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

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Abstract – The tectonized 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, Variscan accretionary prism, Kaczawa Complex, Sudetes.

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; Stern, 2002; Clift & Vannucchi, 2004; Scudder, Murray & Plank, 2009), but the unconsolidated sediment is difficult to sample for a 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, Morimoto & Flower, 2009). However, remarkable, communist-era deep borehole core material from Poland (Figs 1–3) has yielded fine detail of tectonic fabrics imposed upon poorly consolidated deposits (Baranowski *et al.* 1998; Collins, Kryza & Zalasiewicz, 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, Cowan & Karig, 1985; Byrne *et al.* 1993; Ujiie, 2002; Hashimoto *et al.* 2006; Moore, Rowe & Meneghini, 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. 1) 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) mélange 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 tholeitic pillow lavas of MORB-type 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 the Variscan collision (e.g. Tait *et al.* 1997; Aleksandrowski & Mazur, 2002; Nance, Murphy & Keppie, 2002; Winchester, Pharaoh & Verniers, 2002; Mazur *et al.* 2006; Linnemann *et al.* 2007; Kroner & Romer, 2013).

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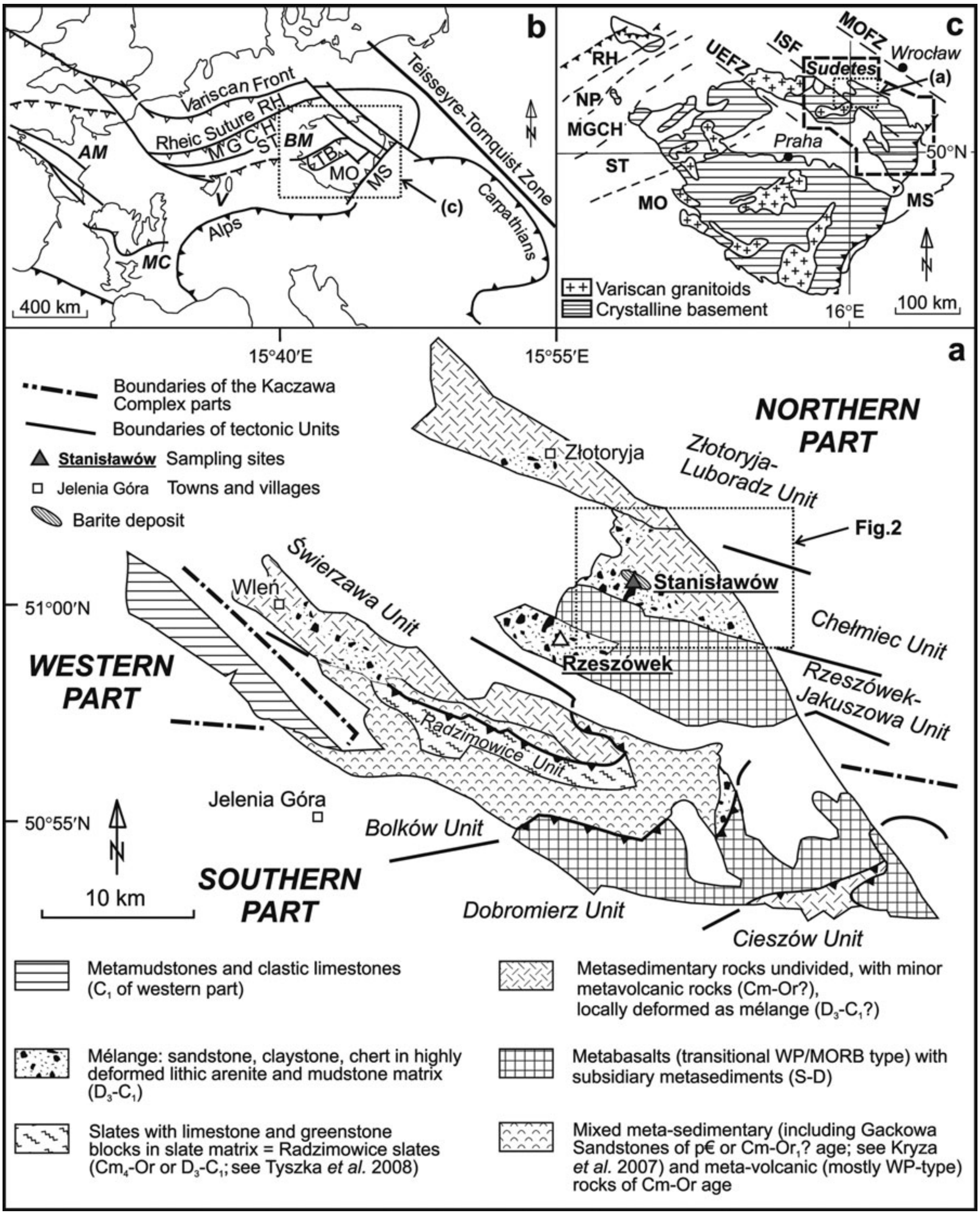

Figure 1. (a) Geological sketch map of the Kaczawa Mountains (based on Baranowski *et al.* 1987, 1990; Kryza & Muszyński, 1992; Kryza *et al.* 2007; Kryza & Zalasiewicz, 2008; Tyszka *et al.* 2008), (b) their tectonic setting in the Variscan Belt (after Aleksandrowski & Mazur, 2002) and (c) their location in the Bohemian Massif (after Aleksandrowski *et al.* 1997). AM – Armorican Massif; BM – Bohemian Massif; ISF – Intra-Sudetic Fault; MC – Massif Central; MGCH – Mid-German Crystalline High; MO – Moldanubian Zone; MOFZ – Middle Odra Fault Zone; MS – Moravo-Silesian Zone; NP – Northern Phyllite Zone; RH – Rhenohercynian Zone; ST – Saxothuringian Zone; TB – Teplá-Barrandian Zone; UEFZ – Upper Elbe Fault Zone; V – Vosges; p€ – Precambrian; Cm – Cambrian; Or – Ordovician; S – Silurian; D – Devonian; C – Carboniferous; P – Permian, Q – Quaternary.

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-sized clasts and olistoliths of greywackes, cherts and rare volcaniclastic rocks embedded in a dark, mud-dominated matrix. Clasts are of centimetre to decimetre scale (Fig. 4a–c), up to a few hundred metres (map scale) across. Rare conodonts and graptolites suggest

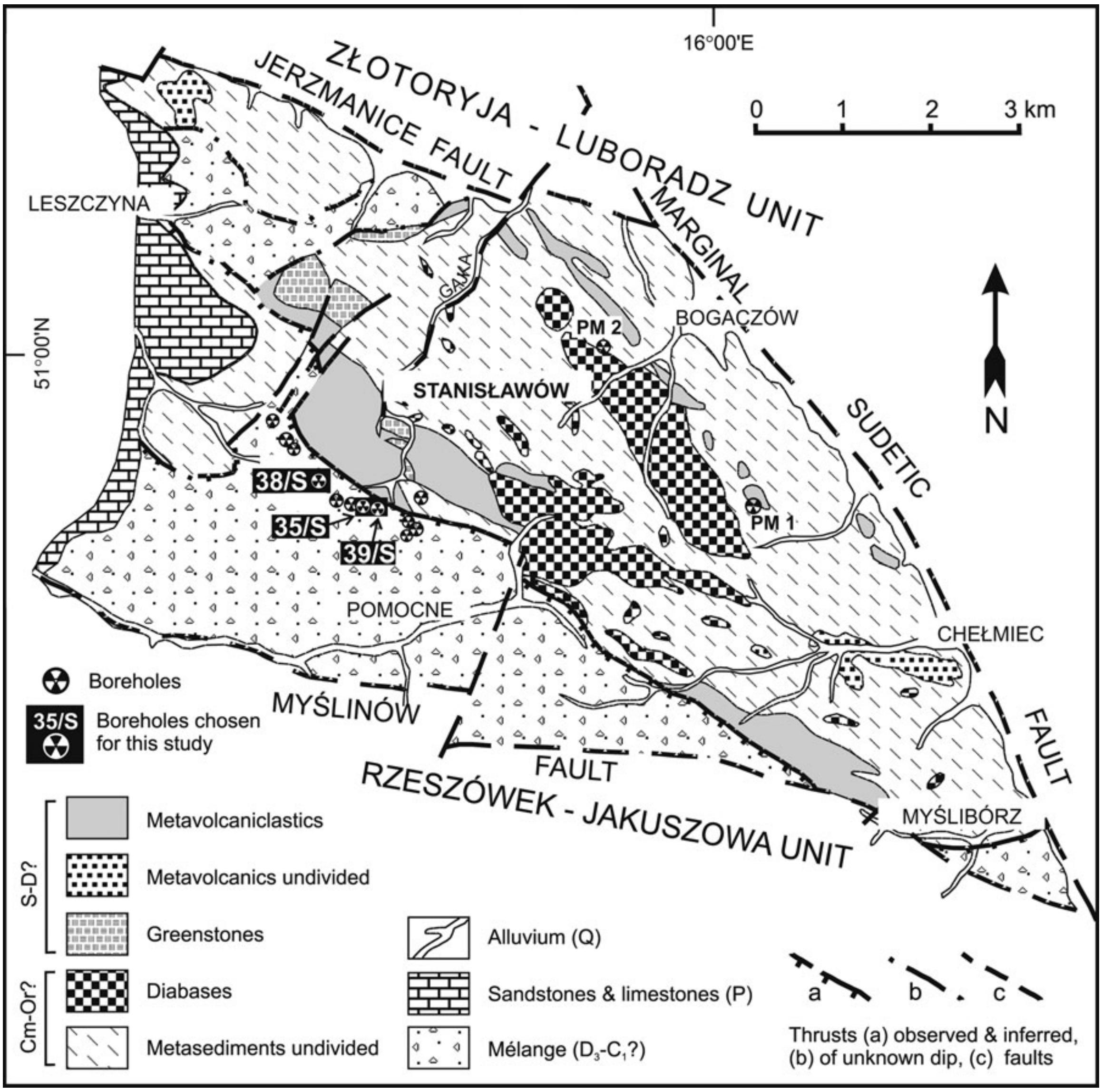

Figure 2. Geological sketch of the Chełmiec Unit (after Baranowski *et al.* 1998). See Figure 1 for location and abbreviations.

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, Kryza & Zalasiewicz, 2000). Overall, the metamorphic grade in the Kaczawa Unit varies from very-low grade (Kostylew, 2008) to blueschist- overprinted by greenschist-facies conditions (Kryza, Muszyński & Vielzeuf, 1990; Kryza *et al.* 2011), suggesting a tectonic assembling of neighbouring rock bodies that descended to different depths and took different pressure–temperature (*P*–*T*) paths. Most of the mélanges are of lower grade than the embedded, more coherent units of the Kaczawa Succession (J. Kostylew, unpub. PhD thesis, University of Wrocław, 2006).

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 *c.* 1500 m deep were drilled during 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). The northern boundary of the largest Stanisławów mélange outcrop south of Stanisławów village (Fig. 2) is a thrust dipping 15–20° to the SW.

The upper part of the profile penetrated by the boreholes comprises Stanisławów mélange (latest Devonian – lower Carboniferous; Figs 3, 4a, b), whereas the lower part consists mainly of likely related, but more coherent fine-grained metasedimentary and metavolcaniclastic rocks of the Kaczawa Succession (*sensu* Kryza & Zalasiewicz, 2008; Figs 3, 4d–l). The contact zone between mélange and underlying volcaniclastic rocks in the borehole cores is intensely mineralized

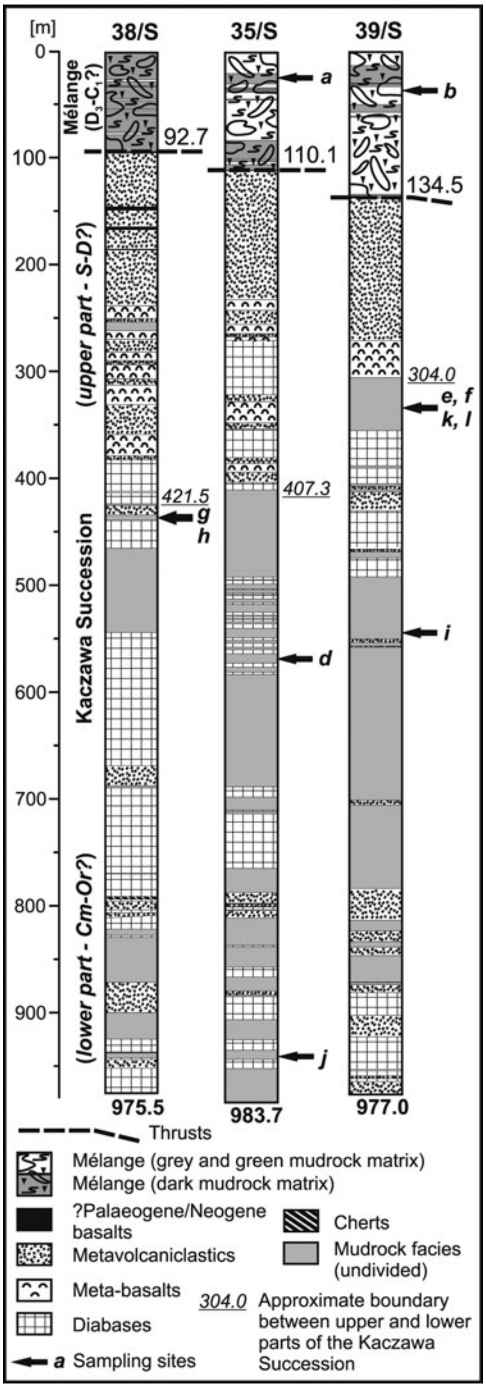

Figure 3. Schematic logs of borehole cores 35/S, 38/S and 39/S from Stanisławów (CH Unit; see Figs 1, 2 for location) selected for detailed investigations (partly based on Baranowski *et al.* 1998). The 38/S borehole core log partly based on: Adamski (unpub. MSc thesis, University of Wrocław, 1989); 'Kaczawa Succession' *sensu* Kryza & Zalasiewicz (2008) = 'stratigraphic sequence' *sensu* Baranowski *et al.* (1987); Baranowski *et al.* (1990); Baranowski *et al.* (1998). 'Lower part' of Kaczawa Succession *sensu* Kryza & Zalasiewicz, (2008) = 'an association of metamudstones and diabases' *sensu* Baranowski *et al.* (1998). 'Upper part' of Kaczawa Succession *sensu* Kryza & Zalasiewicz, (2008) = 'an association of metavolcaniclastic rocks' *sensu* Baranowski *et al.* (1998). The first appearance of the assemblage of metamudstones and diabases designates an approximate boundary between upper and lower parts of Kaczawa Succession. For detailed description of sampling sites see Fig. 4a–l.

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 – early Carboniferous; Baranowski *et al.* 1998). 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 1–3), 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 mélange (Figs 1, 4c).

Our work concerns very low-grade metasedimentary rocks (Kostylew, 2008), where the primary sedimentary features are well preserved. In this paper we therefore omit the prefix 'meta' in the 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. Mélange

While large-scale features of the mélange can be seen at outcrop scale and in scattered natural exposures (e.g. Rzeszówek mélange; 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 (rarely greenish) slates are typical Stanisławów mélange matrix, containing clasts of lithic greywacke, quartzite, chert, graphitic and siliceous slates, greenstones and various laminated silt- and clay-rich slates. The fragments resembling different stage of disruption are set in a muddy, partly brecciated matrix and include completely disarticulated clasts of fine-grained sandstone which range in size from >1 mm to a several centimetres across; these are typically 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). No trace of fossils has been found to date. The Rzeszówek mélange crops out in the eastern part

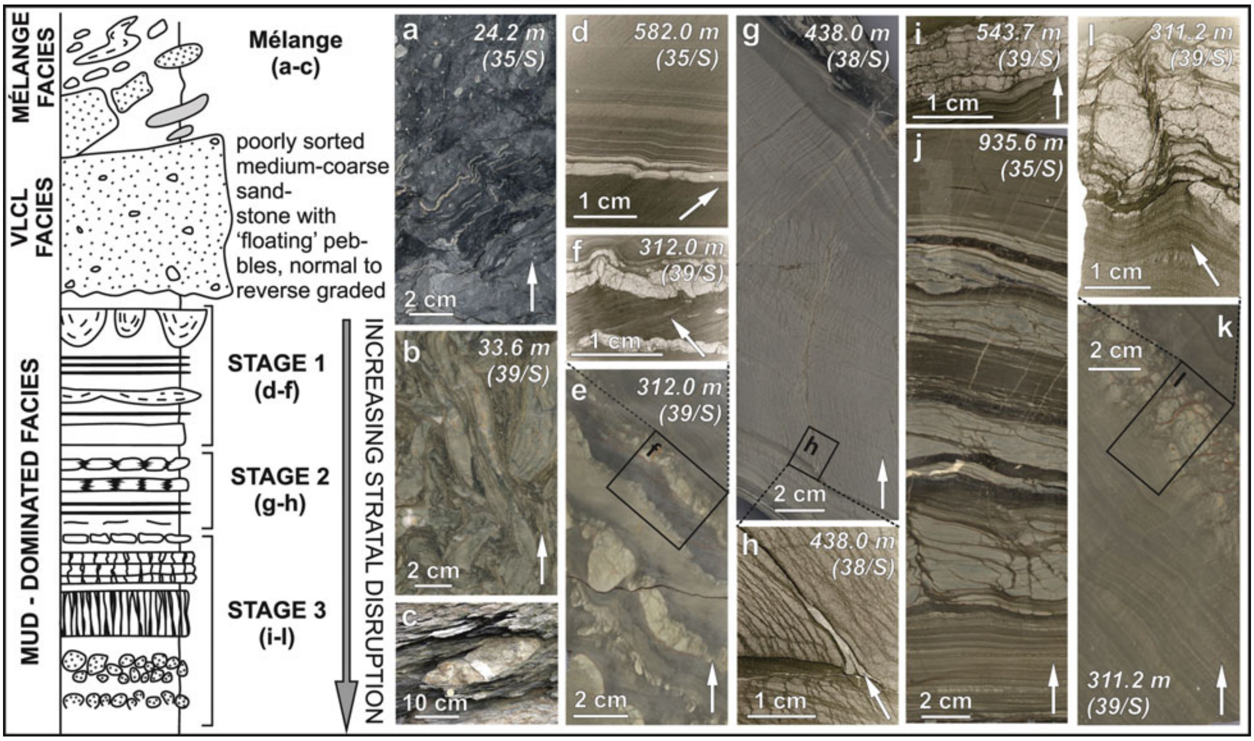

Figure 4. (Colour online) Idealized log of sedimentary facies described in this study; not to scale and sense of progressive stratal disruption does not necessarily indicate increasing depth. (a–c) Mélange: disaggregated clasts of all sizes. (a) Typical black Stanisławów mélange, containing disarticulated clasts in a carbon-rich muddy matrix. (b) Grey-greenish type of Stanisławów mélange; lenticular sandy layers are broken and chaotically spaced in a carbon-poor muddy matrix. (c) Typical black Rzeszówek mélange of foliated and strongly disrupted slate. Host lithology for lenses and large (up to 2 m) clasts of sandstone and chert. (d–f) First stage of post-depositional disruption; for the location of the Rzeszówek mélange outcrop see Figure 1a. 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. (g, h) Second stage of post-depositional disruption. 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, Kemp & Maltman, 1996). (i, j) Third stage of post-depositional disruption. Cross-cutting mud veins and chequer-board segmentation of sand/mud layers; rounding of sandstone 'segments'. 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 Figures 1–3 for location. VLCL – volcaniclastic.

of the large section near to Rzeszówek village in the northern part of the Kaczawa Mountains (Fig. 1a). The mélange 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, slates, cherts and volcanic rocks (Fig. 4c). In one of these fragments – a partly disrupted layer of grey silica-rich slate adjoining black muddy matrix – Late Devonian–early Visean conodonts have been found (Haydukiewicz & Urbanek, 1987). Due to the petrographic and structural similarities between Stanisławów and Rzeszówek mélanges, the former is also interpreted as probably latest Devonian – early Carboniferous in age (Baranowski *et al.* 1998).

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 *c.* 10–50 m thick (T. Szaynok, unpub. MSc thesis, University of Wrocław, 1989; Fig. 4). These are massive and show both indistinct fining-upwards and coarsening-upwards 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 millimetre-centimetre 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-upwards) 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 shows interlamination of mud and silt on a millimetre 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. This facies might therefore 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; J. Kostylew, unpub. PhD thesis, University of Wrocław, 2006). In many samples of mudstone, considerable quantities of submicroscopic ($<10\ \mu$m) 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); likewise, they may have been deposited on a significant slope, as thick (>10 cm) units have not been recognized and associated sedimentary mélanges (see above) are common. They differ from typical slope/apron deposits in the style of pervasive soft sediment deformation however, 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 to an increasing effect of fluid throughput through the sediment mass.

(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 seafloor, with the coarse material accumulating in seafloor 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 Rzeszówek; 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 seafloor because of a highly unconsolidated substrate (cf. the ‘soupy’ seafloor 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 seafloor, as was common in Palaeozoic times (Davies *et al.* 1997, 2009). 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 upwards 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. These small (millimetre- to centimetre-scale) veins, often sigmoidal in shape, occur in regularly spaced arrays, approximately perpendicular to the bedding. The divergent ‘fish tail’ endings of the veins are filled with clay-rich, originally unconsolidated sediment (Fig. 4g, h; Allen, 1986; Brothers, Kemp & Maltman, 1996; Collins, Kryza & Zalasiewicz, 2000; Pandey *et al.* 2009). The origin of such veins has been described by Brothers, Kemp & Maltman (1996), and they were first observed in the drill core material from the Kaczawa Complex by Collins, Kryza & Zalasiewicz (2000).

We interpret this assemblage as the early burial predecessors of the deformation structures described by Collins, Kryza & Zalasiewicz (2000) who detailed the development of cleavage-related fabrics in the same rocks while they were still soft. We therefore 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, Kryza & Zalasiewicz (2000; Fig. 5). Given the ubiquity of these features, we infer that sedimentary conditions on the seafloor were dominated by a combination of rapid sedimentation, frequent seismicity and upwardly expelled pore fluids, perhaps locally including cold seeps, a widespread indicator of fluid escape today along active margins (Buerk *et al.* 2010).

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 prisms similar deposit thicknesses have been described in the most active, frontal parts of prisms, for example: a *c.* 4 km sedimentary succession in the Makran accretionary prism offshore Iran (Grando & McClay, 2007); or the *c.* 2 km succession of the Hawke Bay basin within the Hikurangi subduction zone in New Zealand (Barnes, Nicol & Harrison, 2002).

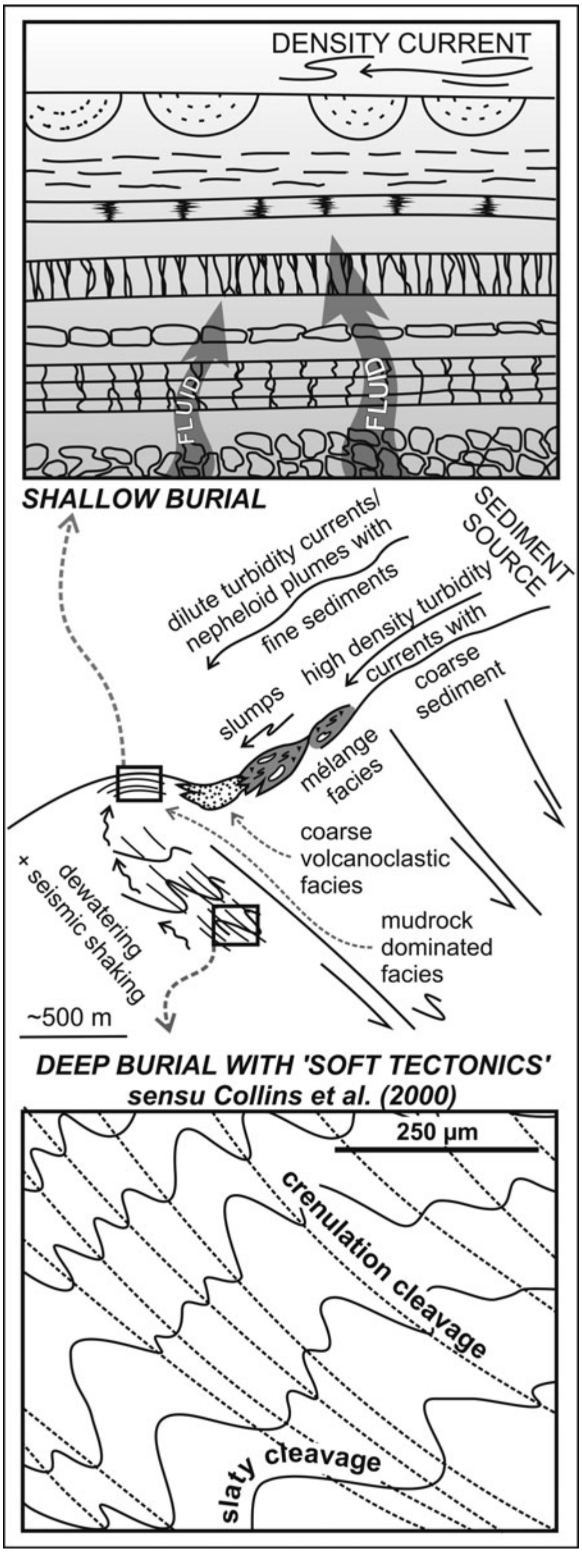

Figure 5. Cartoon illustrating environment and processes inferred for the ocean trench active in the area of the present-day Kaczawa Mountains during closure of the Rheic Ocean. See text for details.

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, Kryza & Zalasiewicz (2000) have indicated (Fig. 5). We further suggest 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 upwards 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.

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Declaration of interest

None.

References

ALEKSANDROWSKI, P., KRYZA, R., MAZUR, S. & ŻABA, J. 1997. Kinematic data on major Variscan strike-slip faults and shear zones in the Polish Sudetes, northeast Bohemian Massif. *Geological Magazine* **134**, 727–39.

ALEKSANDROWSKI, P. & MAZUR, S. 2002. Collage tectonics in the northeasternmost part of the Variscan Belt: the Sudetes, Bohemian Massif. In *Palaeozoic Amalgamation of Central Europe* (eds J. A. Winchester, T. C. Pharaoh & J. Verniers), pp. 237–77. Geological Society of London, Special Publications no. 201.

ALLEN, J. R. L. 1986. Earthquake magnitude-frequency, epicentral distance, and soft-sediment deformation in sedimentary basins. *Sedimentary Geology* **46**, 67–75.

BARANOWSKI, Z., HAYDUKIEWICZ, A., KRYZA, R., LORENC, S., MUSZYŃSKI, A., SOLECKI, A. & URBANEK, Z. 1990. Outline of the geology of the Góry Kaczawskie (Sudetes, Poland). *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen* **179**, 223–57.

BARANOWSKI, Z., HAYDUKIEWICZ, A., KRYZA, R., LORENC, S., MUSZYŃSKI, A. & URBANEK, Z. 1987. Rozwój struktury wschodniej części Gór Kaczawskich na podstawie dotychczasowego rozpoznania stratygrafii, warunków sedymentacji i wulkanizmu. *Przewodnik 58 Zjazdu Polskiego Towarzystwa Geologicznego*, 17–19 Września 1987, Wałbrzych.

BARANOWSKI, Z., HAYDUKIEWICZ, A., KRYZA, R., LORENC, S., MUSZYŃSKI, A. & URBANEK, Z. 1998. The lithology and origin of the metasedimentary and metavolcanic rocks of the Chełmiec Unit (Góry Kaczawskie, Sudetes). *Geologia Sudetica* **31**, 33–59.

BARNES, P. M., NICOL, A. & HARRISON, T. 2002. Late Cenozoic evolution and earthquake potential of an active listric thrust complex above the Hikurangi subduction zone, New Zealand. *GSA Bulletin* **114**, 1379–405.

BETTELLI, G. & VANNUCCHI, P. 2003. Structural style of the offscraped Ligurian oceanic sequences of the Northern Apennines: new hypothesis concerning the development of mélange block-in-matrix fabric. *Journal of Structural Geology* **25**, 371–88.

BROTHERS, R. J., KEMP, A. E. S. & MALTMAN, A. J. 1996. Mechanical development of vein structures due to the passage of earthquake waves through poorly-consolidated sediments. *Tectonophysics* **260**, 227–44.

BUERK, D., KLAUCKE, I., SAHLING, H. & WEINREBE, W. 2010. Morpho-acoustic variability of cold seeps on the continental slope offshore Nicaragua: Result of fluid flow interaction with sedimentary processes. *Marine Geology* **275**, 53–65.

BYRNE, T., MALTMAN, A., STEPHENSON, E., SOH, W. & KNIPE, R. 1993. Deformation structures and fluid flow in the toe region of the Nankai accretionary prism. In *Proceedings of the Ocean Drilling Program* (eds HILL, I. A., TAIRA, A., FIRTH, J. V., *et al.*), pp. 83–101. College Station, Texas. Scientific Results 131.

CAVE, R. 1979. Sedimentary environments of the basinal Llandovery of mid-Wales. In *The Caledonides of the British Isles* (eds A. L. Harris, C. E. Holland & B. E. Leake), pp. 517–26. Geological Society of London, Special Publication no. 8.

CLIFT, P. & VANNUCCHI, P. 2004. Controls on tectonic accretion versus erosion in subduction zones: Implications for the origin and recycling of the continental crust. *Review of Geophysics* **42**, RG2001: 1–31.

COLLINS, A. S., KRYZA, R. & ZALASIEWICZ, J. 2000. Macrofabric fingerprints of Late Devonian–Early Carboniferous subduction in the Polish Variscides, the Kaczawa complex, Sudetes. *Journal of the Geological Society of London* **157**, 283–8.

COWAN, D. S. 1985. Structural styles in Mesozoic and Cenozoic mélanges in the western Cordillera of North America. *Geological Society of America Bulletin* **96**, 451–62.

DAVIES, J. R., FLETCHER, C. J. N., WATERS, R. A., WILSON, D., WOODHALL, D. G. & ZALASIEWICZ, J. 1997. Geology of the country around Llanilar and Rhayader: Memoir for 1:50,000 geological sheets 178 and 179 (England and Wales). British Geological Survey, London, xii + 267 pp.

DAVIES, J. R., WATERS, R. A., WILLIAMS, M., WILSON, D., SCHOFIELD, D. I. & ZALASIEWICZ, J. A. 2009. Sedimentary and faunal events revealed by a revised correlation of post-glacial Hirnantian (Late Ordovician) strata in the Welsh Basin, UK. *Geological Journal* **44**, 322–40.

FURNES, H., KRYZA, R., MUSZYŃSKI, A., PIN, C. & GARMANN, L. B. 1994. Geochemical vidence for progressive, rift-related early Palaeozoic volcanism in the Western Sudetes. *Journal of the Geological Society, London* **151**, 91–109.

GRANDO, G. & MCCLAY, K. 2007. Morphotectonics domains and structural styles in the Makran accretionary prism, offshore Iran. *Sedimentary Geology* **196**, 157–79.

HASHIMOTO, Y., NAKAYA, T., ITO, M. & KIMURA, G. 2006. Tectonolithification of sandstone prior to the onset of seismogenic subduction zone: Evidence from tectonic mélange of the Shimanto Belt, Japan. *Geochemistry, Geophysics, Geosystems* **7**, Q06013.

HAYDUKIEWICZ, A. & URBANEK, Z. 1987. Melanż z Rzeszówka (dolina potoku Kamiennik). *Przewodnik 58 Zjazdu Polskiego Towarzystwa Geologicznego*, Wałbrzych, 17–19 Września 1987, pp. 112–4.

KLEIST, J. R. 1974. Deformation by soft-sediment extension in the coastal belt, Franciscan Complex. *Geology* **2**, 501–4.

KOSTYLEW, J. 2005. Mélange and metamudstones from Stanisławów (Kaczawa Complex, Sudetes): selected petrological aspects. *Mineralogical Society of Poland – Special Papers* **26**, 193–6.

KOSTYLEW, J. 2008. Very low-grade metamorphism in the Variscan accretionary prism of the Kaczawa Complex (Sudetes, SW Poland): new data from illite 'crystallinity' index. *Mineralogical Society of Poland – Special Papers* **32**, 98.

KRONER, U. & ROMER, R. L. 2013. Two plates – many subduction zones: The Variscan orogeny reconsidered. *Gondwana Research* **24**, 298–329.

KRYZA, R. & MUSZYŃSKI, A. 1992. Pre-Variscan volcanic-sedimentary succession of the central southern Gory Kaczawskie, SW Poland: outline geology. *Annales Societatis Geologorum Poloniae* **62**, 117–40.

KRYZA, R., MUSZYŃSKI, A. & VIELZEUF, D. 1990. Glaucophane-bearing assemblage overprinted by greenschist-facies metamorphism in the Variscan Kaczawa Complex, Sudetes, Poland. *Journal of Metamorphic Geology* **8**, 345–55.

KRYZA, R., WILLNER, A., MASSONNE, H.-J., MUSZYŃSKI, A. & SCHERTL, H.-P. 2011. Blueschist-facies metamorphism in the Kaczawa Mountains (Sudetes, SW Poland) of the Central-European Variscides: P-T constraints by a jadeite-bearing metatrachyte. *Mineralogical Magazine* **75**, 241–63.

KRYZA, R. & ZALASIEWICZ, J. 2008. Records of Precambrian–Early Palaeozoic volcanic and sedimentary processes in the Central European Variscides: A review of SHRIMP zircon data from the Kaczawa succession (Sudetes, SW Poland). *Tectonophysics* **461**, 60–71.

KRYZA, R., ZALASIEWICZ, J. A., CHARNLEY, N., MILODOWSKI, A. E., KOSTYLEW, J. & TYSZKA, R. 2004. In situ growth of monazite in anchizonal to epizonal mudrocks; first record from the Variscan accretionary prism of the Kaczawa Mountains, west Sudetes, SW Poland. *Geologia Sudetica* **36**, 39–51.

KRYZA, R., ZALASIEWICZ, J., MAZUR, S., ALEKSANDROWSKI, P., SERGEEV, S. & LARIONOV, A. 2007. Precambrian crustal contribution to the Variscan accretionary prism of the Kaczawa Mountains (Sudetes, SW Poland): evidence from SHRIMP dating of detrital zircons. *International Journal of Earth Sciences* **96**, 1153–62.

LEVIN, L. A. 2003. Oxygen minimum zone benthos: Adaptation and community response to hypoxia. *Oceanography and Marine Biology: An Annual Review* **41**, 1–45.

LINNEMANN, U., NANCE, R. D., KRAFT, P. & ZULAUF, G. (eds) 2007. *The Evolution of the Rheic Ocean: From Avalonian-Cadomian Active Margin to Alleghenian–Variscan Collision*. Geological Society of America, Boulder, Special Paper no. **423**, 630 pp.

MARTILL, D. M. 1993. Soupy substrates: A medium for the exceptional preservation of ichthyosaurs in the Posidonia Shale (Lower Jurassic) of Germany. *Kaupia: Darmstäder Beiträge zur Naturgeschichte* **2**, 77–97.

MAZUR, S., ALEKSANDROWSKI, P., KRYZA, R. & OBERC-DZIEDZIC, T. 2006. The Variscan Orogen in Poland. *Geological Quarterly* **50**, 89–118.

MOORE, J. C., COWAN, D. S. & KARIG, D. E. 1985. Structural styles and deformation fabrics of accretionary complexes. *Geology* **13**, 77–9.

MOORE, J. C., ROWE, C. & MENEGHINI, F. 2007. How can accretionary prisms elucidate seismogenesis in subduction zones? In: *The Seismogenic Zone of Subduction Thrust Faults* (eds T. H. Dixon & J. C. Moore), pp. 288–315. New York: Columbia University Press.

NANCE, R. D., GUTIERREZ-ALONSO, G., KEPPIE, J. D., LINNEMANN, U., MURPHY, J. B., QUESADA, C., STRACHAN, R. A. & WOODCOCK, N. H. 2010. Evolution of the Rheic Ocean. *Gondwana Research* **17**, 194–222.

NANCE, R. D., MURPHY, J. B. & KEPPIE, J. D. 2002. A Cordilleran model for the evolution of Avalonia. *Tectonophysics* **352**, 11–31.

OSOZAWA, S., MORIMOTO, J. & FLOWER, M. F. J. 2009. 'Block-in-matrix' fabrics that lack shearing but possess composite cleavage planes: A sedimentary mélange origin for the Yuwan accretionary complex in the Ryukyu island arc, Japan. *Geological Society of America Bulletin* **121**, 1190–203.

PANDEY, P., KUMAR, R., SURESH, N., SANGODE, S. J. & PANDEY, A. K. 2009. Soft-sediment deformation in contemporary reservoir sediment: A repository of recent major earthquake events in Garhwal Himalaya. *Journal of Geology* **117**, 200–9.

SAFFER, D. M. 2010. Hydrostratigraphy as a control on subduction zone mechanics through its effects on drainage: an example from the Nankai Margin, SW Japan. *Geofluids* **10**, 114–31.

SCUDDER, R. P., MURRAY, R. W. & PLANK, T. 2009. Dispersed ash in deeply buried sediment from the northwest Pacific Ocean: an example from the Izu-Bonin arc (ODP Site 1149). *Earth and Planetary Science Letters* **284**, 639–48.

STERN, R. J. 2002. Subduction zones. *Reviews of Geophysics* **40**, 4.

TAIT, J. A., BACHTADSE, V., FRANKE, W. & SOFFEL, H. C. 1997. Geodynamic evolution of the European Variscan fold belt: palaeomagnetic and geological constraints. *Geologische Rundschau* **86**, 585–98.

TYSZKA, R., KRYZA, R., ZALASIEWICZ, J. A. & LARIONOV, A. N. 2008. Multiple Archaean to Early Palaeozoic events of the northern Gondwana margin witnessed by detrital zircons from the Radzimowice Slates, Kaczawa Complex (Central European Variscides). *Geological Magazine* **145**, 85–93.

UJIIE, K. 2002. Evolution and kinematics of an ancient décollement zone, mélange in the Shimanto accretionary complex of Okinawa Island, Ryukyu Arc. *Journal of Structural Geology* **24**, 937–52.

VON HUENE, R. & SCHOLL, D. W. 1991. Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental-crust. *Reviews of Geophysics* **29**, 279–316.

VON HUENE, R. & SCHOLL, D. W. 1993. The return of sialic material to the mantle indicated by terrigenous material subducted at convergent margins. *Tectonophysics* **219**, 163–75.

VON HUENE, R. & SUESS, E. 1988. Ocean Drilling Program Leg-112, Peru continental-margin. 1. Tectonic history. *Geology* **16**, 934–8.

WINCHESTER, J. A., PHARAOH, T. C. & VERNIERS, J. 2002. Palaeozoic amalgamation of Central Europe: an introduction and synthesis of new results from recent geological and geophysical investigations. In *Palaeozoic Amalgamation of Central Europe* (eds J. A. Winchester, T. C. Pharaoh & J. Verniers), pp. 1–18. Geological Society of London, Special Publications no. 201.