

Abundant soft-sediment deformation structures in the Upper Cretaceous sequence of the Chelopech sub-basin, Central Bulgaria

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Abstract. Soft-sediment deformation structures (SSDS) in the Upper Cretaceous sequence of the Chelopech sub-basin (Central Bulgaria) provide a high-resolution record of the regional geodynamic evolution, from syn-rift to orogenic stages. Detailed analysis identifies a high-density distribution of synsedimentary slump folds, convolute bedding, diapiric structures, and peperites. The stratigraphic distribution of these features reveals three distinct evolutionary phases: (1) Lower Turonian basal units characterized by storm-induced reworking during initial subsidence; (2) Middle Turonian (Chelopech Formation) peperites and clastic diapirs triggered by coupled seismic activity and sub-aqueous magmatism during the late syn-rift phase; and (3) Santonian–Maastrichtian (Mirkovo and Chugovitsa formations) large-scale gravitational slumps and mass-gravity flows. This terminal phase reflects a shift toward regional tectonic inversion and steepened basin margins during orogenic closure. These results demonstrate that SSDS serve as a critical diagnostic tool for reconstructing the rapid transitions in the tectonic regime of the Srednogorie Zone.

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INTRODUCTION

Soft-sediment deformation structures (SSDS) represent a key diagnostic feature indicative of rapid sedimentary loading, liquefaction, and mass movement events, offering a window into past geological processes and their impacts on sedimentary basins. SSDS encompass a wide range of deformation structures observed in unconsolidated sediments, such as load cast, convolute bedding, flame structures, dish structures, and injection features,

among others (summary in [Shanmugam, 2017](#), and references therein). These structures form through the displacement, folding, and disruption of sediment layers under rapid loading conditions, leading to the generation of complex deformation patterns within the depositional sequence. Accurately interpreting SSDS requires meticulous analysis of sedimentary facies, stratigraphic relationships, and structural characteristics to reconstruct paleoenvironmental events. By carefully analysing these complex deformation patterns, researchers can re-

construct paleo-signatures and understand the dynamic processes that shaped ancient sedimentary environments.

In general, SSDS documented in sedimentary records of varying ages and geological settings are commonly interpreted as seismically induced (*e.g.*, Alsop and Marco, 2011; Berra and Filetti, 2011; Hilbert-Wolf *et al.*, 2016; Novak and Egenhoff, 2019). The mechanism of soft-sediment deformation structures involves water-saturated deposit liquefaction, fluidization, and deformation ranging from brittle to ductile. These structures are triggered by diverse processes, including seismic shakes, syn-sedimentary tectonics, magmatic activity, unstable substratum due to rapid sedimentation rates, storm events, biogenic gas escape, bottom currents, gravity-driven creeps and slides, etc., or a combination of these factors (*e.g.*, Lowe, 1976; Allen, 1982; Pratt, 2019).

The term SSDS could be expanded to all unconsolidated, water-saturated deposits affected by different event processes. They could include destroyed primary sedimentary structures like creeps, slides, slumps, storm-wave-induced structures, or redeposition of large amounts of material by mass-gravity flows (the entire spectrum of debris and turbidite flows). Some of them could cover thousands of square kilometers, but also could be on a centimeter scale. In some instances, an initial trigger may initiate a cascade of secondary deformation processes, obscuring the primary causative mechanism. Later processes, like lithification, hydrothermal activity, or overimposed tectonics, could also obscure the primary ones.

By analyzing the characteristics, distribution, and implications of SSDS within this geological framework, this study enhances understanding of the sedimentary and tectonic processes that shaped the Upper Cretaceous Chelopech sub-basin and their broader significance for interpreting regional geological evolution. This sub-basin, situated in Central Bulgaria, represents a tectonically active region during the Late Cretaceous characterized by complex sedimentary sequences, magmatic and hydrothermal activities, fault systems, and variable basin-fill deposits and paleoenvironments. Various sedimentary, magmatic, volcanoclastic, and epiclastic lithologies form the Upper Cretaceous sequence in the Chelopech sub-basin. The SSDS of different types, scales, and triggering mechanisms were documented throughout the entire succession. The occurrence of SSDS provides evidence of past geological processes, reflecting the response of unconsolidated sediments to rapid loading events, such

as earthquakes, sedimentation pulses, or fluid expulsion events. These events have occurred during the deposition of the Upper Cretaceous sediments, influencing sedimentation rates and sedimentary facies distributions within the Chelopech sub-basin.

Here, we will present one example of the eastern part of the Chelopech sub-basin, part of the wide-spread Upper Cretaceous basin system, where almost the entire Upper Cretaceous sequence is characterized by the existence of different types of SSDS, indicating specific events during the depositional evolution. Some of the SSDS described below may have polygenetic origins; they are classified primarily by their morphological characteristics to separate factual observation from genetic interpretation.

GEOLOGICAL SETTING

The Upper Cretaceous rocks are widespread in the Srednogorie Zone in Bulgaria and surrounding territories and are referred to as part of the Apuseni-Banat-Timok-Srednogorie (ABTS) basin system (Gallhofer *et al.*, 2015, and references therein). It is widely recognized that this system formed in a back-arc setting, due to the northward subduction of the Tethys ocean below Eurasia (Neubauer, 2002; Gallhofer *et al.*, 2015). The Srednogorie part of the basin system consists of a series of small, partly isolated sub-basins. These local depocenters, rather than large, continuous depositional systems, make correlation difficult, even over short distances, particularly for shallow-water deposits (Fig. 1). On the other hand, the presence of intermediate magmatic rocks, global-spread facies like CORB or turbidite rocks in the topmost part of the Upper Cretaceous sequence allows general correlation of the system and interpretation as a back-arc basin system of archipelago type (Neubauer, 2002; Vangelov *et al.*, 2019).

In the Central Srednogorie, two main sub-basins, Chelopech and Panagyurishte, usually referred in Bulgarian literature as “strips”, are known (Bončev, 1940; Moev and Antonov, 1978). The products of this basin system are sealing an Early-Alpine orogenic basement, which is characterized by diverse rock types. These range from Paleozoic metamorphic complexes, with varying degrees of metamorphic overprint, to remnants of Mesozoic rocks that predate the Upper Cretaceous. The tectonic setting is also complex, marked by deformation events of different ages and intensities. The Chelopech sub-basin, developed mainly over Paleozoic metamor-

phites, hosts its only magmatic center in its easternmost part. This center, Chelopech volcano (Cham-befort and Moritz, 2014, and references therein) is situated directly on the Sturgel-Boluvanya ductile shear zone, which marks the tectonic boundary between high- and low-grade metamorphic complexes (Lazarova and Gerdjikov, 2024), suggesting a strong structural control on its emplacement.

MATERIALS AND METHODS

The main goal of the research was to gain a better understanding of the lithostratigraphic scheme of the area, the relationships between the individual units, and specific features of the depositional systems.

We carried out detailed field work (mapping in 1:10 000 scale) in the upper course of the Ilindenska

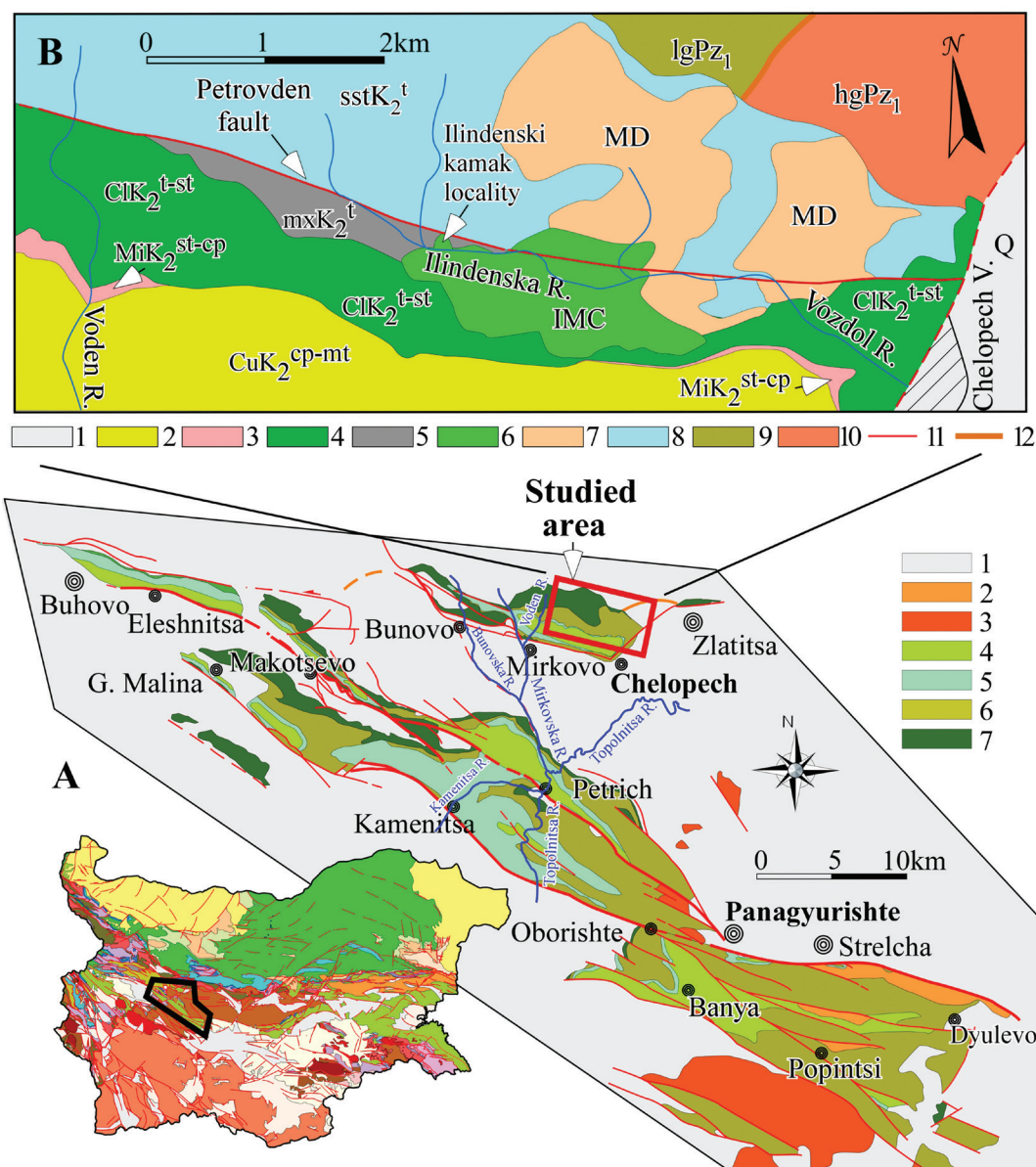


Fig. 1. A. Schematic geological map of the Central Srednogorie Panagyurishte and Chelopech sub-basins: 1 – pre- and post-Upper Cretaceous rocks; 2 – Paleocene (?); 3 – Upper Cretaceous plutons; 4 – Chugovitsa Formation; 5 – Mirkovo Formation; 6 – Chelopech Formation; 7 – basal amagmatic rocks of the Upper Cretaceous sequence; B. Schematic geological map of a part of the eastern Chelopech sub-basin: 1 – Quaternary; 2 – Chugovitsa Formation; 3 – Mirkovo Formation; 4 – Chelopech Formation; 5 – “Mixed” unit; 6 – Ilindenski Kamak magmatic center IMC; 7 – Murgana (magmatic) dome (MD); 8 – “Basal” sandstone unit; 9 – Paleozoic low-grade metamorphic basement; 10 – Variscan high-grade metamorphic basement; 11 – fault; 12 – ductile shear zone (Sturgel-Boluvanya).

River near Ilindenski Kamak locality. In addition, several north-south trending cross-sections were made in order to document the transition from lower Upper Cretaceous clastic sequences to upper volcanic-bearing levels. Bed-by-bed logging was performed to document the vertical and lateral distribution of soft-sediment deformation structures (SSDS), with particular attention to their host-rock facies.

Crucial data were obtained from drill core analysis at the Dundee Precious Metals facility in Chavdar Village. Three drill holes intersected the lowermost volcanic-bearing levels, revealing abundant SSDS. All these data were complemented by an extensive regional study that covers the whole Chelopech sub-basin, thus including the uppermost parts of the Cretaceous sequence.

STRATIGRAPHIC NOTES

The lithostratigraphic scheme for the Chelopech sub-basin was introduced by Moev and Antonov (1978). We have slightly modified it, including some larger and distinguishable rock successions, mainly in the lowermost part of the sequence, within the frames of the Chelopech Formation.

The Upper Cretaceous sequence in the eastern part of the Chelopech sub-basin is subdivided into the following units: 1) Lower Turonian basal Murgana sandstone unit; 2) Middle Turonian–Lower Santonian volcano-sedimentary rocks of the Chelopech Formation subdivided into: magmatic rocks, “Mixed” unit, volcanic and volcanoclastic rocks, epiclastic turbidite unit and “two mica” sandstone unit; 3) Lower Santonian–Lower Campanian limestones (carbonate turbidites) of the Mirkovo Formation (CORB facies); and 4) Upper Campanian–Lower Maastrichtian low-density sandy turbidites of the Chugovitsa Formation (Fig. 2). The lithologies referred to these lithostratigraphic units are in very complicated lateral and vertical interrelations, which is especially true for the Chelopech Formation, in which variable sedimentary, volcanic, volcanoclastic and epiclastic rocks were included.

Murgana sandstone unit

The basal sandstone unit (Murgana sandstones), crops out along the northern board of the Chelopech sub-basin and presents the shallow-marine deposition of clastic sediments: irregularly bedded, medium-grained to gravelly sandstones, dominated by quartz and feldspar, with a lack of mica and mud content and rare lenses of pebbly conglomerates.

Chelopech Formation

A significant part of the Chelopech Formation contains magmatic and volcanoclastic rocks with very changeable lateral and vertical characteristics, which makes it impossible to correlate even at short distances, especially around the main magmatic center in the easternmost part of the sub-basin. In some places it is difficult to recognize the original rocks due to intensive alteration and hydrothermal activity overprint. Westward better-stratified successions of mainly mass-gravity flows, volcanoclastic and epiclastic deposits with specific structures can be observed, but hydrothermal influence and occasional coherent lava flows were also documented. Mass-gravity flow deposits like volcanoclastic, epiclastic, and avalanche breccia can also be observed in the eastern part. Within the formation, five different litho-bodies/units could be recognized with unclear and laterally transitional interrelations and/or interfingering.

Magmatic rocks

Magmatic rocks are located in the eastern part of the Chelopech sub-basin, presented by the main Chelopech magmatic (volcanic) center (Moev and Antonov, 1978), Ilindenski Kamak subaqueous volcanic center (Velev *et al.*, 2021), and Murgana magmatic dome or shallow intrusion (Stoykov *et al.*, 2004), situated north of the Petrovden fault system (Popov and Mutafov, 1979) (Figs 1, 2), composed mainly of andesite and trachyandesite.

“Mixed” unit

On the Chelopech sub-basin northern basin margin, along the Ilindenska River (Figs 1, 2), an interval of mixed sedimentary and volcanoclastic deposits, almost entirely dominated by SSDS, was documented at the basal part of the Chelopech Formation. We designate it as a “Mixed” unit since these strata are transitional between the Lower Turonian basal “Murgana” sandstone unit rocks and the coherent magmatic rocks, which are common along the Ilindenska River. The “Mixed” unit is represented mainly by dark grey to black siltstones and shales. However, lens-like, fine-grained sandstones and epiclastic polyimictic pebbly-cobbly conglomerates with dark grey matrix also occur. Laterally, in the frames of the unit were established interactions between sedimentary, epiclastic, and auto-brecciated volcanic rocks to coherent andesite, which proves the synchronous occurrence of synsedimentary ex-

tensional tectonics and magmatic activity. The newly characterized local sub-aqueous volcanic center and the interrelations between magmatic rocks and synchronous volcano-sedimentary deposits around them were reported by Velev *et al.* (2021) for the Ilindenski Kamak locality. Stoykov *et al.* (2004) previously dated the magmatic rocks as Middle Turonian, but the measured sample was taken from a younger stratigraphic level. The “Mixed” unit is supposed to interfinger with the volcanic and volcanoclastic rocks southward to the main magmatic

center. To the north, it is limited by the Petrovden fault (fault system), which separates the “Mixed” unit (hanging wall) from the Basal sandstone unit (footwall) (Figs 1, 2).

Our field data indicates that the “Mixed” unit (or similar lithologies) is also present at the Bounovo River valley and in some isolated Cretaceous outcrops north of the town of Zlatitsa. In any case, the localized occurrences of these rocks denote a deposition in the local depocenter(s) during the (Early?) Middle Turonian time.

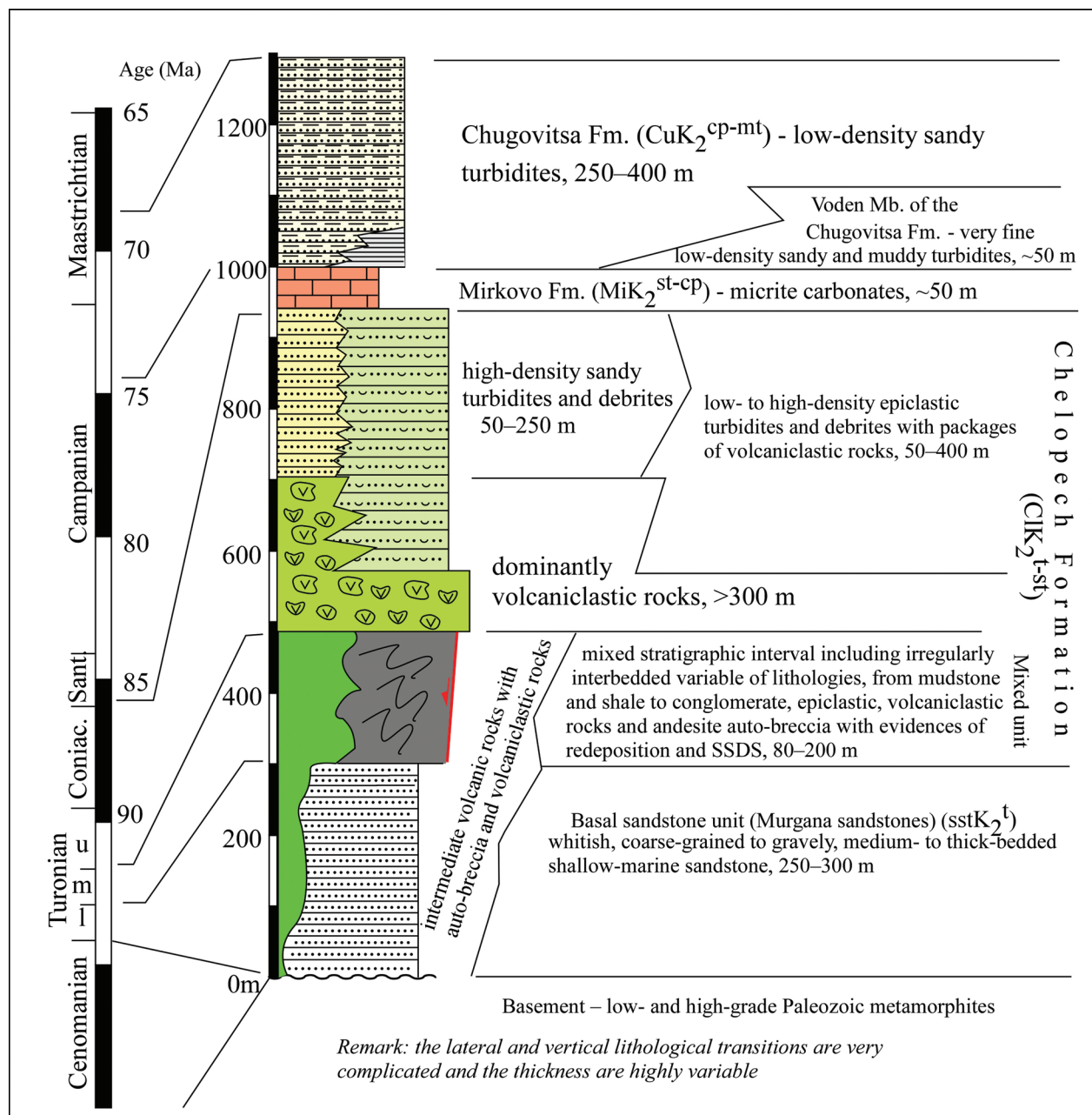


Fig. 2. Schematic lithostratigraphic section of the Chelopech sub-basin.

Volcanic and volcanoclastic unit

Along the ridge between the southern slopes of the Stara Planina Mountain and the valley of the Ilin-denska River can be recognized a mixed pile of volcanic and volcanoclastic rocks, several hundred meters thick, presented by lava flows, lava-breccias, and volcanoclastic and epiclastic flow deposits. It is cropped out, both on the main magmatic center and west of it, and the lateral interrelations with the lower part of the epiclastic turbidite unit are complex.

Epiclastic turbidite unit

West of the valley of Voden River, north of Mirkovo Village, the Chelopech Formation is presented by a stratified pile of high- to low-density epiclastic turbidites with diminishing thickness westward. It is supposed to be synchronous with the rest of the lithobodies/units of the formation eastward. The present day's outcrops suggests redeposition of the eroded epiclastic material for a maximum of 5–8 km along the Chelopech sub-basin axis westward.

“Two-mica sandstones” unit

On top of the main magmatic center and along the eastern and southern board of the Chelopech sub-basin was subdivided a locally developed but well-recognizable unit, named “two-mica sandstones” unit, composed of dominantly high-density sandy turbidites, indicating oversupplied terrigenous material in one local depocenter. The presence of mica (mainly muscovite) suggests input from the micaceous high-grade metamorphic basement from the south. The unit is overimposed on the volcano-sedimentary sequence but also interfingers with the uppermost part of it.

Mirkovo Formation

The Mirkovo Formation covers with a sharp boundary or fast transition the different lithologies of the Chelopech Formation. It consists of low-density carbonate turbidites (limestone), and includes syn-sedimentary slump folds of different scales all over its distribution. The slump folds are a very common element for the unit. According to Moev and Antonov (1978), Dimitrova *et al.* (1984), Popov (2005), and many other authors no erosional lower unit boundary has been identified. The Mirkovo Formation is covered by the sandy and muddy turbidites of the Chugovitsa Formation and partly by its Voden Member. It is impossible in one continu-

ous turbidite succession to find an interruption in the deposition, although these three units indicate a rapid change in depositional systems, confirmed by the field data.

Chugovitsa Formation

The topmost part of the Upper Cretaceous succession in the studied area corresponds to the Chugovitsa Formation. It is composed of medium-bedded sandy low-density turbidites, but occasionally, packages or single beds of muddy turbidites can also be observed. The sequence is usually monotonous, but in the stratotype section along the Chugovitsa Valley, variable resedimented deposits, even without typical turbidite features, including an interval of large-scale synsedimentary slump folds, were documented (Vangelov *et al.*, 2019).

MORPHOLOGICAL TYPES AND RHEOLOGICAL CLASSIFICATION OF SSDS

The term SSDS includes a wide spectrum of event deposits taking place in every depositional system during the different stages of basin evolution. The SSDS were established in the entire Upper Cretaceous sequence, both on the field and in the drill-hole cores, and can be summarized in the following types: *a)* folds and convolute beds; *b)* diapiric structures; *c)* water-escape structures; *d)* load cast and flame structures; *e)* boudinage structures; *f)* pygmatically folded seams and dykes; *g)* micro faults; *h)* contorted/disturbed strata; *i)* lithoclastic breccia; *j)* clastic and muddy dykes, peperites; *k)* structureless shale-, silt- and sand-beds, *l)* mass-gravity flows deposits.

The Upper Cretaceous sequence of the Chelopech sub-basin contains a diverse assemblage of soft-sediment deformation structures (SSDS), occurring across various depositional settings. To provide a systematic characterization, we classified these features based on their morphological characteristics and inferred rheological behavior (*e.g.*, Owen *et al.*, 2011). The observed SSDS are categorized into four genetic groups:

1. Liquefaction-induced features, including water-escape structures, clastic dykes, and structureless beds;
2. Gravitational density-instability structures, such as load casts, flame structures, and diapirs;
3. Convolute and plastic deformation features, comprising synsedimentary folds and pygmatically folded seams; and

4. Mass-transport deposits, ranging from micro-faulted strata to large-scale slumps and mass-gravity flows.

In the volcanic-bearing levels, these are further complemented by peperites, indicating synchronous magmatism and sedimentation.

The folds and convolute beds (a) indicate overloading caused by rapid sedimentary input over the unstable, not horizontal substratum in water-saturated soft sediments. Sliding, creeping, seismic shakes, dewatering and storm events are also some of the reasons (see [Shanmugam, 2017](#)).

The diapiric structures (b) can result from rapid deposition of different as lithology, grain size, and the possibility for liquefaction without excluding the sedimentary overloading. The water escape structures (c) can be explained by some or all of the abovementioned processes. The load cast and flame structures (d) are very common in deposits characterized by rapid deposition of coarser material over background finer sediments, storm events and the overloading also. The boudinage structures (e) could result from several processes like sliding, seismic shakes, overloading, and dewatering in thin-bedded contrast lithologies, etc. The pygmatically folded seams and dyke formation (f) could be explained by the combination of mechanisms – from sliding and slumping, seismic shakes, dewatering, micro faulting, etc.

The micro faults (g), in most cases, result from seismic activities. The contorted/disturbed strata (h) and the lithoclastic breccia (i) should have the same mechanism as the pygmatically folded seams and dykes. The clastic and muddy dykes, peperites (j) also indicate a combination of mechanisms – rapid terrigenous input, different as lithology, grain size, and the possibility of liquefaction rocks, overloading, dewatering, but could be (especially the peperites) a product of lava flow or mass-gravity flow. The structureless shale-, silt-, and sand-beds (k) in a sequence of another SSDS could be explained by the replacement of unconsolidated, water-saturated material by mass-gravity flows, but with a short transport.

Considering our understanding for including the mass-gravity flows (replacement of unconsolidated material by turbidite or debris flows) in a group of SSDS, it could be said that almost the entire Upper Cretaceous sequence is dominated by SSDS.

In the literature, the different types of SSDS have been interpreted as formed by various triggering mechanisms, depending on the geological setting, depositional system, basin type, etc. ([Shan-](#)

[mugam et al., 1994](#); [Nogueira et al., 2003](#); [Fortuin and Dabrio, 2008](#); [Rudersdorf et al., 2015](#), and many others). We cannot comment on the authors' ideas and their interpretation, because the described cases concern different stratigraphic levels, lithologies, and paleoenvironments, all the more that [Shanmugam \(2017\)](#) assumed some of the interpretations as unreliable.

DISTRIBUTION OF THE SSDS IN DIFFERENT UPPER CRETACEOUS STRATIGRAPHIC INTERVALS

The basal Murgana sandstone unit, composed of monotonous QFL coarse-grained deposits, indicated reworked by storm waves unconsolidated material. The dominant light mineral grains, lack of mica and mud content, the erosional lower bed boundaries, the medium to large scale hummocky cross stratification (HCS), the incised storm channels infilled after that, tempestites, and the presence of plant debris are proof for the reworking of not lithified deposits in situ or on short distances. Therefore, we accept these sediments as SSDS (Fig. 3).

The Chelopech Formation includes a variety of lithologies. The magmatic/volcanic rocks are presented by subaerial and sub-water magmatic centers, shallow intrusions, or dyke swarms and can trigger SSDS formation ([Velev et al., 2021](#)). The lava flows, avalanche breccias, lava breccias, lava clastic breccias, and hydrothermal activity could be a trigger for SSDS also (Figs 4–7). [Chamberfort and Moritz \(2014\)](#) recognized in the Chelopech magmatic center andesitic and dacitic lava flows and domes, volcano-sedimentary breccia, polymictic volcanoclastic breccia, hyaloclastites, massive lava flow and autobreccia, epiclastic breccia, sub-aqueous syn-volcanic breccia, and hydrothermal breccia.

West of the magmatic center, the presence of volcanic and volcanoclastic rocks decreases, and they interfinger with high- and further west low-density epiclastic turbidites or an entirely stratified turbidite sequence.

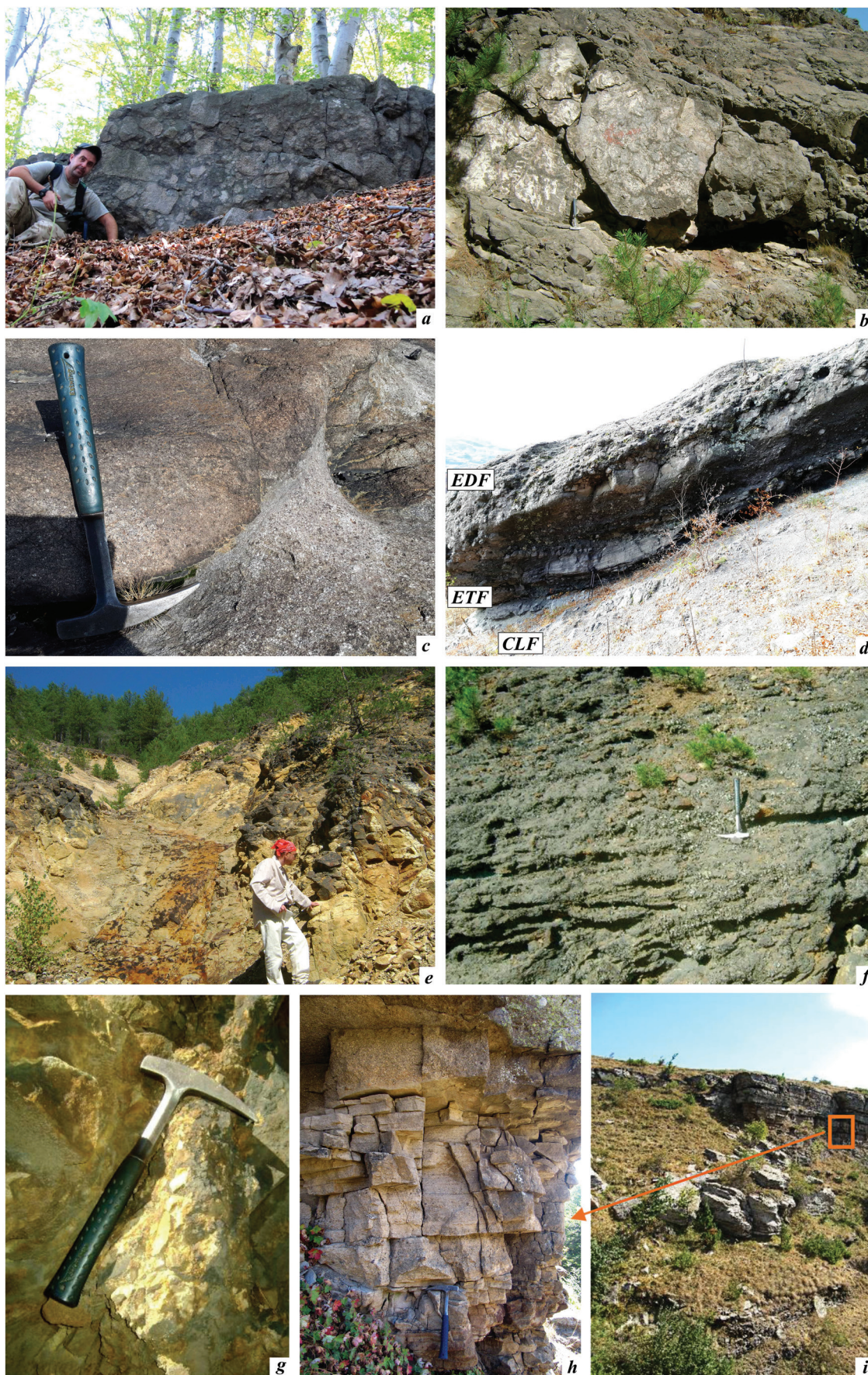
The “Mixed” unit, composed of variable lithologies, is dominated by SSDS all along its vertical and lateral distribution – slump folds, convolute bedding, lithoclastic breccia, mixed volcano-sedimentary debrites, lava dome, lava flows, lava autobreccia, hydrothermal overprint, etc.

The two-mica unit is a sequence of high-density sandy turbidite flows and can also be interpreted as event deposits.



Fig. 3. The basal “Murgana” sandstone unit: *a*) dominantly quartz-feldspar sandstones, irregularly and unclearly bedded in coarse grain-size subdivisions and small-scale hummocky cross-stratification (lower part of the package, behind the hammer), south of Murgana hut; *b*) truncation surface, most probably the lateral end of a large-scale storm channel, “White rock” locality; *c*) the prominent hummocky cross-stratification is widespread, south of Murgana peak and north of Ilindenski Kamak locality; *d*) incised storm channel (ISC), southwest of Murgana hut; *e*) proximal tempestite beds, enriched in bivalves shells and detritus, north of the town of Zlatitsa; *f*) coalified plant debris, north of Mirkovo Village, “Mirkovo red rock locality”.

Fig. 4. The Chelopech Formation: *a*) jig-saw breccia (lava flow?), south of Ilindenski Kamak local magmatic center; *b*) andesite lava and lava-breccia flow deposits, Vozdol River valley, north of Chelopech Village; *c*) coherent lava flow (below) and lava-breccia (above) with load cast and flame structures, most probably caused by very fast lava eruptions or, more plausibly, the product of a single magmatic pulse, west of Frunkaya locality; *d*) coherent lava flow (CLF), epiclastic turbidite (ETF) and epiclastic debris deposits (EDF), southwest of Frunkaya locality; *e*) intensive alteration of phreatomagmatic breccia, Vozdol River valley, south of Murgana hut; *f*) avalanche volcanoclastic breccia, Vozdol River valley, north of Chelopech Village; *g*) gas-pipe breccia dyke, intruded into phreatomagmatic breccia, Vozdol River valley, north of Chelopech Village; *h*) and *i*) further west of the magmatic center, the unit is represented by well-stratified epiclastic turbidite flow deposits, “Mirkovo Red rock” locality.



The Mirkovo Formation also consists of different types of SSDS, but they are located only along the southern board of the Chelopech sub-basin. They are mainly represented by different-scale syn-sedimentary slump folds, but carbonate turbidites, mixed carbonate, and epiclastic turbidites,

and disturbed/destroyed strata can be observed as well (Fig. 8).

The Chugovitsa Formation is composed of terrigenous low-density turbidites, but among the successions could be documented packages with large-scale syn-sedimentary folds and structureless shale



Fig. 5. The “Mixed” unit, part or member of the Chelopech Formation: a) the unit is represented in the easternmost outcrops by monotonous, finely laminated dark-gray shales, north of the town of Zlatitsa; b) contorted/disturbed strata in a mixed sandy/epiclastic/muddy sequence, caused by matrix-supported epiclastic debris flow deposits, product of rapid deposition and overloading, Zli Dol locality, southwest of Ilindenski Kamak local magmatic center; c) mixed breccia-conglomerate of volcanic clasts and background black shales, resulting from cascading processes, where epiclastic debris flows incorporated and disrupted host sediments, Zli Dol locality, southwest of Ilindenski Kamak local magmatic center; d) fine-grained epiclastic turbidite bed affected by hydrothermal alteration with floating clasts of volcanic and background rocks, Zli Dol locality, southwest of Ilindenski Kamak local magmatic center; e) diapiric structure of epiclastic sandstone with muddy matrix into coherent andesite lava flow, Zli Dol locality, southwest of Ilindenski Kamak local magmatic center; f) andesite diapir into background deposits, Ilindenski Kamak local magmatic center.

and sand beds, especially along the stratotype in the Chugovitsa Valley. Along the Chelopech sub-basin northern board, the sediments included in the frame of the unit do not indicate redeposition but a shallower paleoenvironment. They are affected by fair and storm waves and seismic shakes, slides, creeps, syn-sedimentary folds, and micro faults, combined by fossil traces for shelf deposition (Fig. 9).

DISCUSSION

Interpreting the synsedimentary structures is a suitable tool for restoring the paleoenvironments and the basin evolution stages or changes in the factors controlling the depositional systems. The Upper Cretaceous sequence in the eastern part of the Chelopech sub-basin is a good example of how



Fig. 6. The “Mixed” unit, part of the Chelopech Formation: a) convolute and diapiric structures and synsedimentary slump folds in epiclastic sandstones of variable grain sizes and background deposits, Ilindenski Kamak local magmatic center; b) convolute and diapiric structures in ceramic-like limestone lens (below) and contorted/disturbed strata in epiclastic turbidite bed, Ilindenski Kamak local magmatic center; c) lithoclastic breccia of background deposits into epiclastic sandstones, Zli Dol locality, southwest of Ilindenski Kamak local magmatic center; d) a diapiric structure of background deposits into epiclastic sandstone, Zli Dol locality, southwest of Ilindenski Kamak local magmatic center; e, f) interaction between background deposits (sandstone) and lava autobreccia flow, Ilindenski Kamak local magmatic center.

to interpret the synsedimentary structures as related to the basin evolution. The short-lived basin system and abundant occurrence of SSDS in almost the entire sedimentary and volcano-sedimentary sequences indicate clearly these changes from its onset to closure.

The basal Murgana sandstone unit indicates the beginning of the tectonic subsidence and is composed of storm-dominated event rocks in shallow marine conditions. The incised storm channels are about a few tens of meters wide and up to 5 meters deep, the preserved 2-meter-high hummocks with large-scale HCS, the proximal tempestites of bioclastic material, evidence the occurrence of re-

working of unconsolidated sediments by big storm waves (Fig. 3). The relatively uniform sequence indicates compensation of tectonic subsidence and depositional rate at the early stages of the sub-basin evolution.

These characteristics are only for the sub-basin northern board, while along the southern one, different lithologies (terrigenous, clayey, carbonate with fast vertical and lateral changes) were observed in the same stratigraphic interval, which we interpreted as a deeper paleoenvironment during the early syn-rift pre-magmatic succession.

Another interesting fact is the rapid transgression in the central and western Srednogorie sub-zones,

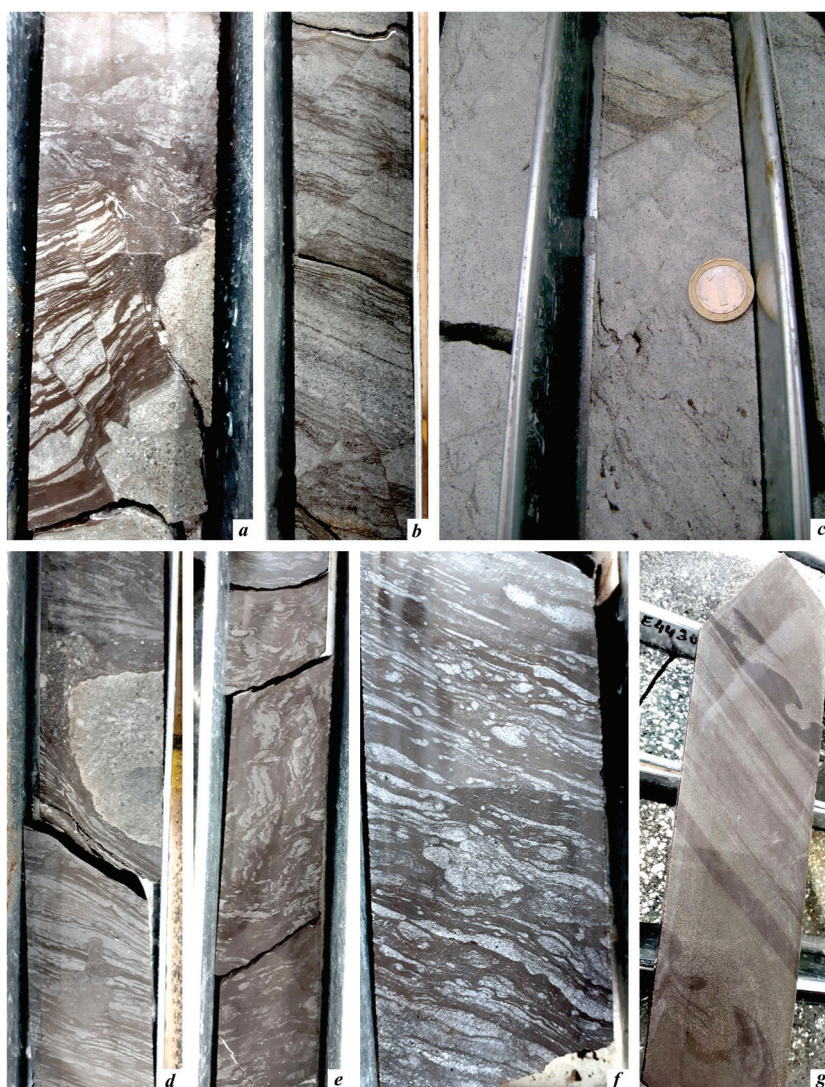


Fig. 7. The “Mixed” unit of the Chelopech Formation, SSDS observed in drill-hole cores: a–c) micro faults; d) diapiric structure in the background deposits (below), caused by matrix-supported epiclastic turbidite flow deposits with floating clast of poorly sorted epiclastic sandstone; e) ptymatically folded seams and dykes; f) ptymatically folded seams; g) load cast and flame structures.

where the basal pre-magmatic terrigenous sequence is dated as deposited during the Early Turonian. In the broadly exposed Upper Cretaceous Eastern Srednogorie sub-zone, the deposition started at the beginning of the Cenomanian. Similar features of abundant presence of SSDS can be observed in the basal pre-magmatic terrigenous sequence in the Panagyurishte sub-basin (Central Srednogorie, Turonian), southern parts of the Eastern Srednogorie (Strandzha Mountain northern slopes, Cenomani-

an), East Balkan Mts. (Aytos Pass and the Balaban Dere river valley), etc.

The magmatic activity during the Middle Turonian is presented by closely distributed magmatic centers – sub-aerial, sub-aqueous volcanoes, and shallow intrusions, marking the late syn-rift stage. Intensive magmatic activity within and around the main Chelopech volcano is evidenced by a diverse range of documented magmatic, volcanic, and volcanoclastic lithofacies ([Chambefort and Moritz, 2014](#)).



Fig. 8. Mirkovo Formation: *a*) large-scale synsedimentary slump fold (the cliff is about 4 m high), “Chelopech red rock” locality; *b*) synsedimentary slump folds and (most probably) inverted/slipped channel, “Chelopech red rock” locality; *c*) small-scale synsedimentary slump folds, southern part of Chugovitsa Valley; *d*) destroyed/disturbed strata at the base of the Mirkovo Formation, “Mirkovo red rock” locality; *e*) small-scale disturbed strata, dewatering structures, micro faults, pillar and dish structures, dykes, “Mirkovo red rock” locality; *f*) the transitional boundary between the epiclastic turbidite and matrix- to clast-supported debrites (Chelopech Formation) and overimposed Mirkovo Formation. The transitional interval also indicates redeposition, rather than an erosional boundary.

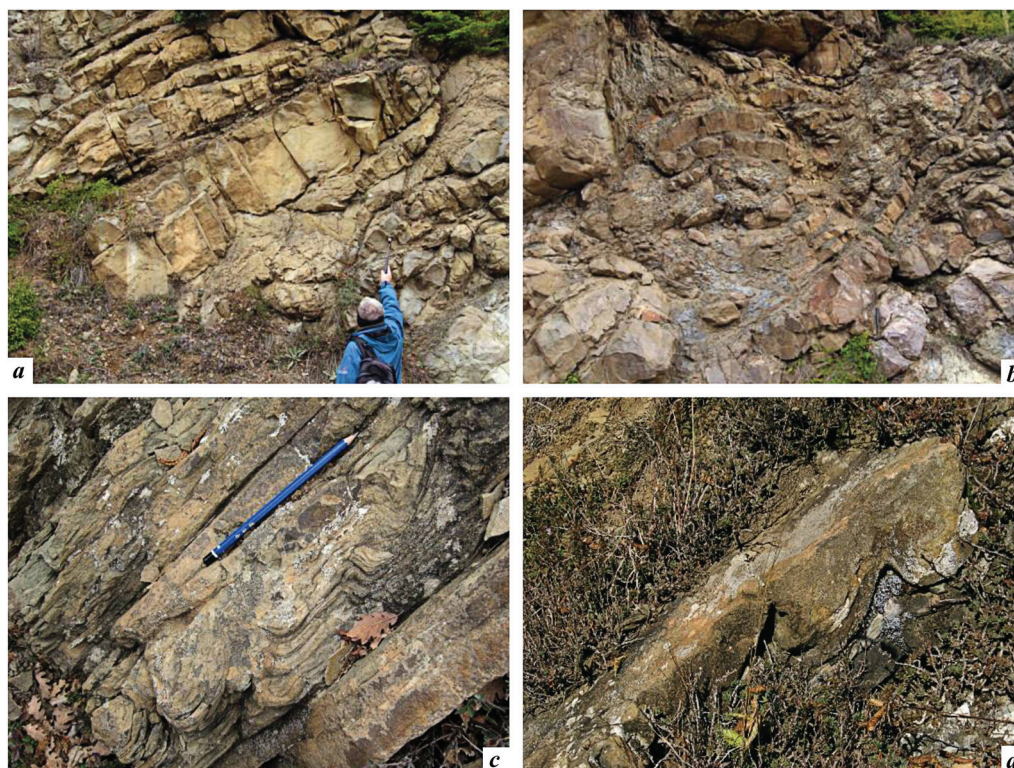


Fig. 9. The Chugovitsa Formation: *a, b*) interval of large-scale synsedimentary slump folds in the upper part of the unit, northern part of the Chugovitsa Valley; *c*) small-scale synsedimentary slump folds, northernmost outcrops of the unit in the sub-basin; *d*) slide load cast and flame structures in a 15 cm thick bed. The structures shown in (c) and (d) are uncommon and observed in isolated beds. The sandstones do not show typical turbidite features and indicate a shallower paleoenvironment.

Similar characteristics were documented in the synchronous late syn-rift magmatic sequence in the Panagyurishte sub-basin along the Topolnitsa River valley. In the East Srednogorie southern part, the magmatic activity occupies a wider chronostratigraphic range from Turonian to early Campanian, but the Turonian part along the Black Sea coast in the Strandza Nature Park is spectacular, representing different types of SSDS.

The synchronous deposition of the “Mixed” unit, dominated by SSDS and laterally interacting with the subaqueous Ilindenski Kamak magmatic center (Velev *et al.*, 2021) are evidence for synchronous magmatic activity and deposition. Southward, we suppose the interfingering of the unit and the thick magmatic rocks pile of the main Chelopech magmatic center, partly confirmed by field and drill-hole data. Due to the “Mixed” unit and partly the Ilindenski Kamak magmatic center, which are limited from the north by the Petrovden normal fault, and most of the SSDS indicate seismic shakes, we presume a combination of magmatic and seismic activities during the formation of this stratigraphic interval (Figs 1, 4–7).

All the recognizable lithologies included in the Chelopech Formation – magmatic, volcanic, volcanoclastic, epiclastic, and the rocks of the “mixed” and “two-mica sandstones” units, can be designated as event rocks. The “Mixed” and “Two-mica sandstones” units are locally distributed lithofacies, but the volcanoclastic and epiclastic rocks are broadly developed across the entire Srednogorie zone, representing different types of depositional settings.

The carbonate turbidites of the Mirkovo Formation, the presence of different scale syn-sedimentary slump folds and disturbed strata (Fig. 8) confirm the seismic activity or deposition on inclined substratum. The contrasting lithology of this stratigraphic interval, observed in almost the entire basin system (ABTS) and especially in its Srednogorie part, allows it to be interpreted as deposited during the post-rift stage of its evolution. The changeable thickness of the unit and the thickest successions on top of the main magmatic center allows it to be interpreted as a local depocenter controlled by thermal subsidence. The location of the other types of event deposits only along the southern outcrops of the unit and

its upper part showing overlapping of the post-rift and inversion stages of the basin evolution.

The dominated terrigenous turbidite sequence (Chugovitsa Formation), deposited by mass gravity flows, and the presence of packages of large-scale syn-sedimentary folds, are evidence for deposition in the orogenic stage of the basin evolution. The cessation of the deposition with relatively deep-water sediments covered by Late Miocene terrigenous deposits could also be interpreted as syn-orogenic deposition and mark the sub-basin and the basin system closure.

Similar are the characteristics in the southern parts of the entire Srednogie Zone – onset of the shortening and active compressional tectonics along the basin system southern board during Late Campanian, beginning of the basin system closure during Late Campanian, and its final closing before the Late Maastrichtian.

CONCLUSIONS

The systematic investigation of the Upper Cretaceous sequence in the Chelopech sub-basin identifies an abundant and diverse record of soft-sediment deformation structures (SSDS) that are stratigraphically pervasive. Rather than being isolated occurrences, these structures represent a high-resolution archive of paleoslope instability and seismic activity throughout the basin history. By documenting these features from the early syn-rift stages to the orogenic closure, this study demonstrates the significance of SSDS as diagnostic tools for reconstructing complex geodynamic transitions where traditional stratigraphic markers may be absent.

Integrating extensive field data from across the entire Chelopech sub-basin and comparative observations from coeval basins within the Srednogie Zone, these findings provide a robust framework for understanding the rapid geodynamic evolution

of the Apuseni-Banat-Timok-Srednogie belt. As a first systematic classification and genetic interpretation of SSDS in the Cretaceous successions of Bulgaria, this work emphasizes the importance of “event stratigraphy”. By focusing on these previously overlooked event rocks, we can more accurately constrain the timing and nature of the regional tectonic pulses that shaped the Balkan Peninsula geological past.

The information on deformations in soft sediments is almost missing in publications on the Bulgarian geology, except some for the carbonate part of the Triassic sequence, but they are not classified as SSDS.

The Chelopech sub-basin is part of the widespread magmatic and metallogenic Apuseni-Banat-Timok-Srednogie belt, but is situated in its marginal parts. Although our fieldwork covers a limited area, the concentration of SSDS, together with other geological characteristics, serves as an excellent basis for interpreting sub-basin evolution and correlation with the other parts of the basin system. We also want to draw more attention to the “event stratigraphy”, events and event rocks in the geological past.

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