Journal of Structural Geology 30 (2008) 1264–1271

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

The effect of non-passive clast behaviour in the estimation of finite strain in sedimentary rocks

Patrick A. Meere [a,*], Kieran F. Mulchrone [b], James W. Sears [c], Michael D. Bradway [c]

[a] Department of Geology, National University of Ireland, Cork, Ireland
[b] Department of Applied Mathematics, National University of Ireland, Cork, Ireland
[c] Department of Geosciences, The University of Montana, Missoula, MT 59812-1296, USA

A R T I C L E I N F O

Article history:
Received 6 June 2007
Received in revised form 8 June 2008
Accepted 17 June 2008
Available online 8 July 2008

Keywords:
Geological strain analysis
Clastic sedimentary rocks

A B S T R A C T

Existing methodologies that use ellipsoidal objects for the analysis of geological strain typically assume that these objects acted passively during deformation. This assumption, when not valid, can lead to significant underestimates of strain in rocks deformed under low-grade conditions in orogenic forelands. This is especially true when clastic sedimentary rocks are utilized to measure strain; the competency contrast between clasts and matrix possibly leading to marked 'non-passive' behaviour. The systematic nature of this finite strain underestimation may allow for a correction of strain estimates when this type of behaviour is evident.

1. Introduction

Crustal deformation is quantified using techniques of strain analysis that are most commonly based on populations of approximately ellipsoidal objects (e.g. sedimentary clasts), which are almost ubiquitous constituents of natural rocks (Ramsay, 1967). Most existing methodologies make the assumption that the ellipsoidal markers acted passively during deformation, i.e. the marker and surrounding rock matrix responded to deformation identically. This requirement, if fully respected, greatly limits the number of valid strain markers available to quantify strain in mountain belts. This is particularly true when sedimentary clasts are used as strain markers, in which case, competency contrasts between the clasts and matrix can be quite significant, especially in sub-greenschist terranes. It has been long recognized that strain in two component clastic sedimentary rocks, especially conglomerates, is by its nature heterogenous and reflects the viscosity contrast between different clast types and matrix (Ramsay, 1967; Gay, 1968a,b). Several papers have provided a theoretical treatment of the deformation of objects within a matrix with variable viscosity contrasts (Gay, 1968a,b; Ghosh and Sengupta, 1973; Bilby et al., 1975; Lisle, 1983; Treagus and Treagus, 2001, 2002). Gay (1968a) was the first to explicitly state that the viscosity ratio between clasts and matrix has a profound effect on the nature of clast deformation with less viscous clasts deforming more rapidly than the strain ellipse, and clasts with a higher viscosity than the matrix deforming more slowly than the strain ellipse. These studies have clearly demonstrated that the use of clasts with high viscosity contrasts to matrix as strain markers in sedimentary rocks will lead to significant bulk strain underestimates in these lithologies. Treagus and Treagus (2002), in attempting to practically address this problem, used Rf/φ analysis (Ramsay, 1967; Dunnet, 1969) to characterize clast strain and Fry 'centre to centre' analysis (Fry, 1979) to characterize bulk rock strain. Treagus and Treagus (2002) also argue that bulk strain can be calculated using the weighted mean of the different component clast strains determined from, for example, Rf/φ analysis. Object concentration, packing and interaction have also been demonstrated to have a significant influence on finite strain estimates from multi-phase mixtures (Gay, 1968a; Lisle, 1979; Mandal et al., 2003; Vitale and Mazzoli, 2005). Mandal et al. (2003) derived a relationship linking strain partitioning (the ratio of object to bulk strain rates, $\dot{e}_i/\dot{e}$) to object concentrations and noted that higher object concentrations lead to reduced strain partitioning. Vitale and Mazzoli (2005) demonstrated that ooid concentration has a profound effect on both object and bulk strain in packstones with high values of packing (>70–80% of the maximum packing) resulting in significantly lower strain estimates, especially in the case where bulk strains are measured using centre-to-centre methods (Fry, 1979; Erslev, 1988). This prompted the authors to describe these latter strain estimates as 'effective' bulk strains distinguishing them from 'true' bulk strain estimates. Meere and Mulchrone (2006) have illustrated that significant underestimates

* Corresponding author.
E-mail addresses: p.meere@ucc.ie (P.A. Meere), k.mulchrone@ucc.ie (K.F. Mulchrone), jwsears@selway.umt.edu (J.W. Sears), michael.bradway@umontana.edu (M.D. Bradway).

0191-8141/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2008.06.008

of strain result from existing methodologies in low strain settings. In many cases there may be no direct evidence of deformation (e.g. cleavage development, intra-granular deformation) in rocks that behaved in this 'non-passive' fashion, which can lead to significant strain being overlooked when constructing orogenic foreland cross sections. This study characterizes this 'hidden' strain in two settings where 'non-passive' behaviour is clearly evident and presents a possible strategy to better quantify finite strain in such settings.

2. Geological settings

The clastic sedimentary rocks analysed for strain in this study come from the Lower Devonian of the Dingle Peninsula, south west Ireland (Fig. 1a) and the Upper Cretaceous of the Sun River Canyon area of the Rocky Mountain Front of western Montana (Fig. 1b). Both geological settings benefit from the presence of high-quality independent strain markers that provide reliable verification of the strain analysis techniques used in this study.

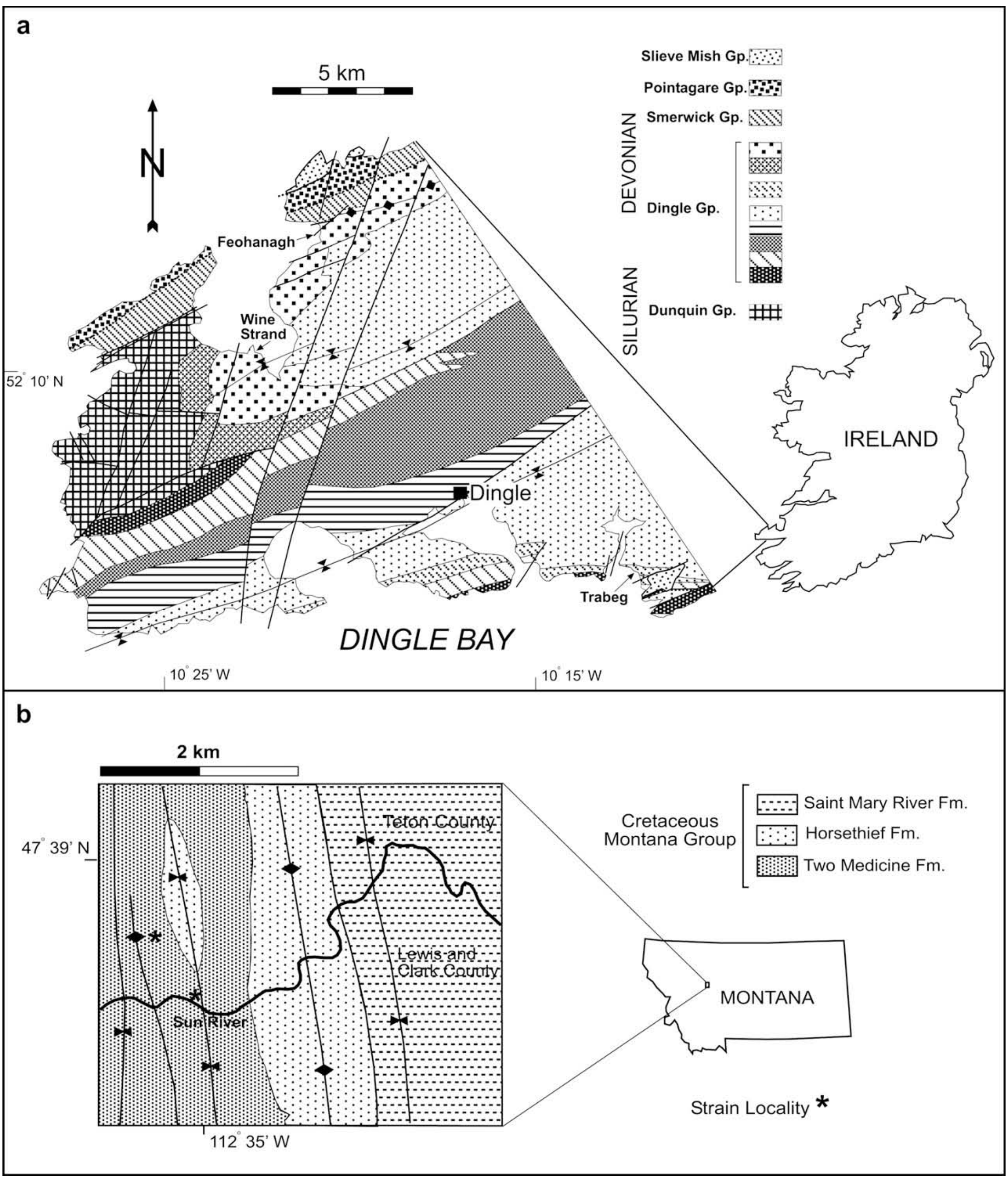

Fig. 1. Generalized geology map of (a) the western end of the Dingle Peninsula, western Ireland and (b) the Sun River area of western Montana showing the strain localities for this study.

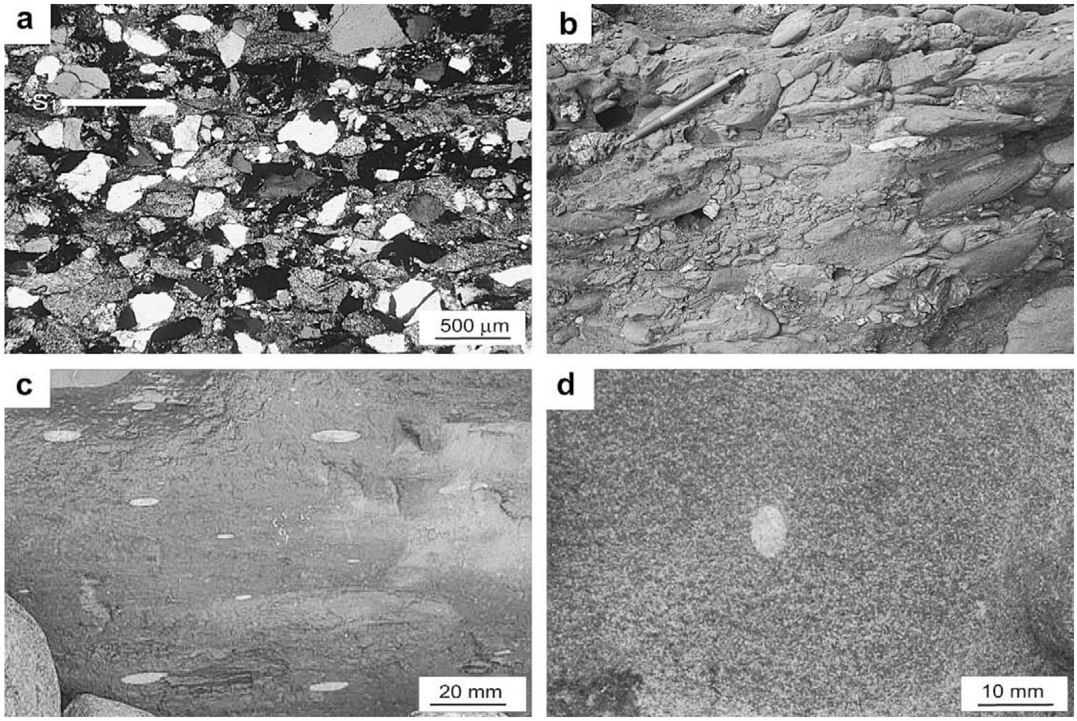

Fig. 2. (a) Photomicrograph of deformed litharenite in the Glashabeg Formation at Wine Strand, Dingle Peninsula. Trace of S_1 cleavage fabric shown. (b) Deformed polymict conglomerate in the Glashabeg Formation at Feohanagh Pier, Dingle Peninsula. (c) Reduction spots (*YZ* plane) in red siltstones of the Glashabeg Formation from the Feohanagh Pier area, Dingle Peninsula. (d) Reduction spot (*XY* plane) in coarse grained sandstone of the Ballydavid Formation from the Feohanagh Strand area, Dingle Peninsula.

The rocks from the Dingle Peninsula consist of two basin-margin conglomerate/sandstone sequences (Glashabeg and Trabeg Conglomerate Formations) that represent part of the continental infilling of the Late Silurian/Early Devonian Dingle Basin (Horne, 1974). The basin extends for c. 60 km along the axis of the Dingle Peninsula following a NE–SW trend and has been described as a pull-apart structure within the Iapetus Suture Zone of the Caledonides (Todd et al., 1988). The basin fill was deformed during the Middle Devonian Acadian orogeny, which imparted a strong penetrative cleavage fabric in the basin fill (Meere and Mulchrone, 2006). Most of the sandstones exhibit little or no evidence of penetrative deformation in hand specimens but display a clear partitioning of strain between clasts and matrix in thin section (Fig. 2a). The sandstones comprise clast supported (15–20% matrix) lithic greywackes (Dott, 1964) with the lithic component predominantly consisting of volcanic material that makes up less than 30% of the total clast component, the remaining clasts consisting of quartz. There is little evidence of pressure–solution effects or of pervasive intra-crystalline deformation mechanisms in the quartz and volcanic clasts; individual clasts retain the angular morphologies of the original, immature sediment. The conglomerates studied predominantly consist of clast supported polymict (volcanics, vein quartz, ‘rip-up’ mudstones, jasper) lithologies that exhibit broadly similar behaviour to the sandstones with some minor brittle fracturing at clast–clast contacts (Fig. 2b). The Dingle material contains well-developed reduction spots in siltstones (Fig. 2c) and more critically, in coarse-grained sandstones (Fig. 2d), which allow a reliable independent estimate of finite strain to be determined from these lithologies. There is limited control on precise *P*–*T* conditions associated with Acadian deformation on the Dingle Peninsula but overburden for the units studied would not have exceeded 1 km at the initiation of basin inversion.

The Sun River localities (Fig. 1b) are found at the leading eastern edge of the Rocky Mountain thrust belt in sandstones of the Two Medicine Formation and conglomerate of the Horsethief Creek Formation. These immature clastic units were deposited in

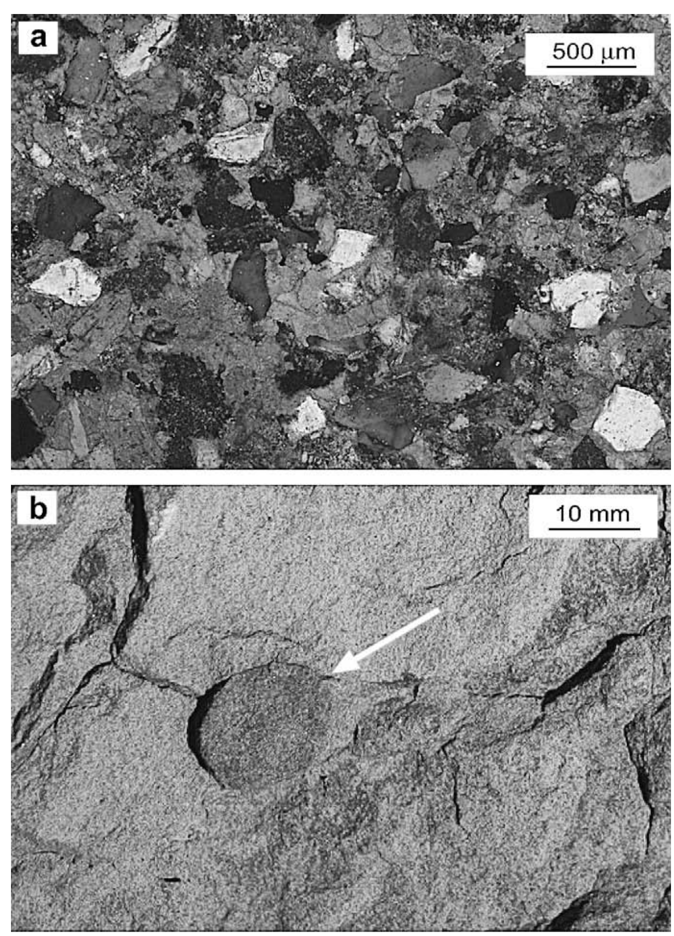

Fig. 3. (a) Photomicrograph of sandstone in the Two Medicine Formation from the Sun River area, western Montana. (b) Deformed ‘crayfish’ (*Camborygma*) burrow in the Two Medicine Formation from the Sun River area, western Montana.

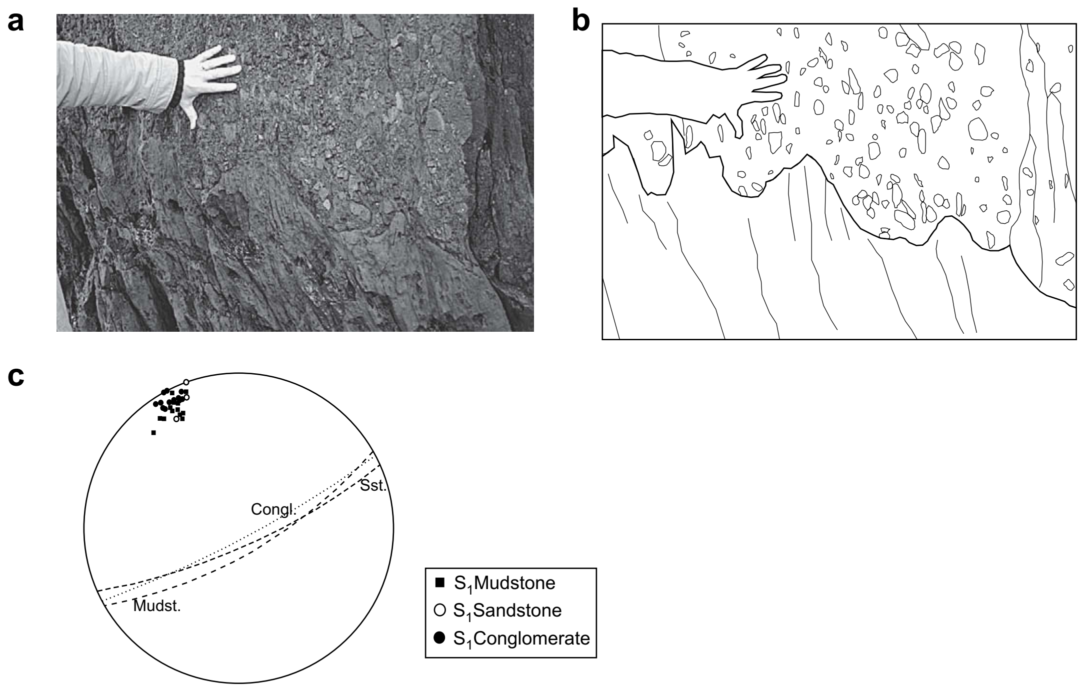

Fig. 4. (a) Photograph and (b) line drawing of an erosive contact with flame structures between a deformed polymict conglomerate and mudstone in the Glashabeg Formation at Wine Strand, Dingle Peninsula. The crests of the flame structures extend into the outcrop parallel to the cleavage fabric, (c) cleavage orientation data from the Wine Strand area for mudstones, sandstones and conglomerates demonstrating the absence of significant cleavage refraction across lithological contacts.

a foreland basin at about 75 Ma and consist of clast supported lithic greywackes with the dominant clast type again being volcanic in origin (Fig. 3a). They were deformed at about 60 Ma at very shallow burial depths of a few hundred metres. The strata experienced layer-parallel shortening prior to buckling and faulting, as evidenced by local pressure–solution cleavage normal to bedding. The samples studied are from structurally-tilted beds above thrust faults. Sandstone beds of the Two Medicine Formation contain originally vertical burrows with elliptical cross-sections that record the strain (Fig. 3b).

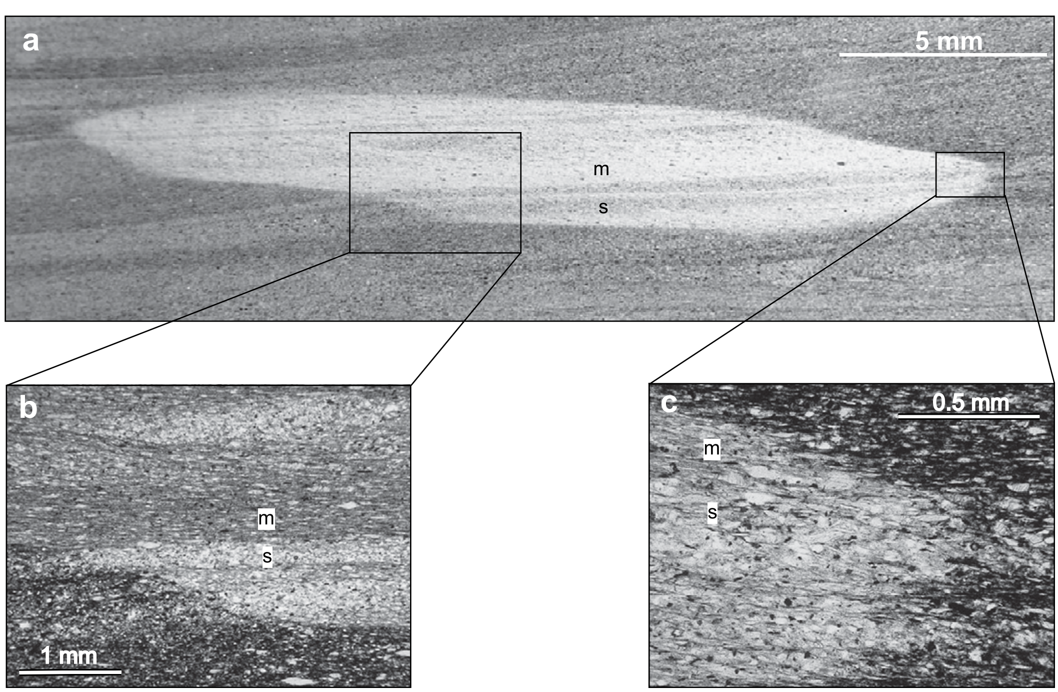

Fig. 5. (a) Photograph of the *XZ* plane of a reduction spot in a mixed mudstone (m)/siltstone (s) lithology with photomicrographs (b and c) of the effect of the main siltstone layer on the reduction spot boundary geometry.

3. Methodology

This study utilizes three established strain analysis techniques, the Robin (Robin, 1977) and mean radial length (Mulchrone et al., 2003) methods to characterize effective clast strain (R_o) and the Delauney triangulation nearest neighbour method (DTNNM) (Mulchrone, 2003) to quantify effective bulk finite strain (R_b) in the lithologies studied. These methods will be taken as representative of the full suite of strain analysis methodologies that assume passive 'strain-marker' behaviour during deformation. The Robin (1977) method, which does not depend on the markers approximating elliptical shapes, involves drawing a set of axes through the centre of a given set of markers parallel to a set of predefined reference axes. The logarithmic average of these axial ratios is taken as the R_s value for the section. The Mulchrone et al. (2003) method is based on the conceptually simple fact that the averaged parameters of an initial ellipse distribution (i.e. the unstrained state) defines a circle, so that in the strained state the averaged parameters define the strain ellipse. The DTNN method (Mulchrone, 2003) involves calculating a Delaunay triangulation for a set of points which generates a set of lines connecting nearest neighbours, thereby providing the information required for a nearest-neighbour strain analysis. The DTNNM does not strictly rely on passive strain marker behaviour; it assumes that the object centres move relative to each other in a passive manner during deformation.

In addition to the 'conventional techniques' listed above and in the absence of internal clast deformation in the lithologies studied, the method of Mark (1973) for quantifying long-axis clast alignment was also used as a proxy measure of strain. If the direction of maximum clustering of clast long-axes is taken as the eigenvector V_1, the degree to which these axes cluster about V_1 in two dimensions can be given by the eigenvalue S_1:

$$S1 = \frac{1}{n}\sum_{i=1}^{n}\cos^2\phi_i \quad (1)$$

where φ_i is the angular deviation of individual clast long axes from V_1.

Strain parameters (aspect ratio/long axis orientation) were extracted from field images and photomicrographs using the semi-automated parameter extraction software (SAPE) of Mulchrone et al. (2005). A minimum of 150 clasts were analysed for each section following the recommendations of Meere and Mulchrone

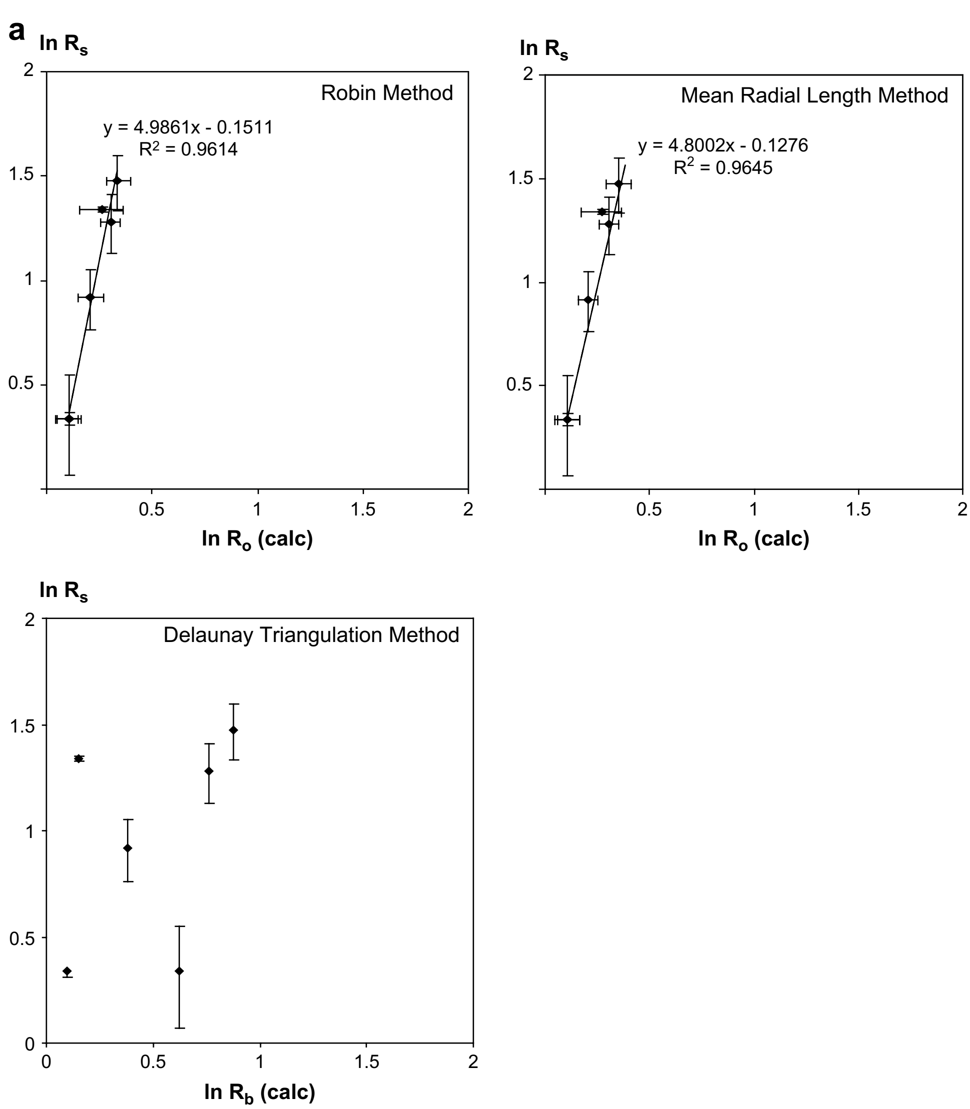

Fig. 6. Plot of natural clast strain [ln(R_o)] and effective bulk strain [ln(R_b)] estimates derived from the methods listed versus best estimate of true strain [ln(R_s)] using independent strain markers for (a) sandstones and (b) conglomerates. The 95% confidence interval error bars are also included.

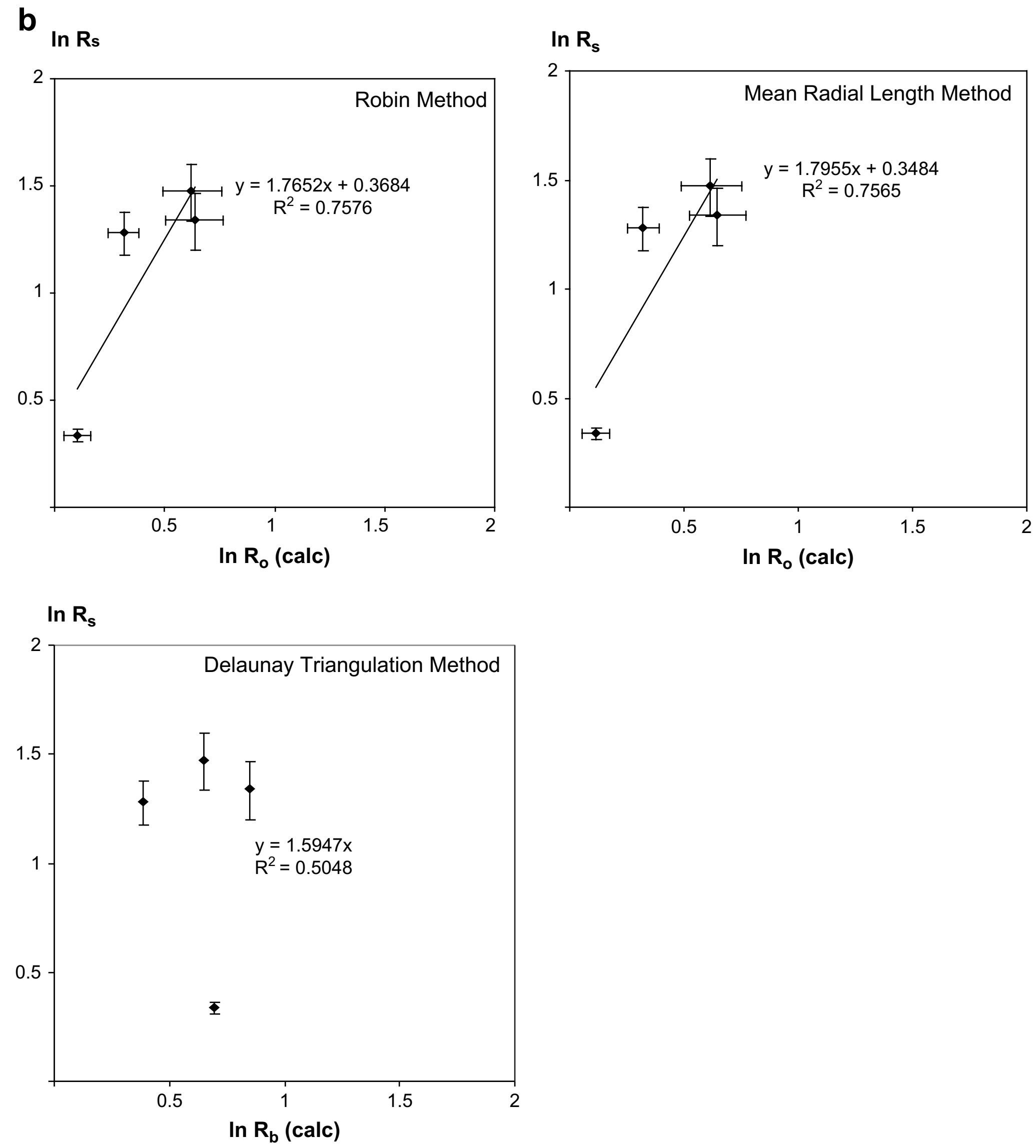

Fig. 6. (*continued*)

(2003). The results from these methods were compared to independent high-quality strain gauges, reduction spots in siltstones and sandstones from the Irish Devonian (Fig. 2c,d) and deformed 'crayfish' burrows (*Camborygma*) from the Two Medicine Formation of western Montana (Fig. 3b). Where possible, calculated strain estimates were compared to reduction spot/burrow data from the same lithology and the same sectional orientation. Where this comparison was not possible within a single lithology, data were only compared where strain compatibility required strain values to be similar from the lithologies in question, e.g. shallow-dipping inter-bedded conglomerates and reduction-spot-bearing mudstones with no evidence of mechanical decoupling or significant cleavage refraction between both lithologies. In the case of the Wine Strand locality, which is close to the core of the Ballyferriter Syncline (Horne, 1976), bedding is dipping at less than 10° with the penetrative cleavage in all lithologies dipping more than 80° (Fig. 4c).

4. Validity of reduction spots as finite strain markers

The use of reduction spots as finite strain markers is well established in the structural geology literature (e.g. Ramsay and Wood, 1973; Tullis and Wood, 1975; Ramsay and Huber, 1983) and is based on the assumption that these features predate tectonic strain and represent early diagenetic spheres of reduced iron. These structures would deform in a totally passive manner as there is no mechanical competency contrast between marker and matrix. Nakamura and Borradaile (2001) have argued however that reduction spots in the Cambrian slates of North Wales are a post strain diffusion feature, the geometry of which reflects a diffusion anisotropy during growth and migration of the reduction front. This anisotropy, is argued, is due to a phyllosilicate petrofabric produced during cleavage development. This therefore raises a fundamental question concerning the validity of reduction spots as strain markers in the lithologies from the Dingle Peninsula of southwest Ireland. Fig. 5a is a detailed *XZ* plane view of a reduction spot in a low angle cross laminated siltstone from the lower Devonian Glashabeg Conglomerate Formation from the Feohanagh Pier area of north Dingle (Fig. 1a). The cross lamination is characterized by alterations in silt grain size and is seen to make a 6–8° angle with the cleavage fabric (defined by the aligned orientation of chlorite-mica stacks and thin dissolution seams) in the plane of section. The long axis of the reduction spot runs parallel to the cleavage fabric. A close examination of the reduction spot geometry in this lithology reveals a marked discontinuity in the curvature of the reduction spot boundary between the fine-grained and coarse-grained siltstone components (Fig. 5b,c). A model of reduction spot development that involves post deformation diffusion from a centre, as proposed by Nakamura and Borradaile (2001), could not produce this dramatic alternation in boundary geometry. This could only be achieved by differential shortening within these lithologies during cleavage development resulting in the less deformed coarser grained boundaries preserving a boundary curvature that reflects this lower strain regime and that is closer to the original unstrained geometry, which in turn supports the assumption that these reduction spots predate deformation and are valid strain markers for these lithologies.

5. Results

Fig. 6 compares the best estimate of true strain (expressed as natural strain, $\ln R_s$) in sandstones and conglomerates using reduction spots and deformed burrows against strain calculated using the Robin and mean radial length methods for clast strains (R_o) and the DTNNM method for effective bulk strains (R_b). It is evident that the strain analysis techniques yield a significant underestimation for both R_o and R_b results. For sandstones this underestimation is up to 75% of the true strain value; the highest discrepancies are recorded in the R_o estimates (Fig. 6a). The bulk strain (R_s) estimates from the DTNNM analysis also show significant underestimates. Results from the analysis of conglomerates, while showing a better estimation of true strain, again demonstrate a significant underestimation (Fig. 6b). However, it is also evident from Fig. 6 that the relationship between the 'true' and calculated strain is systematic and linear, especially in the case of sandstones where R^2 correlation values greater than 0.9 are the norm with the R_o estimates. Conglomerates do not exhibit the same level of correlation between 'true' and calculated strain values.

Fig. 7 presents clast alignment (measured using the S_1 eigenvalue of Mark, 1973) versus 'true' strain and shows a systematic linear relationship across the range of strain values studied. This is best demonstrated by conglomerates with an R^2 value greater than 0.9.

6. Discussion

It is our contention that a relatively incompetent clay-rich matrix facilitated the non-passive strain behaviour of the clasts analysed in this study, effectively cushioning these clasts from internal deformation. The long-axis alignment of the competent clasts was probably achieved by a combination of rigid body rotation, layer boundary slip and most likely involved significant particle–particle interactions. This type of behaviour would be expected in wacke lithologies where there is a sufficient amount of matrix. It is interesting to note that the matrix component of the Sun River lithic wackes shows little evidence of penetrative deformation and represents a low strain end-member for this type of behaviour. This type of deformation may well have been facilitated by elevated fluid pressures and a low effective stress regime during deformation. The Dingle lithologies show evidence of tectonic dewatering, including well-developed planar arrays of large scale flame structures in the Wine Strand area (Fig. 4).

Results from this study clearly show that existing strain analysis techniques using sedimentary clasts yield significant underestimates of finite strain when these clasts have not behaved passively. This is especially true in the case of R_o values from sandstones with underestimates of up to 70%. It is our contention that the primary reason for this behaviour is the absence of intra-clast deformation in these lithologies, i.e. the methods utilized are recording the amount of rigid body rotation and repacking of clasts achieved by grain boundary slipping during deformation. It may well be the case that ongoing thinning in the shortening direction would lead to increased clast/clast contacts that would in turn result in a mechanical stress supporting framework that would limit further strain. These lithologies also demonstrate partitioning of strain into the rock matrix where there is clear evidence of penetrative strain and the development of strong microscopic and mesoscopic fabrics.

As expected, the effective bulk strain values (R_b) are generally closer to the true strain estimates. However, it is important to note that these (R_b) data are still showing significant underestimates and poorer correlations with true strain. In addition to the processes outlined above it may well be the case that clast concentration has an important role to play in this behaviour. The observed R_b underestimation and poor correlation with true bulk strain values support the contention of Vitale and Mazzoli (2005) that higher

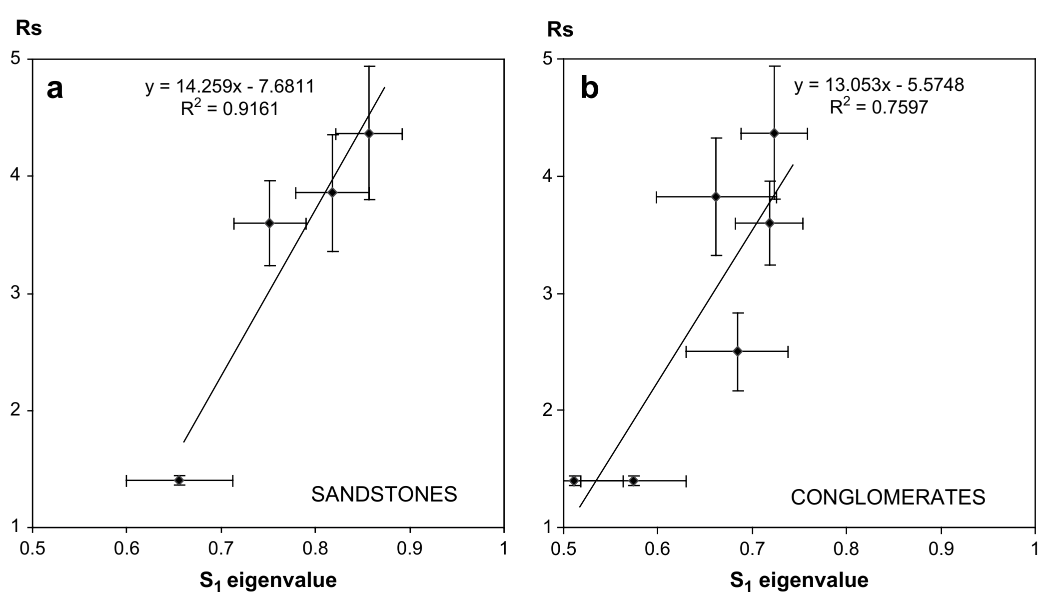

Fig. 7. Plot of S_1 eigenvalue (fabric strength) versus best estimate of true strain using independent strain markers for (a) sandstones and (b) conglomerates.

clast concentrations lead to higher underestimates of bulk strain with less of an effect on object strain (R_o). Overall, the higher underestimation observed in the R_o values from the sandstones may reflect higher packing and clast concentration values than those observed in the conglomerates.

While the underestimation of strain is evident from these results, it is also clear that the degree of this underestimation is consistent across the full range of strain regimes studied; this consistency is demonstrated by high R^2 correlation values between calculated R_o estimates and 'true' strain values, especially in the case of sandstones where R^2 values >0.9 are the norm. This consistency in the relationship between calculated and 'true' strain provides the opportunity for calculated strain values to be 'corrected' for this underestimation in cases where non-passive behaviour is demonstrated. A sensible strain analysis strategy would involve calibration and correction of existing techniques, including S_1 eigenvalue data, to true strain using high-quality strain markers across a range of lithologies.

It is our contention, based on this analysis, that significant penetrative strain, in the absence of independent reliable strain markers, can remain effectively 'hidden' in low grade foreland settings where conventional clast-analysis techniques may be the only option available for the estimation of finite strain. This study also confirms the earlier arguments of Gay (1968a,b, 1976); Bilby et al. (1975), Treagus and Treagus (2001) and Treagus and Treagus (2002) that this type of non-passive strain behaviour is closer to the rule than the exception during the deformation of clastic sedimentary rocks in such low-grade foreland settings.

Acknowledgements

The authors would like to thank Sudipta Sengupta and an anonymous reviewer for two very constructive reviews that made us aware of important previous work not included in the original manuscript. PM would like to acknowledge the support of the Sabbatical Leave Committee of University College Cork.

References

Bilby, B.A., Eshelby, J.D., Kundu, A.K., 1975. The change of shape of a viscous ellipsoidal region embedded in a slowly deforming matrix having a different viscosity. Tectonophysics 28, 265–274.
Dott, R.H., 1964. Wacke, greywacke and matrix – what approach to immature sandstone classification? Journal of Sedimentary Petrology 34, 625–632.
Dunnet, D., 1969. A technique of finite strain analysis using elliptical particles. Tectonophysics 7, 117–136.
Erslev, E.A., 1988. Normalized center-to-center strain analysis of packed aggregates. Journal of Structural Geology 10, 201–209.
Fry, N., 1979. Random point distributions and strain measurement in rocks: Tectonophysics 60, 69–105.
Gay, N.C., 1968a. Pure shear and simple shear deformation of inhomogeneous viscous fluids. 1. Theory. Tectonophysics 5, 211–234.
Gay, N.C., 1968b. Pure shear and simple shear deformation of inhomogeneous viscous fluids. 2. The determination of the total finite strain in a rock from inclusions such as deformed pebbles. Tectonophysics 5, 295–302.
Gay, N.C., 1976. The change of shape of a viscous ellipsoidal region embedded in a slowly deforming matrix having a viscosity – a discussion. Tectonophysics 35, 403–407.
Ghosh, S.K., Sengupta, S., 1973. Compression and simple shear of test models with rigid and deformable inclusions. Tectonophysics 17, 133–150.
Horne, R.R., 1974. The lithostratigraphy of the late Silurian to early Carboniferous of the Dingle Peninsula, County Kerry, Ireland. Geological Survey of Ireland Bulletin 1, 395–428.
Horne, R.R., 1976. Geological Guide to the Dingle Peninsula. Geological Survey of Ireland Guide Series No. 1, 36–37.
Lisle, R.J., 1979. Strain analysis using deformed pebbles: the influence the initial pebble shape. Tectonophysics 60, 263–277.
Lisle, R.J., 1983. Estimation of viscosity contrast and finite strain from deformed elliptical inclusions. Journal of Structural Geology 6, 603–609.
Mandal, N., Samanta, S.K., Bhattacharyya, G., Chakraborty, C., 2003. Deformation of ductile inclusions in a multiple inclusion system in pure and simple shear. Journal of Structural Geology 25, 209–221.
Mark, D.M., 1973. Analysis of axial orientation data, including till fabrics. Geological Society of America Bulletin 84, 1369–1374.
Meere, P.A., Mulchrone, K.F., 2003. The effect of sample size on geological strain estimation from passively deformed clastic sedimentary rocks. Journal of Structural Geology 25, 1587–1595.
Meere, A., Mulchrone, K.F., 2006. Timing of deformation within Old Red Sandstone lithologies from the Dingle Peninsula, southwest Ireland. Journal of the Geological Society of London 163 (3), 461–469.
Mulchrone, K.F., 2003. Application of Delaunay triangulation to the nearest neighbour method of strain analysis. Journal of Structural Geology 25, 689–702.
Mulchrone, K.F., O'Sullivan, F., Meere, P.A., 2003. Finite strain estimation using the mean radial length of elliptical objects with bootstrap confidence intervals. Journal of Structural Geology 25, 529–539.
Mulchrone, K.F., Meere, A., Roy Choudhury, K., 2005. SAPE: a program for semi-automatic parameter extraction for strain analysis. Journal of Structural Geology 27, 2084–2098.
Nakamura, N., Borradaile, G., 2001. Do reduction spots predate finite strain? A magnetic diagnosis of Cambrian slates in North Wales. Tectonophysics 340, 133–139.
Ramsay, J.G., 1967. Folding and Fracturing of Rocks. McGraw-Hill, New York, 568 pp.
Ramsay, J.G., Wood, D.S., 1973. The geometric effect of volume change during deformation processes. Tectonophysics 16, 263–277.
Ramsay, J.G., Huber, M.I., 1983. Strain Analysis. The Techniques of Modern Structural Geology, Vol. 1. Academic Press, 307 pp.
Robin, P.F., 1977. Determination of geologic strain using randomly oriented strain markers of any shape. Tectonophysics 42, 7–16.
Todd, S.P., Boyd, J.D., Dodd, C.D., 1988. Old Red Sandstone sedimentation and basin development in the Dingle Peninsula, southwest Ireland. In: McMillan, N.J., Embry, A.F., Glass, D.J. (Eds.), The Devonian of the WorldMemoir, 14(II). Canadian Society of Petroleum Geologists, pp. 251–268.
Treagus, S.H., Treagus, J.E., 2001. Effects of object ellipticity on strain, and implications for clast-matrix rocks. Journal of Structural Geology 23, 601–608.
Treagus, S.H., Treagus, J.E., 2002. Studies of strain and rheology of conglomerates. Journal of Structural Geology 24, 1541–1567.
Tullis, T.E., Wood, D.S., 1975. Correlation of finite strain from both reduction bodies and preferred orientation of mica in slate from Wales. Geological Society of America Bulletin 86, 632–638.
Vitale, S., Mazzoli, S., 2005. Influence of object concentration on finite strain and effective viscosity contrast: insights from naturally deformed packstones. Journal of Structural Geology 27, 2135–2149.