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Lacustrine Slope-Related Soft-Sediment Deformation Structures in the Cretaceous Gyeokpori Formation, Buan Area, SW Korea, and Volcanism-Induced Seismic Shocks as Their Possible Trigger

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Abstract: The Gyeokpori Formation in the Buan volcanic area primarily contains siliciclastic rocks interbedded with volcanoclastics. These sediments are characterized by a variety of soft-sediment deformation structures (SSDS). The SSDS in the Gyeokpori Formation are embedded in poorly sorted conglomerates; slump folds are also present in the formation. The deformation mechanisms and triggers causing the deformation are not yet clear. In the present study, the trigger of the SSDS in the Gyeokpori Formation was investigated using facies analysis. This included evaluation of the reworking process of both cohesive and non-cohesive sediments. The analysis indicates that the SSDS are directly or indirectly associated with the alternation of conglomerates and mud layers with clasts. These layers underwent non-cohesive and cohesive deformation, respectively, which promoted SSDS formation. The slump folds were controlled by the extent of cohesive and non-cohesive deformation experienced by the sediment layers in the slope environment. The SSDS deformation style and morphology differ, particularly in the case of reworking by slump activity. This study contributes to the understanding of lacustrine slope-related soft-sediment deformation structures.

Keywords: Gyeokpori Formation; soft-sediment deformation structures; slumps; lacustrine environment

1. Introduction

Soft-sediment deformation structures (SSDS) develop in unconsolidated sediments during or shortly after deposition. Such structures occur in all sedimentary environments and are caused by liquefaction of sediments, which is sometimes followed by fluidization [1–4]. SSDS in lacustrine sediments of all ages have been reported in the past few decades [2,5–12].

The Cretaceous Gyeokpori Formation comprises sediments that accumulated on the slope of a subaqueous fan-delta system, an environment that is favorable for creating and preserving SSDS [9,13–17]. However, the deformation mechanism and trigger of these structures are not always clear. This is partly because small differences in sediment characteristics or depositional processes can produce different SSDS. To understand the formation mechanisms of different SSDS, facies analysis [3,4] is a useful but still underexplored approach.

In the present study, facies analysis was used to investigate the lacustrine slope-related Gyeokpori Formation in the Dakibong section (Figure 1). The objectives of this investigation are to determine the triggers of the SSDS and to decipher their deformation mechanisms. The analysis involves evaluation of the reworking of both cohesive and non-cohesive sediments.

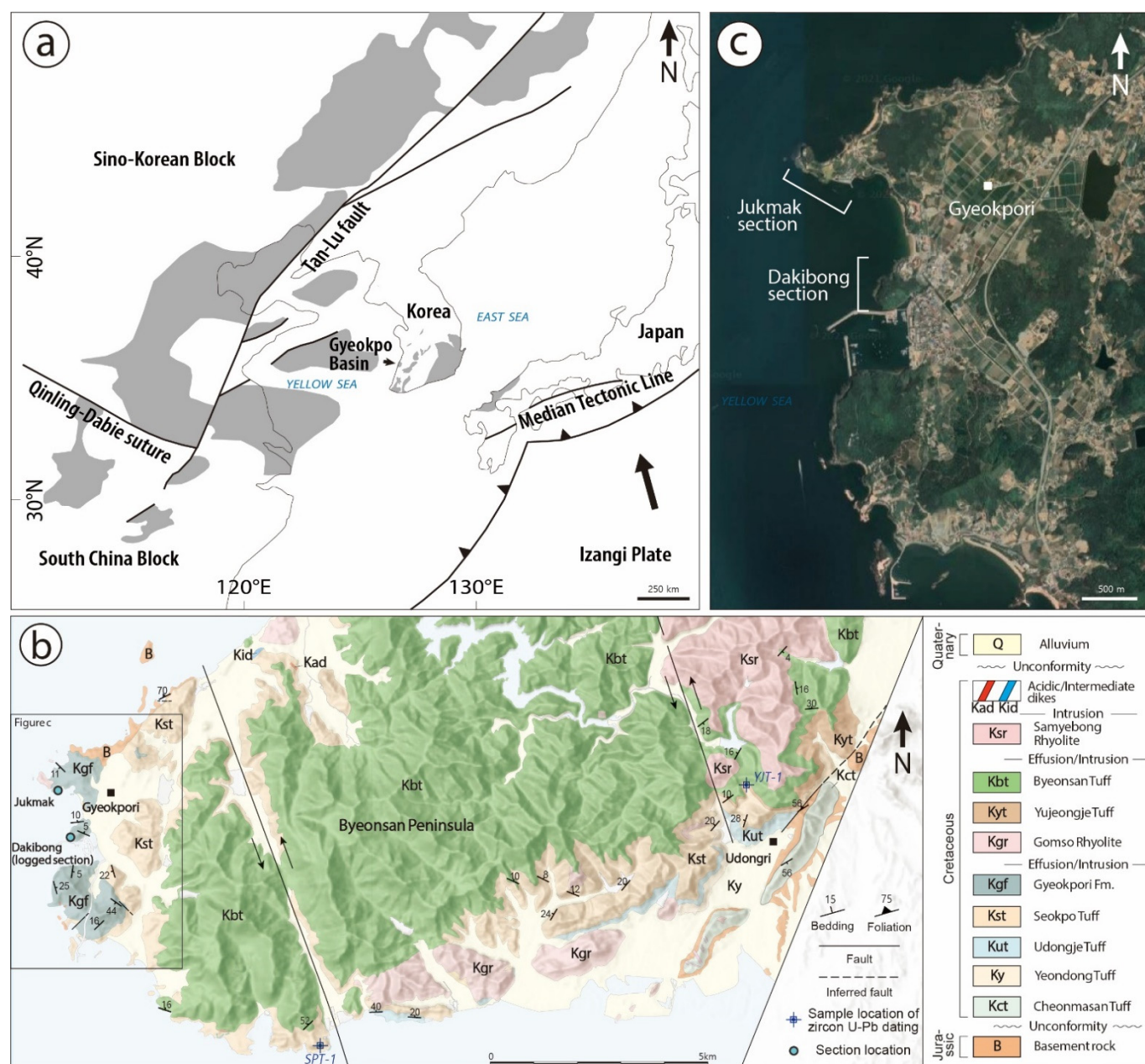


Figure 1. Location maps. (a) Tectonic outline and distribution of Cretaceous (Tertiary) sedimentary basins including volcanic rocks (shaded areas) and fault systems in eastern Asia (modified after [18]). (b) Geological map of the Buan volcanic area, showing the study area in the western part of the area (modified after [19]). (c) Satellite image map showing the study area and the locations of the studied sections.

2. General Geology

During the Cretaceous, the Korean peninsula underwent left-lateral crustal deformation and arc volcanism induced by oblique subduction of the Izanagi Plate under the Eurasian Plate (Figure 1a). As a result, numerous volcano-sedimentary successions were formed by this crustal deformation; the Buan volcano-sedimentary succession is one of them [20–24].

The Buan volcano-sedimentary succession comprises nine units that are distinguished based on the lithology, associated eruption style (explosive vs. effusive), grain size, mineral composition, and lithic components. These units (partly still informal), from old to young, are the Cheonmasan Tuff, Udongje Tuff, Seokpo Tuff, Gyeokpori Formation, Gomso Rhyolite, Yujeongje Tuff, Byeonsan Tuff, and Samyebong Rhyolite (Figure 1b) [20].

The Gyeokpori Formation is characterized by abundant SSDS [21,22]; the sediments can be studied in the Jukmak and Dakibong sections (Figure 1c), where they are exposed in coastal cliffs and wave-cut terraces along the west coast of the Byeonsanbando National Park [23,24].

The present study involves an analysis of the sediments in the Dakibong section, which represents the upper part of the Gyeokpori Formation. The formation, which is approx. 290 m thick, comprises conglomerates with clasts of variable sizes, gravelly sandstones, mudstones, and abundant volcanoclastics (Figure 2). Deposition occurred at alternately low and high sedimentation rates on the steep slope and on the plain of a lacustrine delta [24]. According to paleocurrent directions deduced from the geometry and dip directions of large delta lobes and bed geometry, as well as from sedimentary structures, the delta in the southern margin of the basin prograded toward the north to northwest. In contrast, the delta on the northern margin prograded toward the south to southwest [24]. Thus, the depocenter was probably in the west of the basin, and the basin floor was also likely gently inclined westward [24].

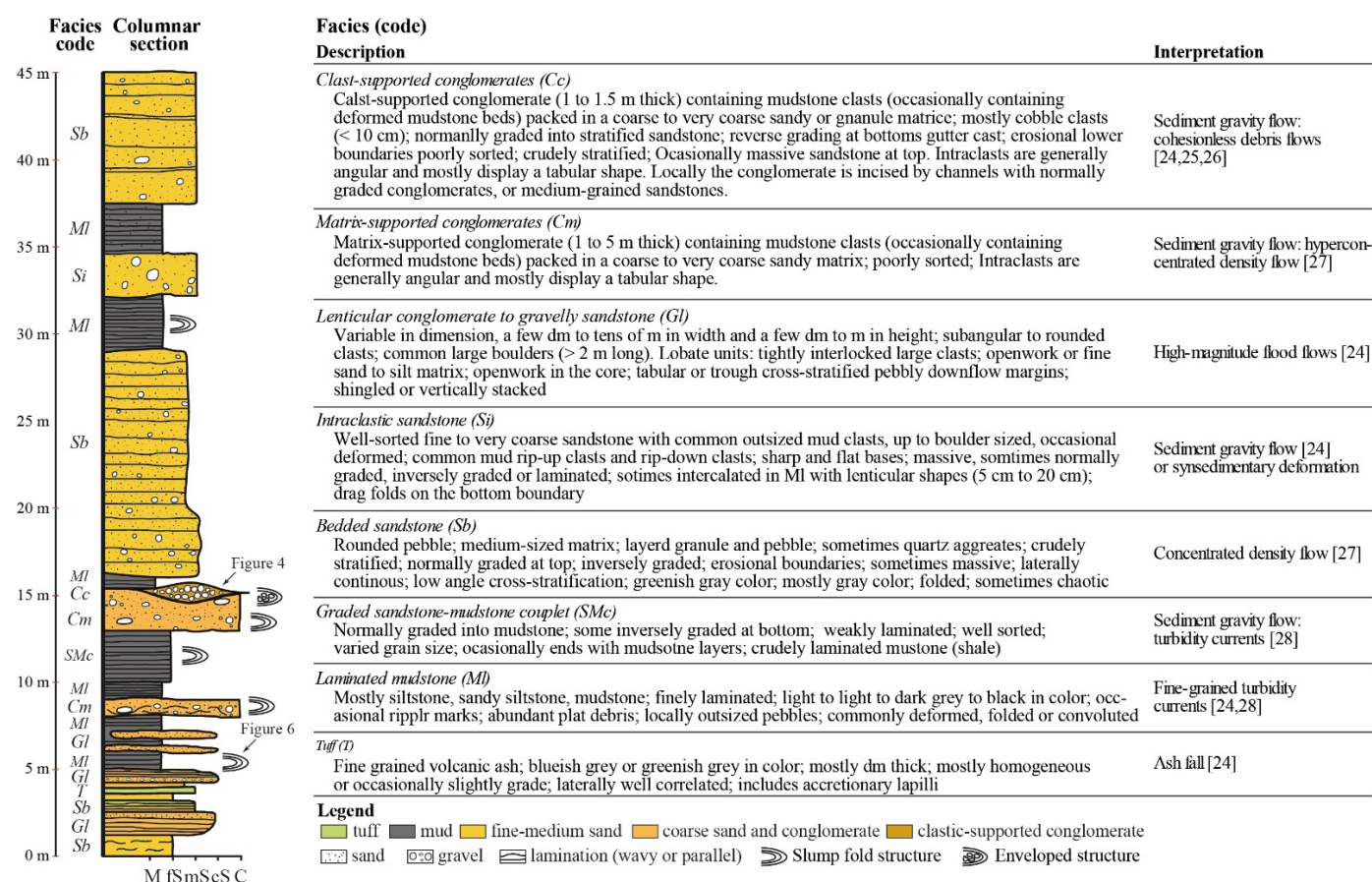


Figure 2. Sedimentary log of the Dakibong section (see Figure 1b) with facies descriptions and interpretation [24–28] (modified after [21]).

Among the main SSDS reported in the formation [22], the envelope structures and slump folds must genetically be related to the paleoslope (Figure 3). Although gravity-flow deposits (formed by debris flows and turbidity currents) are dominant [24], ten sedimentary facies have been distinguished in the Gyeokpori Formation, and eight facies have been distinguished in the Dakibong section, based on textures and sedimentary structures [22]. These ten facies can be grouped into five facies associations, four of which represent subaqueous fan systems, while one represents a basin plain [22].

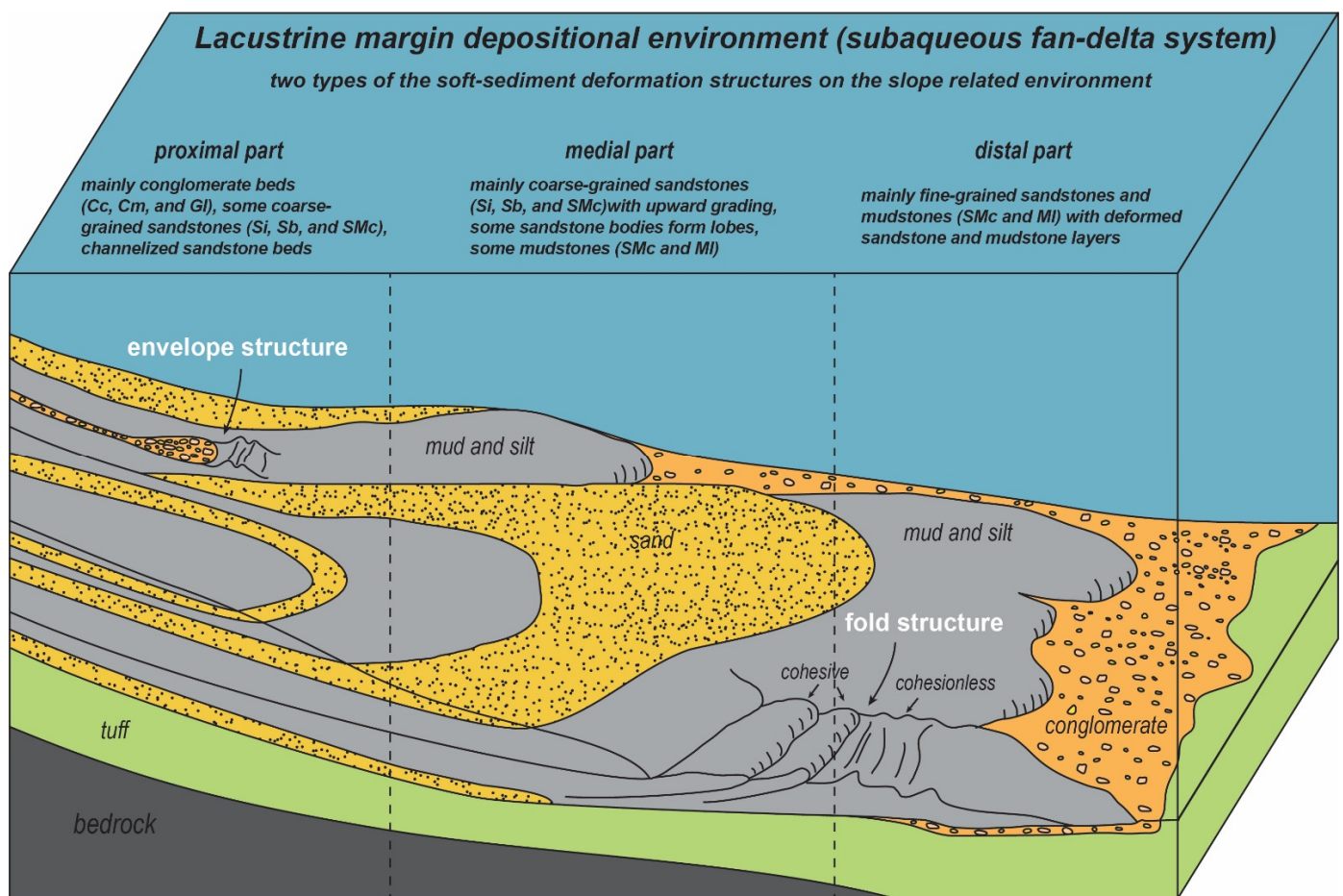


Figure 3. Depositional environment model of the Gyeokpori Formation showing areas where the various types of slope-related soft-sediment deformation structures are present. Depositional model is not to scale.

3. Methods

Facies analysis is a useful approach to understand the formation mechanisms of SSDS [3,4], but this method is, unfortunately, commonly neglected in SSDS analyses. Detailed facies analysis and inference of depositional environments have been performed for the Gyeokpori Formation [21–24]. In the present study, facies analysis is used as a tool that helped to reconstruct the deformational processes of two types of SSDS in the Gyeokpori Formation that occur in the Dakibong section (Figure 2) that could not well be understood without insight into the sedimentary facies. This analysis involves an evaluation of the reworking processes of both cohesive and non-cohesive sediment. The age of the Gyeokpori Formation (and thus of the SSDS) has been constrained by zircon U–Pb dating using a SHRIMP IIe/MC ion microprobe (Australian Scientific Instruments, Canberra, Australia) in the Ochang Center of the Korea Basic Science Institute (KBSI). The zircons were separated from samples of the underlying Seokpo Tuff (SPT-1) and the overlying Yujeongje Tuff (YJT-1) (Figure 1). The internal textures of the zircon grains were examined before analysis using a scanning electron microscope (JSM-6610LV; JEOLUSA, MA, USA) in back-scattered electron (BSE) and cathodoluminescence (CL) imaging modes. U–Th–Pb isotopic analysis was conducted following the procedure described by [29]. To calculate the U and Th contents of the zircon grains, the SL13 (Sri Lankan gem zircon; U = 238 ppm) zircon reference material was used [30], while the $^{206}\text{Pb}/^{238}\text{U}$ ratio was calibrated using the FC1 zircon standard (1099 Ma old Duluth gabbro with $^{206}\text{Pb}/^{238}\text{U} = 0.1859$) [31]. Common Pb contributions were corrected using the measured ^{204}Pb and the common Pb composition suggested by [32]. The Pb–Th–U isotopic ratio in the analyzed zircon and the weighted mean age were calculated using SQUID 2.50 and Isoplot 3.75 [33,34]. Owing to the lack of

$^{204}\text{Pb}_c$ correction, each analysis point displayed in the Tera–Wasserburg diagram involves an error range of 2σ . The reported mean zircon ages are ^{207}Pb corrected $^{206}\text{Pb}/^{238}\text{U}$ values, with the uncertainties calculated at the 95% confidence level. The U–Pb dating results for the Seokpo and Yujeongje Tuffs are presented in Supplementary Materials—Table S1.

4. Results

4.1. SSDS in the Gyeokpori Formation

4.1.1. Sediment Lenses Embedded in Poorly Sorted Conglomerate

The clast-supported conglomerate (facies Cc of [22]) exhibits an uncommon deformation structure (Figure 4). The dark grey matrix consists of sand, silt, and mud; most grain boundaries between the clasts and the sandy matrix are sharp, but boundaries between successive layers are not pronounced. The thickness of the deformed conglomerate bed varies significantly (from 0.1–0.8 m) within lateral distances of 0.2–1 m, and the most severe deformation occurs in the thickest layer.

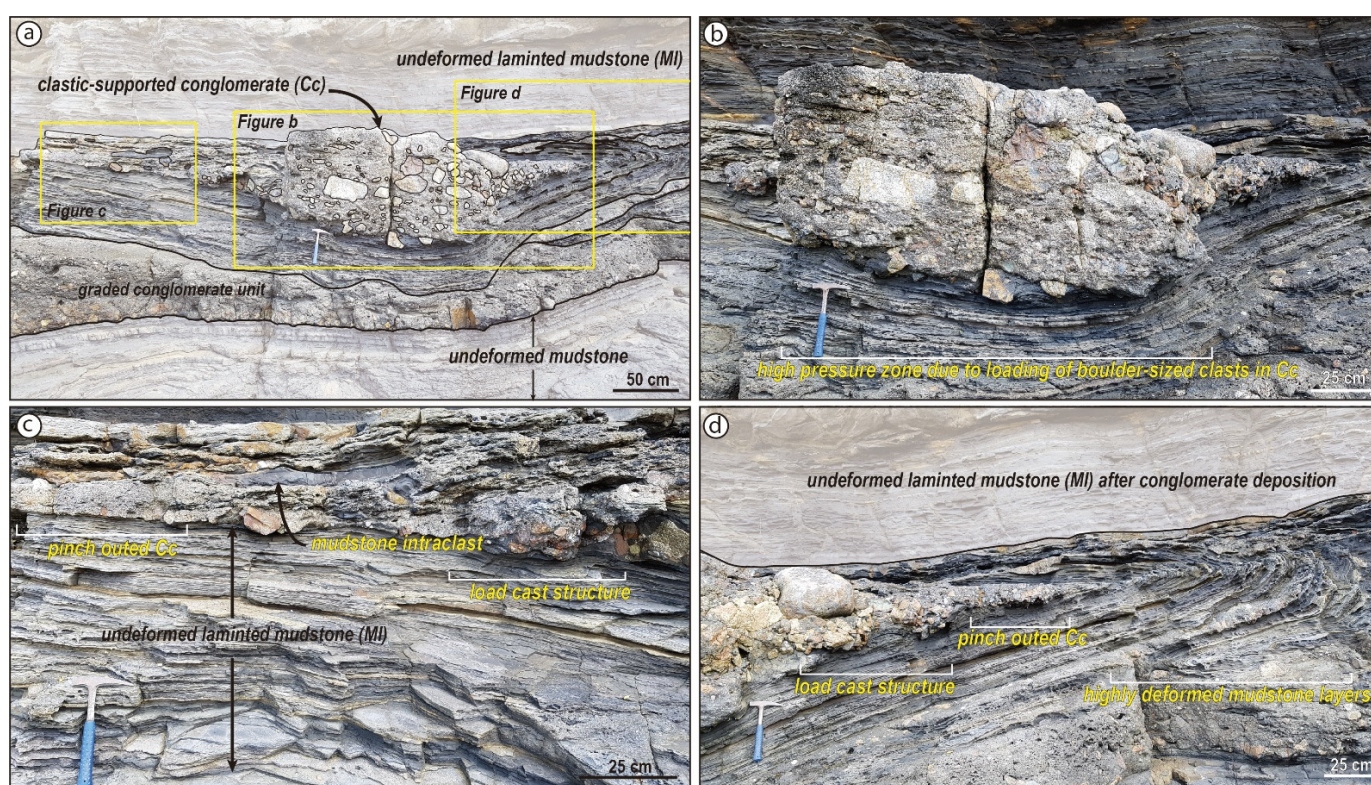


Figure 4. The envelope structure in Jukmak Section. (a) Overview with the boundaries between the layers. (b) Close-up of the block of clast-supported conglomerate embedded in deformed mudstone. (c) Close-up of the layered mudstone under the conglomerate block. (d) Highly deformed part of the mudstone alongside the conglomerate block, with layered mudstone forming a fold with limbs both above and below the conglomerate block.

The deformed conglomerate is intercalated between Ml facies beds, and the overlying bed is connected to the underlying bed through a fold structure engulfing the conglomerate. The conglomerate bed locally contains numerous huge clasts (up to 0.2 m high and 0.5 m wide) of Ml material, and some of these clasts are folded.

4.1.2. Slump Fold Types

The slump folds in the Gyeokpori Formation are composed of sediments belonging to the Ml, Sb, and SMc facies (Figure 5). The fold structures in the laminated mudstones are not characterized by thin beds, but rather occur in sets with thicknesses of commonly over 1 m, but of at least 30 cm (Figure 5a). Many slump folds have been preserved incompletely

because their upper parts were eroded by subsequent slumping material (Figure 5c). The grain-size distribution in the composing layers also varies, resulting in layers dominated by mud (Figure 5a,c), by sand (Figure 5g), or by mixtures of sand and mud (Figure 5e) in different proportions.

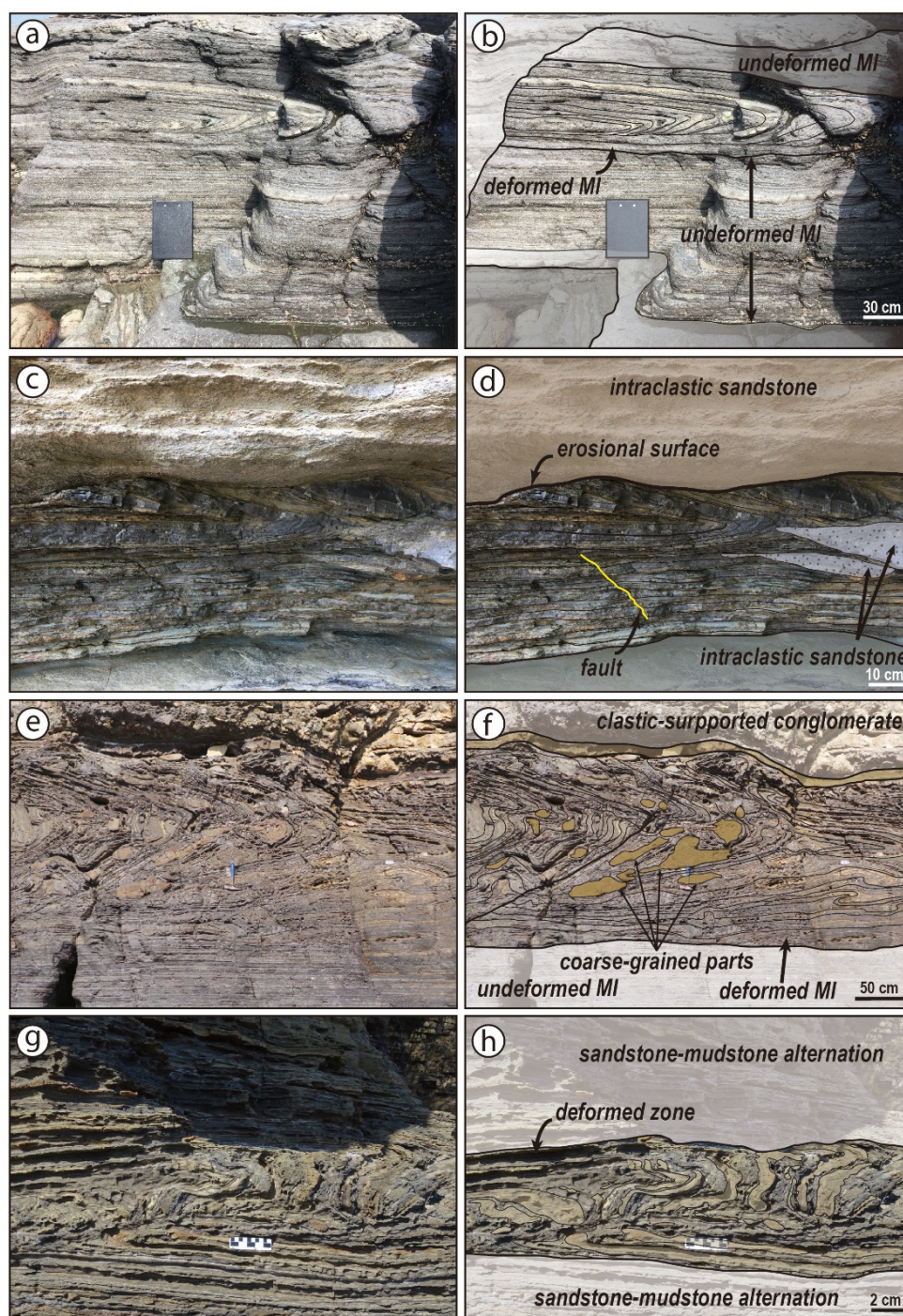


Figure 5. Different types of slump fold structures in *MI* and *SMc* with (a) a slump fold mainly composed of fine-grained sediments (mud and silt), (b) idem, with the boundaries between layers indicated, (c) slump fold consisting of fine-grained sediments (silt and fine sand), (d) idem, with the boundaries between layers indicated, (e) slump fold dominated by fine-grained sediments but containing some coarse-grained sediment, (f) idem, with the boundaries between layers indicated, (g) slump fold containing comparable amounts of fine-grained and coarse-grained sediment, and (h) idem, with the boundaries between layers indicated.

Primary features, such as bedding planes and lamination, are well-preserved in the mud-dominated fold structures (Figure 5b), and these are locally associated with low-angle reverse and normal faults. The fold axial surfaces are characterized by low dip angles (i.e., these are sub-parallel or parallel to bedding). Deformation increases with an increasing sand proportion, creating undulations and discrete lamination. Occasionally, the folds contain rock fragments interrupting the original lamination, so that the lamination looks broken (Figure 5f). In the top layers, some fold structures also show water-escape structures (Figure 6).

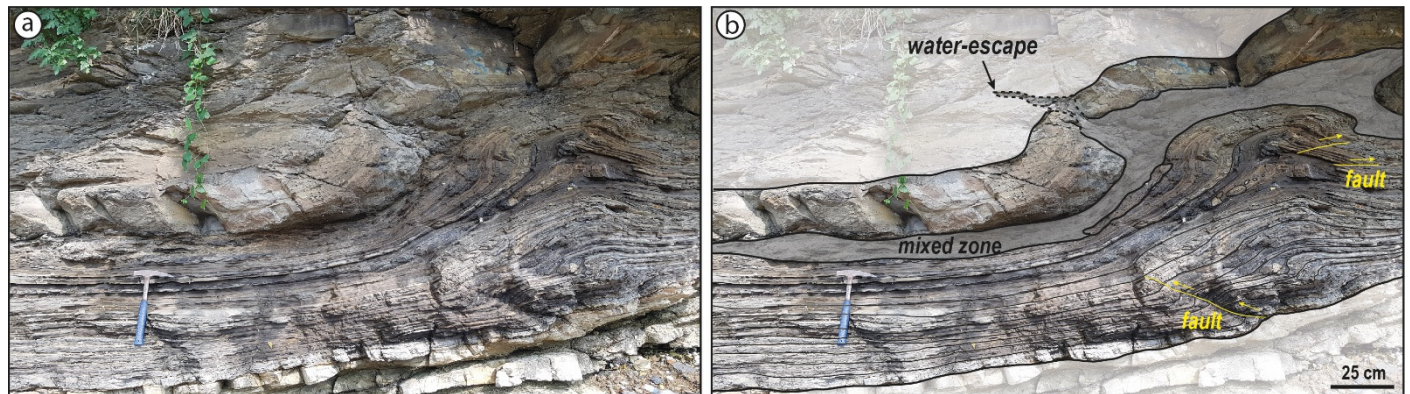


Figure 6. (a) Slump fold structures in *Ml* with water escape. (b) idem, with the boundaries between layers indicated.

4.2. Dating Results

4.2.1. Seokpo Tuff

CL images show euhedral shapes of zircons from the Seokpo Tuff, characterized by zoning, which suggest a magmatic origin. The grain sizes range from 50 to 130 μm , with length/width ratios of 0.3 to 1 (Figure 7a). The measured U and Th concentrations for the zircons are in the range of 119–1039 and 185–1210 ppm, respectively, with Th/U ratios ranging from 1.06 to 2.96 (Table S1). Analyses of nine zircon grains yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 87.06 ± 1.0 Ma (2σ , MSWD = 0.0035) for this tuff (Figure 7b).

4.2.2. Yujeongje Tuff

CL images of zircons from the Yujeongje Tuff also show euhedral shapes and zoning, thus also indicating a magmatic origin. The grain sizes range from 80 to 150 μm , with length/width ratios of 0.25 to 1 (Figure 7c). U and Th concentrations in the zircon samples are in the range of 81–689 and 113–1068 ppm, respectively, with Th/U ratios ranging from 0.74 to 1.67 (Table S1). After excluding data for outliers based on the t-test (UJT-1_1.1, 13.1), data from the analyses of fourteen zircon grains yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 87.26 ± 0.57 Ma (2σ , MSWD = 1.09) for this tuff (Figure 7d).

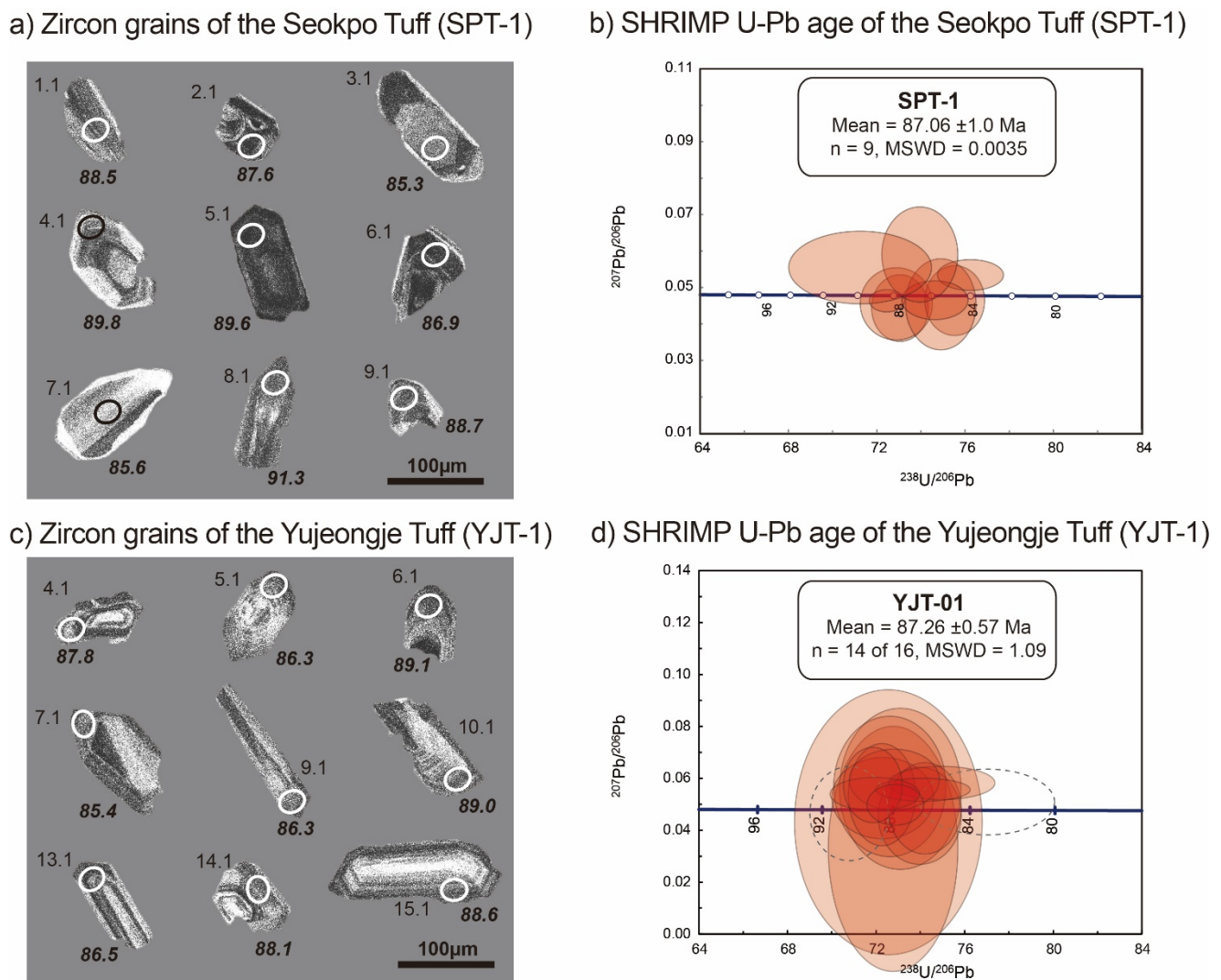


Figure 7. Cathodoluminescence (CL) images of zircon grains from (a) the Seokpo Tuff and (c) the Yujeongje Tuff with analyzed points and ages. Concordia plots of the SHRIMP U–Pb isotopic analyses of zircons from (b) the Seokpo Tuff and (d) the Yujeongje Tuff. The dotted ellipsoid was excluded from the weighted mean calculation based on the t-test.

5. Discussion

5.1. Deformation Mechanisms of the Slope-Related SSDS

5.1.1. Sediment Lenses Embedded in the Poorly Sorted Conglomerate

Pebbly and cobbly sediments were deposited on the layered mud deposits in the proximal or middle parts of the fan delta (Figure 8). This triggered failure of the underlying cohesive layered mud deposits and simultaneous slumping of the non-cohesive coarse-grained sediments.

Considering the clast sizes in the conglomerate, the density of these sediments certainly surpassed that of the underlying unconsolidated sediments significantly. This density contrast between the underlying cohesive mud deposits and the overlying non-cohesive conglomerate facilitated the deformation of the layered mud deposit. In addition, the shear stress parallel to the slope exerted a pressure on the sediments downslope. The simultaneous downslope pressure and flow of both sediment types caused different deformations [21]. The cohesive, laminated mudstones became locally deformed, producing slump folds engulfing sediment of the non-cohesive overlying conglomerate (Figure 8). An earlier study [21] suggested the term “envelope structure” for this structure.

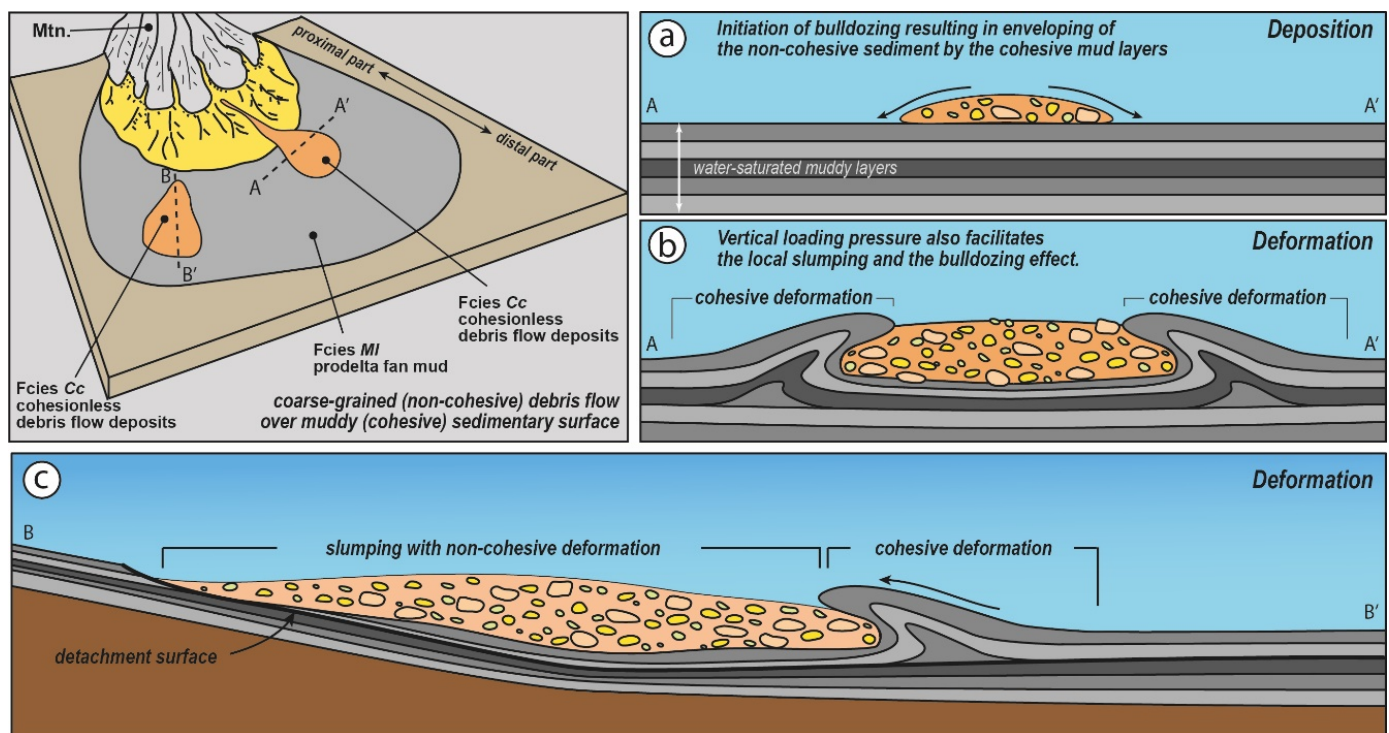


Figure 8. Schematic model of the development of an envelope structure, with A–A′ and B–B′ representing the profiles shown in (a–c). (a) Deposition of the underlying fine-grained sediments and overlying coarse-grained sediments on the slope. (b) Deformation of the underlying and overlying sediments. (c) Detached slump in the underlying fine-grained sediment showing coarse-grained sediments on fine sediments. Schematic model and profiles are not to scale.

5.1.2. Slump Fold Types

Considering the primary structures preserved in these sediments, the process that produced the slump folds is liquefaction. According to facies analysis, deposition occurred on the marginal slope of the basin. Therefore, considering the orientations of the fold axes, the folding likely occurred during slumping of the layered sediments. Slumping of soft sediment is commonly attributed to the steepening of the depositional surface [35,36] because of either tilting or rapid accumulation of sediment. The most commonly invoked mechanism for the initiation of slumping is a “metastable” slope condition, but seismic shocks are also considered in many cases to trigger slumping because liquefaction commonly requires an excess pore pressure [1,9,13,16]. The difference in the deformation structures has been attributed [21] to differences in the proportion of cohesive and non-cohesive sediment. Therefore, two deformation modes (cohesive deformation and non-cohesive deformation) associated with different amounts of cohesive mud layers produced different slump fold types.

5.2. Probable Trigger of the Deformations

In a lacustrine environment, the most common triggers of soft-sediment deformation are both endogenic triggers such as overloading [1,37], wave-induced cyclical and/or impulsive stresses [2,38], sudden changes in the groundwater level [33], and exogenic triggers such as earthquakes [39,40]. However, previous sedimentological studies in the study area exclude wave-induced cyclical and/or impulsive stresses and sudden changes in the groundwater level [22,24]. Thus, rapid sedimentation or earthquakes can be considered as the most likely triggers.

Some phases in the evolution of a basin are commonly accompanied by seismic activity. This tends to result in the presence of seismically-induced slumps with a variety of soft-sediment deformations [41–48]. Additionally, volcanic activity within and/or outside

the basins is commonly accompanied by seismic shocks and block tilting during the collapse of the roofs of shallow magma chambers (e.g., [49,50] and references therein). This syn-eruptive block tilting of a volcano is important for the instantaneous deformation or mobility of unconsolidated sediments. However, little attention has been devoted thus far to the impact of volcanic activity on soft-sediment deformation, in spite of some exceptions [51].

The SHRIMP U–Pb zircon datings for the underlying (Seokpo Tuff) and overlying (Yujeongje Tuff) stratigraphic units support the occurrence of volcanic activity during sedimentation of the Gyeokpori Formation (88–86 Ma). In addition, the Gyeokpori Formation contains volcanoclastic sediments and interbedded thin tuff layers, and its conformable contacts with the under- and overlying thick volcanic rocks indicates that its deposition was contemporaneous with regional volcanic activity. Continental arc volcanism with subduction of the Izanagi (oceanic) Plate under the Eurasian Plate occurred during the Early to Late Cretaceous [19]. Owing to this subduction, non-marine volcano-sedimentary successions were deposited, and plutonic rocks were emplaced in the Korean Peninsula, along NE–SW-trending fault systems, which created the Gyeokpo Basin [19]. The subduction also likely led to numerous volcanic rocks and must have caused significant seismic activity. SSDS in the Wido volcanic area, which is adjacent to the study area, have been ascribed to earthquake-induced processes caused by syndepositional volcanism [16]. It is therefore most likely that the trigger of the slumping in the Gyeokpori Formation is seismic activity associated with the nearby volcanism.

6. Conclusions

Two types of SSDS were studied in sediments of a sloping lacustrine fan-delta using facies analysis. The occurrence of each of them is restricted to specific locations on the fan-delta slope. The main findings are summarized as follows:

1. Envelope structures occur in the proximal to middle parts of the slope, whereas the middle to distal parts are characterized by slump folding;
2. The envelope structures were caused by the density contrast between muddy sediments and the overlying gravelly sediments, in combination with a shear stress parallel to the slope;
3. Volcanic activity took place during sedimentation of the Gyeokpori Formation (88–86 Ma), and volcanism-induced earthquakes significantly contributed to the development of slump folds;
4. The structures of slump folds differ depending on their sand content. Mud sediments promote uniform deformation by acting as cohesive ductile material. The present study allows distinguishing three types of fold structures based on the ratio between sand and finer material (silt and clay).

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/min11070721/s1>, Table S1: SHRIMP U–Pb zircon data of the Seokpo and Yujeongje Tuffs in the Buan Volcanics, South Korea.

Author Contributions: Conceptualization, data acquisition, writing of the original draft, review, and editing, visualization, U.H.B., A.J.v.L. and K.K. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data are contained within the article and Tables S1.

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