Pervasive near-surface stratal disruption in an accretionary prism setting: Kaczawa Complex, SW Poland

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Abstract

The tectonised and metamorphosed mudrocks within the Variscan accretionary prism of the Kaczawa Mountains in SW Poland comprise sedimentary mélanges together with more coherent stratigraphic units; some represent large olistoliths, deposited in a submarine trench. We infer a trend of progressive near-surface stratal disruption in mud-dominated deposits due to dewatering that forms a continuum with subduction-related tectonic structures imposed on unconsolidated sediment during deeper burial. The assemblage of characters suggests that an accretionary prism environment can influence, and leave characteristic traces of, the total burial history of a trench succession.

Keywords: soft sediment deformation; stratal disruption; mélange; Devonian-Carboniferous Variscan accretionary prism; Sudetes; Bohemian Massif; Kaczawa Complex; Poland.

1. Introduction

The processes taking place in active submarine trenches are difficult to study because such regions are poorly accessible. The study of deep sea cores allied with geophysical analysis has provided an overall picture of this environment (e.g. von Huene & Suess, 1988; von Huene & Scholl, 1991, 1993; Clift & Vannucchi, 2004; Stern, 2002; Scudder *et al.* 2009) but the unconsolidated sediment is difficult to sample for detailed study of sedimentary

fabrics. Ancient examples are typically intensively disrupted through metamorphic and tectonic activity associated with subduction (e.g. Bettelli & Vannucchi, 2003; Osozawa *et al.* 2009, and refs. therein). However, remarkable, communist-era deep borehole core material from Poland (Figs. 1, 2, 3) has yielded fine detail of tectonic fabrics imposed upon poorly consolidated deposits (Baranowski *et al.* 1998; Collins *et al.* 2000).

Although a rapid loading of water saturated sediments in a trench environment and the stratal disruption due to dewatering on a very shallow level has been reported (e.g. Kleist, 1974; Cowan, 1985; Moore *et al.* 1985; Byrne *et al.* 1993; Ujiie, 2002; Hashimoto *et al.* 2006; Moore *et al.* 2007; Saffer, 2010), their relation to processes taking place at greater depths within the accretionary prism environment has not been explored to date. We here suggest that characteristic fabrics associated with the deeper environment extend up into shallow burial conditions and, together, these form a spectrum of micro- to meso-scale textures that may be used to help identify an accretionary prism setting.

2. Geological context

The Variscan basement of the Sudetes Mountains in SW Poland is complex (e.g. Mazur *et al.* 2006), but its pre-orogenic history is now revealing a picture of early Palaeozoic ocean opening and late Palaeozoic ocean closure (Linnemann *et al.* 2007; Kryza & Zalasiewicz, 2008; Nance *et al.* 2010). Within this, the Kaczawa Complex (*sensu* Kryza & Zalasiewicz, 2008; Fig. 2) is composed of low-grade metasedimentary and metavolcanic rocks ranging from Cambrian or older to early Carboniferous in age. It comprises: (a) thrust slices and likely nappe fragments representing generally coherent metasedimentary-volcanic units of ?Precambrian – Devonian age (= the Kaczawa Succession), and (b) mélangé bodies containing various fragments of these units, mostly chaotically distributed in a dark, muddy matrix (Baranowski *et al.* 1990).

The lower part of the Kaczawa Succession (e.g. Świerzawa and Bolków units of Fig. 1) is mainly formed of Cambro-Ordovician metasedimentary and within-plate-type metavolcanic rocks, regarded as products of initial rift processes in a continental crust setting (Furnes *et al.* 1994; Kryza & Zalasiewicz, 2008). The upper part comprises thick tholeiitic pillow lavas of E-MORB to N-MORB affinity, associated with condensed, locally graptolitic Silurian-Devonian mudrocks and cherts (Dobromierz and Rzeszówek-Jakuszowa units, Fig. 1). This part developed in the Rheic Ocean (Furnes *et al.* 1994; Kryza & Zalasiewicz, 2008), that separated Baltica/Avalonia from Armorican terranes, amalgamated during Variscan collision (e.g. Tait *et al.* 1997; Aleksandrowski & Mazur, 2002; Nance *et al.* 2002; Winchester *et al.* 2002; Mazur *et al.* 2006; Linnemann *et al.* 2007; Kroner & Romer, 2013).

The *mélange*-type rocks were developed in an accretionary prism environment during the Variscan Orogeny (latest Devonian – early Carboniferous; Baranowski *et al.* 1990; Kryza & Zalasiewicz, 2008; Fig. 3). They are composed of various size clasts and olistoliths of greywackes, cherts and rare volcanoclastic rocks embedded in a dark, mud-dominated matrix. Clasts are cm- to dm-scale (Fig. 4a-c), up to a few hundred meters (map scale) across. Rare conodonts and graptolites suggest blocks of Ordovician-Devonian age in matrix that includes Devonian – lower Carboniferous material (Haydukiewicz & Urbanek, 1987).

The *mélanges* are polygenetic, both in terms of sediment provenance and formation mechanism. A tectonic fabric developed within water-saturated and only partially consolidated sediments (Collins *et al.* 2000). Overall, the metamorphic grade in the Kaczawa Unit varies from very-low grade (Kostylew, 2008) to blueschist- overprinted by greenschist-facies conditions (Kryza *et al.* 1990, 2011), suggesting a tectonic assembling of neighboring rock bodies that descended to different depths and took different P-T paths. Most of the *mélanges* are of lower grade than the embedded more coherent units.

Our research material mostly comes from around a barite deposit at Stanisławów within the Chełmiec unit (Figs. 2, 3), where several continuously cored boreholes up to ~ 1500 m deep were drilled in 1986-1989 (Baranowski *et al.* 1998). The boundaries between the Chełmiec unit and the adjacent Rzeszówek-Jakuszowa and Złotoryja-Luboradz units are tectonic: (1) the units form three nappes thrusting over each other towards the north, with the Chełmiec unit in the middle, or (2) the Chełmiec unit forms a graben between horsts of the Rzeszówek-Jakuszowa and Złotoryja-Luboradz units (Baranowski *et al.* 1998, and refs. therein). The northern boundary of the largest Stanisławów mélangé outcrop south of Stanisławów village (Fig. 2) is a thrust dipping 15-20° to the southwest.

The upper part of the profile penetrated by the boreholes comprises Stanisławów mélangé (latest Devonian – lower Carboniferous; Figs. 3, 4a-b) whereas the lower part consists mainly of likely related, though more coherent fine-grained metasedimentary and metavolcaniclastic rocks of the Kaczawa Succession (*sensu* Kryza & Zalasiewicz, 2008; Figs. 3, 4d-l). The contact zone between mélangé and underlying volcaniclastic rocks in the borehole cores is intensely mineralized with quartz emphasizing its tectonic character and suggesting brittle-type deformation within this thrust zone (Baranowski *et al.* 1998).

An observed continuum between depositional, diagenetic and tectonic characters suggests a narrower age range than was previously suggested (Ordovician to early Carboniferous). However, until the Stanisławów deposits are dated isotopically or by fossils, the age and affinities of this distinctive rock suite must remain open.

3. Methods

Detailed logging and facies analysis have been performed on preserved sections of three borehole cores: 35/S, 38/S and 39/S from Stanisławów (CH Unit, Figs. 1, 2, 3), which are stored at the Institute of Geological Sciences of the University of Wrocław in Poland. The

observations have been supported by microstructural and petrological analysis (Fig. 4).
Observations have been made in the field of a relatively well-exposed section of the
Rzeszówek mélangé (Figs. 1, 4c).

Our work concerns very low-grade metasedimentary rocks (Kostylew, 2008), where
the primary sedimentary features are well preserved. Therefore in this paper we omit the
prefix ‘meta’ in names of the very-low grade metamorphic rocks and use sedimentary rock
nomenclature, as recommended by Baranowski *et al.* (1998).

4. Results

4.a. Sedimentary facies

4.a.1. Mélangé

While large-scale features of the mélangé can be seen at outcrop scale and in scattered
natural exposures (e.g. Rzeszówek mélangé; Figs. 1, 4c), surface weathering and jointing
hinders examination of sedimentary detail. The coherent, unweathered borehole material
enables detailed examination of fine texture: it shows units up to 150 – 200 m thick of
seemingly chaotic to partly organized deposits, dominated by either mud or coarse sand.

Dark-grey and black slates are typical Stanisławów mélangé matrix, containing clasts
of lithic graywacke, quartzite and chert. The disrupted fragments are set in a muddy matrix
and include completely disarticulated clasts of fine-grained sandstone which range in size
from > 1 mm to a several cm across; these typically are partly to wholly rounded and
lithologically closely resemble the sandy layers in the mud-dominated facies, described
below. There are also more or less articulated slabs of the sand-mud turbidite facies that may
show either imbrication or pull-apart structures (Fig. 4a-b).

The Rzeszówek mélangé crops out in the eastern part of the large section near to
Rzeszówek village in the northern part of the Kaczawa Mountains (Fig. 1a). The mélangé

matrix is built of fine-grained, black, foliated and strongly disrupted slates, which are host sediments for fragments, lenses and large (up to 2 m in size) clasts of various sandstones and cherts (Fig. 4c). In one of these fragments – a partly disrupted layer of grey silica-rich slate adjoining black muddy matrix – Late Devonian to Early Visean conodonts have been found (Haydukiewicz & Urbanek, 1987).

4.a.2. Coarse sandstone facies

This facies comprises medium to coarse, moderately to poorly sorted sand with scattered ‘floating’ clasts of fine to medium gravel-grade arranged in units typically ~10 to 50 m thick (Szaynok, 1989¹; Fig. 4). These are massive and show both indistinct fining-up and coarsening-up trends. These rocks are the ‘volcaniclastic facies’ of Baranowski *et al.* (1998). Typical Bouma sequences have not been recognized. This facies is consistent with deposition from high-density turbidity currents in which the suspended sediment immediately above the aggrading surface was at sufficiently high concentrations to suppress turbulence and prevent the formation of tractional sedimentary structures.

4.a.3. Mud-dominated facies

More coherent units (olistoliths in part?) of mud-dominated facies comprise dark grey mudstone, often laminated or interbedded on a mm-cm scale with fine sandstone (Fig. 4d-l). The thinner layers of mudstone tend to be continuous on the scale of a core sample while the thicker sandstone layers tend to be discontinuous (Fig. 4i-l), locally showing ripple forms and load/flame structures (Fig. 4e-f). Most individual layers have sharp bases and tops with distinct graded (fining-up) units being rare. Homogeneous mud layers, up to 2-3 cm thick, sporadically occur (Fig. 4d-g). Interspersed with, and grading into, this facies is one that

¹ SZAYNOK, T. 1989. Petrographical description of metavolcanic and metasedimentary rocks from drill cores in the vicinity of Stanisławów, Kaczawskie Mts. (*in Polish*). Institute of Geological Sciences University of Wrocław, Poland. Unpublished MSc thesis.

shows interlamination of mud and silt on a mm scale, individual laminae being generally sharply defined and continuous (Fig. 4d-e).

The style of primary bedding in thicker layers is consistent with deposition from low-density mud-rich turbidity currents and may be interpreted in terms of Bouma D (with sand-mud interlamination) and E (homogeneous mudstone) units, with rare Bouma C. The finely laminated component of this facies may broadly represent hemipelagic sedimentation, though this facies differs from typical Palaeozoic hemipelagites (cf. Davies *et al.* 1997) in comprising layers that are thicker and more continuous and that do not obviously contain enhanced amounts of pelagically-derived organic matter. Hence, this facies might more closely represent very thin-bedded turbidites that include both intervals of mud-rich Bouma D intervals (in which multiple alternations arise from a single depositional event) and/or successive individual very thin-graded units derived from small, low-density turbidity currents or nepheloid plumes.

The mineralogical composition of the rocks is quite monotonous. Homogenous mudstones are built mainly of white K-mica (illite/phengite), Fe-Mg chlorite, subordinate very small grains of quartz and, sporadically, albite. White K-micas and chlorites often form intergrowths (chlorite-mica stacks). The accessory mineral assemblage contains framboidal pyrite, small grains of apatite and rutile (Kostylew, 2005, 2006²). In many samples of mudstone, considerable quantities of submicroscopic (< 10 µm) grains of monazite are present (Kryza *et al.* 2004). Some samples contain substantial amounts of dispersed organic matter. Overall, these deposits resemble, for example, the early Silurian slope-apron mud turbidites of central Wales (Davies *et al.* 1997) and likewise may have been deposited on a

² KOSTYLEW, J. 2006. Mineralogical and geochemical processes in mudrocks during diagenesis and epimetamorphism: examples from the Kaczawa Complex in the Sudetes, SW Poland (*in Polish, abstract in English*). Institute of Geological Sciences University of Wrocław, Poland. Unpublished PhD thesis.

significant slope, as thick (> 10 cm) units have not been recognized and associated sedimentary mélanges (see above) are common. They differ, though, from typical slope/apron deposits in the style of pervasive soft sediment deformation, as described below.

4.b. Post-depositional structures

Small-scale disruption of the layering is abundant and we suggest a trend in its progressive development that we link with an increasing effect of fluid throughput through the sediment mass. Thus:

(1) The sedimentary lamination is essentially undisturbed, except where disruption has taken place by the clear effects of loading of sand layers into underlying mud immediately following deposition (Fig. 4d-f).

(2) Diffuse streaks of mud more or less perpendicular to bedding are superimposed upon the primary stratification and locally grade into discrete mud veins that begin to cut across and disrupt bedding (Fig. 4g-h).

(3) The mud veins become better defined than in (2), more closely spaced and pervasively cut across the bedding. Where there is a marked contrast in lithology (in sand-mud interlayering), the sand laminae become pervasively disrupted into a chequer-board style appearance (Fig. 4i-j). Commonly the sand layers become yet more fragmented with the edges of the segments being rounded and diffuse, the whole assuming a ‘cloudy’ appearance (Fig. 4k-l).

Typically, individual sand layers are segmented by variably spaced more or less distinct vertically aligned mud streaks while loaded ball-like structures and synsedimentary faults are common (Fig. 4i-j: e.g. to left of arrow in 4i)). The thicker sandstone layers are much more commonly disrupted than the thin sandy laminae (Fig. 4i-l).

5. Discussion

5.a. Depositional setting

This succession is dominated by gravitational sedimentation and, commonly, remobilization and redeposition, in a deep marine environment with no evidence of wave or tidal action or emergence. Where preserved as more or less coherent slabs, the deposits are broadly turbiditic, with coarser material deposited from high-density currents and finer material deposited as low-density turbidites (mainly Bouma D-E). This might be interpreted in terms of significant, shifting relief on the sea floor, with the coarse material accumulating in sea floor lows and the thin-bedded mudstones on adjacent slopes and/or highs.

There are almost no body and trace fossils. Fine lamination is almost invariably undisturbed by any trace of animal activity. Indeed, the only fossils recorded from these rocks are rare conodonts and a single example of possible burrows from an exposure at Rzeszów; the Stanisławów boreholes have yielded no fossils. This likely reflects very high rates of sedimentation, diluting any fossil material present and also hindering colonization of the sea floor because of a highly unconsolidated substrate (cf. the ‘soupy’ sea floor of Martill, 1993; Levin, 2003). A contributory factor to the absence of benthic macrofossils may have been the continual or intermittent presence of anoxia at the sea floor, as was common in Palaeozoic times (Davies *et al.* 1997, 2009, and refs. therein). However, typical organic-rich ‘anoxic’ hemipelagic laminae (cf. Cave, 1979) were not recognized in this study, perhaps because of sustained high rates of sedimentation.

5.b. Stratal disruption

A characteristic feature of these deposits is the widespread evidence of immediately post-depositional disruption of the bedding by loading and fluid/mud injections. This is so pervasive a feature that it essentially defines a distinct facies. The pattern of progressive deformation observed involved the upward movement of intra-stratal fluid which locally took

the form of mass transfer of sediment-fluid mixtures (Figs. 4, 5). In detail, the layer-disrupting structures resemble the typical load and flame structures also present but differ from them in the more marked segmentation of the coarser layers, the more intergradational and fluidal appearance of the contacts at the points of disruption and the widespread presence of mud veins cross-cutting the primary lamination. The key factors here seem to be a rapid rate of sedimentation overall to give rise to successions of water-saturated muddy sediment; the resultant compactional dewatering may have been enhanced by throughput of fluid expelled from actively deforming strata atop the descending plate. The mud veins in particular resemble similar phenomena that have been attributed to multiple fracture formation in soft sediment by the passage of earthquake waves (Fig. 4g-h; Allen, 1986; Brothers *et al.* 1996; Collins *et al.* 2000, and refs. therein; Pandey *et al.* 2009).

We interpret this assemblage as the early burial predecessors of the deformation structures described by Collins *et al.* (2000) who detailed the development of cleavage-related fabrics in the same rocks while they were still soft. We thus suggest that the deformation processes effectively began immediately upon sedimentation (Figs. 4, 5), were widespread in, and typical of, the depositional environment, and then persisted through burial before grading into the shear-dominated tectonic deformation described by Collins *et al.* (2000; Fig. 5). Given the ubiquity of these features, we infer that sedimentary conditions on the sea floor were dominated by a combination of rapid sedimentation, frequent seismicity and upwardly expelled pore fluids, perhaps locally including cold seeps as are a widespread indicator of fluid escape today along active margins (Buerk *et al.* 2010, and refs. therein).

In the borehole cores from Stanisławów up to 1500 m of material has been preserved and the bottom of the sedimentary/volcanic sequence has not been reached. In modern accretionary prism similar deposit thicknesses have been described, in the most active, frontal parts of prisms eg: a ~4 km sedimentary succession in the Makran accretionary prism

offshore Iran (Grando & McClay, 2007) or the ~2 km succession of the Hawke Bay basin within the Hikurangi subduction zone in New Zealand (Barnes *et al.* 2002).

We interpret this set of characters as being consistent with deposition in a submarine trench with active subduction, as regional geological studies (Kryza & Zalasiewicz, 2008) and the tectonic fabric studies of Collins *et al.* (2000) have indicated (Fig. 5). We suggest, further, that the assemblage of characters that we have recognized, particularly in the mud-dominated strata, might prove useful elsewhere as indicators of accretionary prism settings.

6. Conclusions

(1) The deposits preserved in the Stanisławów boreholes penetrating the Kaczawa Unit, Polish Sudetes, comprise interbedded mélanges, coarse turbidites and mudrocks that contain relict evidence of primary depositional conditions in an oceanic trench during the evolution and closure of the Rheic Ocean.

(2) The mudrock facies show exceptional preservation of a suite of sedimentary deformation phenomena attributable to upward fluid streaming linked to sedimentary compaction associated with tectonically driven fluid expulsion. We distinguished three stages of development of early soft-state deformation linked to dewatering and increasing stratal disruption. These structures appear to represent a distinctive facies that may be used to help recognize accretionary prism environments elsewhere.

(3) Deformation processes effectively began immediately upon sedimentation, were widespread in, and typical of, the depositional environment, and then persisted through burial before grading into shear-dominated tectonic deformation of poorly compacted deposits.

Acknowledgements

267 The study was supported by the Polish National Research Committee KBN and the National
268 Science Centre of Poland (J.K., R.K., grant number 3 P04D 045 25 and N N307 062036); and
269 from the University of Wrocław, Poland (R.K., J.K., grant number 1017/S/ING/10-II).

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271 Declaration of Interest

272 None

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FIGURES

Figure 1. (a) Geological sketch map of the Kaczawa Mountains (based on Baranowski *et al.* 1987; Baranowski *et al.* 1990; Kryza & Muszyński, 1992, Kryza & Zalasiewicz, 2008; modified), (b) their tectonic setting in the Variscan Belt (after Aleksandrowski & Mazur, 2002; modified) and (c) their location in the Bohemian Massif (after Aleksandrowski *et al.* 1997; modified).

AM – Armorican Massif; BM – Bohemian Massif; ISF – Intra-Sudetic Fault; MC – Massif Central; MGCH – Mid-German Crystalline High; MO – Moldanubian Zone; MOFZ – Middle

443 Odra Fault Zone; MS – Moravo-Silesian Zone; NP – Northern Phyllite Zone; RH –
 444 Rhenohercynian Zone; ST – Saxothuringian Zone; TB – Teplá-Barrandian Zone; UEFZ –
 445 Upper Elbe Fault Zone; V – Vosges, pЄ - Precambrian, Cm – Cambrian, Or – Ordovician, S –
 446 Silurian, D – Devonian, C – Carboniferous.

447
 448 Figure 2. Geological sketch of the Chełmiec Unit (after Baranowski *et al.* 1998, modified).
 449 See Fig. 1 for location. Cm – Cambrian, Or – Ordovician, S – Silurian, D – Devonian, C –
 450 Carboniferous, P – Permian, Q – Quaternary

451

Figure 3. Schematic logs of borehole cores 35/S, 38/S and 39/S from Stanisławów (CH Unit – see Figs. 1 & 2 for location) selected for detailed investigations (partly based on Baranowski *et al.* 1998). The 38/S borehole core log partly based on Adamski, unpub. M.Sc. thesis, University of Wrocław, 1989. ‘Kaczawa Succession’ *sensu* Kryza & Zalasiewicz, (2008) = ‘stratigraphic sequence’ *sensu* Baranowski *et al.* (1987); Baranowski *et al.* (1990); Baranowski *et al.* (1998). For detailed description of sampling sites – see Fig. 4a-l. Cm – Cambrian, Or – Ordovician, S – Silurian, D – Devonian, C – Carboniferous.

Figure 4. (Colour online) Idealized log of sedimentary facies described in this study; not to scale and sense of progressive stratal disruption does not necessarily indicate increasing depth. MÉLANGE (a-c): disaggregated clasts of all sizes. (a) – Typical black Stanisławów mélangé, containing disarticulated clasts in a carbon-rich muddy matrix. (b) – Gray-greenish type of Stanisławów mélangé: lenticular sandy layers are broken and chaotically spaced in a carbon-poor muddy matrix. (c) – Typical black Rzeszów mélangé of foliated and strongly disrupted slate – host lithology for lenses and large (up to 2 m) clasts of sandstone and chert. 1st STAGE of post-depositional disruption (d-f): mudrock/fine sandstone strata undisrupted except for local load and flame structures. (d) – Homogeneous, dark-grey mudstone. Lamination is almost undisturbed, individual layers have sharp bases and tops. (e) & (f) – Thicker sandstone layers showing load and flame structures, with homogeneous mud layers to 2 cm thick. 2nd STAGE of post-depositional disruption (g-h): mud-dominated facies; discrete streaks of mud perpendicular to bedding (diffuse mud veins in sand layers). (g) – Thick homogeneous mud layer to 10 cm thick. (h) – Small mud veins are sigmoidal in shape and bifurcate into ‘fish-tail’ terminations, characteristic of earthquake-generated structures in

soft sediment (Brothers *et al.* 1996). 3rd STAGE of post-depositional disruption (i-j): cross-cutting mud veins and checkerboard' segmentation of sand/mud layers; rounding of sandstone 'segments'. (i) & (j) – Mud veins are better defined, more closely spaced and pervasively cut across the bedding, while sand laminae are pervasively disrupted into a chequer-board style appearance. (k) & (l) – 'Cloudy' sand layers – more fragmented with rounded segment edges. Arrows indicate top of cores. 35/S, 38/S and 39/S denote boreholes; see Figs. 1, 2 & 3 for location. VLCL – volcaniclastic.

Figure 5. Cartoon illustrating environment and processes inferred for the ocean trench active in the area of the present-day Kaczawa Mountains during closure of the Rheic Ocean. See text for details.