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Pre/syn-lithification tectonic foliation development in a clastic sedimentary sequence.

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ABSTRACT

The current view regarding the timing of regionally developed penetrative tectonic fabrics in sedimentary rocks is that their development postdates lithification of those rocks. In this case, fabric development is achieved by a number of deformation mechanisms including grain rigid body rotation, crystal-plastic deformation and pressure solution. The latter is believed to be the primary mechanism responsible for the domainal structure of cleavage in low-grade metamorphic rocks. In this study we combine field observations with strain studies to characterize considerable (>50%) Acadian crustal shortening in a Devonian clastic sedimentary sequence from southwest Ireland. Despite

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these high levels of shortening there is a marked absence of the domainal cleavage structure and intra-clast deformation, which are expected with this level of deformation. Fabrics in these rocks are predominantly a product of rigid body rotation and repacking of extra-formational clasts during deformation of a clastic sedimentary sequence before lithification was complete.

INTRODUCTION

Attempting to understand the key physical/chemical processes of tectonic foliation formation has occupied the minds of some of the leading geologists for nearly 200 years (Darwin, 1846; Sorby, 1849) with answers to some fundamental questions still outstanding. Research since the early seventies has emphasized the central role pressure dissolution plays in the formation of tectonic cleavage (Wood, 1974, Vernon, 1998). As a consequence, cleavage foliations are typically domainal with alternating phyllosilicate-rich dissolution cleavage domains and lithon domains of relatively un-deformed host lithology (Powell, 1979; Borradaile et al., 1982; Vernon, 1998). Deformation mechanisms involved in the formation of these fabrics include grain rigid body rotation producing grain shape preferred orientation (GSPO), crystal-plastic deformation and pressure dissolution (Vernon, 1998). The current orthodoxy is that these processes predominantly operate to produce a slaty cleavage after the host lithology has become fully lithified (Vernon, 2004, *and references therein*). While there have been advocates for pre-lithification development of tectonic fabrics (Maxwell, 1962; Alterman, 1973) these examples are viewed as ‘local’ aberrations that are not regionally significant (Geiser, 1975). However in recent years there has been a growing awareness of the role of ‘lateral compaction’ in producing a distributed shortening strain in partially lithified sediments (Paterson and Tobisch, 1993; Henry et al., 2003; Butler and Paton, 2010, Alsop and Marco, 2014). Butler and Paton (2010) estimated up to 25% distributed longitudinal strain in a gravity driven thrust system from the Orange Basin offshore Namibia. Here we describe a Devonian clastic sedimentary sequence from southern Ireland that has experienced considerable shortening associated with tectonic foliation development yet exhibits minimal evidence of structures typically associated with deformation of lithified rocks. Evidence is presented that regional tectonic shortening was achieved by translation and rigid body rotation of clasts with possible concomitant sediment dewatering of a not fully lithified sedimentary sequence.

BACKGROUND GEOLOGY

The Dingle Peninsula of southwest Ireland consists of a series of distinct tectono-stratigraphic units representing alternating periods of localized crustal extension and compression extending from the late Silurian to the early Carboniferous. One of these, the Dingle Group represents the early continental infilling of the Lower Devonian Dingle Basin. This basin extends for ~60 km along the axis of the Dingle Peninsula and has been described as a pull-apart structure within the Caledonian Iapetus Suture Zone (Todd, 2000). The basin fill, the Dingle Group, is predominantly fluvial and includes two marginal conglomerate units, the Glashabeg Formation preserved along the northern margin of the basin and Trabeg Formation along the southern margin (Horne, 1974). This study focuses on the Glashabeg Formation in the Wine Strand area (52.17871°N, 10.38488°W) on the northwestern side of the peninsula (Fig. 1). Compositionally the Glashabeg Formation consists of a series of fining-upward cycles consisting of polymict basal conglomerates overlain by red sandstones, siltstones and mudstones. The

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conglomerates predominantly consist of volcanic and siltstone extra-formational clasts with variable amounts of jasper, vein quartz and critically intra-formational ‘rip up’ mud/siltstone clasts set in a very coarse grained sandstone matrix (Figs. 2a–2d). After deposition, this basin fill was deformed by the mid-Devonian Acadian orogenic event (Meere and Mulchrone, 2006) leading to regional fabric development, folding and localized reverse faulting. The study area sits close to the core of an open and upright Acadian syncline, the Ballyferriter Syncline, which plunges gently to the northeast. A penetrative tectonic fabric (Fig. 2e) transects the syncline axis by ~14° anticlockwise (Fig. 1) consistent with regional dextral Acadian transpression (Meere and Mulchrone, 2006). The xy (flattening) principle planes of finite strain (R_s) derived from oblate reduction spots lie parallel to the cleavage fabric with a mean xz R_s value of 2.73 ± 0.25 (Meere and Mulchrone, 2006). This equates to ~50% bulk shortening, assuming constant volume deformation, or ~65% shortening, assuming a volume loss deformation process. The maximum principle strain *x* axis of the xy section ellipses consistently pitch steeply in the cleavage plane indicating a component of sub-vertical thickening associated with tectonic shortening. The deformation occurred under very low grade (sub-greenschist) metamorphic conditions with no evidence of metamorphic mineral growth.

Palynomorphs taken from Dingle Group rocks are black in color (Higgs et al., 2014) indicating a thermal alteration index (TAI) of 4.5–5 indicative of maximum paleo-temperatures in excess of 250 °C but below greenschist metamorphic facies conditions.

FIELD EVIDENCE

A number of features have been recognized in Glashabeg Formation lithologies that are unusual for rocks that have undergone such significant levels of tectonic shortening;

(1) With the exception of some very localized Mode 1 fracturing, there is an absence of intra clast deformation in conglomerate extra-formational clasts (Figs. 1a and 1b). There is no evidence of pressure dissolution indenting at clast/clast contact points. Isolated extra-formational clasts in matrix-rich conglomerates display strong ‘wrap around’ fabrics developed in the vicinity of the clast indicating more competent behavior with respect to the enclosing matrix during deformation (Figs. 2a and 2b). In addition, there is no evidence of such features as ‘rolling structures’ (Van den Driessche and Brun, 1987) indicating clast rotation that would be expected with ductile deformation of a fully lithified conglomerate. Similar fabrics have been described in the Lafonia Diamictite of the Falkland Islands (Curtis and Hyam, 1998).

(2) In sharp contrast, intra-formational mud and fine siltstone ‘rip up’ clasts have behaved less competently during deformation with clast/matrix boundaries often displaying convex inward ‘bulging’ structures (Fig. 2c) (Waldron and Gagnon, 2011). While this indicates that the ‘rip-up’ clasts were less competent than the surrounding matrix, it also requires that both materials were in a less competent weakly lithified state during deformation. Where competent extra-formational clasts are in direct contact with ‘rip-up’ clasts they are seen to project into the less competent mudstone/siltstone of the ‘rip-up’ clasts (Fig. 2b). Intra-formational clasts also consistently show very strong alignment parallel to the tectonic fabric, even in areas where there is significant discordance between this fabric and the primary bedding fabric (Fig. 2d).

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(3) Overall, finer grained siltstone and mudstone lithologies exhibit a high level of less competent behavior during deformation. High amplitude mullion structures are typically developed at mudstone/conglomerate contacts (Figs. 2e and 2f) with the less competent mudstone cusps projecting into the more competent conglomerates. This mullion lineation is parallel to the regional bedding/cleavage intersection lineation.

(4) On a microscopic scale there is a marked absence of a pervasive domainal microstructure, grain flattening and pressure solution seam development .The absence of these microstructure is indicative of soft-sediment deformation fabrics the development of which is characterized by rigid body grain rotation (Waldron and Gagnon, 2011; Alsop and Marco, 2014). Qualitative element concentration maps of the finer grained lithologies were made using a JEOL JXA-8200 electron probe micro-analyzer at the Universität Potsdam (Germany) which is equipped with five wavelength-dispersive spectrometers and operated at 15 kV accelerating voltage and 35 nA sample current. Critically, these maps confirm the absence of Si depleted seams as described by Meere et al. (2013). Structures indicative of intra-crystalline deformation such as pervasive undulose extinction, sub-grain development or any recrystallization mechanisms are absent and ought to be present in the case of pervasive deformation of lithified sedimentary rocks. Where dissolution seam development occurs it is very localized, typically developing in intra-formational mudstone clasts, due to high mean stress concentrations at the apices of extra-formational clasts projecting into the less competent ‘rip-up’ clast material (Fig. 3b). Boundaries between siltstones and coarse sandstones are often characterized by isolated sandstone clasts completely embedded in siltstone (Fig. 3a).

STRAIN ANALYSIS

Finite strain (R_s) estimates obtained from reduction spots were compared to those derived in this study from siltstone, sandstone and conglomerate samples using the R_f/φ mean radial length (MRL) (Mulchrone et al., 2003) strain analysis method. This method assumes passive clast/matrix material behavior as well as an initial random distribution of clast orientations and a radial symmetry of clast axial ratios. With increasing departure from these assumptions the MRL method will increasingly underestimate the true R_s value. A minimum of 150 clast aspect ratios/orientations were collected from each analyzed sample to reduce error associated with the finite strain estimates (Meere and Mulchrone, 2003). Data were collected from shallow dipping units where the tectonic fabric was ~90° to bedding and where there was good control on finite strain from high quality reduction spot data in adjacent mudstones and siltstones. Data has been extracted using semi-automatic analysis of digital images (Mulchrone et al., 2013). Previous studies on the reduction spots show marked discontinuities in the curvature of the reduction spot boundaries between fine-grained and coarse-grained siltstone components. This indicates differential shortening within these lithologies during cleavage development which in turn indicates they developed before deformation and are as such valid finite strain markers (Meere et al. 2008).

Results for all sediment grain sizes (Fig. 4a) clearly show significant underestimates of finite strain with respect to the reduction spot data ($Rs = 2.73 \pm 0.25$) strongly indicating that the assumptions of MRL, principally passive clast/matrix behavior are not valid. In all cases the finite strain *x* axis is closely aligned to the trace of the cleavage fabric (S_1). By contrast, the intra-formational 'rip-up' clast sample gives the highest MRL strain estimate (R_s = 2.2). Field evidence which suggests less competent behavior is consistent with finite strain estimates that more closely approximate the true strain value.

STRAIN MODELING

Structures observed in the field strongly indicate that conglomerates reacted to deformation in the unconsolidated state. Therefore associated clast fabrics cannot be explained in terms of traditional passive behavior (Mulchrone et al., 2003). In the unconsolidated state clasts behave like rigid inclusions by comparison with the enclosing matrix. The motion of rigid inclusions with no-slip at the boundary is well understood (Jeffery, 1922) and it is possible to relate distributions of clast long axis orientations to finite stain and strain history (Mulchrone, 2007a). Models of the case of rigid inclusions with slip on the boundary have also been developed (Mulchrone, 2007b). By deriving probability distribution functions for both no-slip and slip boundary conditions, maximum likelihood methods allow for estimation and comparison of finite strain from long axis distributions (Mulchrone and Meere, 2015) for both cases. Therefore an appropriate model of clast behavior can be determined by calculating clast fabric intensity under these two different boundary conditions and comparing the results with natural data.

The axial ratios and orientations of 315 conglomerate clasts from the Glashabeg Formation were measured in a section normal to bedding and the tectonic fabric. The data were analyzed assuming pure shear, and both 'rigid no-slip' and 'rigid slip' boundary conditions. The results are summarized as a plot of fabric intensity versus bulk strain (R_s) (Fig. 4b). Under the assumption of 'rigid no-slip' it takes a finite strain of R_s > 14.0 to produce the observed clast fabric intensity whereas assuming 'rigid slip' behavior the observed distribution is explained by a finite strain of Rs = 2.4 which is close to the bulk strain estimate derived from reduction spots.

CONCLUSIONS

A number of lines of evidence from the Glashabeg Formation support the contention that these rocks were deformed before the process lithification was complete. These include;

(1) An absence of a pervasive dissolution seam (Si depleted) fabrics.

(2) A spectrum of clast/matrix interactions from rigid extra-formational clast behaviors (e.g., fabric wrapping around clasts) to less competent behaviors (e.g., bulging) for less competent intra-formational clasts.

(3) An absence of 'rolling structures' indicating clast rotation in a lithified matrix during deformation.

(4) The presence of high amplitude lobate mullion structures are developed at mudstone/conglomerate contacts

(5) Strain analysis results for extra-formational clasts clearly show significant underestimates of finite strain while results for the more incompetent 'rip up' clasts yield higher estimates (R_s = 2.2) closer to the true strain values from reduction spot data (Rs = 2.73 ± 0.25).

(6) Strain modeling indicates that the observed clast fabric intensities are consistent with 'rigid slip' behavior of extra-formational clasts in a weak matrix.

The deformation of poorly lithified sediments proposed in this study is consistent with the close temporal proximity of the deposition of the Lower Devonian Dingle Group sediments in the Dingle Basin and their subsequent deformation by the mid-Devonian Acadian event in southwest Ireland. This study revives the argument for a mechanism of developing a well-defined tectonic fabric prior to lithification (Maxwell, 1962) and requires geologists to consider the possibility of such a mechanism contributing to tectonic strain in a range of geological settings. It also has implications for sediment mobility during deformation. This includes the preferential exploitation of pre-existing tectonic fabrics by emplacement of clastic dikes (Dewey and Ryan, 1990, Phillips and Alsop, 2000). These results also highlight the importance of demonstrating passive clast/matrix behavior when deriving meaningful finite strain estimates using most conventional strain analysis techniques based on clast population behavior during deformation.

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FIGURE CAPTIONS

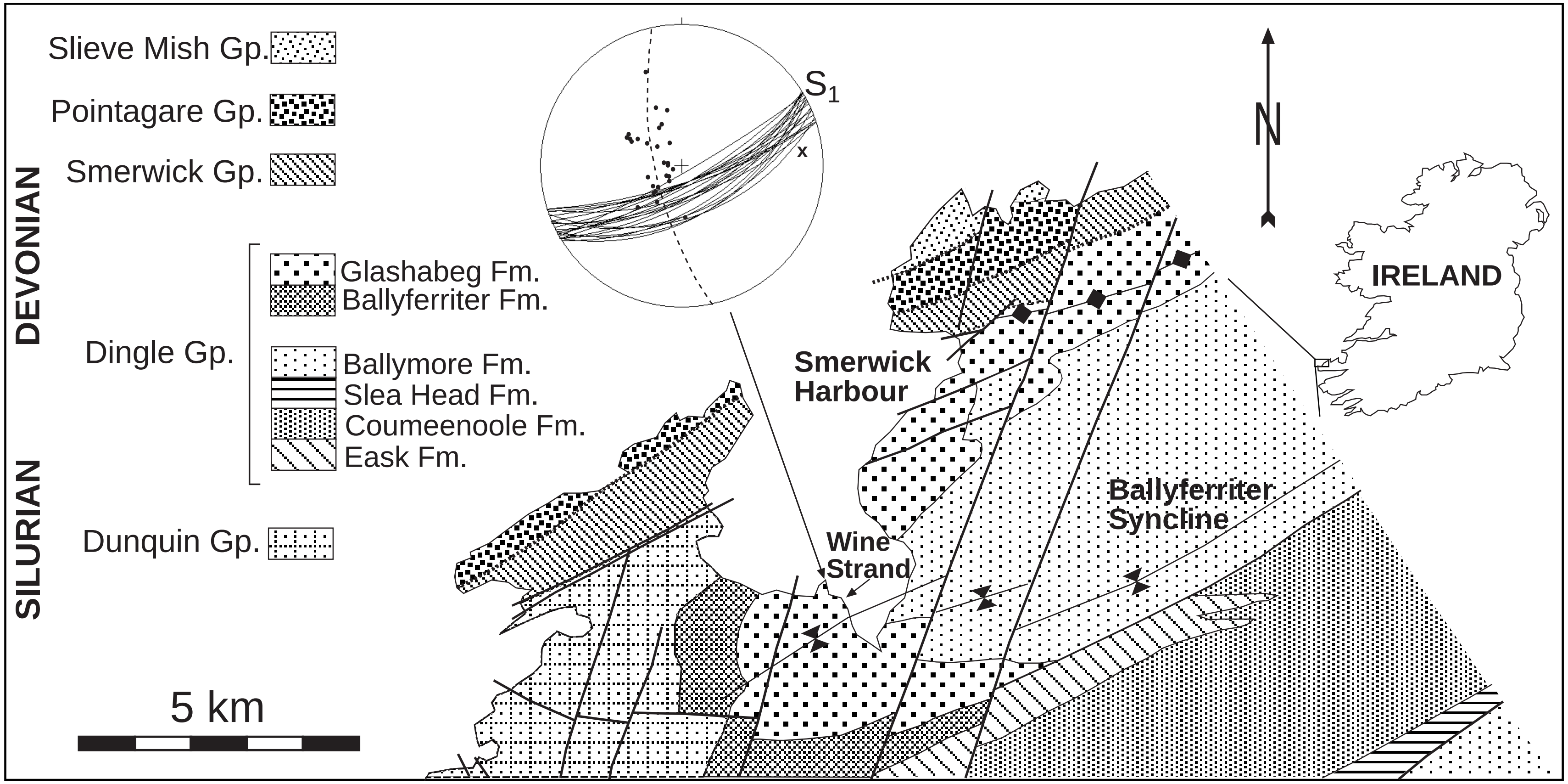
Figure 1. Geological map of the northwestern Dingle Peninsula (Ireland) with an equal area projection of structural data for the Ballyferriter Syncline in the Wine Strand area demonstrating anticlockwise transection of the calculated fold axis (x) by the associated tectonic fabric (S_1). Filled points are poles to bedding, solid great circles are S_1 planes. Gp.—Group; Fm.—Formation.

Figure 2. Meso-structural field evidence of the contrasting competencies between competent extra-formational and incompetent intra-formational (rip-up) clasts, and the surrounding incompetent sand grade matrix. A: Field image of deformed conglomerate with competent jasper (j), mudstone (m), and volcanic clasts (v) in addition to ‘rip-up’ incompetent red mudstone clasts (r-u) set in a sand grade matrix. Note wrapping of cleavage fabric (S_1) around jasper clast while the sand matrix is seen to ‘bulge’ into the less competent ‘rip-up’ clast (23-mm-diameter coin for scale). B: View of more competent volcanic clast projecting into less competent ‘rip-up’ clast, note localized development of dissolution seams (ds) associated with high tectonic stress concentrations at the apices of the more competent volcanic clast. Also note the highly angular nature of the sandstone matrix clasts, the absence of cleavage domains and a clast shape fabric parallel to S_1 in the lower third of the image. C: Bulging (arrows) of coarse-grained sandstone and pebble conglomerate matrix into mudstone rip-up clast. D: Strong alignment of ‘rip-up’ clasts parallel to the cleavage fabric and at a high angle to the

bedding fabric (S_0). E: View of mullioned contact across the cleavage (S_1), detail shows reduction spot in approximately the xz plane of the finite strain ellipsoid with an R_s value of ~3.5. F: View of mudstone/conglomerate mullion contact in the plane of cleavage, note lobate nature of contact along the mullion lineation.

Figure 3. Photomicrographs and electron microprobe Si concentration maps of siltstone (Siltst.) close to a siltstone/sandstone (Sst.) boundary (A), note lack of silica depleted dissolution seams in the siltstone (sample 24–6–13–3), and siltstone close to a siltstone/sandstone boundary with a very large volcanic clast impinging on the siltstone (B) resulting in the very localized development of dissolution seams (DS) now outlined by Mn-oxides (sample 24–6–13–1b). C—chlorite, M—muscovite, P—plagioclase, Q—quartz, V—volcanic clast.

Figure 4. A: Plot of finite strain (R_s) estimates with 95% confidence interval error bars determined using mean radial length analysis of sedimentary clasts versus deviation of principle strain axis ϕ from cleavage (S_1). B: Plot of variation in clast fabric intensity versus bulk strain (Rs) for slipping and sticking clast/matrix behaviors.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Dingle Gp.
Glashabeg Fm.
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Ballymore Fm.
Slea Head Fm.
Coumeenoole Fm.
Eask Fm.
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Ballyferriter Syncline

Figure 2

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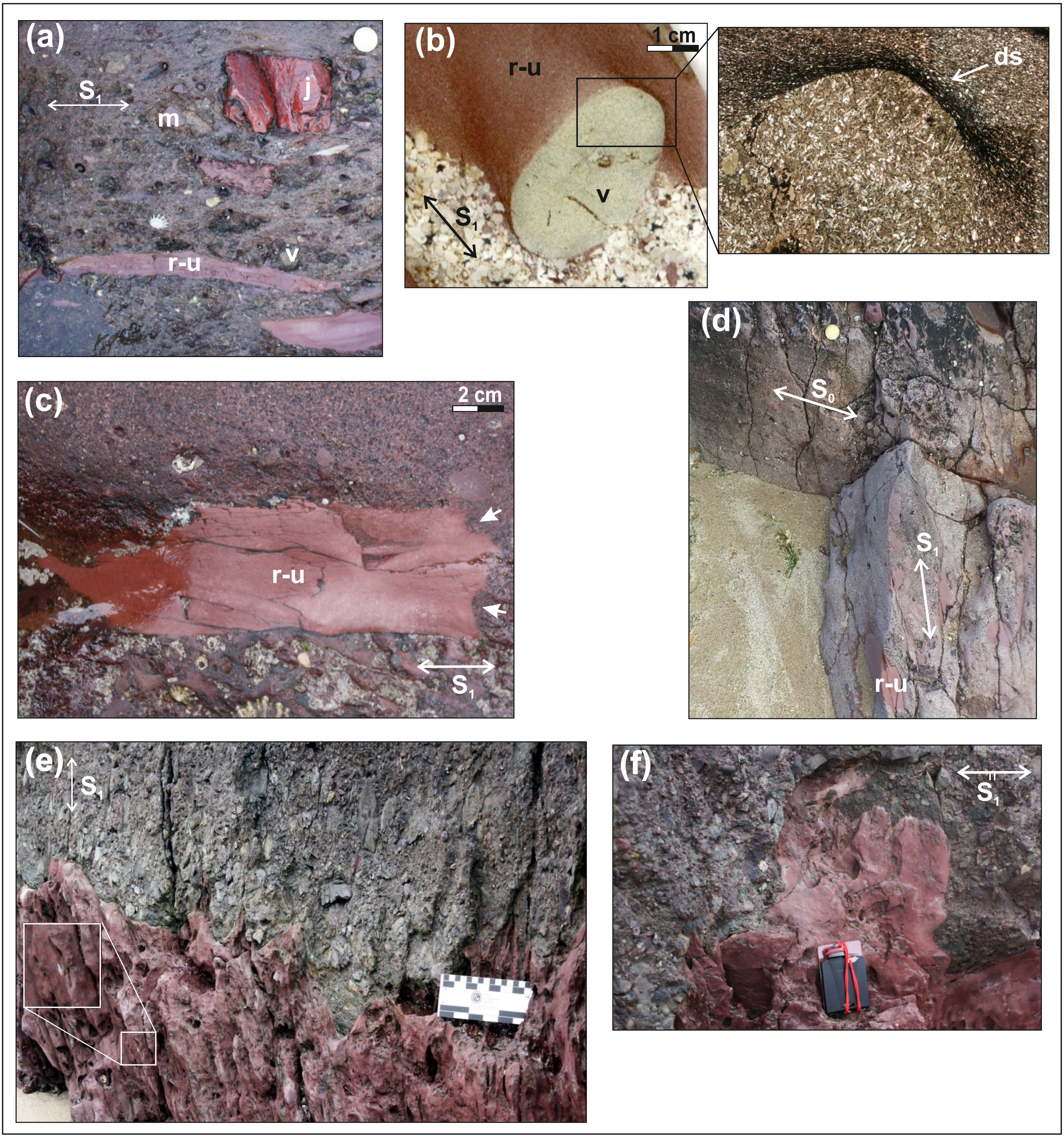

Figure 3

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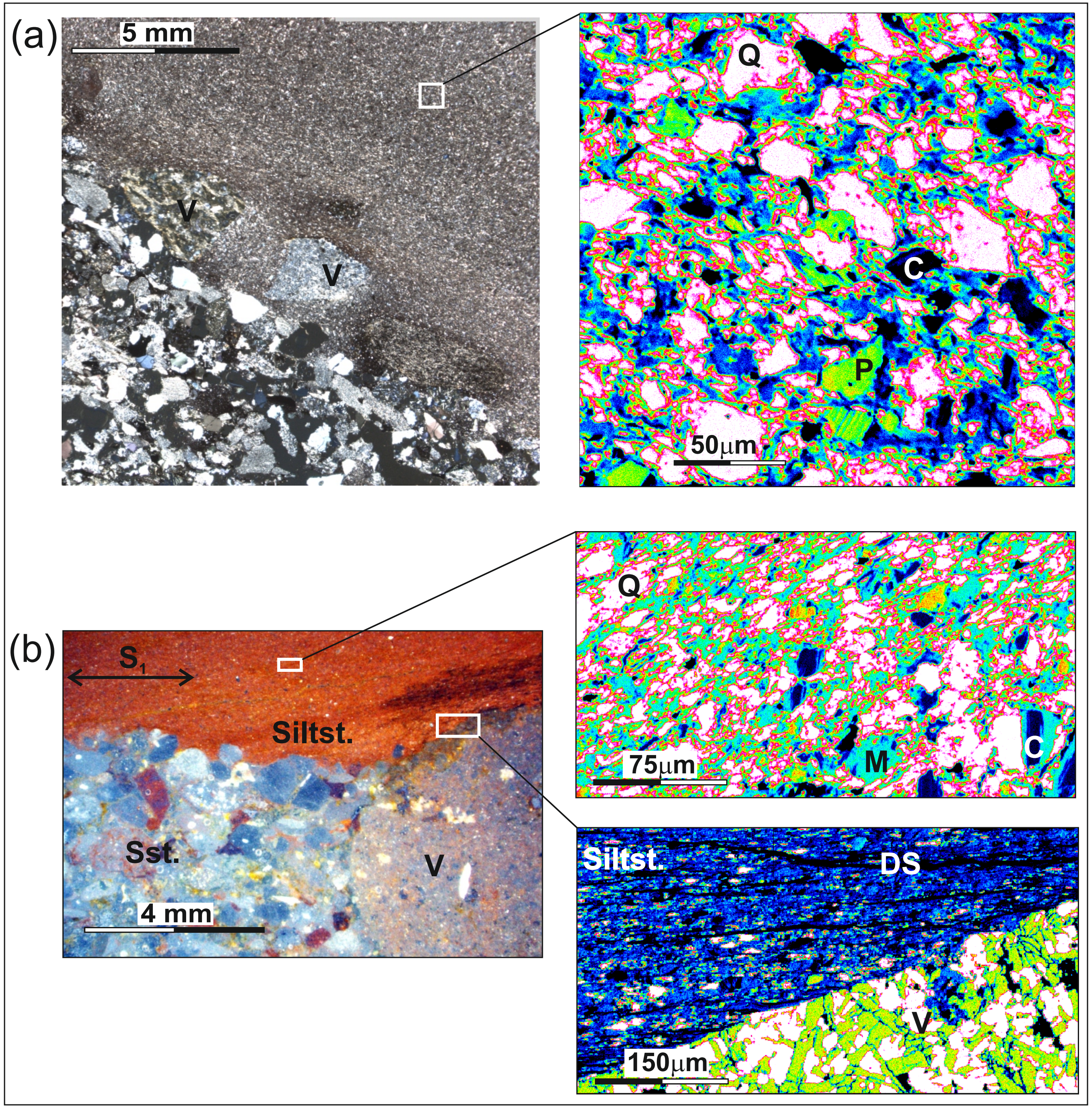

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