Journal of Structural Geology 33 (2011) 271–279

Contents lists available at ScienceDirect

Journal of Structural Geology

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

Recognizing soft-sediment structures in deformed rocks of orogens

John W.F. Waldron*, Jean-François Gagnon [1]

Department of Earth and Atmospheric Sciences, University of Alberta, 1-26 ESB, Edmonton, AB, Canada T6G 2E3

ARTICLE INFO

Article history:
Received 31 January 2010
Received in revised form
13 May 2010
Accepted 20 June 2010
Available online 30 June 2010

Keywords:
Soft-sediment deformation
Slope processes
Liquefaction
Folds
Overprinting

ABSTRACT

Soft-sediment deformation structures are common on passive continental margins, in trenches at subduction zones, and in strike-slip environments. Rocks from all these tectonic environments are incorporated into orogens, where soft-sediment deformation structures should be common. However, recognizing soft-sediment structures is difficult where superimposed tectonic structures are present. In seeking characteristic features of soft-sediment deformation, it is important to separate questions that relate to physical state (lithified or unlithified) from those that address the overall kinematic style (rooted or gravity driven). One recognizable physical state is liquefaction, which produces sand that has much lower strength than interbedded mud. Hence structures which indicate that mud was stronger than adjacent sand at the time of deformation can be used as indicators of soft-sediment deformation. These include angular fragments of mud surrounded by sand, dykes of sand cutting mud, and most usefully, folded sandstone layers displaying class 3 geometry interbedded with mud layers that show class 1 geometry. All these geometries have the potential to survive overprinting by later superimposed tectonic deformation; when preserved in deformed sedimentary rocks at low metamorphic grade they are indicators of liquefaction of unlithified sediment during deformation.

1. Introduction

Soft-sediment deformation is a widespread phenomenon in a variety of tectonic settings including passive continental margins, subduction zones, and strike-slip environments. Because basins from these environments occur in orogens, soft-sediment structures would be expected to be equally common in the deformed rocks of orogens. However, separating soft-sediment deformation structures from those induced by later tectonism is challenging.

This article stems from a discussion in the early 1980s, between the senior author and Paul F. Williams, to whom this issue is dedicated, about the nature of structures in deformed clastic sedimentary rocks at low grade in central Newfoundland (Williams, 1983). Subsequent work by Paul and his students (e.g. Elliott and Williams, 1988) elsewhere in Newfoundland indicated that folds previously interpreted as synsedimentary had in fact formed much later in the deformation history. In the process, they showed that many of the features previously used as indicators of 'soft-sediment deformation' are invalid. Maltman (1994a) lamented the lack of clear criteria for recognizing the products of soft-sediment deformation where later tectonic overprints are present, a problem which has concerned both sedimentary and structural geologists for many decades. Since that time much has been learned about processes that deform sediment on present-day continental margins. The purpose of this article is briefly to review the occurrence of present-day soft-sediment deformation in environments that have the potential for preservation in future orogenic belts, and to suggest some geometrical criteria for the recognition of soft-sediment structures, particularly folds, in ancient orogens, where they have been overprinted by later tectonic events.

2. Soft-sediment deformation: definition

We define soft-sediment deformation, following Maltman (1984, 1994b) as any deformation, other than vertical compaction, of a sediment or sedimentary rock that is achieved by rearrangement of the original sedimentary particles, without internal deformation of those particles or of any interstitial cement. Deformation occurs primarily by the mechanism of grain-boundary sliding. Soft-sediment deformation, thus defined, passes imperceptibly into sedimentary processes such as debris flow. In general, processes like slumping, that leave some of the original bedding of previously deposited sediment, are included in 'soft-sediment deformation' whereas those that largely destroy pre-existing structures, such as debris flow, are generally regarded as

* Corresponding author. Tel.: +1 780 492 3892; fax: +1 780 492 2030.
E-mail address: john.waldron@ualberta.ca (J.W.F. Waldron).
[1] Present address: Shell Canada Limited, 400 4th Avenue S.W., P.O. Box 100, Station M, Calgary, Alberta T2P 2H5, Canada.

0191-8141/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2010.06.015

sedimentation processes, but the distinction is arbitrary (Maltman, 1994b). In sandstones or conglomerates where grains have low sphericity, soft-sediment deformation typically produces no penetrative fabric at grain-scale. Where sedimentary grains have inequant shapes, however, it is possible for soft-sediment deformation to produce a fabric, though it is usually weak. Inequant grain-shapes are almost universal in fine-grained sediments (silt and mud) and indeed, fine-grained sedimentary rocks typically display a fabric (fissility), resulting from the preferred orientation of inequant grains during compaction. Because a fabric acquired during synsedimentary deformation might conceivably be emphasized mimetically during later tectonic deformation, the presence of a related fabric cannot unequivocally be taken as evidence that a structure is of tectonic origin.

3. Occurrence of soft-sediment deformation

Deformation of unlithified sediment occurs in numerous present-day environments, including unstable terrestrial slopes, areas of rapid marine and marginal marine sedimentation such as deltas, and sedimentary basins that are cut by active faults. In many such areas, soft-sediment deformation is a major hazard for human populations (e.g. Brunsden and Prior, 1984). To reduce the associated risk, significant research and engineering effort have been devoted to the prediction and even prevention of soft-sediment deformation (e.g. Hearn and Griffiths, 2001).

Actualism suggests that analogous structures must exist in ancient sedimentary rocks, and studies in undeformed sedimentary basins have typically been successful in identifying the products of soft-sediment deformation where contemporary tectonic structures are absent (e.g. Collinson, 1994; Strachan and Alsop, 2006; Strachan, 2008). In many such areas, soft-sediment deformation is associated with gravitationally driven movement of sediment down slopes that were formed during sediment deposition. The acquisition of deep seismic reflection profiles from continental slopes has enormously increased our knowledge of such structures on passive continental margins (e.g. Bilotti and Shaw, 2005; Morgan, 2003; Morley and Guerin, 1996; Morley, 2003).

Two challenging and distinct groups of questions arise in the discussion of soft-sediment deformation processes recorded in ancient rocks. The first group relates to the mechanical state of the sediments at the time of deformation: where they compacted, cemented, or otherwise lithified, and how strong were they? The second group of questions relates to the larger scale driving forces that led to deformation. This group includes questions like 'was deformation entirely due to gravitational instability of slopes or was part of the differential stress for deformation supplied by tectonic movements at depth?'. The second group of questions is often summarized as a dichotomous choice between 'gravity-driven' and 'tectonic' deformation. However, this statement of the dichotomy makes a false distinction, because gravitational forces acting on slopes are responsible for a large part of the differential stress even in clearly 'tectonic' deformation processes. For example, in foreland fold and thrust belts, surface slope is a large component of the 'critical taper' required for the self-similar growth of a tectonically driven deformed zone (Dahlen et al., 1984; Davis et al., 1983). A clearer distinction can be made on kinematic grounds between deformation that is 'superficial' because it occurs above a basal detachment that is linked to the surface in both up-slope and down-slope directions, and deformation that is 'rooted' in a shear zone or fault zone at depth (Fig. 1).

Even with this clarification, confusion between the two groups of questions is still common. Most practising geologists have a tendency, once it is shown that deformation occurred in unlithified sediment, to assume that it occurs by superficial, down-slope gravity-driven processes. However, soft-sediment deformation is clearly occurring at many present-day plate boundaries, where the driving force and overall kinematics are driven by rooted, tectonic processes. Furthermore, under some circumstances it is possible for pockets of unlithified sediment to become mobilized during deformation in otherwise lithified sedimentary packages undergoing tectonic deformation (Phillips and Alsop, 2000). Conversely, it is possible for quite large slabs of lithified rock to move, and even deform internally, in a scenario where movement occurs entirely down-slope, displaying 'superficial' kinematics. Fig. 1 presents an idealized, two dimensional representation of the spectrum of deformational processes, with four end-member environments. End-member A (superficial, unlithified) represents superficial down-slope movement of unlithified sediment in slumps and gravity slides. End-member B (rooted, unlithified) includes deformation of unlithified sediments in trenches and strike-slip fault zones. C represents the down-slope movement of lithified material, which, while arguably less common than A or B, is still capable of moving bodies of rock covering many square kilometres (Schultz, 1986). D represents the vast majority of classic rock deformation environments studied by structural geologists working in orogens, in which lithified materials are deformed by rooted processes.

Because answers to the two types of questions are independent, different evidence must be collected in order to answer each. For the second question group – whether the deformation is superficial or rooted – it is unlikely that observations at microscopic or outcrop-scale can provide answers. This can be simply demonstrated with a 'thought experiment'. Sediments at the toe of a continental slope gravity slide (case A) and at the leading tip of a subduction complex with a small 'critical taper' (case B) experience practically identical stresses. The rocks being deformed 'cannot tell' which environment they are in. Therefore, a geologist examining the rocks after deformation is unlikely to be able to tell from evidence in the outcrop, which process occurred. This is born out by the close geometric similarities between fold-thrust belts found at the base of the continental slope on passive continental margins, and those found in compressional orogens (e.g. Bilotti and Shaw, 2005). Only by mapping the basal detachment, to determine whether it links into an up-slope zone of extension in case A, or into a down-dip zone of high pressure metamorphism, in case B, is it possible to distinguish the two cases. Even where an up-slope extension zone is present, careful section balancing calculations are necessary to establish whether shortening at the base of a submarine slope is entirely balanced by up-slope extension, or whether a 'rooted' component is present (Hesse et al., 2009).

However, the distinctions represented by the first question group are based on the mechanical state ('unlithified' vs 'lithified') of the material being deformed; like other deformation mechanisms, soft-sediment deformation can potentially leave microscopic or outcrop-scale evidence of the deformation process. The remainder of this paper addresses the problem of identifying this evidence.

4. Recognition of soft-sediment deformation

Because orogens typically involve former passive margins, major strike-slip faults, and subduction zones, it is extremely likely that they contain numerous examples of soft-sediment deformation structures. However, overprinting by later deformation complicates the understanding of these structures enormously, to the point where few unequivocal criteria are available for their recognition (Maltman, 1994a). In some cases (e.g. Elliott and Williams, 1988; Karlstrom et al., 1982; Pajari et al., 1979; Pickering, 1987; Williams, 1983) major differences of regional interpretation have resulted from contrasting interpretations of the same structures by sedimentologists and structural geologists.