Sedimentology (1998) **45**, 71–89

Interstratal dewatering origin for polygonal patterns of sand-filled cracks: a case study from late Proterozoic metasediments of Islay, Scotland

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ABSTRACT

Sand-filled cracks from the Lower Fine-grained Quartzite of Dalradian (late Proterozoic) age on the Island of Islay, western Scotland, may be divided into two main types, both of which form orthogonal and non-orthogonal closed patterns on bedding surfaces. Type 1 cracks are short and lenticular in cross-section, contain sand which had been injected *downwards*, and are found on the bottoms of cross-laminated sandstone beds. Type 2 cracks cut several beds and preserve evidence of *upward* flow of water-saturated sand. Both types of crack developed through the interstratal intrusion of water-saturated sand into shrinkage cracks in mud or muddy sand, not, as previously thought, as a result of sub-aerial desiccation, or sub-aqueous cracking of the sediment surface (synaeresis). These cracks likely resulted from layer-parallel contraction caused by compaction of mudstone layers during burial. Seismic shock may have provided the trigger for the preferential development of polygonal crack patterns in these layers instead of the more usual small-scale dewatering structures. From a detailed comparison with published descriptions of filled cracks from a number of different geological environments, it is concluded that interstratal cracking is a mechanism which rivals sub-aerial desiccation in importance, and is more common in the geological record than is currently realized.

INTRODUCTION

The palaeoenvironmental significance of polygonal patterns seen on the surfaces of sedimentary beds is difficult to interpret and, in the past, such patterns have been too readily interpreted as indicators of either sub-aerial exposure (desiccation) or shrinkage at the sediment–water interface (synaeresis). Important inferences have been drawn from the occurrence of such structures, which 'hold many unexploited clues to depositional patterns in environments subject to repeated submergence and emergence' (Allen, 1993; p. 421), but their external morphology, particularly when only seen in plan view, is an inadequate basis on which to decide their origin.

The brief summary given below of published interpretations of polygonal crack patterns seen in relatively undeformed Dalradian sedimentary rocks from the Island of Islay and adjoining areas of SW Scotland (Fig. 1; Table 1), provides an illuminating case history, and one of these occurrences is analysed in detail in this paper.

Small filled cracks which appear to penetrate down from the bases of sandstone and carbonate beds have been described from several localities in the Islay Subgroup of the Neoproterozoic Dalradian rocks on Islay (Fig. 1). They are common in the Bonahaven Dolomite Formation and because they generally appear sinuous in cross-section, were originally interpreted as 'worm casts' (i.e. Wilkinson, 1907). However, those which form polygonal patterns on the bedding planes were interpreted as 'sun cracks' resulting from sub-aerial exposure (Wilkinson, 1907; Green, 1924; Peach & Horne, 1930). Subsequent workers favoured a sub-aqueous, 'synaeresis', origin for these cracks (Spencer & Spencer, 1972), although Fairchild (1980) considered that *both* desiccation and synaeresis had taken place.

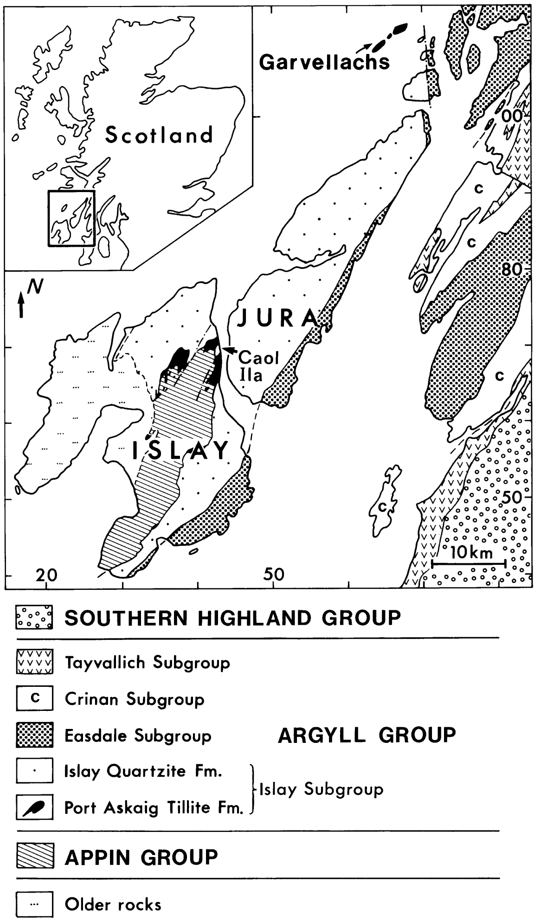

Fig. 1. Location of the mudcrack locality at Caol Ila on the Island of Islay in the Western Highlands of Scotland and its stratigraphical setting. Further details of the stratigraphy are given in Table 1.

Borradaile & Johnson (1973; p. 252) rejected a tectonic de-watering origin for the dykelets, and concluded that they had 'formed by a passive infilling of cracks in contracting layers'.

Table 1. Occurrence of filled cracks in the Dalradian sequence of the Islay–Jura area.

Southern Highland Group
Argyll Group
Tayvallich Subgroup
Crinan Subgroup
Easdale Subgroup
Islay Subgroup
*Islay Quartzite Formation
*Bonahaven Dolomite Formation
*Lower Fine-grained Quartzite
*Port Askaig Tillite Formation
Appin Group

* Polygonal sets of filled cracks

By comparison, polygonal patterns from rocks of similar age (the Marble Hill Dolomitic Limestone) from Ballymore, Co Donegal, Ireland, were first interpreted by McCall (1954) as 'sun cracks', but Wolfe (1969) concluded that they had been made by burrowing organisms. Re-examination of these structures by Bliss *et al.* (1978) supported the original interpretation, and concluded that the patterns had likely originated as desiccation structures.

Small-scale polygonal patterns (< 10 cm across) are likewise not uncommon on bedding surfaces in the underlying Lower Fine-grained Quartzite (Table 1) on Islay and have been interpreted as 'sun cracks' (Knill, 1963) or mud cracks (Klein, 1970; Fairchild, 1991) which had formed as a result of desiccation during sub-aerial exposure, and been subsequently infilled with sand. Knill (1963) also considered a frost-wedging origin for these structures. Kessler & Gollop (1988), working on the well-studied section north of the Caol Ila Distillery, concluded that the polygonal patterns on the bedding planes found there had resulted from the sub-aerial exposure and rapid desiccation of algal (stromatolite) mats, with the cracks being infilled from below by unlithified silty sediment. Similar polygonal patterns formed by sandstone dykelets occur in the stratigraphically higher Jura Quartzite on the neighbouring island of Jura (Fig. 1), and were interpreted as synaeresis cracks by Anderton (1971, 1976).

The origin of metre-scale polygonal patterns in the underlying tillites of the Port Askaig Tillite Formation on Islay and on the Garvellachs (Fig. 1; Table 1) has been the subject of a strenuous debate between those who support a sub-aerial periglacial origin (i.e. Spencer, 1971a, 1985) and those who infer that they formed as a result of sub-aqueous gravitational loading promoted by seismic shock (i.e. Eyles & Clark, 1985). Johnson (1993) has recently described similar structures in the stratigraphically equivalent Glencolumbkille Boulder Bed in Ireland, and concluded that they formed as ice-wedge casts during sub-aerial exposure.

Thus many possible origins ranging from organic, to desiccation, to synaeresis, to frost-wedging, and gravitational loading, have been proposed for the polygonal patterns of filled cracks seen in sedimentary rocks of lower Dalradian age in Scotland and Ireland. This account focuses on the morphology and origin of such polygonal patterns in the Caol Ila section of the Lower Fine-grained Quartzite on Islay, and some of the other occurrences mentioned above are then discussed in the light of these findings.

The Islay filled cracks

The polygonal structures described here occur on Leac Thiolastaraidh 370 m N of the pier at the Caol Ila Distillery near Portaskaig on the east coast of Islay (Fig. 1)(NR 42977037). They are found within the Lower Fine-grained Quartzite described by Klein (1970), who has summarized the regional stratigraphical setting and made a detailed sedimentological study of the formation. Kessler & Gollop (1988) published a palaeoenvironmental study of part of the Quartzite based on a 14 m logged section at this locality, and Fairchild (1991; their Fig. 17) provided a generalized sedimentary log of both these rocks, and of the sequence in which they occur. The area lies on the western limb of the D1 Islay Anticline (Bailey, 1917), and the rocks were only weakly deformed during the Grampian orogeny.

There has been considerable debate over the stratigraphical affinity of the Quartzite (for review, see Klein, 1971), and disagreement over the position of its boundary with the Dolomitic Formation (Spencer, 1971b): it can be considered either as a thin 'formation' lying between the separate Port Askaig and Bonahaven formations (Bailey, 1917); be included in member 5 of the Port Askaig Tillite (Spencer, 1971a; Spencer & Spencer, 1972; Kessler & Gollop, 1988); or be considered as unit 4, member 1, of the Bonahaven Dolomitic Formation (Fairchild, 1991). The stratigraphical affinity of the Quartzite is not of concern here but, as it is a distinctive lithostratigraphic unit, I believe that there is some merit in retaining the original informal name, following Bailey (1917).

The Lower Fine-grained Quartzite consists of quartzose sandstones which show wavy bedding surfaces (amplitude to 50 cm) and occur as cross-stratified units (Klein, 1970). They preserve straight-crested ripple marks, which have mudstone drapes and commonly occur in intersecting sets. The quartzose rocks are accompanied by units of thinly bedded dark grey mudstone and siltstone with lenticular bedding which show cross-lamination, and contain ubiquitous 'mudcracks' (Klein, 1970). The part of the formation studied by the author on Leac Thiolastaraidh includes beds of feldspathic sandstone up to 30 cm thick which commonly have lobate erosional bases (?flute marks), preserve interfering sets of ripple marks on their tops, show small cm-scale slump folds with eroded tops, and are cut by channel structures up to 70 cm across, which may be gutter casts but are not seen in three dimensions. Contrary to previous reports that mudflake breccias are absent from the sequence (Klein, 1971; Spencer, 1971a), at this locality orange-brown weathering sandstone horizons a few cm thick, are commonly seen to be crowded with mud flakes to 4 cm long which, from their shape and organization, are original depositional features and not due to subsequent sand injection or similar processes. Most sandstone beds contain numerous sets of cross-laminae in sets with opposing transport directions, and some show graded bedding at the base. Polygonal patterns formed by sandstone dykelets up to 1 cm wide are commonly seen on the bedding surfaces.

Klein (1970, 1971) and Spencer (1971a) agreed that the Lower Fine-grained Quartzite was deposited in an intertidal to shallow sub-tidal environment. From a more detailed sedimentological analysis, Kessler & Gollop (1988) refined this interpretation and concluded that the Quartzite represents the transition from a storm-dominated inner-shelf-shoreface, to an intertidal depositional setting in which the sediments have been subject to sub-aerial exposure. Fairchild (1991) interpreted the Quartzite sequence as being washover deposits which were laid down on the lee side of a barrier island.

The polygonal crack structures in the Lower Fine-grained Quartzite were first examined by the author in 1968, during collection of samples for Rb-Sr analysis (Leggo *et al.*, 1969). Their internal organization was studied initially from acetate peels (examples illustrated below), but it was only during a more recent visit that further samples, critical to an understanding of their origin, could be collected. Before describing these structures, and to provide a basis for a later discussion on their origin, the general classification of filled cracks in sediments and their genesis is briefly reviewed.

ORIGIN OF FILLED CRACKS IN SEDIMENT

Families of sediment-filled shrinkage cracks in sediment which give rise to linked polygon-like patterns on the bedding planes, may form in argillaceous sediments in one of three main ways:

1 Sub-aerial desiccation;

2 Sub-aqueous cracking at the water/sediment interface;

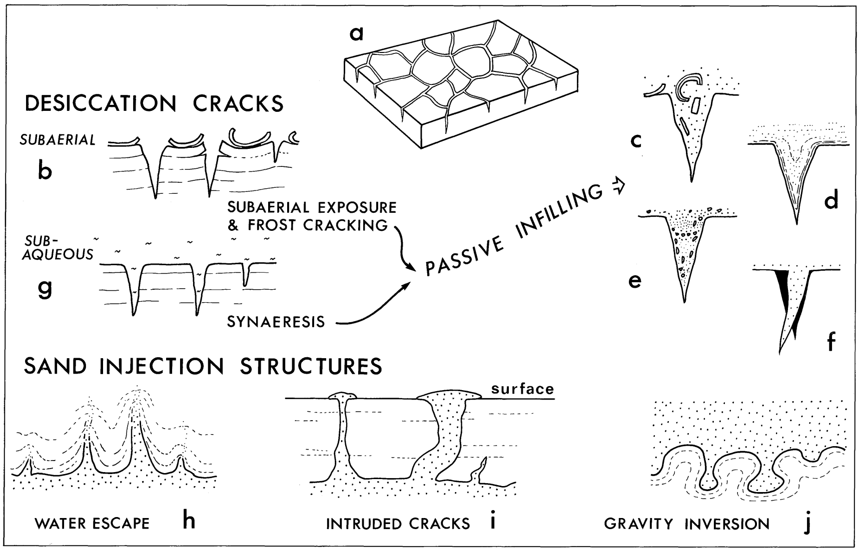

Fig. 2. Profile sections showing the main features of a variety of naturally occurring unfilled and filled cracks in sediment. See text for further explanation.

3 Interstratal cracking within the sedimentary pile due to compaction, sediment injection, water-release, etc.

The main features considered to be diagnostic of these different types of filled crack are briefly described and discussed.

Sub-aerial cracks

These are thought to be the most common type of sediment-filled crack preserved in rocks, and their mode of origin has been confirmed by detailed field observation of modern examples on estuarine mudflats (Allen, 1987), by laboratory experiments (Corte & Higashi, 1964), and by theoretical studies (Lachenbruch, 1962). Sets of desiccation cracks typically show the following features:

(a) The cracks commonly form complete, linked patterns on the bedding surfaces and generally meet at right angles (orthogonal cracks; Fig. 2a).

(b) They have a tapered, sometimes stepped, V-shaped profile (Fig. 2b).

(c) Mud curls (either upward- and downward-curved) are commonly found above the pillars between the cracks, either in place or preserved as clasts in the overlying sediment or in the crack infills (Fig. 2b & c).

(d) The cracks have been passively filled with sand or other sediment (Fig. 2d & e), and sometimes preserve evidence of repeated episodes of desiccation and infilling (Fig. 2f).

(e) Erosion may modify the crack profile before deposition of the overlying bed.

As well as cracks which are passively infilled with sediment, situations have been described where the cracked surface layer is *intruded* by the underlying water-saturated material, which then flows out on to the surface (Fig. 2i). Oomkens (1966) reported sand dykes from Recent desert sands which had formed by the intrusion of wet sand into polygonal desiccation cracks in an overlying clay layer forming the desert floor. He also referred to an analogous example from the Lower Permian rocks of western Germany in which there is evidence of an upward flow of sand within a dyke which was emplaced into cracked shale. Extrusion of wet mud into the polygonal cracks formed in an overlying mud crust was described by Bradley (1933) and Wells & Jah (1982). Freezing of water contained in sediments also causes layer-parallel contraction resulting in the formation of a great variety of structures such as frost cracks, desiccation polygons etc., but this class of structures is not considered further, as they are morphologically distinct from the structures described here.

All of these processes give rise to structures whose origin should be clearly recognizable, provided that the rocks in which they are preserved are well exposed and the cracks can be examined in three dimensions.

Sub-aqueous shrinkage cracks

Laboratory experiments have demonstrated that sub-aqueous, or synaeresis, cracks form as a result of shrinkage of rapidly floccated clay (White, 1961), or changes in salinity which causes shrinkage in montmorillonitic clays (Burst, 1965). However, it has proved difficult to recognize these structures with certainty in rocks (cf.

Picard, 1966), and the criteria which have been proposed for their recognition are of doubtful use, as pointed out by Pettijohn (1957; p. 123), White (1961; p. 556), and Allen (1982; p. 553).

Possible criteria include the following:

(a) They commonly occur as sets of aligned, unconnected individuals and seldom form closed patterns (Fig. 2g).

(b) The cracks have discontinuous, lenticular, and commonly sub-circular, profiles.

(c) The cracks occur in mudrocks and are filled from above.

Plummer & Gostin (1981) concluded that many of the examples described as synaeresis cracks are 'substratal' in origin and formed during simultaneous loading and dewatering of the sediment, and Astin & Rogers (1991) have more recently concluded that, if they exist at all, synaeresis cracks are extremely rare in rocks. Astin & Rogers re-examined so-called synaeresis cracks at one of only two classic localities for these structures, in the Devonian rocks of the Orcadian basin (Donovan & Foster, 1972), and concluded that most of them were desiccation cracks localized by the presence of gypsum crystals and filled by wind-transported sand grains.

No unambiguous examples of synaeresis cracks have been documented from natural occurrences.

Cracks of interstratal origin

This type of cracking is not thought to be common in the geological record and the main causes which have been suggested for the formation of this type of crack include the following.

Compaction

Twenhofel (1932), Richter (1941), Rich (1951), Van Houten (1964), and Glaessner (1969) have invoked compaction as a crack-forming mechanism, and expulsion of pore water during compaction is invoked by Kidder (1990) to explain one category of spindle-shaped cracks from Middle Proterozoic mudstones in Montana, USA. However, there must be some other factor(s) involved or cracks of this type would be universally common.

Synaeresis

Several authors have suggested that this can occur substratally through the action of saline pore fluids (Young, 1969; Plummer & Gostin, 1981), but confirmation of this is bedevilled by the problem of identifying synaeresis cracks. If they do exist naturally, these cracks could be filled from either above or below.

Sediment injection

Examples of this process likely occur as a result of gravity inversion (Fig. 2j). Morrow (1972) reports the injection of one type of lime mud into an overlying partly lithified layer of mud of similar composition, to produce a polygonal injection pattern on the bedding surface in the host. This effect was modelled experimentally by Butrym *et al.* (1964) but natural examples are rare. Small-scale mud diapirs have been reported recently by Cave & Rushton (1995) but as their material is from a borehole core the three-dimensional pattern made by the diapirs is not known.

Water-release during sedimentation and/or diagenesis

Many workers including Daley (1971), Lowe (1975), Lowe & Lo Piccolo (1974), Plint (1983), and Johnson (1986), have described structures such as cusps, dish structures, pillars, pipes and clastic dykes resulting from this process (Fig. 2h) but neither polygonal nor closed crack patterns have been reported in association with this phenomenon.

Syn-sedimentary deformation

Operation of this mechanism was very clearly demonstrated by Cowan & James (1992), who provided a well-documented account of 'diastasis cracks' from Upper Cambrian limestones and dolomites from western Newfoundland. The structures show a variety of crack profiles from straight to tapered and bulging, with some hairline fractures, which are filled with non-stratified sedimentary fragments. They are thought to have originated as shear-tensile fractures of stiff mud layers intercalated with loose carbonate sand, at or just beneath the sediment–water interface. They form patterns of isolated or interconnected polygonal cracks and were previously interpreted as desiccation cracks. There is no evidence of fluid flow within the crack infills but some of the small-scale structures indicate that local liquifaction of sand has occurred.

Summary

The following features, when taken in conjunction, may indicate the presence of interstratal cracks:

(a) Randomly orientated to aligned cracks are developed, which are spindle-shaped in cross-section.

(b) The cracks form closed polygonal (generally orthogonal) patterns on the bedding surface.

(c) Individual cracks may cross several beds of different lithology, including non-argillaceous layers which would not form shrinkage cracks.

(d) Cracks are 'blind', having been sourced from a bed beneath (or possibly above) the cracked horizon, or show diffuse upward-pointing terminations.

(e) In some cases, material flowing into the cracks can be shown to have moved upward towards the sediment/water interface, but not to have reached it.

No single criterion is diagnostic but there is clear evidence for the existence of several types of interstratal cracks and they could be more common than is realised.

It is against the above background that the origin of the Islay mudcracks is assessed, based on a detailed examination of the vertical profiles of individual cracks.

MORPHOLOGY OF THE ISLAY FILLED CRACKS

The morphology of sand-filled cracks (which, for brevity, will be referred to subsequently in this section as 'cracks') seen at Leac Thiolastaraidh on the Island of Islay (NR 42977037) is now described. Both orthogonal and non-orthogonal linked patterns (terminology after Allen, 1982) of cracks occur on bedding planes in a sequence of interbedded fine-grained, cross-laminated, feldspathic sandstones and mudstones.

The cracks almost always occur on rippled or slightly undulatory bedding surfaces, the undulations varying in amplitude from 3 to 15 cm. The cracks vary from < 1 mm to over 1 cm in width on the exposed surface, form a variety of different patterns, and many of them show slight irregularities or are curved.

The polygons in the non-orthogonal sets are 3–5 sided and up to 2–3 cm across (Fig. 3). Orthogonal patterns (in which the majority of the cracks meet at right angles) are the more common and vary from cm-scale polygons (Fig. 4b) to the larger scale structures in which there is a basic

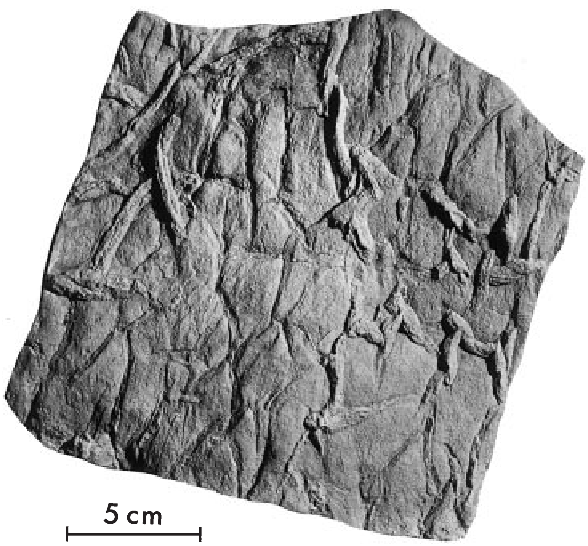

Fig. 3. A non-orthogonal pattern of sand-filled cracks seen in relief on the base of a sandstone bed from Leac Thiolastaraidh on Islay (NR 42977037).

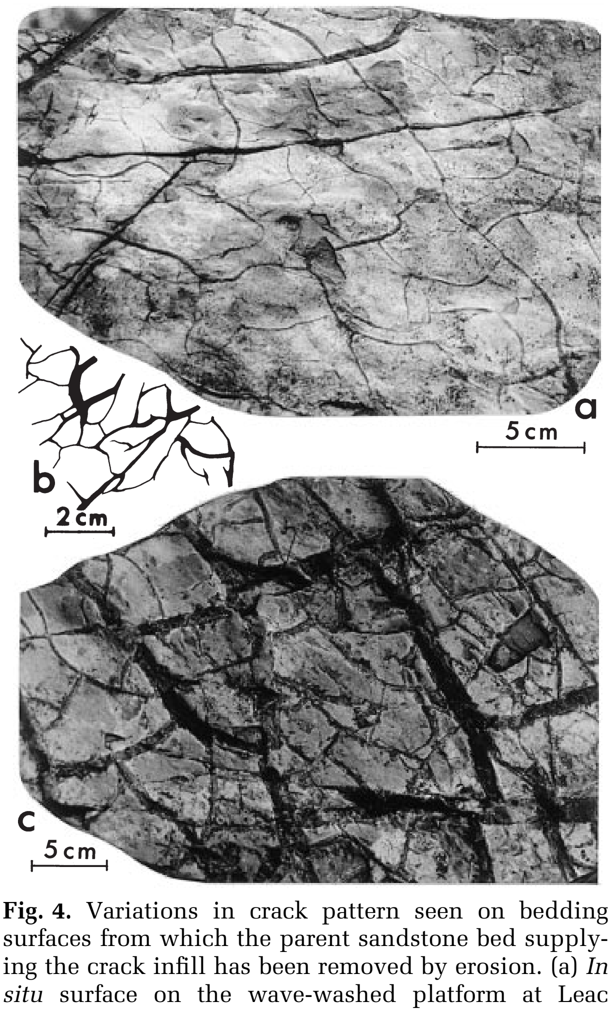

Fig. 4. Variations in crack pattern seen on bedding surfaces from which the parent sandstone bed supplying the crack infill has been removed by erosion. (a) *In situ* surface on the wave-washed platform at Leac Thiolastaraidh on Islay (NR 42977037); (b) tracing from a hand-specimen from the above locality; (c) surface of a large displaced block found just south of Leac Thiolastaraidh.

framework of cracks > 1 cm wide which divide the surface into crude polygonal shapes, within which sets of thinner cracks define a second-order pattern (Fig. 4c). Some surfaces show the development of linked patterns of *curved* cracks (Fig. 4a).

All types of crack pattern may be very slightly distorted, with the polygonal pattern being almost imperceptibly shortened normal to a fine striation lineation (?bedding-cleavage intersection) in some specimens (i.e. Fig. 5a). Likewise, a very fine slaty cleavage defined in thin section by minute flakes of white mica (20–40 μm) is slightly deflected around the sand bodies in some samples, and local pressure-solution effects are revealed by a darkening of the cleaved mudrock, but apart from these effects the original features are very clearly preserved.

Although the polygonal crack patterns can be clearly seen on the bases, and sometimes tops, of thick cross-bedded sandstone units, the continuation of the individual cracks through the sandstone beds is difficult to see, either in the field or in hand specimen, as the crack infill is very similar in lithology to the host rock. Large orientated specimens were therefore collected and sawn into 5–10 cm blocks. Using a thin diamond wheel, some of these were then sawn into serial 2 cm-thick slices, the surfaces of which were finely ground and used for the preparation of acetate peels. For the latter, the samples were etched for about 15 s in 40% HF and methyl-ethyl-ketone was used instead of acetone as a solvent to soften the acetate film when presenting it to the prepared rock surface, as it is less volatile than acetone and makes manipulation easier. The peels were left for 24 h before removing them from the specimen so as to produce optically flat replicas from which photographic negatives could be made. Some samples were subsequently sawn into serial mm-thick slices to examine the continuity of cracks across the specimen. Most attention has been paid to the structures developed in alternating (*c.* 0·5 cm) mudstone and siltstone bands in which the crack morphology and internal structure can be clearly seen on the cut surface and in thin section.

Study of the polished faces of samples, and of thin sections and acetate peels, shows that the

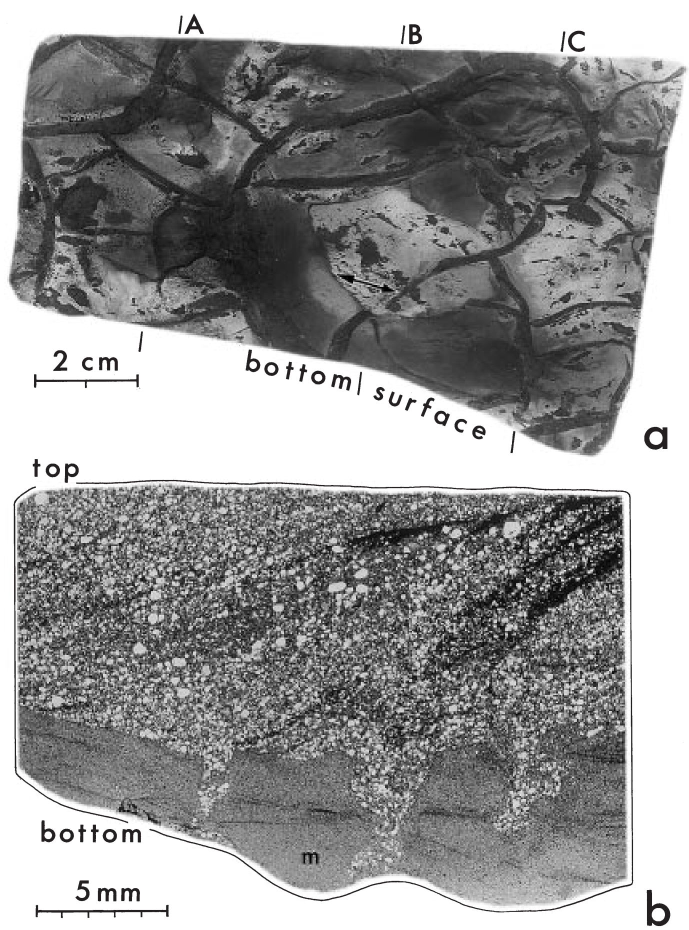

Fig. 5. Type 1 cracks. (a) View of the bottom of a sandstone bed from Leac Thiolastaraidh which was subsequently sliced along lines A, B & C. The double-headed arrow marks the orientation of a faint structural lineation seen on the surface of the specimen. (b) Positive print of a thin section prepared from the middle portion of the slice taken along line C showing coarse sandstone infilling cracks in siltstone. The curved line at the bottom of the section shows the natural relief on the surface of the mudstone (**m**).

polygonal patterns are the surface expression of a network of thin sand-filled cracks which are mainly at right angles to bedding. It is particularly noticeable on cut surfaces of samples that where the mudstone is cut by a filled crack, or drawn out into thin processes enclosed in the crack-fill, it develops a thin bleached-looking halo at the interface. A similar feature has been reported by Cave & Rushton (1995) from small-scale mud diapirs which develop a phosphate-rich selvage around their margins during early diagenesis, but in that case the selvage is *dark*-coloured.

The cracks can be divided into two main types. *Type 1 cracks* originate from the bases of sandstone beds, and are seen as a series of intersecting ridges on these surfaces (Fig. 3). They penetrate for less than 1 cm down from the base of the parent sandstone and where the latter has been eroded or removed, the cracks appear as flat, or slightly recessed, dark-looking ribs cutting the underlying pale-weathering mudstone layer (Figs 4–7). *Type 2 cracks* cut several mudstone and siltstone layers, and do not have a clearly defined source for their sandstone infill (Figs 8–10).

The main features of these cracks are as follows:

Type 1

The sand-filled cracks are a few mm to 1 cm wide and give rise to both orthogonal and non-orthogonal patterns on the bases of sandstone beds (Figs 3–5). They form short, fat cracks which are ovoid or lenticular in vertical section, and which, although they may be over 1 cm wide in plan view, only penetrate for 0·5–1·0 cm beneath the surface. Their morphology is described with reference to three specific examples, all from Leac Thiolastaraidh.

Example A. An orthogonal crack pattern (Fig. 5a) is seen on the base of a 2·2 cm thick feldspathic sandstone bed which has ripple cross-laminae up to 1 cm thick at the base, and parallel lamination at the top. Most of the cracks seen in plan view on the base (Fig. 5a) are sections through fingers of sand which project down from the sandstone layer and intrude the mudstone beneath it (Fig. 5b). Narrow zones of disturbance are seen above the sand-filled cracks in Fig. 5b, especially the central one, and locally destroy the cross-lamination. These cracks do not continue upwards for more than 7 mm but some of the thicker cracks found elsewhere in the same specimen link to narrow zones of disturbed bedding which pass upwards through the complete sandstone unit.

Example B. The curved cracks making up the orthogonal pattern in Fig. 4a are similar in cross-section to those in example A, except that here the depth of the specimen permits structures in the rocks *beneath* the crack terminations to be studied. The sand-filled cracks vary in profile from elongate V-shapes to bulbous protrusions, and are sometimes linked by thin sill-like sand bodies (Fig. 6).

In thin-section, the filled cracks are seen to cut bedding-parallel laminations in siltstone picked out by compositional variations, and by aligned detrital white micas and elongate opaque grains. The fine sand infill consists of a structureless aggregate of grains of quartz, minor feldspar and tourmaline, and rare detrital white micas, in the same proportions and with the same grain size as those in the overlying sandstone. Where the contact of the crack with the base of the sandstone

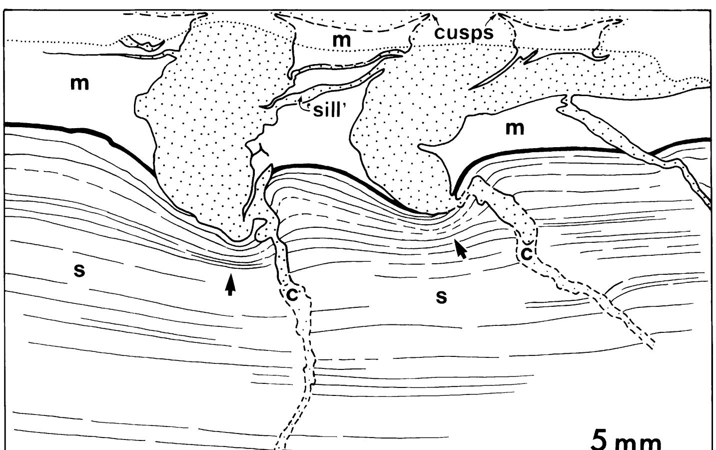

Fig. 6. Type 1 cracks. Tracing made from a thin-section print showing a bedding-normal section through some of the cracks illustrated in Fig. 4a. The sand infill is shown stippled, but below the point **c** in each of the main cracks, the crack passes into a conduit marked by a narrow zone of bedding disturbance rather than by introduced clastic grains. The heavy line is drawn to emphasise the lower boundary of the mudstone unit (**m**; shown blank) against the underlying laminated siltstone (**s**). The fine dotted line marks the top of the specimen; detail above this was obtained from adjoining samples. The two arrows highlight areas affected by differential compaction.

bed is seen, narrow upward-pointing processes, or cusps, of mudstone penetrate the sandstone much in the manner of flame structures associated with load casts. This feature, which is preserved in other sections through the same suite of cracks, is shown diagrammatically in the upper part of Fig. 6.

There has likely been some modification of the original relationship of the infilled crack to the host rock by compaction, for example in the bending and thinning of laminae in the country rock immediately adjacent to, and around the tips of the filled cracks (arrowed on Fig. 6), and by later deformation.

The most intriguing feature of these filled cracks are long, narrow conduits up to 1 mm thick which extend down from near the tip of the filled cracks, into the underlying bed. They are seen as subtly defined zones ('c' on Fig. 6) in which the bedding fabric in the host rock is disturbed, and sometimes offset, until at distances of several times the length of the filled crack they become diffuse and disappear. All crack infills show this feature in some form.

Example C. A typical 'desiccation crack' pattern is seen on the top surface of a large loose block found south of the headland of Leac Thiolastaraidh; an hierarchical ordering of different generations of cracks (Fig. 4a,b & c)(see Allen, 1987; their Fig. 3) is particularly noticeable in this specimen. The cracks occur on the top (stratigraphical) surface of a thick homogeneous sandstone bed with parallel laminations which is capped by a 1 cm-thick unit which contains layers of mudstone up to 3 mm thick (Fig. 7). All of the cracks, even those which are over 1 cm across where they emerge from the top surface, can be seen on vertical cut faces to terminate within 2–3 cm of that surface (Fig. 7b), and some (X,Y) are linked laterally by sill-like bodies of sand. They cut the bedding laminations in the host rock, which are depressed beneath their tips (Fig. 7, Y). Close examination shows that the cracks continue as conduits a few hundreds of μm wide that pass into, and merge with, the laminated siltstone beds below. Some of the wider filled-veins (Fig. 7, Z) have a 'brecciated' internal structure and consist of irregular-sided fissures filled with structureless sand containing angular mudstone chips, and irregularly shaped patches of fine-grained sandstone.

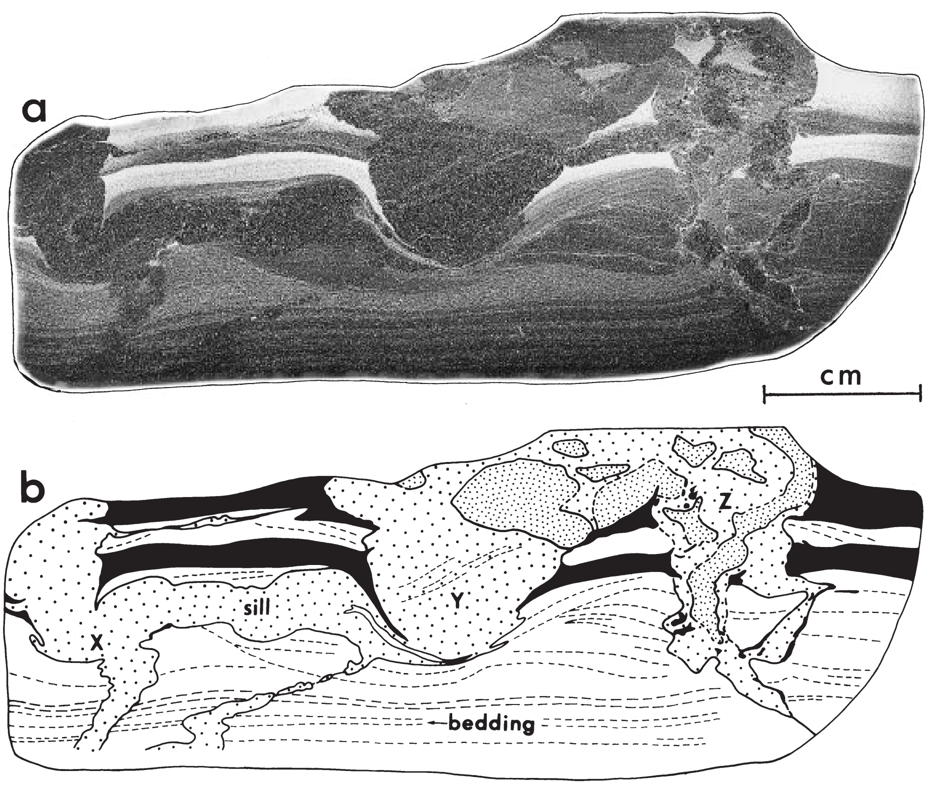

Fig. 7. Type 1 cracks. Thin-section print(a) and corresponding tracing (b). Fine to very fine sandstone (coarse stipple) infilling cracks (X-Z) in interbedded mudstone (solid black) and coarse siltstone (blank, with bedding traces). Patches of structureless siltstone in cracks Y and Z are shown by a fine stipple.

Type 2

These sand-filled cracks are up to 1 cm wide and form well-defined non-orthogonal to orthogonal patterns on both the tops and bottoms of beds. In most instances no source bed for the crack infill is found, and in thin section the cracks can be traced vertically for many centimetres through successive sandstone, siltstone and mudstone layers, and have the same texture regardless of host rock.

Example A. The bottom surface of a 1·8–2·0 cm-thick sandstone bed has a distinctive pattern of non-orthogonal cracks, and the top surface shows that only two cracks pass through the whole specimen (Fig. 8).

Acetate peels have been made of a number of parallel, bedding-normal surfaces which show that the filled cracks within this specimen make relatively wide bulbous shapes within the mudstone layers, but are narrow and sinuous in the adjoining sandstone or siltstone. The peels shown in Fig. 9 illustrate the main features of these filled cracks and show how a single crack (X-Y on Figs 8 & 9) changes laterally in morphology over a distance of 5·9 cm. A notable feature of sections a–c (Fig. 9) is the prominent mudstone chip (likely sections through a single elongated raft of mudstone in three dimensions) which has been detached from the surface of the mudstone at the point where the crack passes from mud to sand ('z', Fig. 9a–c). Delicate cuspate processes (for example, 'c' in Fig. 9b & c) emanate from some of the corners of the chips, and from the edges of the breached mudstone layer which gave rise to them.

The major sand-filled cracks narrow to less than 1 mm where they pass through the overlying sandstone/siltstone layers, and become diffuse with gradational margins against the host rock (Fig. 9). They can only be recognized by their lighter colour, uniform grain size and homogeneous texture, in contrast to the finely laminated, varicoloured, graded and cross-laminated sandstone beds which they cut. They contain some angular shards of mudstone, and in one example (Fig. 9d) a smeared-out layer of mudstone is seen along one side of the crack, partially connected with the underlying mudstone. In some examples, quartz-rich sandstone of uniform grain size marks the main flow paths through both sandstone and mudstone, as shown by the coarser grained stippling on the right-hand side of the main crack in Fig. 9b & d.

Example B. Several blocks about 10 cm thick, consisting of alternating 1–2 cm layers of yellowish feldspathic cross-laminated sandstone, siltstone, and homogeneous mudrock, have been serially slabbed and polished. Bedding surfaces at the top and bottom of the specimens are highly irregular in profile and show fine polygonal networks of sandstone ribs which represent filled cracks.

A prominent feature of the polished faces, but one not readily seen on the naturally weathered sides of the blocks, is the presence of irregular sandstone-filled veinlets which contain angular fragments of mudrock, and can be traced normal to bedding across the entire block in each case. In the mudrock layers the cracks are seen in vertical section to form a series of highly irregular, interlinked bodies which reach several cm across, but which become generally narrower and more focused where they cross the sandstone beds.

ORIGIN OF THE ISLAY FILLED CRACKS

Although they may have a common origin, the two types of crack are first discussed separately as they show significant differences in morphology.

Type 1

The following features of type 1 cracks (Fig. 10a) require explanation (not all of them formed at the time of crack initiation: some result from subsequent differential compaction):

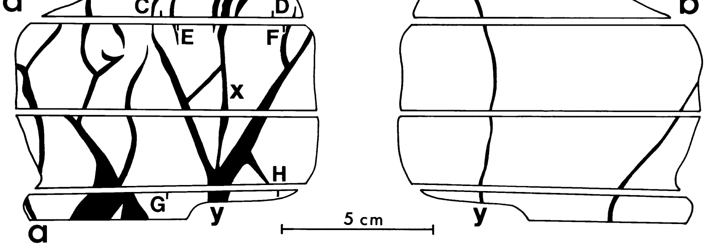

Fig. 8. Type 2 cracks. Mirror-image tracings of (a) the top and (b) the bottom surfaces of a 2·5 cm thick sandstone bed showing the geometry of the filled cracks (solid black). A–B, C–D, etc. refer to the positions of the vertical sections illustrated in Fig. 9. x–x–y shows the position of the main crack on the base of the bed which is the central feature in Fig. 9a–d.

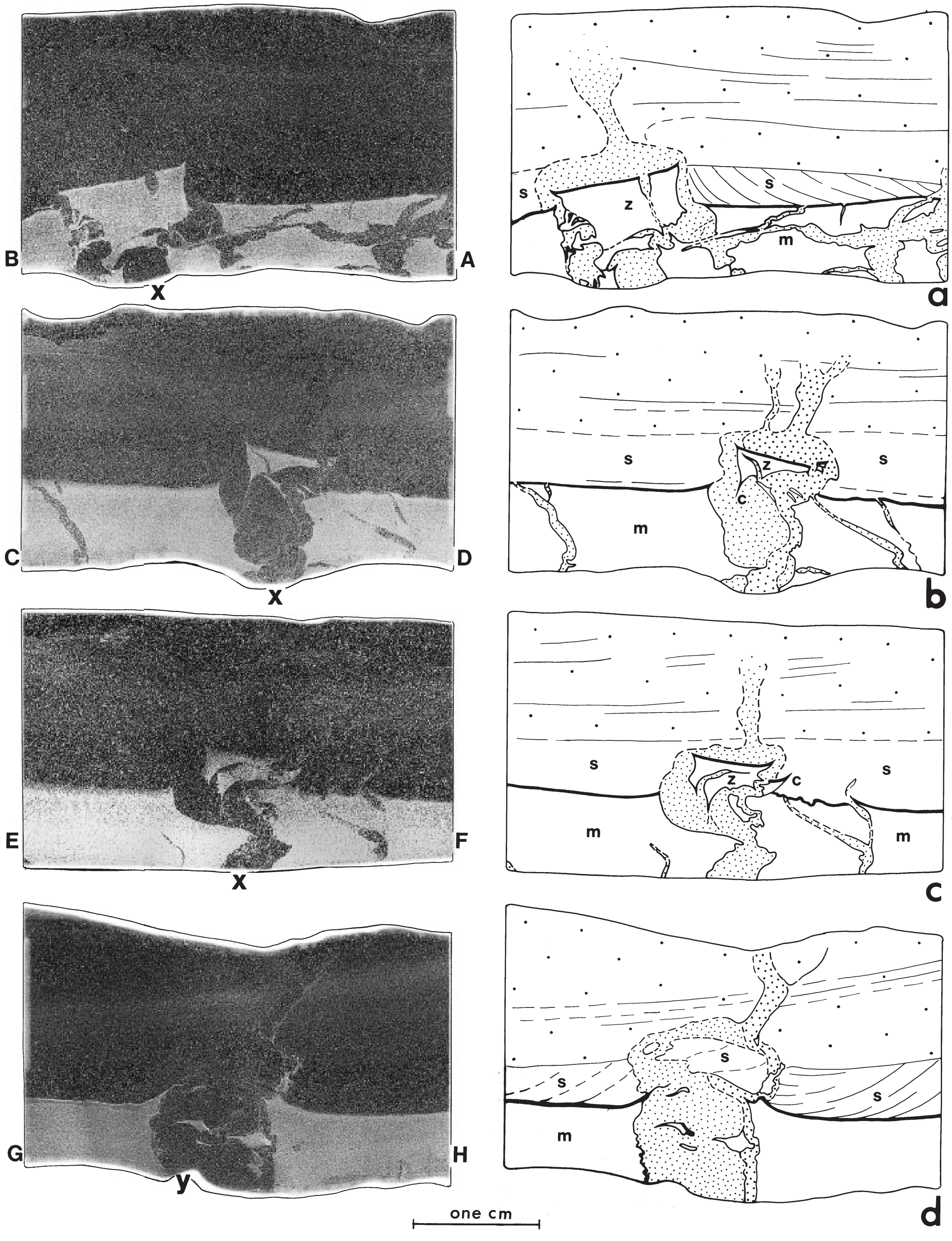

Fig. 9. Type 2 cracks.The left-hand column consists of negative prints of acetate peels taken of polished surfaces at right angles to the bedding along lines A–B, C–D, etc. across the specimen shown in Fig. 8. Annotated tracings of these prints are shown in the right-hand column; in preparing these, reference was also made to the original specimen where, due to colour differences, some of the features are more clearly seen than on the peels. All sections are right-way-up. x–x–y in the left-hand column refers to the main crack labelled on Fig. 8. A heavy line has been drawn to emphasise the upper boundary of the mudstone unit (**m**) against the overlying cross-laminated fine sandstone unit (**s**), and does not indicate a separate lithology. Laminated very fine sandstone/siltstone is shown stippled. **c**, mudstone cusp, and **z**, mudstone chip, are referred to in the text.

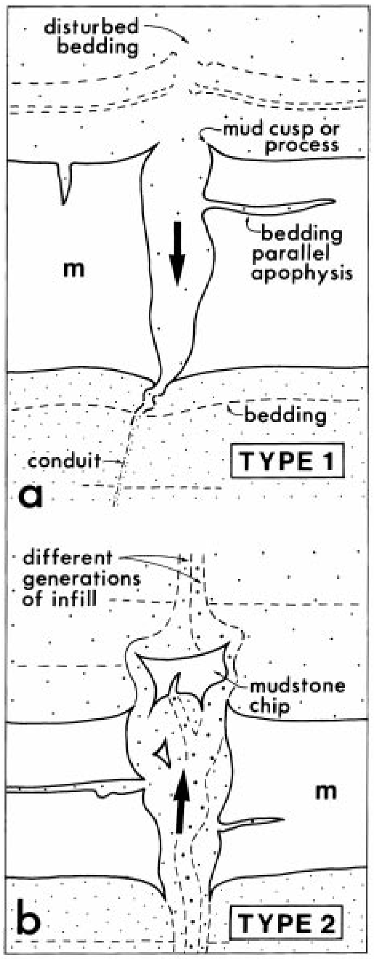

Fig. 10. Main features of (a) type 1 and (b) type 2 filled cracks. Open stipple – sandstone; close, fine stipple – siltstone; **m,** mudstone. Bold arrows show the dominant direction of fluid flow in each case.

1 Cracks filled with homogeneous sandstone protrude down from the bases of cross-laminated sandstone beds, and show a polygonal pattern on bedding surfaces.

2 Sand-filled cracks cut primary bedding lamination, and this is commonly disturbed or breached for some distance above the top of the crack infill.

3 Elongate cusps and processes of mud projecting from the breached mudstone layers tend to close-off the crack near to the overlying source bed, and generally project upwards into it.

4 Some cracks develop narrow apophyses of sandstone, which are approximately parallel to bedding, and in some cases connect with adjoining cracks.

5 The filled cracks commonly pass downwards into subtle, very narrow, conduits several cm long within which the bedding fabric of the host rock is disturbed. The conduits eventually become diffuse and disappear.

In their diversity of orthogonal to non-orthogonal crack patterns, the presence of both straight and curved cracks, and in some cases the development of primary and secondary generations of cracks, the Islay cracks mirror the variations in morphology displayed by sub-aerial desiccation cracks (cf. Allen, 1987). However, the formation of several generations of cracks is a reflection of the fractal geometry of all such crack patterns (Skjeltorp & Meakin, 1988) and characteristics (**3**) (**4**) and (**5**), together with a lack of an ordered internal structure in the sand infill, do not support an origin by sub-aerial desiccation or sub-aqueous 'synaeresis'. There is also a lack of features diagnostic of sub-aerial exposure such as mud curls (Fig. 3b), and no evidence to suggest that crack formation took place between the deposition of the mudstone now containing the filled cracks, and that of the overlying sandstone layer.

In the type 1 cracks it appears that sand has been injected *downwards* into the underlying mudstone, giving rise to a polygonal pattern of short dyke-like bodies. The preservation of a system of conduits beneath the crack tips, combined with zones of disturbance immediately above the tops of the cracks (Fig. 10a), demonstrates that crack infilling occurred *after* deposition of the sandstone beds and was possibly accompanied by some upward movement of water within the system. The narrow conduits in the sandy layers, which pass down from near the tips of the infilled cracks may be part of a network of fissures which developed synchronously with the large cracks in the mudstone layers, and allowed some fluid to drain from the sandstone. The narrow zones of disturbance seen in the parent sandstone *above* the cracks could have partly occurred in response to the downward movement of water-saturated sand into the cracks, but also seem to indicate that some upward movement of fluid took place.

Type 2

The main features of these cracks (Fig. 10b) are as follows:

1 They make orthogonal patterns on the bedding planes on both the tops and bottoms of beds.

2 In profile the cracks are seen to cut several beds and in most examples there is no obvious source for the infill.

3 They are filled with sandy material of different generations, are thick and bulbous in mudstone, and much narrower and difficult to detect in sandstone.

4 Mud chips and other internal structures indicate that the material in the cracks flowed upwards.

5 In some cases the cracks die out both upward and downward into narrow diffuse conduits.

These cracks share many of the features of the type 1 cracks but they differ from them in that there is clear evidence, from the uplift and tilting of mudstone chips, and from the internal structures in the sand infill, that a major component of *upward flow* was involved in their formation. As concluded for the type 1 cracks, the mudstone layers must have been at least partially lithified at the time the sand was injected. No evidence for the presence of desiccated algal mats reported by Kessler & Gollop (1988) was seen in these rocks, either in hand specimen or thin section.

Features 2–5 of the type 2 cracks, and especially the continuity of the cracks through several beds and the systematic narrowing of the crack infills as they pass through successive sandstone beds separated by mudstone, clearly preclude their formation by sub-aerial desiccation or shrinkage at the sediment–water interface. Their primary role is clearly to act as dewatering structures in already-buried sediments. As in the case of the type 1 cracks, some of the main vertical cracks are connected laterally by sinuous, sill-like, sand-filled veinlets (i.e. Figure 9a).

The early history of development of the type 2 veins may be seen in the small sandstone dyke which penetrates the upper surface of the chip in Fig. 9a (to the right of 'z') and appears 'blind', but is in fact connected to the undersurface of the chip by a narrow conduit. This may be a relict type 1 vein, one of the family responsible for creating the initial fracture system. The later set is represented by the upward-closing cracks on the *undersurfaces* of the detached mudstone chips (left of 'z' in Fig. 9b & c).

A feature common to both type 1 and type 2 cracks is the development of the cusps or narrow, pointed processes where the filled crack meets the host bed. These cusps have a variety of orientations and most appear to have formed *during* the formation of the cracks and not as a result of subsequent gravitational loading or compaction. Stewart (1962; Fig. 5) reported similar features associated with sandstone-filled cracks in Torridonian mudstones from Colonsay, Scotland. He inferred that the cracks opened as a result of downslope creep of the mudstone layers, were subsequently filled with sand, and that the mudstone 'flanges' on either side of the vein mouths developed as a result of compaction of the muddy sediment. In the case of the Islay cracks, some of the cusps appear to be too long and thin to have formed in this way, and many 'point' in the wrong direction (i.e. on the mudstone chip 'z' in Fig. 9b & c) – but if they did *not* post-date the infilling of the cracks, how was the sand infill able to make its way into the opening cracks without destroying the fragile cusps? The explanation may lie in the fact that expulsion of sand into the embryonic cracks in the underlying mudstone will result in a loss of material from the parent bed which will be compensated by a drawing in of mudstone into the potential space, much in the way that a rim syncline develops around an intrusive salt plug. This effect will then be accentuated by subsequent compaction giving the cracks the appearance that they are in the process of being pinched and detached from the parent bed. However, some cusps, such as those found where the mudstone layers terminate against the crack infills in Figs 6 & 7, may be largely due to differential compaction of the mud and sand layers; this also resulted in the downbending of bedding laminae at the sides and the tips of the cracks.

Having concluded that the Islay cracks formed by some form of interstratal cracking, the following problems have to be addressed: (a) how and why did the polygonal set of cracks develop in the mudstone layers? (b) what was the sequence of events which led to the present morphologies? and (c) how are the type 1 and type 2 cracks related?

Causes of interstratal cracking of mudrock

Possible mechanisms include (a) gravitationally unstable density inversion, (b) seismic shock, and (c) layer-parallel contraction resulting from compaction.

(a) A possible explanation for the polygonal patterns seen on the bases of some of the sandstone beds is that they resulted from a reversed density gradient of the type modelled experimentally by Anketell *et al.* (1970) which gave rise to downward injected polygonal patterns of sand dykelets. Although this mechanism could explain the formation of short, fat cracks on the bases of some of the beds (type 1), it could not explain the type 2 cracks, as density inversions of this type generally cause a folding of the interface between the layers (Owen, 1996; Fig. 2j), and ultimately, the formation of load structures such as 'pseudonodules' (Allen, 1982). An alternative interpretation would see the increased fluid pressure in the sandstone beds, which arises during burial and dewatering of the sediments, as causing the active intrusion of water-saturated sand as dykelets into the muddy layers, but it is difficult in this case to understand why the bodies should form polygonal sets.

(b) Liquifaction by seismic shocking of sediment situated near to the sediment–water interface is well documented. It gives rise to a distinctive, spatially restricted, association of small-scale internal dewatering structures including load structures, pseudonodules, water-escape structures and sandstone dykes (Sims, 1975; Seilacher, 1984; Plint, 1985; Davenport & Ringrose, 1987; Obermeier *et al.*, 1991). Interstratal shrinkage of buried mud layers could be promoted by a seismic shock which caused thixotropic behaviour of the muddy layers and consequent expulsion of water from them: this could result in volumetric shrinking of the mud and the development of a system of bedding-normal cracks. Because of the lack of quantitative experimental work in this field, it is difficult to assess the importance of this mechanism as a primary cause of interstratal cracking in sediments.

(c) The most likely cause of interstratal cracking of mudrock is compaction due to burial. Mudrocks undergo their main bulk volume loss at burial depths of 500–1000 m, and contract in volume by 50% within the first 1000 m of burial (Cartwright & Lonergan, 1996). In thick mudstone-dominated sequences in the North Sea Basin, these authors have identified a pervasive pattern of extensional faults with a mean dip of 45° which they infer have formed directly as a result of layer-parallel volumetric contraction of the mudrocks (Fig. 11a,b). This regional-scale contraction is inferred to have taken place in response to fluid expulsion during compaction. Cartwright & Lonergan (1996) draw an analogy between this mechanism and that which results in the formation of vertical desiccation cracks in mudrock as a result of sub-aerial exposure. Their model could be modified to explain the formation of vertical interstratal cracks in mudstone if, instead of forming inclined, conjugate sets of extensional fractures, the layer-parallel volumetric contraction experienced by mudrock in thin,

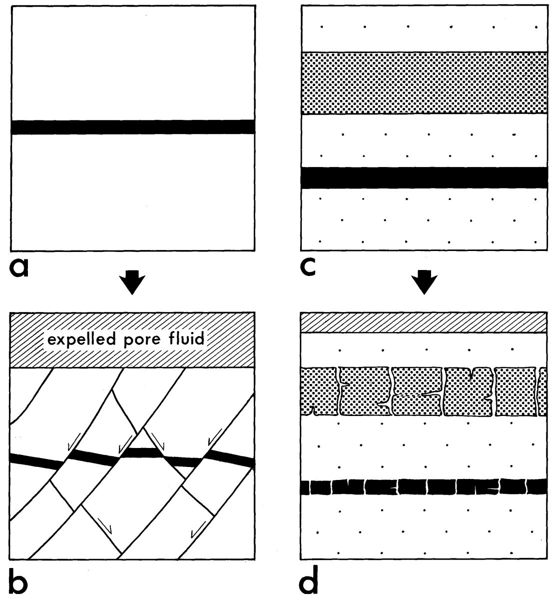

Fig. 11. Alternative models showing the results of volumetric contraction of mudrock during burial, in situations where the vertical sides in **b** and **d** are pinned and lateral extension is not permitted to take place. (**a**) An homogeneous mudrock unit with a single marker horizon (solid black) which is affected by kilometre-scale extensional faults (**b**) as contraction takes place, and pore fluid is expelled (after Cartwright & Lonergan, 1996; their Fig. 6B). (**c**) Decimetre-scale model in which two mudstone horizons (solid black and heavy stipple) enclosed in sandstone (open stipple) develop bedding-normal contraction cracks (**d**) as a result of burial compaction and the expulsion of pore fluid (cross-hatched). Neither volumetric contraction of, nor loss of pore fluid from the sandstone are taken into account.

confined layers resulted in the formation of a population of vertical cracks (Fig. 11c,d). If the mudrock is homogeneous then the radial stress pattern which accompanies burial compaction will be expressed in plan view as a set of polygonal fractures.

The following generalised sequence of events for the formation of the type 1 and type 2 cracks is envisaged:

1 Burial led to compaction and cracking of the mudrock (as described in (c) above), and a corresponding increase in pore fluid pressure in the interbedded sandy layers. As polygonal sets of cracks developed in the partly lithified mudrock they were intruded by water-saturated sand from overpressured adjoining sandstone beds to form type 1 cracks. Both upward- and downward-injection of sand could occur at this stage, as well as the formation of bedding-parallel filled cracks in the mudstone, some of which would enable adjoining cracks to form linked arrays. Two sets of structures geometrically continuous with the cracks formed at this stage: narrow conduits passing down into the beds beneath the crack tips, and analogous zones of disturbance in sandstone beds above the mouths of the cracks.

If the fluid pressure in the mudrock *exceeds* that in the sandstone layer then release of fluid from the latter, accompanied by opening of the cracks in the mudstone, could result in an upward flow of water accompanied by the downward injection of sand, as suggested by Plint (1983; their Fig. 10) to explain the evolution of fluidization pipes in sand beneath an impermeable bituminous layer.

2 As the mudrock dewatered further, the cracks would propagate and amplify, use the existing conduits link up through intervening beds, and form a system of dewatering veins which are now seen as type 2 cracks. The narrow sinuous zones of 'cleaner' sand seen in some of the crack infills (Fig. 9b & d) likely represent pathways along which major dewatering and upward flow of sand took place.

3 Once the type 1 and type 2 cracks were filled and stabilized, the crack profiles were further modified by compaction, gravitational sinking of the crack infill, and finally by weak tectonic deformation.

COMPARISON WITH PUBLISHED EXAMPLES

Filled cracks from a wide variety of inferred environments show unexpectedly close similarities in morphology with the type 1 and type 2 cracks described above. This is particularly clear in well documented descriptions of crack morphology referred to below, and suggests that cracks having a similar origin to those from Islay may be common in the geological record.

Van Houten (1964; p. 511) described and illustrated shrinkage-crack polygons which in three dimensions closely resemble the Islay cracks. He concluded that much of the shrinkage occurred either under shallow water, or after burial, and reported vertical zones of brecciation up to 2 cm wide and 5–8 cm high, some of which connect with the shrinkage-crack casts and likely provided pathways for upward-moving water and fluid mud.

Dzulynski and Walton (1965; their Fig. 113) described upward-penetrating dykelets from the Oligocene of the Middle Carpathians which form a polygonal pattern which is very similar in appearance to that from Islay (Fig. 3). They explain the cracking of the mud layer as a result of expansion of the sandstone bed, but it could be equally well explained by layer-parallel contraction of the mud layer followed by upward intrusion of wet sand into the cracks. Whether this occurred interstratally or just below the sediment surface is not known.

Young (1969) described spindle-shaped crack fills from the early Proterozoic rocks of Ontario which, although they do not form polygonal patterns on bedding, show in profile many of the features of the Islay cracks, in particular the presence of bedding-parallel linkages. In the examples figured by Young (1969) there are breaks in the primary lamination in the sandstone above the crack infills (Young's Fig. 6 A & B), suggesting that upward flow of water had taken place. He noted 'significant disruption of cross-laminations in a zone immediately above several downward-filled injection structures' (p. 798) and concluded that the mudcracks cannot have originated by sub-aerial exposure but formed at a depth of 5–10 cm below the surface.

The cracks described by Young (1969) extend both upward and downward from the parent bed, as do the crack-fill ridges described by Daley (1968) from non-marine siltstones of Oligocene age from the Isle of Wight, UK and considered by him to be of problematical origin. Daley noted the presence of 'hairline cracks' which continue upwards from some of the crack fills (cf. Islay), and suggested that they may be relics of previously open cracks which extended as far as the sediment surface, were partially filled with silty sediment, and were then closed by downslope movement of the sediment.

Similarities are also seen with the three types of crack (A-C) reported by Daley (1970) from laminated argillaceous limestones of Oligocene age from the Isle of Wight, UK. Although these cracks are in limestone, the processes by which they formed are likely similar to those which give rise to 'mudcracks'. Type A cracks appear to have formed at the sediment surface and most were filled from above. Type B cracks are long and narrow, cut several beds, and were thought to have originated by volume change during the dehydration of certain limestone beds below the sediment surface. They occasionally widen upwards, are linked by horizontal fissures (Daley, 1970; their Fig. 8), and enabled upward flow of water from the sediments to take place. They clearly resemble the Type 2 Islay cracks described in example B. Daley's Type C cracks are short and narrow and possibly formed at the sediment surface by dewatering.

In their review of crack-forming mechanisms, Plummer & Gostin (1981) discussed the formation of shrinkage cracks from late Precambrian rocks in South Australia, which occur as randomly orientated or aligned crack casts on the bases of the arenaceous beds. They concluded that these had formed substratally at the same time as the associated load structures, purely as a result of loading, dewatering and eventual shrinkage of clay layers beneath sandstone or siltstone.

Kidder (1990) illustrated cracks 2–3 mm wide and up to 40 mm long from the lower part of the Middle Proterozoic Libby Formation in Montana, USA, which form incomplete polygonal patterns in plan view. They have V-shaped cross-sections and cut many thin beds, but are almost isolated from the parent bed by cusps of mudrock (Kidder, 1990; their Fig. 4) in the same manner as the Islay cracks (Figs 6 & 9d). Kidder considered them to be of desiccation origin, and discounted a 'compaction origin' for the cracks because of the thinness of the beds above the cracked horizon. However, spindle-shaped cracks in the upper Libby formation were thought to have 'formed sub-aqueously during expulsion of pore waters when overlying beds were rapidly deposited on silty argillite' (Kidder, 1990; p. 950).

In addition to this literature review, some of the Scottish and Irish examples of sand-filled cracks mentioned in the Introduction have been examined in the field and laboratory. Those from the younger Dolomitic Formation were studied in some detail by Fairchild (1980) and interpreted as synaeresis cracks, but remain enigmatic. Serial sections show that most of the cracks do indeed penetrate downwards from the host layer but, because of the lithology (carbonate mud and silt), the blurring of textures due to the recrystallization of fine-grained carbonate crystals, and the subsequent penetrative deformation of the rock which lead to a tectonic rotation of the filled cracks (Borradaile & Johnson, 1973), they do not preserve the delicate features in the host rock and in the crack infill which are necessary for determining their origin. Anderton's (1972, 1976) illustrations of the cracks from the Jura Quartzite show that they could have formed in the same way as the Islay type 2 cracks, and there is no specific evidence for their having formed either by synaeresis or desiccation.

The polygonal pattern on the bedding surface at Ballymore, Co Donegal, Ireland, interpreted by Wolfe (1969) as organic in origin, and by Bliss *et al.* (1978) as desiccation cracks, was examined and sampled in 1967, and found to have features identical to those of the type 1 crack pattern illustrated in Fig. 3.

DISCUSSION

The Islay cracks likely formed as a result of layer-parallel contraction caused by compaction of mudstone during burial, accompanied in the most highly developed cracks by significant interstratal dewatering. As all mudrocks have the potential to be affected in this way, this raises the question of why the polygonal sets of filled cracks which result from this process are not more commonly preserved in the geological record. The answer is perhaps twofold: in general fluids are lost from rocks in ways which do not result in the formation of discrete crack patterns; and special conditions may be required for such cracks to initiate, especially those forming polygonal patterns.

As to the general expulsion of fluids from sediments, Lowe (1975) and others have described many ways in which fluidization and liquifaction permit this to occur and on p. 157, Lowe states that the development of water-escape structures is 'particularly favoured by upward-decreasing permeability within sedimentation units such as normally graded turbidites' and lists a number of sedimentary environments in which such structures are particularly common. Thus in the majority of cases, fluids would appear to be progressively lost from sediments by means of small-scale, often subtly defined, dewatering structures and some special trigger may be needed for the production of patterned cracks. As mentioned earlier, seismic shock could have provided the necessary trigger in the present case, because Anderton (1988) has concluded that major syn-depositional transfer faults such as the Islay Transfer Fault (Anderton, 1985) and the Bolsa Fault (Fairchild, 1980) were active within 10 km of the study area during deposition of the Lower Fine-grained Quartzite in which the cracks occur.

The degree to which the different mechanisms were responsible for the formation of the filled cracks is not known, and there was likely a continuum between cracking of the mud layers due to volumetric contraction during burial, the injection of over-pressured, water-saturated sand into the developing cracks, and the modification of crack profiles and wallrock geometry due to the resultant gravitational loading.

The main conclusion to be drawn from this study is that sand-filled cracks forming polygonal patterns on the bases of beds should not be automatically interpreted as having been caused by sub-aerial desiccation or some form of synaeresis. Detailed studies of vertical cross-sections of cracks and of their infill are required in order to assess the cause of the cracking and the mode of development of any filled cracks. It is a surprising fact that there is at present a lack of well-documented ancient examples of true desiccation cracks, comparable to the descriptions of modern examples given by Allen (1987). Synaeresis cracks likely do not exist in natural systems, but interstratal cracking caused by layer-parallel contraction, accompanied or followed by water escape, is recognized here as an important mechanism for the development of filled cracks in sedimentary rocks.

ACKNOWLEDGMENTS

I am grateful to Drs B. Daley and L. G. Kessler II for their helpful and constructive reviews, and to Dr Guy Plint for much advice, and useful comments.

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Manuscript received 11 April 1995; revision accepted 10 April 1997.