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First evidence of seismically-induced deformations in fluvial deposits of the Lower Rotliegend in the Intra-Sudetic Basin, SW Poland

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The Lower Rotliegend in the Intra-Sudetic Basin, situated at the northern margin of the Bohemian Massif, is represented in the Polish part of the basin by the Krajanów and Słupiec formations. Both formations consist of fluvial and lacustrine deposits. The sedimentary processes during the deposition of the Słupiec Formation were influenced by volcanic activity that resulted in subvolcanic intrusions, lava flows and ignimbrites. Some slabs of fluvial sediments from the Słupiec Formation show a level consisting entirely of soft-sediment deformation structures, in particular load casts, sometimes representing successive phases of loading. These deformations are interpreted to record volcanism-related earthquakes. Also a level full of load casts in the fluvial part of the Słupiec Fm. can feasibly be explained only be earthquakes that must be ascribed to a volcanic eruption.

Key words: Intra-Sudetic Basin, Early Permian, sediments deformation structures, synsedimentary earthquakes.

INTRODUCTION

Several isolated slabs of red sandstone, found in an active quarry near Bieganów in the central part of the Intra-Sudetic Basin (Fig. 1), were derived from fluvial sediments belonging to the Słupiec Formation (Lower Rotliegend). These slabs each contain a single strongly deformed level that must be present in a still not recognized level of the currently mined quarry wall. The deformed levels consist predominantly of load casts that often deform each other. Such levels with laterally continuous soft-sediment deformation structures (SSDS) have not been found so far in the Lower Rotliegend of the Polish part of this basin, neither in this quarry, nor elsewhere.

The origin of the high concentration of SSDS in the deformed levels was investigated by defining the geological and sedimentary setting, by analysing the possible origins of the deformations, and by comparing the deformed layers with similarly deformed levels described from other locations.

A fairly small slab with a lower bedding plane that is entirely deformed by loading, found in a nearby quarry in the same member of the Słupiec Formation, supports the conclusion that seismic activity occasionally (but rarely) affected the sediments of the Lower Rotliegend regionally.

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GEOLOGICAL SETTING

The Intra-Sudetic Basin is one of the large late- to post-Variscan intramontaneous troughs in central Europe. It contains the most complete record of Permo-Carboniferous sedimentation and volcanism of the region. The basin is located at the northern margin of the Bohemian Massif (Fig. 1) and forms a fault-bounded synclinorium-like structure, representing a tectonically quiet depression that was surrounded by tectonically active margins (Nemec et al., 1982; Dziedzic and Teisseyre, 1990; Mastalerz and Prouza, 1995). Volcanic activity evolved during deposition of the succession under study. It resulted in the emplacement of subvolcanic intrusions, effusion of lava flows and widespread deposition of ignimbrites (Awdankiewicz, 1999a, b; Awdankiewicz et al., 2003).

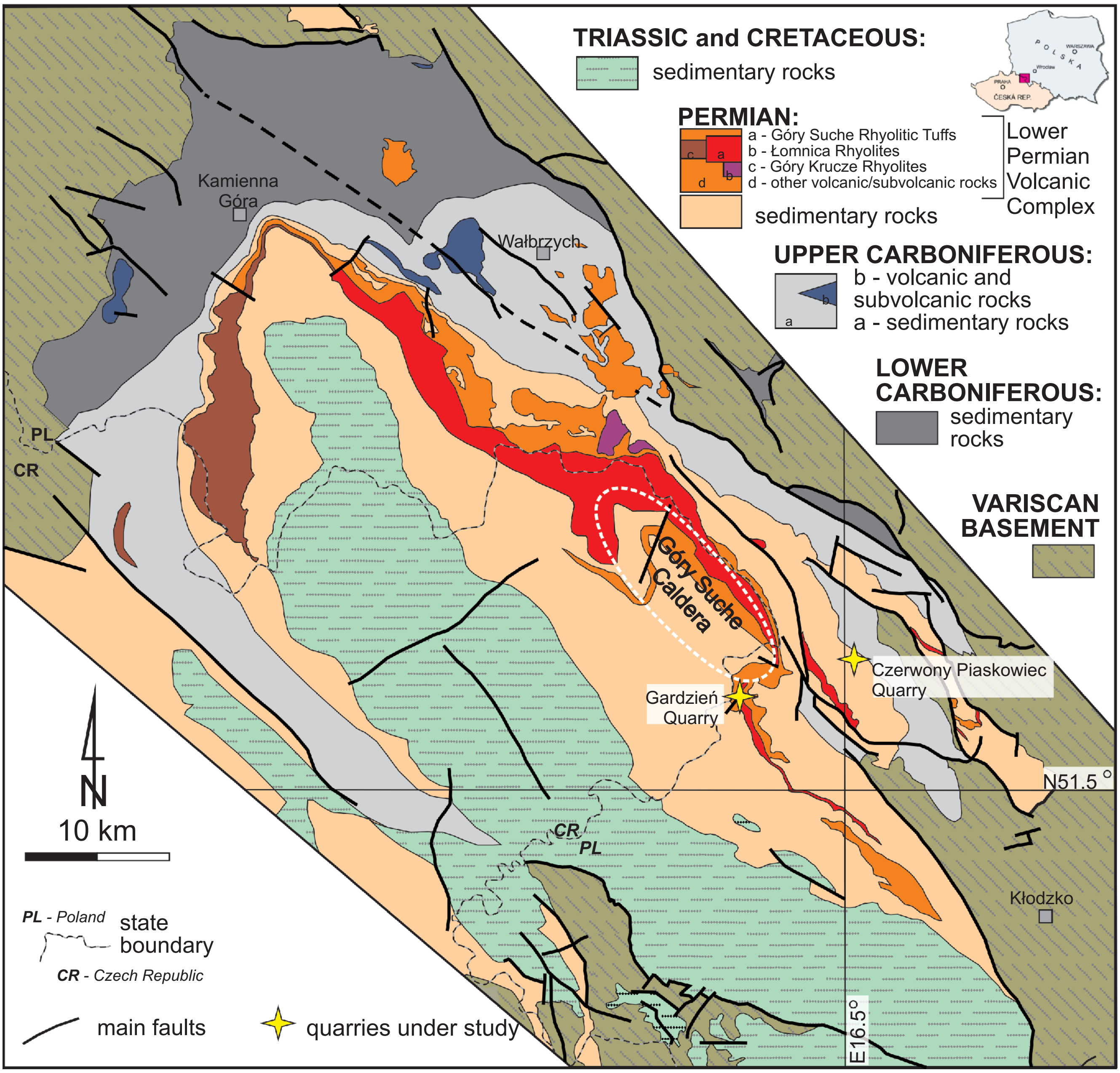

Fig. 1. Geological map showing the locations of the two quarries under study

The caldera resulted from the ignimbrite eruption of the Góry Suche Rhyolitic Tuffs; later activity included the emplacement of trachyandesite sills along the margins of the caldera, whereas successive eruptions must have caused severe earthquakes

STRATIGRAPHICAL AND SEDIMENTOLOGICAL SETTING

The sediments under study form part of the Lower Rotliegend, which is divided into a lower and an upper complex. The lower complex (Lower Rotliegend) is in Poland represented by the Krajanów and Słupiec formations (Fig. 2). The latter is informally subdivided, from bottom to top, into the "Building Sandstones", the "Lower Permian Volcanic Complex" and the "Walchia Shales". These sediments have for long been considered to be Asselian in age (Opluštil et al., 2016), but recent U-Pb zircon datings suggest that they should rather be assigned to the uppermost Carboniferous and Asselian (Ploch et al., 2023; Awdankiewicz et al., 2023); the exact boundary is still not clear. Overall, the Rotliegend shows a megacyclic structure with three fining-upward megacyclothems, linked to three major events of rapid subsidence, which also led to landscape rejuvenation (e.g., Wojewoda and Mastalerz, 1989).

The sediments at which the present study focuses primarily belong to the Słupiec Formation, which has been interpreted as an alluvial fan fringed with playa-like, shallow lakes in the centre (Kurowski, 2001, 2004). The extent of the lakes in the basin centre probably fluctuated as a result of cyclical climate fluctuations (e.g., Kurowski, 2004) or due to an autocyclic mechanism

System	Stage	Regional stratigraphic unit	Formation: Polish	Formation: Czech	Member: Czech	Member: Polish (informal)	Characteristics
Uppermost Carboniferous (?)/Lower Permian	Wordian	Upper Rotliegend II	Radków	Trutnov			predominantly coarse-grained fluvial deposits, age not certain
	Roadian	Upper Rotliegend I					
	Kungurian		Hiatus				
	Artinskian						
	Sakmarian						
	Asselian	Lower Rotliegend	Słupiec	Broumov	Martinkowice	„Walchia Shale“	predominantly fine-grained fluvial to lacustrine (s.l.) deposits, active volcanism
	?				Olivětin	„Lower Permian Volcanic Complex“	
					Nowa Ruda	„Building Sandstones“	
	Gzhelian		Krajanów	Chvalec			

Fig. 2. Schematic regional lithostratigraphic subdivision of the Lower and Upper Rotlingend (modified after Stamberg and Zajic, 2008)

(e.g., Wojewoda and Mastalerz, 1989). However, sedimentation was also affected by volcanic processes, such as a formation of a caldera in the basin centre (Awdankiewicz, 2004).

Several eruptive stages at distinct volcanic centres are reflected in a number of volcanic rock units in the middle part of the Słupiec Formation (Fig. 2) above the "Building Sandstone" and below the "Walchia Shale" (Awdankiewicz, 1999a, b). The most extensive unit in the volcanic rocks of the "Lower Permian Volcanic Complex" is the Góry Suche Rhyolitic Tuffs (GSRT), which overlies older volcanic rocks with an erosional unconformity in the central part of the basin (Awdankiewicz, 1999a). The subvolcanic intrusions are grouped around the Góry Suche Caldera (Fig. 1). The younger volcanic rocks, post-dating the GSRT, are relatively minor in extent and occur mainly within the Góry Suche Caldera and in the eastern to southeastern parts of the basin (Awdankiewicz et al., 2003).

QUARRIES UNDER STUDY

The most interesting material presented here comes from the Czerwony Piaskowiec Quarry at Bieganów (Fig. 3A). Some additional data come from the Gardzień Quarry at Tłumaczów (Fig. 3B). Both quarries are currently actively mined.

CZERWONY PIASKOWIEC QUARRY

The sedimentary rocks in the Czerwony Piaskowiec Quarry (Fig. 3A) consist mainly of red sandstones (predominantly subarkosic to sublithic arenites) with subordinate polymict conglomerates and fine-grained sediments (mainly sublithic to subarkosic mudstones). The latter occur in the lower part of the "Building Sandstone". According to Wójcik (1958) and Kurowski (2001), the rocks belong to the Słupiec Formation. It should be mentioned here, however, that Wojewoda (2008b) attributed the sedimentary rocks from this quarry to the Krajanów Formation, although without a clear argumentation. Considering the arguments for either stratigraphic setting, we feel that these rocks should be attributed, at least for the time being, to the Słupiec Formation.

The sediments dealt with here occur in the lower part of the "Building Sandstone". This informal member is 400 m thick, and particularly its upper part shows features (e.g., fragments of volcanic ejecta) pointing at possibly intense volcanic activity. The member shows a complex sedimentary architecture, with slightly fining-upward cyclic successions in which coarse- and medium-grained particles prevail (Kurowski, 2004). The deposits show predominantly parallel lamination (Fig. 4), but also fairly frequent flat-bottomed channels with a low depth/width ratio as well as small channels with a somewhat higher depth/width ratio (Fig. 5); the channels may be flanked by deposits with a terrace morphology. Current ripples are relatively rare (Fig. 6); burrows (Fig. 7) are locally rare, but fairly common at other places. The combination of these and other features points to deposition in the distal part of fans (Kurowski, 2001, 2004).

An interesting feature is present in several sandstone blocks and slabs; they show each a level characterized by a continuous lateral occurrence of load casts (Fig. 8) and other deformations. The SSDS in this level are the main study subject of the present study.

GARDZIEŃ QUARRY

Upper Lower Rotliegend sediments occur also in the nearby Gardzień Quarry near Tłumaczów. The quarry is located in the marginal part of the Góry Suche Caldera (Fig. 1). The Rotliegend sediments became well-exposed in an over 20 m large section (Fig. 3B). The sediments are mainly reddish-brown to greyish-brown mudstones and fine-grained sandstones with some conglomerate horizons. They show current ripples (most common in channels); mud-cracked surfaces, often with tracks of tetrapods (Fig. 9). Red fine-grained sandstones with some conglomerate horizons became exposed in the northern part of the quarry when exploitation of trachyandesites started. These sediments have been interpreted as fluvial and lacustrine, belonging to the upper part of the "Building Sandstone" of the Słupiec Formation (Krechowicz, 1964; Nemec, 1981; Nemec et al., 1982; Mastalerz and Prouza, 1995).

Fig. 3. The two quarries under study

A – sandy fluvial sediments in the highest exploited level of the Czerwony Piaskowiec Quarry, from where the sandstone slabs with SSDS levels were derived; **B** – Gardzień Quarry with fine-grained sediments partly bent into inclined positions by trachyandesite intrusion

Fig. 4. The most common appearance of the sediments under study: almost only parallel lamination due to alternations of fine sandy and sandy/muddy streaks

Fig. 5. Example of the frequently occurring small channels in the sediments under study; the depression is filled with relatively coarse sediment

Although such lacustrine deposits are known for their possible excellent preservation of seismically-deformed layers (seismites), thus forming a palaeoenvironmental archive (e.g., Ricci Lucchi, 1995; Monecke et al., 2004), hardly any seismically-induced traces have been found until now, although intense volcanic eruptions must, as indicated in the previous section, have occurred during their deposition. Only one slab showing a lower bedding plane with numerous load casts (Fig. 10) seems to represent a deformed level comparable to that of the other quarry.

Fig. 6. Fine-grained sandy current ripples in the fluvial facies of the Słupiec Formation

The small differences in grain size make even the grain-size differences in the foresets of the ripples difficult to recognize; due to the fairly uniform grain size, even SSDS are difficult to recognize in the walls of the quarry

Fig. 7. Characteristic burrow

The responsible animal lived probably close to the surface of the fine-grained (mud-rich) material, which was suddenly covered by a layer of coarser sand, through which the animal tried to escape upwards

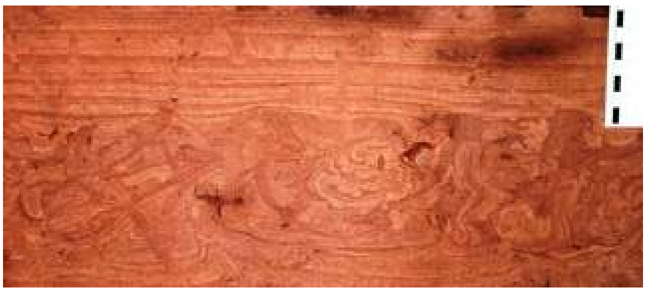

Fig. 8. Detail from the deformed level

Note that the majority of deformations consist of load casts that have become deformed themselves. Numerous small faults were produced during deformation in order to solve the space problem

Fig. 9. Tetrapod footprints of *Ichniotherium cottae* on the mud-cracked surface of fine-grained fluvial sediments

Fig. 10. Cross-section through the rock fragment found in the Gardzień Quarry, with a lower bedding plane that was completely deformed by load cast

METHODS

Analysis in the field of the textural characteristics and the sedimentary structures of the sediments in the Czerwony Piaskowiec Quarry did not show anything unexpected. However, some sandstone slabs from a block derived from a still not recognized level, and cut during work in a local stonemason's workshop, showed uncommonly complex sedimentary deformation structures. The most interesting slabs with the best-preserved SSDS could, fortunately, be collected. Some more stone blocks in the quarry show comparable deformed levels. They have not been collected, but they were documented in the form of photographs.

One of the collected slabs is currently stored in the Geological Museum of the Polish Geological Institute (NRI) in Warsaw, with collection number PIG 1732.II.57 (Fig. 11A). All photos shown in the present contribution are from this slab, unless indicated otherwise. Three more slabs, with collection numbers MGUWr 2316r/II (Fig. 11B) and MGUWr 2363r/II are currently

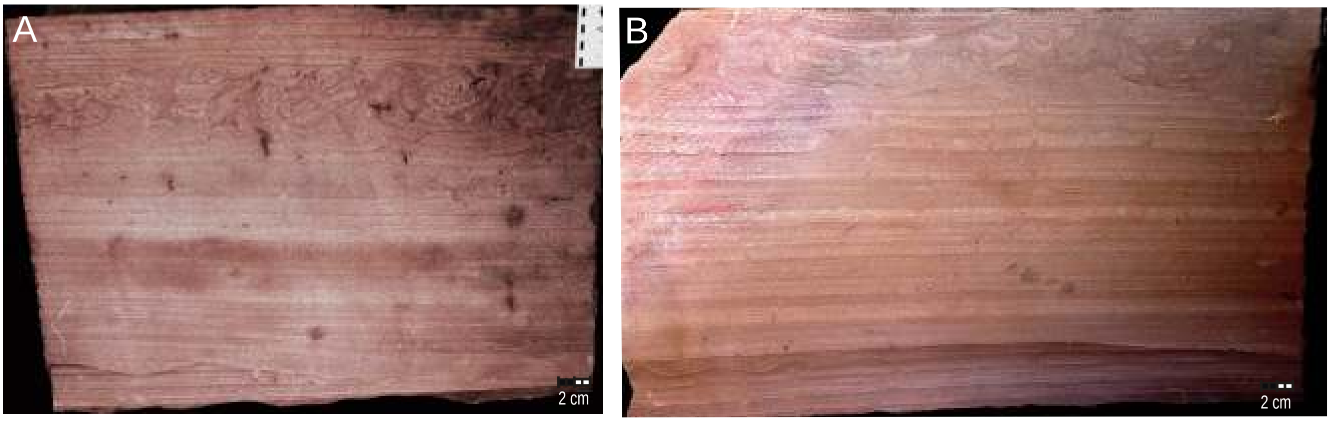

Fig. 11. The two of the collected slabs

A – slab no. 1732.II.57, stored in Warsaw; almost all photos shown in the present contribution are from this slab; **B** – slab no. 2316r/II stored in Wrocław

stored in the Geological Museum of the University of Wrocław, and one slab, with collection number ZGSUWr 1215, is stored in the Faculty of Earth and Environmental Science of the University of Wrocław. Samples for petrographic analysis in thin-section were taken from the various sandstone slabs.

It should be mentioned here that the uniform grain size of the sediments and the overall reddish colour make it difficult to distinguish structures in the sediments. Photos do not show the structures clearly either. Most photos presented in the present contribution therefore have been digitally processed so as to show the structures more clearly. A consequence is, unfortunately, that the sediments shown do not always show their natural colour.

RESULTS

In areas affected by volcanism, seismic records can be expected even from volcanic activity alone. Such seismic records may be present in the form of sedimentary deformations, occasionally (if both the seismic shocks and the sedimentary characteristics of near-surface sedimentary layers are suitable) in the form of seismites. Fine-grained sediments with a relatively high siliciclastic silt content are particularly sensitive to seismically-induced deformations.

SEDIMENTS AND SSDS IN THE CZERWONY PIASKOWIEC QUARRY

In the Czerwony Piaskowiec Quarry, several types of SSDS are present, but the deformed levels could not be traced in the exposed walls. However, several cut sandstone slabs show these levels clearly (Fig. 11). Additional examples of deformed levels were recognized on single 'waste' blocks in the quarry. Considering the types of deformations, it is highly unlikely that all these deformed bands represent the same stratigraphic level.

DESCRIPTION

At the top part of one of the sandstone slabs (collection number 1732.II.57), consisting of a fine-grained sublithic/subarkosic arenite, a level with numerous load casts is present (Fig. 12). It is obvious that the load casts developed during successive deformation stages, thus deforming (during loading) earlier developed load casts. Interesting is that combinations of some multi-stage load casts form masses that can be considered themselves as a loading mass (Fig. 13); this explains the well-developed large flame structures that are present alongside these masses. It is remarkable that the layer does not exist more or less exclusively of load casts, but that numerous much more complex SSDS are also present (Fig. 14A, B).

The deformed level in the other collected slab (No. 2316r/II) shows comparable deformations. As mentioned earlier, deformed levels have also been found in isolated blocks in the quarry. Some examples are shown in Figure 15A, B.

Fig. 12. Part of a deformed level, showing well-developed multi-phase load casts that are indisputable proof of an origin due to the passage of a seismic shock wave

INTERPRETATION OF THE SSDS

Load casts are probably the most widespread SSDS, both in time and in space. This is because even very small differences in the composition or water content of successive layers can cause differences in density. As known already for a long time, reversed density gradients, e.g., due to a sandy layer on top of a muddy layer (Anketell and Dżułyński, 1968), result easily in loading. Commonly a trigger is required, however, to start the loading process, but a situation in which several stages of loading follow each other so quickly that the loading masses deform the (not yet strongly consolidated) earlier formed load casts is exceptional.

Fig. 13. Example of a load cast consisting of a sediment mass containing several smaller load casts

The finding of slabs with such concentrations of multi-stage load casts in a specific level is remarkable since no such levels have been recognized in the exposed rocks. This must be ascribed to the condition of the walls: not only are they covered by a dust layer (which is quite common in active quarries), but the uniform grain size prevents differential weathering. Structures tend to become visible only if the rock is washed and brushed (as in the workshop where slabs are prepared). Our attempts to trace levels with SSDS in the quarry wall failed thus far.

The apparently rare occurrence of completely deformed levels suggests that these levels do not represent deformational processes that are inherent to the depositional environment. Rather they must represent an exceptional situation that allowed some quick repetition of conditions that triggered loading. Such conditions have commonly been interpreted on the basis of detailed sedimentological analyses in combination with insight into the physics of earthquakes as representing a succession of seismic shock waves, resulting either from an earthquake with several aftershocks, or from successive phases of volcanic eruptions. As indicated above, the possibility of tectonically induced earthquakes can be ruled out. Volcanic activity seems not to have affected the older sandstones in this quarry

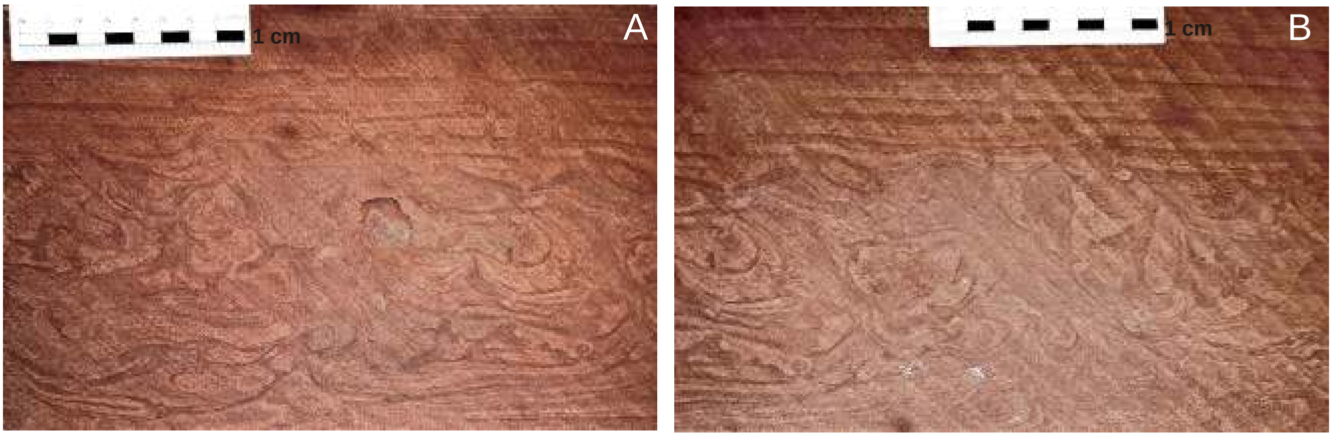

Fig. 14. Complex SSDS in the Warsaw slab

A – note the overall load structures with load structures inside; **B** – note the irregular character

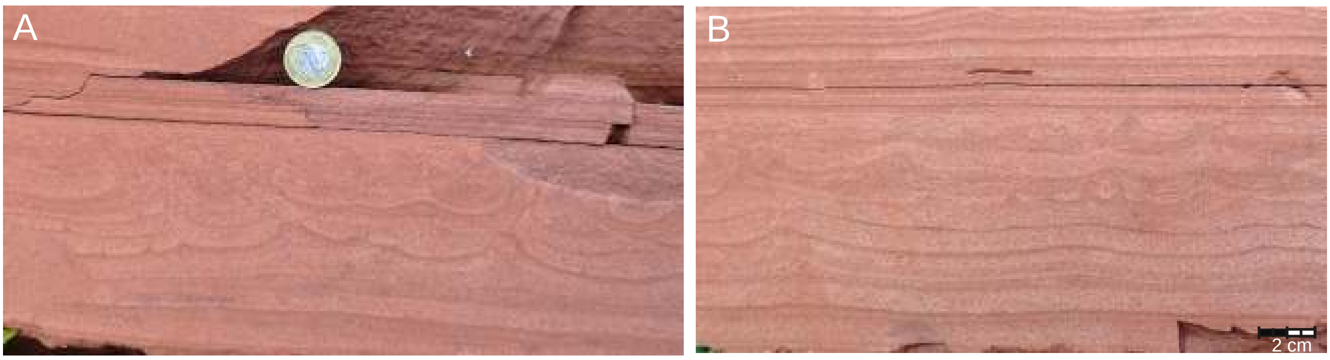

Fig. 15. "Waste blocks" in the Czerwony Piaskowiec Quarry, each showing a completely deformed level with SSDS that resemble those in the levels described from the main slabs to different degrees, and that are different in thickness, complexity of the SSDS, etc.; these "waste blocks" thus most probably come from different stratigraphic levels, indicating that several intense seismic shocks must have occurred: A – rock fragment with a deformed layer consisting predominantly of load structures; B – rock fragment with a deformed layer consisting of relatively badly developed SSDS, indicating seismicity with a lower intensity than in Figure 15A

because tuff layers of the same age have been found only at relatively large distances. However, previous research (e.g., Awdankiewicz, 1999a, b, 2004 and references therein) has provided indisputable evidence that volcanic activity was present throughout the area during accumulation of the upper part of the Słupiec Formation, so that one may reasonably assume that volcanically-induced seismic shock waves passed the sediments under study. This interpretation will be dealt with in more detail in the Discussion section.

It is interesting that, despite intensive searching, only a few sandstone slabs from one sandstone block with a high concentration of multiphase load casts with flame structures in between, as well as some isolated "waste blocks" in the quarry with similar deformations, have been found thus far. The possible implications are detailed in the Discussion section. Thus far, earthquake-triggered SSDS have been described from the Intra-Sudetic Basin only from fluvial sediments of the Radków Formation, above the Słupiec Formation (e.g., Wojewoda, 2008a).

The lower part of sandstone slab 1732.II.57 does not show any complex deformations, but some other, more or less vertical, structures. Part of them can be interpreted as escape structures for water/sediment mixtures, but other ones are more likely burrows (Fig. 7). Such structures are quite common in the sandstones of this quarry.

SEDIMENTS AND SSDS IN THE GARDZIEŃ QUARRY

A well-exposed 20 metre-high wall of sedimentary rocks is present in the Gardzień Quarry. The rocks in this wall, which show gradual changes in colour, grain size and composition, represent lacustrine sediments that contain some fish remains (Fig. 16). Parts of the rocks in this wall are now in an almost vertical position due to trachyandesite intrusion (Fig. 3B).

DESCRIPTION

The light grey to grey lacustrine deposits in the wall are mainly in the range from claystones to very fine-grained sandstones. Some limestone layers occur intercalated between the fine-grained siliciclastic layers. The clayey sediments contain some uncoated quartz grains and a few feldspars. The main clastic components of the fine-grained sandstones are quartz, feldspar and mica; their cement seems in the field to consist mainly of clay and ferruginous clay, but thin-section analysis indicates that carbonate cement is also present.

Volaniclastic material is present in the form of tuffaceous sandstone intercalations 0.5–1 cm thick (Fig. 17A). This material is poorly sorted, commonly fine- to very-fine-grained, but occasionally contains, dispersed throughout the sediment, irregular pebble-sized pink clasts of andesite or trachyandesite of up to 4 mm in size. Some fragments of devitrified glass and infrequent rust-coloured plagioclase crystals are also present (Fig. 15B). The volcaniclastic sandstone layers material shows a vague lamination which is sometimes deformed. Investigation of the northern part of the Gardzień Quarry yielded a single rock fragment that is of interest in the context of the present study. The red fluvial sandstone slab shows abundant load casts that cover the entire lower bedding plane of the, unfortunately, fairly small rock fragment (Fig. 18; see Fig. 10 for a cross-section).

INTERPRETATION OF THE SSDS

The character of the fine-grained sediments in this quarry indicates fluvial and lacustrine depositional environments, occasionally affected by influx of volcaniclastic (pyroclastic?) material. Interesting in the context of the present study is the rock fragment of which the lower bedding plane is entirely deformed by load casts (Figs. 10 and 18). Such an uncommon concentration of load casts is rare in fine-grained sands with a fairly good sorting. Whereas such concentrations are common in sediments with frequent reversed density gradients (such as tidal-flat deposits), such concentrations of load casts in fine-grained fluvial sediments have – as far as we are aware of – only be interpreted as a result of a passing seismic wave. We cannot come to any other feasible interpretation, so we consider this deformed bottom plane as additional evidence for seismic activity affecting the Słupiec Formation.

DISCUSSION

Only a few observations in sediments of the Słupiec Formation (levels with a high concentration of SSDS in slabs of the fine-grained sands in one quarry and a lower bedding plane that is completely deformed by load casts in another quarry) form

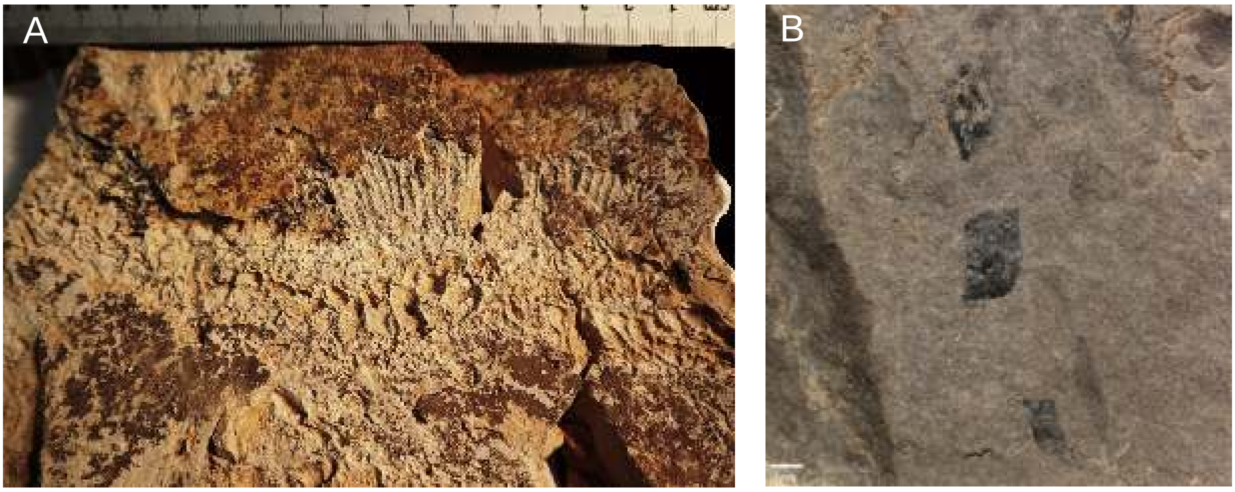

Fig. 16. Fish fossil: A – imprint of skeleton; B – scales from the Słupiec Formation in the Gardzień Quarry

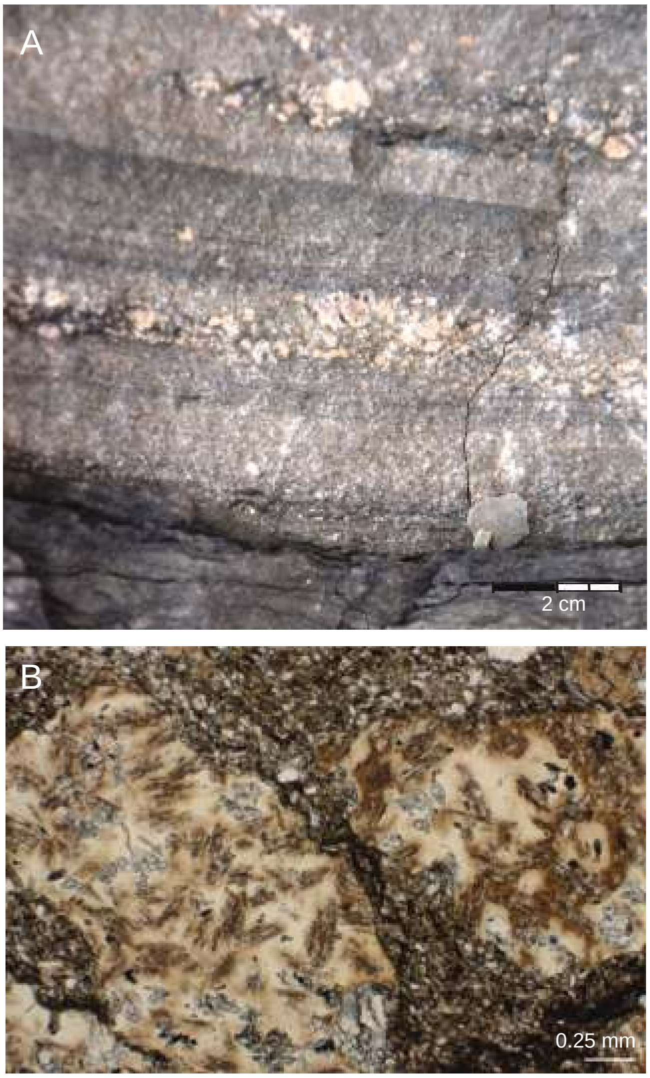

Fig. 17. Proof of contemporaneous active volcanism

A – pyroclastic tuffaceous sandstone intercalations of 0.5–1 cm thick; this material is poorly sorted, commonly fine- to very-fine-grained, with sparse clasts of andesite or trachyandesite; **B** – thin-section (scale bar 0.25 mm) with fragments of devitrified glass and infrequent rusty-coloured plagioclases crystals

Fig. 18. The rock fragment found in the Gardzień Quarry with a lower bedding plane that is completely covered with load casts (see Fig. 10 for a cross-section)

the basis for our interpretation that volcanism-induced seismic shock waves affected the sediments. Although the scarcity of data is, obviously, reason to question the validity of the interpretations, the fact that this is the first evidence of seismically-induced SSDS in the Lower Rotliegend of the Intra-Sudetic Basin in Poland (some comparable findings have been reported only from Germany: Heubeck, 2009) is worth being communicated, although certainly additional thorough analysis is most wanted. Consequently, we pay attention in this discussion to the characteristics of seismic waves and to the deformation process that affects sediments when a seismic wave passes. Finally, we compare the SSDS that we found with those described from elsewhere.

NEAR-SURFACE SEISMIC SHOCK WAVES

When tectonics in the form of faulting or volcanic activity affect the rocks in the subsoil, shock waves run away from the centre point (hypocentre) into all directions. Some of these seismic waves will reach the earth surface, and part of their energy is used to produce P-waves or Rayleigh waves that spread from the epicentre into all directions (Telford et al., 1990). These waves select the nearby (almost always unlithified) layers that provide the least resistance to such waves. This implies that such waves commonly affect a layer (or a level of several layers) that tends to be limited in thickness (commonly a few centimetres to a few decimetres; exceptionally up to 10 m: see, e.g., Simms, 2003; Mugnier et al., 2011; Sakai et al., 2015). The thickness of the deformed level is independent of the magnitude of the earthquake but depends primarily in the thickness of the sedimentary unit that is susceptible to liquefaction (Alfaro et al., 2010). The energy of these waves is used to move the particles of the affected layer. P-waves and Rayleigh waves both can do so, but the most complex deformations are caused by Rayleigh waves because they have both a horizontal and a vertical component. This implies that the sediment, during passing of the wave, undergoes both extension and compression, both horizontally and vertically (Telford et al., 1990). This explains why both compressional and extensional SSDS may occur closely together in a seismically affected layer.

The transfer of wave energy to the sediments (in the form of deformation) implies that the energy of the seismic wave gradually diminishes. This is expressed in seismites in the form of diminishing frequency and intensity of the SSDS with increasing distance from the epicentre. Consequently, seismically-induced SSDS tend to be restricted for >90% of recent seismic events to maximum distances from the epicentre of 40 km (Galli, 2000; Moretti, 2000). Papadopoulos and Lefkopoulos (1993) mention even that most of the SSDS related to earthquakes with a magnitude of 5–7 occur within a distance of <20 km away from the epicentre.

Unfortunately, the extent of the exposures under study here is insufficient to check this, but the absence of the possibility to check this is, obviously, no argument against a seismic origin of the SSDS.

COMPARISON WITH OTHER SEISMICALLY-INDUCED SSDS

The most common types of SSDS that are formed due to the passage of a seismic wave are load casts and small faults. Commonly these occur together (see the numerous small fault planes in the photos showing the levels with complex SSDS). In the slabs and blocks under investigation here, the load casts are fairly complicated, commonly showing deformations themselves. This is best expressed where successive phases of loading can be distinguished (Fig. 12). This can be ascribed only to successive phases of shock-induced loading, resulting in load casts that deformed earlier formed load casts. Similar concentrations of such multi-phase load casts have been depicted in numerous publications, e.g., figures 3–5 in Van Loon and Pisarska-Jamroży (2014), figure 9 in Tian et al. (2015), figure 9 in Mazumder et al. (2016), figure 7 in Van Loon et al. (2016), figure 6 in Pisarska-Jamroży et al. (2018), figure 2 in Pisarska-Jamroży et al. (2019), and many more. Considering that the area was subsiding but tectonically quiet but that nearby volcanism was active, the only reasonable conclusion can be that successive volcanism-induced seismic shock waves caused the multi-phase load casts.

It should be mentioned in this context that the well-documented volcanic activity (see also Fig. 17) must have caused significant tremors. This explains why a unit of possibly originally several layers has been affected several times within a geologically short time (consolidation could not proceed much further during the relatively short quiet phases in between the successive volcanism-induced seismic shocks). This might well be ascribed to repeated eruption phases of the same volcano.

A final point to be mentioned is that the combination of a few slabs with abundant SSDS, prepared from a single sandstone block, deformed levels in isolated “waste blocks” in the same quarry and a rock fragment with a deformed lower bedding plane in a nearby quarry represents a very limited set of evidence. We consider it of utmost importance, however, to present this evidence, because it is the first documented information about the Lower Rotliegend of the Intra-Sudetic Basin in Poland that volcanism led to seismic shock waves that were intense enough to deform a layer. Earthquakes require a magnitude of about 4.5 ≈5 to do so. This implies that the volcanic eruptions must have been severe, even though there is no mathematical relationship between the intensity of a volcanic eruption and the magnitude of a resulting earthquake. This is due to (1) the more or less unique character of a volcanic explosion (duration, material erupted, rock types surrounding the volcano, depth of degassing, etc.), (2) the nature of the rocks through which the seismic wave runs, and (3) the susceptibility of superficial sediments that might be deformed by a passing seismic wave.

Obviously, the finding of levels with laterally continuous occurrences of SSDS should start renewed investigation of the sediments under study, also at levels in the quarry that are not easily accessible. Such investigations might lead to the recognition of one or more layers (or sets of layers) that show more characteristics that would prove (or falsify) the hypothesis of seismite activity as a trigger for the deformation of the sediments under study.

CONCLUSIONS

The SSDS described here from the Słupiec Formation are the first found in the Lower Rotliegend of the Polish part of the Intra-Sudetic Basin that should be interpreted as seismically-induced. They consist predominantly of complex load structures. The responsible seismic shock waves were presumably related to the well-documented contemporaneous volcanic activity in the region.

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REFERENCES

Alfaro, P., Gibert, L., Moretti, M., García-Tortosa, F.J., Sanz de Galdeano, C., Galindo-Zaldívar, J., López-Garrido, T.C., 2010. The significance of giant seismites in the Plio-Pleistocene Baza palaeo-lake (S Spain). Terra Nova, **22**: 172–179. https://doi.org/10.1111/j.1365-3121.2010.00930.x

Anketell, J.M., Dżułyński, S., 1968. Patterns of density controlled convolutions involving statistically homogeneous and heterogeneous layers. Rocznik Polskiego Towarzystwa Geologicznego, **38**: 401–409.

Awdankiewicz, M., 1999a. Volcanism in a late Variscan intramontane trough: Carboniferous and Permian volcanic centres of the Intra-Sudetic Basin, SW Poland. Geologia Sudetica, **32**: 13–47.

Awdankiewicz, M., 1999b. Volcanism in a late Variscan intramontane trough: the petrology and geochemistry of the Carboniferous and Permian volcanic rocks of the Intra-Sudetic Basin, SW Poland. Geologia Sudetica, **32**: 83–111.

Awdankiewicz, M., 2004. Sedimentation, volcanism and subvolcanic intrusions in a late Palaeozoic intramontane trough (the Intra-Sudetic Basin, SW Poland). Geological Society Special Publications, **234**: 5–11. https://doi.org/10.1144/GSL.SP.2004.234.01.02

Awdankiewicz, M., Kurowski, L., Mastalerz, K., Raczyński, P., 2003. The Intra-Sudetic Basin – a record of sedimentary and volcanic processes in late- to post-orogenic tectonic setting. Geolines, **16**: 165–183.

Awdankiewicz, M., Pańczyk, M., Ploch, I., Raczyński, P., Awdankiewicz, H., Górecka-Nowak, A., Pawlak, W., Peryt, T., 2023. The Góry Suche Rhyolitic Tuffs, a large-scale, caldera-related ignimbrite deposit in the Intra-Sudetic Basin: U-Pb SHRIMP zircon dating, regional correlations and stratigraphic implications. Mineralogia-Special Papers, **51**: 35.

Dziedzic K., Teisseyre, A.K., 1990. The Hercynian molasse and younger deposits in the Intra-Sudetic Depression, SW Poland. Neues Jahrbuch für Geologie und Paläeontologie, Abhandlungen, **179**: 285–305.

Galli, P., 2000. New empirical relationships between magnitude and distance for liquefaction. Tectonophysics, **324**: 169–187. https://doi.org/10.1016/S0040-1951(00)00118-9

Heubeck, Ch., 2009. Geröllführende sedimentäre Gänge der Eisenach-Formation (Oberrotliegend): modifizierte artesische Injektionen am Fuß alluvialer Flächer? Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, **160**: 41–56.

Krechowicz, J., 1964. Mapa Geologiczna Sudetów 1:25000, arkusz Radków (in Polish). Wyd. Geol., Warszawa.

Kurowski, L., 2001. Fluvial sedimentation of the Słupiec Formation (middle Lower Permian) in the Nowa Ruda area (Intra-Sudetic Basin, Sudetes, SW Poland). Geolines, **13**: 86–87.

Kurowski, L., 2004. Fluvial sedimentation of sandy deposits near Nowa Ruda (Intra-Sudetic Basin, SW Poland). Geologia Sudetica, **36**: 21–38.

Mastalerz, K., Prouza, V., 1995. Development of the Intra-Sudetic Basin during Carboniferous and Permian. In: Sedimentary Record of the Variscan Orogeny and Climate – Intra-Sudetic Basin, Poland and Czech Republic (eds. K. Mastalerz, V. Prouza, L. Kurowski, A. Bossowski, A. Ihnatowicz and G. Nowak): 5–15. Guide to Excursion B1. XIII International Congress on Carboniferous-Permian. August 28–September 2, 1995, Kraków, Poland.

Mazumder, R., Van Loon, A.J., Malviya, V.P., Arima, M., Ogawa, Y., 2016. Soft-sediment deformation structures in the Mio-Pliocene Misaki Formation within alternating deep-sea clays and volcanic ashes (Miura Peninsula, Japan). Sedimentary Geology, **344**: 323–335. https://doi.org/10.1016/j.sedgeo.2016.02.010

Monecke, K., Anselmetti, F.S., Arnfried Becker ,A., Sturm, M., Giardin, D., 2004. The record of historic earthquakes in lake sediments of central Switzerland. Tectonophysics, **394**: 21– 40. https://doi.org/10.1016/j.tecto.2004.07.053

Moretti, M., 2000. Soft-sediment deformation structures interpreted as seismites in Middle-Late Pleistocene aeolian deposits. Sedimentary Geology, **135**: 167–179. https://doi.org/10.1016/S0037-0738(00)00070-1

Mugnier, J.L., Huyghe, P., Gajurel, A.P., Upreti, B.N., Jouanne, F., 2011. Seismites in the Kathmandu basin and seismic hazard in central Himalaya. Tectonophysics, **509**: 33–49. https://doi.org/10.1016/j.tecto.2011.05.012

Nemec, W., 1981. Tectonically controlled alluvial sedimentation in the Słupiec Formation (Lower Permian) of Intrasudetic Basin. International Symposium on Central European Permian, Jabłonna, April 27–29, 1978. Instytut Geologiczny, Warszawa.

Nemec, W., Porębski, S.J., Teisseyre, A.K., 1982. Explanatory notes to the lithotectonicmolasse profile of the Intra-Sudetic Basin, Polish part. Veröffentlichungen des Zentralinstituts für Physik der Erde, **66**: 267–278.

Opluštil, S., Schmitz, M., Kachlík, V., Štamberg, S., 2016. Re-assessment of lithostratigraphy, biostratigraphy, and volcanic activity of the Late Palaeozoic Intra-Sudetic, Krkonoše-Piedmont and Mnichovo Hradiště Basins (Czech Republic) based on new U-Pb CA-ID-TIMS ages. Bulletin of Geosciences, **91**: 399–432. https://doi.org/10.3140/bull.geosci.1603

Papadopoulos, G.A., Lefkopoulos, G., 1993. Magnitude-distance relation for liquefaction in soil from earthquakes. Bulletin of the Seismological Society of America, **83**: 925–938.

Pisarska-Jamroży, M., Belzyt, S., Börner, A., Hoffmann, G., Hüneke, H., Kenzler, M., Obst, K., Rother, H., Van Loon, A.J., 2018. Evidence from seismites for glacio-isostatically induced crustal faulting in front of an advancing land-ice mass (Rügen Island, SW Baltic Sea). Tectonophysics, **745**: 338–348. https://doi.org/10.1016/j.tecto.2018.08.004

Pisarska-Jamroży, M., Belzyt, S., Börner, A., Hoffmann, G., Hüneke, H., Kenzler, M., Obst, K., Rother, H., Steffen, H., Steffen, R., Van Loon, A.J., 2019. The sea cliff at Dwasieden: soft-sediment deformation structures triggered by glacial isostatic adjustment in front of the advancing Scandinavian Ice Sheet. DEUQUA Special Publications, **2**: 61–67. https://doi.org/10.5194/deuquasp-2-61-2019

Ploch, I., Awdankiewicz, M., Pawlak, W., Peryt, T., Raczyński, P., Voigt, S., Pańczyk, M., 2023. Problematic age and stratigraphic position of the volcano-sedimentary Słupiec/Broumov Formation in the Permian of the Intrasudetic Basin, EGU General Assembly 2023, Vienna, Austria, 24–28.04.2023, EGU23-5168, https://doi.org/10.5194/egusphere-egu23-5168

Ricci Lucchi, F., 1995. Sedimentological indicators of paleoseismicity. Association of Engineering Geologists Special Publication, **6**: 7–17.

Sakai, T., Gajurel, A.P., Tabata, H., 2015. Seismites in the Pleistocene succession and recurrence period of large earthquakes in the Kathmandu Valley, Nepal. Geoenvironmental Disasters, **2**: 25.

Simms, M.J., 2003. Uniquely extensive seismite from the latest Triassic of the United Kingdom. Evidence for bolide impact? . Geology, **31**: 557–560. https://doi.org/10.1130/0091-7613(2003)031<0557:UESFTL>2.0.CO;2

Štamberg, S., Zajíc, J., 2008. Carboniferous and Permian faunas and their occurrence in the limnic basins of the Czech Republic. Muzeum východních Čech v Hradci Králové..

Telford, W.M., Geldart, L.P., Sheriff, R.E., 1990. Applied Geophysics*.* Cambridge University Press. https://doi.org/10.1017/CBO9781139167932

Tian, H., Van Loon, A.J., Zhang, Z., Zhang, S., Zhang, B., Lü, M., Li, F., Ma, X., 2015. Neogene paleoseismic events and the Shanwang biota's burial in the Linqu area, Shandong Province, China. Acta Geologica Sinica (English ed.), **89**: 1103–1119. https://doi.org/10.1111/1755-6724.12517

Van Loon, A.J., Pisarka-Jamroży, M., 2014. Sedimentological evidence of Pleistocene earthquakes in NW Poland induced by glacio-isostatic rebound. Sedimentary Geology, **300**: 1–10. https://doi.org/10.1016/j.sedgeo.2013.11.006

Van Loon, A.J., Pisarska-Jamroży, M., Nartišs, M., Krievans, M., Soms, J., 2016. Seismites resulting from high-frequency, high-magnitude earthquakes in Latvia caused by Late Glacial glacio--isostatic uplift. Journal of Palaeogeography, **5**: 363–380. https://doi.org/10.1016/j.jop.2016.05.002

Wojewoda, J., 2008a. Diffusional cells – an example of differentiated rheological reaction of granular sediment to seismic shock (in Polish with English summary). Przegląd Geologiczny, **56**: 842–847.

Wojewoda, J., 2008b. Stanowisko 2: Nowa Ruda (Góra Świętej Anny) (in Polish). Polska Konferencja Sedymentologiczna POKOS'3 [wycieczki] Kudowa Zdrój, 15–21.09.2008: 70–72.

Wojewoda, J., Mastalerz, K., 1989. Climate evolution, allo- and autocyclity of sedimentation: an example from the Permo-Carboniferous continental deposits of the Sudetes (in Polish with English summary). Przegląd Geologiczny, **37**: 173–180.

Wójcik L., 1958. Szczegółowa mapa geologiczna Sudetów 1:25000, arkusz Nowa Ruda (in Polish). Wyd. Geol., Warszawa.