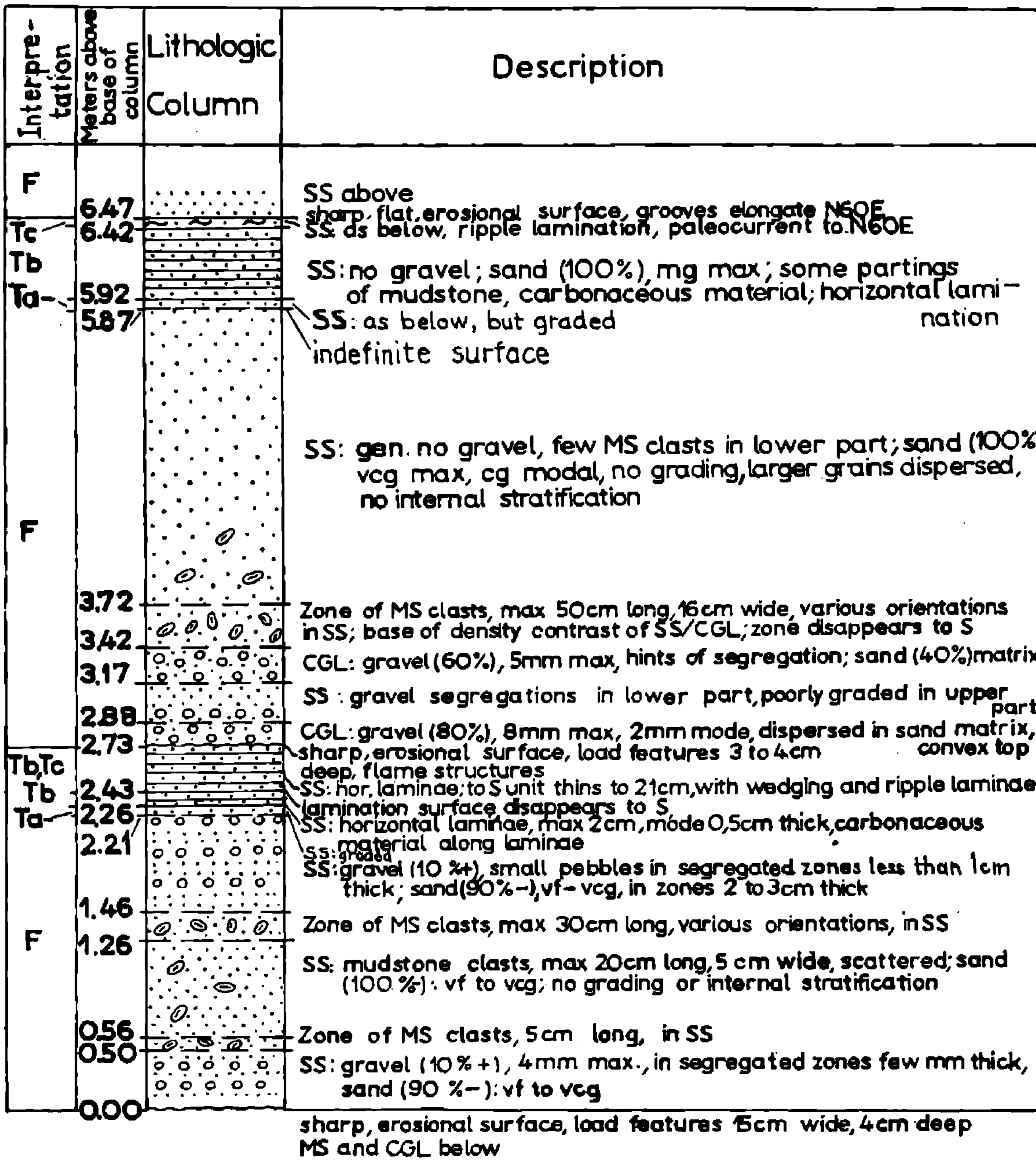

Fig. 6a. Columnar section at Rożnów (Loc. 1) of Lower Istebna beds (Upper Cretaceous). Two fluxoturbidite beds show many characteristic features. Thin zones of gravel segregations occur in the grain-flow deposits. Mudstone clasts generally appear to be confined to zones marking boundaries of density contrast within the flows. The tops of the grain-flow deposits (F) are gradational with the overlying turbidity-current deposits (Ta- intervals are thin). Symbols are the same in the following columnar sections

Fig. 6a. Profil odsłonięcia warstw istebniańskich dolnych w Rożnowie (lok. 1). Obie ławice fluksoturbidytów wykazują liczne cechy charakterystyczne. Cienkie strefy segregacji żwirowej widoczne są w osadach potoków piaszczystych. Klasty mułowcowe związane są zwykle ze strefami granic gęstościowych w obrębie prądu. Osady potoków piaszczystych (F) przechodzą stopniowo ku górze w osady prądów zawiesinowych (interwał Ta jest cienki). Symbole na wszystkich załączonych kolumnach są takie same

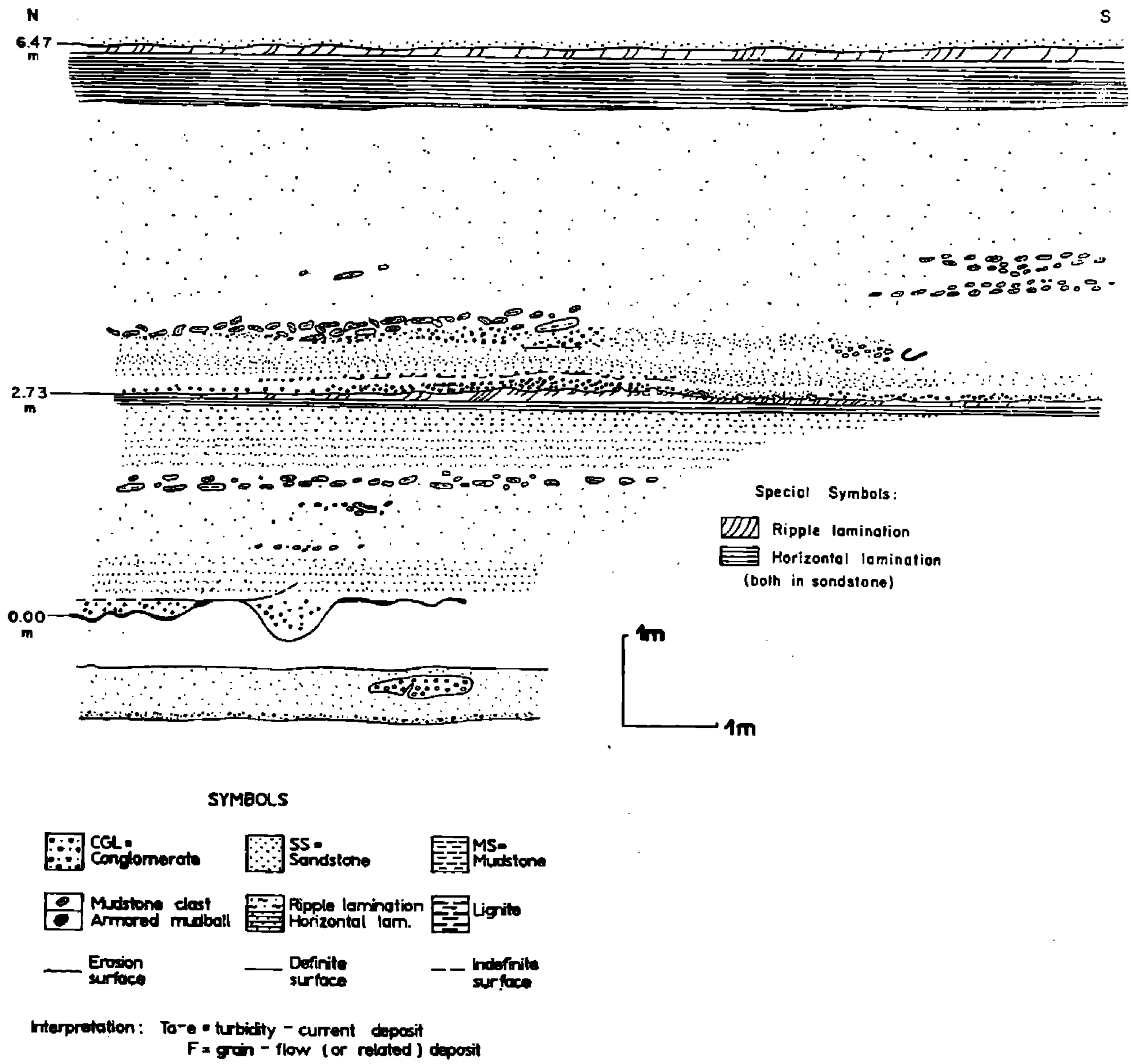

Fig. 6b. Cross section, north-south, of quarry wall at Rożnów. Fig. 6a is located on left side. Principal bedding surfaces occur at 0.00 m, 2.73 m, and 6.47 m. Lateral variability within beds is shown. In lower bed (0.00 to 2.73 m) are lenses and load pockets of gravel in grain-flow deposits. Zones of gravel segregations and mudstone clasts die out laterally. Conglomerate at base of upper bed thickens locally with a convex top indicating a buildup over a slightly higher part of the bottom. Symbols generally are the same as those used in columnar sections; special symbols are indicated

Fig. 6b. Przekrój północ-południe kamieniołomu w Rożnowie.
Fig. 6a. reprezentuje lewą część przekroju. Główne powierzchnie uławicenia występują na poziomach 0.0 m, 2.73 m, i 6.47 m. Widoczna jest pozioma zmienność w obrębie ławic. W dolnej ławicy (0.00—2.73) widoczne są soczewki żwirów w osadach potoków piaszczystych. Strefy segregacji żwirów i klastów mułowcowych lateralnie wyklinowują się. Zlepieńce w dolnej części wyższej ławicy lokalnie zwiększają miąższość, ich wypukła górna powierzchnia wskazuje na nadbudowę. Symbole są ogólnie takie same jak w profilach, symbole odmienne są objaśnione obok rysunku

and conglomerate below. Thin sheets of gravel segregations are found within the sandstones and may be the result of liquefied flow. Both the zones of mudstone clasts and the gravel segregations die out laterally, so they do not represent normal layers of bedding or lamination.

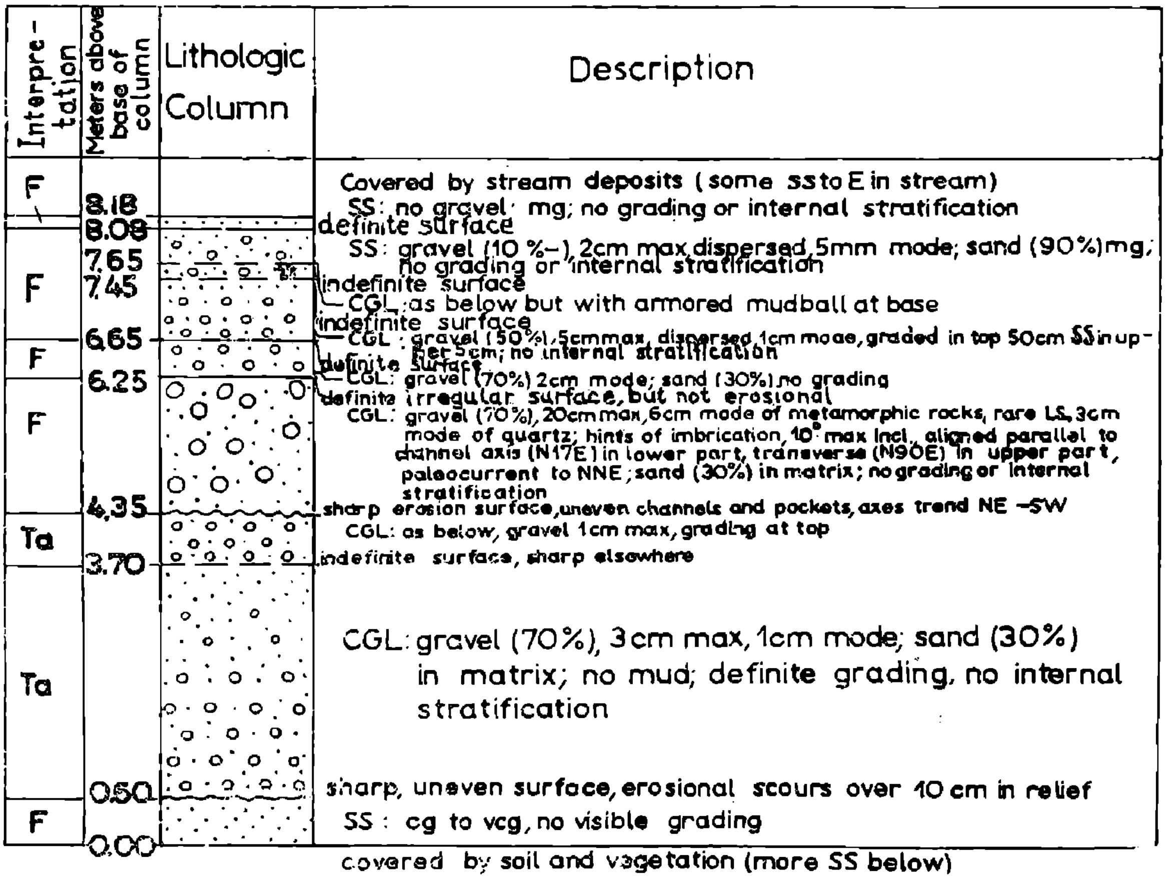

Fig. 7a. Columnar section at Mucharz (Loc. 2) of Lower Istebna Beds (Upper Cretaceous). From 0.00 to 0.60 m is the upper, truncated part of a fluxoturbidite bed. From 0.60 to 3.70 m, and 3.70 to 4.35 m are two, thick, normal turbidite beds (Ta). From 4.35 m to 8.18 m is a sequence of fluxoturbidite beds (F) with the upper (T) parts missing. The definite stratification surfaces at 6.25, 6.65, and 8.08 m are depositional discontinuities with no evidence of erosion; possibly they may be lamination surfaces within a complex fluxoturbidite bed. The indefinite surfaces at 7.45 and 7.65 m are recognized by grain-size contrasts, but show no evidence of depositional discontinuity; they are interpreted as boundaries produced by internal variations of grain concentrations within the flow

Fig. 7a. Profil odsłonięcia warstw istebniańskich dolnych w Mucharzu (lok. 2). Odcinek 0.00—0.60 m reprezentuje górną, częściowo zerodowaną część ławicy fluksoturbidytowej. Odcinek od 0.60 do 4.35 obejmuje dwie grube ławice normalnych turbidytów. Od 4.35 do 8.18 m występuje seria ławic fluksoturbidytów (F) z brakującymi wyższymi partiami (T). Wyraźne powierzchnie uwarstwienia na poziomach 6.25, 6.65 i 8.08 m reprezentują strefy nieciągłości jednak bez śladów erozji; mogą one być powierzchniami lamin w obrębie jednej złożonej ławicy fluksoturbidytu. Niewyraźne powierzchnie na poziomie 7.45 i 7.65 m są związane ze zmianą wielkości ziarn; Powierzchnie te są interpretowane jako granice spowodowane zróżnicowaną koncentracją ziarn w prądzie

Mucharz (Loc. 2; Fig. 7; Pl. II, Fig. 2; Pl. III, Fig. 1)

M. Książkiewicz informed us that the locality on the Skawa River is one of the main examples that he, S. Dżułyński, and Ph. H. Kuenen

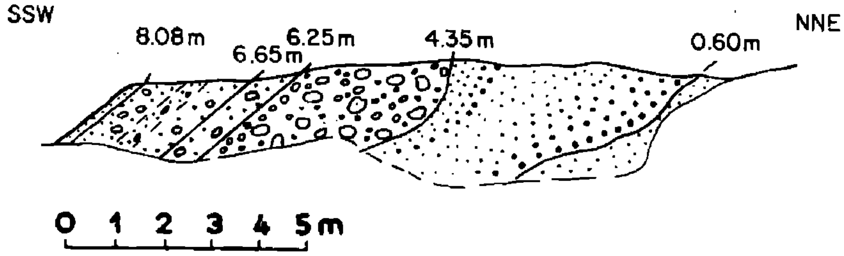

Fig. 7b. Cross section, south—southwest — north — northeast, at Mucharz. Structural dip is 40° south. Bedding surfaces at 0.60, 4.35, 6.25, 6.65, and 8.08 m above base of columnar section are labelled

Fig. 7b. Przekrój SSW—NNE odsłonięcia w Mucharzu. Upad warstw 40° ku S. Granice warstw na poziomach 0.60, 4.35, 6.25, 6.65 i 8.08

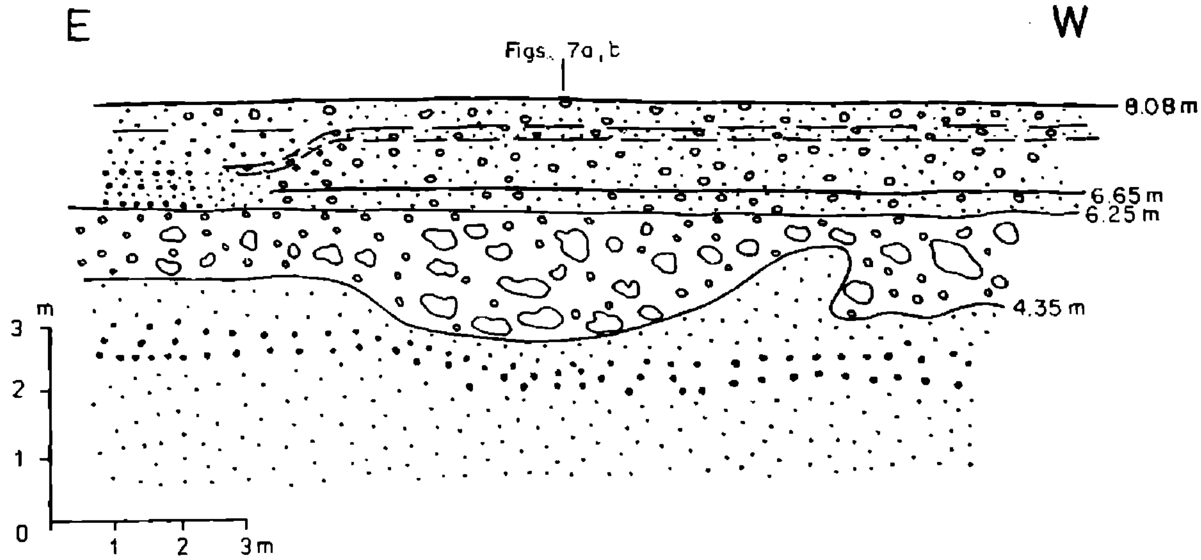

Fig. 7c. Cross section, east—west, view downdip, at Mucharz. Figs. 7a, b are located near middle. Surface at 4.35 m is base of fluxoturbidite channel, but much of the relief and irregularity is the result of loading

Fig. 7c. Przekrój E—W odsłonięcia w Mucharzu. Przekrój poprzedni (fig. 7b) i kolumna (fig. 7a) odpowiadają części centralnej. Powierzchnia 4.35 jest dnem kanału częściowo zmieniona w efekcie występowania pogrązów

studied during the development of the fluxoturbidite concept. Although we did not find complete fluxoturbidite (FT) beds here, we did see some important relationships within sequences of grain-flow (F) deposits. This section is in one of the coarsest facies of fluxoturbidites; many beds contain 50% to 70% gravel.

Normal turbidites are present within the main exposure and in nearby outcrops. In grain-flow deposits, elongate pebbles tend to be oriented parallel to the flow direction, and flat ones tend to be imbricated to dip upcurrent. This fabric indicates deposition from a clast dispersion, with no bed-load rolling (Walker, 1975, p. 146).

No shear surfaces of sliding (or slumping) were recognized, but the presence of sandstone boulders suggests erosion into subjacent turbidites and falling or sliding of blocks into the flow. One exposure indicated breaking and sliding of sandstone blocks into a mudflow. These features

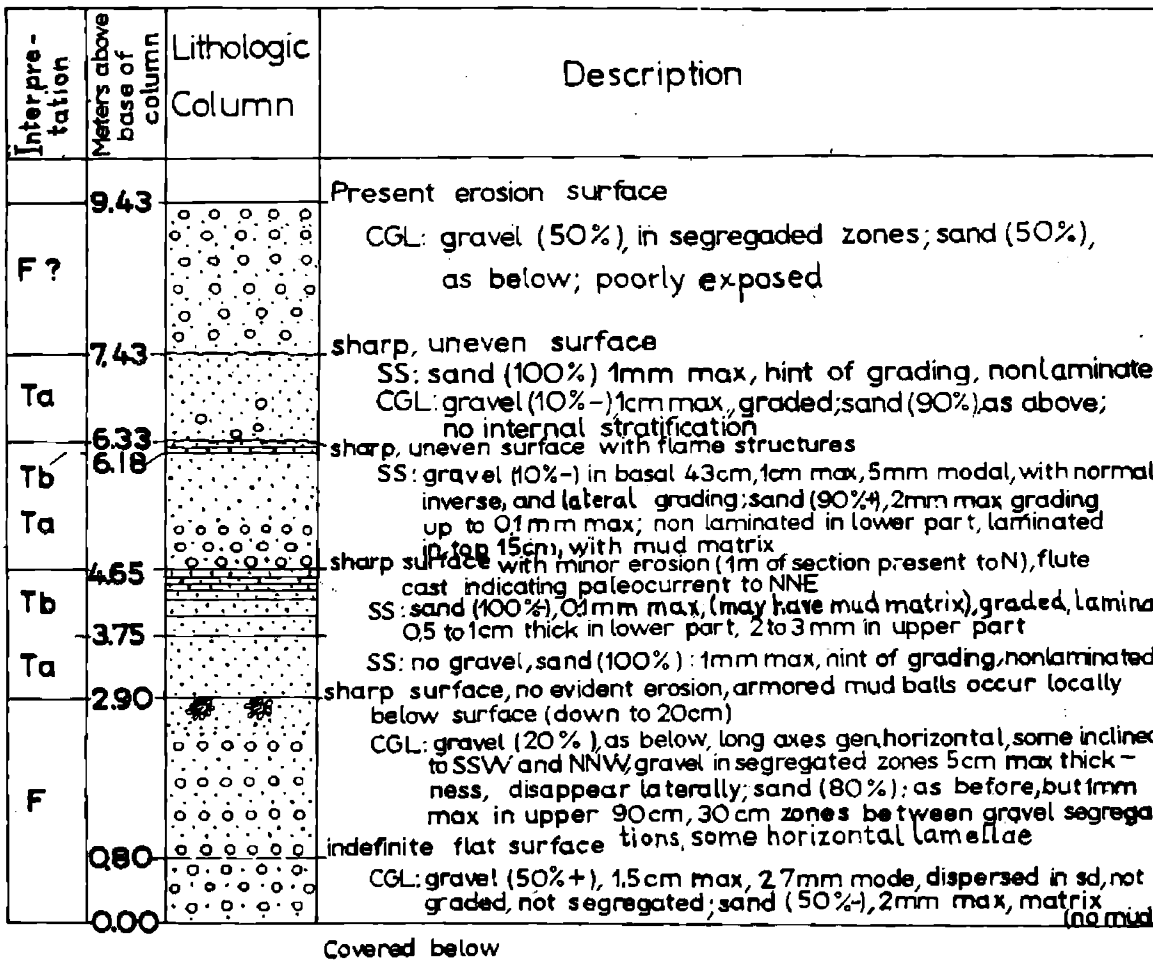

Fig. 8a. Columnar section at Sowa in Ciężkowice area (Loc. 3) of Ciężkowice Sandstone (Paleocene to Lower Eocene). From 0.00 to 2.90 m is the upper part a fluxoturbidite bed. The basal exposure from 0.00 to 0.80 m is a conglomerate with gravel dispersed through the sand matrix. The overlying interval from 0.80 to 2.90 m is a conglomerate with gravel segregations and some horizontal lamellae in the upper part that have diffuse boundaries. Three normal turbidite beds are present between 2.90 and 7.43 m. At the top of the sequence, from 7.43 to 9.43 m, is the lower part of a possible fluxoturbidite bed, but it is poorly exposed

Fig. 8a. Profil piaskowców ciężkowickich w skałce Sowa. Skamieniałe miasto koło Ciężkowic. Odcinek 0.00—2.90 m reprezentuje górną część ławicy fluksoturbidytu. Część dolną (od 0.00 do 0.80 m) stanowi zlepieniec z rozproszonymi dużymi ziarnami kwarcu w matrix piaszczystym. Interwał wyższy (0.80—2.90 m) to zlepieniec z poziomami żwirowymi, a w wyższej części horyzontalnie laminowany. W interwale 2.90—7.43 m występują trzy ławice normalnych turbidytów. Górną część profilu stanowi dolna część ławicy przypuszczalnie fluksoturbidytowej may have suggested the process intermediate between "slumping" and normal turbidity currents proposed by Dżułyński and others (1959) for the deposition of fluxoturbidites.

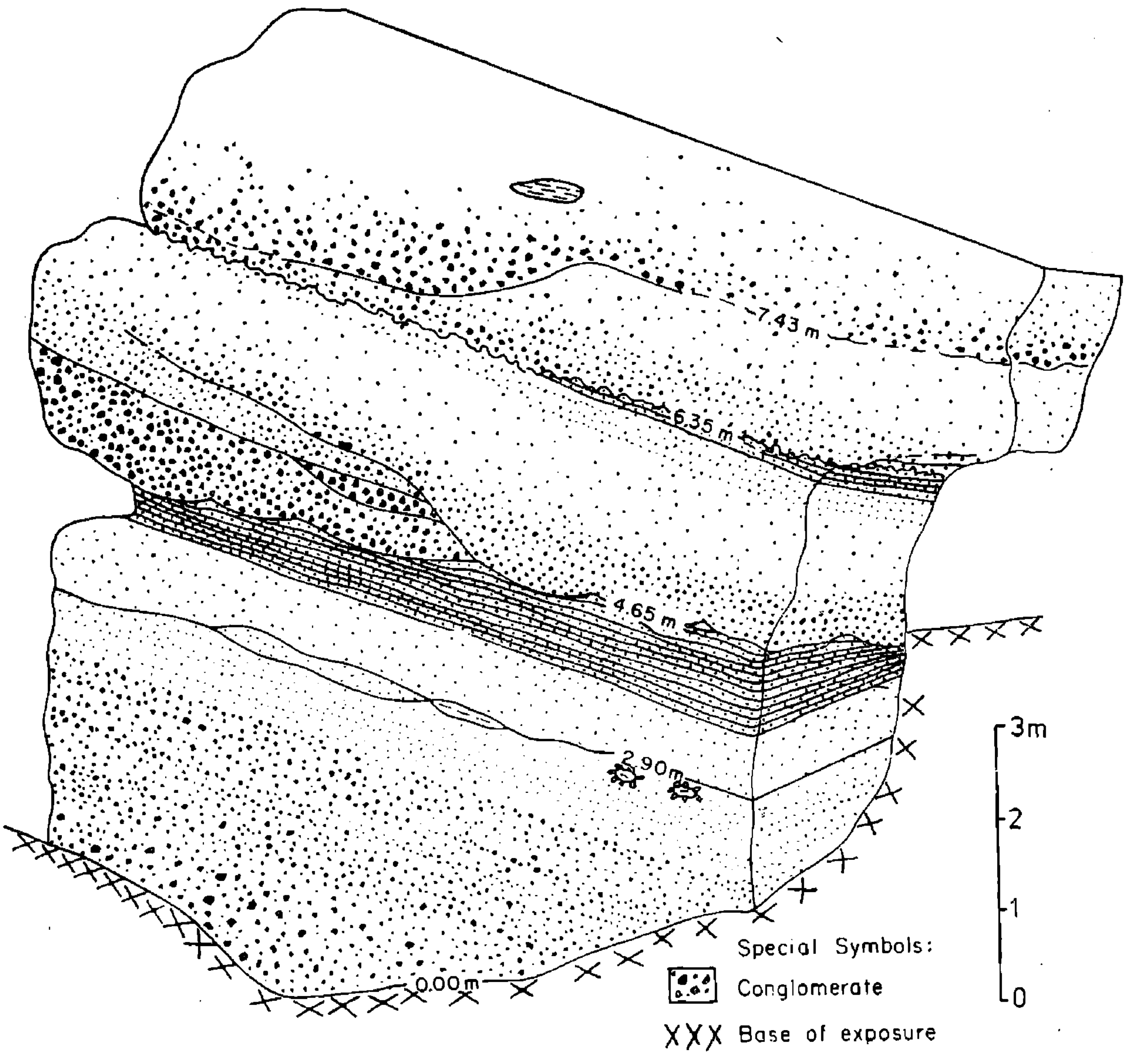

Fig. 8b. Block diagram, view southeast, at Sowa. Fig. 8a is located on right side. Several beds are truncated by erosion surfaces of moderate relief. (Modified from Koszarski, 1956, 1963)

Fig. 8b. Blok diagram skałki Sowa, widok ku SE. Zwraca uwagę ścinanie ławic przez powierzchnie erozyjne (wg Koszarski 1956, 1963, nieco zmienione)

On the columnar section (Fig. 7a) at 6.25 m above the base, a bedding surface separates a lower conglomerate from an upper one with a smaller modal size of gravel clasts. The surface is irregular and no erosion is evident (Pl. III, Fig. 1). Apparently, the upper bed was deposited from a lower velocity flow that either was incapable of eroding coarser material in the substratum, or was dumped so rapidly that there was insufficient time to erode the irregular surface.

Ciężkowice (Loc. 3; Fig. 8; Pl. III, Fig. 2; Pl. IV; Pl. VI, Fig. 2)

In the national park, Skamieniałe Miasto, are exposures of the Ciężkowice Sandstone at its type locality. This formation was recognized as one of the main examples of fluxoturbidites (Dżułyński and others, 1959).

At Sowa, in the middle of the park, is one of the best exposed sedimentary sequences (Fig. 8a, b; Pl. VI, Fig. 2). Some of the sedimentary structures were described and illustrated previously by Koszarski (1956, 1963). The base of the lowest grain-flow deposit is not exposed, but the lowest exposed part is massive conglomerate with dispersed pebbles (0.00 to 0.80 m). Next above (0.80 to 2.90 m) is a conglomerate with gravel and sand segregations, and thin horizontal lamellae (Fig. 8c) with diffuse boundaries that may also be products of liquefied flow, or may be products of lamellar flow shearing, or may be crude lamination developed during a brief tractional phase prior to deposition. No erosion

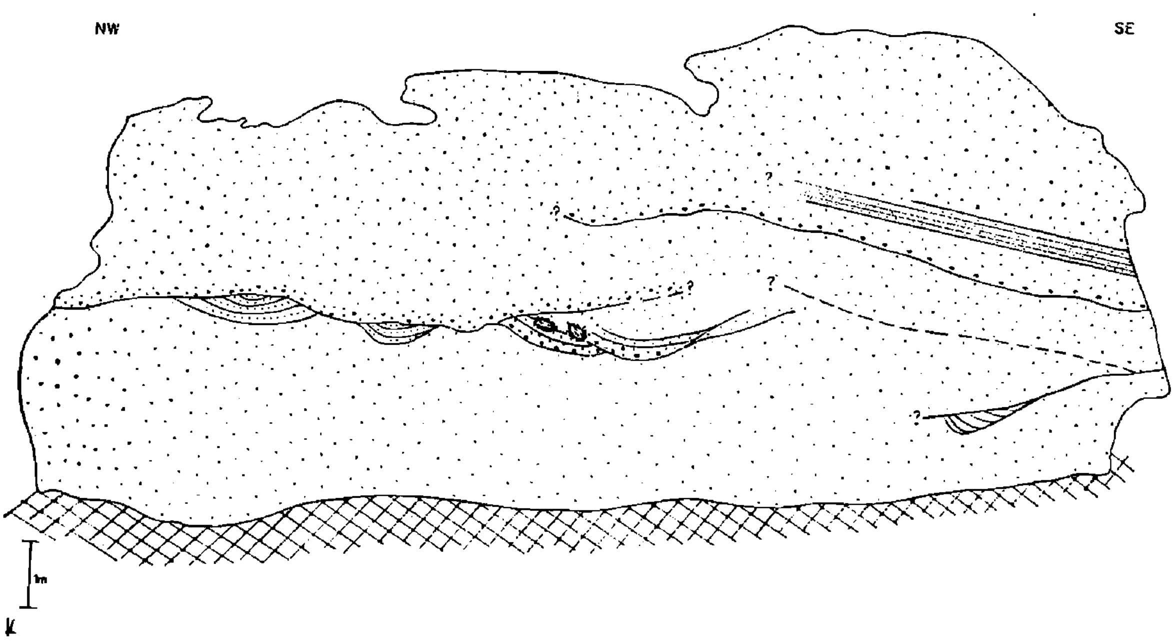

Fig. 8c. Cross section, northwest—southeast, of prominent exposure at Ratusz in Ciężkowice area. Structural dip is about 12° south. On left (northwest) are two thick fluxoturbidite beds composed mainly of massive sandstone with dispersed pebbles. At top of lower bed are erosional channels filled with trough laminae, indicating associated traction currents. Largest trough is 4 m wide and 1 m deep. On right, relationships in lower part are questionable because of weathering and vegetation cover, but in upper part above a basal conglomerate is a sandstone with lamination

Fig. 8c. Przekrój NW—SE skałki Ratusz. Skamieniałe Miasto koło Ciężkowic. Upad około 12° ku S. Po lewej dwie grube ławice fluksoturbidytów reprezentowanych głównie przez masywne piaskowce z rozproszonymi żwirami. Na granicy ławic obecne są kanały erozyjne wypełnione piaskowcami skośnie warstwowanymi, co wskazuje na obecność prądów trakcyjnych. Największy kanał posiada szerokość 4 m, a głębokość 1 m is evident at the top of the grain-flow deposit in the line of section (2.90 m, Fig. 8a), but erosional remnants are seen to the northeast (Fig. 8b).

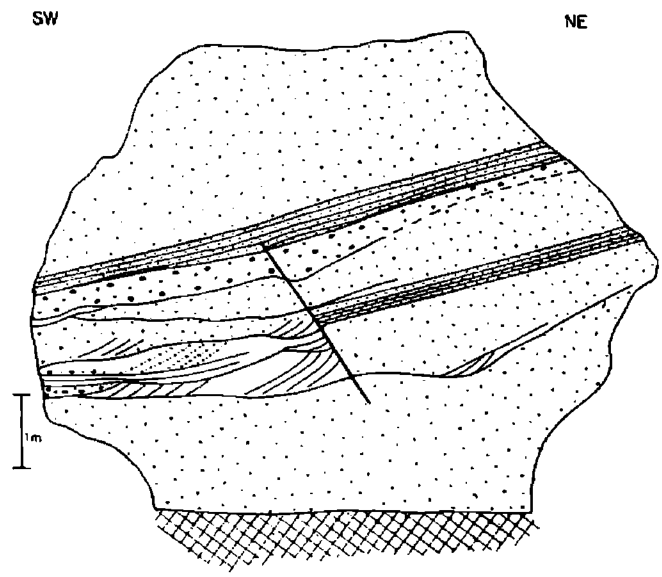

Fig. 8d. Cross section, southwest—northeast, on southeast side of exposure at Ratusz. Trough and horizontal lamination are present. Foresets in troughs indicate a paleocurrent to SW. Small fault complicates relationships

Fig. 8d. Przekrój SW—NE (ścianka SE) skałki Ratusz. Widoczne laminowanie horyzontalne i skośne. To ostatnie wskazuje na kierunek paleoprądu ku SW. Zwraca uwagę częściowe zróżnicowanie struktur po obu stronach niewielkiej dyslokacji

At Ratusz, in the southwestern part of the national park, is a complicated exposure of probable grain flow and other deposits (Fig. 8c, 8d; Pl. VI, Fig. 2). Channels with trough laminae are seen at the tops of some grain-flow beds (Pl. IV) and probably were produced by traction currents. A transverse view of the troughs (Fig. 8d) shows foresets indicating a paleocurrent to the southwest. To explain the troughs, Książkiewicz (1975, p. 320, 349) postulated a filling of the basin up to near wave base so that the structures could be formed in shallow water. Although unusual, large channels with trough laminae have been reported in other deep-marine basins, and we see no need for shallowing.

Above the troughs, exposed in cliffs, are probable horizontal laminae that may have been produced by traction currents developed in overbank areas, or during the latest stages of channel filling, or after the channels were buried. In a more accessible exposure toward the southeast, similar features appear to be horizontal lamellae or segregations of fine sand within conglomeratic sandstones.

Farther southeast are exposures of red pelagic mudstones overlying the Ciężkowice sandstones. These pelagites support the interpretation of deep-marine deposition.

Odrzykoń (Loc. 4; Fig. 9)

On the north side of the castle, Odrzykoń, is another well-known exposure of Ciężkowice with fluxoturbidites. Grain-flow deposits (Fig. 9, 0.00 to 2.20 m) pass upward into turbidites (2.20 to 4.50 m) with multiple grading. A conglomerate wedge, with gravel up to 1.5 cm in diameter,

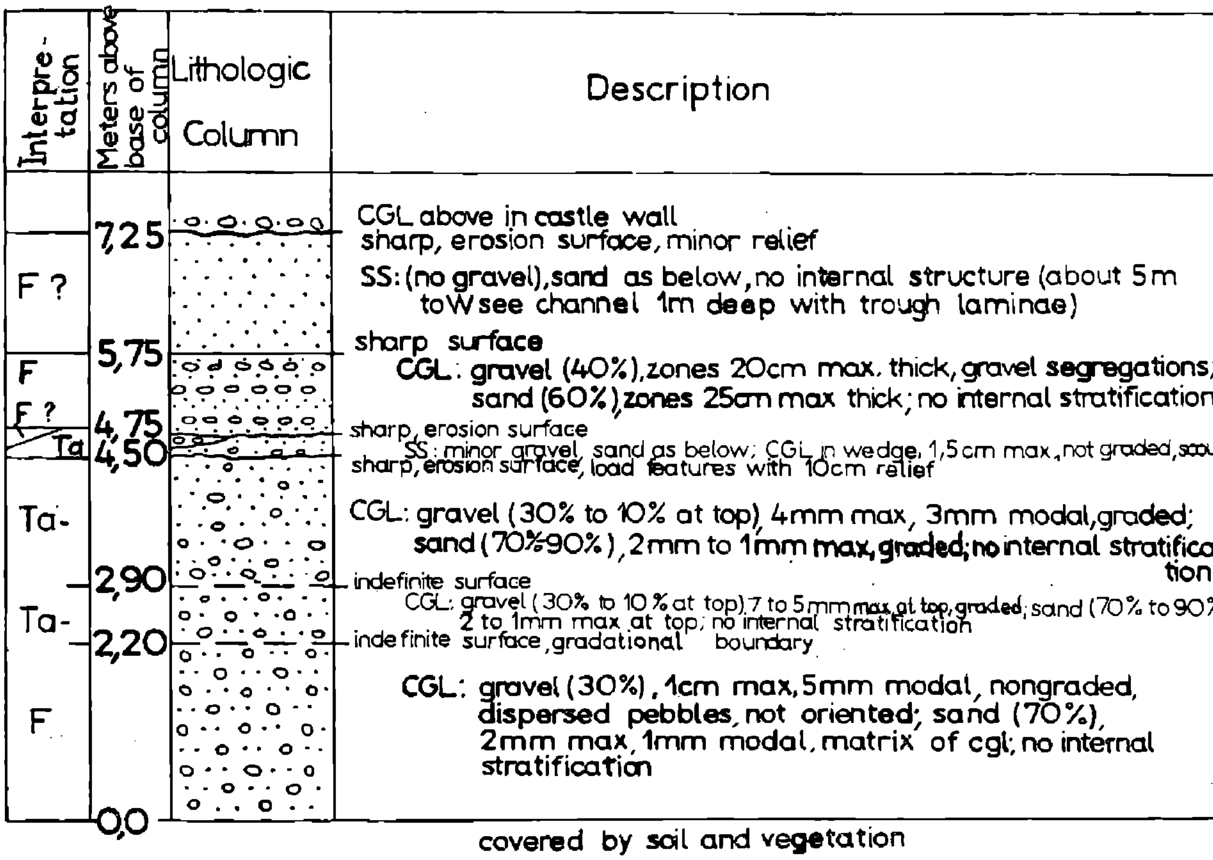

Fig. 9. Columnar section at Odrzykoń (Loc. 4) of Ciężkowice Sandstone (Paleocene to Lower Eocene). Lower fluxoturbidite bed (0.00 to 4.50 m) contains two intervals of Ta-. Wedge and trough laminae are seen in upper beds

Fig. 9. Profil piaskowców ciężkowickich w odsłonięciu pod zamkiem w Odrzykoniu. Dolna ławica fluksoturbidytowa (0.00—4.50 m) zawiera dwa interwały Ta. Występują kanały erozyjne i wyklinowywanie się ławic

may be a grain-flow deposit (F?) scoured into a normal turbidite (Ta, 4.50 to 4.75 m). Gravel segregations up to 20 cm thick are present in a higher grain-flow bed (4.75 to 5.75 m). The sandstone above contains channels 1 m deep with trough laminae indicating deposition from associated traction currents.

To the south east in the national park, Prządki, are additional exposures of massive sandstones and conglomerates several meters thick which show no grading or internal stratification. These rocks probably are grain-flow deposits, but exposure quality is only fair and no turbidites were recognized in that area.

Koniaków (Loc. 5; Fig. 10; Pl. V)

In the quarry at this locality is one of the best exposures of a fluxoturbidite sandstone bed, with grain-flow deposits gradationally overlain by a complete turbidite sequence (Fig. 10a). At the base of the main bed (0.00 to 0.20 m) is a sandstone with hints of grain segregations; the transitional boundary above is not a bedding surface, but is uneven

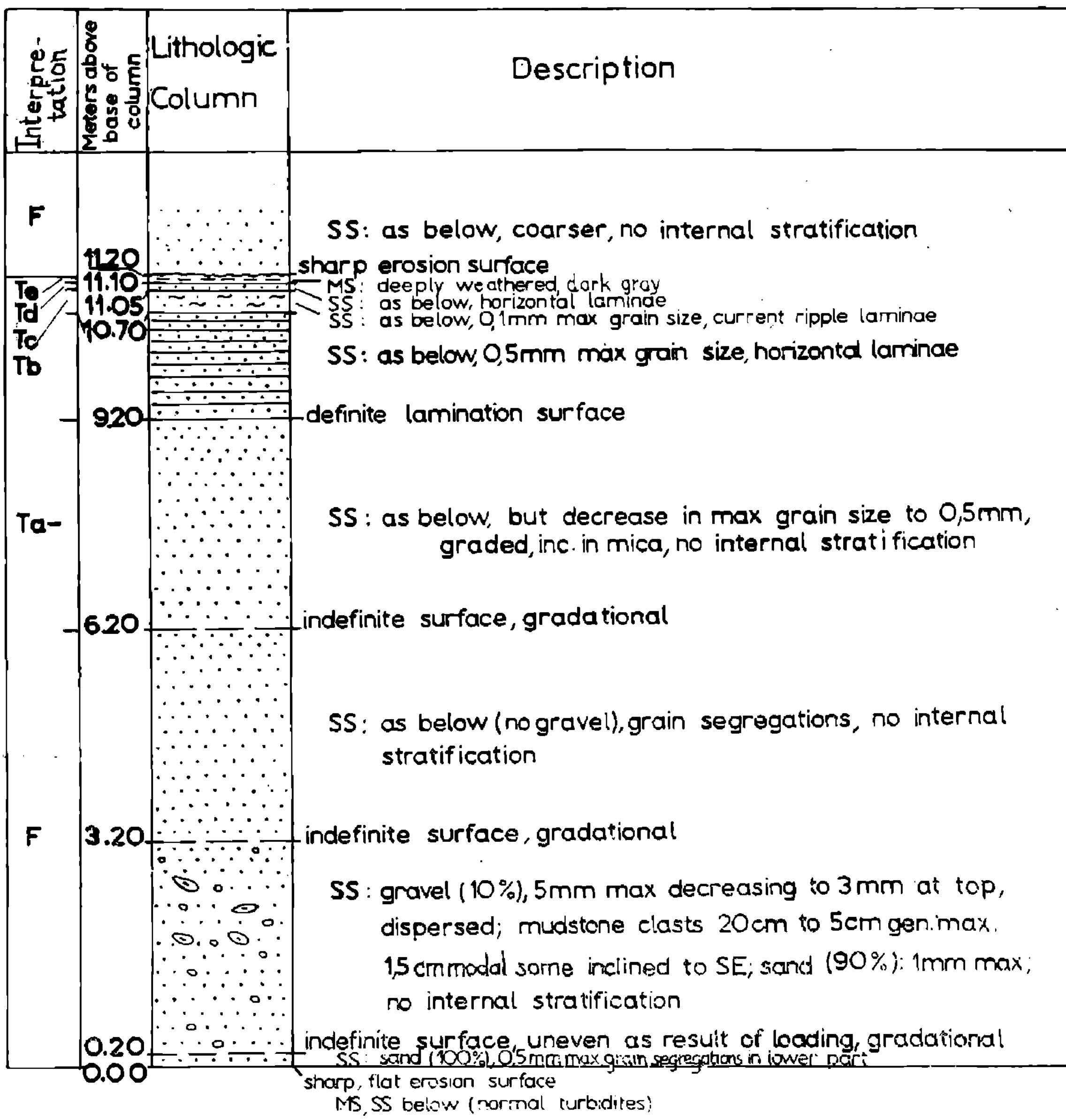

Fig. 10a. Columnar section at Koniaków (Loc. 5) of Krosno Beds (Lower Oligocene). Best type example of a fluxoturbidite bed that is dominantly sandstone (0.00 to 11.20 m). In upper part (6.20 to 11.20 m) is a complete turbidite sequence of Bouma (1962) from Ta- (no erosional base) to Te

Fig. 10a. Profil warstw krośnieńskich z kamieniołomu w Koniakowie (lok. 5). Najlepszy przykład ławicy fluksoturbidytu składającego się głównie z piasku (0.00—11.20 m). W części wyższej (6.20—11.20 m) występuje ławica turbidytowa z wszystkimi interwałami Boumy (1962) od Ta do Te as a result of loading. Pebbles are widely dispersed in the next sandstone unit (0.20 to 3.20 m) and mudstone clasts are not confined to zones; these facts indicate a lack of marked density contrasts within this part of the grain flow. The next sandstone (3.20 to 6.20 m), being nongraded and without internal stratification, is interpreted as the upper part of the grain-flow deposit. The transitional boundary at the top (no sharp bedding surface) indicates a gradual change into the graded sandstone at the base of the turbidite sequence (Ta- to Te, from 6.20 to 11.20 m).

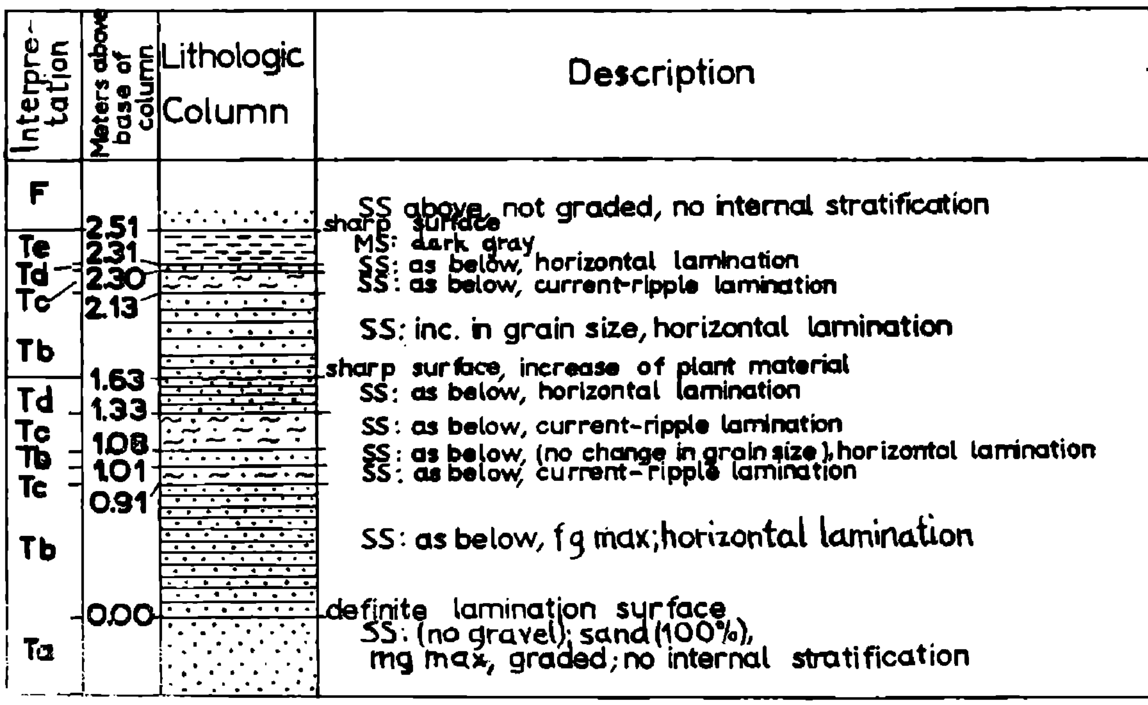

Fig. 10b. Columnar section at Koniaków, across fault to south of Fig. 10a. In upper part of fluxoturbidite bed (0.00 to 1.63 m) is repetition of intervals Tb, Tc, Tb, Tc, Td. Above is a normal turbidite bed (1.63 to 2.51 m), but the Ta interval is absent

Fig. 10b. Profil warstw krośnieńskich z kamieniołomu w Koniakowie, na południe od dyslokacji. W górnej części ławicy fluksoturbidytowej (0.00—1.63 m) występuje powtarzanie się interwałów Tb, Tc, Tb, Tc, Td. Powyżej występuje normalna ławica turbidytowa, ale brakuje interwału Ta

Across a fault to the south is another excellent exposure of the upper part of the same bed (Fig. 10b; Pl. V, Fig. 1). The Bouma sequence is more complex, with repetitions of the Tb to Td subdivisions. In a normal turbidite, the successive subdivisions show a decrease in grain size. The same general pattern is seen in this upper part of a fluxoturbidite bed. However, the lowest Tc (0.91 to 1.01 m) is overlain by a Tb (1.01 to 1.08 m), recognized as an interval of horizontal lamination with no decrease in grain size, that in turn is overlain by another Tc (1.08 to 1.33 m), and a Td (1.33 to 1.63 m) at the top of the bed.

Polana (Loc. 6; Fig. 11)

In this active quarry into Ostre Ridge (near Czarna) an accessible, well-exposed sequence was seen near the top (Fig. 11a). A massive flow deposit consisting of sandstone with a calcareous matrix (0.00 to 1.40 m) is gradationally overlain by a turbidite sequence (1.40 to 1.71 m), but the Tb subdivision is composed of detrital lignite, and the Tc subdivision is missing. A massive flow deposit above is similar (1.71 to 6.17 m), but it contains dispersed coarse grains in the lower part. The Ta- to Td subdivisions above are sandstones, and the Te subdivision is truncated. The massive deposits may represent transitions between grain flows and debris flows.

About 6 m below the base of the columnar section (see cross section, Fig. 11b) is a massive sandstone with deformed layers at the top and apparently rafted blocks of mudstone and sandstone. These characteristics suggest a debris-flow deposit even though the matrix consists of minor amounts of mud. This massive flow deposit is not transitional with an overlying turbidity-current deposit. Instead, it is overlain by another massive flow bed with a sharp contact between.

OTHER LOCALITIES

In addition to the six main localities discussed previously, we have studied several others. Selected features from some of these other localities will be described and illustrated in this section to show important varieties of typical fluxoturbidites and provide additional evidence for interpretations of the more significant sedimentary structures and textures.

At Borzęta (Loc. 7 on Fig. 5) the Istebna beds are seen in an abandoned quarry, but exposure quality is only fair, and some bedding surfaces are barely recognized. Both composite grain flow-turbidite beds and normal turbidite beds are present (Fig. 12). Armored mudballs appear to be concentrated in a zone within the upper grain-flow deposit, rather than at the top as seen in many cases (Unrug, 1963, p. 62). Possibly they do lie near the top of a bedding surface obscured by weathering; alternatively, they may be concentrated at a surface of density contrast within the flow, or at an indefinite surface bounding the grain-flow (F) and turbidite (Ta-?) parts of the composite bed.

At Muchówka (Loc. 8), the Lower Istebna Beds contain normal

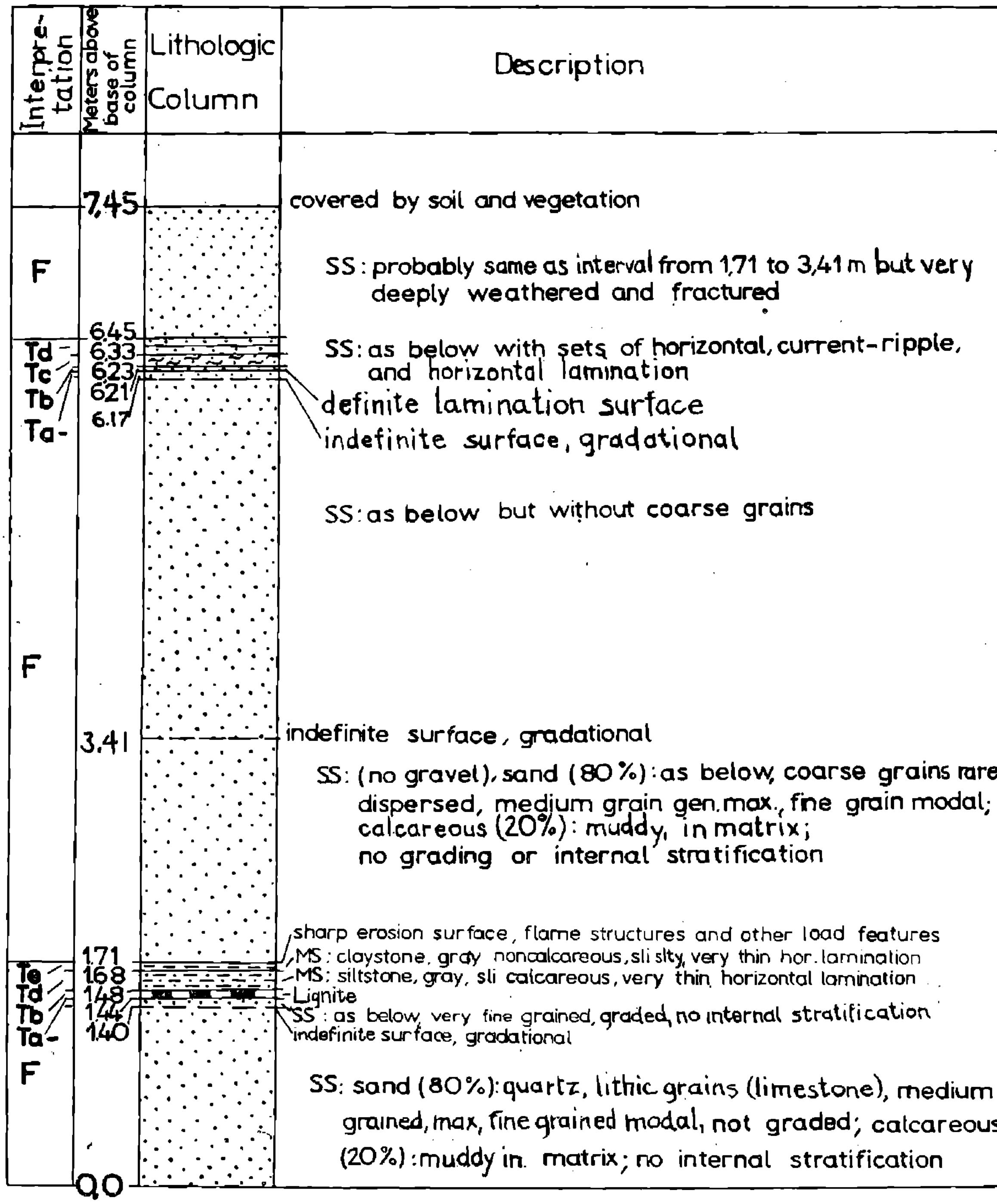

Fig. 11a. Columnar section at Polana (Loc. 6) of Krosno Beds (Lower Oligocene). In lower fluxoturbidite bed (0.00 to 1.71 m), the Ta- interval is thin (1.40 to 1.44 m), and the Tb interval appears to be represented by lignite (1.44 to 1.48 m), with the Tc missing. In the overlying fluxoturbidite bed (1.71 to 6.45 m), the Ta- interval is also thin (6.17 to 6.21 m)

Fig. 11a. Profil warstw krośnieńskich z kamieniołomu w Polanie (lok. 6). W dolnej ławicy fluksoturbidytowej (0.00—1.71 m) interwał Ta jest wyjątkowo cienki (0.04 m), a interwał Tb reprezentują laminowane lignity. Brak interwału Tc. Również w wyższej ławicy fluksoturbidytowej interwał Ta jest wyjątkowo cienki

turbidites and grain-flow deposits with a gravel content up to 90%. Where gravel is dominant, sand segregations tend to develop (Fig. 13), and vice versa. Some finer grain segregations are present in the sand-

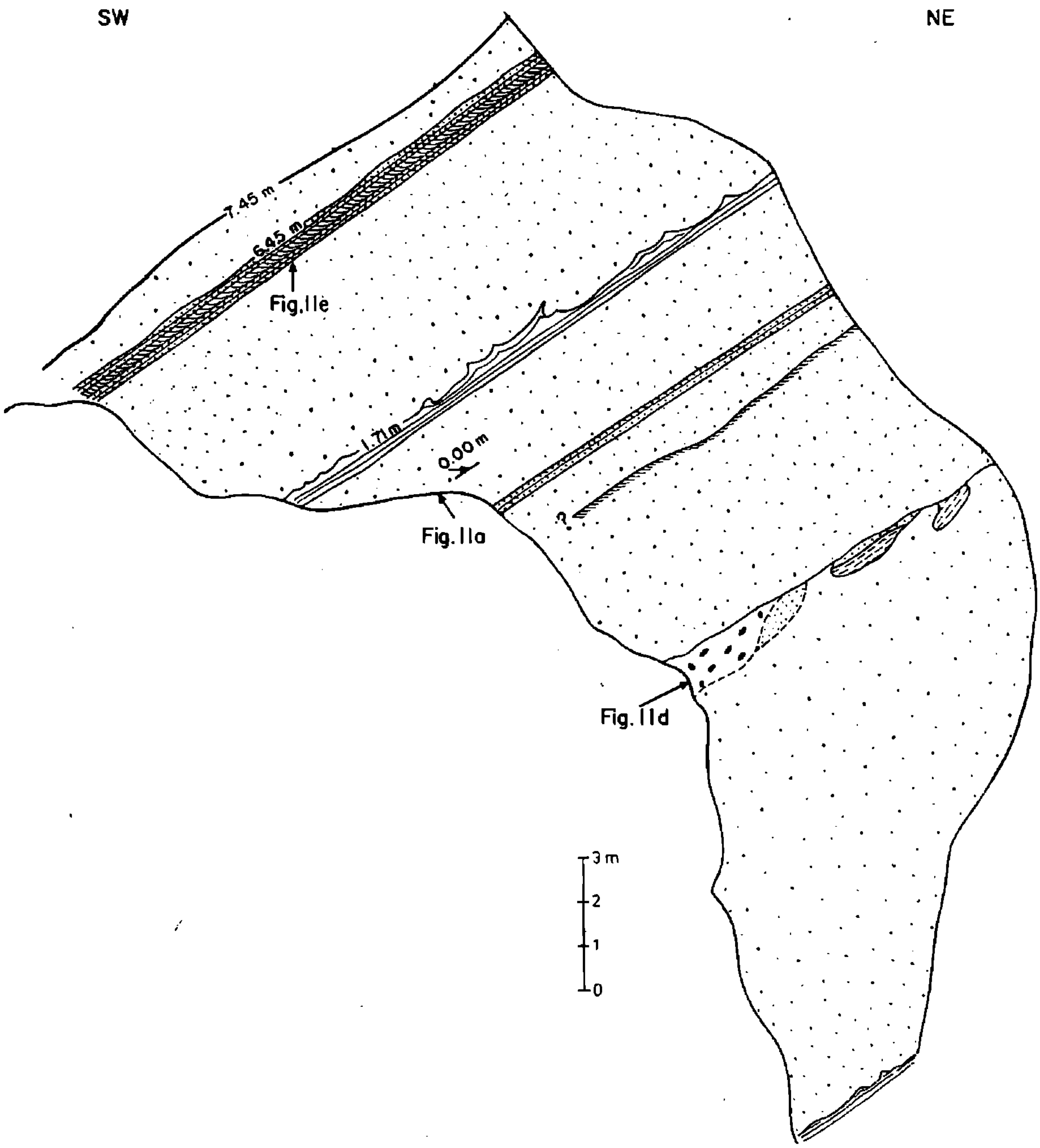

Fig. 11b. Cross section, southwest—northeast, at Polana. Dip is 40° southwest. At base of section is a 10.5 m bed of muddy sandstone, probably a debris-flow deposit, with large conglomerate, sandstone, and mudstone blocks rafted at top of the bed. Overlying beds are fluxoturbidites. At the top of the cross section is the sequence described in the columnar section (Fig. 11a, 0.00 to 7.45 m). At base of fluxoturbidite (1.71 m), the bedding surface is highly deformed by loading

Fig. 11b. Szkic południowo-wschodniej ściany kamieniołomu w Polanie. Upad warstw 40° ku SW. W dolnej części ściany występuje 10.5 m ławica piaskowca mułowcowego, przypuszczalnie osad spływu podmorskiego z wielkimi blokami zlepieńców, piaskowców i mułowców w stropie ławicy. Wyżej leżą ławice fluksoturbidytów. Wyższa część profilu przedstawiona jest szczegółowo na fig. 11a

stones. Horizontal lamellae, similar to those at Ciężkowice, are seen in the lower part of some beds.

At Tylmanowa (Loc. 9), the Magura Sandstone (Upper Eocene)

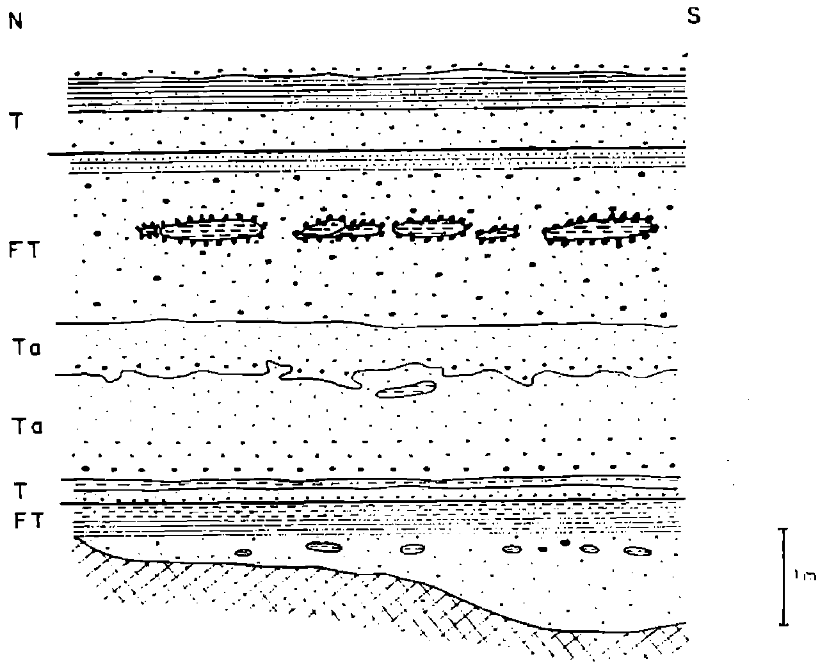

Fig. 12. Cross section, north-south, at Borzęta (Loc. 7) of Lower Istebna Beds (Upper Cretaceous). Composite beds (FT) and normal turbidite (T, Ta) beds are recognized. Near the middle, the base of a turbidite (Ta) bed has been deformed by loading. Armored mudballs are concentrated in a zone within the upper composite bed (FT), and have been flattened by compaction

Fig. 12. Szkic południowej ściany starego kamieniołomu warstw istebniańskich w Borzętach (lok. 7). Widoczne są ławice złożone (FT) i ławice normalnych turbidytów (T, Ta). Powierzchnia spągowa jednej z ławic zaburzona jest przez pogrązy. Uzbrojone toczeńce, spłaszczone przypuszczalnie w wyniku kompakcji, tworzą wyraźną, horyzontalną strefę

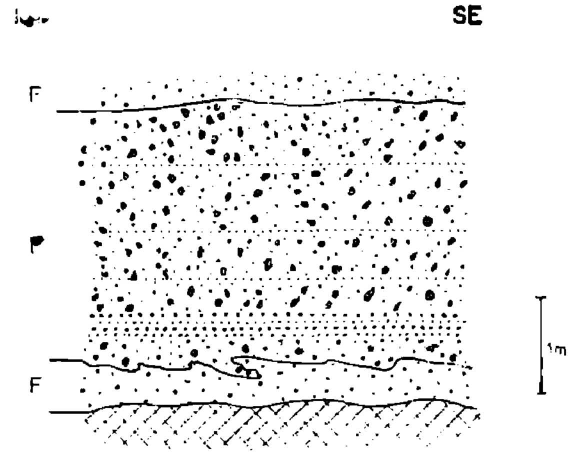

Fig. 13. Cross section, northwest-southeast, at Muchówka (Loc. 8) of Lower Istebna Beds (Upper Cretaceous). In the middle fluxoturbidite bed (F), sand segregations are present in gravel-rich intervals. Horizontal lamellae are seen about 1 m above the base of the exposure

Fig. 13. Szkic NE ściany skałki piaskowca z warstw istebniańskich dolnych w Muchówce. Wśród materiału grubszego widoczne są pojedyncze laminy piaszczyste

consists mainly of normal turbidites. In a 2 m grain-flow deposit near the top of the exposure, some scattered lenses of gravel (4 mm max) are present in the sandstone, but the boundaries of the lenses are diffuse.

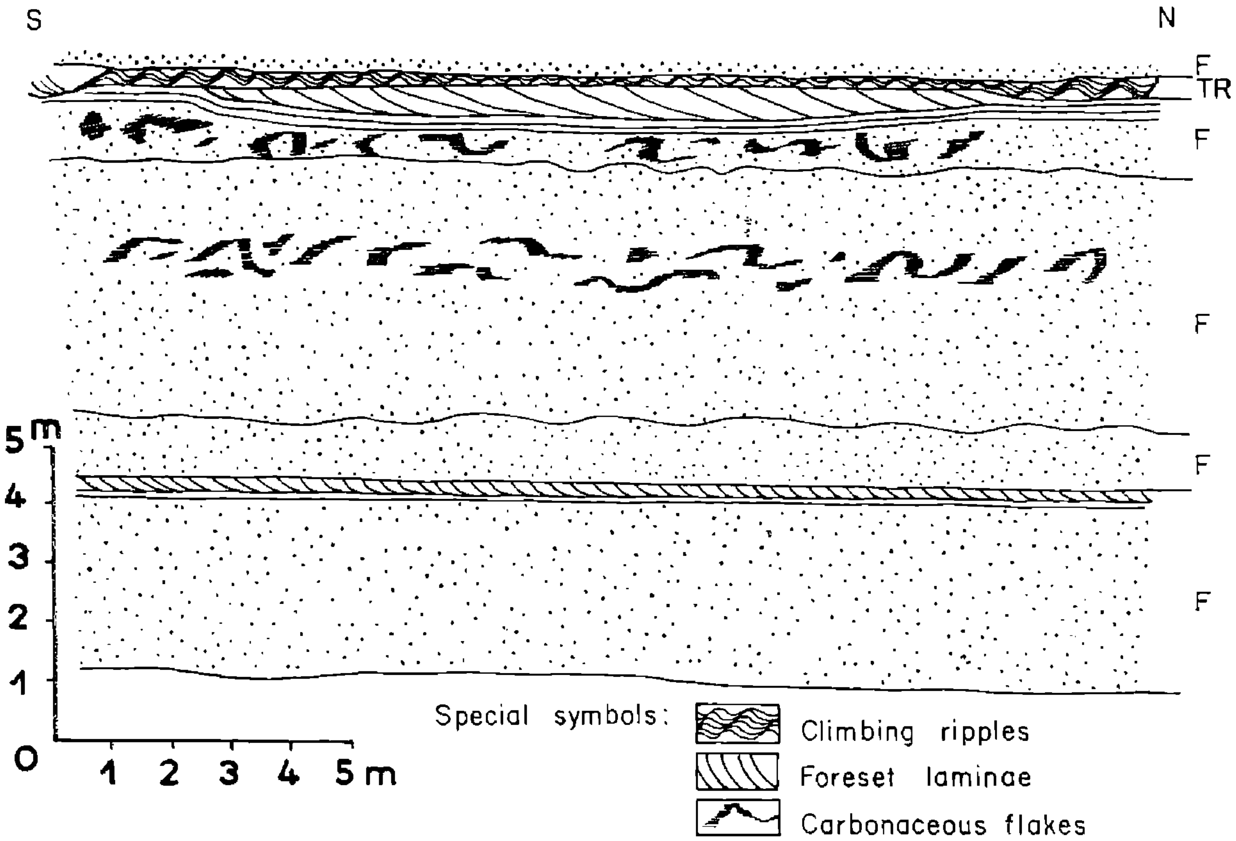

Fig. 14. Cross section, south-north, at Śleszowice (Loc. 11) of Krosno Sandstone (Lower Oligocene). Composite (FT), grainflow (F), and traction-current (TR) beds are recognized. Carbonaceous flakes appear to be distributed along flow paths in grain-flow beds. Traction deposits contain foreset laminae dipping 28°, and overlying climbing ripples, both indicating paleocurrents toward the northwest
Fig. 14. Szkic zachodniej ściany kamieniołomu piaskowców z warstw krośnieńskich w Śleszowicach. Występują tu osady zarówno spływów piaszczystych, prądów zawiesinowych, jak i prądów trakcyjnych. Zwęglony detrytus roślinny zgrupowany w horyzontalne strefy wykazuje ślady zaburzeń synsedymentacyjnych. Upad lamin w osadach trakcyjnych dochodzi do 28°. Kierunek prądu z południowego wschodu

At Komańcza (Loc. 10) there croppes out a bed of the Cergowa Sandstone (Lower Oligocene) which contains sets of climbing ripples (Pl. VI, Fig. 1) associated with grain-flow deposits and turbidites. In the latter are several beds with only Ta and Tc subdivisions (Ślączka and Unrug, 1966).

At Śleszowice (Loc. 11), the Krosno Sandstone contains thick grain-flow deposits (Fig. 14) with carbonaceous flakes that may lie along flow paths. Near the top of the section is a set 40 cm thick of steeply inclined (28°), foreset laminae about 2 m long. Above is a set of ripple laminae, some of which are climbing. These traction-current deposits indicate a paleocurrent toward the northwest. This direction is generally parallel to the regional paleocurrents of the fluxoturbidites, and suggests a genetic association.

FLUXOTURBIDITE MODEL

Based on observations in the type examples, we have constructed a model for fluxoturbidites analogous to the model for normal turbidites presented by Bouma (1962). Such columnar models are useful in identification of deposits in isolated surface exposures or subsurface cores. However, analytical value is enhanced if the vertical sequence of sedimentary structures in a given bed is considered along with other environmental indicators in the same bed, and with the entire depositional framework including adjacent beds.

Fig. 15 is a generalized, simplified, and idealized model of a fluxoturbidite (FT) bed, consisting of conglomerate and sandstone with a thin mudstone at the top. This model is also a preliminary one, and future analyses should improve it. Our main purpose here is to present significant sedimentary features in a realistic sequence.

This product is interpreted as the result of a composite sediment-gravity flow. A sediment-gravity flow (Middleton and Hampton, 1973, p. 1—2) is a subaqueous flow in which gravitative forces move detrital sediment, and the motion of the sediment moves the interstitial fluid. Of the types of sediment-gravity flows (see revision by Middleton and Southard, 1977, p. 8.4), we recognize a combination in this model of turbidity current, grain flow, and possibly liquefied sediment flow. Debris flow (of their definition) is omitted from this model because most examples consist of clean sandstones and conglomerates with a scarcity of mud, such that no significant matrix strength is indicated.

Consideration of the grain-flow mechanism is enhanced by the combination with an overlying turbidity current. A minimum slope angle of 30° is needed to maintain a grain flow operating alone, and the scarcity of such steep slopes would practically preclude the occurrence of widespread, thick beds being deposited in this manner. However, an overlying turbulent turbidity current can exert the shear needed to maintain the dispersive pressure in the underlying grain flow, and a steep slope is no longer necessary (Middleton and Southard, 1977, p. 8.14—15).

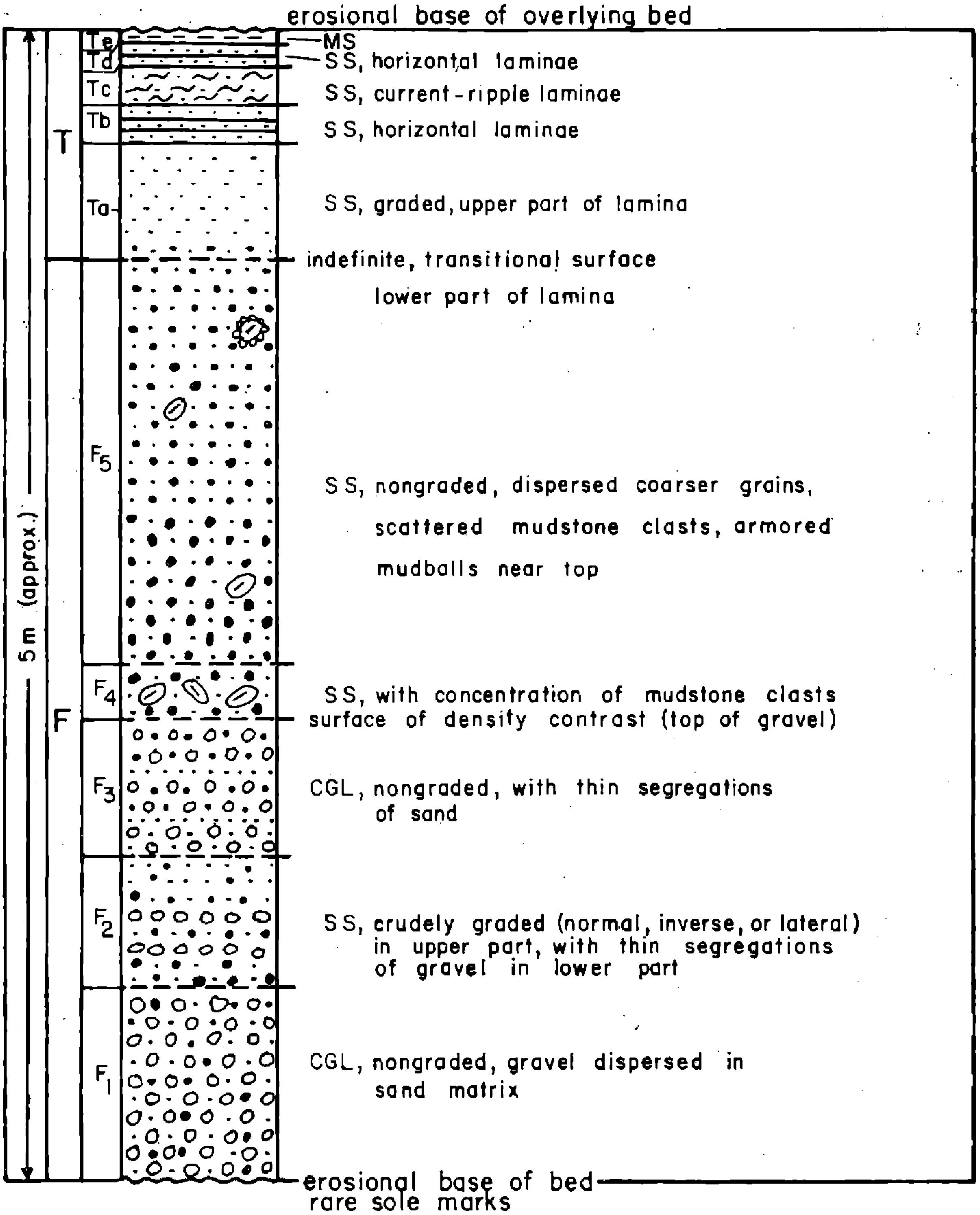

Fig. 15. Fluxoturbidite model (see text)
Fig. 15. Model fluksoturbidytu, objaśnienia w tekście

Liquefaction may be an important mechanism during initiation of a composite sediment-gravity flow and/or during the depositional phase. A liquefied sediment flow may be developed on a slope as low as 3°, but continued transportation downslope is likely to produce a change from laminar to turbulent conditions and a transformation into a turbidity current (Middleton and Southard, 1977, p. 8.12—13). Perhaps an overlying turbidity current may tend to preserve a liquefied sediment flow in the lower part of a composite flow, and permit a substantial distance of transport.

LOWER PART (F)

The lower part (F) of the model is interpreted as the product of the grain-flow, and/or possibly the liquefied sediment flow, part of the composite sediment-gravity flow. Internal stratification is absent or poorly expressed, so this part cannot be subdivided into a sequence of laminasets as is done in the upper part. However, internal zones of differing sedimentary features are recognized as products of different phases of sediment-gravity flow. Apparently the lower part of the composite flow moves generally as a massive body, but inhomogeneities of sand and gravel concentrations, irregularities of the channel boundary, variable conditions within the flow, or differences in the depositional processes, tend to produce the internal zones with different features.

For discussion purposes, the zones in the lower part of this model are numbered in vertical order from base to top as they may be recognized in the field. Not all zones are found in each case, and the order may vary. When traced laterally, some zones are seen to disappear. At this beginning stage of our investigation, we use a numbered sequence only as a means to describe the model. If later work shows that some or all zones are indicative of particular transport or depositional mechanisms, they may be redesignated with appropriate letter subscripts. Differences in vertical order may also be significant, even though the order does not represent a characteristic sequence of depositional layers as does the Bouma turbidite model.

At the base is an erosion surface. Generally the erosional relief is less than a few centimeters, yet it may range to more than one meter. Differential loading can accentuate the total relief of the base. Sole marks are rare; they may be load features or very rare tool marks. Flutes have not been observed; their absence lends support to the interpretation that fluxoturbidites are produced by composite sediment-gravity flows with massive lower parts, in contrast to normal turbidites produced by individual flows at the bases of which turbulent vortices form flute scours.

The lowest zone (F_1) in the fluxoturbidite model consists mostly of gravel with a sand matrix. The pebbles generally are evenly dispersed, and no grading or grain segregations are evident. Of the mechanisms suggested by Middleton and Hampton (1973, p. 2; see also

Middleton and Southard, 1977, p. 8.4), grain flow appears to be the most likely. Grain interaction keeps the particles in suspension. Deposits in this zone appear to be products of grain flows with such high concentrations of sediment that no differential settling, grading, or liquefaction occurs.

The next zone (F_2) consists mostly of sand that contains thin segregations of gravel in the lower part, and is crudely graded in the upper part. Both the lower and upper boundaries of this and subsequent zones (F_3 to F_5) are indefinite transitional surfaces, indicating that they lie within a composite bed.

This occurrence of a zone of mostly sand (F_2) between zones of mostly gravel (F_1 and F_3) may be a result of inhomogeneities with the flow producing a crude stratification. The thin sheets of gravel at spacings of a few centimeters within the sand zone may also be crude stratification on a smaller scale, but the sheets die out laterally and do not appear to be depositional layers. They may be a form of grain segregation produced during hindered settling by interaction of concentrated grains (Middleton and Southard, 1977, p. 4.17—20). However, the mechanism of producing the multiple gravel segregations at spaced intervals is not understood.

Crude grading in the upper part of the sand zone may be normal, inverse, or lateral, and may blend laterally into nongraded deposits. Normal grading may be explained by hindered settling of variably concentrated grains. Inverse grading may occur if the matrix sand is medium grained or coarser (Sanders, 1965, p. 208). Lateral grading may be attributed to variable competency away from the head of the flow.

The next zone (F_3) is composed of gravel and sand with thin segregations of sand. Gravel (usually consisting of pebbles) constitutes over one-half of the volume, and sand fills the interstices. At spacings of up to several centimeters are sheets of finer sand only a few millimeters thick. These sheets have diffuse lower and upper boundaries, and they blend laterally into massive flow deposits. They contrast markedly with the laminae in the upper part (T) of the model that have distinct boundaries and are laterally extensive. Thus we do not consider such grain segregations to be normal laminae.

Many previous workers have described "faint lamination" in fluxoturbidites or grain-flow deposits (Stauffer, 1967, p. 492). Such features may be what we call grain segregations. Alternatively, they may be what we describe as horizontal lamellae at Ciężkowice and Muchówka in zones approximately equivalent to this position (F_2 or F_3). The lamellae are so rare that they were excluded from the model, but additional research is needed to evaluate their significance.

Grain flow may also have been the main mechanism of transport of the material in this zone, but liquefied-sediment flow may have become more important during deposition. Fluids rising through the spaces between larger settling grains may have transported finer grains upward, but again the mechanism for producing the multiple sheets of sand at spaced intervals is not understood. Because no mud laminae were present to confine the fluids, no dish structures or other water-escape features generally characteristic of liquefied-sediment flows were produced.

The next zone (F_4) is composed of sand similar to the one above (F_5), but this zone contains a concentration of mudstone clasts. Such clasts appear to have been eroded by the sediment-gravity flow from slightly older deposits which have undergone enough lithification to have become indurated. As observed by Stauffer (1967, p. 501), mudstone clasts may occur at any level within a grain flow. However, they tend to sink within the flow and be concentrated in a zone immediately above a surface of density contrast (Mutti and Ricci Lucchi, 1975, and personal communication). In the model, we have show the mudstone-clast zone above the surface marking the top of higher density gravel (derived generally from igneous and metamorphic rocks). In some examples, the zone overlies a more subtle density contrast between different sizes and/or compositions of sand grains.

Long axes of the mudstone clasts in some cases are oriented parallel to the direction of flow. Where imbricated, the clasts tend to dip up-current. However, various orientation may occur within the same zone, so this criterion should be used with caution in determining the paleo-currents of fluxoturbidites.

The highest zone (F_5) in the lower part of the fluxoturbidite model is shown as one of dispersed coarser sand in a matrix of finer sand. Some of the coarser grains may be in contact, and may aggregate into small lenses, but in general they are "floating". The material appears to have been transported as a concentrated mixture of sand and water in a grain flow. Mudstone clasts may be scattered through the zone.

While indurated mudstone clasts tend to sink within grain flows, armored mudballs generally are lighter and tend to rise, as observed by Unrug (1963, p. 62). They may be trapped by upward increases in density within the flow, or by overlying beds in a rapidly deposited sequence.

Disregarding the locally derived mudstone clasts and mudballs, the two upper zones (F_4 and F_5) contain essentially no gravel in contrast to the lower zones (F_1 to F_3) that contain appreciable quantities of gravel. Thus a crude, gross grading may be noted through the lower part of the model, but it contrasts markedly with the well-developed, systematic grading in the upper part.

UPPER PART (T)

The upper part (T) of the model is adapted from Bouma (1962) and is interpreted as the product of a turbidity current in the upper part of the composite sediment-gravity flow. Upward grading from sand to mud through the sequence of lamination indicates the waning of a turbulent current from the upper to the lower flow regime (Harms and Fahnestock, 1965). The sequence consists of the graded, upper part of a lamina (Ta-), overlain by laminasets (Campbell, 1967) of horizontal (Tb), current ripple (Tc), and horizontal (Td) laminae. At the top of a complete sequence is a mudstone (Te) deposited by the tail of the turbidity current. It in turn may be overlain by a pelagite representing quiescent deposition in the deep-marine environment. Most of the fluxoturbidite beds we have seen are overlain by other fluxoturbidites or normal turbidites, generally with an erosion surface between.

In a normal turbidite, the base of the Ta subdivision is an erosional bedding surface. In a fluxoturbidite, the lowest turbidite subdivision, designated Ta- (minus), has at its base an indefinite, transitional surface between the upper, graded part of a lamina and the lower, nongraded part. Previously, some workers have ignored the nongraded part, lumped the two together, and classified the entire bed as a normal (or "proximal") turbidite. Where most of the bed consists of a Bouma sequence (Ta to Te) and the thickness is less than one meter as in most normal turbidites, the lumping makes little practical difference. However, in the complete fluxoturbidite beds we have studies, the thickness is several meters, ranging up to at least 10 meters, and only about 10% to 20% of the upper part is a Bouma sequence.

Determination of the precise boundary between the graded and nongraded parts of a fluxoturbidite bed is a difficult task in the field. Slabs may be cut across the probable position and the boundary determined by laboratory methods. In reconnoissance work, an approximate boundary commonly can be located within a few centimeters, and small errors of that magnitude generally are negligible. Our field distinction between graded and nongraded textures may correspond to a laboratory distinction made by others between obvious grading of the entire size distribution or at least of the coarser sizes, and subtle grading of only the mean or finer sizes. Nevertheless, we see the difference as an expression of the inability of the upper (turbidity) part of the composite flow to mix coarser and finer grains, in contrast to the ability of the lower part to disperse coarser grains among the relatively finer grains in that part.

VARIABILITY OF FLUXOTURBIDITE TYPES

Exposures at the Rożnów quarry were used to develop this model as they include most of the features observed, and represent sediment-gravity flows with approximately equal percentages of sand and gravel. The Koniaków locality exposes an end member that is dominantly a sand-flow deposit. The Mucharz locality contains units that are dominantly gravel-flow deposits. At Polana, the minor mud designation of debris flow; the tops of some associated beds are irregular and contain rafted blocks characteristic of debris flows. Although we could not construct one realistic model to include all these facies variants, we hope the reader will review the type examples to appreciate the range of possibilities evident in the Polish Carpathian Flysch.

Variations within the sequence of sedimentary features shown in the model can also occur. The upper (T) part is relatively constant and the minor variations are similar to those described by Bouma (1962) and others. Within the massive part, zones F_1, F_2 and/or F_3 may be missing. Especially in sand-flow deposits (Koniaków), the lower and upper zones of the massive part may contain grain segregations. These variations may be due to different concentrations of sand and gravel within the grain flows, and different flow conditions or depositional histories.

Closely associated with some fluxoturbidite sequences are channels, ranging in depth from a few centimeters to a few meters, with trough laminae or climbing ripples that are interpreted as traction-current deposits. At Ratusz (Ciężkowice) such channel lenses are seen to overlie massive grain-flow deposits.

CONCLUSIONS AND RECOMMENDATIONS

In summary, a fluxoturbidite is redefined as the depositional product of a composite sediment-gravity flow, with a massive grain flow (or related type) in the lower part and a turbidity flow in the upper part. The lower, massive part of the flow may be a grain flow, a liquefied sediment flow, or possibly a debris flow.

A fluxoturbidite (FT) bed may be identified with the aid of the model presented in the previous section. Variations from gravel- to sand- and possibly mud (debris)-flow deposits should be considered, as well as possible differences in the vertical sequences and lateral changes within the beds. In the examples studied, we have not recognized a composite bed that is definitely a debris-flow deposit grading upward into a turbidity-current deposit. Owing to their internal strength, debris flows can form massive deposits without the confinement of overlying turbidity currents, and an analogous debris flow-to-turbidite type of fluxoturbidite may not be a mechanical necessity. Hampton (1972) showed how a turbidity current can be generated from the turbulent cloud above a debris flow, so such a composite bed is a mechanical possibility.

Massive sandstone or conglomerate beds, which contain features shown in the lower (F) part of the model, may be identified as fluxoturbidites even though the upper (T) part is not evident. However, the interpretation is strengthened if such beds are located within a succession containing normal turbidites. Because the tops of the (F) beds generally are erosional surfaces, the upper (T) parts may have been deposited and removed by erosion. Possibly the upper (T) parts bypassed the depositional sites of the lower (F) parts.

To develop a model with wide application, we have used mainly macroscopic criteria that can be recognized in outcrops and subsurface cores. Additional field study of the Polish examples as well as those of other areas is encouraged to test the validity of our observations. Moreover, laboratory analyses of petrography, radiography, granulometry, and other methods would help to determine more precisely the kinds and sequences of sedimentary features present within fluxoturbidite beds.

We are reasonably confident that the lower (F) parts of the fluxoturbidites generally are grain-flow deposits and the upper (T) parts are turbidity-current deposits. However, our attempts to explain the internal features of the lower part are based only on a limited knowledge of the literature. Those who have a better command of sedimentary mechanics through experimentation and mathematical models could elucidate the development of those features and provide us with a better understanding of the processes involved.

In spite of the limited exposures, Polish geologists have been able to relate these occurrences of fluxoturbidites to depositional systems of submarine canyons and fans. Generally such deposits are found in canyons and fan valleys. In contrast to statements of some previous workers in other areas, fluxoturbidites are found several tens to hundreds of kilometers downcurrent from the mouths of submarine canyons and therefore are not limited to the proximal parts of the fans. This fact should be considered in petroleum exploration of deep-marine basins where the usually clean fluxoturbidite sandstones and conglomerates are much better reservoir objectives than the usually muddy normal turbidites that comprise many fan deposits.

More rigorous facies analyses of fluxoturbidites in submarine fans, such as those made by Mutti and Ricci Lucchi (1975) and their associates, would promote a better understanding of the sedimentologic distribution, and permit more accurate projections in petroleum exploration. They use a broader concept of the term turbidite to include deposits of many different types of sediment-gravity flows, not just those of normal turbidity currents. What we call fluxoturbidites can be found in their turbidite facies A (especially A_1, the liquefied grain--flow type) and B (especially B_1, the liquefied sediment-flow type), and our normal turbidites are found in their facies C and D (see also Ricci Lucchi, 1975). Although some communication problems are evident with the differences in nomenclature and designations, the basic concepts are essentially the same, and their experience with submarine-fan facies can be very helpful in the development of fluxoturbidite and related models.

Additional research on the sediment sources of fluxoturbidites may explain the general absence of mud in contrast to normal turbidites. The sediments of the latter are considered in many cases to have been derived from submarine sliding off the fronts of deltas, which generally contain appreciable percentages of mud. Cleaner sands transported by littoral drift across the heads of submarine canyons may have been funnelled into deeper marine environments and deposited as fluxoturbidites.

We recommend the use of the term fluxoturbidite as redefined to express the concept of a composite sediment-gravity flow deposits. The denotation and connotation are explicit as they convey a composite bed with a grain-flow or related deposit (fluxo-) gradational with an overlying Bouma sequence (turbidite). Incomplete fluxoturbidites may be recognized even though the upper Bouma seqence is missing. Although the concept may be somewhat different, our redefinition would not change significantly the determinations of fluxoturbidites made by previous workers (see those listed in Walker, 1970, p. 234 to 239.).

In response to the objections with the original definition raised by Walker (1967, p. 38 to 39) and others, we offer the following considerations. First, the general type of fluxoturbidite bed as shown in the model is significantly different from the general type of normal turbidite bed shown in the model of Bouma (1962). Specific subtypes of fluxoturbidites may be expected ranging from gravel-flow to sand-flow, and possibly mud-flow deposits, parts of which may be liquefied, but at least some of these deposits can be recognized with the present model. Moreover, lumping all such deposits with some normal turbidites into the category of "proximal turbidites" would result in a backward step in sedimentological analysis, the loss of a valuable distinction in petroleum exploration, and a misleading designation of deposits which can be found in relatively distal parts of submarine fans. In regard to Walker's second objection, we agree that the term fluxoturbidite should not be used as a type of flysh. To those few geologists who continue this practice, we suggest that the adjective form of fluxoturbiditic flysch be used instead. Third, we agree that the restricted modern concepts of slumping and sliding (as redefined by Dott, 1963) are not directly involved in the processes that form fluxoturbidites. However, we consider it useful to communicate a genetic concept even though the exact mechanism (or group of mechanisms) is not understood completely.

Schlager W. and Schlager M. (1973, p. 74), preferred to use fluxoturbidite instead of the "proximal turbidite" of Walker, especially in a descriptive sense. More importantly, they (p. 71, fig. 3, slab no. 67/68) observed independently a nongraded zone overlain with a transitional, indefinite surface by a Bouma sequence. They referred to this bed as a "transition from fluxoturbidite"; we would classify the whole bed as a fluxoturbidite. Although they accepted a grain-flow mechanism for their fluxoturbidite, a transformation into a high-density turbidity current and a return to grain flow before deposition was postulated to circumvent the mechanical problems with a solitary grain flow. We simplify the explanation by combining the grain flow with an overlying turbidity current into a composite sediment-gravity flow. Several other observations by Schlager W. and Schlager M. (1973) are helpful in understanding fluxoturbidites, especially in such cases where the clasts were derived locally from carbonate rocks in tectonically active areas.

Carter (1975) discussed the concepts and nomenclature of subaqueous gravitative transport mechanisms and their deposits. He considered (p. 169) a fluxoturbidite to be a: "bed deposited from the basal layer of a dense turbidity current in which the immediately predepositional transport was by inertia flow". He used inertia flow as a general term to include grain flow and slurry flow (mud flow or debris flow of other geologists). His concept of a fluxoturbidite appears to be essentially the same as ours, but we are more cautious about including mud flow as one of the types in the lower part of the composite sediment-gravity flow. Carter and Lindqvist (1975) illustrate many features of fluxoturbidites (including grain-flow deposits) in the terrigenous fill of a submarine canyon-fan system.

In the future, it may become useful to construct separate models and developed an appropriate nomenclature to express more precisely the varieties of fluxoturbidites. The basic types should distinguish those in which the lower (F) part was deposited from a grain flow, liquefied sediment flow, or possibly a debris flow. Other types, if needed, may distinguish carbonate and terrigenous products, and the latter may be further subdivided into gravel, sand, mud, and mixed end members of fluxoturbidites. Variations in the sequences of sedimentary structures may represent subtypes with different transport and/or depositional conditions.

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STRESZCZENIE

W pracy przedstawiono wyniki badań typowych osadów fluksoturbidytowych w Polskich Karpatach Fliszowych. Badania te wskazują, że tworzenie się ławic fluksoturbidytowych było wynikiem złożonego procesu sedymentacyjnego rozpoczynającego się potokami piaszczystymi, a kończącego się normalnymi prądami zawiesinowymi. Zaproponowany został koncepcyjny model pełnego fluksoturbidytu, dla oznaczenia którego zastosowano symbol FT. Część niższa, oznaczona symbolem F jest zwykle masywna. Wyróżnić tu można kilka interwałów (fig. 15): F_1 — niewarstwowany, gdzie grubsze ziarna są rozproszone bezładnie w matriks piaszczystym; F_2 — z poziomami żwirowymi w części niższej, a słabo zaznaczonym frakcjonowaniu normalnym lub odwróconym w części wyższej; F_3 — masywny, bez frakcjonowania z cienkimi, pojedynczymi laminami piaszczystymi; F_4 — poziom zawierający klasty łupkowe; F_5 — odcinek niefrakcjonowany z rozproszonymi, pojedynczymi, grubszymi ziarnami, pojedynczymi klastami łupków oraz uzbrojonymi toczeńcami w części wyższej. Granice pomiędzy poszczególnymi interwałami są na ogół nieostre i występują ciągłe przejścia. Część wyższa oznaczona symbolem T reprezentuje wszystkie interwały Boumy i jest osadem normalnego prądu zawiesinowego. Kontakt pomiędzy oboma częściami (F i T) jest z reguły nieostry, istnieje ciągłe przejście między nimi. Przedstawiony, kompletny model, występuje w rzeczywistości sporadycznie, zwykle brakuje jednego lub nawet kilku interwałów (szczególnie F_2 do F_4) przy czym stałym składnikiem fluksoturbidytu jest interwał F_5. Niekiedy pojawia się interwał dodatkowy, laminowany przekątnie, zwykle rozpoczynający ławicę fluksoturbidytu. Niekiedy występuje on w stropie.

Osady fluksoturbidytowe są charakterystyczne dla proksymalnych obszarów stożków podmorskich, w niektórych jednak przypadkach stanowią również istotny składnik części dystalnych stożków i wtedy cały stożek ma charakter fluksoturbidytowy (m. in. piaskowce ciężkowickie i piaskowce dolnoistebniańskie).

EXPLANATION OF PLATES — OBJAŚNIENIA PLANSZ

Plate — Plansza I

Fig. 1. Photograph of two fluxoturbidite beds at Rożnów, view east-northeast of quarry wall. Location is immediately north of fig. 6a. Principal bedding surface at 0.00, 2.73 and 6.47 m are shown. Evident in lower bed is zone of mudstone clasts dying out to north (left), and subtle lamination at top. In upper bed is prominent zone of mudstone clasts, and obvious lamination at top.

Fig. 2. Cross-cutting channel is filled with fluksoturbidite bed. Rożnów, quarry.

Fig. 1. Dwie ławice fluksoturbidytów z warstw istebniańskich dolnych. Kamieniołom w Rożnowie. Granice ławic znajdują się na poziomach 0.00, 2.73 i 6.47 m. W obu ławicach występują poziomy z klastami łupkowymi. W ławicy niższej poziom ten wyklinowuje się. Górna część ławic jest laminowana.

Fig. 2. Kanał erozyjny około 2-metrowej głębokości wypełniony ławicą fluksoturbidytu. Warstwy istebniańskie dolne, kamieniołom w Rożnowie.

Plate — Plansza II

Fig. 1. Photograph of gravel segregations at Rożnów, view south-east. Location is south of fig. 6a, equivalent to interval 2.73 to 3.17 m above base. In this upper fluxoturbidite bed, an interval of sandstone (2.88 to 3.17 m) contains very faint gravel segregations. In the conglomerates below and

above, the gravel clasts are dispersed randomly through the sand matrix. Scale is 15 cm (6 inches) long; it is used in other closeup photographs.

Fig. 2. Photograph at Mucharz of contact at 4.35 m, between turbidite bed and fluxoturbidite bed. View is west along western bank of Skawa River.

Fig. 1. Poziomy żwirowe w ławicy fluksoturbidytu z kamieniołomu w Rożnowie. Zdjęcie wykonano bezpośrednio na południe od profilu przedstawionego na fig. 6a, zaznaczone są ekwiwalenty odpowiednich poziomów (2.73, 2.88, 3.17 m). Występują wyraźne poziomy żwirowe, pomiędzy którymi obecne są strefy, gdzie grubsze ziarna są rozproszone w matriks piaszczystym. Linijka ma 15 cm długości.

Fig. 2. Kontakt na poziomie 4.35 pomiędzy ławicą turbidytu i fluksoturbidytu. Mucharz, odsłonięcie na zachodnim brzegu Skawy.

Plate — Plansza III

Fig. 1. Photograph at Mucharz of bedding surface at 6.25 m. Fairly sharp, irregular surface on top of conglomerate with large protruding clasts, overlain by conglomerate with smaller clasts. No erosion is evident, but a depositional discontinuity is indicated. View is south-southwest, scale is normal to bedding.

Fig. 2. Photograph at Sowa of gravel segregations and horizontal lamellae in sandstone of fluxoturbidite bed about 2 m above base of columnar section. Gravel segregations are 5 cm thick (maximum); alternating sandy intervals are 30 cm thick (max.), and contain thin lamellae. View is southeast.

Fig. 1. Powierzchnia uławicenia na poziomie 6.25. Stosunkowo ostra nieregularna powierzchnia stropowa zlepieńca. Widoczne wystające duże bloki. Brak wyraźnych śladów erozji. Mucharz, odsłonięcie na zachodnim brzegu Skawy.

Fig. 2. Poziomy żwirowe i laminacja piaszczysta w ławicy fluksoturbidytu. Skałka Sowa, około 2 m powyżej podstawy profilu na fig. 8a. Poziomy żwirowe posiadają grubość 5 cm.

Plate — Plansza IV

Fig. 1. Photograph at Ratusz of faint through laminae (lower rigth of fig. 8c). Channel is 35 cm deep and 180 cm wide. View is northeast.

Fig. 2. Photograph at Ratusz (on left side of fig. 8c). Below overhang, cross-cutting channels are filled with through laminae. Curved joints above may be following large troughs. View is northeast.

Fig. 1. Kanał erozyjny (35 cm głęboki, 180 cm szeroki) wypełniony przekątnie warstwowanym piaskowcem. Skałka Ratusz w Ciężkowicach. Fragment prawej dolnej części rysunku na fig. 8c i dolnej części fig. 2, Pl. VI

Fig. 2. Kanał erozyjny (poniżej przewieszki) wypełniony przekątnie warstwowanym piaskowcem. Występujące wyżej wklęsłe spękania odzwierciedlają przypuszczalnie powierzchnie wklęsłych lamin. Skałka Ratusz. Ciężkowice.

Plate — Plansza V

Fig. 1. Photograph at Koniaków of complete fluxoturbidite bed (0.00 to 11.20 m, Fig. 10a.). View is east-southeast. Dip is 40° south—southeast

Fig. 2. Photograph at Koniaków of turbidite bed (1.63 to 2.51 m, fig. 10b) above fluxoturbidite bed. View is east

Fig. 1. Ławica fluksoturbidytu (interwał 0.00—11.20 m na fig. 10a). Piaskowce krośnieńskie. Kamieniołom w Koniakowie

Fig. 2. Ławica turbidytu (interwał 1.63—2.51 m na fig. 10b). Piaskowce krośnieńskie. Kamieniołom w Koniakowie

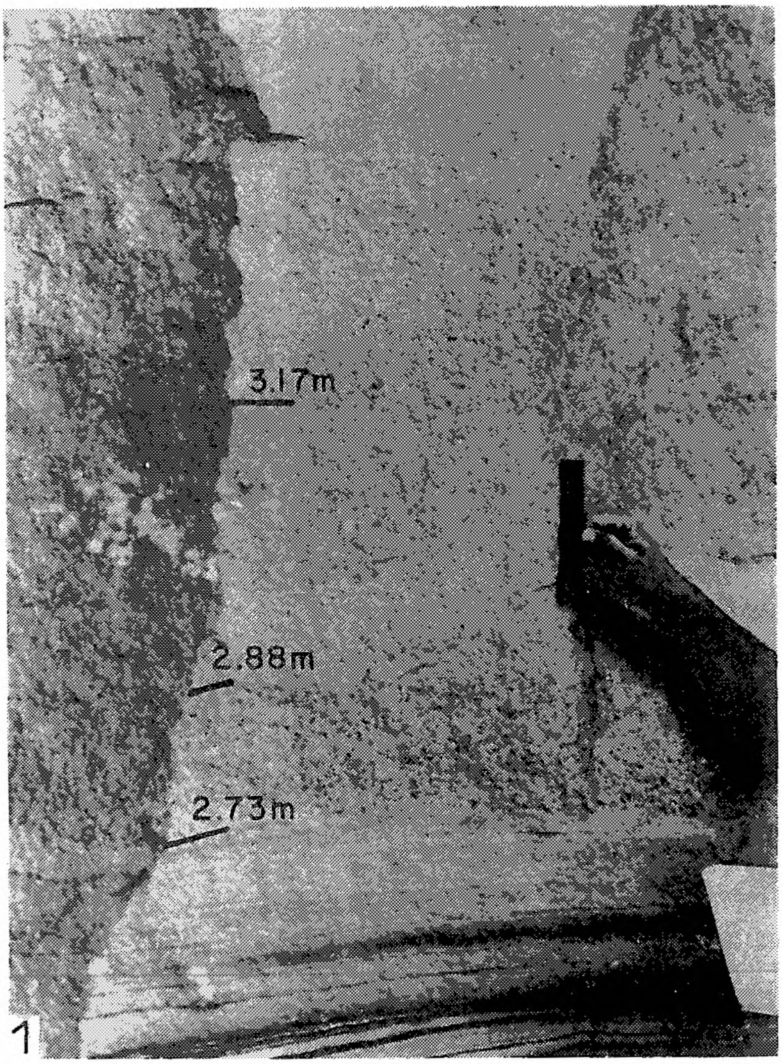
Plate — Plansza VI

Fig. 1. Photograph at Komańcza (Loc. 10) of Cergowa Sandstone (Lower Oligocene). Climbing ripples are seen in bed below fluxoturbidite. View is west—northwest. Dip is 15° west—southwest.

Fig. 2. Photograph at Ratusz. Set of fluxoturbidites. View is northeast.

Fig. 1. Ripplemarki występujące w spągu ławicy fluksoturbidytowej. Piaskowce cergowskie. Kamieniołom w Komańczy

Fig. 2. Zespół ławic fluksoturbidytowych. Piaskowce ciężkowickie. Skałka Ratusz w Ciężkowicach. (fot. S. Leszczyński)



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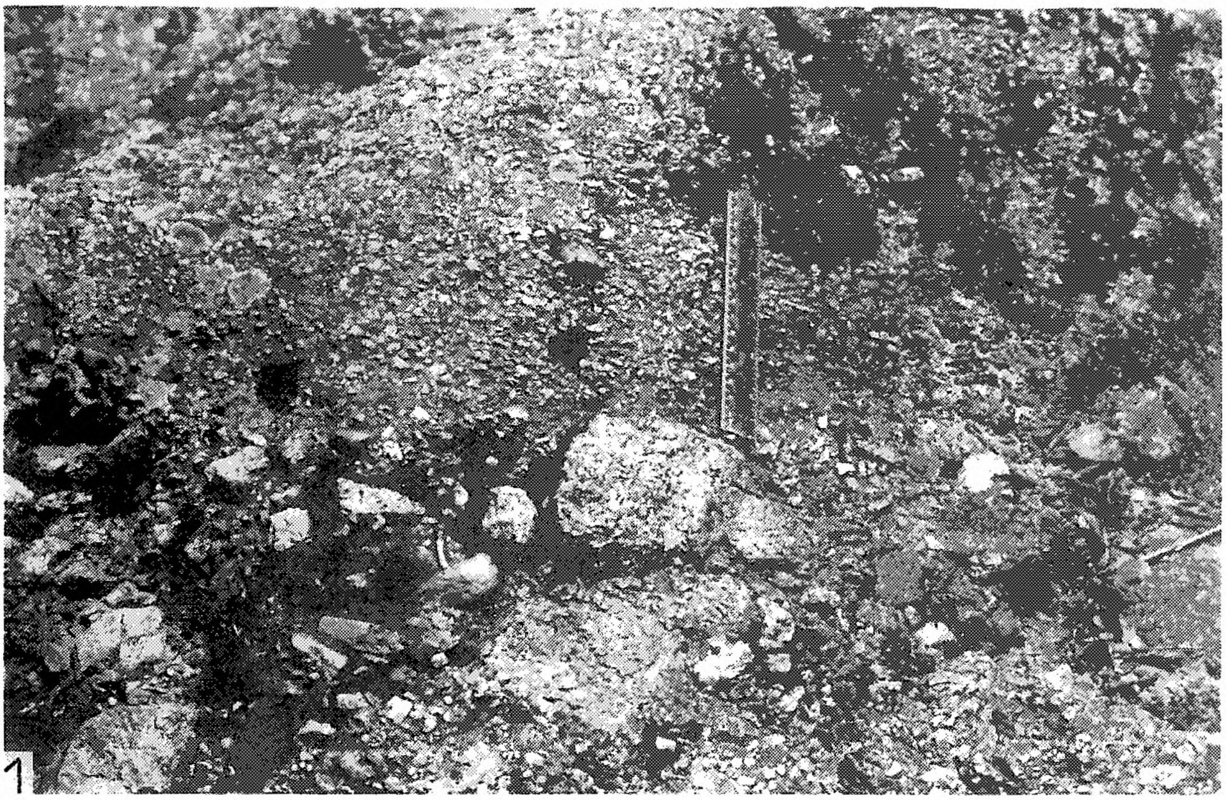

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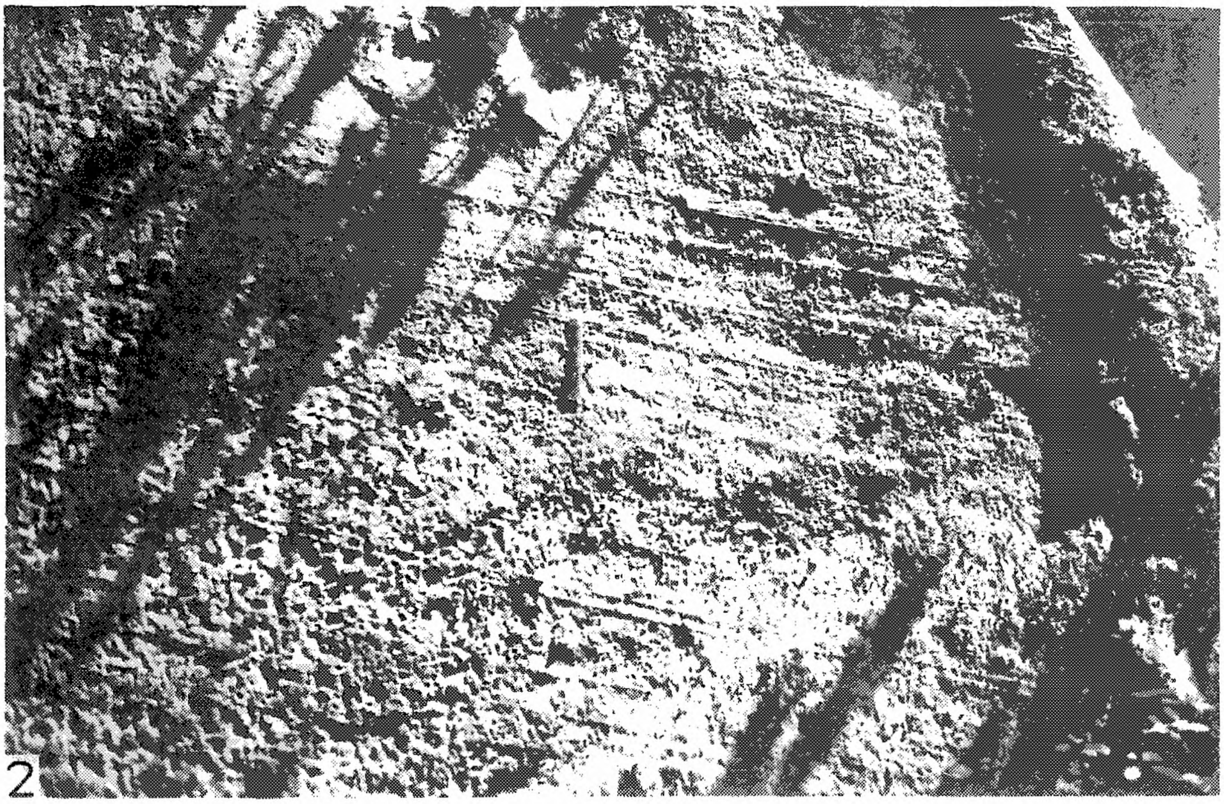

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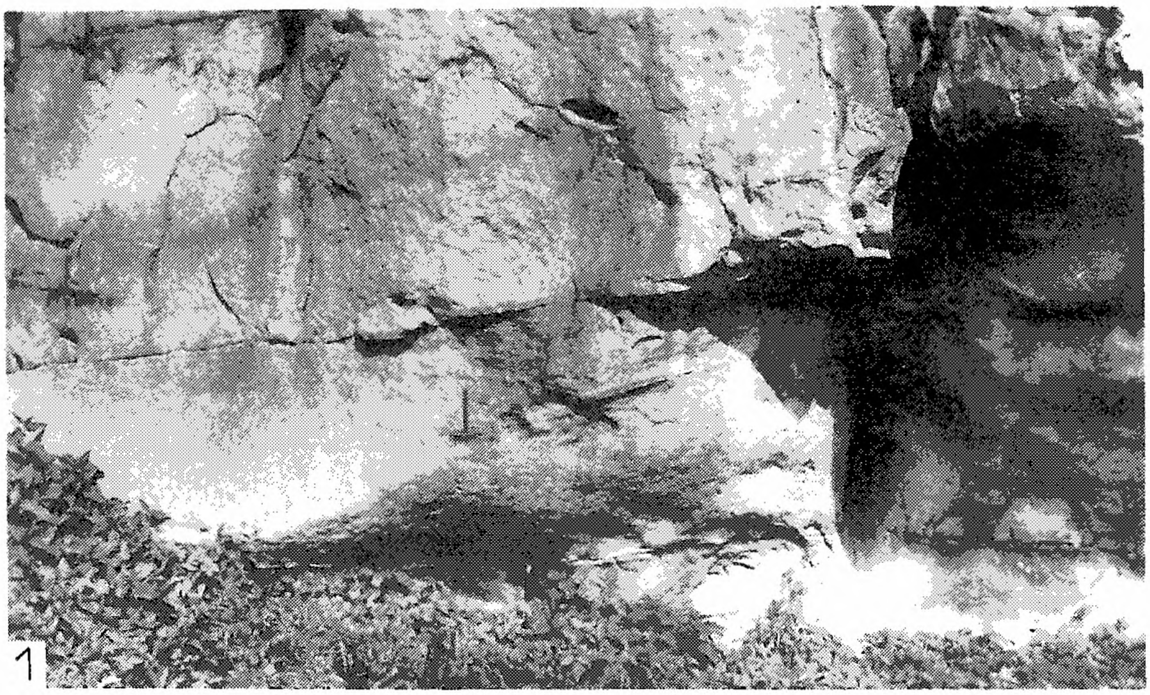

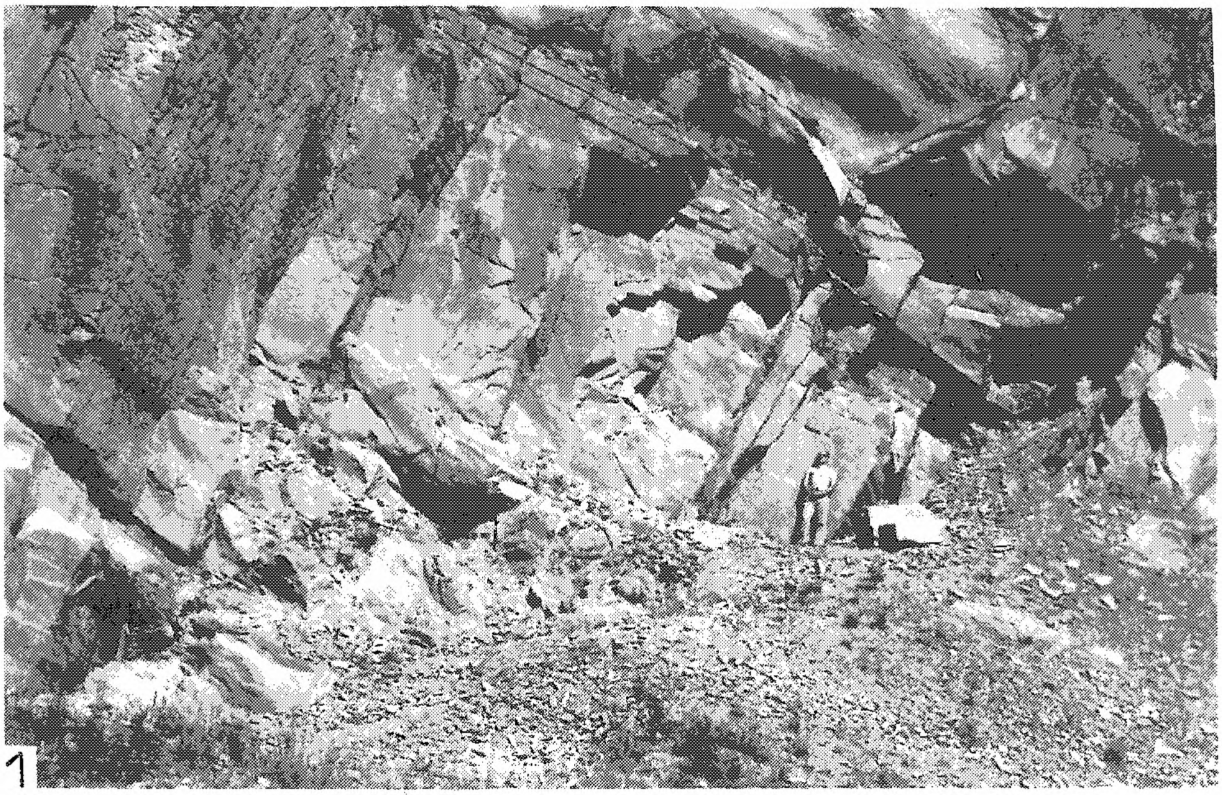

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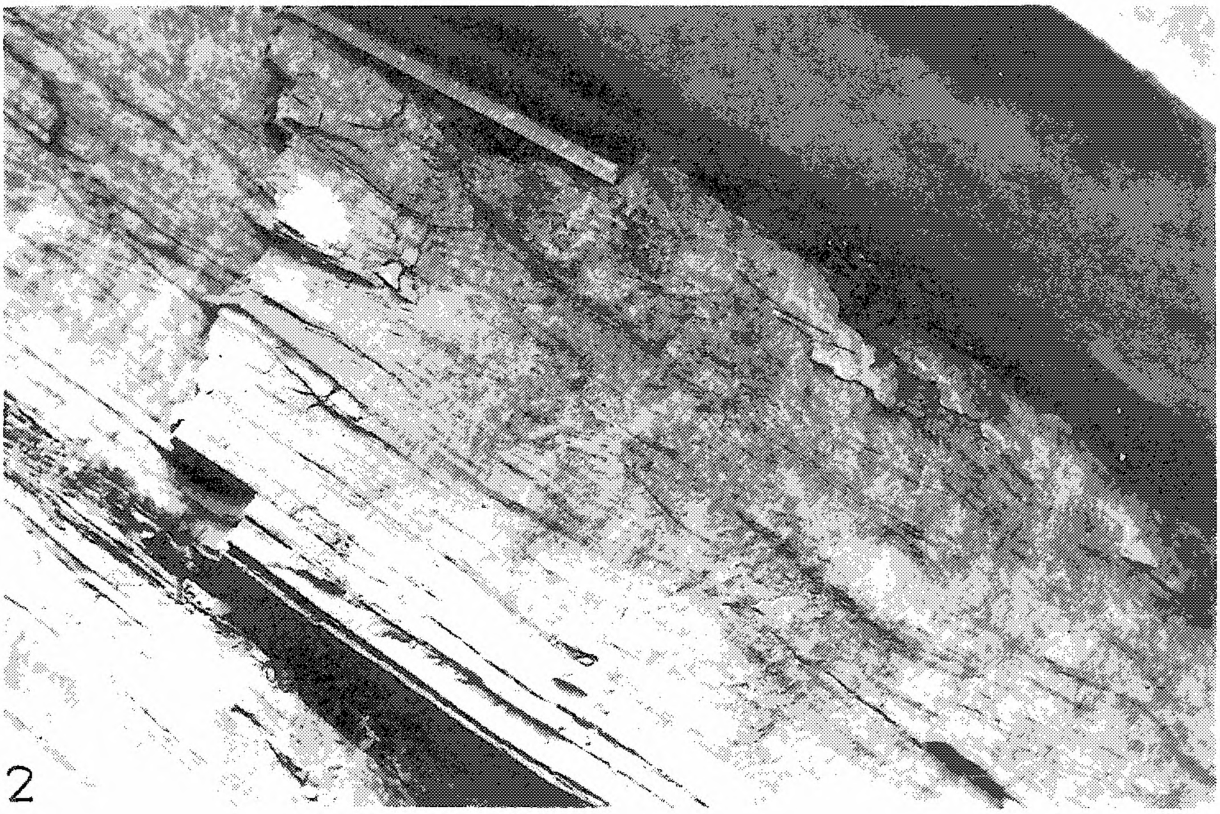

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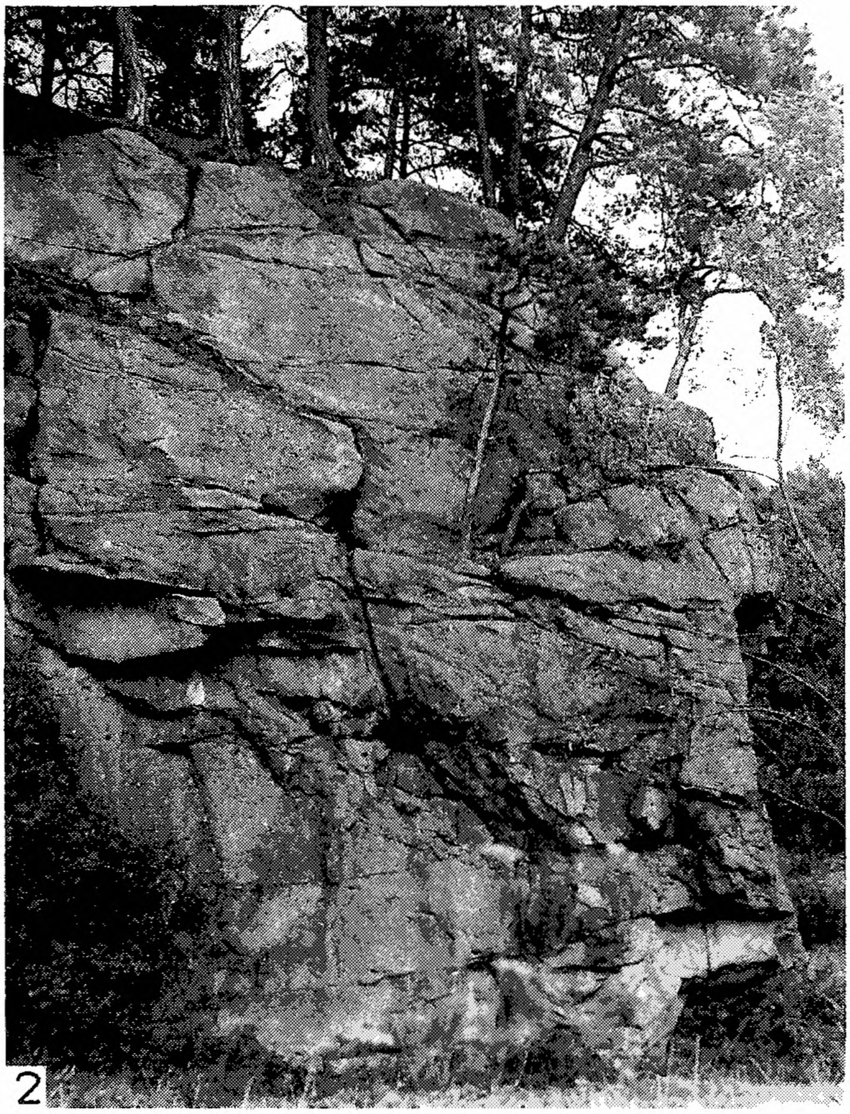

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