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On the term 'soft-sediment deformation'

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Abstract—The term 'soft-sediment deformation' includes a range of processes and resulting structures whose breadth is only now being recognized. The phrase is therefore often misleadingly loose and fails to convey the nature of the process or structure being reported. Various difficulties, especially the masking of the nature of the material at the time of deformation by later changes, preclude rigorous definitions, but more careful usage is urged. The kind of structure should be specified. The softness of the material is suggested to be equivalent to its cohesion, which in near-surface sediments might be judged from the form of the structure. Inclusion of words such as early or late would help clarify the timing. Of particular growing need is an indication of the generating force, which could derive from some local movement, from gravity, or from tectonism, all of which are now known to act on unlithified material.

THE PHRASE 'soft-sediment deformation' is heard increasingly among structural geologists but nowhere is there a written discussion of the meaning of the term. At the same time there is growing recognition of the range of processes and structures which it might include. While this looseness does have some advantages, it is easy for misleading connotations to be carried. One common usage implies a restriction to gravity-driven surficial slump-folding whereas other workers seem to include all processes of deformation, whether induced by gravity, tectonism, or otherwise, as long as it has taken place in sediment which has not reached the stage of lithification. It is sometimes interchanged with terms such as penecontemporaneous and syn-sedimentary so that a time element is implied as well.

This discussion attempts to air some relevant points with a view to fostering more precise usage of the term, although it remains premature to give rigorous definitions.

SOFT SEDIMENT

Imprecision of meaning arises in the first part of the term partly because the word sediment is now very commonly used as a jargonistic synonym for sedimentary rock, thereby destroying the distinction between lithified and unlithified material, and partly because soft is used with a variety of connotations. For some workers soft means a material of very low strength, whereas for others the term covers the entire range of conditions in which a sediment might exist as long as it is not lithified.

It seems more useful to restrict the meaning of the term to a specific material condition, perhaps in a way analogous to the usage in soil mechanics. There, the consistency of a soil is assessed by qualitative terms such as very soft, soft, medium, stiff, very stiff and hard (Terzaghi & Peck 1948) which can be arbitrarily quantified. Geologists would probably prefer to equate such a scale with the cohesion (ability to resist shearing stress) of the sediment rather than consistency, using either the kinds of adjectives mentioned above or weakly cohesive, strongly cohesive, etc. Consolidation (water loss through burial) seems of less direct use for the purpose of analysing structures in so far as the response to stress of some sediments can be independent of water content. However, the real difficulty in geology is that any such property of the material at the time of its deformation is no longer available in the rock record for measurement.

Moreover, although it is the mechanical properties and their progressive change which are of most relevance to structural geology, ideal definitions of the advance to lithification would also take account of the textural and mineralogical processes which are responsible for the change. However, the relationship is not a straightforward one. To give two examples, sub-aerial sediment might simply dry out and acquire considerable cohesion only to lose it again on rewetting; at deeper levels fluctuating pore-pressure will cause large variations in material behaviour independent of the stage of diagenesis. The petrographic aspect is also hindered by inaccessibility because the mineralogical and textural state of the material at the time of its deformation will almost certainly have been diagenetically altered.

As a working expedient for structural geology, it is suggested that the softness or amount of cohesion of a sediment during the early, water-rich part of its history can be judged from the form of the structure produced by the deformation, in a similar way to the ductility of a deformed rock being assessed from structural style (e.g. Donath & Parker 1964). Although some clays can have mechanical properties independent of the amount of water, for most near-surface sediments the dominating factor is the water content. Factors such as strain-rate, pore-pressure and temperature become important with burial. A water-rich sediment will have very low cohesion (that is, be very soft), grain-boundary sliding will be easy, and the sediment will be macroscopically very ductile. The ductility will be reduced as water is progressively lost and grain slippage is curbed.

Rapid dewatering of sediment at or near the surface might enable brittle structures to be produced. Such structures, could be produced very early but the sediment (in the usage suggested here) could be interpreted as having been hard or strongly cohesive rather than soft, especially if the fractures were sharply bounded. There are cases, of course, as workers such as Helwig (1970) and Woodcock (1976) have made clear, where even very early structures can mimic those formed after lithification, but often such early structures can be recognized by their geological setting or by some special features such as truncated sedimentary boundaries (e.g. see Hobbs *et al.* 1978).

Difficulties of recognition and analysis compound as the material undergoes the commonly long gradation through diagenesis into a rock (e.g. Cowan 1982). A visual appraisal of the structure will be too precarious a way of deducing the state of the deforming material. At this stage in the deformation sequence, criteria for distinguishing even between structures formed in the pre- and post-lithification states are extremely elusive. Fold styles do not differ and orientations are not dependent on the state of the material (Woodcock 1976). The presence of fractures is of little use, because they can form in unlithified material, and mineralization of the fractures might not be reliable, as even at shallow levels of burial, the pore-pressure may be sufficient (although the absolute values would be small) to sustain an open fracture and the fluids able to precipitate solutes. Fibre veins of calcite can form at the soles of glaciers (Ramsay & Dietrich 1981). Striations (often wrongly referred to as slickensides) form readily on shear fracture surfaces in clays with 30% water content.

Kink bands can form in moist clays (Maltman 1977), and they exist in Pleistocene glacial clays. Axial-plane foliations have been recorded from well-documented pre-lithification folds (Williams *et al.* 1969). A feature which is known to form at a specific depth of burial or stage of lithification would form a useful datum plane for separating structures formed earlier and later than that feature, but such objects are rare. Tremlett (1982) has suggested that chlorite–mica stacks form such a datum, but according to Craig *et al.* (1982) their mimetic habit and wide variability in depth of formation would limit their use. Raiswell (1978) has argued that certain concretions form at a depth of about 3 m, and these have been used in the southwest Ceredigion area of Wales for distinguishing between very early ductile faults and those formed after additional burial (J. Craig, pers. comm.). Unambiguous criteria for recognising pre-lithification folds are of such restricted distribution as to be of little general use (e.g. Hobbs *et al.* 1978, p. 157). It still seems true that "the geologist has to assess the cumulative weight of several not infallible criteria" (Fitches & Maltman 1978, p. 245) in order to make a distinction.

Might some more general criterion be discovered in the future? The kinds of macroscopic properties discussed above appear to offer little potential as at that scale of observation the various mechanisms producing the fracture or flow are indistinguishable. The essential difference between pre- and post-lithification behaviour is at the grain scale. Unlithified sediment deforms largely by inter-granular movement, normally with virtually no component of intra-crystalline deformation, whereas, the latter mode dominates after lithification. There are exceptions (e.g. see Borradaile 1981), and a gradation must exist, but it is suggested that for the purposes of discussing the evolution of structures, a material can be regarded as lithified when its cohesion has increased, by either chemical or mechanical means, to the extent that intra-grain deformation is dominant. Records of the latter process such as deformation bands, lamellae, twins and pressure solution features, will be vulnerable to change due to further deformation and the onset of metamorphism, but in some instances they will be adequately preserved.

In addition, it might be that the fabrics at the microscopic scale will be of varying character in different states of lithification, with differences that may be more persistent or of recognizable influence on later structures. For example, the creases reported by Maltman (1978) from experimentally deformed clays but apparently not known in rocks have now been recognized by the author in D.S.D.P. material (cf. Lundberg & Moore 1981), which is still unlithified. Continued investigation of deformed sediments at the microscopic scale, may reveal some fabric or related feature which enables distinction from post-lithification structures.

DEFORMATION

The phrase 'soft-sediment deformation' not only covers a range of conditions of the material as discussed above, but the deformation can be due to forces arising from a variety of causes, which the phrase fails to differentiate. Some of these are discussed here, in three groups: local, gravity and tectonic.

Structures such as convolute lamination, ball-and-pillow, and sedimentary boudinage (e.g. see Collinson & Thompson 1982), are due to local forces arising from essentially sedimentological processes such as sediment liquefaction, reverse density gradients and shearing due to current movement. Sedimentologists commonly term these sorts of structures penecontemporaneous, and although they are sometimes referred to as being due to soft-sediment deformation, (e.g. Blatt *et al.* 1972, p. 175), it would seem more pragmatic to maintain a distinction where possible and not additionally extend the range covered by the latter term.

However, there are cases where the local forces are arising not from the sedimentation process or the sediment itself, but from some other local movement. Examples would be disturbance associated with vulcanicity [thought to have produced the early ductile shear zones at Veryarc'h, on the Crozon Peninsula, Brittany, (Maltman & Fitches 1982)]; arising through glacial processes (e.g. Banham 1975; Bell 1981); and resulting from the nearby emplacement of slumped masses (Maltman 1981, p. 479).

The importance of gravity in disturbing sediments by slumping and sliding has long been recognized (e.g. Hoedemaeker 1973), and it is now known to be responsible for moving very large masses (Woodcock 1979, Saxov & Nieuwenhuis 1982). There is considerable overlap with the local processes mentioned above, as slump structures can be small and of only very local significance, and even in large masses responding to gravity on a regional scale, various localized deformations can commonly arise within the moving body. Kleist (1975) demonstrated that structures due to shearing, compression, and extension are found in close proximity to each other within units which have slumped on the regional scale. Helwig (1970) pointed out that the styles, wavelengths, and orientations of slump folds may vary between different sites within a slump sheet and that structures such as slump folds may only occur in a fraction of the material which has undergone bulk sliding.

All the gravity-driven processes and structures mentioned above would probably be included within the term soft-sediment deformation by most workers, but difficulties compound where tectonic forces are acting on sediment which is still unlithified. Classically, long intervals were inferred between deposition, lithification and orogeny, but the advent of plate tectonic theory has introduced the concept of sediments being subject to tectonism early in their history, well before lithification. Now evidence of the resulting structures is beginning to be reported from recent sediments, in a variety of environments and on differing scales. For example, Moore *et al.* (1982) have reported major thrust or reverse faults and associated structures in muds of the Barbados Ridge; Hancock & Barka (1981) have described tectonic faulting associated with the North Anatolian Transform affecting unlithified sediment; White (1977) has reported folds of up to 10 km wavelength in sediment in the Gulf of Oman; and Lundberg & Moore (1981) have described a variety of fabrics in unlithified sediment from the Middle America Trench Slope. Scholl *et al.* (1980) have discussed the interaction of various tectonic processes in sediments at converging plate margins, and Cowan (1982) has explained how in the sediments of an accretionary prism, gravity and tectonic forces may be acting simultaneously at different levels. It is in this area of tectonic deformation acting on unlithified sediment that the shortcomings and potential difficulties of the phrase under consideration become most apparent.

In the rock record, Morris (1978) reported structures from the Longford-Down Inlier, Ireland, which may represent a stage intermediate between surficial gravity deformation and tectonic, post-lithification structures, implying tectonic forces acting on sediments. Maltman (1978) proposed that the incipient stages of cleavage development occur through the tectonic deformation of unlithified sediment, and Max (1978) drew attention to the gradational nature of sedimentary deformation and structures due to tectonism. Cowan (1980) has considered the pre-lithification tectonic structures preserved in part of the Franciscan complex of California.

The notion that the process of pre-lithification deformation is an isolated entity and quite distinct from tectonic deformation will become increasingly obsolete as further examples of interaction and gradation between the two are reported.

CONCLUSIONS

The phrase soft-sediment deformation can imply such a wide range of sediment conditions and varieties of deformation that wherever possible a more specific term should be used. It might be possible to judge the degree of softness from the form of the structure. Adjectives such as early or late might be added in order to help clarify when in the evolution of the material the structures are thought to have formed. If the deformation was due to primary sedimentological processes then penecontemporaneous would be more appropriate.

If the mechanical state of the sediment cannot be judged then pre-lithification should be resorted to. This will commonly be necessary for material at more advanced burial, at which level any structures formed will be extremely difficult to distinguish from later, post-lithification examples, until some criterion for distinction is found. It seems likely that any such criterion will be at the microscopic scale as it is at the grain scale that the essential difference between pre- and post-lithification deformation is manifest.

The cause of deformation should be specified as far as it is possible. Referring to a structure thought to be a gravity slump fold as soft-sediment deformation is unnecessarily vague. Moreover, the range of pre-lithification processes will undoubtedly grow as research continues into the behaviour of material during diagenesis and into deformation processes taking place on the present-day ocean floor.

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