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Current-aligned dewatering sheets and 'enhanced' primary current lineation in turbidite sandstones of the Marnoso-arenacea Formation

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ABSTRACT

Turbidite sandstones of the Miocene Marnoso-arenacea Formation (northern Apennines, Italy) display centimetre to decimetre long, straight to gently curved, 0.5 to 2.0 cm regularly spaced lineations on depositional (stratification) planes. Sometimes these lineations are the planform expression of sheet structures seen as millimetre to centimetre long vertical 'pillars' in profile. Both occur in the middle and upper parts of medium-grained and fine-grained sandstone beds composed of crude to well-defined stratified facies (including corrugated, hummocky-like, convolute, dish-structured and dune stratification) and are aligned sub-parallel to palaeoflow direction as determined from sole marks often in the same beds. Outcrops lack a tectonic-related fabric and therefore these structures may be confidently interpreted to be sedimentary in origin. Lineations resemble primary current lineation formed by the action of turbulence during bedload transport under upper stage plane bed conditions. However, they typically display a larger spacing and micro-topography compared to classic primary current lineation and are not associated with planar-parallel, finely-laminated sandstones. This type of 'enhanced lineation' is interpreted to develop by the same process as primary current lineation, but under relatively high near-bed sediment concentrations and suspended load fallout rates, as supported by laboratory experiments and host facies characteristics. Sheets are interpreted to be dewatering structures and their alignment to palaeoflow (only noted in several other outcrops previously) inferred to be a function of vertical water-escape following the primary depositional grain fabric. For the Marnoso-arenacea beds, sheet orientation may be genetically linked to the enhanced primary current lineation structures. Current-aligned lineation and sheet structures can be used as palaeoflow indicators, although the directional significance of sheets needs to be independently confirmed. These indicators

also aid the interpretation of dewatered sandstones, suggesting sedimentation under a traction-dominated depositional flow – with a discrete interface between the aggrading deposit and the flow – as opposed to under higher-concentration grain or hindered settling dominated regimes.

INTRODUCTION

Dewatering structures are a common feature of sandstone beds in deepwater turbidite systems (Lowe, 1975; Hurst & Cronin, 2001). These deposits are particularly prone to water escape due to the rapid manner in which sediment often deposits from turbidity currents and other types of sediment gravity flow (for example, transitional 'slurry' flows, cohesive and non-cohesive debris flows). Flows with high depositional rates produce underconsolidated, highly porous beds with a metastable grain framework. Subsequent pore-fluid expulsion occurs as the sediment loses strength, allowing the initial grain fabric to reorganise to form a closer packing (Lowe, 1975; 1976; Collinson & Thompson, 1989; Sylvester & Lowe, 2003a). This process may operate during or after deposition before substantial compaction. Water escape involving liquefaction and fluidisation is responsible for deforming and partially or completely destroying primary sedimentary structures and grain fabric. It is also responsible for the formation of a diverse range of distinct soft sedimentary structures including convolute laminae, consolidation laminae, dish, pillars, pipes and load structures, as well as producing beds with swirled or ill-defined fabrics and possibly structureless massive beds (Lowe, 1975; Collinson & Thompson, 1989).

In this paper, several relatively rare potentially genetically related structures, found in metre-thick dewatered sandstone beds of the Miocene Marnoso-arenacea turbidite system, are discussed: (i) relatively large-scale current-aligned lineations on stratification planes; and (ii) dewatering sheets with a similar expression in plan view and also aligned to the palaeoflow of the parental depositional current. These structures have apparently not been reported from these deposits previously and rarely from other formations.

Whilst sheet structures can be common in turbidite sequences, they have only been noted to be aligned to palaeoflow in several outcrops, as discussed by Laird (1970): the Silurian of Galway in Ireland and the Aberystwyth Grits in Wales. In these locations the strike of dewatering sheets have a ‘general parallelism’ to sole marks within the succession. For the Galway sandstones, textural analysis showed that sheets are parallel to the preferred long axis of grains and have no relationship to tectonic fabric. In the case of the Aberystwyth Grits, however, sheets are also parallel to cleavage and hence could be inferred to be tectonic in origin. Laird (1970) interpreted the Galway flow-aligned sheets as a ‘primary sedimentary fabric’ formed during suspension sedimentation.

The relationship between the primary (depositional) bed structure and grain fabric and subsequent patterns of dewatering is in general poorly understood. The current-aligned dewatering sheets described here and by Laird (1970) are of significant interest because they suggest, under certain conditions, an intimate relationship between the primary depositional fabric and secondary dewatering processes. The following describes the characteristics of the lineation and sheet structures, the facies types they occur within, and discusses models for their formation as related to primary current and secondary dewatering processes and the potential use of sheets as current indicators.

STUDY AREA

The sandstones described in this study come from outcrops of the Miocene Marnoso-arenacea Formation in the Apennine fold and thrust belt of Italy (Fig. 1). This formation records deposition by clastic-bearing and less commonly carbonate-bearing sediment gravity flows in a deepwater basin-plain environment of a foreland basin (Ricci Lucchi & Valmori, 1980; Argnani & Ricci Lucchi, 2001; Amy & Talling, 2006; Muzzi Magalhaes & Tinterri, 2010). Flows travelled axially along the elongate basin either towards the south-east or north-west depending upon their provenance (Ricci Lucchi & Valmori, 1980). Most of the outcrops discussed herein are of Serravallian age, positioned immediately above the Contessa marker bed (Ricci Lucchi, 1995). This particular stratigraphic interval was previously studied in detail by the present authors in order to constrain the geometry and lateral facies changes within beds (Amy & Talling, 2006; Talling *et al.*, 2007a; Sumner *et al.*, 2012).

DESCRIPTION OF STRUCTURES

The current-aligned lineations and sheets described are observed in medium-grained and fine-grained sandstone beds that are 0.4 to 1.5 m thick (Fig. 2). The Marnoso-arenacea Formation sections studied typically display a bimodal distribution in sandstone thicknesses (Ricci Lucchi & Valmori, 1980; Talling *et al.*, 2007b); these structures occur in the thicker sandstone bed population. They usually occur at least a few tens of centimetres above the base of sandstone beds, above planar stratified and/or massive sandstone divisions. In the majority of cases, lineations are associated with corrugated-stratified sandstones (referred to as ‘groove stratified’ or ‘corrugated’ sandstone facies in Amy & Talling, 2006). However, they also occur in association with several other stratified sandstone facies including consolidation, hummocky-like, small-scale dune cross-stratified and convolute-stratified sands. Intervals with lineations are commonly succeeded by muddy debritic sandstone ('slurried' interval, *sensu* Ricci Lucchi & Valmori, 1980), convolute laminated fine sandstone or mudstone intervals with the latter invariably capping these ponded basin-plain beds. In the following description, the characteristics of these structures are first described and then the associated facies in which they occur.

Sedimentary structure characteristics

Lineations

Lineations occur on stratification planes within fine-grained sandstones as a series of sub-parallel bands differentiated primarily by their colour that may appear lighter or darker than the 'host' sandstone (Fig. 3). These lineations are 2 to 10 mm wide, up to several millimetres in relief and extend for tens of centimetres in length being straight or gently curved; their spacing is regular to semi-regular, typically being about 1 cm apart with thicker lineations sometimes displaying wider spacing. In most cases, textural differences are difficult to see with the naked eye (Fig. 3E). In some rare cases, however, a textural difference compared to the host sandstone is apparent owing to enhanced cementation within the lineations (Fig. 3F); they often form a microtopography of closely spaced, low-relief, ridges and grooves, which in profile imparts a small (millimetre) scale 'crenulated' or 'corrugated' appearance to stratification, with lineations often but not always coinciding with the crests of ridges (Fig. 3A and B).

Sheets

In the majority of cases where lineations are observed, they do not extend vertically through sandstones. However, in a number of outcrops (for example, the Galeata and Taverna measured sections and Cabelli river section: see map in Fig. 1) lineations are actually the depositional plane expression of sheets extending through the host sandstone and seen as pillars (*sensu* Lowe 1975) in cross-section (Figs 3D, 4B and 5A to D). Sheets are usually normal or steeply dipping to bedding (90 to 80^{o}), 2 to 10 mm wide and millimetres to several decimetres in vertical length; they have a simple straight geometry in profile and are rarely observed to bifurcate. Sheets in some cases are texturally distinct, being apparently cleaner and better cemented than the host sandstones (Figs 3D and 6D). Others are only discernible based on colour. Sheets may cross-cut consolidation or convolute laminae but also may end abruptly at a particular horizon. In some intervals, distinct sheet structures cannot be clearly seen but may be inferred from the vertical stacking of 'lineations' on successive stratification planes (Fig. 3B).

Facies with lineations and sheets

Corrugated-stratified sandstone

Lineations are most commonly found within sandstones characterized by crude to well-developed flat-lying centimetre-thick stratification that possess a distinct superimposed corrugation on the upper and lower contacts of individual strata (Fig. 4). The corrugated wavy micro-topography is typically semi-regular and can often be directly related to lineations on stratification planes with lineations usually forming crests. Stratification may also show irregular strata with gentle pinching and swelling similar to consolidation laminae (Lowe, 1975; Hurst & Cronin, 2001). Sheets seen in profile as faint texturally indistinct millimetre-scale pillars are sometime observed as well as more distinct centimetre-scale pillars (Fig. 4B) and vertically stacked lineations (Fig. 3B).

Hummocky-like stratified sandstone

Sandstones with a similar scale of stratification to the corrugated-stratified sandstone may show more complex ‘hummocky’ geometries with pinching and swelling over decimetre to metre scales and decimetre-scale wave heights (Fig. 4C and D). These strata may also show a corrugated-type micro-topography related to the lineations on stratification planes occasionally with centimetre- long pillars related to sheets. Outcrops of this facies are typically highly friable and intensely weathered. Bedding does not show distinct forms of hummocky cross-stratification as seen in shallow-marine, storm-wave influenced successions, nor similar structures reported from deepwater turbidites (Mulder *et al.*, 2009). This type of stratification is interpreted to be produced by consolidation with significant hydroplastic deformation (Lowe, 1975).

Dish-structured sandstone

Occasionally beds display discrete dish structures with upturned margins up to several decimetres wide. Dish structures are indicative of consolidation and are commonly associated with consolidation lamination and pillar structures (Lowe & LoPiccolo, 1974; Lowe, 1975; Hurst & Cronin, 2001).

Convolute-stratified sandstone

Sandstones occasionally show distinct convolute lamination and bedding towards the tops of beds (Fig. 5C to F). These structures indicate soft sediment folding and loading which may be induced by a variety of processes (see discussion in Lowe, 1975). Sheets noted in this facies are vertically more extensive than seen elsewhere being decimetres long and inclined (Fig. 5D).

Dune cross-stratified sandstone

In several outcrops sheets occur at the top of beds within dune cross-stratified sandstone (Fig. 6). Dunes are relatively small scale, having maximum amplitudes of several decimetres and wave lengths of up to several metres. Sheets are most pronounced on the dune crests but extend across both lee and stoss sides. On the lee side they tend to flare in width. Sheets are orientated perpendicular to the dune crest and, in some cases, change strike locally remaining perpendicular to curved dune crests (Fig. 6C).

Palaeoflow and lineation direction

Directional data for lineations and other structures are summarised in Fig. 7. Flutes and ripples show a south-east directed trend and grooves a south-east/north-west trend; these indicate a unimodal palaeoflow direction for siliciclastic-bearing depositional currents towards the south-east. Lineations also show a south-east/north-west trend close to that of palaeoflow indicators, albeit with a discernible clockwise deviation. The deviation of lineations from sole marks on the same bed is on average less than 10° (Fig. 7E). Lineations on stratification planes usually show a consistent directional mode with a relatively small ($<5^{o}$) variance in direction between individual structures. In isolated cases, beds show several differently oriented sets of lineations occurring on the same or successive stratification planes (for example, Bed 4 in the Taverna section; Fig. 2). Those associated with curve-crested dunes show a systematic variation in direction around the dune crest (Fig. 6C).

THIN-SECTION ANALYSIS

A sample was taken of sandstone with sheets from cross-stratified sandstone facies in Bed 3 of the Taverna section (Fig. 2). Thin sections were cut in bedding parallel and perpendicular orientations for grain-fabric analysis. In the cut sample, sheets are much better defined, seen as regular spaced light-coloured bands that extend across consolidation-related stratification (Fig. 8E and F).

Sheets are also clearly visible in thin sections being lighter than the surrounding sandstone with relatively well-defined boundaries (Figs 9 to11). Colour variations between sheet and inter-sheet correspond to differences in matrix clay content, with sheets being significantly cleaner and more heavily cemented by calcite (Figs 9 and 11). Compositionally the sheet and inter-sheet areas otherwise appear similar.

Black and brown coloured elongate grains, mostly biotite mineral grains, were measured in scanned images of thin sections (using the software application Image J) and plotted as rose diagrams (using the application Rozeta) (Fig. 10). These grains display an imbricated (upcurrent) flow-aligned fabric: this being the commonest type in turbidite sandstones and indicative of rapid sedimentation from suspension (Baas *et al.*, 2007). The grain long-axis mean direction is within 10^{o} of sheets (Fig. 10B and C). Grain orientations in stratification plane-perpendicular sections are the same for sheet and inter-sheet areas (Fig. 10D and E). Elongate grains seen in photomicrographs with lengths greater than *ca* 100 um, were also measured in the thin section taken parallel to bedding (Fig. 11). These mostly quartz grains show more variation than black/brown grains in scans, but have a similar mean direction which is close to that of the sheet orientation. Grains in sheets also show a similar mean orientation to the total grain population of photos (Fig. 11).

DISCUSSION

Outcrops have been described focussing on the occurrence of several structures: (i) lineations on stratification planes with no apparent vertical extent; and rarer (ii) sheets seen as similar lineations in planform and pillars in cross-section with millimetre to centimetre-scale vertical extent. The orientation of both structures in most cases is similar to palaeoflow of the same or adjacent beds, as determined independently from other current structures. Both lineations and sheets have similar simple plan-form geometries and length scales; they also occur in similar sandstone facies which often display dewatering features. In the following discussion, the significance of these structures and their likely process of formation are considered. It is important to emphasize that these are sedimentary and not structural features. Outcrops generally lack pervasive tectonic rock fabric (for example, cleavage in mudstones) being positioned away from faults and fold crests, usually in relatively undeformed, albeit tilted stratigraphic sections. Instead, lineations and sheets tend to be locally developed, within particular divisions of beds supporting a depositional origin.

Lineations: comparison to primary current lineations and their interpretation

The lineations considered in this study, which are not demonstrably sheets, bear a resemblance to parting or primary current lineations (PCL). These lineations, however, are characteristically different to PCL being developed at a larger scale, and hence herein are referred to as '*enhanced lineations*'. Primary current lineations (PCL) is a type of bedding plane 'microtopography' composed of a system of quasi-parallel offset ridges and hollows with very low relief (Allen, 1964; 1965; 1982). These lineations are characteristic of the upper stage plane bed of unidirectional flows, but also occur in association with wave deposits, hummocky cross-stratified sands and foreshore deposits (Allen, 1964; Cheel 2003). In detail, PCL comprise linear mounds, a few grain diameters high, centimetres to decimetres long and spaced several millimetres to over 1 cm apart (Cheel, 2003). These mounds extend parallel to the depositional current direction. In contrast, enhanced lineations are significantly larger, with reliefs of up to several millimetres and semi-regular spacing rarely less than a centimetre.

Based on laboratory experiments, PCL is understood to be a product of the burst and sweep microturbulence in the turbulent boundary layer that has the effect of transporting bedload sediment within flow-parallel lanes ['sand streaks', *sensu* Weedman & Slingerland (1985)]. The typical mean spacing of sand streaks in fine and medium sand is 3 to 7 mm with a dependency on grain size (see tables 2 and 3 in Weedman & Slingerland, 1985). Sand streaks with a wider spacing of *ca* 15 mm, however, can occur in flows with relatively high shear velocities or grain concentrations (Weedman & Slingerland, 1985). In other experiments by Best (1992), visualisation of the near-bed turbulence consisting of high-speed sweeps and low-speed streaks, showed that sweep structures may be grouped such that patches of sediment entrainment may be wider than individual streak/sweep impacts. Longitudinal ridges generated by sweeps can also stabilize the position of subsequent low-speed streaks and sweeps. These aspects of flow character (velocity and near-bed sediment concentration) and boundary layer turbulence over a mobile sand bed may provide a basis for explaining the larger scale of enhanced lineations.

Enhanced lineations are not preserved within flat finely planar-parallel laminated sandstone typically associated with PCL (for example, Bouma T_b division in turbidites). Parting-step lineation that often accompanies PCL in upper stage planar beds (Cheel, 2003) is also absent. Instead as described above, lineations tend to be associated within crudely centimetre-stratified facies. The scale and poor development of the stratification in these facies in conjunction with dewatering processes probably reflect deposition under relatively high (near-bed) sediment concentrations and depositional rates. Experiments show that under these conditions, relatively thick centimetre-scale stratification can develop by a process of episodic collapse of near-bed 'layers' with locally high-sediment concentration (Arnott & Hand, 1989; Vrolijk, 1997; Sumner *et al.*, 2008). This manner of forming stratification is fundamentally different to that which produces finer-scale planar laminations of the upper stage plane bed by the migration of low-relief 'bed waves' (Best & Bridge, 1992; Paola *et al.*, 1989). Dewatering is evident in many beds with lineations, as also suggested by consolidation-like stratification. This is also indicative of relatively high sedimentation rates and near-bed sediment concentrations during deposition.

In summary, enhanced lineations are considered here to be distinct from classic PCL on account of their scale. They are likely to be formed by similar near-bed turbulent processes but under higher near-bed sediment concentrations and depositional rates compared to those under which PCL typically forms. Sediment concentrations and depositional rates, however, were not high enough to limit the existence of a bed (i.e. a sharp rheological interface between the flow and the substrate) on which bedload transport could occur: as can be the case for turbidity currents with very high depositional rates (Kneller & Branney, 1995). It should be noted that the effects of fluid expulsion from a dewatering bed on the turbulent boundary layer, sediment transport and bedform development is largely unknown. This could also have played a role, given the association of enhanced lineations with dewatering structures. In some cases, as discussed below, they may also be interpreted as incipient dewatering sheets.

Flow-aligned dewatering sheets

The sheets described in this study are interpreted as dewatering structures produced by water escape (Sylvester & Lowe, 2003b). This interpretation appears relatively straight-forward where sheets are well-developed (centimetres long vertically), cross-cut stratification and are associated with other dewatering features (for example, Figs 4 and 5), but less so where they are poorly developed (millimetres long) and unambiguous dewatering structures are absent in the same interval. Many studies report dewatering pillars in deepwater sandstones, usually in association with dishes and, as discussed by Lowe (1975), there are a wide variety of recognisable types. A small number of studies interpret these as dewatering sheets (e.g. Lowe & Guy, 2000; Stow & Johansson, 2000; Sylvester & Lowe, 2003b; Sylvester & Lowe, 2004; Barker *et al.* 2008; Jackson *et al.*, 2009; Mather *et al.*, 2009; Eggenhuisen *et al.*, 2010) and only a few studies discuss the orientation of sheets relative to palaeoflow (Wood & Smith, 1958; Laird, 1970; Haughton, 1994). Interestingly, the sheets seen in the sandstones discussed here show a clear parallel alignment with palaeoflow direction as determined independently from sole marks and ripples (Fig. 7) and the preferred grain orientation fabric of sandstones in thin section (Figs

10 and 11). Also, in cross-stratified beds the orientation of sheets changes locally (Fig. 6C), such that they remain quasi-perpendicular to dune crest orientation; this, in addition, suggests alignment of sheets to localised flow patterns over these bedforms.

Comparison with other current-aligned sheets

Current-aligned sheets have only been noted in a few other outcrops as discussed by Laird (1970): these are summarised and compared to those of the present study in Table 1. The simple physical form of the Galway sheets is comparable to those of the Marnoso-arenacea Formation examples. Those shown by Laird (1970, fig. 1) are similar, albeit more pervasively developed, to the vertically more extensive (centimetre-scale) sheets described here (for example, Fig. 5C and D). The Galway sheets occur in coarse-grained massive sandstones greater than medium grade, but are absent from laminated/stratified intervals and commonly display branching patterns. The Marnoso-arenacea sheets, in comparison, occur within finer (fine-grained) sandstones, often with discernible stratification and rarely display branching patterns in outcrop (although this may be seen in slabbed sections, for example Fig. 8E). Texturally the Galway and Marnoso-arenacea sandstones both show an imbricated flow-parallel preferred grain orientation fabrics (a(p)a(i), *sensu* Baas *et al.*, 2007) being also parallel to sheets. In both examples, sheets are lighter with comparatively low matrix (mud) content. Laird (1970) notes that sheets may be coarser grained than the surrounding rock. Sheets in sandstones of the Aberystwyth Grits in Wales show alignment with grooves in associated beds and are texturally distinct with a larger grain size and 'less matrix' (Wood & Smith, 1958). Those of the Marnoso-arenacea typically only display subtle variations in grain size between sheet and surrounding rock in outcrop or the thin sections examined. Uniquely in the examples described here, the alignment of sheets with sole marks can be demonstrated within the same bed.

Formation of current-aligned sheets

Laird (1970) interpreted flow-aligned sheets to be produced by suspension sedimentation from sediment gravity flows. In this model, convention cells are proposed to develop during differential settling of grains with mud being preferentially elutriated in upwelling zones. This idea was developed with reference to settling tube experiments by Kuenen (1968), who observed the formation of tube-like water escape routes and 'veins' of cleaner sand in the deposits. Laird (1970) proposed sheets developed by tubes coalescing into continuous water-escape structures, encouraged by the primary flow-aligned grain fabric. However, it is difficult to envisage how a strong primary grain fabric, as seen in the Marnoso-arenacea and Galway turbidites, could have formed or been preserved if such features were produced by convention cells *during* settling of grains within a fluidised or hindered-settling dominated depositional-boundary layer, *sensu* Branney & Kokelaar (2002).

Based on the Marnoso-arenacea sandstones, a modified model is proposed to explain the formation of current-aligned sheets (Fig. 12). Here sheets are considered to be a product of gentle dewatering soon after deposition as opposed to *at* the time of deposition as in the Laird (1970) model. First, deposition occurs from a suspension flow, followed by a period of bedload transport under upper stage plane bed probably with high near-bed concentration conditions, forming a deposit with a strong preferred current-aligned grain fabric and enhanced lineations. Water escape subsequently occurs preferentially along higher permeability zones, as controlled by subtle textural and permeability variations within the primary depositional fabric. In this manner enhanced lineations probably controlled the development of sheets. With dewatering focussed along current-aligned heterogeneities, sheet-like water expulsion channels propagated upward forming texturally distinct sheets by the elutriation of clay, a process that subsequently controlled local cementation patterns.

The basal parts of beds usually show no dewatering structures, including an absence of sheets as do those examples from Galway and Aberystwyth; this suggests that a critical thickness of sand was required to initiate significant water escape. Dewatering (and liquefaction) within sheet-bearing sands was non-catastrophic, preserving the primary fabric and hence probably occurred by slow percolation of water through a grain-supported framework (i.e. seepage, *sensu* Lowe 1975). More vigorous water escape with localised fluidisation may have occurred in the case of the Galway and Aberystwyth Grits sheets causing stronger textural differences. The timing of dewatering and sheet formation was probably before deposition of the whole event bed, as suggested by undisturbed capping mudstones that lack sandstone/siltstone injections. Sheets terminate at horizons within sand beds, as for example can be clearly seen in the Cabelli River section example (Fig. 5). These sheets may therefore be interpreted to have formed during deposition of the aggrading sand bed.

Use of sheets as palaeocurrent indicators

The Marnoso-arenacea and Galway dewatering sheet examples demonstrate that such structures could be useful palaeoflow indicators. However, their use without other current structures to confirm their palaeoflow significance is problematic. Assuming that sheets form by water escape following the primary grain orientation fabric, they could have a variety of orientations relative to current direction given that parallel, transverse and oblique grain-orientation fabrics can occur in sandstones (as shown for turbidites by Baas *et al.*, 2007). Moreover, sheets are noted with no obvious orientation relative to palaeoflow (e.g. Haughton 1994). In the case for sandstones with no preferred grain orientation fabric or undergoing hydroplastic shear their orientation may be expected to be random or locally highly variable. This feature may be obvious in outcrops with good 'bedding' plane exposures but more difficult to identify in core. This makes the use of sheets as 'stand-alone' current indicators at present challenging.

An alternative method for determining palaeoflow from dewatering sheets is by using the vergence of inclined sheets, where their inclination can be related to shearing of an overpassing flow (e.g. Haughton, 1994). Shearing must be in a direction normal or at a relatively high angle to sheets to generate significant inclination. A current-aligned dewatering sheet would not be expected to show significant inclination, assuming that the current maintains a consistent flow direction, because shear will be in the same direction as the sheet strike. Dewatering sheets developed transverse or oblique to current direction, however, should show inclination. Current direction, however, can change direction during a flow event and in this case current-aligned sheets could become inclined. A deflected flow model, for example, is proposed for beds of the Sorbas Basin, to explain the difference in vergence of inclined sheets and overturned soft-sediment folds to that of sole marks within the same bed (Haughton, 1994). The Galway sheets also show significant inclination in some beds despite being current-aligned (for example, fig. 2 in Laird, 1970). Their inclination could potentially be related to shear imposed by an overpassing flow moving in a different direction to the initial current.

Implications for hydrocarbon reservoirs

Dewatering sheets of various types are noted to be common in a number of deepwater sandstone reservoirs, for example, Palaeocene, Heimdal Formation, North Sea (Hurst & Buller, 1984) and the Late Cretaceous, Britannia Formation, North Sea (Lowe & Guy, 2000; Barker *et al.*, 2008; Eggenhuisen *et al.*, 2010). Their presence may enhance overall reservoir quality (porosity and permeability) if sheets are relatively clean (mud and carbonaceous poor) or have the converse effect if they are more heavily cemented (as is the case for the Marnoso-arenacea outcrop examples and Britannia Formation core; Barker *et al.*, 2008). Studies from cores do not provide details of sheet orientation or their relation to palaeoflow probably because this is difficult to ascertain. For reservoirs where sheets are petrophysically distinct and are pervasively developed within key flow units, determining their orientation may be important given this could have implications for permeability anisotropy and hydrocarbon recovery.

CONCLUSIONS

Lineations and dewatering sheet structures have been described that show alignment to the palaeoflow direction of the depositional currents, as ascertained independently from palaeoflow indicators within beds. Such structures occur within sandstones often displaying dewatering fabrics but also within dune cross-stratified sandstones.

Lineations on depositional planes are inferred to be an enhanced type of primary current lineation produced by turbulence on the bed during bedload transport under upper stage flow conditions. Their larger physical scale compared to ‘classic’ primary current lineation is taken to reflect formation under certain flow conditions, notably relatively high near-bed sediment concentrations (as supported by laboratory studies on sediment transport, e.g. Weedman & Slingerland, 1985). This interpretation can also explain the presence of dewatering structures within beds and the lack of typical upper stage plane bed facies (i.e. sandstones with well-defined planar-parallel lamination).

Current-aligned dewatering sheets are inferred to be a product of gentle dewatering (seepage or localised fluidisation) where pathways of water escape were controlled by the initial bed permeability heterogeneity, dictated by enhanced lineation structures and the flow-parallel grain orientation fabric developed during deposition. Such structures are known from only a few other outcrop examples (Laird, 1970). Uniquely in the Marnoso-arenacea examples, the alignment of sheets with sole marks can be demonstrated within the same bed providing additional proof of their relationship to depositional flow.

Current-aligned sheets can provide an additional measure of palaeoflow direction in certain systems such as the Marnoso-arenacea. However, using these structures more widely is problematic given that current-aligned dewatering sheets are at present indistinguishable from those that lack a relationship with palaeoflow. Furthermore, if their direction is controlled by the primary grain fabric they may also be expected to have transverse and oblique modes relative to palaeoflow, as occurs in the primary grain fabric of turbidite sandstones. Other flow indicators are hence required to verify the directional significance of dewatering sheets. Whilst current-aligned sheet structures are a relatively rare sedimentary structure, they are important because they demonstrate the intimate relationship between the primary sedimentary fabric and subsequent dewatering processes.

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FIGURE CAPTIONS

Fig. 1. Location map of the Marnoso-arenacea Formation in northern Italy showing measured sections of the Contessa stratigraphic-level: those with lineations/sheet structures are numbered. Photographs of current-aligned lineations and sheets in subsequent figures come mostly from the Taverna section (43) and a river section close to the Cabelli-1 section (29). Further details of measured sections including grid references can be found in Table S1 of Amy & Talling (2006).

Fig. 2. Sedimentary logs of beds with current-aligned lineations and sheets from the Cabelli river and Taverna section (numbered 29 and 43 in Fig. 1, respectively). Beds typically show an upwards succession from: (i) erosional based traction structured or structureless sandstones into; (ii) corrugated, hummocky-like, dish-structured and convolute millimetre to centimetre-scale stratification with lineations and/or sheets passing finally into; (iii) capping mudstone. Some beds contain an additional muddy sandstone 'slurried' debritic interval (grey shading) between (ii) and (iii). In each bed palaeoflow derived from sole marks have a similar orientation to the strike of lineations and sheets within the bed.

Fig. 3. Stratification planes displaying current-aligned lineations from the Taverna and Cabelli river sections. (A) Subtle lineations with no apparent vertical continuity defined by a small-scale wavy microtopography. (B) Light-coloured lineations with a well-developed ridge and trough type microtopography. Pillars cannot be seen in cross-section but the vertical stacking of some lineations (arrowed) suggests these are vertical sheet structures. (C) Sheet-related, dark-coloured lineations in an interval expressed as centimetre to decimetre-scale pillars in cross-section (see Fig. 5A to D). (D) Very distinct centimetre-scale sheets that cross crude stratification (arrowed). (E) Close-up of lineations shown in (B) illustrating the lighter coloured texturally indistinct (at this scale) nature of ridges. (F) Close-up of lineations shown in (D) showing the more heavily cemented lineations (arrowed). Bottom left scale bar in each photo is 1 cm.

Fig. 4. Examples of facies containing lineations and current-aligned sheets. (A) Corrugated stratification displaying pinching and swelling and a distinct smaller-scale microtopography on bedding surfaces. (B) Similar type of facies albeit with less clear stratification and with sheets seen as pillar structures in cross-section (hammer handle for scale). (C) Corrugated stratification and hummocky-like sandstones with lineations on depositional planes (A4 notebook for scale). (D) Hummocky-like stratified sandstone showing typical friable weathering pattern (compass for scale circled). Photographs (C) and (D) are from the Taverna section.

Fig. 5. Photographs of a bed in the Cabelli river section that displays well-developed current-aligned sheets (see Fig. 2A for graphic log). (A) and (B) Exposure showing flat-lying

dish structures in the lower part of the bed overlain by a zone of sheets (arrowed). (C) and (D) A nearby less weathered exposure showing several sets at different levels within the bed (marked ‘1’ and ‘2’) of weakly inclined sheets. Convolute lamination occurs towards the top of the bed and is cross-cut by sheets that stop at the boundary with the overlying slurry unit. (E) Stratification plane exposure showing corrugated-type stratification and (F) undulating-convolute stratified sandstone with current-aligned fold axes above which sheet-related lineations are seen with the same orientation (Fig. 3C).

Fig. 6. Small-scale, dune cross-stratified sandstones with sheet structures seen in Bed 3 of the Taverna section (see Fig. 2D for graphic log). (A) Lineations on the lee-side of a curved crested dune. (B) Foreset cross-strata. (C) Sandstone bedding plane showing the local variation in lineation trend locally around the curvature of the dune crest. (D) Close-up of lineations on the dune crest which are relatively distinct, thick and vertically continuous.

Fig. 7. Directional data for (A) flutes, (B) grooves, (C) ripples, (D) lineations including five sheet structures and (E) the deviation of lineations from sole marks in the same bed. The number of measurements (*n*), mean resultant direction (α) and circular standard deviation (β) are shown in the inset table. Data recorded from measured sections of the post-Contessa Bed stratigraphic interval reported in Amy & Talling (2006).

Fig. 8. Photographs of sheeted sandstone sample from Bed 3 in the Taverna section (see Fig. 2 for measured section) taken for thin sectioning. (A) Top weathered surface showing faint lineations. (B) Underside showing more distinct lineations on fresh surface. (C) Upcurrent side view normal to bedding showing corrugated-type stratification and faint sheets. (D) Current-parallel view normal to bedding showing cross stratification. (E) and (F) Internal surfaces of the cut section (bed normal and perpendicular to sheet strike) showing more clearly sheets in cross-section. Thin sections with various orientations relative to sheets were taken from this sample. Scale: the sample is 14 cm long and 4 cm thick.

Fig. 9. Photomicrographs of a thin section (B1) cut in a bed normal and transverse to sheet orientation. The sandstone is a calcite cemented quartz arenite with subordinate feldspar, biotite and lithic grains. (A) View of lighter coloured sheet and (B) magnified view of sheet

showing heavily calcite cemented grains and limited clay matrix. (C) View of intra-sheet area and (D) magnified view showing common interstitial clays between grains.

Fig. 10. Scanned images of thin sections and rose plots of the long-axis orientations of elongate black and brown grains. Thin sections are cut: (A) normal to both bedding and sheets; (B) and (C) parallel to bedding; (D) normal to bedding and parallel to sheets within a sheet and; (E) normal to bedding and parallel to sheets between sheets. Lightered coloured sheets are clearly visible in (A), (B) and (C). Plotted long axis directions are normalised to vertical (as indicated by way-up arrow) in (A), (D) and (E) and to the average sheet direction in thin section for (B) and (C) (i.e. $0/360^{o}$ = vertical or sheet direction).

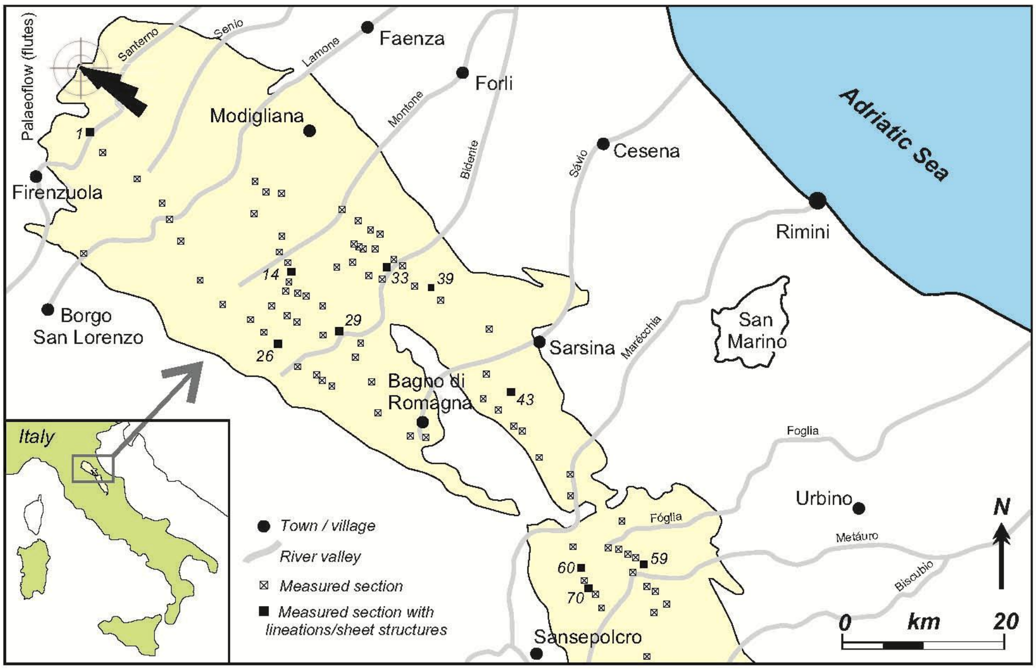
Fig. 11. (A) and (B) Photographs of two sheets in thin section B2 (cut parallel to bedding) with sheet margins indicated by dotted lines. Rose diagrams showing the orientation of (C) and (D) all elongate grains larger than *ca* 100 um in each photograph, (E) all grains for both photographs and (F) and (G) those grains only within sheets as indicated by dotted lines. Note that grain directions are normalised to photograph orientations.

Fig. 12. Model for the formation of current-aligned dewatering sheets. (A) Deposition under upper stage plane bed conditions with high near-bed sediment concentrations forming a sand interval with a current-aligned grain fabric and enhanced primary current lineation structures. (B) Gentle dewatering of sand soon after deposition possibly before cessation of the sandy current. Water escape follows the primary current fabric locally elutriating detrital clay forming cleaner vertical sheets and modifying the stratification.

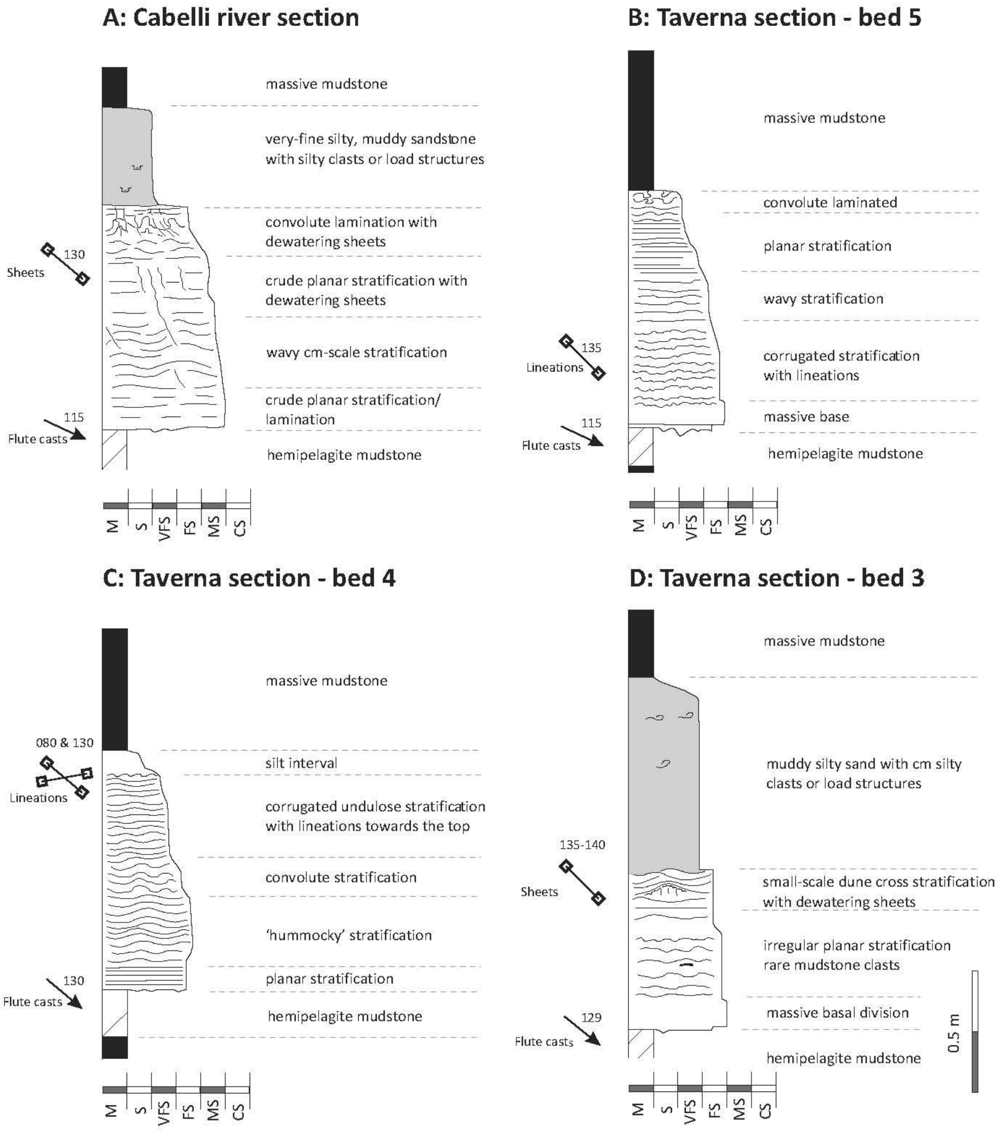
Table 1. Summary of the characteristics of current-aligned sheets in the Marnoso-arenacea Formation (this study) and from other outcrops.

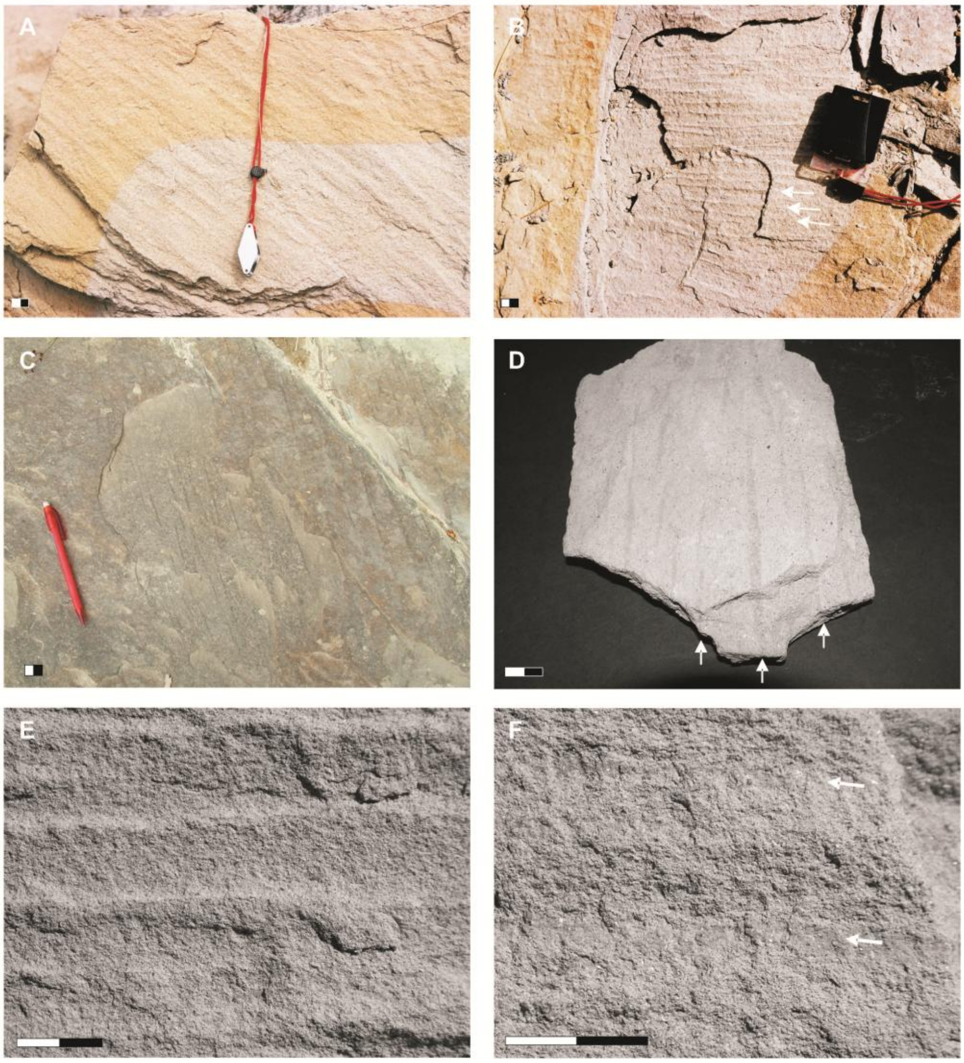
Characteristics	Marnoso-arenacea, Italy (this study)	County Galway, Ireland (Laird, 1970)	Aberystwyth, Wales (Wood & Smith, 1958)
Sheet morphology	Cross-section: Usually straight, vertical normal to bedding, millimetres to several centimetres long, subtle lighter coloured pillars sometimes harder and texturally distinct. Often terminate at internal stratification but can pass through. Rarely branch downwards (for example, Fig. 7E). Single example of longer (tens of centimetres), steeply dipping sheared forms (Fig. 4E). Plan view: Straight to gently curved, 1 to 5 mm in width, up to 0.5 m long and 1 to 3 cm apart usually regularly spaced. Usually ubiquitous across bedding plane.	Cross-section: Slightly sinuous, sub-parallel, mainly vertical – normal to bedding – streaks, lighter coloured and more resistant than host rock, 1 to 50 cm in height. Occasionally branch downwards, steeply dipping and/or highly sinuous wave-like form (sheared). Plan view: Straight or slightly wavy pattern of sub-parallel lines, 1 to 2mm in width and spaced 1 cm apart occurring in swarms.	Thin, light-coloured, semi-parallel sheets with lower matrix content and larger grain size. Developed normal to bedding, planar in form with occasional branching. Do not occur within the base of beds.
Grain fabric (from thin section)	Subtle difference between sheets and interstitial material. Light-coloured sheets have less matrix mud content and enhanced calcite cement. No discernible grain size difference. Strong long axis grain fabric aligned to palaeo-flow direction and with an up-current imbrication.	Subtle difference between sheet and interstitial material. Light-coloured sheets have slightly less matrix and larger grains of quartz and feldspar. Strong long-axis grain alignment – parallel to as the sheet direction – and preferred long axis imbrication.	N/A
Host facies	Usually occurs within the middle to upper parts of sandstones beds (not in basal divisions) and within fine/fine-to-medium, relatively clean, sand. Sheets with limited vertical extent occur in sandstones exhibiting crude to well-developed planar, wavy, hummocky stratification often with a distinct superimposed corrugated form (interpreted as consolidation stratification). Rarer longer sheets occur in consolidation and dish-structured, convolute and dune-cross stratified sandstones.	Limited to lower coarser and massive unlaminated portion in Bouma-type beds. May start anywhere in this interval and terminates abruptly upwards at the top of the massive interval or at an internal erosion surface. No sheets penetrate laminated intervals. Few start at the base of beds. None observed in beds with maximum grain sizes less than coarse sand.	N/A
Orientation to palaeoflow	Sub-parallel, usually within 10^{o}, to sole marks in the same of other beds (Fig. 6). Local deviation around dune crests. Parallel to primary current grain fabric: clear relationship with larger elongate mica grains (Fig. 9); identifiable but less clear for quartz and feldspar grains (Fig. 10).	Generally parallel to sole marks in other beds (not observed in the same bed). Very clear parallel relationship with primary current grain fabric.	Sheet strike parallel to grooves on the base of associated beds but also nearly parallel to the strike of cleavage.

Table 1. Summary and comparison of the characteristics of current-aligned sheets in the Marnoso Arenacea Formation reported in this study to those of other outcrops.

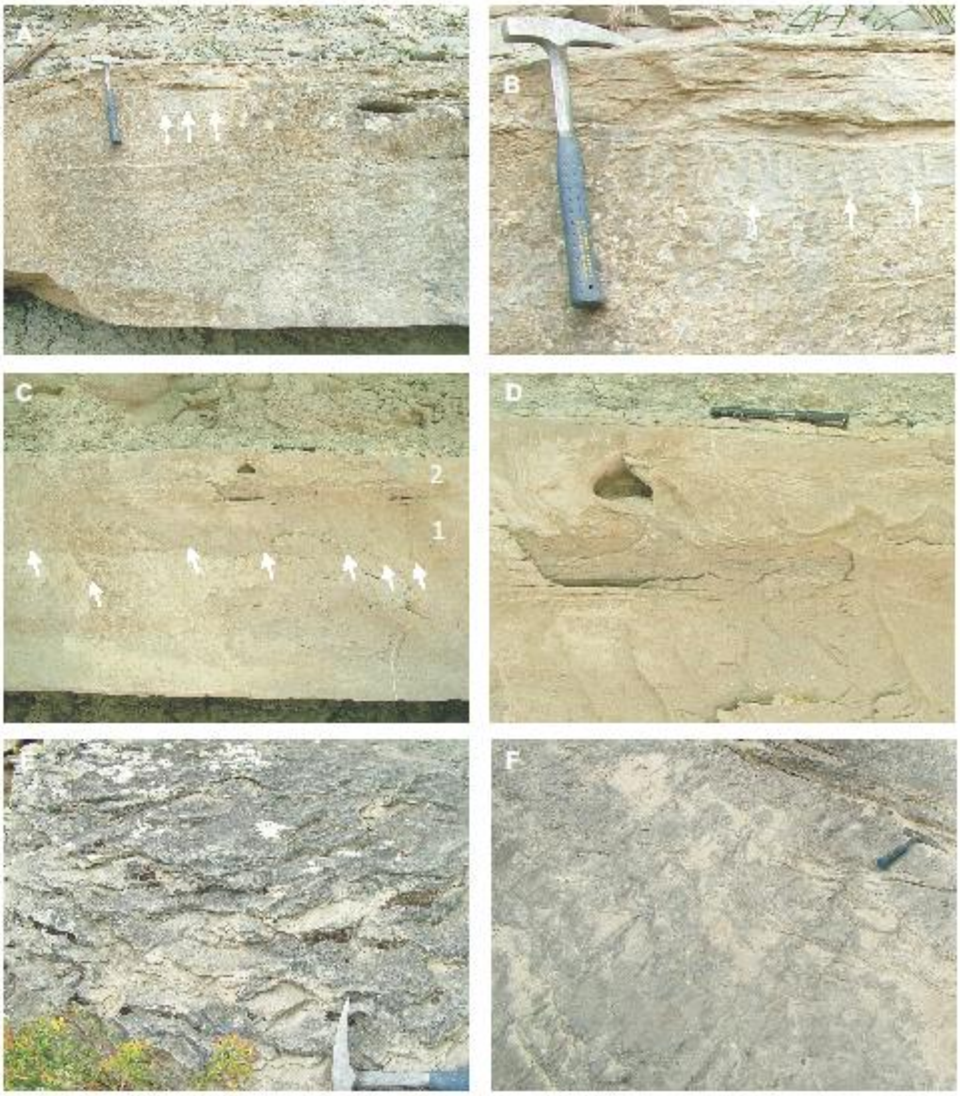


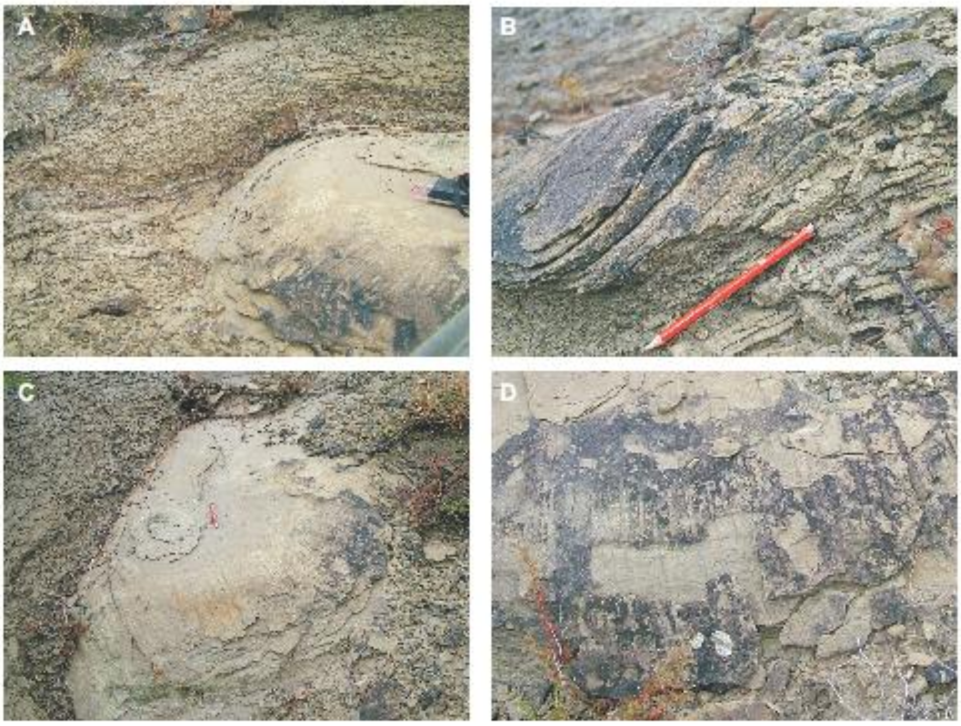
Palaeoflow (flutes)
Santerno
Senio
Lamone
Faenza
Forlì
Montone
Modigliana
Bidente
Savio
Cesena
Adriatic Sea
Rimini
Firenzuola
1
14
33
39
29
26
43
Borgo
San Lorenzo
San
Marino
Sarsina
Marecchia
Bagno di
Romagna
Italy
Foglia
Urbino
N
Town / village
River valley
Measured section
Measured section with
lineations/sheet structures
Fóglia
Metáuro
Biscubio
59
60
70
0
km
20
Sansepolcro

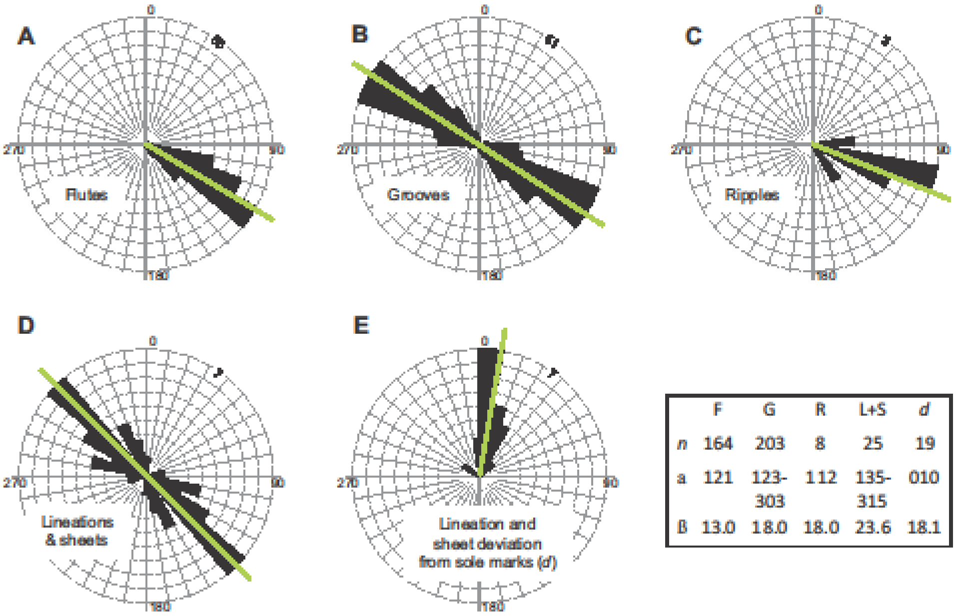

A: Cabelli river section
massive mudstone
very-fine silty, muddy sandstone with silty clasts or load structures
convolute lamination with dewatering sheets
crude planar stratification with dewatering sheets
wavy cm-scale stratification
crude planar stratification/ lamination
hemipelagite mudstone
130
Sheets
115
Flute casts
M S VFS FS MS CS
B: Taverna section - bed 5
massive mudstone
convolute laminated
planar stratification
wavy stratification
corrugated stratification with lineations
massive base
hemipelagite mudstone
135
Lineations
115
Flute casts
M S VFS FS MS CS
C: Taverna section - bed 4
massive mudstone
silt interval
corrugated undulose stratification with lineations towards the top
convolute stratification
'hummocky' stratification
planar stratification
hemipelagite mudstone
080 & 130
Lineations
130
Flute casts
M S VFS FS MS CS
D: Taverna section - bed 3
massive mudstone
muddy silty sand with cm silty clasts or load structures
small-scale dune cross stratification with dewatering sheets
irregular planar stratification rare mudstone clasts
massive basal division
hemipelagite mudstone
135-140
Sheets
129
Flute casts
0.5 m
M S VFS FS MS CS


A
B
C
D
E
F


A
B
C
D

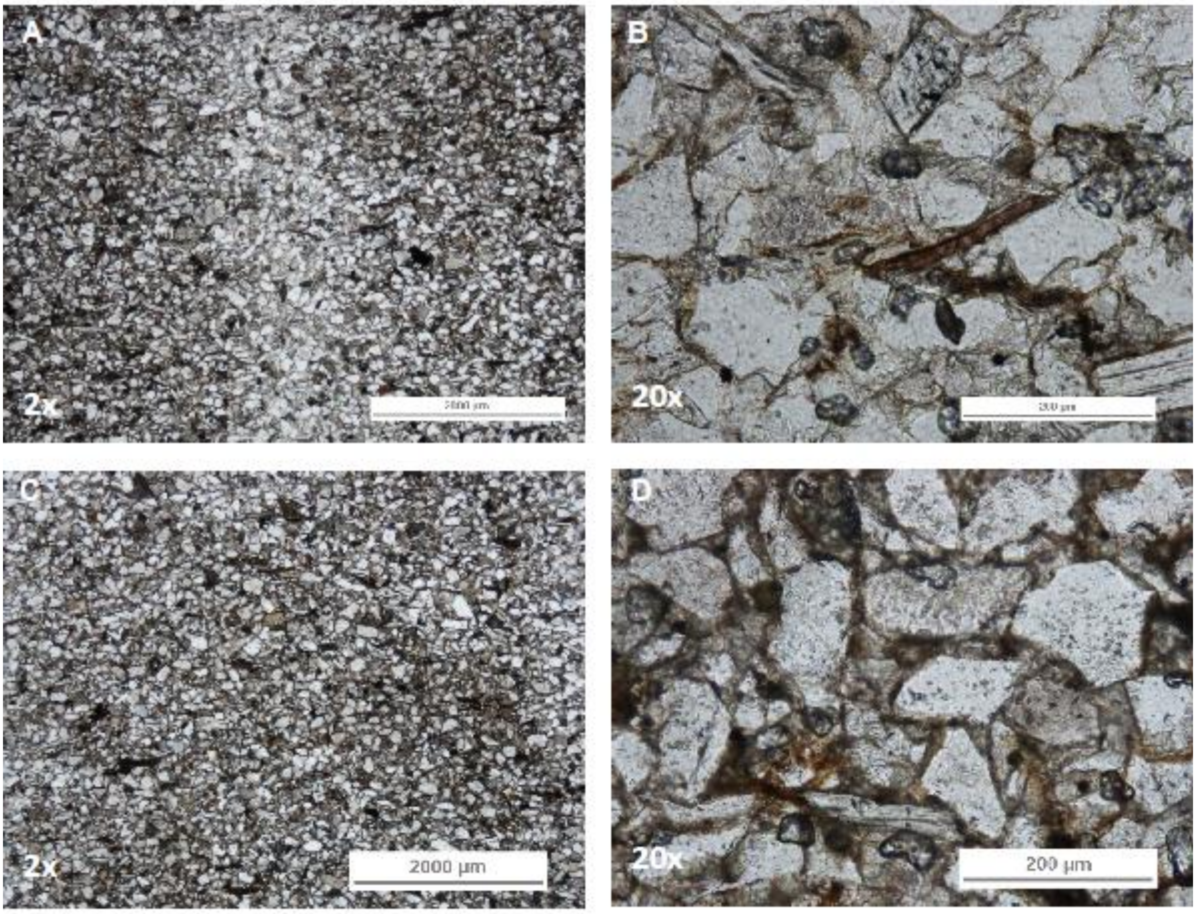

A
B
C
2
1
D
F

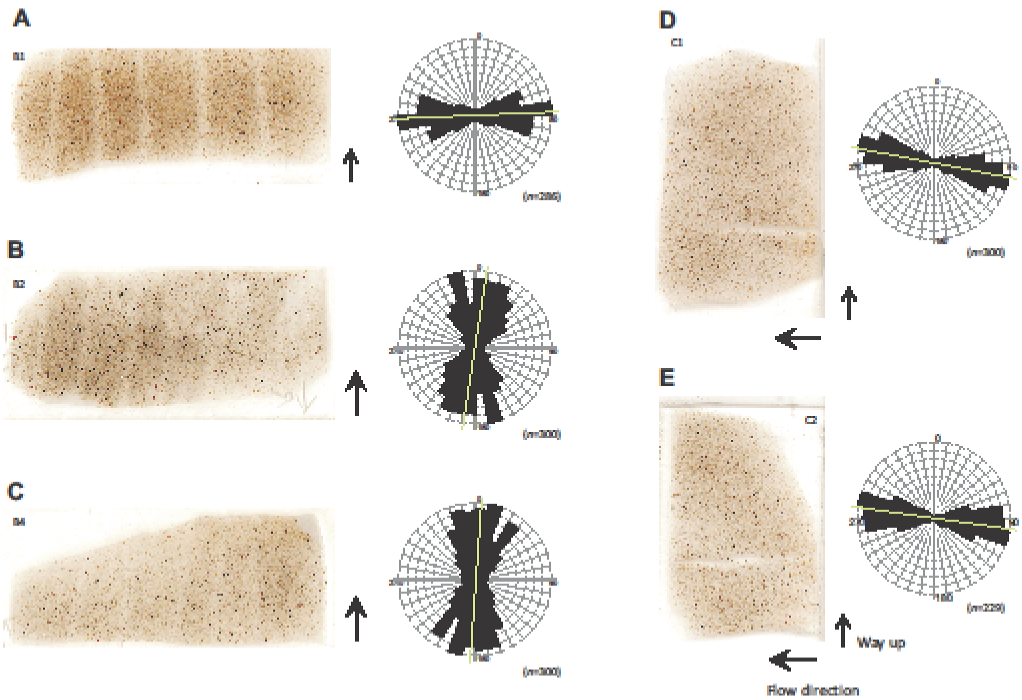

A
B
C
D

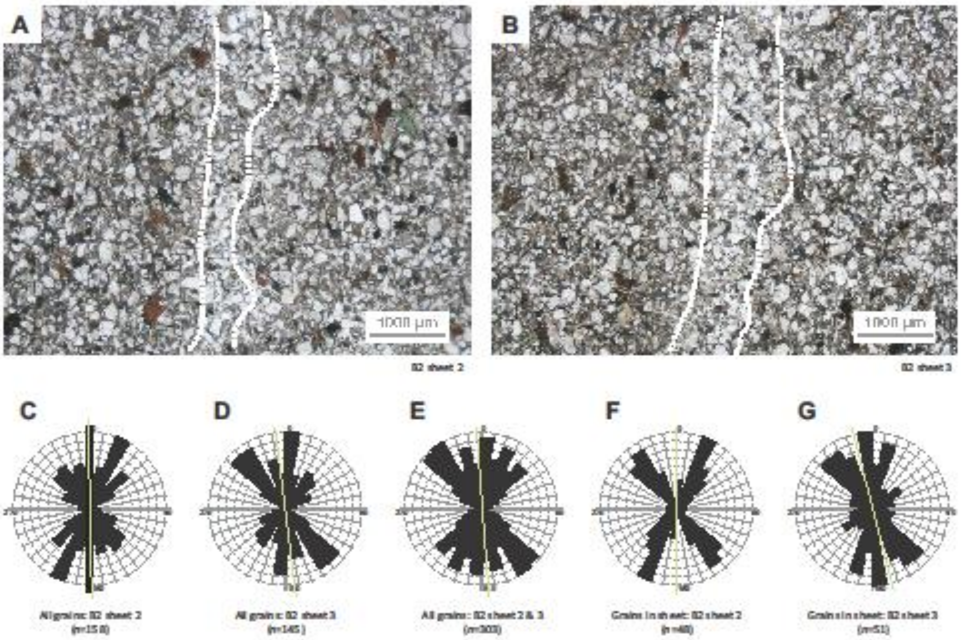


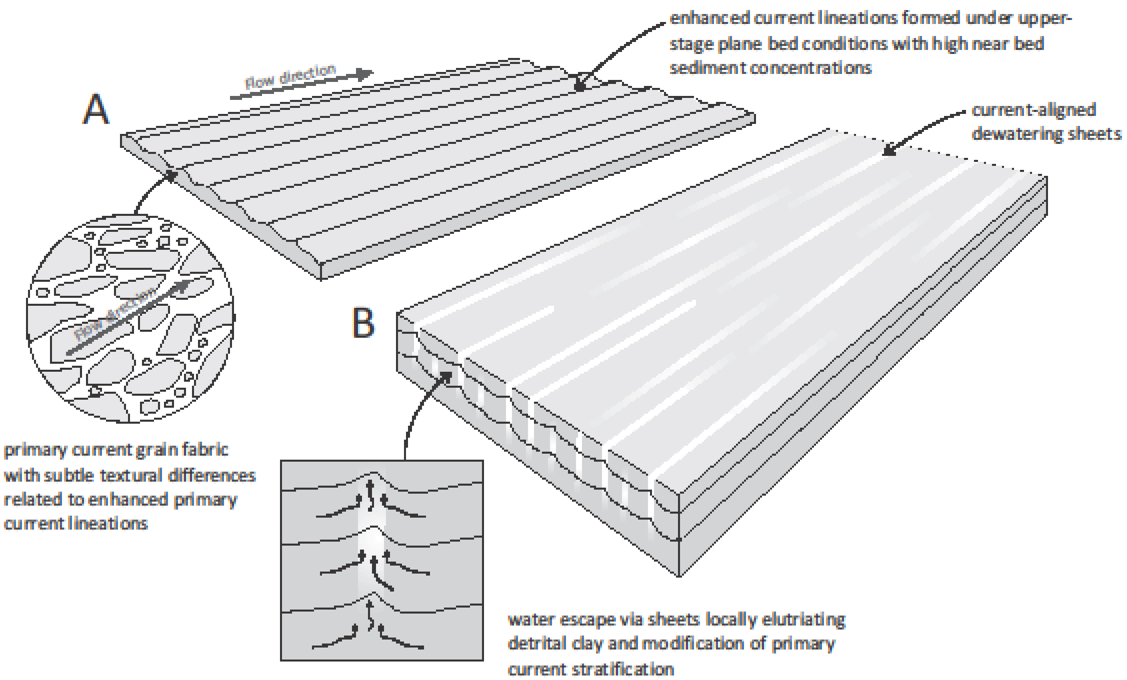
	F	G	R	L+S	*d*
n	164	203	8	25	19
a	121	123-303	112	135-315	010
ß	13.0	18.0	18.0	23.6	18.1


A
235
TAV:
3.1
235?
B
C
D
E
F


A
2x
B
20x
C
2x
2000 µm
D
20x
200 µm


A
B
C
D
E
Way up
Flow direction


A
B
1000 µm
1000 µm
C
D
E
F
G


enhanced current lineations formed under upper-stage plane bed conditions with high near bed sediment concentrations
Flow direction
A
current-aligned dewatering sheets
Flow direction
B
primary current grain fabric with subtle textural differences related to enhanced primary current lineations
water escape via sheets locally elutriating detrital clay and modification of primary current stratification