

Deformational structures in the Iskur Carbonate Group (Lower - Upper Triassic) from the Western Balkanides

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А. Чаталов — Деформационные текстуры Искырской карбонатной группы (триас) в Западных Балканах. Деформационные текстуры в породах Искырской карбонатной группы (нижний - верхний триас) из Западных Балканид концентрированы главным образом в трех литостратиграфических единицах (Могильская, Любашкая и Бабинская свиты), которые обхватывают хроностратиграфический интервал спат-ладин. Текстуры находятся в основном в известняках и в небольшой степени в песчаниках.

Субпараллельные поверхности скалывания наблюдаются только в самых нижних уровнях Могильской свиты (Оплетненская подсвита) и интерпретируются как образованные в процессе периодической палеосейсмической деятельности. Различаются четыре морфологические подтипа таких поверхностей (дуговидные, сигмоидальные, зигзаговидные и субвертикальные). Конволютная ламинация (Могильская свита), волнистая и смятая слоистость (Бабинская свита) формированы как прямое следствие из первоначальной неустойчивости неомогенного осадка из более чистых и более глинистых известковых ламин, не исключая участие и внешних факторов. Оползневая текстура (Бабинская свита) имеет за предпосылку слабый наклон среднетриасской карбонатной рампы и генерирована посредством неконсолидированных массовых движений в латеральном направлении. Текстура нагрузки (Могильская свита) выражается в проникновении более крупнозернистого карбонатного материала в подстилающий гидропластичный карбонатный ил вследствие перегрузки. Пламенная текстура (Бабинская свита) имеет сходное происхождение, но характеризуется проникновением неконсолидированного карбонатного ила вверх в позже отложенный карбонатный песок. Единственная текстура, которая установлена в песчаниках это шаровидно-подушечная (Любашкая свита). Её интерпретация связывается со сравнительно быстрым и неравномерным вертикальным погружением кlastического материала вниз в нелитифицированный карбонатно-глинистый осадок.

Корреляция стратиграфских уровней содержащие субпараллельные поверхности скалывания показывает самую большую вертикальную насыщенность в

Abstract. The deformational structures in the rocks of the Iskur Carbonate Group (Lower - Upper Triassic) from the Western Balkanides are concentrated mainly in three lithostratigraphic units (Mogila Formation, Lyubash Formation and Babino Formation) which cover a chronostratigraphic interval from the Spathian to Ladinian age. The structures occur mostly in limestones and to a lesser extent in sandstones.

The subparallel shear surfaces are observed only in the lowermost levels of the Mogila Formation (Opletnya Member) and are interpreted as formed during a periodical paleoseismic activity. Four morphological subtypes are differentiated (arcuate, sigmoidal, serpentine and subvertical). The convolute lamination (Mogila Formation) and wavy to crumpled bedding (Babino Formation) emerged as a direct result from the primary instability of a non-homogeneous system built up of purer carbonate and marly laminae without excluding the participation of external factors. The slump structure (Babino Formation) was predetermined by the small dip of the Middle Triassic carbonate ramp and generated through gravitational mass movements in lateral direction. The load structure (Mogila Formation) was formed by means of downward penetration of coarser carbonate material into underlying hydroplastic carbonate mud due to overloading. The flame structure (Babino Formation) is interpreted in a similar way, but as a result from upward penetration of carbonate mud into later deposited carbonate sand. The only structure that is established in sandstones is ball-and-pillow (Lyubash Formation). Its interpretation is related with a comparatively rapid and irregular collapse of clastic material into unlithified carbonate-clayey sediments.

The correlation of the stratigraphic levels with subparallel shear surfaces shows highest vertical density in some cross sections from the Iskur river valley (between Lacatnic railway station and hamlet of Sfrashen). The supposed major epicentre zone of the ancient earthquakes was situated in this region. The whole seismic activity in the study area from the end of the Lower Triassic epoch resembles the paleoseismic manifestations known from the German Lower Muschelkalk. As earthquakes must have been at least partially a controlling factor for some of the other described structures it is quite probable that

части из разрезов в Искырском ущелье (между железнодорожной станции Лакатник и махалы Сфражен). Предполагается, что в этом районе была расположена и главная эпицентровая зона землетрясений. Целостная сейсмическая деятельность на исследованной площади в конце нижнетриасской эпохи является похожей на палеосейсмические проявления, известные в Германском нижнем мушелькалке. Так как допускается, что землетрясения были по крайней мере частично контролирующим фактором и в отношении некоторых из остальных текстур весьма вероятно, что сейсмическая активность продолжилась и в анизком веке. Присутствие типичных сейсмиков в нижнетриасских седиментах предполагает будущие исследования с целью более региональной корреляции с изохронными породами.

the seismic activity in the area has continued through Anisian times. The presence of typical seismites in the Lower Triassic sediments is a prerequisite for further investigations aiming at a more regional correlation with isochronic rocks.

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Key words: structures, deformational, limestones, sandstones, paleoseismicity, correlation, Triassic, Western Balkanides

Introduction

Various deformational structures occur in the sedimentary rocks of the Iskur Carbonate Group (Lower - Upper Triassic) (Тронков, 1981) cropping out in the Western Balkanides. They are concentrated mainly in three lithostratigraphic units - Lyubash Formation (Spathian), Mogila Formation (Spathian-Anisian) and Babino Formation (Anisian-Ladinian). The deformed lithotypes are predominantly limestones and sporadically sandstones. The present paper deals with both the description and interpretation of the observed deformational structures. Some problems of their classification and terminology are also discussed herein. Interpreted paleoseismic signatures are considered in the light of a correlation with other Triassic rocks from Europe.

Deformational structures like desiccation cracks, tepees and fenestrae were established earlier in the Mogila Formation and discussed in a separate work (Chatalov, 1994). Such structures were described also in the Svidol Formation (Spathian) by Тронков (1960) and in the Rusinovdel Formation (Ladinian-Carnian) by Бенатов и Чаталов (2000) and should have analogous interpretation.

In historical aspect a review of some deformational (crumpled and load) structures in the Iskur Carbonate Group from the Central Balkanides (Teteven anticlinorium) was made by Чаталов (1972).

Problems of classification and terminology

In most genetic classifications of sedimentary structures one of the major divisions comprises deformational structures (Градзински и др., 1980; Reineck & Singh, 1980; Петтиджон, 1981; Selley, 1988; Collinson & Thomson, 1989; Boggs, 1995). Their formation is controlled by purely physical processes (often acting in a combined manner) before the complete lithification of sediments. The deformation proceeds at the time of or shortly after deposition so that the resulting structures are sometimes termed penecontemporaneous or soft-deformational. Lateral and/or vertical movements of sedimented material take place causing variable deformation from slightly disturbed layers to intensive brecciation. A common feature is that deformation occurs in single beds (or packages) confined to undeformed ones. Other terminology to denote these specific structures like "metasedimentary" (Van Loon & Wiggers, 1976) or "post-depositional" (Selley, 1988) did not become popular in the sedimentological literature.

The further subdivision of deformational structures into varieties is mostly based on their morphological properties (Potter & Pettijohn, 1977; Градзински и др., 1980; Reineck & Singh, 1980; Петтиджон, 1981; Collinson & Thomson, 1989; Chamley, 1990; Demicco & Hardie, 1994; Boggs, 1995) as genetic criteria

are not commonly used (Selley, 1988). However, some discrepancies between the applied specific terms prevent from creation of a unified classification causing inconsistency between the different proposed schemes (Mills, 1983; Van Loon & Brodzikowski, 1987). The main reason for this are the various interpretations of the physical processes which control the penecontemporaneous deformation of sediments. An attempted compilation from different sources may result in the following list of deformational structures: load structure, flame structure, ball-and-pillow structure, convolute lamination, dish structure, slumps and slides, wavy and crumpled bedding, injection structures, soft-sediment folds, desiccation and synaeresis cracks, fenestral structure. In order to comply with some modern works, problems of terminology regarding the concrete structural types treated in this study, are further discussed in the text.

Subparallel shear surfaces

Description

Subparallel shear surfaces were recently established in the lower part of the Mogila Formation (Opletnya Member) in its outcrops from the Iskur river valley (Chatalov, 2000). A later field investigation showed, however, a wider geographic distribution of this peculiar structure. It occurs almost in the whole southern part of the Western Balkanides (s. s. after Бончев, 1986) covering an area between the villages of Gintsi, Tserovo, Ochindol and Zgoriograd (Fig. 1). Stratigraphically the subparallel shear surfaces come at different number of levels in the separate cross sections. A correlation is possible between some of these cross sections (see below).

The subparallel shear surfaces are observed only in lime mudstones which build up volumetrically most of the subtidal subfacies units in meter-scale peritidal shallowing-upward successions (Чаталов, 1997). These limestones are predominantly thin (<10 cm) but also medium-bedded (10-30 cm) (Plate I, 1, 2, 3). The single beds with subparallel shear surfaces alternate in the peritidal hemicycles with undeformed (mostly micritic) limestones as the latter display massive structure, horizontal lamination, traces of bioturbation and convolute lamination. Only in some cases the subparallel shear surfaces occur in two vertically successive beds. Locally just a part of the beds is deformed with

the bottom and top boundaries of these horizons being parallel to the bedding surfaces (Plate I, 2). The undeformed sectors of such beds have either mud-supported or grain-supported texture and show various structures. Lateral transitions are observed with respect to the distinctness of the subparallel shear surfaces in certain beds, e. g. the structure may be continuous or gradually become less distinct (Plate I, 3). Elsewhere the shear surfaces pass into genuine convolute lamination. In some deformed beds other coexisting synsedimentary and early diagenetic structures (horizontal lamination and bioturbation) are clearly recognized.

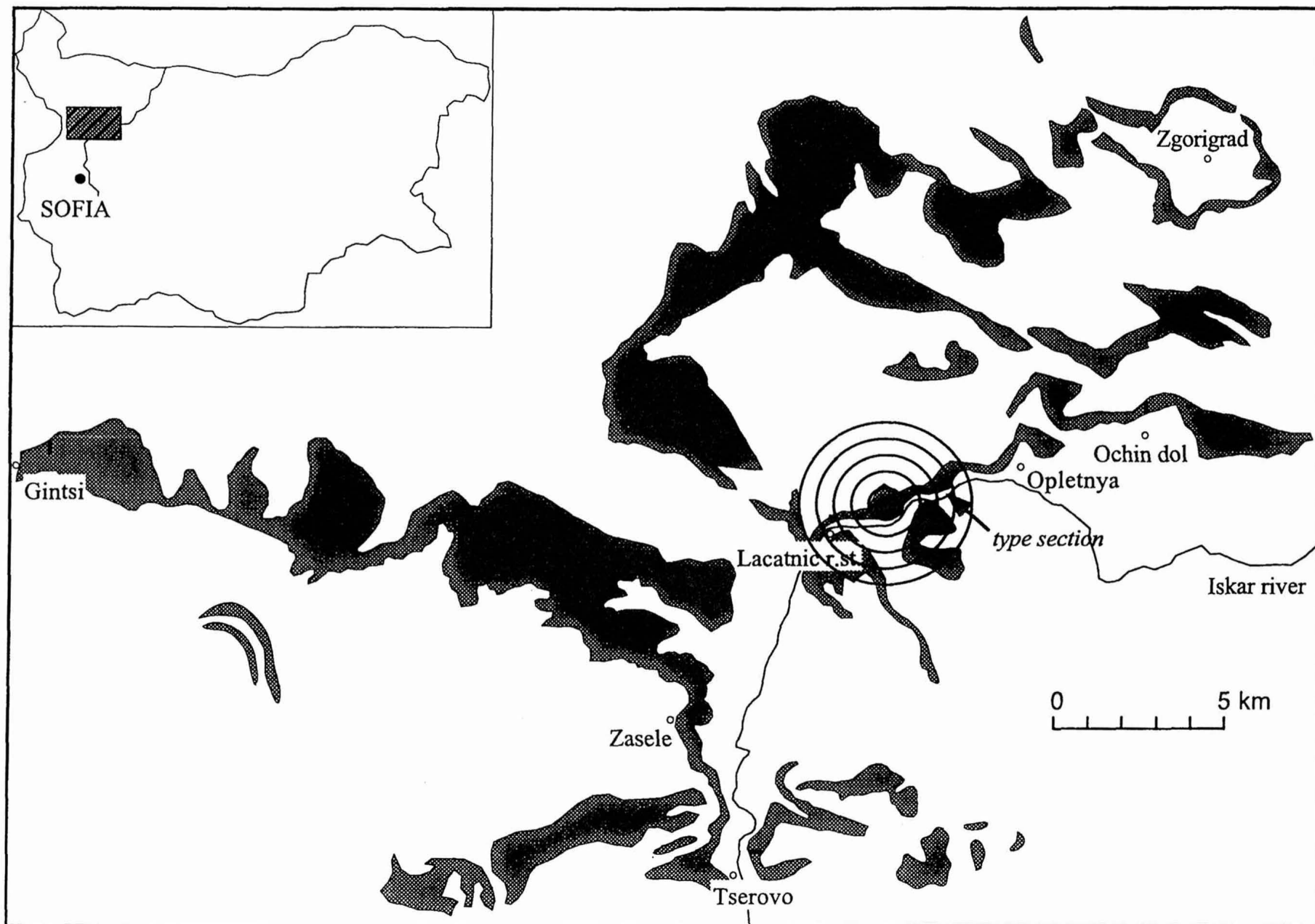
The specific outer appearance of the deformed limestones is marked by the occurrence of subparallel "slab joints" which are best visible on strongly weathered surface (Plate I, 1). The density of the shear surfaces varies between the different beds as the thickness of the slabs ranges from a few millimeters to a maximum of 3 cm. The thickness of each slab is mostly constant along its length (that is why the shear surfaces are termed subparallel) and all slabs in a certain bed have only slightly variable thickness. Four different subtypes of subparallel shear surfaces are recognized on the basis of their geometry (Fig. 2):

a) The arcuate shear surfaces are unilaterally oriented symmetrical curves (resembling recumbent folds) which have one common axial plane in each bed, e. g. are parallel to each other (Plate I, 1). The axial plane itself is constantly parallel to the bedding surfaces. With respect to the interlimb angle the folds are predominantly open (>70°). However, in some thin beds (or intrabed horizons) the curving of the shear surfaces is less pronounced. Such closed (30-70°) folds have almost planar limbs and thus resemble rather a chevron shape (Plate I, 2).

b) The sigmoidal shear surfaces represent vertical (predominantly symmetric) couples of one synform and one respective antiform (Plate I, 3). The height (H) of these "ripples" is commonly smaller than their wave length (L) thus making the "ripple indices" ($I = L/H$) bigger than unity.

c) The serpentine shear surfaces differ from the sigmoidal ones only by having more than one synform/antiform couple. The number of the respective antiforms and synforms, which may be either symmetric or asymmetric, is not proportional to the bed thickness.

d) The subvertical shear surfaces have only their lower part deviating from perfectly linear vertical position. The curving of the adjacent shear surfaces is constantly unidirectional.



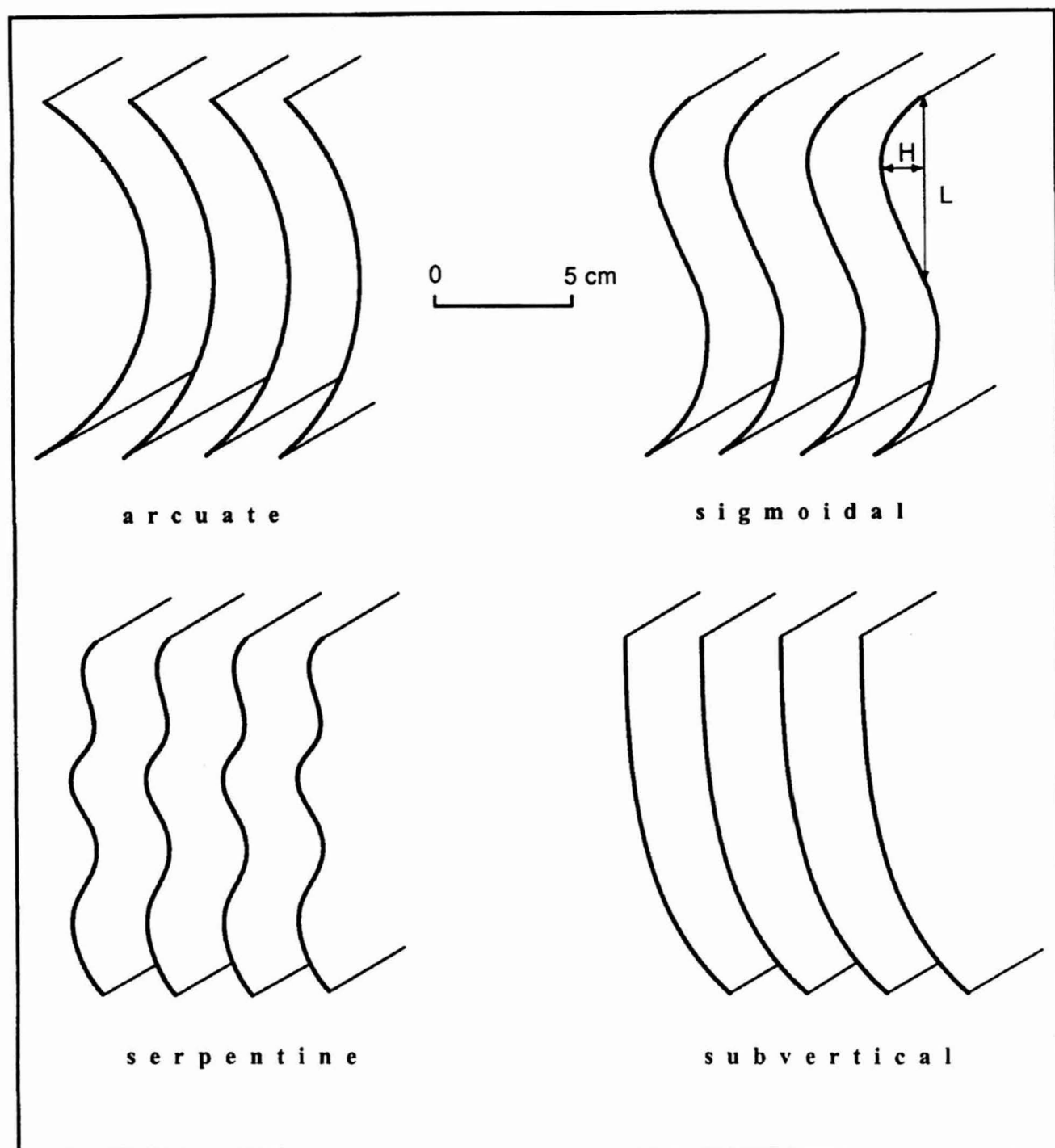


Fig. 2. Schematic drawing of the four morphological subtypes of subparallel shear surfaces. Notes: The arcuate shear surfaces are open with respect to the interlimb angle; H is the height and L is the length of the "ripples" in the sigmoidal subtype

An important conclusion from the field observations is that there is no conspicuous dependance between the specific morphology of the subparallel shear surfaces (e. g. the particular subtype) and the bed thickness. On the other hand, the arcuate and sigmoidal subtypes show greatest stratigraphic occurrence.

Interpretation

Numerous terms have been used to designate subparallel shear surfaces since the end of the previous century when this peculiar structure has been described in the German Muschelkalk: "Querplattung", "Längsplattung", "shear

Fig. 1. Outcrops and studied cross sections of the Mogila Formation in the Western Balkanides with occurrence of subparallel shear surfaces. The concentric circles plotted on the map indicate the probable epicentre zone of paleoseismic activity during the Lower Triassic epoch

PLATE I

1. Medium lime mudstone bed with subparallel arcuate shear surfaces. The latter predetermine the appearance of numerous "slabs" of almost equal thickness. The common axial plane of the folds, which are open with respect to the interlimb angle, is parallel to the bedding surfaces (recumbent folds). Mogila Formation (Opletnya Member). Cross section east of the village of Tserovo.
2. Thin intrabed horizon (shown by arrows) in a lime mudstone bed of medium thickness with arcuate shear surfaces. As the measured interlimb angle is about 45° (closed folds) and the limbs are almost planar this morphological variety rather resembles a chevron shape. The lower undeformed part of the bed has also mud-supported texture but displays only indistinct horizontal lamination. Mogila Formation (Opletnya Member). Cross section north of the hamlet of Sfrazhen.
3. Sigmoidal shear surfaces in a medium lime mudstone bed with an asymmetric synform/antiform couple. The "ripple index" ($I = L/H$) is invariably bigger than unity. The density of the shear surfaces is very high predetermining the millimeter thickness of the separate "slabs". Lateral transitions into indistinct manifestation of the structure are well visible. Mogila Formation (Opletnya Member). Cross section north of the hamlet of Sfrazhen.
4. Convolute lamination in lime mudstone bed of medium thickness characterized by a complex system of folds which show various morphology. Laminae of different carbonate content are well discerned on the weathered surface both for their colour and relief variations. The degree of deformation is variable in vertical direction as gradual transition is traced from the lower undeformed sector of the bed (showing horizontal lamination). Mogila Formation (Opletnya Member). Cross section north of the hamlet of Sfrazhen.
5. Wavy bedding in a package of limestones with changeable amount of siliciclastic mud admixtures. Both the bed surfaces and the purer carbonate intrabed horizons are slightly to moderately undulose. Lyubash Formation. Cross section north of the Chepurlyantsi railway station (Бенатов и Чаталов, 2000).
6. Wavy bedding in thick-bedded lime wackestones containing numerous marly intercalations. The latter display negative relief on weathered surface. The boundaries of the intrabed limestone horizons are slightly undulose. Babino Formation (suite of the clayey and nodular limestones). Outcrop along the road from the Lacatnic railway station to the village of Milanovo.

PLATE II

1. Crumpled bedding in a package of thin-bedded clayey limestones which are characterized by an alternation between wavy horizons of purer carbonate and marly intercalations. Unlike the wavy bedding the purer limestone horizons are broken into tightly packed fragments. Transitions are well visible in the package from typical wavy bedding as well as into indistinct nodular structure. Babino Formation (suite of the clayey and nodular limestones). Cross section north of Lacatnic railway station.
2. Slump structure in a decimetric package of predominating clayey micritic limestones and subordinate allochemic limestones. This stratigraphic level is laterally continuous throughout a great part of the study area but the observed degree of deformation is variable. The scale of the available folding is bigger than in the described convolute lamination affecting not single beds but the stratification. Babino Formation (suite of the clayey and nodular limestones). Cross section north of the hamlet of Sfrazhen.
3. Manifestations of load structure on the boundary between a lime mudstone layer and an overlying lime grainstone bed. The latter has partially penetrated downwards (centimeter range) into the non-consolidated carbonate mud during the early diagenesis resulting in protrusions of different shape but constantly rounded delineations (shown with black marker). Mogila Formation (Opletnya Member). Outcrop between the village of Opletnya and the hamlet of Sfrazhen along the mainroad Sofia-Mezdra.
4. Flame structure observed on the boundary between a lime mudstone layer with vertical burrows and an overlying bioclastic floatstone bed. Predominantly sharp-ended tongues of semi-consolidated carbonate mud (shown by arrows) have penetrated penecontemporaneously upwards into the coarse-grained sediment. Note the lack of preferential orientation of the "flames". Babino Formation (suite of the clayey and nodular limestones). Cross section north of the hamlet of Sfrazhen.
5. Ball-and-pillow structure displayed by fine-grained sandstones in a marl package. The detached sandstone "pillows" have flat upper surface but rounded curved bottom with both boundaries indicating the direction of material collapse. Lyubash Formation. Outcrop north of the village of Tuden.
6. Ball-and-pillow structure with similar size of the sandstone bodies which form a continuous row parallel to stratification. The inner laminated fabric of the balls testifies to the lack of complete lithification at the time of deformation. It might be supposed that the vertical range of the "balls" is roughly proportional to the primary sandstone bed thickness. Lyubash Formation. Outcrop north of the village of Tuden.

PLATE I

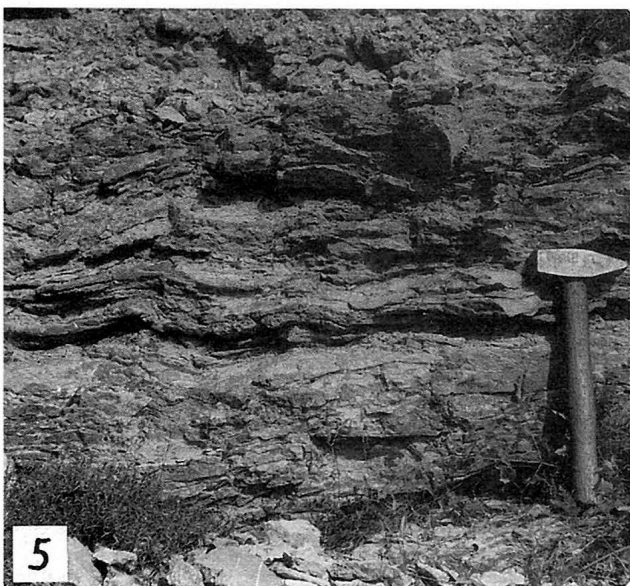
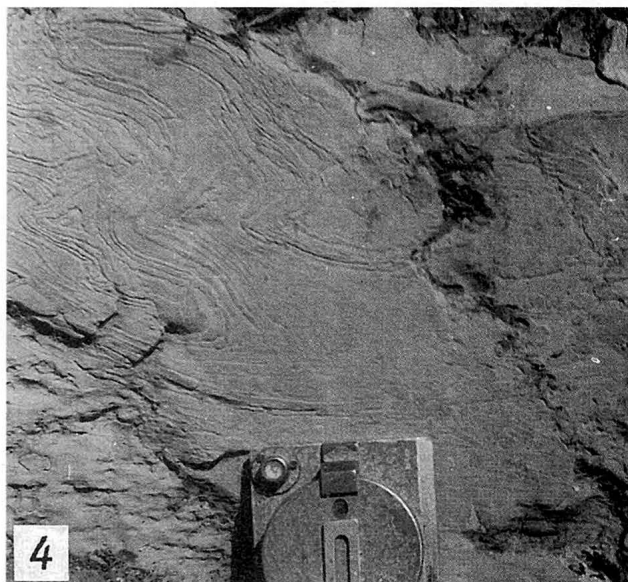
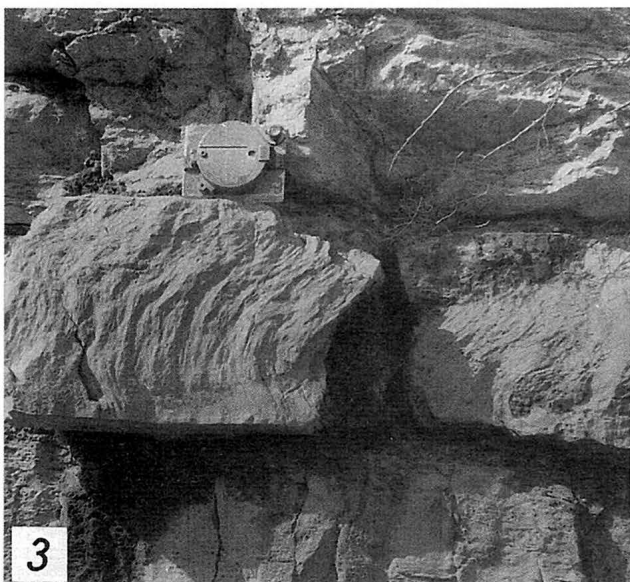
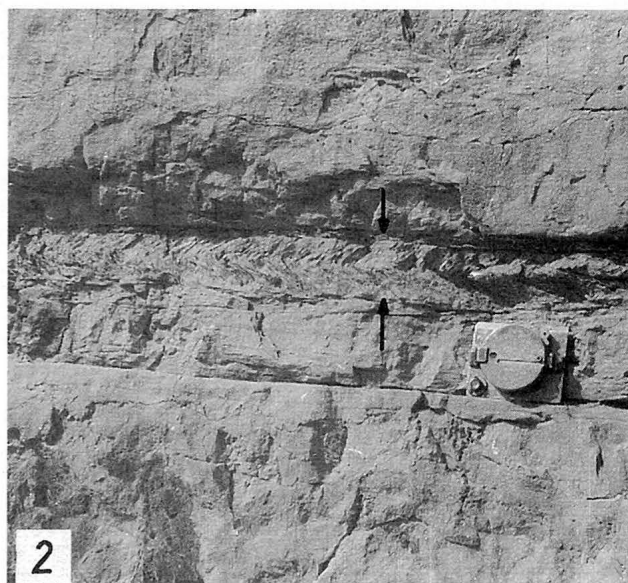
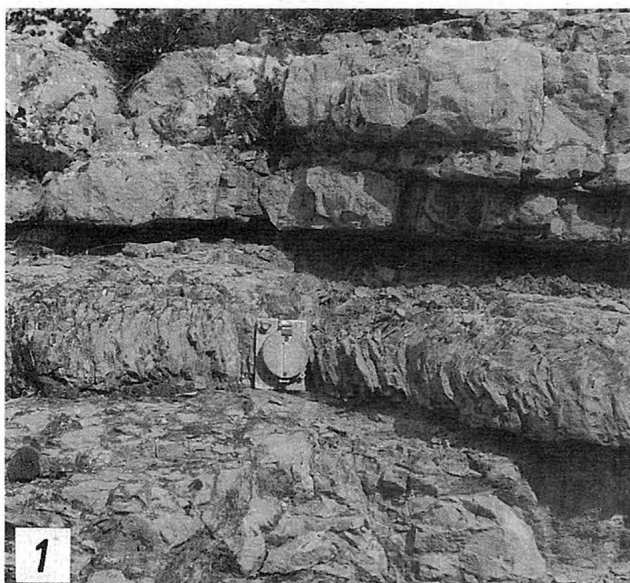
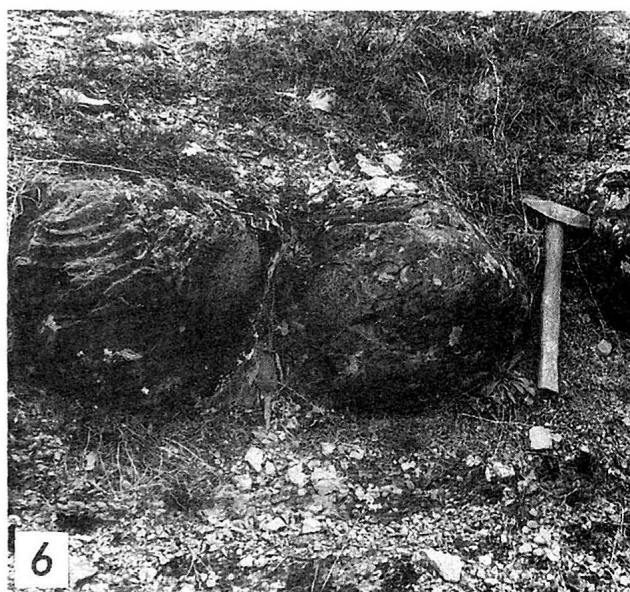
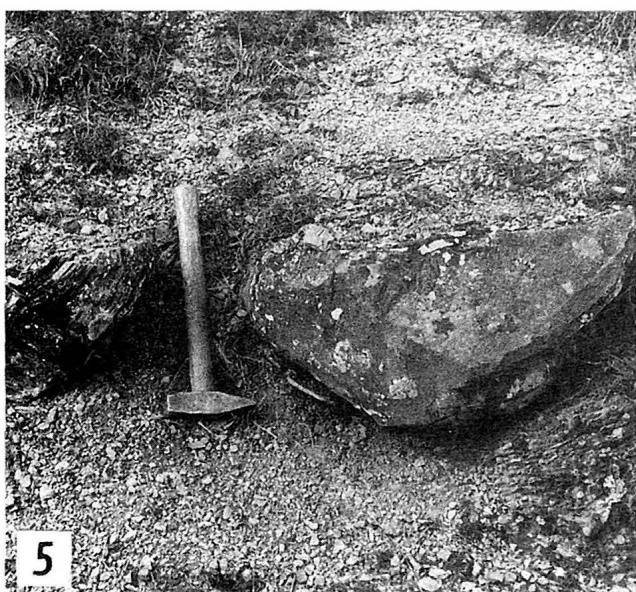
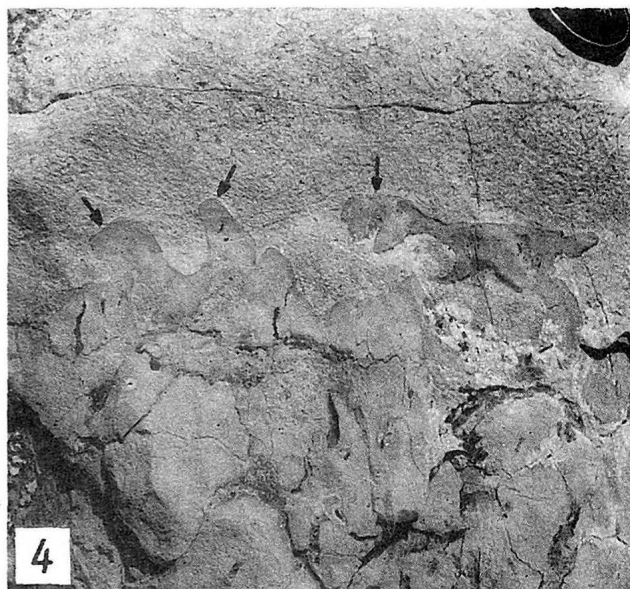
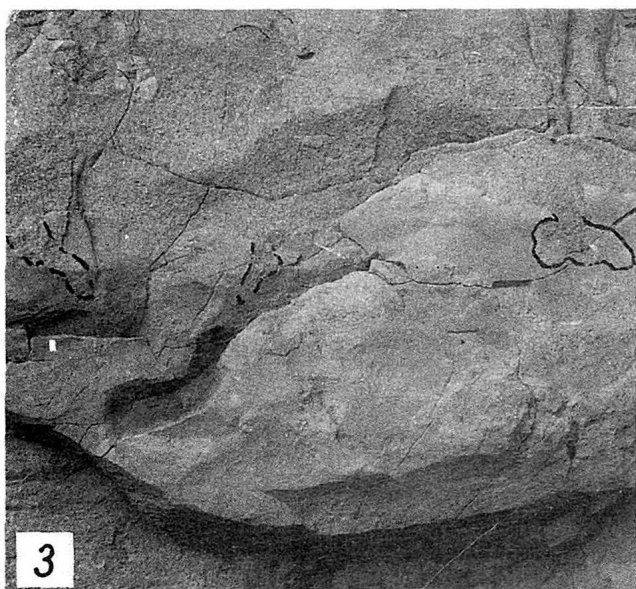
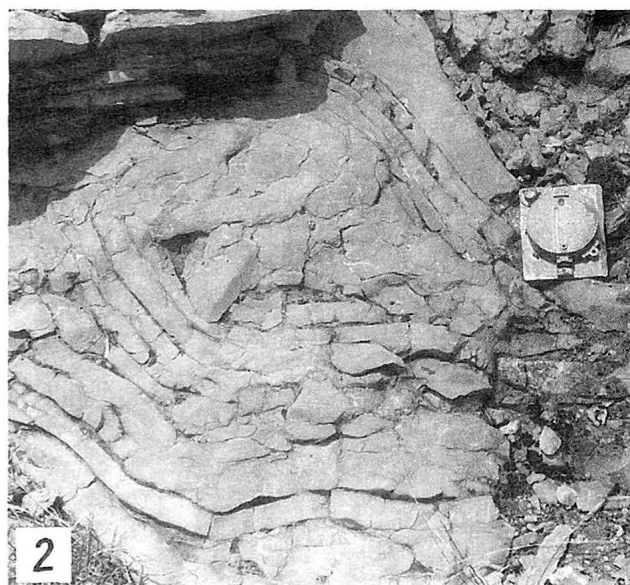
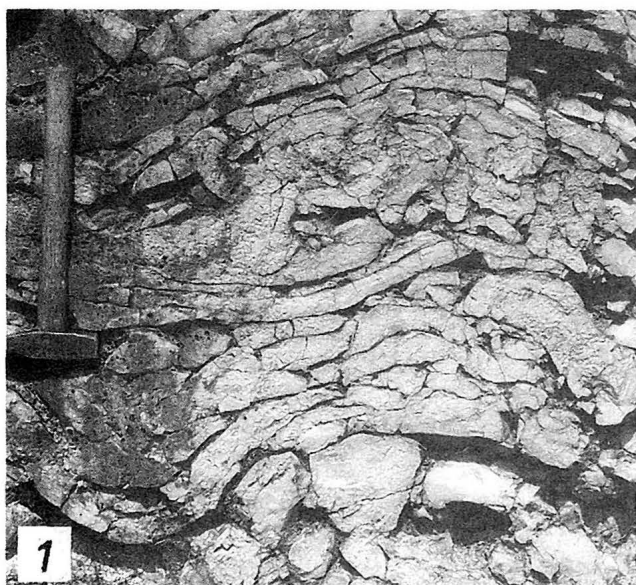


PLATE II



slab joints", "Sigmoidalklüftung", "piezoclasti", "micro-fault systems", "rope-ladder structure", "sinusoidally deformed veins", "parallel shear surfaces, joints and fractures", etc. Their origin is still under debate as the proposed genetic hypotheses have been based on various factors: general tectonic influences (Engels, 1956; Damiani, 1973), vertical compression (Schüller, 1967), Earth rotation and tides (Kurze, 1981), earthquakes (Schwarz, 1975; Török, 1993; Knaust, 1998), tsunamis (Michalik, 1997), initial crack formation and subsequent vertical sheet injection (Neuweiler et al., 1999). Although the greatest occurrence of subparallel shear surfaces has been recorded in Triassic sediments this structure is also known from Precambrian, Jurassic and Cretaceous rocks (Engels, 1956).

The nature of the studied deformed micritic limestones precludes high-energy conditions as a controlling factor for the generation of the subparallel shear surfaces. This is so because their facies interpretation is related with low-energy sedimentation in a shelf lagoon of restricted circulation (Чаталов, 1997). Thus the possible analogy with overturned cross-bedding in sandstones (termed also recumbent folds or foresets) caused by strong current activity (Allen & Banks, 1972) is absent. Alternatively, the specific trigger mechanism of the deformation is suggested to have been linked with paleoseismic activity (some recumbent folds in clastic rocks are also interpreted as resulting from earthquakes - Sims, 1973; Guiraud & Plaziat, 1993). Obviously the earthquakes took place during the early diagenesis of the sediments at the time when they were not completely consolidated (semi-lithified). The deposited material possessed some instability expressed in water saturation and the shocks led firstly to its fluidization, and later, to its soft-deformation. In all four cases (arcuate, sigmoidal, serpentine and subvertical subtypes) the deformation proceeded in lateral direction without any evidence for vertical displacement. The plastic/elastic behaviour of the soft sediments was predetermined by the high pore water pressure during the shock event. The internal bed movement resulted in shear surfaces and their subsequent deformation in different manner. The mentioned variability of observed distinctness between the different deformed beds (or intrabed horizons) must have been controlled mostly by the strength of deformation. In this sense, it is logical that the same shear strength would re-

sult in just shear planes in a less lithified sediment but fractures and joints in a more lithified one. In particular, the variability of distinctness in a single bed along meter distances may be due to mass compensation. Besides, possibly other factors like grain size, siliciclastic content, pore water pressure, degree of earlier bioturbation, etc., may have influenced the resulting soft deformation, too. In some cases it seems that the observed traces of bioturbation have been overimposed on the already deformed soft sediment. Elsewhere, however, these traces roughly follow the geometry of the shear surfaces, i. e. the bioturbation has clearly preceded the deformation. The oriented nature of the arcuate surfaces may be due to stronger shocks which caused unidirectional translation of the sediments, i. e. without their elastic return in original position (the same must be valid for the subvertical variety). On the contrary, the sigmoidal and serpentine folds probably were formed through seismic waves of weaker magnitude, or alternatively, the sediments were more consolidated thus not allowing large volume displacement. Whatever the major control was, eventually bidirectional deformation took place in these two cases and at least partly elastic behaviour of the sediment is highly probable.

Irrespective of the specific parameters in each particular case the common penecontemporaneous sedimentary origin of the resulting folding is well indicated by its confinement to single beds between undeformed ones or to deformed horizons inside undeformed beds (Plate I, 1, 2, 3). Another evidence are the observed local truncations by erosion surfaces with the latter being overlain by limestones with grain-supported texture. Apparently, each bed deformation took place before the deposition of the next layer. The lack of relation between the observed shear surfaces and the locally present genuine joints or veinlets (i. e. cemented by sparry carbonate) precludes the late tectonic origin of the former after the complete consolidation of the lime sediments. Furthermore, the observed late tectonic joints and veinlets are well traced in the vertically adjacent undeformed beds and commonly show random geometry.

With earthquakes being assumed as the most probable agent for the generation of the described subparallel shear surfaces it is suggested that the latter should be designated as seismites (Seilacher, 1969).

Convolute lamination

Description

Prior to this study convolute lamination was described in the Mogila Formation by Чаталов (1997) and was also established by Бенатов и Чаталов (2000) in the Lyubash Formation. This structure occurs stratigraphically on a minor scale principally in clayey lime mudstones.

The observed convolute lamination is characterized by intrabed deformation of the building laminae into a complex system of small folds (Plate I, 4). These are best seen on weathered surfaces as contrasts in colour and relief are well visible. The folds display various morphology with respect to their axial plane position, interlimb angles, hinge pattern, relation between limbs and axial plane, etc. The chaotically undulating laminae show either constant thickness or may pinch out along centimeter distances. An important regularity is that the scale of the undulations is roughly proportional to the bed thickness. Very typical is also that the degree of convolute deformation constantly changes laterally along the respective beds. Besides, gradual or sharp transitions from undeformed sediment (with massive structure or horizontal lamination) are locally traced in upward direction (Plate I, 4). As mentioned above, rare transitions are also available from the subparallel shear surfaces. The total deformation of the sediments makes sometimes the recognition of the pre-deformation structures impossible although traces of bioturbation and horizontal lamination may be locally discerned. An important characteristic is the absence of faulting in the convoluted beds.

Interpretation

This is one of the most problematical structures in sedimentary rocks. Descriptions, classifications and interpretations on the basis of investigation of terrigenous rocks are more frequent in the literature probably on account of its wider occurrence in clastic sequences. On the other hand, convolute lamination is relatively rare in shallow marine carbonates unlike in deep marine environments.

With respect to carbonate rocks important experimental work was accomplished by Bogacz et al. (1968) who studied the specific mechanism of deformation. According to these authors the origin of convolute lamination may be explained by the so called "intrastratal flow" and vertical deformation conditioned mainly by

"density stratification". A basic prerequisite is the liquefaction of clayey-carbonate (marly) laminae associated with purer carbonate ones. If ductile deformational behaviour of the layers in such a multilayered unstable system predominates the original continuity of the layers is not lost and the deformation of the beds takes the form of convolute lamination. As a result from their different composition and rate of lithification, and therefore from the common instability of the primary unconsolidated sediment, a triggering-off of the latter takes place. The sudden fluidization may be triggered by seismic shocks, turbulent currents or rapid sediment loading (Allen, 1984; Collinson, 1994).

The hypothesis cited above finds support in the present case study as clearly purer carbonate laminae (light coloured) and marly ones (darker) can be discerned in the deformed beds. The fact that the observed convolute lamination shows transitions from horizontal lamination indicates that most probably the original (primary) laminae have undergone subsequent deformation. Thus the coexistence between deformed and undeformed bed sectors is a major evidence for the penecontemporaneous nature of convolute lamination. On the other hand, the constantly small thickness of the convoluted beds as well as their parallel surfaces testify against gravitational (slump) origin of this structure. The common lack of preferential orientation of the fold axes also precludes such slump origin and does not allow to predict any predominant direction of external pressure. Yet, unlike the subparallel shear surfaces discussed above, mostly vertical displacement must have taken place during the formation of the convolute lamination.

Wavy and crumpled bedding

Description

The presence of "wave-like folded clayey limestones" in the Babino Formation was mentioned by Тронков (1968). Actually wavy bedding occurs predominantly in the lower part of this lithostratigraphic unit (suite of the clayey and nodular limestones - after Тронков, 1995) and is established in all outcrops from the Western Balkanides. It is also very typical of the lower part of the Lyubash Formation. Irrespective of the particular lithostratigraphic unit this structure is observed regularly in lime mudstones to wackestones having elevated clayey content.

With respect to the stratification pattern wavy bedding is marked by slightly to moderately undulose surfaces at the top and bottom of beds (Plate I, 5, 6). Meanwhile thin "layers" inside the beds, which are built up of purer carbonate, follow these surfaces or multiply come into contact with each other because of wedging out. Dark grey marly material is present as intercalations among the purer calcareous layers showing higher degree of weathering (and hence more negative relief) (Plate I, 6). Commonly typical wavy bedding grades into so called crumpled bedding which is characterized by the presence of the same wavy horizons composed of purer carbonate but this time broken into tightly packed irregular fragments (Plate II, 1). This transition is traced principally in vertical direction - sometimes in a repeated manner. Another structural transition was established between wavy bedding and convolute lamination. In its turn, the crumpled variety locally shows gradual transitions into indistinct nodular structure.

Interpretation

Similarly to convolute lamination in carbonate rocks the formation of wavy to crumpled bedding was explained by Bogacz et al. (1968) in terms of intrastratal flow and vertical deformation triggered off in multilayered unconsolidated system which is characterized by instability of density stratification. The purer calcareous layers are more competent and the marly ones are prone to liquefaction. However, unlike the ductile behaviour of layers which generates convolute lamination, more brittle properties of the layers of high density account for minor downward collapse deformation. These brittle properties preclude the other extreme deformation manner, e. g. real brecciation, so that wavy to crumpled bedding appears as an intermediate type of deformation between the two end-members - convolute lamination and intraformational breccia (in this sense the observed transition from convolute lamination to wavy bedding is a solid evidence). A critical difference from the formation of convolute lamination is the conspicuous absence of any indication for lateral displacement.

On the other hand, it is suggested that the deformation might take place without any substantial external pressure or loading. This was demonstrated by the experimental work accomplished by Bogacz et al. (1968) who proved that the nature of the trigger forces is of minor importance for the onset of deformation since the latter proceeds almost entirely on account of

the potential energy stored in the sediments during deposition. Yet, a few trigger mechanisms have been proposed to launch the deformation process itself (wave and current action, critical loading due to intensive sedimentation, earthquakes, etc.) but neither of them can be considered as dominating in natural conditions (Bogacz et al., 1968). Whether typical wavy bedding or the crumpled variety is produced depends mainly on the relative thickness of the more clayey intercalations. The thinner they are the bigger is the chance to produce wavy bedding and not crumpled structure.

Slump structure

Description

Slump structure was established sporadically only in the lower part of the Babino Formation (suite of the clayey and nodular limestones) whereupon it occurs in one laterally continuous stratigraphic level. The slumps have always affected sediment packages in the decimetric range. The lithologic composition is characterized mainly by clayey micritic limestones but subordinately represented are pure limestone beds (some of them with grain-supported textures). The degree of deformation varies even in one single outcrop from isolated fragmented blocks to intensively deformed zones exhibiting chaotical folding of sediments (Plate II, 2). The boundaries of the slump level are locally changeable but preferentially are parallel to stratification. Faulting is a common feature, and along with the bigger scale of the folds and the distorted stratification, represent the major evidence to differentiate slumps from the observed convolute lamination.

Interpretation

Slumps are generated by gravity mass movements whereupon principally lateral movement takes place. This appears as a substantial difference with respect to the formation of convolute lamination. On the other hand, the supposed dip of the Middle Triassic ramp where the studied sediments were deposited, must have been only in the range of few degrees (on the analogy of modern examples - Schlager, 1997). It has been assumed that such values are sufficient to initiate a slope failure (Knaust, 1998). The specific trigger mechanism of slumps may be attributed to seismic shocks but other factors can be also strong currents and waves, high sedimentation rates, methane inclusions and sea

level changes (Martinsen, 1994). As an important prerequisite in this study case should be pointed out the predominant lithological composition of the deformed sediments (clayey limestones) making them highly susceptible to subaquatic slumping.

Load and flame structures

Description

Load structure shows massive occurrence in the Mogila Formation in many cases where a grain-supported limestone bed overlies a mud-supported one. The coarser material of the former penetrates locally and to different extent into the mud-supported layer showing downward protrusions of bulging, subspherical, elongated or simply irregular shapes (Plate II, 3). Rounded outlines are typical of the collapsed material. The dimensions of the protrusions reach up to several centimeters and their orientation varies from vertical to oblique. Load casts are locally observed on the lower surface of the grain-supported layers.

Flame structure (the term was introduced by Walton, 1956) occurs in the Babino Formation (suite of the clayey and nodular limestones) at the boundary between an underlying lime mudstone layer (with predominantly vertical burrows) and an overlying bioclastic floatstone bed. Sharp-ended tongues of carbonate mud (flame-shaped), ranging from a few millimeters to several centimeters, penetrate upwards into the coarser material (Plate II, 4). Irrespective of the various shapes the mud protrusions locally display certain sideward bending but without any preferential orientation.

Interpretation

The observed load structure was formed through overloading by the coarser deposited material against the underlying unconsolidated carbonate mud. The vertical sinking took place at irregular length intervals. It might be suggested that the deformation was related to periods of rapid mud sedimentation which were followed by also rapid carbonate sand accumulation. Thus the described load structure greatly resembles the same phenomenon frequently observed on the boundary between an overlying sand layer and an underlying mud layer in siliciclastic sequences, whereupon analogous liquefaction of layers takes place in a gravitationally unstable system and a denser material overlies a lighter one.

The genetic explanation of the observed flame structure is very similar. The interpretation may be related to a deformational process which is due to unequal loading and liquefaction. These brought about the upward penetration of the semi-consolidated carbonate mud into denser coarse-grained carbonate sediment. The lack of preferential orientation of the "flames" testifies to the penecontemporaneous origin of this structure, e. g. unrelated to the bottom current direction during the deposition of the sandy layer. Yet the observed bendings might be indication for a slight horizontal movement of the sediments during their deformation.

Ball-and-pillow structure

Description

This structure was observed only sporadically in sandstone beds from the lower part of the Lyubash Formation. Subspherical and oval bodies of fine-grained sandstones (sized from 15 cm to 35 cm) occur in marl packages. They are either closely packed or detached in centimeter to decimeter intervals but constantly form continuous rows (Plate II, 5, 6). Locally, some of the balls and pillows are positioned at some vertical (centimeter) distance below the basic sandstone layer. Very characteristic is the constantly rounded bottom of the bodies opposed to their flat upper surface as well as their laminated inner fabric. The laminations conform to the boundaries of the balls and pillows.

Interpretation

Ball-and-pillow structure (Potter & Pettijohn, 1977), which is sometimes termed "pseudonodules", belongs to these deformational structures where vertical displacement of the deposited material takes place. The specific inner fabric of the balls and pillows indicates that the primary sand has not reached complete lithification before deformation. The sinking or collapse took place at irregular intervals along the sand layer thus forming spatially discontinuous bodies of sand inside the soft mud. The particular shape of the bodies might have been dependent on the relative time of deformation whereas the size of the balls and pillows might be considered as an approximate indicator for the sand bed thickness. In this study case it is suggested that some vibration or shock caused the rapid sinking or collapse of the sand material into the underlying muddy one (this phe-

nomenon was experimentally demonstrated by Kuenen, 1958). The origin of the controlling stress could have been related with earthquakes or other catastrophic events. Alternatively and analogously to load and flame structures, ball-and-pillow structure may testify to rapid sedimentation, and therefore, be caused at least partially by overloading, e. g. without the influence of any external factor.

Signatures of palaeoseismic activity

Correlation over the study area

The most convincing signatures of paleoseismic activity in the studied sediments are represented by the deformed beds with subparallel shear surfaces. The latter are well correlated between some of the Lower Triassic cross sections along the Iskur river valley although they occur, as mentioned above, over a broader geographic area. The biggest number (eleven) of such deformed horizons is established in the type section of the Mogila Formation (near the hamlet of Sfrazhen) and the cross section north of the Lacatnic railway station. The correlation between both cross sections is facilitated by the almost perfect correlation between the peritidal hemicycles in them (Fig. 3). The number of beds with distinct occurrence of this structure is sharply reduced in northeastward, westward and southward direction. For example, only five levels are convincingly established in the cross section near the village of Zgorigrad, and respectively three and one in the cross sections around the villages of Tserovo and Gintsi. Consequently, it is assumed that main epicentre zone of the ancient earthquakes must have been situated in the area around the present Lacatnic railway station and hamlet of Sfrazhen (Fig. 1). On the other hand, some of the seismic shocks were probably of higher magnitude so that signatures from them are available in more remote areas. This conjecture is also supported by the presence of several beds with indistinct subparallel shear surfaces in the mentioned more peripheral cross sections.

The precise lateral correlation of the deformed horizons with seismites is difficult for some reasons. A major obstacle represents the spatial and time facies variability and different rates of sedimentation throughout the peritidal complex. These have caused changeable bed thickness and vertical range of the subfacies units in the shallowing-upward successions from the different cross sections. On the other hand, the occurrence of subparallel shear sur-

faces may have been texturally controlled. For example, if a grain-supported lime sediment has been deposited before the onset of a seismic shock, the imprint on the this packstone/grainstone bed will be negligible as proved by other workers (Knaust, 1998). Other obstacles for the precise correlation are the observed lateral transitions of the shear surfaces into various deformational structures (for example, convolute lamination), indistinctness of the structure itself (less intensive deformation, overimposed bioturbation, clastic admixtures), and finally, the nature of the outcrops (the structure is not observed in cross sections which are oriented parallel to the shear surfaces, i. e. perpendicular to the direction of deformation).

Correlation with Triassic rocks from Europe

On a more regional scale subparallel shear surfaces are widespread and stratigraphically continuous in the Lower Muschelkalk of the epicontinental Germanic Basin (Szulc, 1993; Török, 1993; Rüffer, 1996; Knaust, 1998; Neuwiler et al., 1999). However, an isochronic correlation with these occurrences is not possible as the age of the sediments is Anisian. Also of Middle Triassic age are the subparallel shear surfaces described from the island of Sardegna by Damiani (1973). To the knowledge of the present author the only known isochronic occurrence of subparallel shear surfaces in Europe is from the Szinpetri Formation of the Hungarian Aggtelek Karst (Michalik, 1997).

It should be mentioned, however, that earthquakes may have played a leading role in generating also the other described deformational structures. Besides, some of these structures are not commonly recorded from shallow-water platform carbonates and thus might be indicators for exceptional events like earthquakes (Demicco & Hardie, 1994). Therefore, the frequency of seismic shocks having affected the studied sediments may have been greater in time, e. g. including the Anisian age. Theoretically, as a barrier for the imprint of such signals in the carbonate rocks may be considered their texture and lithological composition. For example, in the Mogila Formation big vertical intervals are occupied by grain-supported limestones and coarse crystalline late diagenetic dolostones. The same might be assumed to some extent for the Babino Formation where tempestite layers occur on a large scale, e. g. the storm-influenced sedimentation presumably may have obliterated any structures related with earlier seismites. Anyhow, the question for the durability and intensity of the seismic activ-

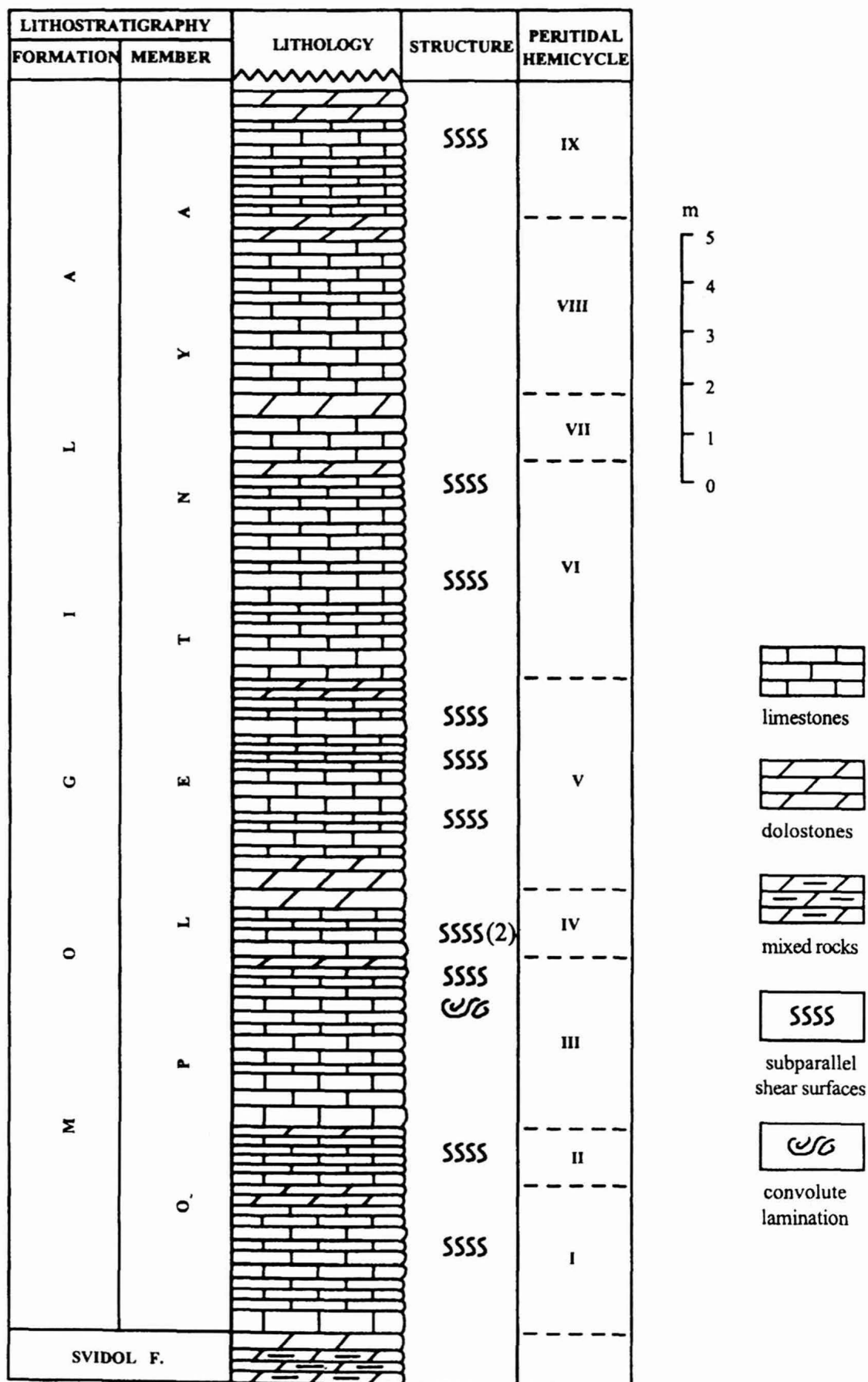


Fig. 3. Lithologic column of the vertical interval with occurrence of subparallel shear surfaces in the Mogila Formation (type cross section near the hamlet of Sphrazhen). Note: the number in brackets indicates the presence of two beds with subparallel shear surfaces

ity remains open as other factors may have controlled the formation of the mentioned structures as well.

Conclusions

Although deformational structures comprise small parts from the sections of the Iskur Carbonate Group in the Western Balkanides they are of specific interest mainly in the light of the interpreted paleoseismic signatures. Therefore a future task should be the field investigation for subparallel shear surfaces and other convincing seismites firstly in isochronic rocks from the nearest outcrops (Western Srednogie, Central Balkanides, Kraishte) and boreholes in order to outline a larger area that has been influenced by the paleoseismic activity. Although a bed-by-bed correlation over great distances is actually not possible eventual occurrences of seismites may be a more reliable indicator for the epicentres and magnitudes of the interpreted earthquakes as additional data may be processed applying suitable techniques (Allen, 1986). The obtained data allow to compose at least a local picture of the paleoseismic activity on the territory of present northwestern Bulgaria at the end of the Lower Triassic epoch.

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(Резюме)

Деформационните текстури в скалите на Искърската карбонатна група (долен - горен триас) от Западните Балканиди са концентрирани основно в три литостратиграфски единици (Могилска, Любашка и Бабинска свита), които обхващат хроностратиграфски

интервал спат-ладин. Текстуриите се установяват главно във варовици и в съвсем малка степен в пясъчници. Като обща тяхна диагностична характеристика се явява наличието на деформирани слоеве или пачки ограничени вертикално от недеформирани седименти.

Субпаралелните повърхнини на срязване се наблюдават само в най-долните нива на Могилската свита (Оплетненски член) в почти цялата южна част на Западните Балканиди. Те са привързани литоложки към варовити мадстоуни, които участват в изграждането на перитайдълни хемицикли. Морфоложки се различават четири подтипа такива повърхнини (дъговидни, сигмоидални, зигзаговидни и субвертикални) като първите два подтипа показват най-голямо стратиграфско разпространение. Произходът на тази текстура е дискуссионен, но в дадения случай се приема, че тя е възникнала като пряко следствие от периодична палеосейсмична дейност по време на ранната диагенеза на седиментите. Деформацията е протекла в латерално направление като различната отчетливост на понастоящем наблюдаваните повърхнини на срязване е била повлияна, наред със силата на сейсмичните трусове, и от редица чисто литоложки фактори. Изхождайки от морфологията на отделните подтипове се допуска протичането както на пластична, така и на еластична деформация.

Конволютната ламинация се установява в глинести микритни варовици от Могилската свита и има относително слабо разпространение. Тя се характеризира с вътрешнослойна деформация на изграждащите скалата ламини в сложна система от малки и морфоложки разнообразни гънки. Степента на нагъване е изменчива в рамките на даден слой и показва преходи в недеформиран седимент или съвсем рядко в субпаралелни повърхнини на срязване. Основна предпоставка за този вид деформация представлява нестабилния характер на утаечната система изградена от по-чисти и по-глинести варовити ламини. Самата деформация е протекла предимно във вертикално направление вследствие на т. нар. плътностна стратификация и посредством пластичното поведение на първичните ламини.

Вълнистата и смачкана слоистост са характерни за долните части на Бабинската и Любашката свита и отново са привързани към глинести варовити мадстоуни. Вълнистата слоистост се отличава с ондулиращи субпаралелни вътрешнослойни участъци докато при смачканата слоистост същите

участъци са фрагментирани в различна степен. Подобно на конволютната ламинация и двата типа слоистост имат за предпоставка първоначалната нестабилност на утайката изградена от ламини с различна плътност без да се изключва участието и на външни фактори. Разликата спрямо нея се свежда до по-крехките свойства на системата по време на деформацията, а конкретното формиране на едната от двете текстури зависи от относителната дебелина на мергелните прослойки.

Свлачищната текстура се установява в рамките на едно издържано ниво от долните части на Бабинската свита като обхваща пачка с дециметрова дебелина изградена преобладаващо от глинести варовици. Нагънатите зони са ограничени от субпаралелни на стратификацията повърхности и в тях се проследява вътрешносвлачищно разломяване. Основната предпоставка за възникването на тази текстура е бил слабият наклон на среднотриаската карбонатна рампа, а конкретният механизъм се е изразявал под формата на гравитационни масови движения в латерално направление. Спусъчният фактор на деформацията може да е бил свързан както със земетресения, така и с други явления като вълнения, течения, евстатични колебания и пр.

Текстурата на натоварване (Могилска свита) и пламъчната текстура (Бабинска свита) имат сходен произход. Образуването на първата е протекло чрез неравномерно проникване на по-едрозърнест и по-плътен карбонатен материал в подстилящата го хидропластична карбонатна тиня вследствие на претоварване. Получените внедрявания се характеризират с различна форма, но постоянно заоблени очертания. Пламъчната текстура е възникнала вследствие на проникване на неконсолидирана карбонатна тиня нагоре в по-късно отложен карбонатен пясък. Образуваните „пламъчета“ се характеризират със заострени краища и незакономерно огъване в горните си части.

Единствената текстура, която се установява в пясъчници е кълбовидно-възглавни-

честата. Тя се проследява в долните части на Любашката свита от разреза при с. Туден (областта Забърде). Морфоложки е представена от полусферични или овални пясъчни тела с дециметрови размери, внедрени в мергели. Долните части на телата са постоянно заоблени за разлика от плоската им горна повърхност. Интерпретацията на тази текстура се свързва със сравнително бързото и неравномерно вертикално потъване на кластичен материал надолу в нелитифицирана карбонатно-глинеца утайка. Допуска се контролиращото въздействие на шок или вибрации, причинени от земетресения или други катастрофични събития.

Въпреки някои трудности, свързани с литоложко-фациалната изменчивост на седиментите, както и природата на самите разкрития, проведената корелация на стратиграфските нива със субпаралелни повърхности на срязване показва най-голяма вертикална наситеност в част от разрезите в Искърския пролом (между гара Лакатник и махала Сфражен). Предполага се, че в този район е била разположена и основната епицентрова зона на древните земетресения. Цялостната сеизмична дейност върху изследваната площ от края на долнотриаската епоха наподобява палеосеизмичните прояви, известни от Германския долен мушелкалк с аниска възраст. От направения литературен преглед беше установен само един изохронен аналог на сеизмити в Унгария.

Тъй като се допуска, че земетресения са били поне частично контролиращ фактор и по отношение на някои от останалите описани текстури, твърде вероятно е сеизмичната активност в района да е продължила и през аниския век. Една възможна пречка за запечатването на по-изобилни палеосеизмични сигнали е голямото вертикално разпространение на неподходящи за това седименти, като например, варовици със зърново-поддържана структура и къснодиагенетични доломити (Могилска свита) или пясъчници (Любашка свита), както и наличието на щормови отложения (Бабинска свита).