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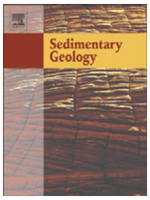

Can once lithified rocks later undergo soft-sediment deformation?

A.J. van Loon [a,*], R. Mazumder [b]

[a] Geological Institute, Adam Mickiewicz University, Maków Polnych 16, 61-606 Poznan, Poland
[b] Geological Studies Unit and Fluvial Mechanics Laboratory, Indian Statistical Institute, 203 B.T. Road, Kolkata 700108, India

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ABSTRACT

Soft-sediment deformation structures (SSDS) have received much attention from sedimentologists, but they use the term 'SSDS' commonly in a loose way. In practice, the term is used, as a rule, for deformation structures that were formed before the sediment has become lithified. This usage is unfortunate because lithification is a gradual process, so that no sharp boundary between soft sediments and lithified rocks exists; moreover, cement can be dissolved again, changing a lithified rock back into a soft sediment. The term 'SSDS' is also sometimes restricted to deformations in sediments that are in a non-brittle state. This usage is unfortunate, because the nature of the deformation (brittle or plastic) depends on the deformation velocity. The type of deformation depends also, however, on temperature and pressure. An exceptional situation is illustrated by a deformation structure in the Proterozoic Chotanagpur Gneissic Complex in eastern India. The gneisses have been intruded after metamorphism by pegmatitic veins, so that the gneisses became plastic again due to the high temperature of the intruding magma. In this plastic state, they became deformed in the same way as soft sediments. The resulting deformation structures can physically not be distinguished from fluid/gas-escape structures in unconsolidated sediments. It seems therefore advisable to distinguish between SSDS (the 'classical' SSDS) and NTDS (non-tectonic deformation structures), which include SSDS formed under extraordinary conditions.

1. Introduction

The term 'soft-sediment deformation structure' (SSDS) is commonly (but colloquially) applied to syn-, meta- and postdepositional deformation structures formed while the sediment is (or was) still not or only slightly lithified (Neuendorf et al., 2005). In this context, 'deformation' is implicitly defined as a change in the original mutual contacts between adjacent grains (Collinson, 2005), with the exception of compaction due to loss of pore water and air (Van Loon, 2009).

In the course of time, it became clear that it is very difficult—if possible at al—to define SSDS precisely and in a satisfactory way, particularly because Nature does not adhere to artificial classifications. Is a salt diapir a SSDS? The formation of a salt diapir is not fundamentally different from the formation of a sand volcano or a mud or browncoal diapir, but plastic deformations in rock salt are commonly considered as 'salt tectonics' rather than as SSDS. Several other deformations exist that have not formed according to the commonly adhered to genesis of SSDS, but that have nevertheless much in common with them and that are difficult to classify in another way. This raises several questions, such as 'Can sediments that have been lithified [e.g. an argillaceous sandstone that has become lithified due to a carbonate cement] undergo soft-sediment deformation afterwards [e.g. if the cement has become dissolved due to acid groundwater]?' or—even more extreme—'Can sediments that have become metamorphosed undergo soft-sediment deformation if—for whatever reason—the metamorphic rock starts to behave physically as a non-lithified rock?' This may seem a matter of semantics, but it is worthwhile to define more exactly what should be considered as soft-sediment deformation, if only because limestones tend to show such a gradual lithification that no sharp boundary exists between 'soft' limestone muds and 'hard-rock' limestones. For this reason, Van Loon (2009) excluded calcareous (and some other) sediments of his classification of SSDS.

In spite of the badly defined terminology, there is a fairly common agreement that SSDS in *siliciclastic* sediments cannot be formed in sedimentary rocks that have reached a stage complete lithification. Yet, it turns out that other processes may result in structures that show all characteristics of SSDS but that were formed after lithification or even after metamorphism. An example of such a situation was found in the Proterozoic Chotanagpur Gneissic Complex in eastern India (Fig. 1).

1.1. Objective

The objective of the present contribution is to reconstruct the process that caused deformation with a SSDS appearance in metasediments of the Chotanagpur Gneissic Complex, so after

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* Corresponding author.
E-mail addresses: tvanloon@amu.edu.pl (A.J. van Loon), mrajat@isical.ac.in (R. Mazumder).

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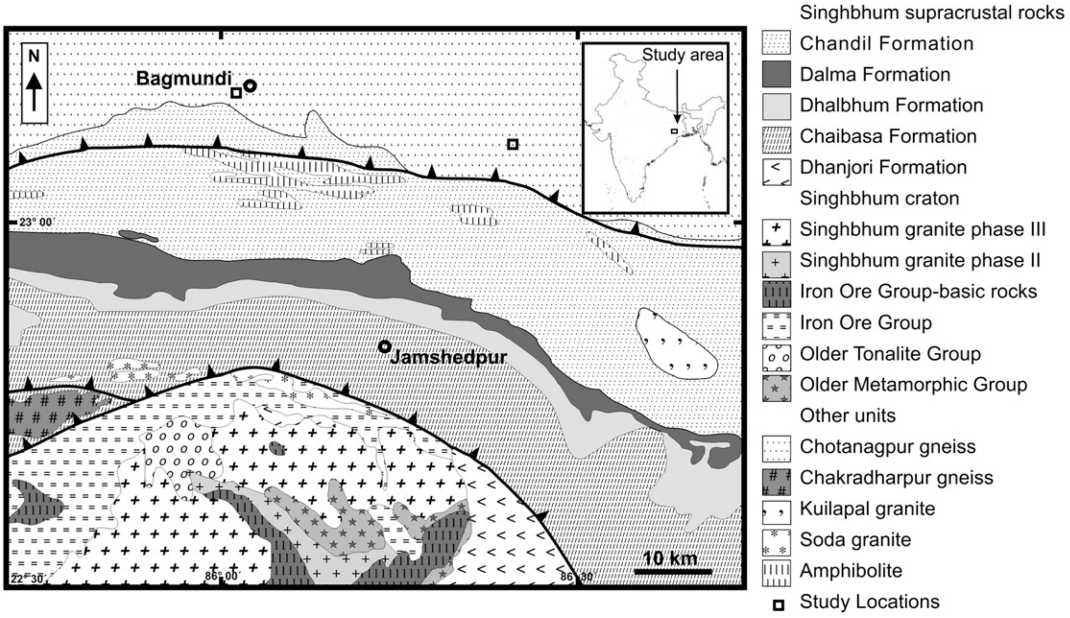

Fig. 1. Geological setting of the study area (modified after Saha, 1994). Study locations are indicated by open squares. The structure detailed in the text is located at the Bagmundi site.

metamorphism. Eventually, it is the intention to indicate under which specific conditions the lithified (metamorphosed) sediments could behave as an unconsolidated siliciclastic sediment that was susceptible for 'soft-sediment' deformation, and what implication this might have for the terminology.

1.2. Geographical and geological setting

The Chotanagpur Gneissic Complex (CGC) is located in the eastern part of India (Fig. 1). It forms an assemblage of migmatites and high-grade gneisses derived from both sedimentary and igneous rocks, intruded by metabasic, anorthositic and granitic pegmatitic rocks (Ghose, 1992; Chatterjee et al., 2008). The suite of metasedimentary rocks includes metapelites, quartzites and calc-silicate rocks. The location studied (Fig. 2) is situated near Bagmundi Hill in the surroundings of Burrabazar (see for more details Ghose, 1992, and Saha, 1994). In contrast to many of the other Proterozoic rock units of this part of the Singhbhum crustal province, the development of the CGC is poorly constrained. The gneisses show polyphase deformation (Figs. 2 and 3), metamorphism and partial melting (Ghose, 1992; Ghose et al., 2005; Chatterjee et al., 2008). The location under study consists of quartzites and metapelites that have become intruded by magmatic veins in various directions (Fig. 2). The veins, which vary from less than a centimeter to about half a meter wide, consist of pink-colored pegmitites that show feldspar crystals up to several centimeters long.

2. The deformation structure

SSDS have been recognized in numerous lithified and even metamorphosed sediments (see, among others, Van Loon, 2009), but it is commonly clear that they must have formed while the deformed sediment was still unlithified. This cannot be the case for the SSDS under study here, as will be shown underneath. This makes this deformation structure special, though not exceptional (cf. Vanderhaeghe, 2001; Bons et al., 2008).

Fig. 2. Exposure of the Chotanagpur Gneissic Complex near Burrabazar. Note the combination of deformed and undeformed pegmatite veins, indicating multiphase intrusions.

Fig. 3. Locally intricately folded vein in the Chotanagpur Gneissic Complex, with roughly parallel thinner veins.

2.1. Description

The 'soft-sediment' deformation structure detailed here consists of bent bedding planes in metasedimentary rocks (gneisses) which were originally presumably alternations of sands, heterolithic units and fine-grained intervals (Ghose, 1992) in which the original layering locally is still visible (Fig. 4) thanks to granulometric and mineralogical differences. The bending is visible at both sides of an irregular pegmatitic vein that runs roughly perpendicular to the bedding plane and that is some 5–20 cm wide; the bent layers are directed in the same upward direction at both sides of the vein (Fig. 5). The bending starts at a distance of approx. 20 cm from the vein at one side of the vein, and at some 5–10 cm at the other side. The bending, which has a curved character, results in a maximum vertical displacement of the deformed layers of about 20 cm.

The resulting structure is identical in appearance to that seen in cross-sections of relatively large fluid-escape structures or small-scale sand volcanoes (see Collinson, 2005; Van Loon, 2010).

2.2. Genetic interpretation

The upward bending of the disturbed gneisses at both sides of the pegmatic vein suggests a causal relationship, particularly because similar bends towards pegmatite veins have been found at several places in the same gneissic complex. This raises the question of whether the bending resulted from the intrusion of the veins, or whether the veins intruded at these specific places taking advantage of some 'zones of weakness' created by earlier formed structures. More specifically, it has to be clarified whether the bending formed (1) as a pre-lithification (=soft-sediment) deformation structure, (2) as a result of low-temperature deformation of a lithified rock (due to movement along a fault plane), or (3) as a result of a post-lithification intrusion.

2.2.1. Arguments against a pre-lithification origin

If the structures under study would have been found in sedimentary rocks without an intrusion, their origin would be easy to explain: they would most likely represent gas/fluid-escape structures. In the case of an escape structure, some reservoir of gas and/or fluid (commonly pore water with dissolved air, sometimes methane) is present in a layer beneath the surficial sediments, and the weight of the overburden eventually forces this gas and fluid (commonly in the form of liquefied sand or mud) to escape into the direction of the lowest pressure (=upwards) (see, among others, Nichols et al., 1994; Netoff et al., 2005; Frey et al., 2009; Davy et al., 2010).

In the case under study, this process cannot have been involved because of several reasons. In the first place, a relationship tends to exist between the height of an escape structure and its width: the escaping fluid or gas erodes material from the sides of the escape pathway, and the longer this pathway is, the more material is carried along. The more material is carried along, the more flows out at the sedimentary surface, and the wider the resulting cone (mud or sand volcano) becomes. In the case under study, the height of the structure is several meters, but the width is only a few decimeters.

Another argument against an origin as a soft-sediment gas- or fluid-escape structure is that the structures are only present as layers that are bent upwards against magmatic veins. It is true that there are veins that are not accompanied by such bent layers, but the same process does not necessarily take place in the same way at each location and at each time. The chance that some of the magmatic veins followed previously formed zones of weakness consisting of escape structures, can be judged as almost nil, the more so considering the small size (dm-scale width) of the deformation structures. Moreover, no escape structures have been found in the gneiss complex, apart from directly along a magmatic vein, which is strong evidence that no escape structures had formed when the sediment was still unconsolidated.

The most convincing argument against a pre-lithification origin of the bent layers—if bent by dragging due to intruding veins—is that intrusion into an unconsolidated sediment would have resulted in heat-induced vitrification of the sands, no signs of which are present (the gneisses around the veins do not show clear signs of contact metamorphism; this suggests that the magma had already cooled down considerably, which, in turn, suggests a highly viscous behavior). In addition, if the veins would have intruded unconsolidated sediments, they would most likely have deformed it, irrespectively of the thickness of the vein or its intrusion velocity. The bent layers are, however, found only at some places, in contact with a few specific veins. Additionally, the gneissic foliation in the metasedimentary rock is clearly cut by the vein, so that the vein must have intruded after metamorphism, which implies, obviously, also after lithification.

2.2.2. Arguments against a relationship with faulting

Veins often form zones of relative weakness during tectonic events, and it can be seen that, at some places, veins in the CGC have acted as fault zones. It is well known that faulting of rocks can result in the bending of the adjacent rocks due to dragging when the rock masses move with respect to one another. It was therefore to be found out whether such tectonic dragging can be held responsible for the bending towards the vein.

In the case of faulting, the dragging caused by the fault movements results in bending of the rocks into different directions (upwards and downwards, respectively) at the two sides of the fault plane, similarly in unconsolidated sediments (Cato, 1989) and lithified rocks (Suppe, 1983; Ramsay and Huber, 1987). In the case studied here, however, the bending is into the same direction at either sides. It must therefore be concluded that the bending of the layers towards the vein cannot be ascribed to dragging resulting from fault movement along the plane where the vein is situated now.

2.2.3. Arguments in favor of bending due to dragging caused by an intruding vein

As mentioned before, the deformation structures show all characteristics of fluid- or gas-escape structures. Their occurrence is, however, as also detailed above, related to a pegmatitic vein, and this vein must have intruded the deformed gneiss after lithification, even after metamorphism. This metamorphosed state implies that it can be excluded that a gas or fluid reservoir existed from where the gas and/or fluid could escape to the then sedimentary surface.

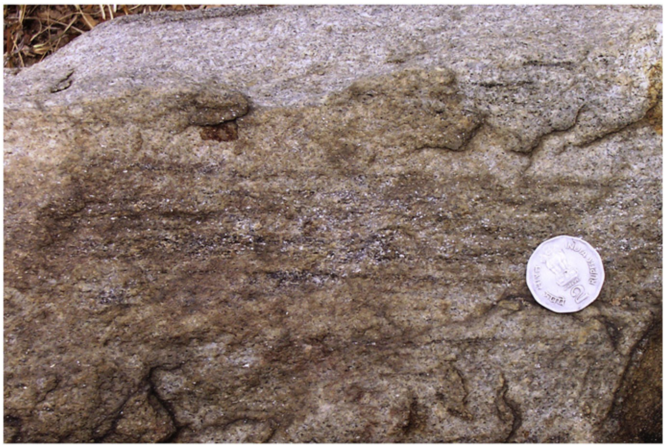

Fig. 4. Still discernable layering in the CGC gneisses, thanks to alternations of more sandy and more muddy layers in the original sediment. Diameter of the coin 25 mm.

Fig. 5. The bending of the layers of the metasedimentary rocks towards a pegmatite vein. The main vein, which is roughly perpendicular to the original layering, is also the source of some thin, sill-like intrusions parallel to the bedding plane. The 'sills' have, like the gneisses underneath and above, been dragged upwards by the slowly intruding, viscous magma of the main vein. The shape of the resulting deformation structure at both sides of the vein is fully comparable to that of fluid/gas-escape structures in unconsolidated sediments. Diameter of the coin 25 mm.

There was, however, another reservoir with a (probably fairly viscous) fluid: the magmatic body from which the intruding veins were derived. As argued above, this hot, viscous material will have moved upwards slowly, heating the surrounding host rock. This host rock consequently must have reached temperatures, certainly in the first few decimeters from the intruding vein that made it even much more plastic than it must have been already because of deep burial. (The fairly coarse character of the pegmatite veins suggests that the intruding magma cooled slowly, indicating relatively deep burial of the rocks—possibly at mid-crust depth—when the intrusion took place. The deep burial must have resulted in a high lithostatic pressure, implying that the intruding veins must have risen slowly).

The heated gneiss alongside the intruding vein thus became plastic, and consequently behaved actually in the same way as an unconsolidated sediment. This 'soft' rock therefore just reacted to the intrusion on the same way as an unconsolidated sediment would do when intruded by an escaping sediment/fluid/gas mixture: the contact zone was dragged upwards, thus forming a structure that is in all respects comparable to an escape structure (cf. Lowe, 1975; Neuendorf et al., 2005; Allaby, 2008).

3. Conclusions

The intrusion of pegmatitic veins in the Chotanagpur Gneissic Complex probably took place at more or less mid-crustal depth. Both the geothermal gradient and the intrusion caused a high temperature in the rocks surrounding the intrusion. This temperature must have been high enough to make the rock sufficiently plastic to become deformed relatively easily.

The slowly intruding vein dragged the adjoining plastic rock along, thus causing bending of this rock over a distance of a few centimeters to a few decimeters, in an upward direction. Consequently, a plastic deformation structure was formed that is comparable in every essential aspect with a fluid-escape structure formed in unconsolidated sediments. As essentially identical conditions prevailed (plastic material, with a reservoir underneath of material that was forced upwards) and as the deformational process (dragging) was identical, it seems—for physical and morphological reasons—attractive to consider such exceptional structures as a special group of soft-sediment deformation structures' (SSDS).

It seems, however, that it might not only lead to misunderstanding if SSDS can be formed in lithified or even metamorphosed sediments, but that the classification of SSDS (even if restricted to siliciclastic sediments) would become much more problematic than it is already (Van Loon, 2009). For this reason, it is suggested that structures like the one described here, be considered as a special group of non-tectonic deformation structures (NTDS). In this context, it seems important for the interpretation of deformation structures in lithified rocks to realize that such deformations need not always be interpreted as tectonic or sedimentary, but that some deformations can also have formed after lithification by a non-tectonic process.

The above will certainly not finish the discussion about the question of whether soft-sediment deformations can be formed after lithification. A previous version of the present manuscript received comments from several reviewers that SSDS can, by definition, not be formed after lithification. They did, however, not comment on the question of whether sediments (e.g. argillaceous sands) that had become lithified (e.g. by a calcite cement) and that had become unlithified again (by dissolution of the cement) can—either for the first time or for a second time—undergo soft-sediment deformation. In other words: is it the earlier history of a sediment or sedimentary rock that determines whether soft-sediment deformations can be formed, or is it the state of the material that is decisive? In our opinion, the best solution is to distinguish between 'classical' soft-sediment deformation structures (SSDS) and non-tectonic deformation structures (NTDS), but any researcher in soft-sediment deformation structures is invited to discuss this viewpoint.

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