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Seismically induced soft-sediment deformation in crevasse-splay microdelta deposits (Middle Miocene, central Poland) – comment

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The Miocene succession of crevasse-splay microdelta deposits in the Jóźwin IIB lignite opencast mine contains some aspects that are more interesting than Chomiak et al. (2019) seem to realize in their analysis of the sediments and the soft-sediment deformation structures that they contain. Moreover, the authors use a terminology that is not completely adequate, leaving some questions about the precise seismic process that induced the deformation structures. Both aspects are detailed in this comment. The interpretation of the deformation structures presented here may change the insight into the tectonic history of the graben, in which the study area is located.

Key words: soft-sediment deformation structures, domino boudinage, seismites.

INTRODUCTION

The contribution by Chomiak et al. (2019) is a most valuable contribution to sedimentology, as it describes and interprets crevasse-splay deposits, a type of sediment that seems largely undervalued in sedimentology. Relatively little is still known about these deposits if compared to most other types of sediment, and particularly the detailed facies analysis provided by Chomiak c.s. is a most welcome addition to our sedimentological knowledge. Actually, I am not aware of another facies analysis of crevasse-splay deposits that is equally thorough and detailed. I read the paper therefore with great interest, also because soft-sediment deformation structures (SSDS) from these deposits are described in quite some detail, and because SSDS have my interest already for many years.

The Poznań Formation, to which the sediments under study belong, are located in a brown coal mine situated in the northernmost part of the Kleczew Graben, a fault-bounded shallow tectonic depression several kilometres north of Konin in central Poland. This setting is of interest, as tectonic activity must have been present both during and after deposition of the examined sediments. It is well known from numerous studies in comparable settings, such as the Kleszczów Graben near Bełchatów, that particularly the synsedimentary tectonics can cause abundant soft-sediment deformation structures (SSDS), although they cannot always with certainty be attributed to seismic activity (e.g., Brodzikowski et al., 1987; Van Loon, 2002; Gruszka and van Loon, 2007).

The SSDS described by Chomiak c.s. seem, indeed, caused by tectonic activity (this holds, at least, for most of them). This activity must have affected the sediments shortly after deposition, as it seems that they were consolidated but not yet lithified. It is noteworthy in this context that numerous analyses of SSDS have convincingly made clear that sediments need not be lithified to show brittle behaviour. On the contrary, even water-saturated, completely (geologically) fresh sediments can show significant faulting (Van Loon and Wiggers, 1976). The behaviour of the sediment depends not only on the state of the sediment, but also on the energy of the deforming process and the velocity of the changes in the stress field (Rodríguez-Pascua et al., 2000; Gladkov et al., 2016; Ko et al., 2017).

Most of the SSDS analysed and depicted by Chomiak c.s. seem “normal” for sediments that were affected by seismic activity. There is, however, one type that they mention specifically and that they depict clearly, but that most probably did not originate due to the passage of seismic shock waves. The responsible tectonic conditions were apparently not recognized by the authors. This concerns what they call “domino-type deformations” in the caption of their figure 9C (similar, also fairly well-developed examples are visible in their figure 7, where they only mention “brittle deformation structures”). These structures consequently deserve some more attention.

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DOMINO STRUCTURES

It is remarkable that the authors give the name "domino-type deformations" to the structure that they show in their figure 9C, as this structure is known in structural geology as "domino boudins". Apparently, the configuration of the broken-up layer into tilted fragments with a more or less imbricated position is so much alike a line of falling domino stones that all researchers come to a comparable name. We presume, at least, that Chomiak c.s. "invented" the name "domino-type deformations" themselves, as they do not come to the same conclusion that structural geologists tend to come to when they find such a structure.

In this context, it should be realized that the authors cannot be blamed for not being aware of the literature of these SSDS, because domino boudins have almost exclusively been described from rocks that were already lithified when the boudinage occurred (e.g., Goscombe et al., 2004; Dąbrowski and Grasemann, 2014). They have also been mentioned from slumped masses in the mainly calcareous Late Pleistocene Lisan Formation in Israel (Alsop and Marco, 2011), but it should be noticed that these rocks now are more commonly considered to represent seismically deformed sediments, originated in the Dead Sea Graben, and thus in a setting that is comparable with that of the sediments described by Chomiak et al. (2019). As far as known, only one single study (Yang and van Loon, 2016) has mentioned domino boudins from a Cretaceous (hard-rock) succession that must have been unlithified when the deformation occurred (Figs. 1 and 2). It is interesting, however, that experiments have indicated that boudins can also form in unconsolidated sediments (Zulauf et al., 2011; Marques et al., 2012).

In all the above field examples, the domino boudins are present in layers that were broken up by small normal faults at fairly equal distances of some centimetres, resulting – in a cross-section – in more or less rectangular blocks of a few centimetres wide and up to about a decimetre high. These underwent a slight rotation due to the faulting pattern. This is essentially what is also shown by Chomiak et al. (2019). As similar SSDS have not been described and interpreted as due to other processes, we deduce that the structures described by these authors also represent domino boudins.

Fig. 1. Domino boudins, formed when the sediment was still unlithified (note the undeformed under- and overlying layers), closely resembling the domino-type deformations depicted by Chomiak et al. (2019) in their figures 7B and 9C

There is no indication for collapse of the underlying sediment; photo adapted from Yang and van Loon (2016)

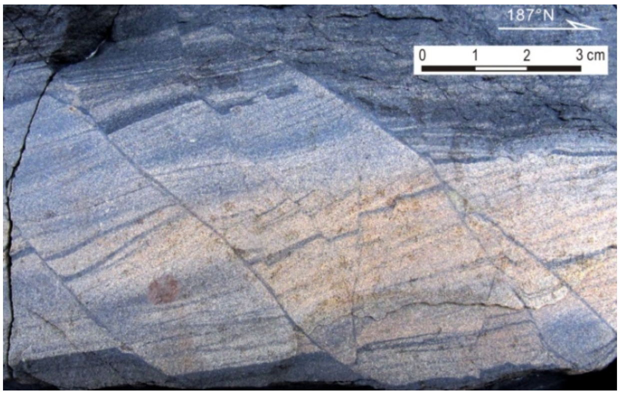

Fig. 2. Detail of a layer with domino boudins in the Cretaceous Lingshandao Fm.

Note the sharp fault, indicating sudden rupturing of the sediment that still must have been unlithified; all "dominos" have essentially the same sizes, like in the examples depicted by Chomiak et al. (2019); photo adpted from Yang and van Loon (2016)

This is interesting, because domino boudins are a specific (and rare) example of boudins, which are, represented as pinch-and-swell structures in a less-developed form, and, in a well-developed form, as isolated masses that have been torn apart from their parent layer. Particularly if diagenetic processes later affect such structures, they may give the false impression of nodules (Fig. 3).

All studies of hard-rock boudins indicate tension as the cause of boudinage; there is no reason to assume that the tectonic conditions in the study area of Chomiak c.s. were different. Moreover, indeed, their study site is situated in a graben, which implies, by definition, a tensional setting. A graben setting differs, however, from many other tensional settings, because of the dominance of normal faults. In many tensional areas, on the other hand, layers become laterally stretched and consequently thinner. It might be interesting to find out whether this stretching and thinning process took also place in the Kleczew Graben, as this might shed a new light on the tectonic history of this area.

TECTONICS *VERSUS* SEISMICS

It is not truly clear from the interpretation by Chomiak c.s. which process they think responsible for the formation of the SSDS, because they mention different processes. In the abstract they mention "*The occurrence in a tectonic graben and characteristic morphological features suggest an origin of these deformational structures with seismic shocks; thus, they can be called seismites*." This is in itself an unfortunate statement: when Seilacher (1969), exactly half a century ago, introduced the seismite concept, he made clear that seismites are layers that are entirely deformed by seismic shocks; the SSDS in these layers should therefore not be called seismites, even though this is sometimes done, even by authors who cite Seilacher's original study (e.g., Anand and Jain, 1987; Alfaro et al., 1997; Rodríguez-Pascua et al., 2000). Moreover, it is, as a rule, impossible to interpret a seismic origin for each individual SSDS, as earlier formed SSDS may also be present and as seismically induced SSDS may be deformed again later by other processes.

More problematic, however, is that the process (or processes) that deformed the sediments is described with much ambiguity. For instance, Chomiak et al. (2019) state that *"… one possible explanation for the dramatic growth in pore-water*

Fig. 3. Weathering of a diagenetically formed structure, resembling nodules

Close analysis indicates that the layers form loops (cf. Su and Sun, 2011), which must have formed when the sediment was still unlithified; Mesoproterozoic Wumishan Fm., near the railway station of Zhuwo (China)

pressure is an abrupt change in the ground water level, caused by strong earthquakes, in the backswamp area. Pore-water pressure can also increase by changing the grain packing during seismically-induced liquefaction, when water can be expelled (Obermeier and Pond, 1998). In such conditions, the water flows upwards, piercing the overlying beds or lifting and bending them." This statement would imply that earthquakes are capable of momentary raising the groundwater table with several decimetres. Such a process is in contrast with what is known: the seismic waves that proceed along the surface (commonly Raleigh waves), selecting a pathway through the most suitable sediments, commonly a few decimetres under the sedimentary surface, pass a specific place rapidly. This leaves insufficient time, particularly in the often fairly fine-grained sediments that are most susceptible to soft-sediment deformation and that house the great majority of seismites described in sedimentological literature (e.g., Alfaro et al., 1997), to raise the groundwater table significantly; the permeability of such sediments is too low. Certainly, it will be physically impossible that a shock-induced sudden rise of the groundwater table results in lifting and bending of the sediments. Piercing in the form of clastic dykes is a process that is known to occur frequently if a seismic wave passes, indeed, and some material will be transported upwards in such cases, occasionally resulting in the characteristic sand blows (Cox et al., 2007; Grube, 2019; Fig. 4), but this process differs fundamentally from processes such as uplifting and bending.

It is true that local bending of layers, resulting in SSDS, occurs when seismic waves pass, but the underlying process is different. Chomiak et al. (2019) are apparently aware, considering what they state in their abstract: "*The deformation takes the form of deformed lamination and load (loadcasts and flame structures) structures as well (plastically deformed) SSDS are the result of liquefaction of a layer due to increased pore-water pressure, so that overlying seismic breccias […]. Ductile deformation structures were generated first by liquefaction* […]." Here it is clear that the authors follow the commonly adhered to explanation that most plastically deformed structures result from fluidization of a layer under the influence of increased pore-water pressure due to the passage of the seismic wave, and that the overlying liquefied layer sinks into the fluid-like sediment below until the latter regains its stability when the shock wave has passed. This implies that sediments sink down by seismic activity. The fact that Chomiak c.s. are apparently well aware of this characteristic process raises the question of why they opted for a physically probably impossible process of uplifting of sediment under the influence of a suddenly rising groundwater table.

The explanations by Chomiak c.s. become even stranger when they state, as a continuation of the sentence quoted in the previous paragraph: "… *and then the breccia was formed under brittle conditions. The brecciation followed a sudden tectonic collapse resulting in an increase in pore pressure related to upward water movement.*" Apart from the question how the brittle conditions originated, the authors introduce here a 'tectonic collapse'. It remains unclear what process they have in mind, how this process was triggered, and how a collapse can occur if no space underneath is present. It seems that they cannot cope well with their observation of what probably concerns the domino-type breccia, which we explained in the previous chapter. There is no need for a collapse, or for an upward water movement!

Moreover, the authors mention "*karst-induced collapse*". This complicates the explanation even more: why would karst-like dissolution occur in an organic-rich sandy layer? And if karst occurred, why did the processes involved not affect other layers, and why just this level, and only this level? If the domino-type breccia resulted from collapse by dissolution of the underlying sediments (which is hardly imaginable, if only because they still form a straight band), they certainly should not be considered as seismically induced! In this respect, the authors are inconsistent in their interpretation. The authors complicated their explanation because they did apparently not realize that a domino-type configuration could be achieved only if some process results in lateral additional space (which is explained above as a result of tensional tectonics that must have been present in an active graben).

Fig. 4. Sand blows, a characteristic feature formed during earthquakes, formed after the 2012 Emilia earthquake in Italy, indicating pore-water escape and liquefaction/fluidization, which must have resulted in the expulsion of a water/sediment mixture from a buried layer (from Emergeo Working Group, 2012)

FINAL REMARKS

Soft-sediment deformation structures have received much interest in the past few decades. They posed problems for a long time (see Van Loon and Brodzikowski, 1987), and many of them still do. One of the main problems is that SSDS are present in rocks from Archean to modern, and in all environments (Van Loon, 2009). Moreover, their origin can be endogenically induced (e.g., tectonics), exogenically induced (e.g., sudden overloading, for instance by an event deposit) or be induced by atmospheric processes ranging from falling raindrops to the impact of meteorites. The unfortunate consequence is that the descriptions and analyses of SSDS are scattered over almost all types of earth-science literature, which makes it almost impossible to keep up with new insights. The most effective way is probably writing some comments that may be found by readers who are interested in the material that is commented upon. Let this contribution be of such help.

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