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On the nature of scaly fabric and scaly clay

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Abstract

Scaly clay, deriving from the Italian *argille scagliose*, is a term that has been used with a range of meanings, from stratigraphic to genetic, and across many scales of observation. Moreover the diagnostic feature of scaly clay—scaly fabric—has a variety of associated expressions used differently in different geological or structural settings. In an attempt to clarify and rationalise these confused terminologies, we have analysed a wide range of scaly clays of clearly contrasting origin. We here describe the appearance and nature of the fabrics at different scales of observations and interpret the mechanisms responsible for their development. Importantly, mesoscopic similarities may well not be reflected at the microscopic scale. As a result, we recommend that the term scaly fabric should only be used for description at the hand-specimen scale, although the fabric can be sub-classified microscopically according to the shape and arrangement of the rock components. Because scaly fabric defines the tendency of the rock to break along specific surfaces and has a morphological expression, we characterise it as a variety of rock cleavage.

Keywords: Argille scagliose; Scaly fabric; Cleavage

1. Introduction

Scattered through the geological literature is the term scaly clay, along with a range of associated expressions such as scaly mudstone, scaly fabric, scaly foliation and, deriving from Italian usage, *argille scagliose*. Since its introduction over 150 years ago in the Apennines of Italy, the use of the term has evolved to such an extent that its meaning is now blurred. For example, scaly clay can have a stratigraphic significance or may have some genetic implication, commonly a type of shearing, and it has been applied to features observed at a variety of scales. In the present paper we summarise this range of use and then describe macroscopically similar scaly clays that are of clearly contrasting origins and that differ in appearance at fine scales of observation. This leads us to the view that scaly clay is solely a rock type, identifiable at the field/hand-specimen scale and carrying no stratigraphic or genetic implications. Its distinctive feature is the scaly fabric-also a purely descriptive macroscopic term and best described using existing cleavage nomenclature.

2. Previous work

The term scaly clay was first established in Italy in its literal translation ‘argille scagliose’. Bianconi (1840) introduced the term to describe clayey sediments in the Apennines near Bologna, in order to highlight the tendency of these sediments to split into progressively smaller flakes characterised by polished surfaces. In most cases the clays were acting as a matrix to variously sized blocks of stronger rock. Argille scagliose was such a successful name that in a few years its use had spread across Italy and its meaning extended to cover any chaotic, mélange-like lithology as a whole, even including the blocks as well as the clay of the matrix (Bombicci, 1882). Moreover, in the Apennines the term argille scagliose acquired a lithostratigraphic connotation (e.g. Merla, 1952) that still exists to some extent. Different stratigraphic, genetic and geodynamic meanings were ascribed to the structural fabric, as illustrated in an influential paper by Page (1963), and ensuing microscopic analyses (e.g. Agar et al., 1989). Additional complications

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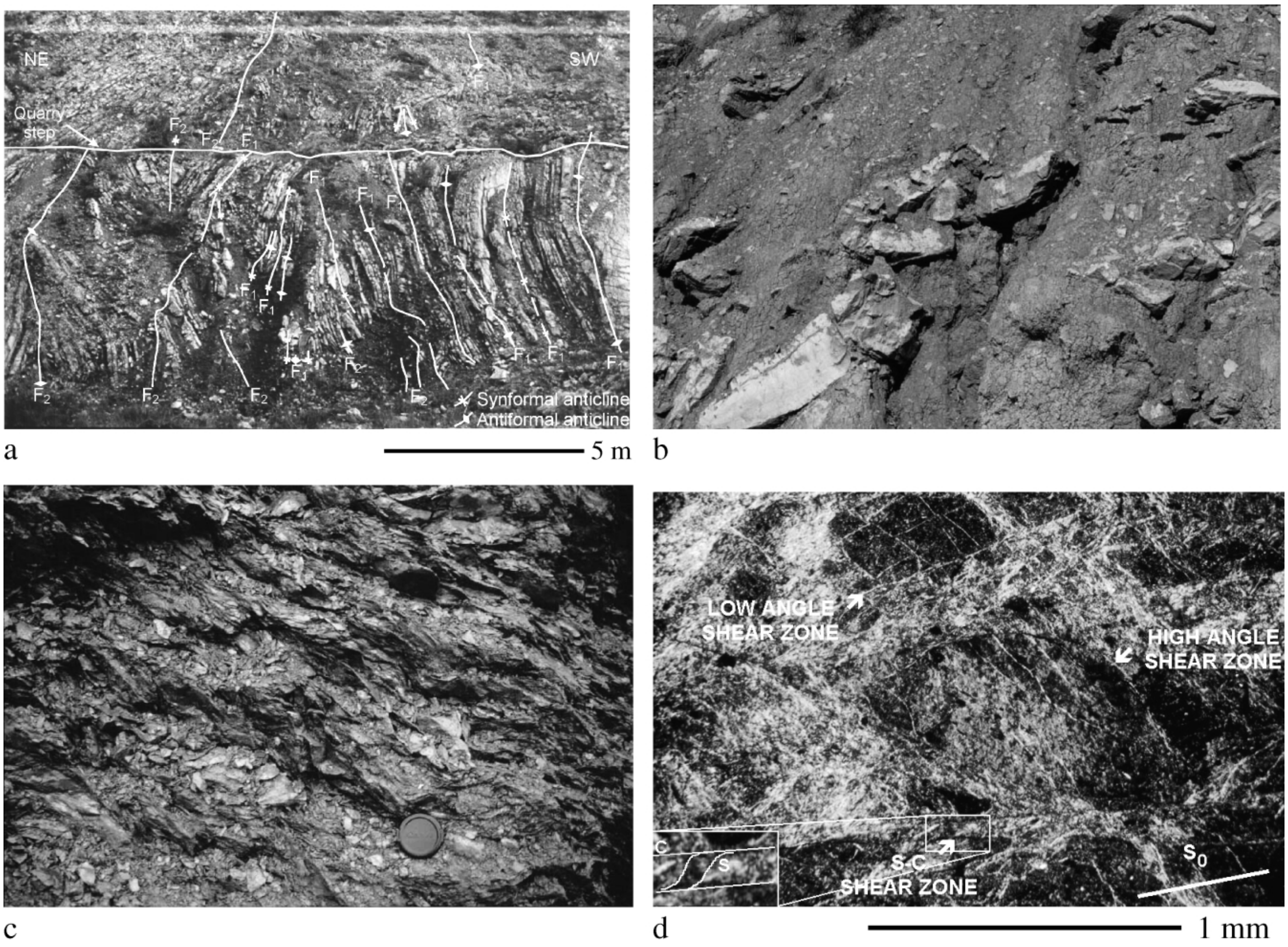

Fig. 1. Ligurian tectonic mélange, in the field and under the optical microscope. (a) Fold and bedding relationships in alternating shales and fine-grained calcareous or siliciclastic turbidites (Palombini Shales, auctt., Lower Cretaceous) Garofano Quarry, S of Vignola, Emilia-Romagna. The scaly fabric dips steeply to the SW, generally parallel to bedding in the fold limbs. F1 and F2 are axial traces of successively generated folds. (b) Incoherent unit in tectonic mélange (Palombini Shales auctt., Lower Cretaceous), Tresinaro Valley (Reggio Emilia), with blocks of bedded limestone in a large volume of scaly clay matrix. (c) Close-up view of scaly clay in varicoloured shales (Argille Varicolori auctt., Cenomanian–Campanian), Tresinaro Valley, Reggio Emilia. (d) Optical photomicrograph of scaly fabric from varicoloured shales.

arose in Italy from the link between bedrock of scaly clay and the derived loose material that commonly gives unstable hillslopes. Consequently, there is a large Italian literature on the geotechnical properties of argille scagliose (e.g. Froldi and Lunardi, 1994; Froldi et al., 1994), with further variations in terminology.

Early treatments of Italian geology in English translated argille scagliose as scaly clay and used the two terms more or less synonymously (Page, 1963; Abbate et al., 1970). Deposits elsewhere have frequently been likened to the argille scagliose of Italy, for example, Audley-Charles (1965) on the Bobonaro Mélange of Timor, Page (1978) on the Lichi Mélange of Taiwan, Horne (1969) on Ordovician volcanoclastic mélanges of Newfoundland, and Hsu (1966) on the Franciscan of California. Only occasionally has English usage had a stratigraphic aspect (e.g. Rangin et al., 1990; Harris et al., 1998) but there is commonly a genetic connotation. Bulk shearing is usually implied, ascribed to processes such as submarine gravity sliding (e.g. Elter and Trevisan, 1973; Boles and Landis 1984), tectonic deformation (e.g. Hamilton, 1979; Byrne, 1984), and diapirism (e.g. Barber et al., 1986; Brown and Orange, 1993). Other situations where the term scaly clay has been employed, also with implied shearing, include glacially deformed deposits (e.g. Suslikov, 1989; Menzies and Maltman, 1992), geomorphology in tropical environments (Fan et al., 1996), and landslides (Larue and Hudleston, 1987; Pettinga, 1987).

The recent resurgence in the use of scaly clay and related terms is primarily due to current interest in actively converging plate margins. For example, on-land scaly clays were described from Japan by Kimura and Mukai (1991) and Kiyokawa (1992), from Nias Island, Indonesia, by Pubellier et al. (1992), from Taiwan by Chen (1997), and from Barbados by Enriquez-Reyes and Jones (1991). Examples of scaly clays described from more ancient orogenic belts include Lash (1989) and Waldron et al. (1993) on the northern Appalachians. This renewed interest has also spawned new, associated terms (Lundberg and Moore, 1986). For example, El Chazi and Huvelin (1981) reported ‘scaly shales’ in a Carboniferous-age Moroccan

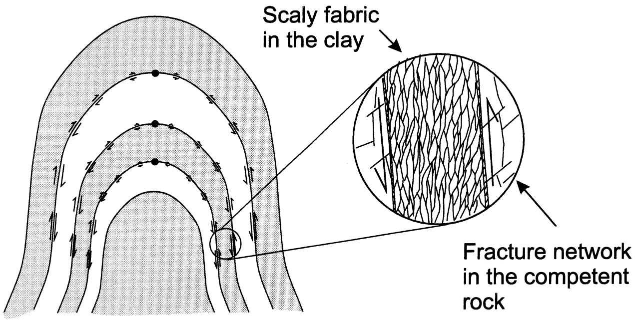

Fig. 2. Relative slip typical of flexural slip/flow folding across fold limbs, where the slip between competent layers (white) is taken up by shear within the shales (grey). Differential slip and limb thinning are accommodated by scaly fabric development as shown in the close-up. The scaly fabric materializes a tectonic foliation parallel to bedding.

olistostrome, Labaume et al. (1991) described 'scaly deformation bands' from the N. Apennines, and Sample and Moore (1987) described 'scaly argillite' from Kodiak Island, Alaska. Working with sub-ocean cores, Cowan et al. (1984) used 'scaly foliation' in describing the submarine Barbados accretionary complex and Auboin et al. (1982) reported what they called 'microflakiness' and 'microscaliness' in sediments cored in the Middle America Trench.

This confusion in terminology is partly due to the practical problems of working with scaly clays, particularly the sampling difficulties that arise from their inherently weak nature. Difficulties include: sampling, both in the field and for microscopy, the actual scaly surfaces as opposed to stronger intervening material; distinguishing between natural and drilling-induced effects in drill-cores; sample preparation for microscopy; the fineness of scale, even when viewed with the electron microscope, of complex clays; defining at what point a scaly fabric evolves from a merely incipient stage (the latter described by Lundberg and Moore (1986) as pervasive on a large scale but without a distinct planar orientation); missing characteristics such as the polished fracture surfaces (Vannucchi and Tobin, 2000); and the masking effects of later deformations.

3. Description and interpretation of some scaly clays

The feature common to virtually all descriptions of scaly clays is the complex array of variably anastomosing surfaces: scaly fabric. Macroscopically, in almost all cases the surfaces show what has variously been referred to as polish, waxiness, lustre or shininess, and they enclose narrow, variable shaped lenticles of less fissile material. Many workers have surmised that some degree of phyllosilicate reorientation is responsible for the lustrous appearance (compatible with the notion that shearing has to be involved), and hence the term has also been used for clay alignments at the microscopic scale. The surfaces can be arranged in a variety of patterns; many bear a fine lineation, from which some degree of slip along the surfaces has commonly been inferred. Beyond this, what have been called scaly clays are remarkably variable. We now describe such materials from a range of geological settings, and of what we interpret to be a variety of origins, to demonstrate that the term scaly clay should be used macroscopically and purely descriptively, without genetic connotation.

3.1. Northern Apennines, Italy

The Northern Apennines of Italy consist of thrust sheets and nappes ('Ligurian') of a Late Cretaceous–Eocene accretionary prism overlaid by a slope-apron sequence ('epi-Ligurian'), both emplaced during Late Miocene plate collision above a younger fold-and-thrust belt, along major detachment faults (e.g. Treves, 1984; Coward and Dietrich, 1989; Marroni and Treves, 1998). Together with mud volcanoes rooted in the fold-and-thrust belt, each of these Ligurian sequences shows fine examples of scaly clays.

3.1.1. Ligurian tectonic mélanges

The Ligurian nappes are typically block-in-matrix mélanges, which include the classical examples of 'argille scagliose' (Page, 1963; Pini, 1999). It was this material, near Passo della Cisa, that Page (1963) described, and from which Agar et al. (1989), collected samples for their microscopic study on scaly fabric. The best development is in the Cretaceous clay-rich basal formations of the nappes, representing abyssal to deep water fan deposits. Here, the claystone alternates either with limestone or sand–siltstone layers (Fig. 1a) forming multilayers that tend to be disrupted where the clay is abundant (Fig. 1b). The complexly undulating shiny surfaces (Fig. 1c) define a scaly fabric that affects the whole volume—*up to several hundred metres thickness*—of the matrix of these broken formations. Since present shear-related explanations of scaly clays in accretionary prisms (e.g. Moore and Byrne, 1987) involve major faults that rarely exceed some tens of metres in thickness; a problem here is to understand how such a large volume of sediment can develop scaly fabric.

The rare coherent portions of the Ligurian sequences show complex folds of three different generations (Fig. 1a) with the clays in the fold limbs being characteristically scaly while in the fold hinges they preserve a bedding-parallel fissility (Bettelli and Vannucchi, 2002). In the incoherent broken formations, isolated refolded hinges are common. A common character of the fold hinges is the presence of pressure-solution features indicating shortening in the concave side, and veins or tensile joints indicating stretching in the convex side of each competent layer. Lineations, as grooves or crystal fibres sub-perpendicular to the fold hinges are common, even though, depending on the competence contrast, the shear appears concentrated along the layer interfaces or uniformly distributed across the incompetent layers. Thus, across a bedding surface, the layer records a relative slip typical of flexural slip/flow folding depending on the slip planes' closeness. Where the

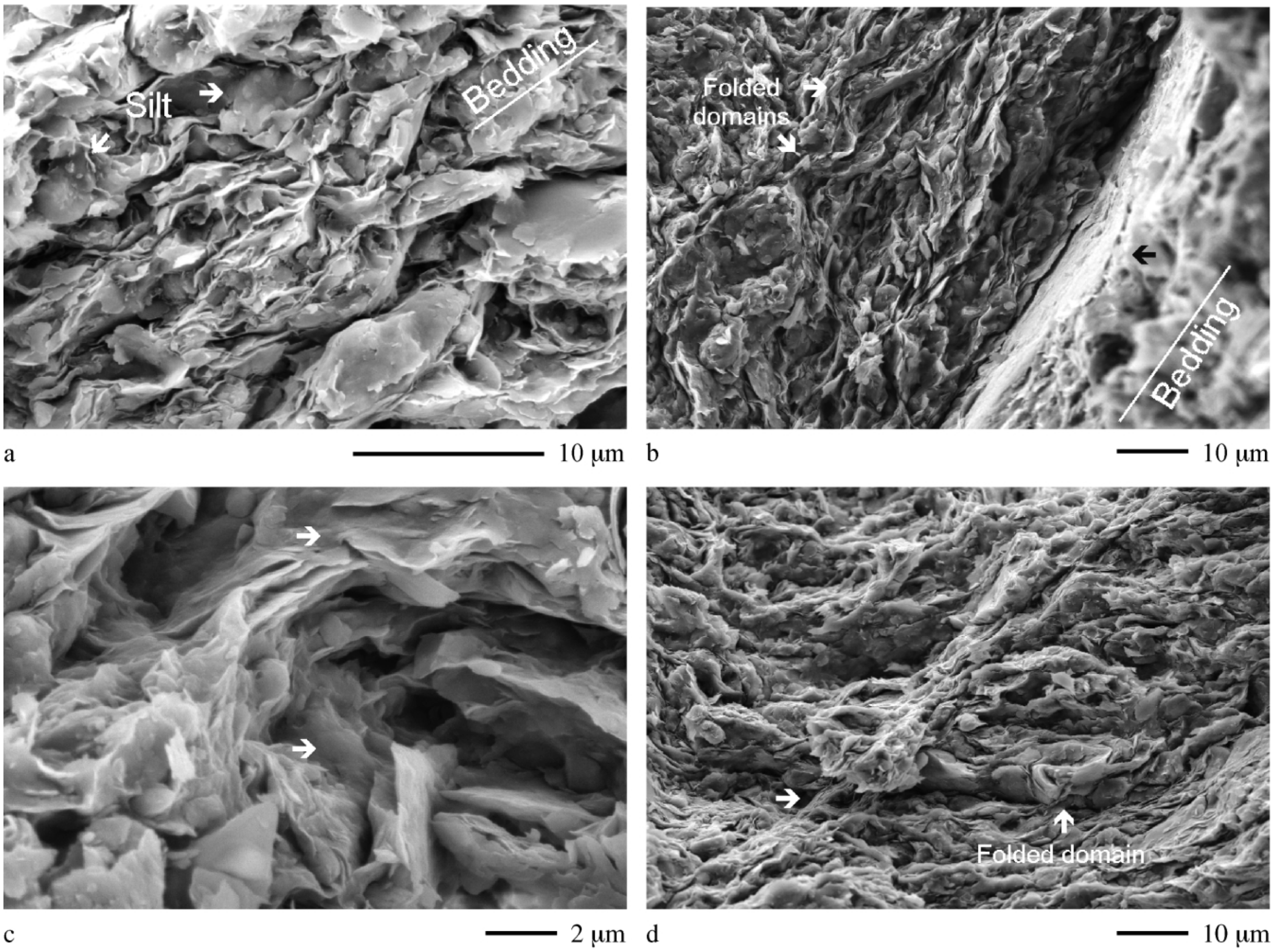

Fig. 3. Secondary-mode SEM micrographs of the Ligurian tectonic mélange, Tresinaro Valley, Reggio Emilia. (a) Clays forming the macroscopic scaly fabric aligned sub-parallel to bedding; where silt particles are present the preferred orientation is less intense. (b) Aligned clays in fold limbs, defining very thin, elongate domains, in places folded. The black arrow points a surface parallel to the fabric. (c) Aligned clays defining parting surfaces (arrowed) contouring fold hinge. (d) High-angle shear zone in fold limbs cutting aligned and slightly folded clays.

shaly layers are thicker than the competent ones, the slip between competent layers is taken up within the shales. The scaly fabric roughly parallels the ghost layering produced by aligned blocks of competent material, forming a tectonic foliation parallel to bedding. The bedding disruption went through progressive extension of the fold limbs as the result of folding, while the degree of fragmentation is the result of the competence contrast between the layers (Bettelli and Vannucchi, 2002). Scaly fabric developed to accommodate either the differential slip among competent and soft layers or the limb thinning (Fig. 2).

Fig. 1d shows a typical appearance of the scaly clay under the optical microscope. Certain domains show pervasive but not especially intense alignments of clay particles, separated by sharply defined, very narrow shear zones that correspond to the scaly films of the hand-specimen and that are parallel to the tectonic foliation. In some examples, the shear zones coalesce into intense arrays. While at the mesoscopic scale there are visible offsets, at the microscopic scale shear is interpreted from the fabric geometry, so that shear across the shaly layers produces slippage at the level of clay particles. At high-angles to the macroscopic tectonic foliation (parallel to bedding S_0 in Fig. 1d) is another shear-zone set, relatively minor but intense enough to divide the domains into blocks. The shear zone arrays have a $S-C$ aspect and disrupt primarily laminations, producing an appearance very similar to the samples described from the décollement of the Barbados accretionary prism (Labaume et al., 1997).

Scanning electron microscope (SEM) observations of coherent, non-folded and non-scaly portions of the clay-rich formations show clays aligned parallel to the bedding (Fig. 3a). Samples from the limbs of folds show a more intense preferred orientation, sub-parallel to the bedding-parallel tectonic foliation, forming in places finely spaced, slightly anastomosing narrow domains (Fig. 3b). As already described at the mesoscopic scale, microscopic clay minerals are well aligned and contour fold hinges (Fig. 3c), locally developing either a crenulation cleavage or parting surfaces arranged as an axial-plane cleavage

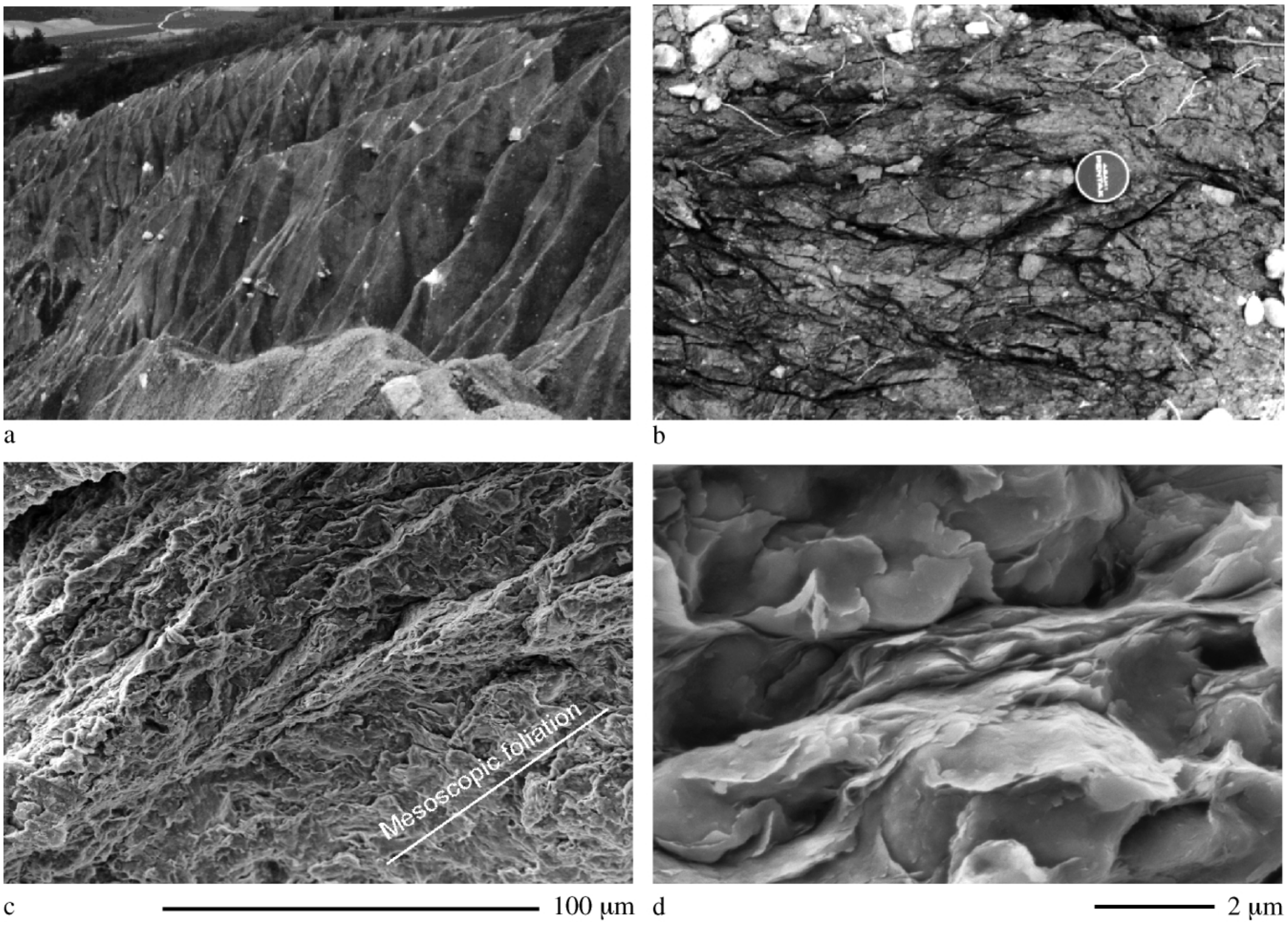

Fig. 4. Epi-Ligurian sedimentary mélanges (basal slope-apron deposits). (a) Panoramic view of a sedimentary mélange, showing blocks isolated in the scaly matrix (Val Tiepido, Reggio Emilia). (b) Macroscopic scaly fabric. (c) SEM secondary mode image showing discontinuous surfaces, a few tens of microns long, oriented parallel to the macroscopic foliation. (d) Pocket of well aligned clays lacking shear zone appearance.

(Fig. 3c). The fabric is cut by disjunctive, spaced surfaces and thin shear zones either parallel or at a high angle (Fig. 3d) to the bedding-parallel fabric.

The bedding-parallel fabric in the coherent units and preserved in fold hinges suggests a flattening due to early compaction in poorly lithified sediments, before the onset of shear. Such early bedding-parallel microfabric was also observed by Agar et al. (1989), who found that scaliness was associated with curviplanar fractures that isolate domains of preserved microfabric, even though the fractures reflect neither microfabric intensity nor its geometry. For this reason Agar et al. (1989) referred scaliness origin to stress-release mechanisms. These observations are only partially confirmed by the present study; in fact the bedding-parallel microfabric is cut by well developed shear zones, which can themselves appear as fractures. The shear zones are numerous and located along the fold limbs where flexural folding created and widened them as shear continued (Fig. 2), in places developing *S*–*C* geometries. This marked bed-to-bed shearing in the fold limbs enhanced the flattening fabric and transposed layering, the grossly parallel fabrics implying that intervening domains underwent differing degrees of passive rotation. In this scenario, therefore, the remarkably thick zones of scaly fabric are not due to bulk shear along discrete zones but are the cumulative effect of limb-parallel shearing during intense folding of these originally markedly layered lithologies. This early multilayer folding took place at all scales and is associated with the first stages of accretion (Bettelli and Vannucchi, 2002).

3.1.2. Epi-Ligurian, slope apron deposits

Scaly clays also occur in the Middle Eocene–Late Miocene slope apron sequence that unconformably overlies the Ligurian units and that are thought to have involved large-scale mass flow. The basal deposits comprise sedimentary mélanges with blocks of previously deformed Ligurian rocks, and pelagic and hemipelagic slope sediments (Fig. 4a). Sedimentary processes such as debris flow and mud flow produced clasts dispersed in a real, detrital matrix, through disaggregation and new deposition (Bettelli and Panini, 1989; Bettelli et al., 1994; Pini, 1999), while tectonic stress induced disruption through a mechanism of layer-parallel extension or layer-parallel shortening, in which blocks are eventually dispersed in a rheologically weak unit.

Macroscopically the scaly fabric of the mélange matrix

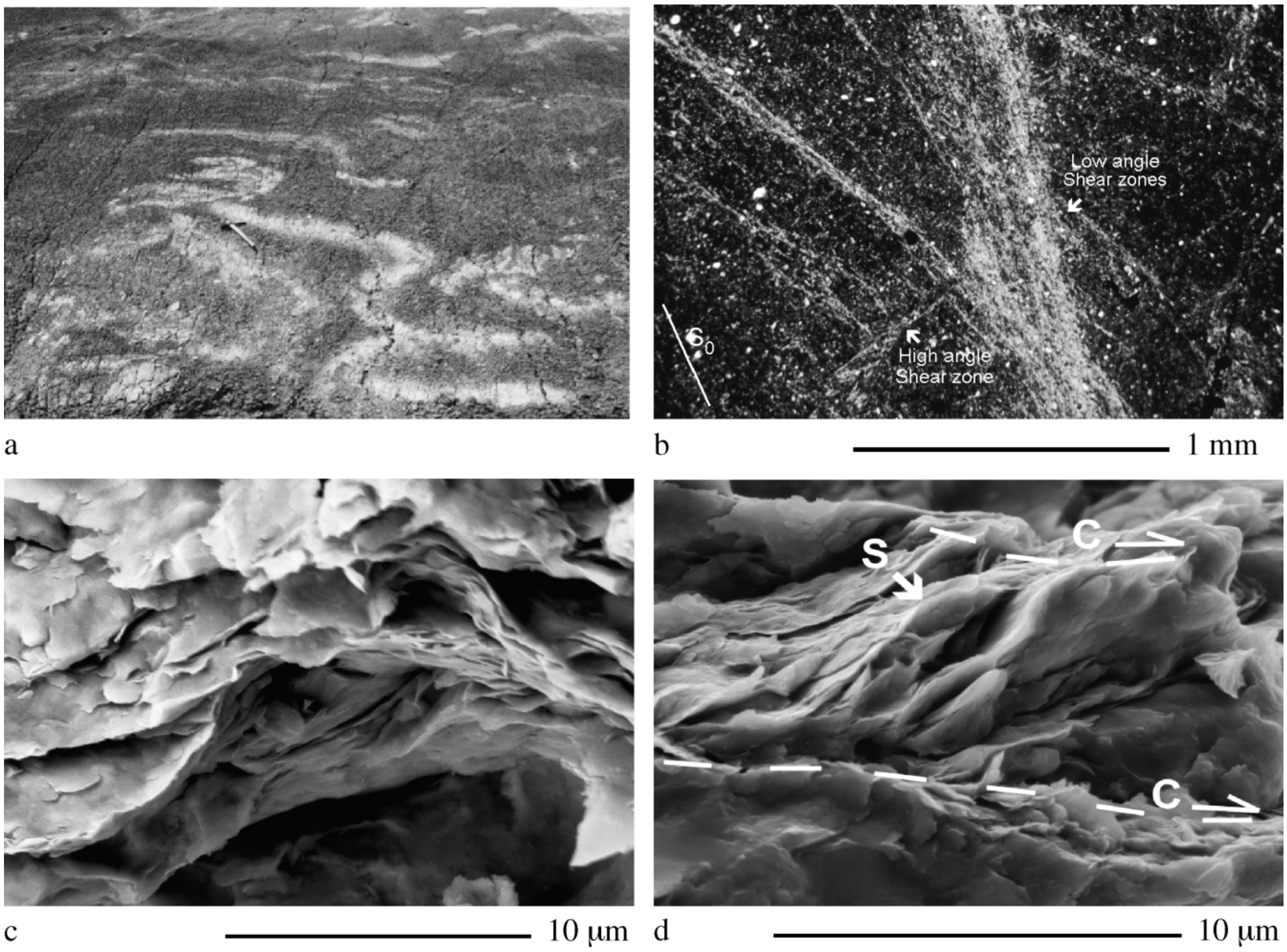

Fig. 5. Epi-Ligurian hemipelagic sediments. (a) Field view of partially disrupted layering in scaly matrix (Val Secchia, Modena). (b) Optical photomicrograph of scaly clay, showing lamination-parallel/low and high angle shear zones. (c) SEM secondary mode image showing narrow domains of well oriented platy grains bound by discrete, curviplanar surfaces. (d) Detail of *S*–*C* zones.

appears as polished anastomosing surfaces (Fig. 4b). At the thin-section scale the appearance is somewhat intermediate between that of the tectonic mélanges and the mud-volcano material described below. There are zones of aligned clays, but they lack clear margins or signs of shear. There are no shear zones at high-angle to the preferred orientation of the blocks. The SEM shows that where silt is sparse the clay particles are closely packed into a good preferred orientation parallel to the macroscopic fabric (Fig. 4c), which is particularly intense in isolated pockets (Fig. 4d), but which lacks the appearance of shear zones.

The poorly delineated pockets of aligned clays, lacking, for example, any sigmoidal or *S*–*C* aspect, imply that the orientation arose chiefly through processes other than sliding. We envisage that the mass-flow lacked sufficient viscosity to move by generating shear zones, but that in the last phases of emplacement, dewatering and subsequent pore collapse caused the alignments, with only minimal displacement, grossly parallel to the macroscopic fabric. An analogous situation has been reported from rain-triggered landslides (Pettinga, 1987), which changed flow mode after dewatering, producing extensive tracts of scaly clay near to the surface.

The late Middle Eocene–Early Oligocene pelagic and hemipelagic sediments that overlie the basal deposits described above are mainly red clays and marls, remobilised and slumped shortly after deposition (Bettelli and Panini, 1989). Consequently they are rarely found with intact original bedding, although there are folds, boudins and pinch-and-swells bounded by shear surfaces (Fig. 5a). These float in a scaly matrix that in the field has a distinctly meshwork appearance. Under the optical microscope the sediments resemble the Ligurian tectonic mélanges, with well developed anastomosing and bifurcating shear zones, sub-parallel to the primary laminations, and narrower zones splaying from them in an oblique, perhaps Riedel shear, orientation (Fig. 5b). High-angle zones are present but seem much less well developed than in the prism scaly clays.

Further differences are apparent under the SEM. The epi-Ligurian sediments reveal a fabric throughout the bulk of the clay with very compact domains of strongly oriented platy grains bounded by discrete, wavy and striated surfaces (Fig. 5c). The clay grains within the domains are progressively oriented from parallel to 45° to the domain edges. They form shear zones characterised by thicknesses

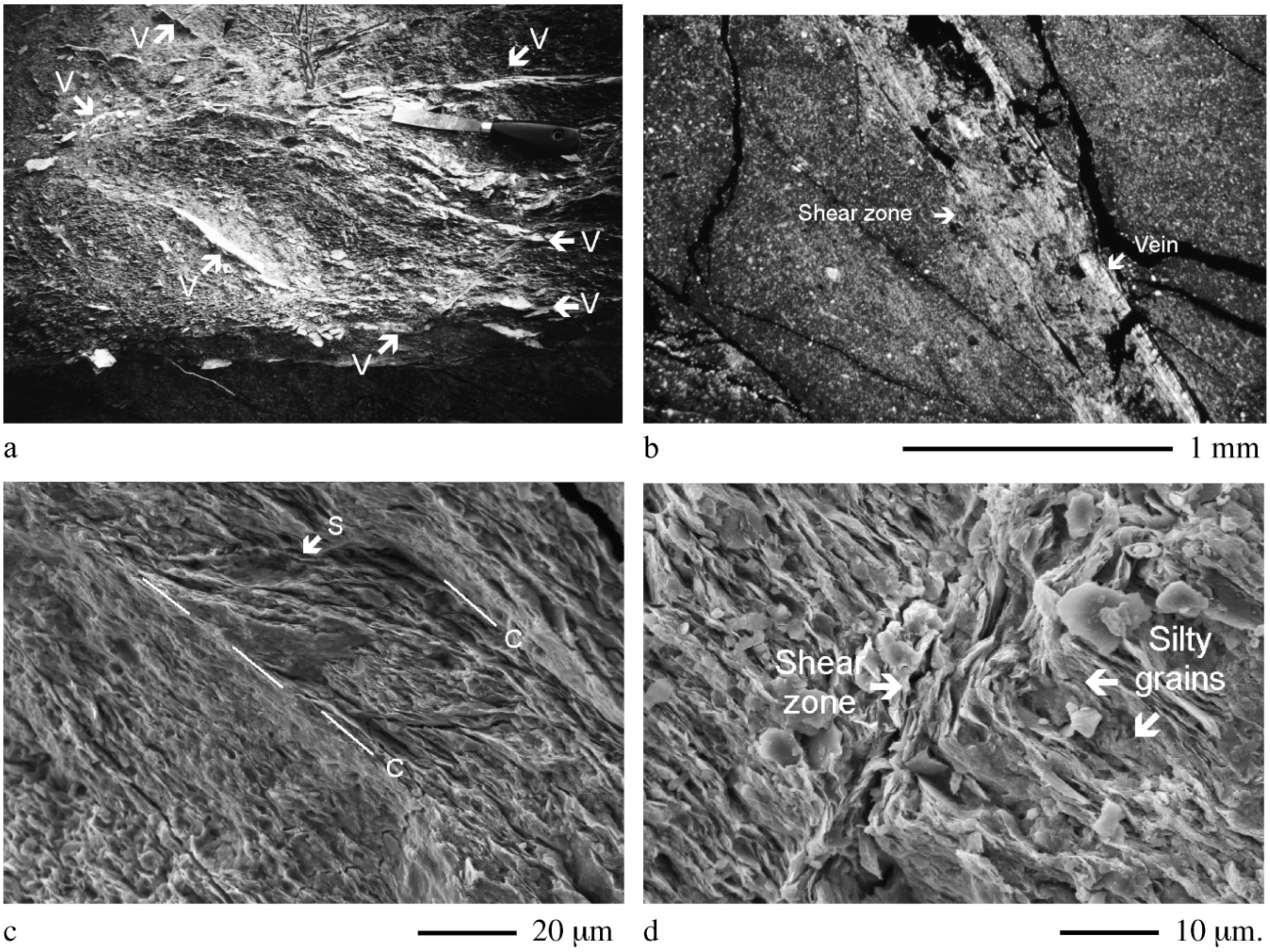

Fig. 6. Fabrics in Apennine detachment faults (Futa Pass to Mt. Falterona, Firenze). (a) Field view of scaly clay showing an intricate array of calcite veins (v on figure) (Scisti Varicolori auctt., Eocene–Oligocene). (b) Optical photomicrograph of well developed shear zone with extensional (fibres perpendicular to walls) veins. (c) SEM secondary mode image showing well developed and homogeneous preferred orientation of the platy minerals cut by a narrow shear zone. (d) Relatively wide shear zone showing internal S–C geometry.

reducing until the boundaries connect up together. The internal geometry of the domains resemble poorly developed S–C zones, with the rotated clays corresponding to the S-foliation flattened between the shear zones closing the domains with antithetic edges (Fig. 5d). These geometric appearances are clearly the product of shearing, not through tectonism as in the Ligurian mélanges but through sedimentary mass-movements, in this case with a rheology that caused movement by bulk ductile shear. The resulting scaly clay resembles the mélanges macroscopically, but it differs in detail and we interpret a different origin.

3.1.3. Collisional thrust faults

The thrust surfaces in the Tuscan–Romagna and Umbrian tectonic belt generated by the Late Miocene plate collision also comprise zones of scaly clay (Coli and Sani, 1990; Vannucchi and Maltman, 2000). The units involved are mainly Late Eocene to Early Miocene turbiditic sequences. The striking aspect of these thrust faults is the intricate calcite veining visible both at the macro-scale (Fig. 6a) and at the micro-scale with the same geometry: sub-parallel and oblique to bedding. Most of the veins are fibrous, with shear and extensional fibres. Microscopically, the fabric shows a discrete zone of severe deformation characterised by diffuse alignment and narrow, anastomosing patches of cloudy, dark material with much veining (Fig. 6b). Many of these are now open fractures whereas others contain accumulations of opaque material, some of which lobes into the zone walls as red or black fringes, indicating flux of (mainly oxidising) fluids. Evidence for pressure-solution is minor, while the presence of veins with their oxidized or reduced fringes suggests mineralization due to fluid flow. The genesis is intricate, involving fluctuating stress orientations and fluid pressure conditions of the kind discussed by Vannucchi and Maltman (2000).

Recent excavation of a tunnel has permitted the recovery of exceptionally fresh samples of this fragile material. Under the SEM the clays show a well developed and homogeneous preferred orientation parallel to bedding. Shear zones are present throughout, best developed at a low angle to the bedding-parallel fabric (Fig. 6c), but in places

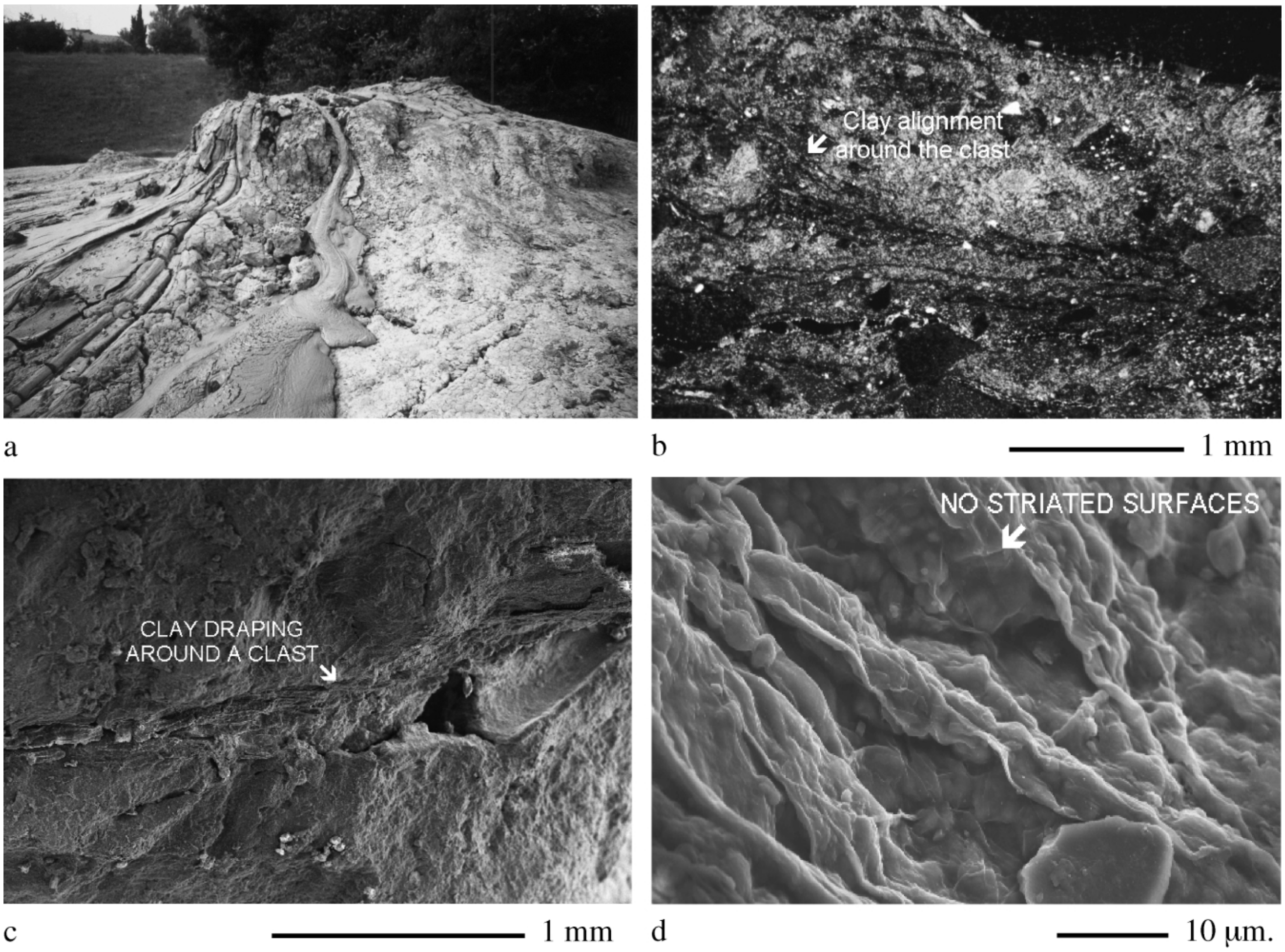

Fig. 7. Mud volcano and associated fabrics. (a) Field view of typical, active mud volcano (Nirano, Modena). (b) Optical photomicrograph showing clay alignment. (c) and (d) SEM secondary mode images showing the good alignment of the clay minerals draping around clasts and partings along no striated surfaces.

perpendicular or oblique (Fig. 6d). Clays are reoriented in the zones to give an $S-C$ geometry (Fig. 6c and d), with clay minerals in the C-surfaces generally more closely spaced than in the S-surfaces, among which euhedral calcite crystals have been also identified. The clear evidence of reorientation of the clay minerals into an $S-C$ geometry suggests that these scaly clays originated through intense shearing.

3.1.4. Mud volcanoes

Active mud volcanoes (Fig. 7a) are present along a 100-km-long belt on the Po Valley side of the Northern Apennines (Conti et al., 2000; Minissale et al., 2000). They extrude sand, pebbles and even blocks in a clay and silty clay matrix mixed with deep connate water and gases such as methane. The nature (composition, texture, age) of the extruded clasts document that the volcanoes root into the allochthonous, Ligurian units.

Mesoscopically, the muddy matrix is pervaded by slightly shiny, roughly parallel undulatory surfaces that equate to scaly clay in appearance. In thin-section, however, there are virtually no shear zones nor are there any open fractures (Fig. 7b). The fabric is essentially a combination of the preferred orientation of those clasts having an elongate shape, some of which are clay chips containing a weak pervasive alignment of the clays, and aligned clays that drape around the clasts. Observation under the SEM confirms a good alignment of the platy minerals, with surfaces that lack striations (Fig. 7c and d).

Taken out of context, hand specimens of this material would probably be labelled scaly clay and some microscopic shear texture invoked. This is demonstrably not the case here: the fabric is due to flow/sliding producing interparticle shearing—which may help in clay alignment prior to collapse of the extruded wet mud—and to consolidation/collapse as a result of desiccation. Not all the mud volcanoes of the Northern Apennines have scaly extruded mud and viscosity is the main parameter affecting the final fabric. The desiccation does not cause extensional fractures but collapse of the clay particles into a crude parallelism, which undulates around lenticles of more competent material.

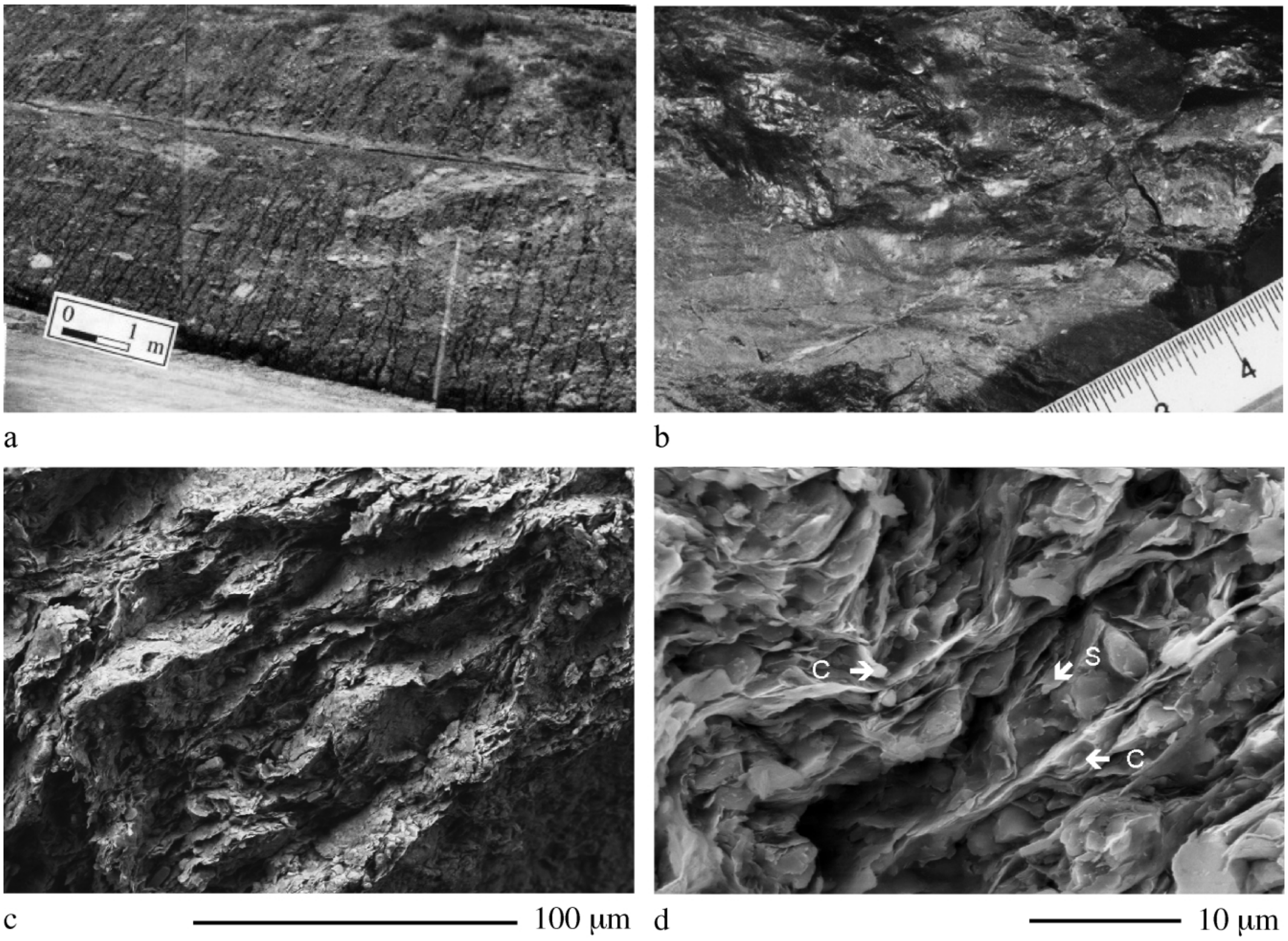

Fig. 8. East Sabah sedimentary mélanges. (a) Field view of mélange, showing blocks in scaly matrix. (b) Low-magnification SEM image of aligned clays. (c) Secondary mode SEM image showing the detail of aligned clays and pervasive scaly surfaces, and (d) S–C geometry of the shear zones.

3.2. East Sabah mélanges, Malaysia

Sabah, a state of Malaysia in northern Borneo, lies at the junction of three marginal oceanic basins: the Sulu to the east, the Celebes to the south-east and the South China to the north-west, where the active Palawan–North Borneo Trench is located. The successive opening and closing of these marginal basins produced a complex on-land geology, which includes scaly clays in mélanges, late faults and mud diapirs (Hamilton, 1979; Barber et al., 1986).

3.2.1. Sedimentary mélange

The East Sabah mélanges involved tectonic faulting and mud diapirism but in the Garinono Unit, Early–Middle Miocene, reported here the main mechanism was sedimentary mass transport (Clennell, 1991). The mélange consists of blocks, mainly deep-water sandstones and siltstones, enclosed by a matrix of scaly clay (Fig. 8a and b). It is the matrix that is of interest here, but it is relevant that within undeformed sandstone beds pockets of clay show an incipient scaly fabric. The folding in these rocks is largely accommodated by slip along bedding surfaces; the only deformation that the mud inclusions within the sandstones can have undergone is some compaction and pure shear. These clay pockets are therefore interpreted as large mudflakes carried inside the gravity flows that deposited the sand layers.

The mélange matrix in the clay-rich portions shows the pervasive undulating surfaces typical of scaly clay, although they are only slightly polished and are not striated (Fig. 7b). In the blocky zones the fabric is developed in clay seams, which anastomose around lensoidal and irregular shaped inclusions. The scaly fabric can grade into the indistinct edges of the soft blocks. Low magnifications under the SEM show domains of poorly compacted platy clay minerals wrapped around by zones of low-porosity fabric reflecting stronger flattening (Fig. 8c). The anastomosing and pervasive nature of the scaliness is because of the sparse shear zones present throughout (Fig. 7c), locally with an S–C geometry (Fig. 8d), but overall there is no clear record of pervasive shearing.

The scaly fabric is here formed by flattening and orientation of platy grains without either structural rearrangement of grains or pressure solution. The domains that characterise the fabric have poorly oriented foliae wrapping around enclosed clasts. Incipient shear zones cut

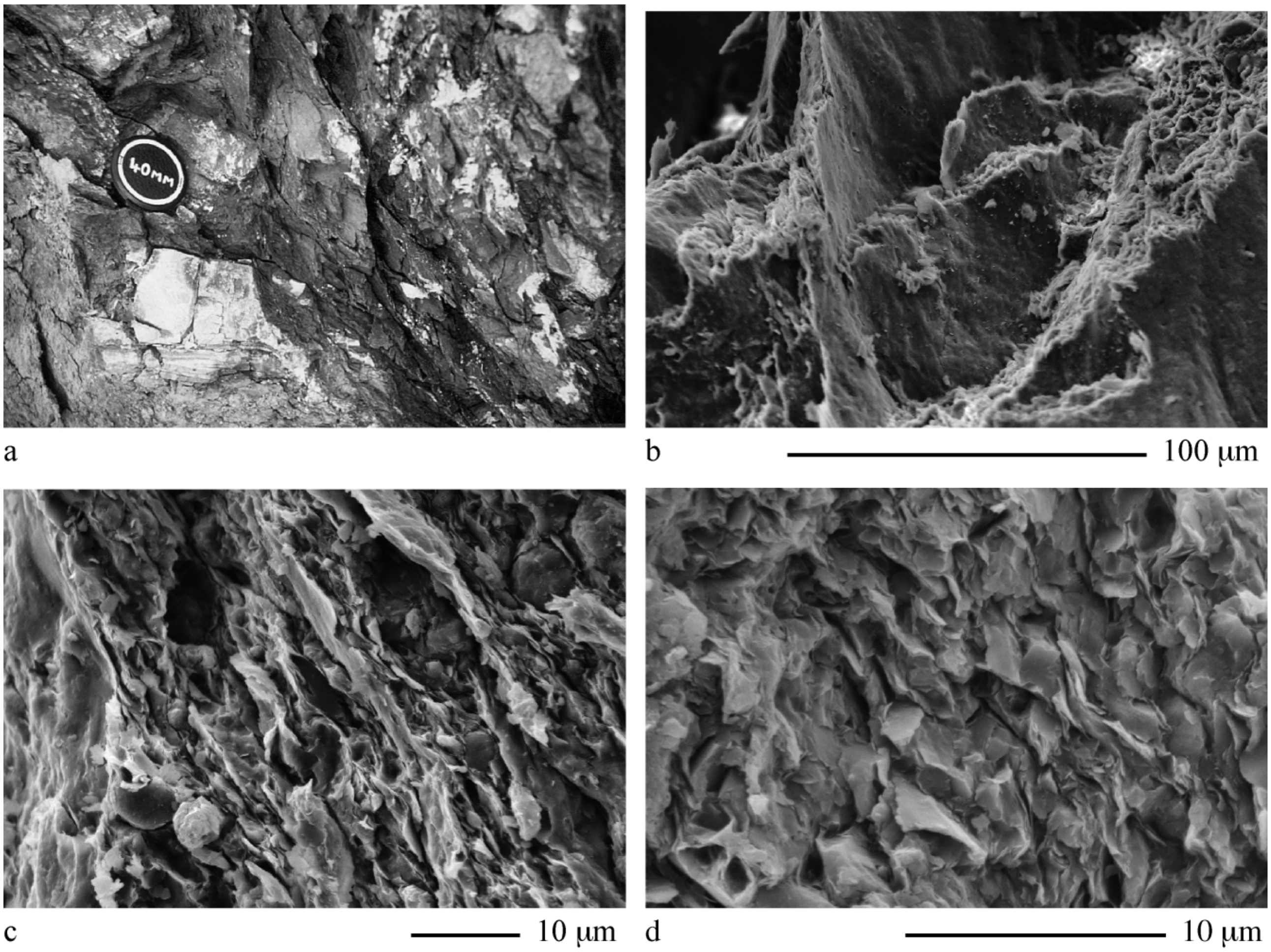

Fig. 9. Fabrics in late fault zones, Dent Peninsula, Sabah. (a) Appearance of fault-related fabrics in fault zone. (b) Secondary mode SEM image showing finely striated and polished surfaces. (c) SEM photomicrograph showing anastomosing fabric. (d) Secondary mode SEM image showing detail of aligned clays.

this texture. Simple shear appears not to be significant in the development of the scaly fabric. As noted by Wilson and Will (1990), some scaly foliation can arise during viscous or ductile flow processes, rather than brittle slip. In this case the scaly partings form during slow dewatering, with the sediment undergoing continuous deformation. The flattening fabric, though, implies also compaction under uniaxial strain. Pure shear involves homogeneous volume loss or heterogeneous compressional failure, perhaps involving some elutriation (Arch and Maltman, 1990). This combination of viscous/plastic flow and pure shear can occur in different ratios within the same olistostromal mudflow, depending upon the lateral confinement and the dewatering rates.

3.2.2. Late fault zones

Early to Middle Miocene extensional faults cut relict-bedded hemipelagic turbidites of the Labang Formation (Oligocene–Early Miocene) in the Dent Peninsula, east of Sabah (Clennell, 1992). The brittle nature of this faulting implies that it occurred after sandstone cementation, and had the effect of fragmenting the rock into rhomboidal pieces progressively rounded and comminuted as they spread off into the clay (Fig. 9a). Scaly fabric is developed in ~50-cm-thick clay zones, each of which accomplished about 1 m of displacement. Each scaly surface therefore accommodated a few millimetres to a few centimetres of movement. The fabric in the scaly clay, though totally tectonic, is geometrically similar at the macroscopic scale to the matrix of the Garinono Mélange, with the glossy clay surfaces wrapping around pea-sized and larger clasts of hard mudstone and sandstone. Under the SEM, the scaly surfaces appear finely striated and polished (Fig. 9b), the clay minerals are finer than the sedimentary mélange, and show a well developed preferred orientation that defines a parallel/weakly anastomosing fabric (Fig. 9c and d). These slip-planes are responsible for the small size of the clay minerals, as they break the grains along the partings. In this case localised brittle–cataclastic shear deformation has to be responsible for the fabric, even though discrete microscopic shear zones and an S–C aspect are lacking, and the cataclasis is not apparent macroscopically.

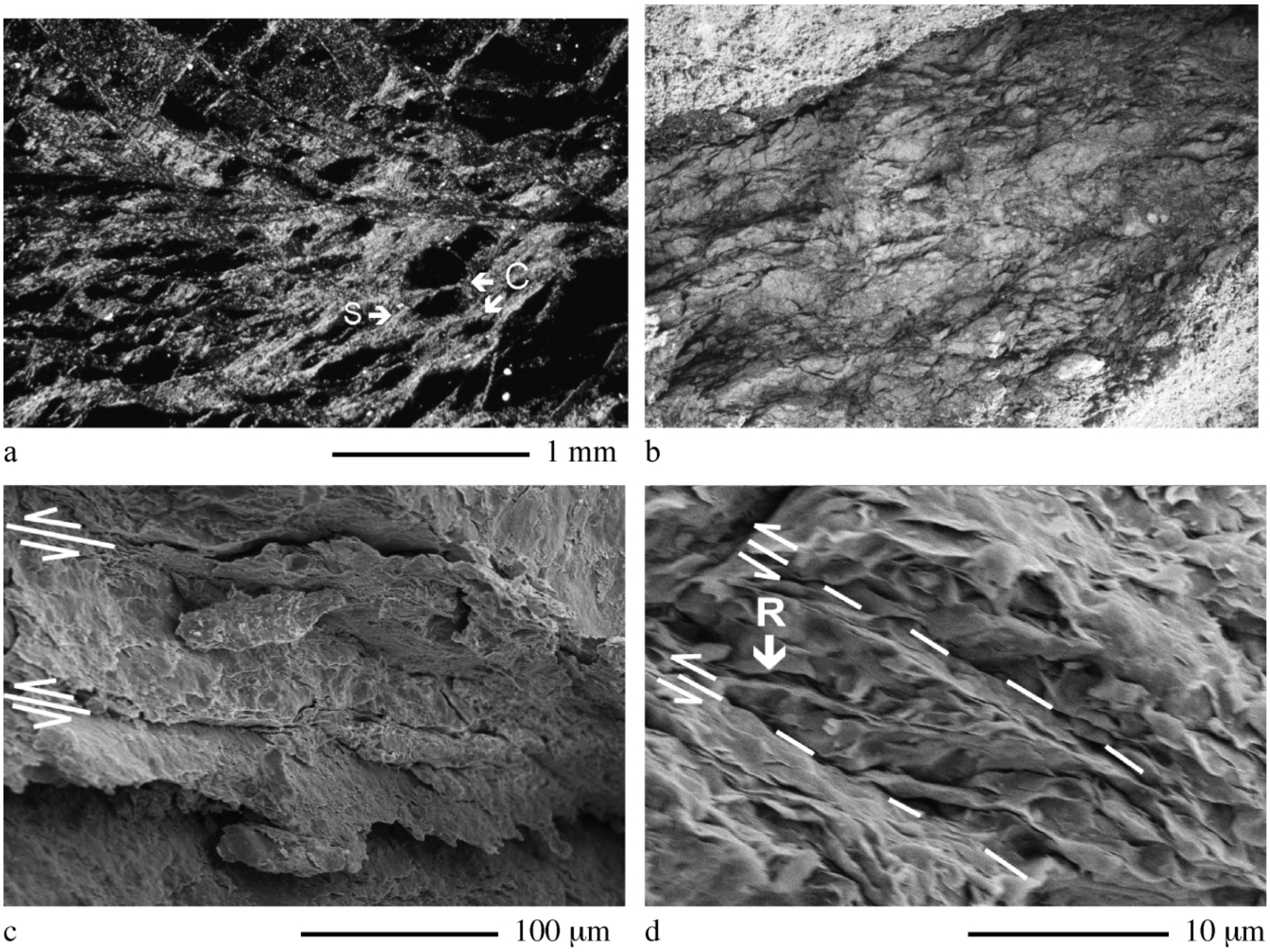

Fig. 10. Fabrics associated with active faults. (a) Optical photomicrograph of aligned clays in the décollement of the Nankai submarine accretionary prism. (b) Field view of scaly clay in the San Andreas Fault, Skeleton Canyon, Mecca Hills, California. (c) Secondary mode SEM image showing aligned clays. (d) Detail of aligned clays, including $S-C$ geometry.

3.3. Active submarine accretionary prisms

Possibly the best known development of scaly clay in submarine accretionary prisms is in the clay-dominated Barbados prism, recently described and interpreted in detail by Labaume et al. (1997). In many ways the scaly clays we describe here that involved some kind of bulk shearing corroborate their ideas. Scaly clays from other cored prisms seem less well developed, such as the Cascadia prism (Clennell and Maltman, 1995), presumably because the lithologies are relatively silty, so that the grain shapes restrict the degree of mineral alignment.

However, the appearance of scaly clay in drill-core varies according to the age and wetness of the sample. Fresh cores from the Nankai accretionary prism examined in 1990 during Leg 131 of the Ocean Drilling Program (Maltman et al., 1993) showed scaly clay only in zones of very high shear strain and even here it resembled a clayey breccia, with lensoid fragments of clayey silt having polished and slickenlined surfaces. A similar appearance was recorded more recently in fresh samples from Nankai (Moore et al., 2001). In all these examples, examined while the cores were fresh, the fabric appeared somewhat less pervasive and the surfaces less lustrous than true scaly clay. However, recent re-examination of the Leg 131 cores from the Nankai basal décollement revealed a distinctly scaly aspect in the basal few centimetres of the zone. Microscopic examination of this scaly material shows that the material does, in fact, comprise an array of narrow shear zones in an $S-C$ geometry (Fig. 10a), closely resembling the Barbados material reported by Labaume et al. (1997). Although this microfabric has, presumably, always been present, it seems that 10 years of core storage, despite the best attempts at conservation, has changed the appearance of the cores and has enhanced the macroscopic scaliness. A similar effect was observed in cores from the Barbados accretionary wedge by Behrmann et al. (1988), Agar et al. (1989) and Prior and Behrmann (1990a), who suggested that elastic rebound in the samples after recovery was contributing to the scaly fabric. We have noticed the same effect in stored on-land cores from sheared glacial sediments.

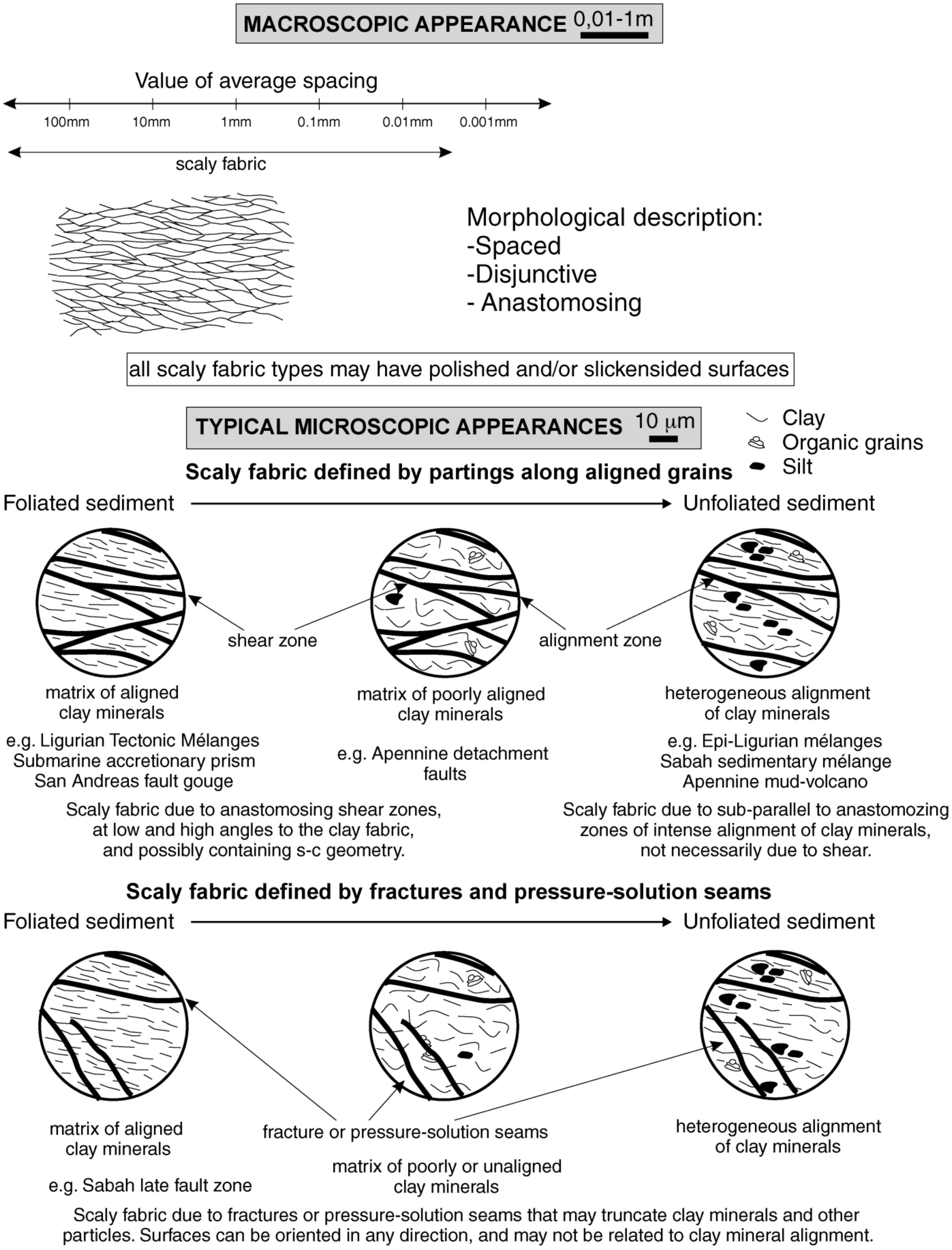

Fig. 11. Synoptic diagram of cleavage terminology (modified from Borradaile et al. (1982)) and macro- to micro-scale fabric elements. Different microscopic appearances of scaly fabric result from different origins and mechanisms of formation.

3.4. San Andreas Fault gouge, Mecca Hills, California

Scaly clay and related terms seem not to have been introduced into the extensive recent literature on clayey fault gouges, even though these materials have a scaly appearance. It would be impossible to distinguish between hand specimens of clay gouge (e.g. Rutter et al., 1986) and those from some of the situations mentioned above, and at the microscopic scale there are many features in common. Fig. 10b shows material in the San Andreas Fault exposed at Skeleton Canyon, at the W margin of the Mecca Hills, Salton Trough, S California (Sylvester and Smith, 1987), which in other settings would be called scaly clay. The scaliness is due principally to a pervasive alignment of clay particles that is paralleled by elongate lenses of disrupted laminations (Fig. 10c) and/or wisps of semi-opaque matter. The undulatory aspect so apparent in hand-specimen results from the Riedel shears, which offset earlier formed features including single minerals (Fig. 10d).

There are patches in which the dominant Riedel shears with the opposite orientation dominate, implying a locally opposite sense of shear. Presumably these are local accommodation effects but it does mean that, as reported by Chester and Logan (1987) from the Punchbowl Fault, the statistics of the orientations have to be assessed very carefully in order to use the microfabrics for deducing the overall shear sense. This material provides a further example of scaly clay showing an essentially $S-C$ geometry. It closely resembles the Barbados material referred to above, though there is much greater cataclasis. This presumably reflects the more mature development of the San Andreas material, which comes not from a detachment in its incipient stages but from a well evolved fault zone in lithified material, which has probably undergone multiple movements in horizontal and vertical directions (Sylvester and Smith, 1976). However, these complexities are unclear in hand specimen. Macroscopically this material has much in common with the other scaly clays described here.

4. Origin of scaly fabric and scaly clay

Although our observations contrast with some of the microstructural analysis of Agar et al. (1989), their conclusion that the term scaly fabric should be restricted to field or hand-specimen use and not applied at the grain scale is amply confirmed by the present work. Material that appears scaly at the macroscopic scale can have a variety of microscopic appearances (Fig. 11), which in turn implies a range of formative mechanisms. On the other hand, the common feature of all our microscopic observations is the reorientation of clay particles into preferred alignments (Fig. 11), which essentially accounts for the macroscopic scaly appearance, so we distinguished two main types of microscopic appearances based on the relationship among the zones of preferred alignment and the surroundings: scaly fabric defined by partings along aligned grains and scaly fabric defined by fractures and pressure solution seams, which can span in any orientation regardless of the background (Fig. 11). These two types have been, then, subdivided from foliated sediment, represented by pure clay, to unfoliated sediment, as clay with abundance of microfossils and silt, in an increasing level of disturbance to the alignment process (Fig. 11). Agar et al. (1989), on the other hand, argued that no part of the scaly fabrics they sampled from the décollement of the Barbados "shows any alignment of phyllosilicates" and hence developed "without development of grain alignment". Prior and Behrmann (1990a,b) went on to develop this notion, with further back-scattered electron imagery of samples from the Barbados prism, concluding that the scaly fabric here corresponds to fractures resulting from unloading during core-recovery. The discrepancy may be the result of the analysis technique or the sample choice (Labaume et al., 1997; Jan Behrmann, 2002, written communication). Our work supports that of Labaume et al. (1997) in explaining the discrepancy by not relying on the back-scattered SEM alone, and by ensuring that the samples of these fragile and highly heterogeneous materials are representative of the actual scaly surfaces.

There is no question that core material does decompress on recovery and we have no objection to the principle of scaly fabric arising from relaxation fractures: we have simply not found evidence for tensile fracture, as open cracks, in fresh scaly samples. The closest situation is that of the compaction/desiccation at the N Apennine mud volcanoes, but the scaly aspect is again due not to extensional fracture but to localised clay alignment, in this case due to a combination of collapse through water loss and flow. The epi-Ligurian and mudflake pockets from Sabah, described above, are further examples of scaly fabric arising essentially through compaction-driven alignment following pore collapse. Other possible ways of generating preferred alignments are through vigorous localised dewatering channels (Arch and Maltman, 1990) and some form of carbonisation, invoked by Lash (1990) to explain the intensely reoriented platy grains in scaly clays from W Newfoundland with an 'extraordinarily high' carbon content.

Clearly, therefore, scaly fabric can have a variety of origins. Even so, most examples evidently involve some form of bulk shearing. We have not observed the spaced foliations and fracture networks reported by Labaume et al. (1997) but we find their model of the flattening followed by progressive development of shear-substructures entirely plausible. Mechanistically, the shear will be more or less localised depending on the conditions, and it may well be episodic. Consolidation alone, whether due to burial or tectonic stress, is likely to produce homogeneous shortening parallel to σ_1 and a homogeneous stretching parallel to σ_3, i.e. pure shear, with some volume loss, so some instability is required to nucleate localised slip and hence allow zones of intense realignment to propagate. Layer-parallel slip during folding, as suggested for the Ligurian mélanges, will constrain certain parts of the already established flattening fabric to undergo shear. Lithology is relevant in that if there is more than about 50% silt, then the shear becomes turbulent and it is difficult to localise the deformation. The consolidation state of the clay sediment will also be of influence. On the wet side of the critical state line, which includes all normally and under-consolidated sediments, shear will cause reductions in volume and a fabric distributed throughout the material. On the dry, over-consolidated side of the critical state line the sediment will deform with a dilatant response, with more localised slip zones (Maltman, 1994).

If deformation is undrained, through the material deforming at a strain rate faster than the permeability will allow pore pressure to dissipate, the slip event itself generates its own pore fluid pressure response. On a path of suddenly increasing shear stress, dilation occurs in the shear zones and the pore fluid pressure drops, hardening the zone and arresting slip on that portion of the shear plane. With suddenly decreasing shear stress, the dilatant zones collapse, and this forces up the pore fluid pressure, temporarily weakening the slip. In nature these scenarios are likely to link together, leading to complex, episodic behaviours during clay alignment.

Such mechanisms arise in response to a range of geological processes that produce scaly clays. We have demonstrated that these include:

- tectonically driven faulting in poorly lithified sediments (e.g. detachment faults of the N Apennines; modern submarine accretionary prisms)
- fold-induced inter-layer shearing (e.g. tectonic mélange of the N Apennines)
- brittle faulting of weak argillaceous rocks (Sabah faults, San Andreas Fault)
- shear through viscous mass movement, including submarine sediment flow (producing mélanges) and on-land landsliding
- halting of fluid mudflows, giving densification and pore collapse
- consolidation/desiccation, associated with subaerial mud volcanoes.

5. Suggested usage and conclusions

The diagnostic feature of scaly clay is its scaly fabric. Both terms should be used solely in the field or for describing hand specimens. Scaly fabric applies to argillaceous materials that macroscopically are pervaded by anastomosing surfaces, on scales down to the smallest visible with the naked eye. The surfaces are more or less undulating and smooth, but may not be distinctly shiny or polished. They are commonly striated, though the lineation is incidental (cf. Prior and Behrmann, 1990a) and can equally arise on non-scaly surfaces (e.g. see Maltman, 1998). Related terms that have been used in the past, such as microscaliness and scaly foliation, add confusion. Incipient scaly fabric can occasionally be a useful term, but only where the texture is known to be in an intermediate stage of formation. Because of the range of scenarios outlined above, the term scaly clay should have no genetic meaning and stratigraphic connotations are also unhelpful.

Where the surfaces have little undulatory aspect and lack polish and striations, the fabric is better called a cleavage, in fact scaly fabric is usefully regarded as a variety of rock cleavage as it defines the tendency of the rock to break along surfaces of a specific orientation. For example, as Agar et al. (1989) suggested, the geometry of the anastomosing surfaces can be described by such terms as parallel, reticulate, and trapezoidal, deriving from cleavage terminology (Borradaile et al., 1982). Within a morphological classification for cleavage—based on shape and/or arrangement of the rock components—scaly fabric would result in a spaced, disjunctive and anastomosing feature (Fig. 11). The average value of spacing can range from sub-millimetre, at the lower limit of eye resolution, to tens of metres in completely unfoliated rock, such as limestones. Such nomenclature describes well the morphology and dimensions of scaly fabric, and makes it unnecessary to invent new and potentially confusing terms.

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References

Abbate, E., Bortolotti, V., Passerini, P., 1970. Olistostromes and olistoliths. Sedimentary Geology 4, 521–557.

Agar, S.M., Prior, D.J., Behrmann, J.H., 1989. Back-scattered electron imagery of the tectonic fabrics of some fine-grained sediments: implications for fabric nomenclature and deformation processes. Geology 17, 901–904.

Arch, J., Maltman, A.J., 1990. Anisotropic permeability and tortuosity in deformed wet sediments. Journal of Geophysical Research 95, 9035–9045.

Auboin, J., von Huene, R. and others, 1982. Site 494: Middle America Trench lower slope. In: Auboin, J., von Huene, R. and others (Eds.), Initial Reports of the Deep Sea Drilling Project, Washington, DC, Government Printing Office 84, pp. 551–570.

Audley-Charles, M.G., 1965. A Miocene gravity slide deposit from eastern Timor. Geological Magazine 103, 267–277.

Barber, A., Tjokrosapoetro, S., Charlton, T., 1986. Mud volcanoes, shale diapirs, and mélanges in accretionary complexes, Eastern Indonesia. Bulletin of the American Association of Petroleum Geologists 70, 1729–1741.

Behrmann, J.H., Brown, K., Moore, J.C., Mascle, A., Taylor, E., 1988.

Evolution of structures and fabrics in the Barbados Accretionary Prism. Insights from Leg 110 of the Ocean Drilling Program. Journal of Structural Geology 10, 577–591.

Bettelli, G., Panini, F., 1989. I mélanges dell'Appennino Settentrionale dal T. Tresinaro al T. Sillaro. Memorie della Società Geologica Italiana 39, 187–214.

Bettelli, G., Vannucchi, P., 2002. 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 in press, PII No. S0191-8141(02)00026-3.

Bettelli, G., Capitani, M., Panini, F., 1994. The mesoscopic structures of a strongly deformed multilayered sequence: a hypothesis of the origin of the "block-in-matrix" fabric and the layer-parallel extension shown by the Ligurian dismembered formations of the Baganza Supergroup in the Reggio Emilia and Modena Apennines. 1st European congress on regional geological cartography and information systems—Bologna, June 13–16, 1994, Excursion guidebook, Post Congress Field Trip No. 3.

Bianconi, P., 1840. Storia naturale dei terreni ardenti, dei vulcani fangosi, delle sorgenti infiammabali, dei pozzi idroppirici e di altri fenomeni geologici oprati dal gas idrogeno e dell'origine di esso gas. Bologna, Marsigli, 164pp.

Boles, J.R., Landis, C.A., 1984. Jurassic sedimentary mélange and associated facies, Baja California, Mexico. Geological Society of America Bulletin 95, 513–521.

Bombicci, L., 1882. Il sollevamento dell'Appennino Bolognese per diretta azione della gravità e delle pressioni laterali. Rend. Sess. Accad. Sci. 1st Bolognese. Ser. 4 3, 105–114.

Borradaile, G.J., Bayly, M.B., Powell, C.McA. (Eds.), 1982. Atlas of Deformational and Metamorphic Rock Fabrics. Springer-Verlag, Berlin, 551pp.

Brown, K.M., Orange, D., 1993. Structural aspects of diapiric mélange emplacement: the Duck Creek diapir. Journal of Structural Geology 15, 831–847.

Byrne, T., 1984. Early deformation in mélange terranes of the Ghost Rocks Formation, Kodiak Islands, Alaska. Geological Society of America Special Paper 199, 21–51.

Chen, W.S., 1997. Mesoscopic structures developed in the Lichi mélange during the arc-continent collision in the Taiwan region. Journal of the Geological Society of China 40, 415–434.

Chester, F.M., Logan, J.M., 1987. Composite planar fabric of gouge from the Punchbowl Fault, California. Journal of Structural Geology 9, 621–634.

Clennell, B., Maltman, A., 1995. Microstructures in accreted sediments of the Cascadia margin. Proceedings of the Ocean Drilling Program, Scientific Results 146, 201–216.

Clennell, M.B., 1991. The origin and tectonic significance of mélanges in Sabah, East Malaysia. Journal of Southeast Asian Earth Sciences 6, 407–430.

Clennell, M.B., 1992. The mélanges of Sabah, Malaysia. Unpublished Ph.D. Thesis, University of London, 404pp.

Coli, M., Sani, F., 1990. Vein distribution in a thrust zone: a case history from the Northern Apennines, Italy. In: Knipe, R.J., Rutter, E.H. (Eds.), Deformation Mechanisms, Rheology and Tectonics. Geological Society Special Publication 54, pp. 475–482.

Conti, A., Sacchi, E., Chiarle, M., Martinelli, G., Zuppi, G.M., 2000. Geochemistry of the formation waters in the Po plain (Northern Italy): an overview. Applied Geochemistry 15, 51–65.

Cowan, D.S., Moore, J.C., Roeske, S.M., Lundberg, N., Lucas, S.E., 1984. Structural features at the deformation front of the Barbados Ridge complex, Deep Sea Drilling Project Leg 78A. In: Initial Reports of the Deep Sea Drilling Project, Washington, DC, Government Printing Office 78, pp. 535–548.

Coward, M.P., Dietrich, D., 1989. Alpine tectonics—an overview. In: Coward, M.P., Dietrich D., Park, R.G. (Eds.), Alpine Tectonics. Geological Society Special Publication 45, pp. 1–29.

El Chazi, O., Huvelin, P., 1981. Presence of an olistostrome in the volcano-sedimentary upper Viséan of Tanncherfi, eastern Morocco: simultaneity of resedimentation and volcanic activity. Comptes Rendus Hebdomadaires des Sciences de l'Academie des Sciences, section II 292, 91–96.

Elter, P., Trevisan, L., 1973. Olistostromes in the tectonic evolution of the Northern Apennines. In: De Jong, K.A., Sholten, R. (Eds.), Gravity and Tectonics, John Wiley and Sons, New York, pp. 175–188.

Enriquez-Reyes, M.D.P., Jones, M.E., 1991. On the nature of the scaly texture developed in mélange deposits. In: Roegiers, J.M., (Ed.), Rock Mechanics as a Multidisciplinary Science, Balkema, Rotterdam, pp. 713–722.

Fan, C.H., Allison, R.J., Jones, M.E., 1996. Weathering effects on the geotechnical properties of argillaceous sediments in tropical environments and their geomorphological implications. Earth Surface Processes and Landforms 21, 49–66.

Froldi, P., Lunardi, P., 1994. Geometric and dynamic properties of landslides in scaly clays in Northern Italy. In: Proceedings, International Association of Engineering Geology, 7th International Congress, Lisbon, pp. 1341–1350.

Froldi, P., Mantovani, S., Lunardi, P., Podesta, G., 1994. "Argille Scagliose" complex in northern Italy: the geotechnical characterisation. In: Proceedings, International Association of Engineering Geology, 7th International Congress, Lisbon, pp. 459–468.

Hamilton, W., 1979. Tectonics of the Indonesian Region. U.S. Geological Survey Professional Paper 1078, 355pp.

Harris, R.A., Sawyer, R.K., Audley-Charles, M.G., 1998. Collisional mélange development: geologic associations of active mélange-forming processes with exhumed mélange facies in the western Banda orogen, Indonesia. Tectonics 17, 458–479.

Horne, G.S., 1969. Early Ordovician chaotic deposits in the central volcanic belt of Northeastern Newfoundland. Geological Society of America Bulletin 80, 2451–2464.

Hsu, K.J., 1966. Franciscan rocks of the Santa Lucia range, California, and the Argille Scagliose of the Apennines of Italy; a comparison in style of deformation. Geological Society of America Special Paper 87, 210–211.

Kimura, G., Mukai, A., 1991. Underplated units in an accretionary complex: mélange of the Shimanto Belt of eastern Shikoku, Southwest Japan. Tectonics 10, 31–50.

Kiyokawa, S., 1992. Geology of the Idonappu Belt, Central Hokkaido, Japan—evolution of a Cretaceous accretionary complex. Tectonics 11, 1180–1206.

Labaume, P., Berty, C., Laurent, Ph., 1991. Syn-diagenetic evolution of shear structures in superficial nappes: an example from the Northern Apennines (NW Italy). Journal of Structural Geology 13, 385–398.

Labaume, P., Maltman, A.J., Bolton, A., Tessier, D., Ogawa, Y., Takizawa, S., 1997. Scaly fabrics in sheared clays from the décollement zone of the Barbados accretionary prism. Proceedings of the Ocean Drilling Program, Scientific Results 156, 59–77.

Larue, D.K., Hudleston, P.J., 1987. Foliated breccias in the active Portugese Bend landslide complex, California: bearing on mélange genesis. Journal of Structural Geology 95, 407–422.

Lash, G., 1989. Documentation and significance of progressive microfabric changes in Middle Ordovician trench mudstones. Geological Society of America Bulletin 101, 1268–1279.

Lash, G., 1990. Carbonization: an alternative mechanism of scaly foliation development in deformed mudstones. Clay Minerals Society, 27th Annual General Meeting, Program with Abstracts 27, 77.

Lundberg, N., Moore, J.C., 1986. Macroscopic structural features in Deep Sea Drilling Project cores from forearcs. GSA Memoir 166, 13–44.

Maltman, A.J., 1998. Deformation structures from the toes of active accretionary prisms. Journal of the Geological Society 155, 639–650.

Maltman, A. (Ed.), 1994. The Geological Deformation of Sediments. Chapman and Hall, 362pp.

Maltman, A.J., Byrne, T., Karig, D.E., Lallemant, S., Knipe, R., Prior, D., 1993. Deformation structures at Site 808, Nankai accretionary prism, Japan. Proceedings of the Ocean Drilling Program, Scientific Results 131, 123–133.

Marroni, M., Treves, B., 1998. Hidden terranes in the Northern Apennines, Italy: a record of Late Cretaceous–Oligocene transpressional tectonics. Journal of Geology 106, 149–162.

Menzies, J., Maltman, A.J., 1992. Microstructures in diamictons—evidence of subglacial bed conditions. Geomorphology 6, 27–40.

Merla, G., 1952. Geologia dell'Appennino Settentrionale. Bollettino della Società Geologica Italiana 70, 95–382.

Minissale, A., Magro, G., Martinelli, G., Vaselli, O., Tassi, G.F., 2000. Fluid geochemical transect in the Northern Apennines (central-northern Italy): fluid genesis and migration and tectonic implications. Tectonophysics 319, 199–222.

Moore, G.G., Taira, A., Klaus. A. and the Leg 190 Shipboard Scientific Party, 2001. Nankai Accretionary prism, Leg 190 of the cruises of the Drilling Vessel JOIDES Resolution, Sites 1173–1178. Initial Reports of the Ocean Drilling Program 190, College Station, Texas.

Moore, J.C., Byrne, T., 1987. Thickening of fault zones: a mechanism of mélange formation in accreting sediments. Geology 15, 1040–1043.

Page, B.M., 1963. Gravity tectonics near Passo della Cisa, northern Apennines, Italy. Geological Society of America Bulletin 74, 655–671.

Page, B.M., 1978. Franciscan mélanges compared with olistostromes of Taiwan and Italy. Tectonophysics 47, 223–246.

Pettinga, J.A., 1987. The Waipoapoa landslide: a complex deep-seated block slide in Tertiary weak-rock flysch. New Zealand Journal of Geology and Geophysics 30, 401–414.

Pini, G.A., 1999. Tectonosomes and olistostromes in the argille scagliose of the Northern Apennines, Italy. Geological Society of America Special Paper 335, 70pp.

Prior, D.J., Behrmann, J.H., 1990a. Thrust-related mudstone fabrics from the Barbados forearc: a backscattered scanning electron microscope study. Journal of Geophysical Research 95, 9055–9067.

Prior, D.J., Behrmann, J.H., 1990b. Backscattered SEM imagery of fine-grained sediments from Site 671-Preliminary results. In: Moore, J.C., Mascle, A., et al. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results 110, pp. 245–255.

Pubellier, M., Rangin, C., Cadet, J.-P., Tjashuri, I., Butterlin, J., Muller, C., 1992. Nias Island, a polyphase tectonic belt along the inner edge of the Sunda Trench Mentawi archipelago, Indonesia. Comptes rendus—Academie de Sciences, Serie II 315, 1019–1026.

Rangin, C., Bellon, H., Bernard, F., Letouzey, J., Muller, C., Sanuddin, T., 1990. Neogene arc-continent collision in Sabah, northern Borneo, Malaysia. Tectonophysics 183, 305–319.

Rutter, E.H., Maddock, R.H., Hall, S.H., White, S.H., 1986. Comparative microstructures of natural and experimentally produced clay-bearing fault gouges. Paleophysics 124, 3–30.

Sample, J.C., Moore, J.C., 1987. Structural style and kinematics of an underplated slate belt, Kodiak and adjacent islands, Alaska. Geological Society of America Bulletin 99, 7–20.

Suslikov, V.N., 1989. Glacial topography and deposits in the Vanch River valley (Pamir). Geomorphology 3, 95–100.

Sylvester, A.G., Smith, R.R., 1976. Tectonic transpression and basement-controlled deformation in the San Andreas fault zone, Salton Trough, California. American Association of Petroleum Geologists 60, 2081–2102.

Sylvester, A.G., Smith, R.R., 1987. Structure section in Painted Canyon, Mecca Hills, southern California. Geological Society of America Centennial Field Guide, Cordilleran Section, 103–108.

Treves, B., 1984. Orogenic belts as accretionary prisms: the example of the Northern Apennines. Ofioliti 9/3, 577–618.

Vannucchi, P., Maltman, A.J., 2000. Insights into shallow-level processes of mountain building from the Northern Apennines, Italy. Journal of the Geological Society, London 157, 105–120.

Vannucchi, P., Tobin, H., 2000. Deformation structures and implications for fluid flow at Costa Rica convergent margin, ODP Sites 1040 and 1043. Journal of Structural Geology 22, 1087–1103.

Waldron, J.W.F., Stockmal, G.S., Corney, R.E., Stenzel, S.R., 1993. Basin development and inversion at the Appalachian structural front, Port-au-Prince Peninsula, Western Newfoundland Appalachians. Canadian Journal of Earth Sciences 30, 1759–1772.

Wilson, C.J.L., Will, T.M., 1990. Slikenside lineations due to ductile processes. In: Knipe, R.J., Rutter, E.H. (Eds.), Deformation Mechanisms, Rheology and Tectonics. Geological Society Special Publication 54, pp. 455–460.