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Soft-sediment deformation structures in siliciclastic sediments: an overview

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Abstract

Deformations formed in unconsolidated sediments are known as soft-sediment deformation structures. Their nature, the time of their genesis, and the state in which the sediments occured during the formation of soft-sediment deformation structures are responsible for controversies regarding the character of these deformations. A definition for soft-sediment deformation structures in siliciclastic sediments is therefore proposed.
A wide variety of soft-sediment deformations in sediments, with emphasis on deformations in siliciclastic sediments studied by the present author, are described. Their genesis can be understood only if their sedimentary context is considered, so that attention is also paid to the various deformational processes, which are subdivided here into (1) endogenic processes resulting in endoturbations; (2) gravity-dominated processes resulting in graviturbations, which can be subdivided further into (2a) astroturbations, (2b) praecipiturbations, (2c) instabiloturbations, (2d) compagoturbations and (2e) inclinaturbations; and (3) exogenic processes resulting in exoturbations, which can be further subdivided into (3a) bioturbations – with subcategories (3a') phytoturbations, (3a'') zooturbations and (3a''') anthropoturbations – (3b) glaciturbations, (3c) thermoturbations, (3d) hydroturbations, (3e) chemoturbations, and (3f) eoloturbations. This subdivision forms the basis for a new approach towards their classification.
It is found that detailed analysis of soft-sediment deformations can increase the insight into aspects that are of importance for applied earth-scientific research, and that many more underlying data of purely scientific interest can, in specific cases, be derived from them than previously assumed. A first assessment of aspects that make soft-sediment deformation structures in clastic sediments relevant for the earth sciences, is therefore provided.

Keywords: soft-sediment deformations, siliciclastics, classification, terminology

1. Introduction

The term 'soft-sediment deformation structures' (called 'SSDS' in the following, for both singular and plural) is commonly used loosely to indicate deformations that reflect deformational processes which affected sediments that were not yet lithified (see Mills, 1983; Maltman, 1984; Brodzikowski & Van Loon, 1987; Collinson, 2003a). This implies that they are, in principle, early-diagenetic features (cf. Chilingarian & Wolf, 1992; Van Loon, 1992, 2002, 2003; Van Loon & Brodzikowski, 1994; Moretti et al., 2001), but few earth scientists do consider them like this, restricting diagenesis mainly to the dissolution of components of the original sediment, and to processes related to authigenesis of minerals. They commonly consider, for instance, the authigenesis of minerals in the cracks in septarian concretions (Fig. 1) due to synsedimentary earthquakes (Pratt, 2001) as an early diagenetic process, but they

Fig. 1. Crystal-filled shrinkage cracks in a septarian nodule (Boulonnais, France).

do not indicate whether they also consider the formation of these cracks as an early diagenetic process. The term 'penecontemporaneous' has been introduced in this context, but its meaning is not well defined and it is commonly used only to indicate a process that takes place before lithification of the sediment; the term 'penecontempraneous' therefore does not provide more information then the better defined term 'early diagenetic'.

The variety of SSDS is extremely wide, as is the variety of processes and agents that induce them (Van Loon & Brodzikowski, 1987). Commonly a number of agents and processes is responsible for their formation so that the structures may be very complex (Fig. 2A) and difficult to explain satisfactorily in all their details. One of the problems that are met when interpreting the genesis of an SSDS is that the various deformational processes involved may act simultaneously or as successive events; sometimes some processes act simultaneously, whereas other processes may act successively, all contributing to the formation of one single SSDS (Fig. 2B) (cf. Hall & Ells, 2002; Gruszka & Van Loon, 2007).

The present author has investigated SSDS during the past decades in rocks ranging from Palaeoproterozoic to Holocene, and with deformations ranging in size from microscopic to more than exposure-wide. Consequently, he was confronted time and again with the problem that not only a genetic interpretation is often difficult, but that also descriptions in the literature use classifications and terminology that make SSDS difficult to compare with one another. The present contribution is therefore aimed, apart from providing examples of SSDS (largely on the basis of own research), at providing a proposal for terminology to be used, as well as a classification of SSDS that can be applied in a flexible way. This is done in a way that does not pretend to cover all aspects of SSDS, but that rather is intended to show how to approach the analysis of SSDS in such a way that communication about them with fellow-earth scientists may gain clarity.

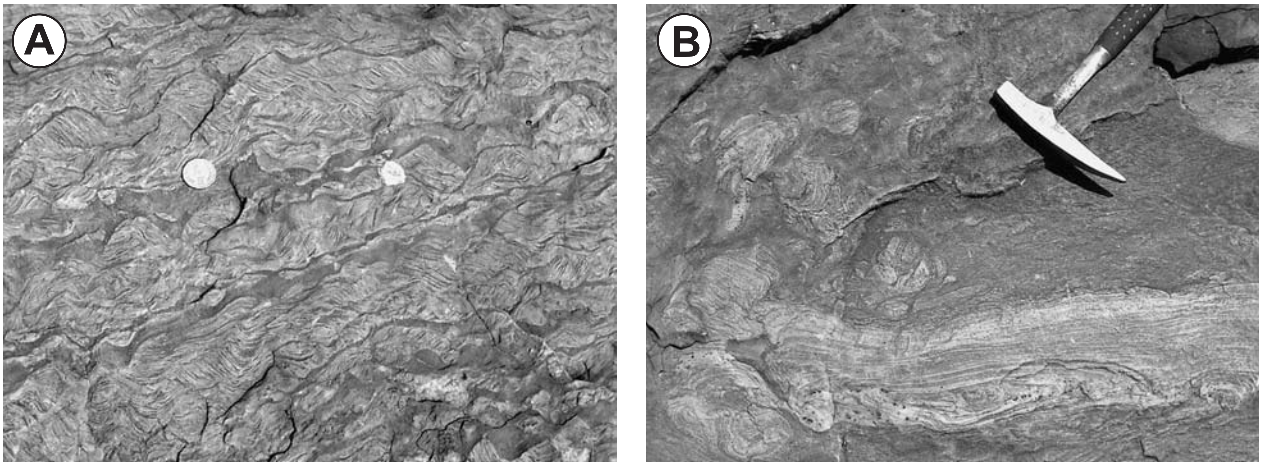


Fig. 2. Complex deformations. A: Complex deformations that are typical of silt-rich layers. Palaeoproterozoic succession affected by seismic shocks (seismites) near Dhalbhum Gar (India). B: Complex deformation due to deformation of an earlier deformed layer: a layer with probably shock-induced deformations (e.g., loadcasts) underwent mass transport that resulted in a slump head. Palaeoproterozoic Chaibasa Fm. (Singhbhum area, E India).

1.1. SSDS that are not commonly considered as SSDS

It is not common use to apply the term 'SSDS' to either deformations in sediments that are doomed to disappear geologically soon after their formation, e.g. traces left in a snow cover (it should be mentioned here that snow is rarely – if at all – the subject of research into SSDS, because only few earth scientists are aware that snow is a sediment; the sedimentary character of snow is obvious, for instance, where snow forms part of a sedimentary succession, as in the case of an alternation of snow layers and layers of volcanic ashes). In addition to clastic sediments, chemical, organogenic, organic and pyroclastic sediments can be deformed by deformational processes while still in an unconsolidated stage. Whether clastic, organogenic or chemical, the transition in carbonates from fresh carbonate mud to slightly consolidated carbonate mud to more strongly consolidated material to lithified carbonate rock is, as a rule, much more gradual than the transition from soft siliciclastic sediment to lithified sedimentary rock. This results in different behaviour, and therefore in different deformational processes as long as the rocks are not entirely lithified. For this reason, the present contribution is restricted mainly to SSDS in siliciclastic sediments.

No attention will be devoted either to deformations that occur in sediments that once have been turned into hard rock, but that became ductile again, for instance rock salt that may move plastically upwards as diapirs under the vertical pressure exerted by the weight of the overlying sediments. A comparable but even more extreme situation occurs if lithified sediments become ductile again under the influence of metamorphosis and/or the heat derived from intruding igneous rocks. It is interesting, however, that under such conditions deformation structures may be formed that are comparable to deformation structures formed in unconsolidated sediments. Representative (and fairly exciting) examples are the drag structures that may be found along intrusions that penetrate Late Archean or Early Proterozoic metasediments that have become ductile as a result of the heat transfer from the intruding magma, while the rocks were under pressure due to burial; the resulting drag structures are much alike escape structures in unconsolidated sediments.

It is quite common that freshly deposited subaqueous sediments, particularly if they contain a significant amount of clay- and/or silt-sized particles, start to compact as soon as new sedimentary layers are formed. If this compaction – which is due to the expulsion of water and air from the interstices and/or reorientation of flat particles such as clay minerals – occurs gradually, this need not result in true SSDS such as escape structures, but only in thinning of the layer(s) involved. This thinning due to compaction is not commonly considered as soft-sediment deformation (but see Kimura et al., 1989), but rather as a natural part of the sedimentary process (De Glopper, 1973), but Lowe (1976) stated that 'normal' compaction, i.e. slow fluid expulsion, should be considered as a deformational process. At least one type of compaction should be considered so, indeed: differential compaction resulting from lateral changes in lithology, can cause folds and faults (Van Loon & Wiggers, 1976a) that should be considered as SSDS.

1.2. A definition of SSDS

Although the above examples might be considered as SSDS according to the loose formulation mentioned in the beginning of the present contribution, such deformations will in practice not be considered as SSDS. It seems therefore appropriate to define the term 'SSDS' for occurrences in clastic sediments as follows: *soft-sediment deformation structures in clastic sediments are deformations that occur in still unlithified sediments or in sedimentary rocks that had not yet undergone lithification before the deformation structures started to be formed.*

1.3. Research into SSDS

SSDS occur in unlithified sediments in a wide variety of types. They have been no-

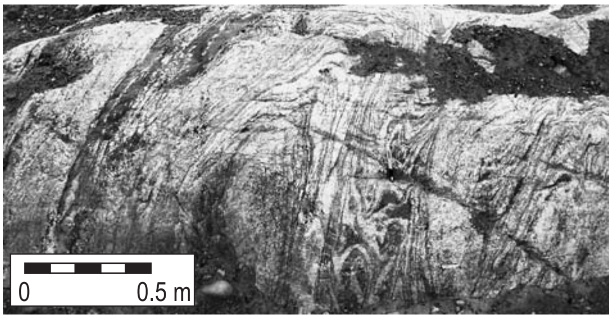


Fig. 3. Layer (right of centre) with soft-sediment deformations in the folded Precambrian basement of the Alstamalm sand quarry (S Sweden).

ticed by earth scientists for over 150 years (Lyell, 1841; Vanuxem, 1842; Dana, 1849; Darwin, 1851), but the structures were long considered as remarkable features rather than as phenomena that could increase insight in the history of the sediment. Only in the 1960s, when sedimentology became gradually apart from stratigraphy and started to become an earth-science discipline on its own, more structured investigations started. It appeared extremely difficult to find some order in the apparently unlimited number of types of SSDS, but some efforts were made soon to establish some kind of classification, and to explain their origin (Potter & Pettijohn, 1963; Pettijohn & Potter, 1964; Dżułyński & Walton, 1965; Nagtegaal, 1965).

Comparisons between recent deformation processes in unconsolidated sediments and the traces of such processes in older sediments remained fairly scarce in the early years of sedimentology. The analysis of SSDS could therefore not yet profit from the much deeper insight into the variety of structures that are known nowadays from almost all sedimentary environments, so that many genetic interpretations had to be based on assumptions rather than on facts. This led to several incorrect conclusions, and interest in the SSDS consequently gradually diminished.

Interest was raised again, however, when insight into facies relationships and the origin of sedimentary structures increased significantly in the late seventies and eighties of the past century. Numerous papers dealing with the importance of SSDS for the reconstruction of the depositional environment were published then (by, among others, Sims, 1978; Allen, 1982; Mills, 1983), and structural geologists also became more and more interested (Maltman, 1984), partly because they became aware that conclusions about the tectonic history of lithified sediments should not be based on the characteristics of SSDS, what had been the case numerous times in the past (cf. Van Loon, 2003). It should be mentioned in this context that the situation in hard rock can be quite complicated because SSDS may have been deformed later – in lithified state, and together with the surrounding rocks (Fig. 3) – by tectonic processes (see, for instance, Ghosh et al., 2002). Another reason why these deformations received increasing attention in the 1980s is that it appeared possible to apply the results of their analysis to palaeogeographical reconstructions (Brodzikowski & Van Loon, 1980, 1983, 1985a).

Although the interest in SSDS has had its ups and downs since the 1980s, these structures have remained a well-studied phenomenon. A large number of works was devoted exclusively to such structures, and many more field studies just mention their occurrence. Sedimentologists, structural geologists and researchers of the Quaternary were – and still are – those most involved. Their work has long been greatly hampered by a confusing terminology, however, which made it difficult to compare the various descriptions with each other unless clear illustrations showed the relationship between the actual structure and the terminology applied. On the one hand, this problem must partly be ascribed to the gradual passage from one type of deformation (e.g. plastic deformation) into another (e.g. liquefaction or brittle deformation). On the other hand, particularly the different terminologies of geologists (who, for the majority, study hard rock) and physical geographers (who do most sedimentological research in unconsolidated Quaternary deposits) have been an almost continuous source of misunderstandings.

2. Interpretation procedure and classification of SSDS

Four main groups of SSDS can be distinguished: folds (Fig. 4A), faults (Fig. 4B), breccias (Fig. 4C) and clastic dykes (Fig. 4D). It was soon recognized that minor structures may be the result of second (or higher) order stress systems, whereas large-scale first-order deformations (e.g. glacitectonic folds) can be highly important for the reconstruction of the more general sedimentary and/or deformational history (Occhietti, 1973). The occurrence of 'lower-rank SSDS' within 'higher-rank SSDS', in combination with the fact that many SSDS have been formed by a number of processes that did not always act simultaneously, makes that classifications of SSDS always have a subjective element, not only because of different genetic interpretations, but also because of the criteria used for classification.

Proposals for the classification of SSDS are therefore numerous (a.o. Potter & Pettijohn, 1963; Nagtegaal, 1965; Lowe, 1976; Jones & Preston, 1987; Owen, 1987; Maltman, 1994; Collinson, 2003b; for classification of seismites, see Montenat et al., 2007). No classification appeared generally acceptable, however, mainly because of either complexity (which hampers practical application) or a too limited number of parameters involved (shape, scale, etc.). It

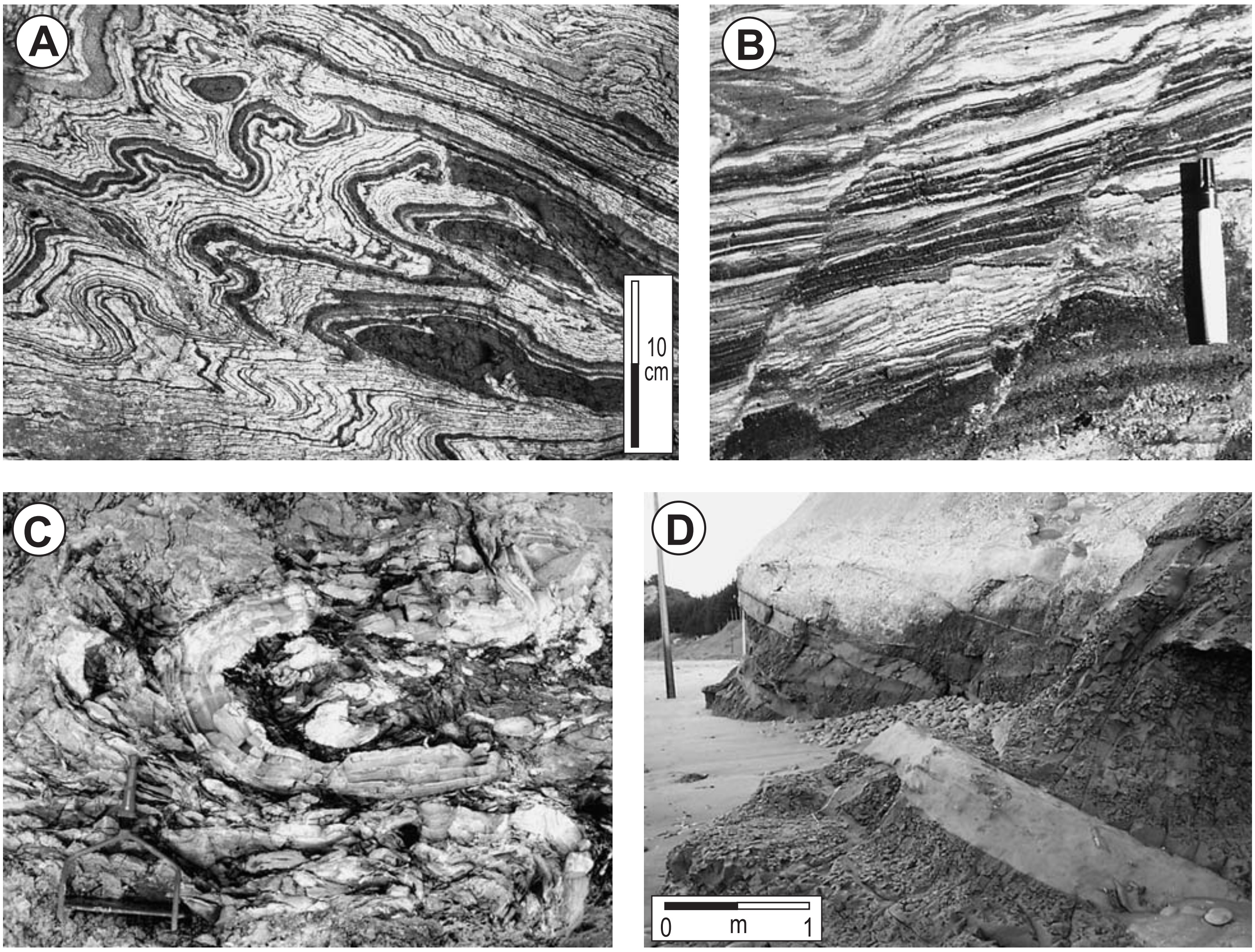


Fig. 4. The four principal types of deformations in soft sediments. A: Folds in a slump structure in the marine, calcareous Pleistocene Lisan Fm. (northern Arava, Israel). B: Faults formed in brackish lagoonal deposits of the subrecent Almere Member of the North Sea Formation while the sediment was still saturated with water. Surroundings of Emmeloord, The Netherlands. C: Breccia in the Pleistocene Ławki Formation. Bełchatów open-cast browncoal quarry (central Poland). Photo Beata Gruszka (Poznań). D: Intrusion of clay (layer with sharp upper and lower boundaries, from centre to lower right corner) into fine-grained Pliocene marine deposits, caused by the pressure exerted by the backwash of a giant tsunami (from Le Roux et al., 2008).

might be ideal if the genesis of a deformational structure could be taken as the prime criterion (as proposed by Van Loon, 1992), but this approach leaves the problem of different interpretations, if a single genesis can be reconstructed at all (most SSDS have a multiple origin: Van Loon, 2006a). In the same context, Leeder (1987) and Owen & Moretti (2008) have proposed to distinguish between 'autokinetic' and 'allokinetic' SSDS. The latter authors also proposed to distinguish between 'seismic' and 'aseismic' SSDS with respect to the trigger mechanisms, and between 'syndepositional' and 'metadepositional' SSDS with respect to their time of formation. In all the above cases, however, interpretation plays a role, which implies that a classification based on such principles may lead to different results if different researchers are involved.

Consequently, it would be much more practical if a classification based on simple structural criteria could be established (e.g. fold structures and fault structures), but there are too few of these simple criteria to provide a sufficiently sound basis for dealing even with relatively simple and common SSDS. It is therefore obvious that both purely descriptive and interpretational classification systems have disadvantages, and that it is even extremely difficult – if possible at all – to define criteria for the selection procedure of criteria for SSDS classification.

2.1. Interpretation procedure

It would be ideal – also from an educational point of view – if the classification criteria were the same as those used for the step-by-step genetic interpretation of the structures. In practice this turns out impossible, mainly because – as mentioned before – most SSDS result from a number of deformational processes, commonly affecting a sediment in an either continuous or interrupted sequence of events. This is a fundamental difference with, for instance, the identification of rock types, where a few specific criteria such as fabric, occurrence of crystals, and mineral content eventually lead to an unambiguous set of data that determine the rock's name. This implies that a classification system for SSDS must inevitably be based on a combination of objective (although often only presumed objective) and subjective criteria. It does not, imply, however, that all parameters used for the genetic interpretation must find a place in the final classification scheme. This can be illustrated by the role played by two parameters: (1) sediment behaviour during deformation, and (2) size of the SSDS.

It is evident that the final characteristics of any SSDS depend largely on the behaviour of the sediment during the deformational process. For a genetic interpretation, one should therefore distinguish first between structures on the basis of sediment behaviour (cf. Owen, 1987), i.e. between structures formed through fluidization/liqueaction, plastic deformation and elastic (brittle) deformation. This subdivision might distinguish between, essentially, homogenized sediments (liquefied: Fig. 5A), all kinds of fold structures (plastic: Fig. 5B) and faults (brittle behaviour: Fig. 5C). This seems simple, but one should keep in mind that the above procedure already involves subjectivity (interpretation of sediment behaviour on the basis of forms). Moreover, few SSDS are so simple that the above criterion can be applied unequivocally: in probably the great majority of SSDS a combination of, for instance, folds and faults is present, indicating that both plastic and brittle behaviour occurred. The question must then be answered whether the two types of behaviour occurred simultaneously or during successive deformational stages, which implies (again) an interpretation (which is, by definition, subjective). In addition, if one does not want to group almost all SSDS in a category (mixed plastic and brittle behaviour), one should decide whether the overall behaviour was plastic (and that the brittle deformation was, for instance, a second-order process), or brittle: once more a subjective decision.

As mentioned above, a second classification criterion could be the size of the structures. The size is important, because it provides insight into the magnitude of the forces involved. One might distinguish between: mega-scale: affecting a thick succession; large-scale: involving

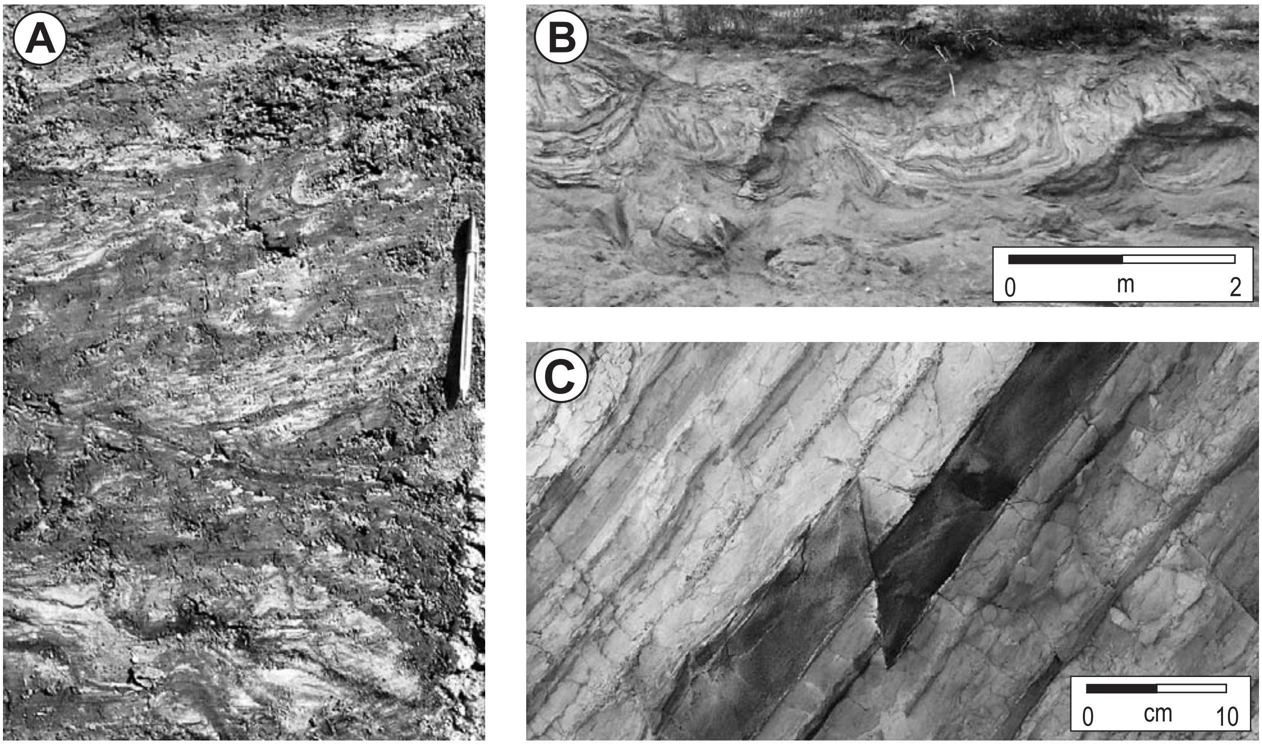


Fig. 5. The three main states of unconsolidated sediments during deformation. A: Partial disappearance of the primary structures in the silt-rich upper part (1250–1600 AD) of the lagoonal Almere Member of the North Sea Formation (Noordoostpolder, The Netherlands), due to partial liquefaction (fluidized state). B: Cryoturbation in the upper layer (Pleistocene) of the Ryssjön quarry (S Sweden), indicating plastic behaviour of the sediment during deformation. C: Synsedimentary fault (indicating brittle behaviour) in the Miocene Misaki Fm. on the Miura Peninsula (Japan). The area underwent frequent seismic activity.

several layers (Fig. 6A); meso-scale: affecting a whole layer (Fig. 6B); small-scale: affecting part of a layer (Fig. 6C); micro-scale: only visible in thin section. Even though the size at first sight seems to be a fairly objective criterion, it is not: decision about what is a thick succession, or whether a loadcast is a structure of one layer or two layers, is subjective. Moreover, a (large-scale) SSDS that affects several thin layers can be smaller in absolute sense than a (small-scale) SSDS that is found in only part of a thick layer. The size criterion should therefore not be taken in an absolute sense, but rather as an indication for the deformational agent.

A third criterion that is important for the genetic interpretation of an SSDS and for its classification is the time of its formation. Obviously, this is an entirely subjective criterion, although the correctness of the interpretation will in many cases not be doubted. The most relevant distinction is between (1) deformations that take place during deposition of the sediment (syndepositional structures), (2) those formed after deposition but before the overlying layer was deposited, although sedimentation apparently was uninterrupted (metadepositional), and (3) those formed later (postdepositional). This distinction, proposed by Nagtegaal (1963, 1965), was an important step forward, particularly because it may help to determine which genetic processes can have been active, and which need not be considered.

The fourth important criterion that must be applied for the genetic interpretation of SSDS is the (highly subjective) deformational process (see the section ‘Deformational forces and resulting SSDS’).

It is obvious that more parameters are in practice taken into account when interpreting the genesis of an SSDS. Which parameters they are, depends on the type of structure. It is always of utmost importance, however, to consider any SSDS in its geological context. Only in this way the genetic interpretations may be consistent with the interpretation of the entire sedimentary succession in which they occur.

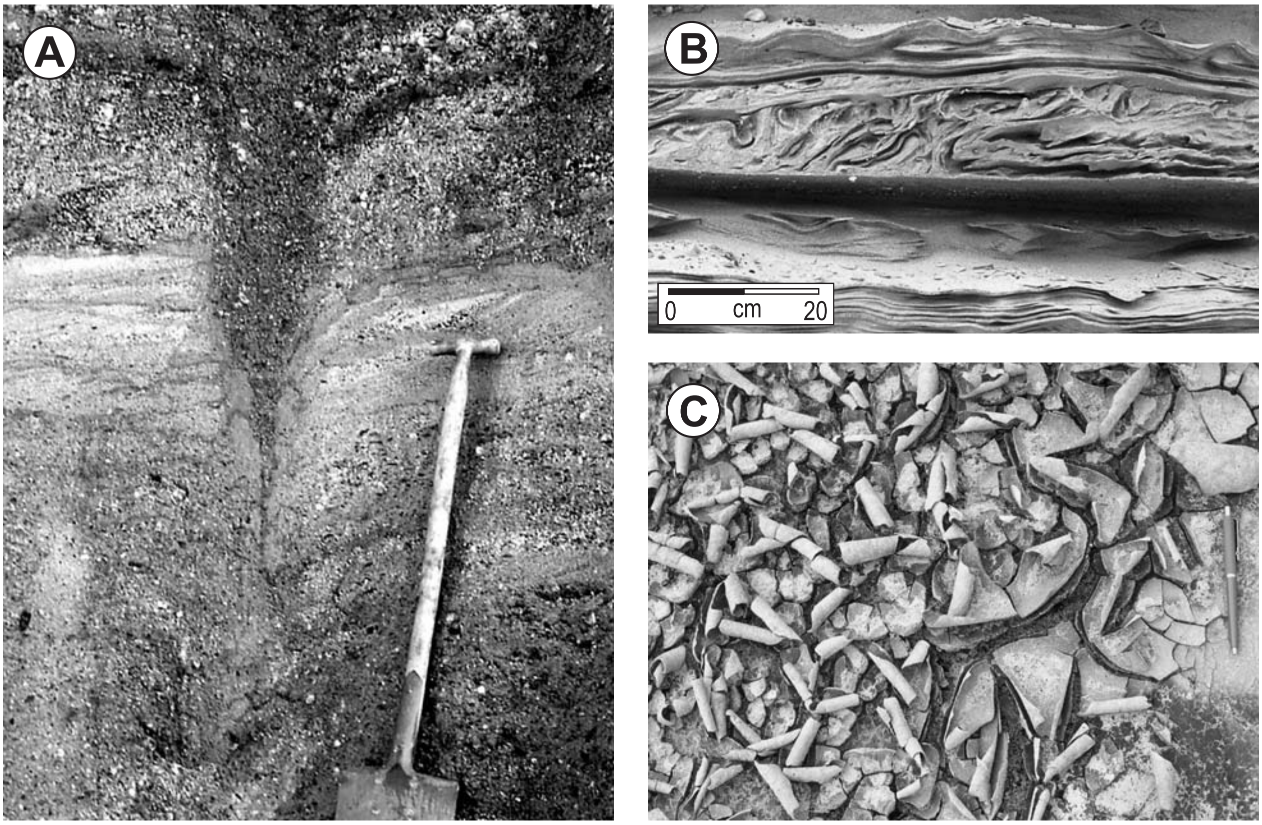


Fig. 6. Soft-sediment deformation structures of different sizes. A: Large-scale frost wedge penetrating several Saalian glaciofluvial layers, including a gravel bank cemented by iron oxides and hydroxides at Balderhaar (Germany). B: Meso-scale deformation affecting an entire layer of spouted sand. C: Small-scale deformations in the form of curled-up clay, caused by differential contraction between the lower, somewhat sandy parts and the more clayey upper parts of a fine-grained layer.

2.2. Proposal for a new classification

On the basis of the above considerations, in combination with field experience, it is considered not feasible to establish a classification of SSDS on the basis of the above considerations. Too many different processes may result in identical structures, and single processes may result in different structures (Kuenen, 1958; Butrym et al., 1964; Dżułyński & Walton, 1965; Brodzikowski, 1982). It is therefore proposed here to classify SSDS merely on the basis of the (interpreted) genesis.

In this context, one should distinguish first between three main groups of SSDS, viz. (1) those due to endogenic forces, called here ‘endoturbations’, (2) those in which gravity plays a dominant role (‘graviturbations’), and (3) those due to exogenic factors (‘exoturbations’).

These above fairly rough genetic groups may be subdivided in themselves, which gives a second level of subdivision, based on the deformational agent. The endoturbations contains only 1 subgroup: (1a) endoturbations (e.g. convolutions in a seismite). The graviturbations contain five subgroups, viz. (2a) astroturbations (all types of SSDS due to the impact of a bolide), (2b) praecipiturbations (all SSDS that are due to the deformational activity caused by precipitation, e.g. rain or hail imprints), (2c) instabiloturbations (due to instability in the original sediment, for instance because of an unstable density gradient, e.g. load casts), (2d) compagoturbations (SSDS caused by compaction, e.g. flexures and faults), and (2e) inclinaturbations (SSDS that are a direct result of gravity-induced processes, e.g. slump faults and faults). The exoturbations consist of six subgroups, viz. (3a) bioturbations (e.g., burrows), subdivided into the third-level groups, viz.(3a') bioturbations caused by plants (called 'phytoturbations'), (3a'') bioturbations caused by animals (called 'zooturbations') and (3a''') bioturbations caused – directly or indirectly – by humans (called 'anthropoturbations'), (3b) glaciturbations (glacitectonic folds and faults), (3c) thermoturbations (periglacial polygon structures; cryoturbate convolutions), (3d) hydroturbations (desiccation cracks), (3e) chemoturbations (crystal-growth imprints), and (3f) eoloturbations (SSDS caused by objects moved by the wind).

Obviously, each of these last-mentioned groups may be subdivided again in itself. Folds, for instance, might be subdivided into regular vs. irregular folds, complex vs. simple folds, etc. As the types of SSDS differ from place to place, no rigid scheme should be followed at this and lower levels, but rather a flexible scheme that is appropriate for the structures under study.

As a classification based on genesis needs insight into the various aspects that are involved in the genesis, these aspects will be dealt with first. The more practical implementation of the above classification scheme will be dealt with in Section 5.

3. The genesis of SSDS

Intergranular movement is the main mechanism involved in the formation of SSDS. It is capable of forming different types of structures including folds, faults, clastic dykes and breccias (Aalto & Miller, 1999). Intergranular movement resulting in SSDS has been discussed extensively, originally particularly in the form of physico-mechanical analyses of some specific features (Mead, 1925; Boswell, 1949; Brodzikowski, 1981, 1982), later more from the point of view of flowage processes (Raitzsch et al., 2007). Most of the structures must be considered as (semi)continuous (because failure sensu stricto in soft sediments requires specific conditions). This is due to the fact that compressional forces are much more common in unconsolidated (i.e., commonly freshly deposited) sediments than the rather rare tensional forces that may result in discontinuous structures.

In most cases it is difficult to establish whether the formation of SSDS is induced by outside stress conditions, as the sediment properties themselves (especially the anisotropy) also induce local, internal stress systems as soon as a deformational process starts. This implies that a rather simple force may result in simple SSDS (Fig. 7A) but also may induce deformations that result in locally more complex stress systems, which then cause deformations on a smaller scale (Fig. 7B) within the SSDS that is being deformed itself. These small-scale deformations themselves also may induce more (spatially restricted) diverging stress systems, etc. (cf. Van Loon and Wiggers, 1976b; Van Loon et al., 1984, 1985). Such increasingly complex stress systems occur quite frequently when the water content in the sediment changes, for instance due to loading. Many deformational processes are therefore greatly favoured by the occurrence of reversed density gradients (Anketell et al., 1970; Allen, 1982) that may induce loading; loading is a simple process that can result in simple loadcasts (Fig. 7A), but continued loading can result in complex structures such as a gravifossum (Van Loon & Wiggers, 1976b) with numerous folds and faults in various directions (Fig. 7B), whereas a series of successive loading events, for instance in the case of successive earthquakes, can result in fairly chaotic masses. Another important factor favouring soft-sediment deformation is the amount of silt, as a high concentration of silt favours dilatant flowage (Brodzikowski, 1981), spontaneous liquefaction, fluidization and thixotropic behaviour (Boswell, 1949; Allen and Banks, 1972; Lowe, 1976).

The genesis of SSDS is commonly complex: most SSDS have formed by a combination of forces. In this case a 'multi-force' structure arises, which will generally be difficult to classify in a simple way. Another complication arises if the forces resulting in slowly developing SSDS continue to affect the material during or even after lithification (for instance by repeated reactivation of a metadepositional fault); the resulting structure is then to be considered as both a soft-sediment and a hard-rock deformation. These aspects are, however, mainly of academic importance and will therefore not be dealt with here.

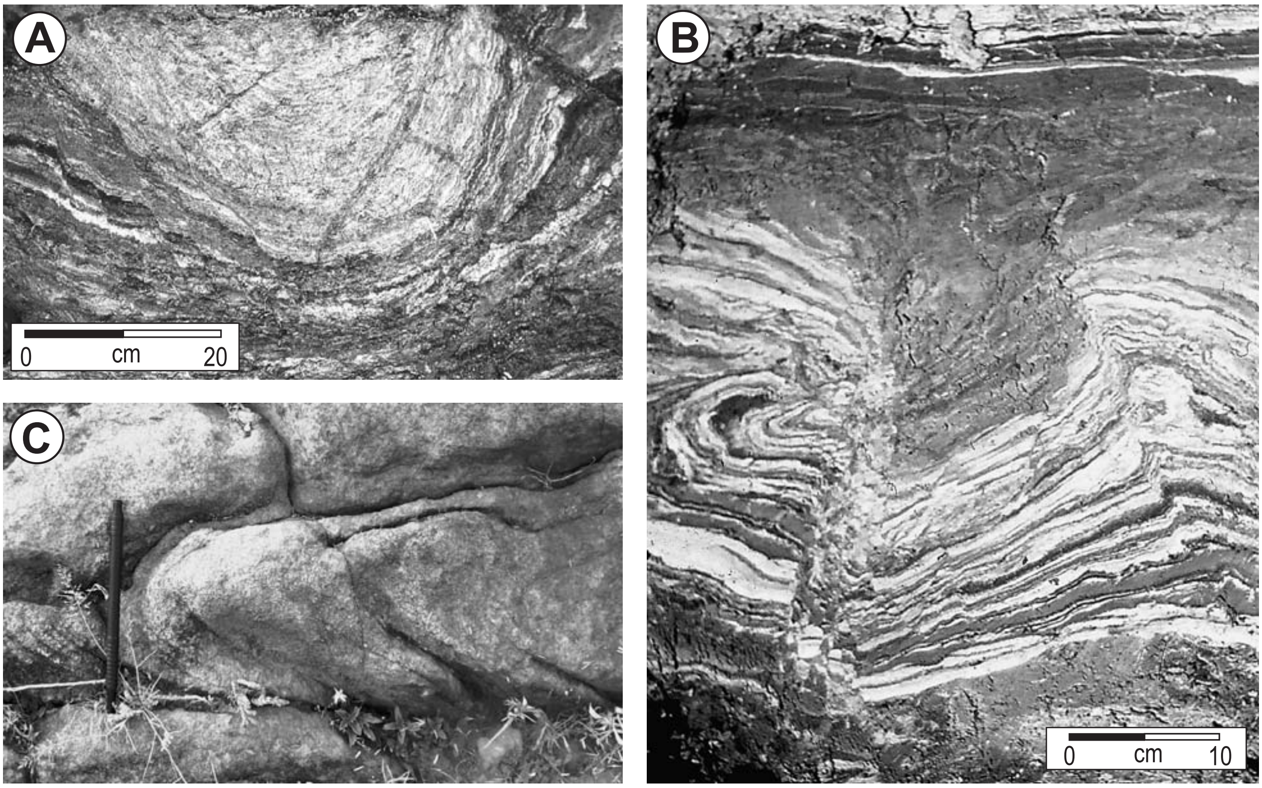


Fig. 7. Small causes can have significant results. A: 'Classical' load cast in the still unconsolidated, silt-rich subrecent Almere Member of the North Sea Formation (Noordoostpolder, The Netherlands). The loading did not cause any further deformations. B: Gravifossum near Emmeloord in the subrecent lagoonal Almere Member of the North Sea Formation near Emmeloord (The Netherlands). The deformation started as simple loading, but this occurred so quickly that a depression at the sedimentary surface resulted. This attracted new sediment, increasing the local weight, stimulating further loading. The load cast sunk ever deeper, until faulting took place along the almost vertical lateral boundaries. This faulting induced local stress systems that resulted in smaller deformations (both faults and faults). C: Simple processes like dragging of unconsolidated sediments can result in structures that are – without thorough analysis – difficult to distinguish from tectonic deformations in lithified rock. SSDS such as this dragging structure in the Palaeoproterozoic Chaibasa Fm. near Tata (E India) have therefore frequently been misinterpreted in the past.

SSDS may look surprisingly similar to deformations formed in hard rock. This common appearance has been noticed early, and criteria for their distinction were formulated already by Leith (1923), Rettger (1935) and Nevin (1942). These authors stated that SSDS are recognizable in hard rock by their occurrence in sedimentary units that are intercalated between non-deformed layers (Fig. 7C).

3.1. Complex deformations formed during several phases

As mentioned above, only rarely one single specific deformational process affects a freshly deposited sediment. Continuing sedimentation, for instance, results in increasing vertical pressure, and inhomogeneities in the sediment may favour differential loss of water. This implies that even the action of one specific force during the development of a deformation structure may result in different types of deformation. For example, it is quite common that convolutions are formed first, then become transformed by ruptures, to become changed ultimately into so-called ball structures (Kuenen, 1953; Sanders, 1960; Dott & Howard, 1962; Dżułyński & Walton, 1965; Rodríguez-López et al., 2007). Another sequence is formed by subsequently kink folds (Fig. 8A), shear planes (Fig. 8B), and finally a wide shear zone (Brodzikowski & Cegła, 1981; Brodzikowski & Van Loon, 1983; Van Loon et al., 1984, 1985). Other successive stages in the development of specific

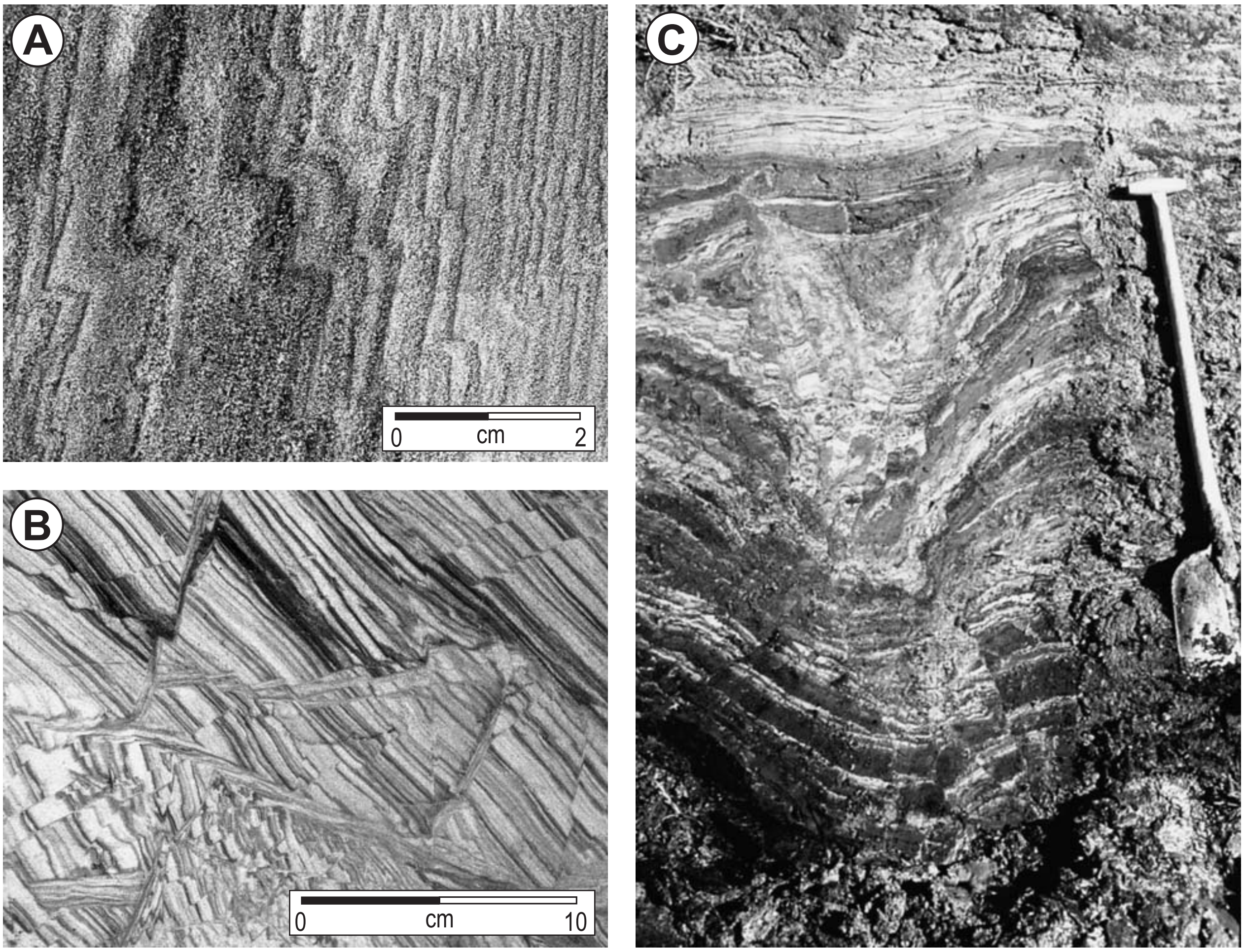


Fig. 8. Complex deformations. A: Kink structures (originally considered as characteristic of crystals – later of crystals and lithified rocks only - in ice-pushed glaciofluvial sands. Bełchatów opencast browncoal mine (central Poland). B: Shear plains genetically related to kink structures in glacitectonically disturbed fluvioglacial sands near Farlebjerghus (Denmark). C: Fairly complex gravifossum (essentially due to reversed density gradients, but see caption of Fig. 7B), formed between 1200 and1600 AD, near Emmeloord (The Netherlands) in the fine-grained lagoonal Almere Member of the North Sea Formation.

SSDS have been described for, among others, glaciation-related deformations such as diapirs that formed in front of the ice margin (Schwan & Van Loon, 1979, 1981; Brodzikowski, 1982) and periglacial deformations such as cryoturbations (Romanovsky, 1973; Jahn, 1975, 1977). The most widely known example, however, concerns the gradual development of load casts (Macar, 1948; Dżułyński & Walton, 1965; Anketell et al., 1970; Van Loon & Wiggers, 1975a, 1976a) which in specific cases may even result in complex structures such as a gravifossum (Figs. 7-B, 8-C), which is a commonly fault-rich or even fault-dominated fold structure due to extreme loading (Van Loon & Wiggers, 1976b). This structure, which had been found until recently only in late Holocene sediments in NW France and the central Netherlands, has now also been found in Weichselian esker deposits in southern Sweden (8-D). This occurrence in Weichselian sediments is in itself sufficient proof that a previous explanation of the subrecent deformations as a result of anthropogenic activities (e.g. as a reaction of the water-saturated silty sediment to the lowering of an anchor: Van der Heide, 1955) must be considered incorrect, and that the reconstruction of the natural development of this remarkable structure as provided by Van Loon & Wiggers (1976b) is much more likely.

Because the final geometry and size of many SSDS are thus related to a sequence of events, all successive stages must be reconstructed (starting with the latest deformational phase and ending with the oldest one) before the genesis of a specific structure can be understood in detail.

3.2. Experiments and insight into the duration of the deformational processes

SSDS have been experimentally produced since about a century, and some of the experiments have already been mentioned in the handbooks by Leith (1923) and Cloos (1936), who produced such deformations mostly as a 'by-product' of tectonics-related experiments. Rettger (1935) devoted a work entirely to what would now be called SSDS, but real interest in this topic was raised only in the middle of the last century, largely thanks to the experiments – mostly with flumes – carried out by Kuenen (Kuenen & Migliorini, 1950; Kuenen & Menard, 1952; Kuenen, 1958); this resulted, among others, in the 'discovery' of turbidity currents and their deposits (turbidites), which would become the 'hottest' topic in sedimentological research during the late 1960s. Other researchers carried out completely different experiments; Emery (1945) experimented with the entrapment and setting free of air in beach sands, Parker & McDowell (1955) modelled salt tectonics, and Stewart (1956) carried out laboratory experiments in order to find an explanation for contorted bedding in a recent lagoon. The sixties witnessed a much more systematic approach to experimental deformations (aimed at, for instance, producing sole marks and load casts) by, among others, Dżułyński (Dżułyński & Walton, 1963, 1965), who also experimented on convolutions (Dżułyński & Smith, 1963), the origin of periglacial polygonal shrinkage structures (Dżułyński, 1963) and other disturbances at the sedimentary surface (Dżułyński & Radomski, 1966). Such experiments formed the basis for a better insight into the structural significance of SSDS, because it became possible to relate these deformations to specific processes.

An important step forward was set by Anketell et al. (1970) who, based on experiments reported by Butrym et al. (1964) about deformations such as cryoturbations in sediments exposed to periglacial conditions, established a physical basis for the analyses, particularly for situations in which reversed density gradients played a role. Numerous experimental studies have dealt with specific (often small-scale) structures, among others by McKee and co-workers, who investigated the genesis of a wide variety of SSDS (McKee et al., 1962), with special attention for contortions (McKee & Goldberg, 1969). Their experiments contributed considerably to the reliability of (theoretical) analytical reconstructions.

There have been less experiments leading to truly new insights in the 1970s and 1980s, possibly because particularly facies analysis, mathematical approach, and modelling were considered as more promising sedimentological topics at the time. More recently, however, a large number of laboratory experiments were carried out again, often under (imitated) natural conditions. Moretti et al. (1999) investigated the origin of SSDS in seismites with a digital shaking table; Harris et al. (2000) carried out centrifuge experiments to investigate the origin of convolutions formed during thawing of frozen soils; Dasgupta (2008) experimentally produced folds and shear plains in order to reconstruct the origin of slump-like structures; and McLoughlin et al. (2008) produced wrinkle structures in synthetic stromatolites in the absence of microbes that were commonly considered to play an important part in the genesis of such structures.

All these experiments indicate that specific types of SSDS may develop within a few minutes, at least under laboratory conditions that reflect natural circumstances; and, indeed, nature is not much slower: it is well known from recent environments that deformation structures may develop within a few days, minutes or even seconds. In other cases, however, it seems to take years, centuries or even longer before the structures have developed completely. Some diapiric folds, for instance, may develop as an effect of differential loading due to inhomogeneities in the overburden, as commonly present along the margin of an ice cover (Schwan et al., 1980b), whereas other diapirs may be due to spontaneous liquefaction and fluidization (Allen & Banks, 1972; Tuttle et al., 2002; Singh & Jain, 2007). The latter process can result in diapirs within much less than an hour, whereas the former process commonly takes many years at least, possibly – in the case of a stagnant ice front – millennia. This implies that many actual observations of deformation structures in modern unconsolidated sediments may concern 'unfinished' structures. It is, on the other hand, also possible that the forces that induced the SSDS have stopped affecting the sediment after some time, and that they thus have left the structure in a stage that remains unfinished.

A number of complex parameters, including the cohesive strength of the sediment, the direction of the stress components with respect to the layering, and the value of the force(s) involved determine how quickly an SSDS is formed. It is commonly impossible to reconstruct the deformational velocity from the final shape of a structure because one single process (e.g. loading due to a reversed density gradient) may take place slowly or rapidly without consequences for the geometry of the structure (Dżułyński & Walton, 1965; Brodzikowski & Van Loon, 1979, 1985b).

4. Occurrence of SSDS

SSDS have long been considered as relatively rare features, but field research in the past few decades has made clear that they occur frequently worldwide, in rocks of all ages, and in deposits formed in most – if not all – sedimentary environments. It is out of the scope of the present contribution to provide a full overview of the occurrences, but is seems worthwhile to provide some characteristic examples that show the wide range of SSDS in time and sedimentary context.

4.1. Stratigraphic distribution

Most geological processes occurred already during early stages of the Earth. This implies that also SSDS were formed in the early Earth history. Relatively little is known about these ancient structures, however. This is due to two reasons: (1) the relative scarcity of exposed pre-Phanerozoic rocks, and (2) the fact that most pre-Phanerozoic sediments have undergone changes (tectonics, metamorphosis) that make SSDS difficult to recognize. For this reason, we shortly mention some of these occurrences. Some general characteristics of Phanerozoic SSDS are also dealt with for the sake of completeness.

4.1.1. Archean

SSDS are known already from the Archean. It is interesting to note that the majority of these SSDS are explained as a result of processes that still are active nowadays, and in environments that are well comparable to present-day conditions. This holds, for example, for SSDS that are described as 'molar structures' (Bishop & Sumner, 2006; Bishop et al., 2006) and environmentally related structures (Sumner & Gotzinger, 2004). There are, however, also Archean 'soft-rock' deformations that have no known present-day equivalents because they were formed in rocks that behaved in a plastic way, although in a metamorphosed state, as a result of heat produced by intruding igneous veins. These SSDS, that might be considered as such if the term is used in a loose sense, do not fulfil, however, all requirements of the definition of SSDS mentioned in the Introduction.

4.1.2. Proterozoic

Many more SSDS are known from the Proterozoic, and a large number of these deformation structures seem to have formed under conditions that do not exist nowadays. It seems, for instance, that many Proterozoic SSDS are related to glacial activity (in a wide sense), but this may be due to the fact that the Proterozoic glaciations (and especially those from the Cryogenian) have recently received much attention, particularly in the framework of studies into 'Snowball Earth'. Indeed, some of these SSDS have been mentioned as sup-

Fig. 9. Dropstone in the Precambrian Banded Iron Formation, a type of deposit that is not formed currently because the then environmental marine conditions do not exist any more, although icebergs were apparently present.

porting evidence for the 'Snowball Earth' hypothesis (Hoffman & Schrag, 2002; Allen et al., 2004). Several more types of Proterozoic SSDS must have formed under conditions that have no present-day equivalents, such as those in the famous banded iron formations (Pufahl & Fralick, 2004) (Fig. 9).

Other Proterozoic SSDS are, in contrast, found in sediments that show many similarities with present-day sediments, for instance in marine sediments, and such structures seems in general well comparable with those formed nowadays under similar conditions (Le Guerroue et al., 2006). Mazumder et al. (2006, 2009) describe SSDS from the Paleoproterozoic that must be ascribed to seismic activity in a tectonically active basin (Fig. 10). Although these authors describe some structures that had not been described before (Mazumder et al., 2006), they state that this is not due to fundamentally different conditions, but that this must be ascribed to the exceptionally well exposed seismites in their study area.

4.1.3. Phanerozoic

Phanerozoic sediments are exposed over a so much larger surface area than Precambrian rocks that it is only logical that SSDS have been described from all Paleozoic epochs. During the Phanerozoic, the environmental conditions were essentially the same as nowadays (oxygen-rich atmosphere, clear distinction between continents and oceans, no 'snowball Earth', etc.). The SSDS found in Phanerozoic rocks therefore are essentially the same as those that can be found in present-day environments. The main difference with the pre-Phanerozoic is that bioturbations suddenly abound.

It is remarkable that the number of descriptions of SSDS from the various Phanerozoic periods does not reflect the duration of these periods. Relatively few SSDS have been described from, for instance, the Silurian (e.g. Davies & Cave, 1976; Garzanti, 1999), whereas those from the Carboniferous are numerous,

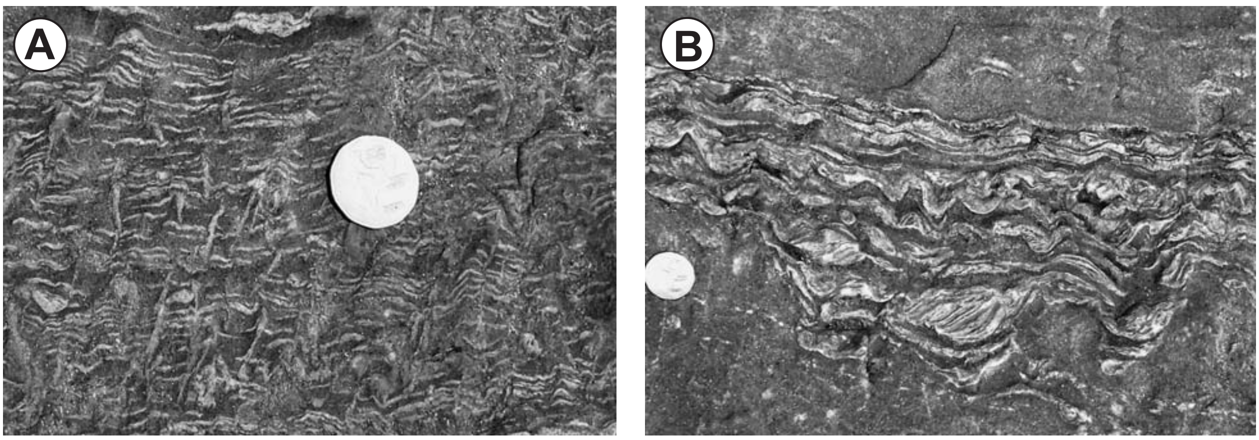


Fig. 10. SSDS in seismites of the shallow-marine part of Palaeoproterozoic Chaibasa Fm. near Dhalbhum Gar (E India). A: Numerous small-scale clastic dykes indicate sudden attempts of pore water to escape, probably under the influence of an earthquake-induced shock wave. B: Strongly disturbed seismite with identical granulometry as the under- and overlying layers.

partly because of the instabilities related to the Hercynian tectonics (e.g. Van Loon, 1970, 1983; Lien et al., 2003). Descriptions of SSDS from the Mesozoic periods abound, but much less SSDS have been described from the Palaeogene and Neogene (former Tertiary).

It is not surprising that by far the greatest majority of Phanerozoic SSDS have been described from Quaternary sediments, as these are commonly still in an unconsolidated state, and as they cover large areas. Much attention has been paid particularly to glaciation-related SSDS, mainly dating from the Pleistocene. One should keep in mind, however, that exposed Quaternary glacial sediments are – apart from in areas that underwent considerable isostatic rebound after the disappearance of the ice cap – almost exclusively continental in nature. This results in an exceptional situation (Van Loon, 2000) as continental deposits from older glaciations are scarce due to erosion; most ancient glacial deposits have been interpreted as glaciomarine, but their glacial origin is at least fairly dubious (Van Loon, 2008b). SSDS that are characteristic for the Pleistocene in glaciated areas will be dealt with in the section about glaciturbations.

4.2. Environmental distribution

As mentioned before, SSDS occur in almost all – if not all – sedimentary environments. This holds for both the marine and the continental realms.

Under marine conditions, the deep-marine environment seems to house relatively few SSDS; most of them are related to seismics (Long, 2004) or to seismics-induced processes such as tsunamis (Mazumder et al., 2006; Cita, 2008; Shiki et al., 2008). SSDS are particularly common in tectonically active areas such as fore-arc basins (Campbell et al., 2006) and back-arc basins (Bryan et al., 2001). Other deep-marine SSDS occur in the levees of channels of submarine fans at the foot of the continental slope (Hickson & Lowe, 2002). Many more SSDS occur on the continental slope itself, mainly as a result of mass movements (Dugan & Flemings, 2002) that cause – or follow – submarine channels (Nakajima & Satoh, 2001; McCaffrey et al., 2002). In addition, deep-sea photographs indicate that the deep-sea can be strongly bioturbated where sufficient oxygen is available, while the sedimentation rate is low (Heezen & Hollister, 1971; see also Rebesco et al., 2008; Wetzel et al., 2008).

In the shallow-marine environment, many processes are active that can cause SSDS (Davies & Gibling, 2003; Campbell et al., 2006; Fielding et al., 2006). Most of the deformations occur near the coast (Loseth et al., 2006), under tidal conditions (Rebata et al., 2006), in estuaries (Plink-Björklund, 2005) and in deltas (Van Loon, 1972; Uličny, 2001; Mellere et al., 2002; Wignall & Best, 2004) or – in the case of carbonate sedimentation – in bioherms (Portman et al., 2005), on carbonate platforms and in carbonate mud mounds (Elrick & Snider, 2002). They are also common in coastal dunes (Mountney & Thompson, 2002).

Evaporites form a (chemical) rock type that may not only form under both deep- and shallow-marine conditions (where SSDS may be developed: Warren, 2000; Orti et al., 2003), but also in saline lakes, where SSDS may also be formed (Paz et al., 2005). Saline lakes may be found in both coastal areas and in desert environments. The deformations in chemical sediments are, however, beyond the scope of the present contribution and will consequently not be dealt with here in detail.

On the continents, it seems that a common environment for SSDS is the fluvial realm (Brodzikowski et al., 1984; Tosolini et al., 1999; Kataoka & Nakayo, 2002; Neef & Larsen, 2003), including braidplains (Marshall, 2000) and, particularly, alluvial fans (Zieliński & Van Loon, 1999a,b, 2000; Went, 2005) – mainly because of the mass flows that take place and the irregular sedimentary successions that often result from unstable density gradients – and valley fills (Plint & Wadsworth, 2003). Deserts seem not a favourable place for SSDS, but Netoff (2002) describes SSDS in an erg succession as a result of fluidisation due to seismic activity. Ergs seem the most favourable places in deserts for SSDS; these are found most commonly in playas between the higher parts (Mountney & Jagger, 2004). A special continental environment where SSDS may be found are caves (Kos, 2001).

Apart from the above continental environments and subenvironments (which are taken only as examples: it is not intended here to provide a complete overview), specific conditions may prevail in an area, however small or large, that give rise to sediments in which frequent SSDS occur. It seems worthwhile to mention only three specific conditions under which SSDS are commonly formed: glacigenic, volcanic and tectonic conditions.

SSDS are perhaps the most commonly formed under glacigenic conditions. The reason is that the depositional conditions change quickly in time and space (Brodzikowski & Van Loon, 1987, 1991), which results in the frequent occurrence of mass wasting (Zieliński & Van Loon, 1996). In addition, the advance of glacial ice causes tectonic push, and the melting of buried dead-ice masses creates collapses. Some characteristic SSDS formed under such conditions have been described by Isbell et al. (2001), Arnaud & Eyles (2004) and Edwards (2004). One glacigenic environment in which SSDS are commonly abundant, consists of glacial lakes (on top of, within, under or in front of an ice mass). The commonly high silt content, the water-saturated nature of the sediments and the rapid lateral facies changes give easily rise to an extremely wide variety of deformations, ranging from loadcasts and flames to breccias to diapirs, to slump folds to faults (see, among others, McDonald & Shilts, 1975; Brodzikowski et al., 1987b,c; Chunga et al., 2007; Gruszka & Van Loon, 2007).

Volcanic sediments that show deformation structures consist mainly of tephra which are deposited either on slopes, or while larger fragments (bombs) setlle causing some kind of small-scale impact craters (Giordano & Cas, 2001; Bryan et al., 2003; Smellie et al., 2006). In addition, the deposits of pyroclastic density currents may show SSDS (Brown et al., 2007) which are in several respects comparable to those found in deposits of submarine high-density currents. SSDS in pyroclastic deposits are, however, beyond the scope of the present contribution and are therefore not be dealt with in any detail.

Obviously, seismically and tectonically active areas frequently show SSDS. Examples are those described by Van Loon (2002), Fodor et al. (2005), Jackson et al. (2005), Ridente & Trincardi (2006) and Rodríguez-López et al. (2007).

5. Deformational forces and resulting SSDS

Deformations formed in hard rock are almost exclusively due to endogenic forces. The forces involved in SSDS show a much larger variety, because exogenic forces also play a role, commonly an even more important role than endogenic activity. Gravity induces processes that may result in SSDS as well.

It should be emphasized here that nature does not follow artificial classifications, and that the majority of SSDS are most probably due to a combination of two or more of the above-mentioned forces. As an example, some SSDS are due to exogenic forces but also require gravity; imprints made by objects transported by the wind belong to this category. A fairly comparable group of SSDS is due to a combination of endogenic activity and gravity; examples are the folds in mudflows that are triggered after an earthquake or in the pyroclastic flows after a volcanic eruption.

A trigger mechanism would seem required to induce the formation of any SSDS, but there are many cases where no specific trigger seems to have been present. This implies that most probably only a threshold value has to be exceeded, for instance by gradual accumulation of heavy sediment on top of a water-saturated less dense sediment; this may easily results in structures such as loadcasts (cf. Kuenen, 1953; Pepper et al., 1954; Van Straaten, 1954; Dott & Howard, 1962; Anketell & Dżułyński, 1969; Berthelsen, 1979; Brodzikowski & Van Loon, 1979, 1985a; Visher & Cunningham, 1981).

5.1. Endogenic forces and endoturbations

The role of endogenic forces in the genesis of SSDS has been stressed by numerous authors (Allen, 1986b; Anand & Juin, 1987; Cojan & Thiry, 1992; Dugué, 1995; Mohindra & Bagati, 1996; Vanneste et al., 1999; Enzel et al., 2000; Upadhyay, 2003; Bowman et al., 2004; Mazumder et al., 2006; Ortner, 2007; Rodríguez-López et al., 2007) but unambiguous structures of this kind are relatively scarce. Apart from specific SSDS such as large-scale earthquake-induced dykes (Hurst et al., 2003), three endogenic processes are responsible for almost all deformations of this origin in soft sediments: (1) earthquakes that result in subaerial or subaqueous mass movements (Reineck & Singh, 1973; Lowe, 1976; Spalluto et al., 2007) that produce, for instance, hydroplastic folds in slumps (Aboumaria et al., 2009) so that these SSDS should be considered as graviturbations (or as combined gravi/endoturbations) rather than as endoturbations, (2) contortion of surficial unconsolidated layers (this is the most common occurrence of endoturbations), and (2) fault activity in the subsoil that also affects the overlying unconsolidated sediments (Ravnås et al., 1997; Neuwerth et al., 2006), such as found where graben tectonics is still active (Van Loon, 2002). An example of a graben with numerous SSDS (Fig. 11) in Neogene and Quaternary deposits is the Kleszczów Graben near Bełchatów in central Poland (Brodzikowski et al., 1987a,b,c,d; Brodzikowski & Van Loon, 1990; Van Loon & Brodzikowski, 1994; Van Loon, 2006b; Gruszka & Van Loon, 2007; Goździk & Van Loon, 2007).

Faulting, even if occurring several kilometres below the sedimentary surface, may induce earthquakes that affect surficial layers by changes in the pore-water pressure (hydroplastic deformation) due to the passage of shock waves. Particularly silty layers and sandy layers with a high silt content easily undergo hydroplastic deformation (although gravels may also be affected: Carter & Norris, 1986), so that such layers may become disturbed, sometimes slightly, sometimes in a chaotic way (Fig. 12). Such layers may show a wide variety of SSDS, ranging from deformation bands (kink folds, shear zones) to hydroplastic folds such as convolutions, load casts and flame structures.

Although it is not always possible to establish an earthquake-induced origin for a specific SSDS with certainty (see discussions in Moretti & Sabato, 2007), and although it is not even easy to classify them (Horváth et al., 2005; Montenat et al., 2007), some layers may show characteristics that make it highly likely that the internal deformations are related to faulting-induced earthquakes (Mazumder et al., 2009). Such layers are called 'seismites' (Ricci-Lucchi & Amorosi, 2003; Neuendorf et al., 2005). They have been found throughout the stratigraphic column (e.g., Precambrian: Mazumder et al., 2006. Paleozoic: Jewell & Ettensohn, 2004; Rossetti & Góes, 2000. Mesozoic: Obi & Okogbue, 2004; Samaila et al., 2006; Rodríguez-López et al., 2007. Cenozoic: Moretti, 2000; Singh & Jain, 2007), and all over the world, and they form in almost all environments. Much attention has been paid to seismites in the past few decades, partly because they may indicate the direction of the epicentre (cf. Rodríguez-López et al., 2007) and the magnitude of the earthquake (Allen, 1986b; Rodríguez-Pascua et al., 2000, 2008; Guiraud & Plaziat, 1993), which may help unravelling the structural history of an area, partly because they can provide valuable information for the exploration of hydrocarbons. Seismites formed during prehistoric and historic times (Schurch & Becker, 2005) can help to understand why cities were destroyed, why people moved from one area to another, etc. (see, for instance, Walker et al., 2003; Galli et al., 2008).

Fig. 11. Small-scale diapir in the Bełchatów opencast mine (central Poland), situated in the still active Kleszczów Graben.

Less common are SSDS which are an indirect result of earthquakes, for instance in the form of deformations due to earthquake-

Fig. 12. Chaotic deformations in a succession of seismites with alternations of fine sandy (light-coloured) and volcaniclastic (dark) sediments of the Miocene Misaki Fm. on the Miura Peninsula (Japan).

induced tsunamis that affected sea-floor sediments (Rossetti et al., 2000; Mazumder et al., 2006) and/or a coastal area (Smoot et al., 2000; Cantalamessa & Di Celma, 2005; Schnyder et al., 2005).

5.2. Gravity and graviturbations

Gravity is neither an endogenic, nor an exogenic force (it is universal). Five groups of gravity-dominated forces are distinguished: (1) astronomical forces, (2) forces resulting in precipitation, (3) forces resulting from reversed density gradients, (4) forces resulting in compaction, and (5) forces resulting in down-slope mass movement.

5.2.1. Astronomical forces and astroturbations

Astronomical forces result in SSDS that have hardly any significance thus far because they have not drawn any attention, in contrast to the deformations caused by impacts in hardrock (Fig. 13A), consisting mainly of brecciation (Rousell et al., 2003; Lafrance et al., 2008). Meteorite craters (as far as made in a soft-sediment cover: Fig. 13B) and imprints from smaller objects (chondrites, etc.) should be grouped in the category of astroturbations. The ringwalls near Morasko, in the vicinity of Poznań, Poland, must be considered as remnants of impacts (Stankowski, 2001) that took place some 5000 years ago in unconsolidated sediments. The SSDS that most probably exist in these ringwalls (which should also themselves be considered as SSDS) have not received any attention thus far, which is remarkable because the deformation structures caused by the impact of a meteorite in lithified rocks commonly receive much attention.

It is only logical that many of the continental impact sites (McCall, 2009) have been covered with unconsolidated rocks when the impact took place, as is known from, for example, the impact that took place about 6600 years ago in an area with a thin Quaternary cover on top of Devonian hardrock near Ilumetsa, Estonia (Raukas, 2000a,b; Raukas et al., 2001) and the impact (forming the Wabar craters) in desert sand dunes in Saudi Arabia (Shoemaker & Wynn, 1997; Wynn, 1998). Most likely, the high tem-

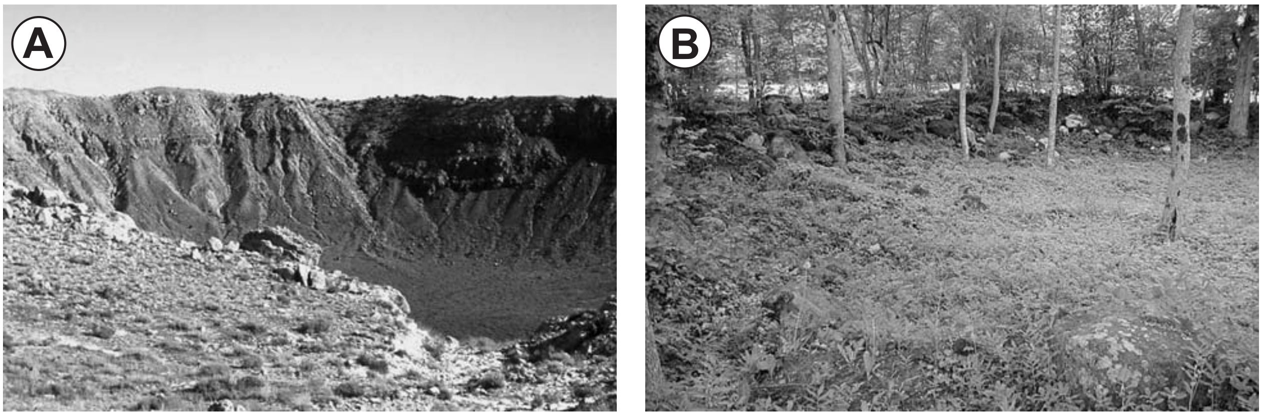


Fig. 13. Impact structures. A: The crater wall of Meteor Crater (Arizona, U.S.A.), seen from the opposite crater wall. B: A small ringwall surrounding a depression formed by the impact of a piece of an exploded meteorite in a thin glacial cover on top of Devonian carbonates near Kaali (Estonia). Photo W. Stankowski (Poznań).

peratures and the shock-induced high pressure during and immediately following the impact of a large bolide must be held responsible for shock-metamorphosis or even vitrification after melting of these unconsolidated sediments, so that no SSDS remain. At larger distances from such an impact site, where SSDS might potentially be preserved, the relationship with the impact might be too difficult to recognise. It may also be, however, that impact craters in unconsolidated sediments are not detectable in the field in the case of a relatively small feature. An example is the 36-m-diameter impact crater formed during the late Holocene near Whitecourt (Alberta, Canada) which has been detected by LIDAR but which is undectable using visible imaginary (Herd et al., 2008).

The situation at Morasko is fairly unique, because hardly any soft-rock locations are known where the explosion of the meteorite took place in the atmosphere, causing numerous fragments (from the few other examples known, the Waber crater in Saudi Arabia and the Ilumetsa crater in Estonia are the best known). Some of the Morasko fragments were still large enough to produce craters of tens of metres in diameter. They were not large enough, however, to penetrate the sedimentary cover really deep, and they had apparently also lost so much of their kinetic energy that the impact did not result in vitrification of the Pleistocene sediments. This makes the site most suitable for investigation of the SSDS in the ringwall; inspection of possible SSDS at the bottom of the impact craters would be much more difficult to achieve, as huge volumes of sediment would have to be removed from the protected site. From a scientific point of view, it might nevertheless be worthwhile to start a detailed sedimentological investigation at this unique site.

Impacts of bolides can also trigger SSDS indirectly, viz. through the shockwave that they produce. A seismite producing SSDS has been ascribed to such an impact by Simms (2007), but it seems that not the impact but the shockwave should in such a case be considered as the cause. Since the shockwave is a result from an impact-derived earthquake, it seems that the SSDS in such a seismite can as well be considered as a form of endoturbation, indicating once more that nature thus not hold strictly to Man-made classifications.

5.2.2. Precipitation and praecipiturbations

It is considered part of the normal erosional and depositional processes in an environment when a heavy rain results in a streamflood that reshapes the topmost part of the local deposit. If, however, a relatively small number of rain drops (Fig. 14) or hail grains result in recognizable imprints in the sedimentary cover, the imprints may be considered as precipitation-induced structures (praecipiturbations). Classifying them as primary structures would be incorrect because the sediments in which the

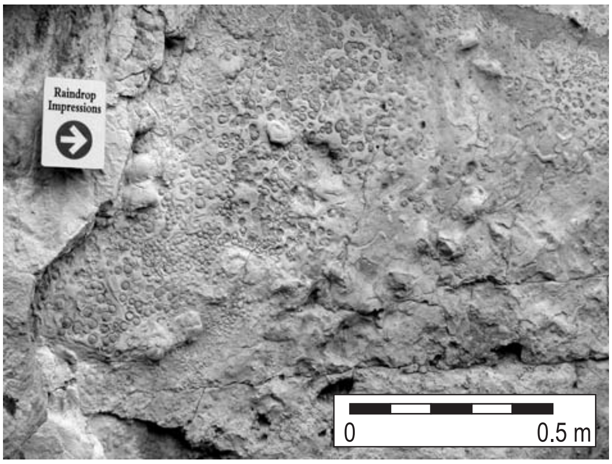


Fig. 14. Fossil imprints of raindrops in Parfet Prehistoric Preserve at Golden (west Denver, CO, U.S.A.). Photo Geoscience Research Institute 2006 Field Conference (Denver).

imprints are formed are not deposited by the rain or hail.

Rain imprints are common, particularly in muddy terrestrial deposits that are found in areas where rain is rare, and/or where only few raindrops fall during rain. In that case, the imprints made in the muddy surface may be preserved when the mud dries up and becomes covered by new sediment (e.g. desert sand on a muddy playa deposit).

Hail imprints are formed particularly if the hail grains have a large size. It looks whether hail with grains of several centimetres in diameter has become more common in the past few years, and some observations of the deep impacts that they can make (Fig. 15) have been reported (West Texas Mesonet, 2008).

Fig. 15. Hail impact craters in a cotton field just south of Lamesa (U.S.A.). The field was soft because it had been flooded first by heavy rain. Photo John Lipe, NWS Lubbock.

5.2.3. Reversed density gradients and instabiloturbations

Many gravity-induced SSDS are formed because differential vertical movements take place in sediments that are unstable because of reversed density gradients. Material may sink into the underlying material, forming load casts that may reach sizes of metres (Fig. 16A and B) (Kuenen, 1958, 1966; Pettijohn & Potter, 1964; Brodzikowski and Van Loon, 1983; Kelley and Martini, 1986; Tipper et al., 2003). They may become fairly complex if the downsagging proceeds for a longer time (Fig. 16C) or during several successive phases (Fig. 16D), and eventually this may result in structures like pseudonodules (Fig. 16E) and gravifossums (Fig. 16F; see also Figs 7B and 8C), or material may be pushed up, forming flame structures between parts that sink down or intrude as diapirs between unaffected sediments.

The most common underlying reason for sudden loading is that unconsolidated sediments are pressed together and/or otherwise deformed. This can happen when some mass, either large or small, is supplied and comes to rest on an unconsolidated fine-grained sediment (Allen, 1984). Scours in fine-grained sediments may, when they become filled with sand, give sufficient density contrast to start the loading process, and large ripples may do so as well (Fig. 16A). More uncommon is loading into underlying sand or even gravel.

5.2.4. Compaction and compagoturbations

Deformations due to differential compaction (Van Loon & Wiggers, 1975c; Denhandschutter et al., 2005) also may be considered as gravity-induced phenomena. Two main processes result in compaction of unconsolidated sediments: the loss of water and/or gases, and rearrangement of the individual grains. This affects not only the volume of the sediment but also its physico-mechanical properties. The degree of compaction may vary within short distances because of inhomogeneities within the sediment. This causes local stress systems;

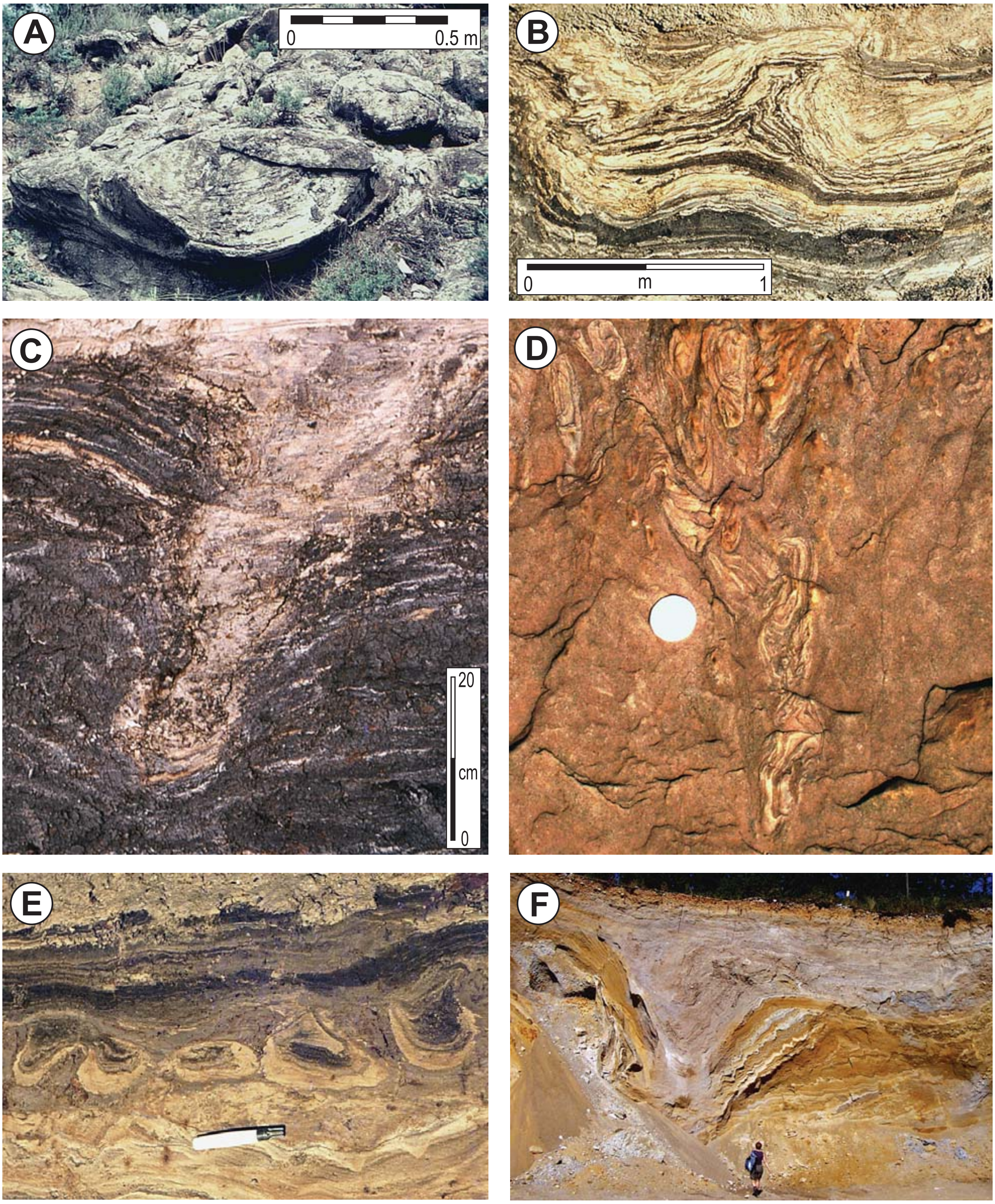


Fig. 16. Load casts and associated SSDS form a wide spectrum of structures, both in size and in shape. A: Loaded trough-shaped megaripples in the Cuisian/Lutetian Perarrua Fm. near Bellestar (Spain). B: Huge loadcasts within subrecent silty lagoonal sediments (North Sea Formation) in the reclaimed Noordoostpolder (The Netherlands). C: Narrow loadcast of some 10 cm wide and some 50 cm deep. Location as Figure 16B. D: Extremely developed, loadcast in the Palaeoproterozoic Chaibasa Fm., near Dhalbhum Gar, E India. The loadcast must have development during several phases, as younger loadcasts deform and push further down older loadcasts. E: Pseudonodules, reflecting an entirely broken-up layer of fine sand. Location as Figure 16B. F: Large-scale gravifossum in Weichselian glaciofluvial sands and gravels in a quarry near Ryssjön (S Sweden).

the sediment is then often not strong enough to withstand deformation. A large number of deformation structures may therefore originate in this way (Dżułyński & Walton, 1965; Jahn, 1975; Brodzikowski and Van Loon, 1979, 1980; Brodzikowski, 1981; Eissmann, 1981). Deformations of this type have been described already long ago by Leith (1923) and Billings (1972) but few studies have been devoted specifically to the topic. It is known, however, that differential compaction results particularly in flexures and faults, although fissure systems and folds are not uncommon. The most detailed information about compaction structures was obtained from studies in glaciated areas. One might discuss whether graben-like deformations due to the melting of buried dead-ice masses (McDonald and Shilts, 1975; Eissmann, 1981) should also be considered as a compaction phenomenon, but the resulting (mainly graben-like) structures can only form if the water formed by ice melting is pressed out of the sediment, which is one of the characteristic compaction processes.

5.2.5. Slopes and inclinaturbations

The last group of deformations due to gravity is found in mass-flow deposits (in the widest sense). Mass flows range from the commonly very slow process such as creep (which might be considered as the highest-density type of mass-transport) to turbidity currents (Bouma, 1962; Sanders, 1965; Dżułyński & Radomski, 1966; Eyles & Clark, 1985; Butler & Tavarnelli, 2006; Sporli & Rowland, 2007), which are the classical form of low-density mass transport (Kuenen & Menard, 1952; Iverson, 2003). There is a complete spectrum of mass-flow types in between (Glover et al., 2000), and all these may give rise to SSDS. On the basis of these deformations, it can be shown that the type of flow may change during the downslope movement (Melvin, 1986; Mulder & Alexander, 2001; Dugan & Flemings, 2002; Haughton et al., 2003; Lowe et al., 2003; Talling et al., 2004).

Both subaerial and subaqueous conditions may result in mass movements. The resulting deposits have attracted much attention, particularly because the structures commonly allow a reconstruction of the mass-transport mechanism, including the physical state of the material (Crowell, 1957; Dott, 1963; Van Loon, 1970; Page, 1978; Lopez-Gamundi, 1993; Hibsch et al., 1997; Hesthammer & Fosen, 1999; Smith, 2000; Rossetti & Santos, 2003).

Solifluction is a subaerial process that should not be considered as a form of mass transport, but rather as the result of a combination of several processes, including forms of mass transport but also grain-by-grain transport. It results in disharmonic folds or even complete destruction of the original internal structure (Clapperton, 1993); under periglacial conditions, this process has also been called 'gelifluction' (Matsuoka, 2001; Harris, 2007). Palaeosols and other 'fossil sedimentary surface layers' show solifluction structures quite frequently. True subaerial mass-movement processes, e.g. sliding, slumping and rock fall, may also result in internal deformations and/or deformation of the underlying sediments. Interesting deformations are formed particularly during subaerial debris flowage (Matsuoka, 2001; Jary, 2009); these include breccias, convolutions, disharmonic folds, shear planes, etc. The effect of large rock masses that may tumble down subaerially and that certainly will affect a soft-sediment cover is much less well known. The preservation potential of such structures is most probably negligible because subaerial slopes are doomed to be eroded.

A different situation – though only at a relatively small scale – exists if walls along a river are undercut, which results in the falling of soft-sediment masses. Particularly if the sediments are cohesive (such as clays), the clay lumps may be transported by the river and become partly eroded, partly rolled up to form contorted clay balls (Fig. 17A). The same holds for clay masses that tumble down from the cliff of a salt marsh as a result of undercutting during high tide (Fig. 17B), and that may become rolled-up under the influence of wave action. Most of such fragments will gradually be washed away during the next flood stages, but some balls with deformations that indicate the rolling up may become embedded in the tidal sedimentary succession and thus be preserved.

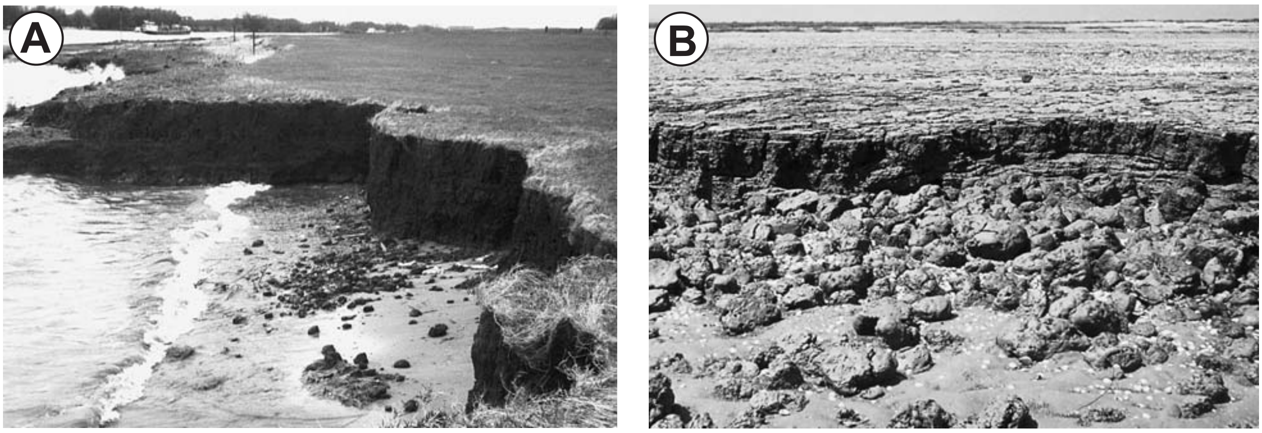


Fig. 17. Deformation of clay balls due to current and wave action. A: Undercutting of natural levees during high-discharge periods cause clay balls to be formed at the foot of the 'cliff'. The clay masses that have fallen down from the cliff become rolled up during transport by the river. Waal River between Oosterhout and Slijk-Ewijk (The Netherlands). B: Clay balls at the foot of a salt-marsh cliff become rolled up mainly by to-and-fro movements under the influence of wave action. Land van Saeftinghe, SW Netherlands.

Data about these deformations are, however, extremely scarce. Some examples of this type of SSDS have been described from intertidal siliciclastic and carbonate environments; the underlying causes are migration of meander-type tidal channels, and macrotidal hydrodynamic processes (see references in Spalluto et al., 2007).

Much more frequent than subaerial mass-flow deposits are their subaqueous equivalents. They comprise both small and very large deposits, ranging from a few millimetres thick (laminites) to tens of metres thick, such as some fluxoturbidites that kept moving – after deposition had started – over the slightly inclined muddy substratum, thus producing large SSDS at their base. The physical mechanism of the subaqueous transport and deposition – and therefore also the deformational structures that can be found in such deposits – depends mainly, even more than in their subaerial counterparts, on the ratio between solid particles and water (but also on the granulometry of the transported particles). This ratio depends – at least partly – on the inclination of the subaqueous slope, so that SSDS in these deposits can sometimes provide much information about the palaeogeographical conditions. The highest particle/water ratio is found in subaqueous slumps; this ratio is less in subaqueous mudflows, and in turbidity currents the ratio is lowest. The terminology of subaqueous mass-flow deposits is fairly chaotic, and no generally accepted classification of mass-flow deposits exist. The terminology used by the original workers is therefore followed here.

Slumps with large-scale deformations (Fig. 18) have been reported by, among others, Miall (1985), Eyles & Eyles (2000) and Schnellmann et al. (2005), whereas Broster and Hicock (1985) mentioned the occurrence of SSDS in a subaquatic (glacigenic) debris-flow deposit (which seems to have formed by deposition from a mass flow intermediate between slump and mudflow). Marine slumps and turbidites

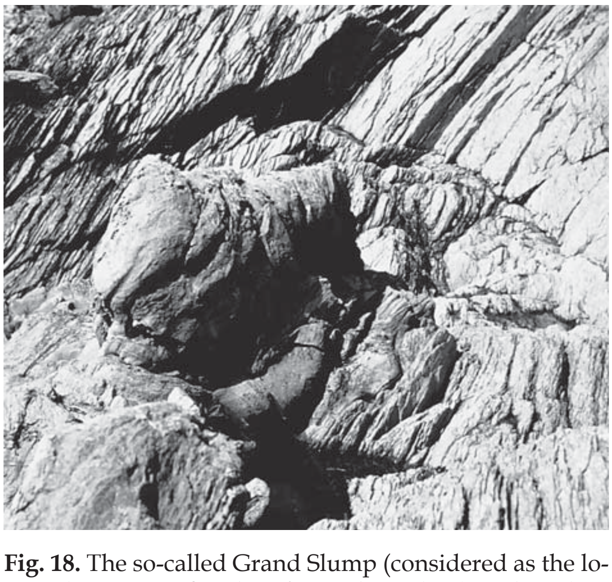


Fig. 18. The so-called Grand Slump (considered as the local Devonian/Carboniferous boundary) in the Pilton Beds at Beggy Point (England).

with SSDS may be associated with submarine canyons (Dilk, 1964) and deep-sea fan channels (Nakajima & Satoh, 2001; Hickson & Lowe, 2002) but occur more generally in subsiding (intramontaneous) basins between areas that are being uplifted (Van Loon, 1972; Yong et al., 2003; Sylvester & Lowe, 2004; Eyles & Januszczak, 2007) and in other sediments formed under syntectonic conditions (Cavazza et al., 2007). Comparable slumps, mainly with fold structures, have also been reported from tidal channels (Brenchley and Newall, 1977) and from shallow fresh-water environments (Rautman and Dott, 1977). Turbidites and the structures inside them have received much attention since the work of Kuenen and Migliorini (1950); they can contain several types of SSDS, but convolutions are the most common type in completely developed turbidites.

It seems worthwhile to mention here to the fairly exceptional conditions under which SSDS are formed by mass-transport processes. One might question whether all deformations visible in mass-flow deposits are SSDS, as some of these deformations are formed already during transport (e.g., the folds in slumps). Such deformations might, in principle, also be considered as sedimentary structures. One should realize, however, that mass flows come to rest gradually (even the ‘freezing’ of mudflows takes some time as distinctly shown by the pebble characteristics and their distribution within a pebbly mudstone: Van Loon, 1970). After deposition of the lowermost material, the ongoing movement of the upper material may trigger deformation of the previously deposited parts, resulting in shear planes, drag folds, etc. This implies that most deformations (for instance, the convolutions in a turbidite or the shear planes in a mudflow deposit) can equally well be considered as SSDS. In addition, many mass-flow deposits have an irregular distribution of fine and coarse particles, which gives rise to unstable density gradients that may also result in the formation of SSDS such as load-casts.

Fig. 19. Groove casts, one of which shows the object that caused the structure at its end. Flysch facies of the San Vicente Fm. near Atiat (Pyrenees, Spain).

SSDS caused by gravity-induced movements over a subaqueous slope, often as a result of gravity-flow deposits, are sole marks, the most characteristic being groove casts (Fig. 19). They were described in detail already by Dżułyński and Walton (1965).

5.3. Exogenic forces

Six groups of exogenic deformations are distinguished: (1) bioturbations, which are due to activities by organisms, (2) glaciturbations, which are due to processes related to the presence of ice masses (3) thermoturbations, which are due to changes in temperature, (4) hydroturbations, which are due to the movement of water, (5) chemoturbations, which are due to chemical proceses, and (6) eoloturbations, which are due to wind activity.

5.3.1. Biological activity and bioturbations

Activities of living organisms that change the original grain-to-grain contact in a sediment result in SSDS that are called ‘bioturbations’. Bioturbations form part of traces of any form that have been left by organisms, but the organism-induced traces (which are commonly known as ‘ichnofossils’) include also purely erosional structures that should not be considered as SSDS. The ichnofossils that are formed by animals that walk, crawl, rest or move otherwise over the sedimentary surface or that make burrows are commonly called ‘trace fossils’ (Seilacher, 1964, 2007; Bromley, 1990). The living organisms may be plants, animals or Man.

It is not always possible to ascribe an ichnofossil to a specific organism, nor are all trace fossils well understood (Bromley & Pedersen, 2008). In order to allow some classification based on the current biological approach, so-called ichnogenera and ichnospecies have been introduced (see, for instance, Knecht et al., 2009).

Trace fossils are important for several reasons, the most important being: they can give information about the sedimentation rate and/or the presence of hiatuses in a sedimentary succession (Gruszczyński et al., 2008); they can give information on reinhabitation of a previously hostile environnment (Benner et al., 2009); they can provide information about the palaeohydrology (De Gibert & Sáez, 2009), they can provide environmental information (Uchman, 2003; Uchman et al., 2008; Carmona et al., 2009), including information about the conditions in environments that house little organisms (Knecht et al., 2009; Uchman et al., 2009).

5.3.1.1. Bioturbation by plants and phytoturbations

It is the growth of roots that is the main deformational activity of plants; this is because roots fissure and flexure the soil (Glennie and Evamy, 1968; Ferreira et al., 2007). The resulting deformation can be particularly clear if the sediment is laminated. In recent sediments, this type of bioturbation is commonly well visible as an interruption along a more or less vertical profile of the original bedding. The roots also tend to create special Eh (redox) conditions, which can result in the precipitation of iron (hydr)oxides or, in contrast, to reducing conditions. This frequently results in a colour that makes bioturbation by roots also visible in hardly stratified sediments. The colouration may still be found as coloured spots (Fig. 20A) after the original roots have disappeared, for instance because the plant was covered with new sediment, died and decomposed consequently (Shuman et al., 2005). Similar structures have also been found in ancient deposits (Rygel et al., 2004). The different micro-environmental conditions around roots can also result in (commonly slight) local cementation, which can result in natural exposure if the non-cemented material is eroded. The resulting ‘columns’ (called ‘rhizoliths’) can reach dimensions of more than a metre high (Fig. 20B) (Alonso-Zarza et al., 2008), but they should be considered as neither fossils, nor SSDS (as no deformation is required for their formation).

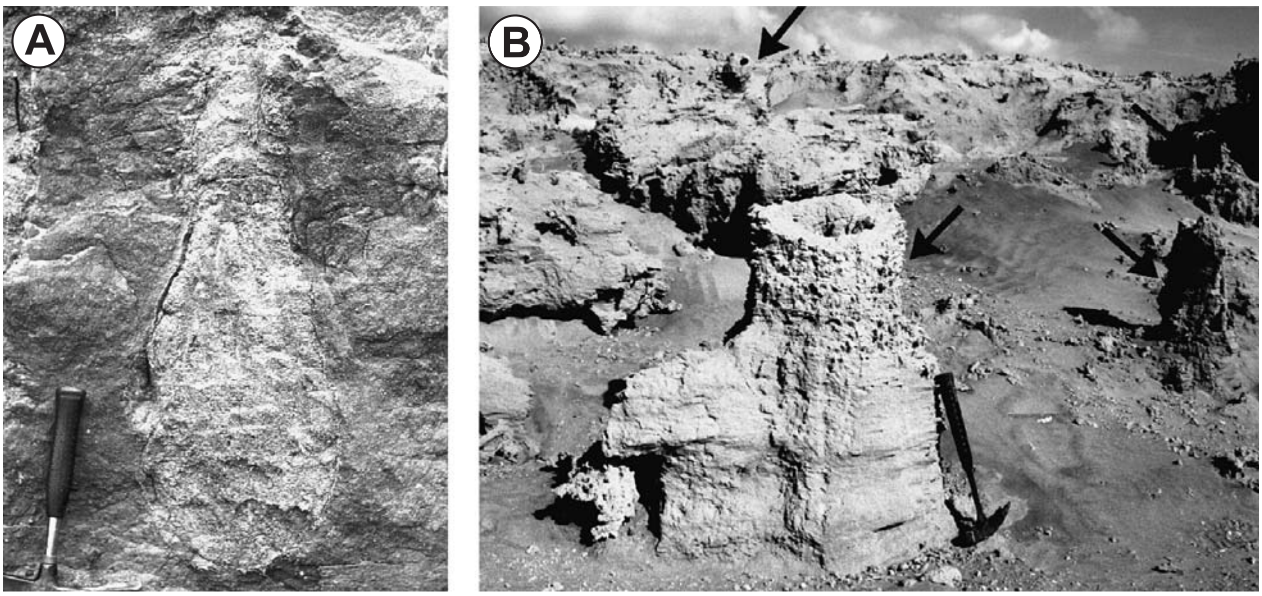


Fig. 20. Sediments affected by soil conditions due to plant roots. A: Reduction zone around roots in (oxidated) Tertiary greensands at Herentals (Belgian Ardennes). B: Megarhizoliths (indicated by arrows) in a Pleistocene dune field on Gran Canaria (Spain). Photo Ana Alonso-Zarza (Madrid).

The sparse irregular bedding that may seem to contain SSDS but that actually results from deposition of sediment on top of, or around, plants (such as commonly occurs in the salt marshes of tidal flats) should not be considered as SSDS, but rather as a primary structure. The same holds for irregular sedimentary structures such as fossilized microbial structures, which are known to have formed already during the Proterozoic (Schieber, 1998)

5.3.1.2. Bioturbation by animals and zooturbations

Whereas 'fossil' SSDS caused by plants are relatively rare, deformations due to animal activity are very common in the geological record. Examples are subaerial structures such as trails (Fig. 21A) and imprints made by resting (Fig. 21B) or walking (Fig. 21C and D) animals (Fornós et al., 1986, 2002; Gong & Si, 2002). Most animal-induced SSDS, however, occur inside the sediment, where they are formed especially under subaqueous (both fresh-water and marine) conditions (Fig. 21E and F).

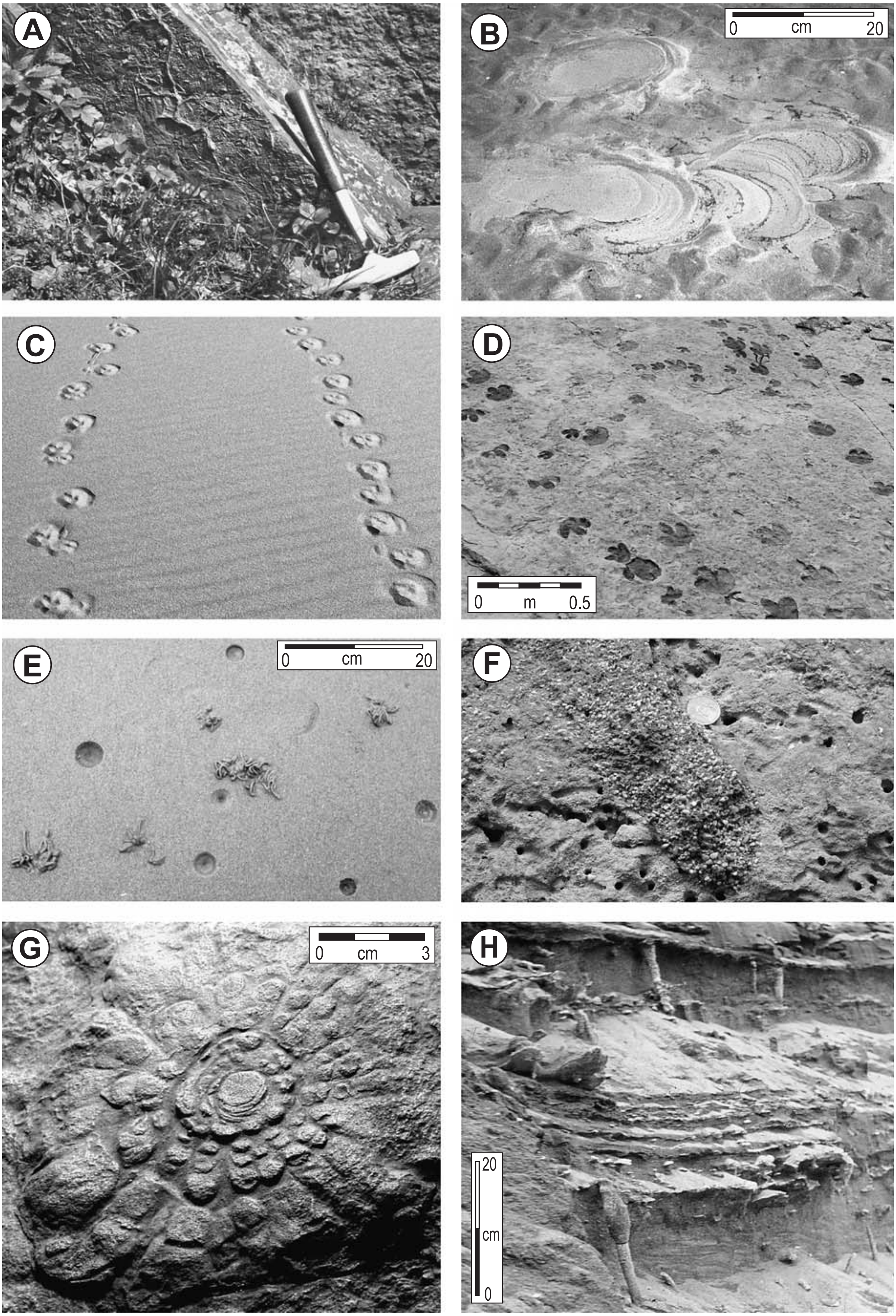
While such structures have frequently been described from both soft, and (now) lithified sediments (e.g. Gutschick & Lamborn, 1975; Bhattacharya and Bhattacharya, 2007; Hertweck et al., 2007), many of them cannot be interpreted with any certainty as being either organic or inorganic in origin. A characteristic example are the different hypotheses regarding a structure in Ediacaran rocks, which has originally been described as a fossil (*Mawsonites*: Fig. 21G) (Glaessner & Wade, 1966), then as some kind of water-escape structure (Seilacher et al., 2005) and then again as a fossil because the origin as an SSDS could be falsified (Van Loon, 2008a). In other cases, however, it must be concluded that Ediacaran structures originally interpreted as fossils seem to be inorganic in nature, indeed (Pflüger, 1995; Hagadorn and Bottjer, 1999). Obviously, the Ediacara fauna still is enigmatic, so that is may not be surprising that some structures are subject of debate, but similar controversies regard also Phanerozoic structures (Knaust and Hauschke, 2004; Goldring et al., 2005). It must therefore be concluded that much research must still be carried out in this field, particularly because of the significance of both SSDS and trace fossils for facies interpretation.

Most commonly, bioturbations are caused by worms. Numerous other types of animal-induced SSDS exist, however, but most of them are relatively rare. They range from fossil termite constructions (Duringer et al., 2007) to crab-made constructions (Fig. 21H) (see also Curran and Martin, 2003). Interpretation is commonly difficult, unless similar SSDS are known from present-day taxonomic relatives from the same environment. An example of this are the burrows that were recently described by Surlyk et al. (2008), who ascribed them to 'possibly' fossil lungfish.

5.3.1.3. Bioturbation by humans and anthropoturbations

Anthropogenic (Man-made) SSDS are by definition restricted to the Quaternary, as earlier predecessors of Man are commonly not classified as hominids. There exist relatively old examples, but most deformations of this type are of Holocene age such as footprints in volcanic ashes (Fig. 22A), traces of prehistoric ploughing: Fig. 22B), prehistoric pits dug

Fig. 21. Typical animal-induced bioturbations. A: Worm trails in the Assise d'Esneux (Famennian) at Comblain-au-Pont (Belgium). B: Traces caused by fishes resting on (or just under) the sedimentary surface in the intratidal zone of Baie Mont-Saint-Michel (France). C: Traces left by a doe in the Great Sand Dunes National Park near Moca, CO (U.S.A.). D: Dinosaur tracks in the Dakota Sandstone at Dinosaur Ridge, W. Denver, CO (U.S.A.). Photo Geoscience Research Institute 2006 Field Conference (Denver). E: Indications of the presence of the burrowing worms *Arenicola marina* and *Nereis* in the intratidal zone of the Baie de Veys (Normandy, France). F: Burrow by the crustacean *Ophiomorpha* in the middle Santonian Salzberg Formation near Quedlinburg (Germany). G: Cast of the holotype of *Mawsonites spriggi*, a ?trace fossil from the Ediacara fauna that has erroneously been described as a pseudofossil (viz. as an SSDS representing essentially a sand volcano). Photo Natural History Museum of the University of Oslo. H: Partly opalized burrows of arthropods in Bruxellian sands near Archennes (Belgium).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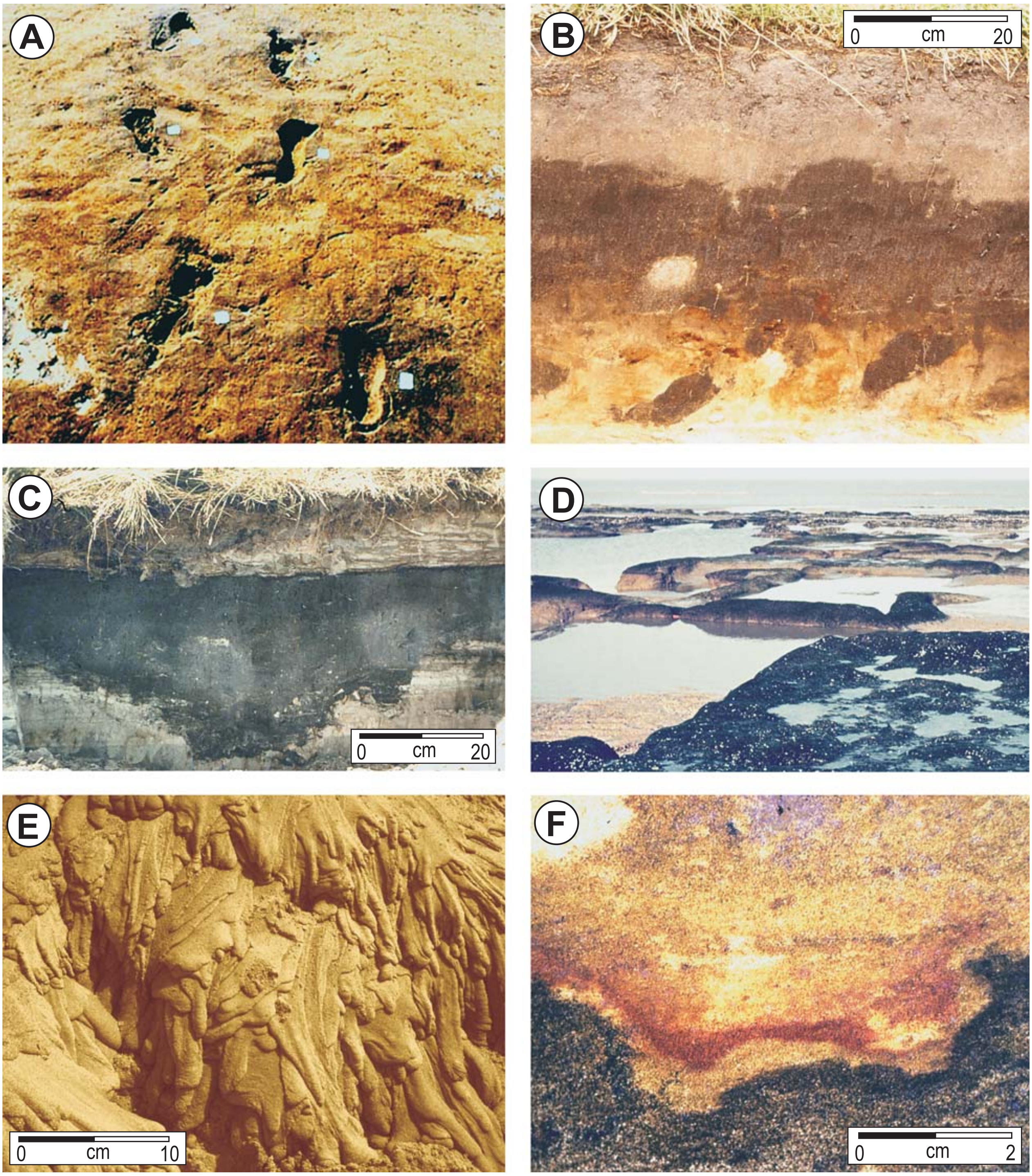


Fig. 22. Anthropogenic deformations. A: Foot steps left behind in fresh volcanic ash by Bronze Age people flying for an eruption of the Vesuvius volcano (Italy). B: Traces of prehistoric ploughing (producing dark pieces of a peaty podzol in the underlying - light-coloured - sands that did not undergo pedogenesis) in the coastal-dunes area of the western Netherlands. C: Pit dug by prehistoric Man as a waste-dump site. Surroundings of Marck (NW France). D: Remnants of Roman and Medieval peat digging exposed during low ebb tide off Raversyde (Belgium). Traces left by the spades used during the peat digging can still be found. E: Flow lobes on the slope of piled wet sands in the Jansen quarry at Uelsen (W Germany). F: SSDS intermediate between bioturbation and anthropoturbation: imprint made in Mediaeval times by cattle in a wet meadow near a farm. Coastal plain, NW France.

as waste-dump sites (Fig. 22C), etc.; recently formed structures are, however, obviously the most common. Some of the activities that remove parts of an original unconsolidated sediment, and that may thus be considered as anthropoturbation, such as peat digging (Fig. 22D), may change the face of the earth entirely (see also Van Loon, 2001), but others have only local significance.

Man not only deforms the sediment directly but also by means of machines or other equipment. This results in a wide variety of structures that cannot always be identified easily as Man-induced. There is also a gradual transition between man-induced and 'natural' deformations, viz. if humans trigger natural processes that result in SSDS. An example are the flow lobes formed when wet sand is dumped to form a storage pile (Fig. 22E).

SSDS that might be interpreted as intermediate between animal-induced and Man-induced structures are the imprints that are made by domesticated cattle in muddy areas around a farm. Such structures are known, for instance, from Mediaeval times (Fig. 22F).

5.3.2. Glacial activity and glaciturbations

Both soft sediments and lithified rocks can be deformed by glaciers and continental ice sheets. These glacitectonic deformations, which are called here 'glaciturbations', have been studied for a century and a half (Sorby, 1859; Geikie, 1882). They may occur on a large scale (Fig. 23A) but also on a small scale or even a micro-scale (Seret, 1993; Phillips et al., 2007). All types of glacigenic and non-glacigenic deformations that are known from lithified rocks have been found in glacitectonically disturbed soft sediments as well (Sjørring, 1978; Berthelsen, 1979; Schwan & Van Loon, 1979, 1981; Brodzikowski and Van Loon, 1980, 1983, 1985a; Brodzikowski, 1982; Van Loon et al., 1985; Boulton et al., 1999; Andersen et al., 2005; Le Heron et al., 2005; Benn & Prave, 2006; Phillips et al., 2007). This is due to the large variability in active-ice behaviour and to the high-pressure conditions that may be present.

Various general models of glacitectonism have been established (although the earlier ones might better be considered as hypotheses: Van Loon, 2004) and detailed characteristics have been described (Gripp, 1929; Moran, 1971; Banham, 1975; Brodzikowski & Van Loon, 1981; Aber et al., 1989; Aber, 1992; Lian et al., 2003; Aber & Ber, 2007). Much work is still being done on detailing these data, but glacitectonic disturbances as a whole can be considered as a rather well known and well understood group of SSDS, particularly since many studies have been carried out in glaciolacustrine and glaciofluvial sediments that show abundant SSDS (Schwan et al., 1980a; Brodzikowski et al., 1997; Van Loon, 1999; Gruszka & Van Loon, 2001, 2007; Sturgeon et al., 2006), sometimes probably due to tectonic shocks (Van Loon et al., 1995), but more often without indications for tectonic activity.

Glacitectonic deformations have been described for an overwhelming majority from Pleistocene deposits (a.o. Brodzikowski & Van Loon, 1991; Jones & Fielding, 2008; Schomacker & Kjaer, 2008), but also from the Permo-Carboniferous glaciation (a.o. Rocha-Campo et al., 2000), the Ordovician glaciation (a.o. Le Heron et al., 2005, 2007; Le Heron, 2007) and the various Proterozoic glaciations (a.o. Williams, 1996; Young et al., 2001; Arnaud & Eyles, 2006; Rieu et al., 2006; Røe & Hermansen, 2006, 2007; Eyles et al., 2007; Mazumder & Altermann, 2007; Arnaud, 2008; Williams et al., 2008).

From the numerous glacitectonic studies it becomes evident that distinctly different types of SSDS occur. One distinction may be made on the basis of the position where the SSDS are formed. Although ice itself may be considered as a (plastic) sediment, deformations within the ice will not be dealt with here as the present work focuses on siliciclastic sediments. Such sediments may occur underneath and in front of the ice (also on top of and inside the ice, but such sediments are, if forming part of a sedimentary succession left behind by a retreating ice cap, difficult to recognize: cf. Brodzikowski & Van Loon, 1991), and therefore will not be dealt with here.

If the ice is underlain by unconsolidated sediment, SSDS will be formed if the ice is

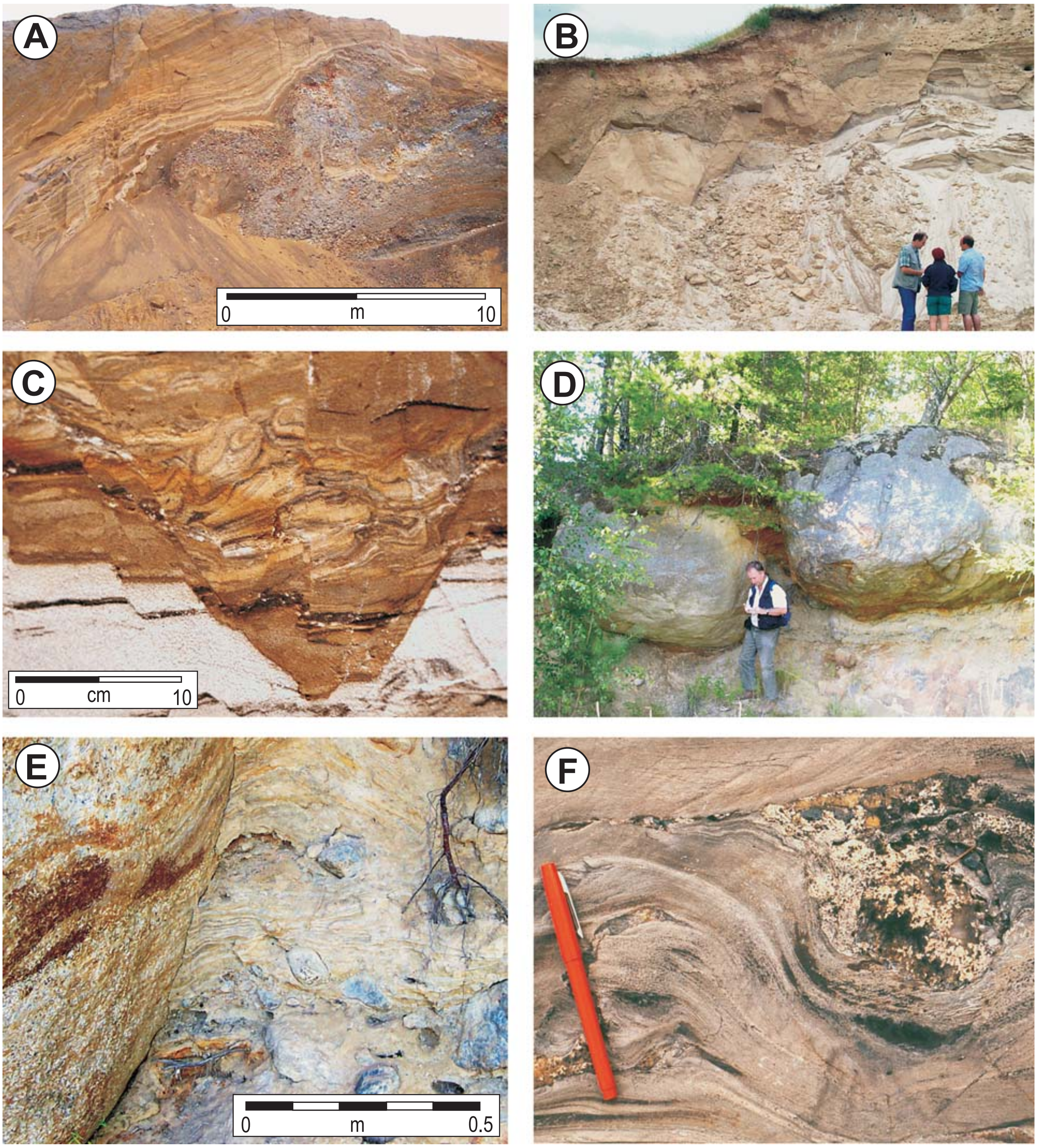


Fig. 23. Glaciturbations are mainly produced by pressure (e.g. in ice-pushed ridges), tension (e.g. occurring when ice under or alongside a glacigenic deposit melts away), or by stones that fall down in water (e.g. from an ice raft or the roof of a subglacial channel). A: Large-scale glacitectonic deformations as a result of pressure in a sand quarry near Hummelhaga (S Sweden). B: Blocks consisting of esker sediments formed by relaxation (de facto tension) after the ice walls had melted away. Surroundings of Wielowiczek (Poland). C: Graben-like deformation (commonly called 'dead-ice structure') in fluvioglacial sands due to melting (de facto resulting in tension) of buried dead-ice underneath. Bełchatów opencast mine (central Poland). D: Huge dropstones in a quarry near Axelsberg (S Sweden). The unconsolidated sediment underneath is relatively slightly deformed, possibly because the stones fell on the slightly inclined hard (Precambrium) substratum and then toppled over. Photo: Amir Mokhtari Fard (Bromma). E: Intense deformation between the two huge dropstones of Figure 23D, possibly caused when the second stone tumbled over on the substratum towards the first one, pressing up the material in between them. F: Small dropstone in Huronian glaciomarine sediments, causing relatively slight deformation of the underlying fine-grained sediment (Alberta, Canada).

moving. Shearing plays a major role (Dreimanis, 1993; Benn & Evans, 1996; Benn & Prave, 2006; Phillips et al., 2007), which is reflected in both numerous shear planes and in the presence of deformed slabs of subglacial (unconsolidated) sediments within the till at the base of the ice (so-called deformation tills: Ruszczyńska-Szenajch, 2001). The shearing process at the ice/substratum contact (Piotrowski & Tulaczyk, 1999) is also responsible for many deformations in the soft-sediment substratum itself (Menzies, 1989; Licciardi et al., 1998; Piotrowski & Tulaczyk, 1999; Lian et al., 2000; Boulton et al., 2001; Piotrowski et al., 2004, 2006; Waller et al., 2008). Not only shearing is responsible for the formation of subglacial SSDS, however: stones carried by the ice at its base scour grooves into a soft-sediment substratum (Houmark-Nielsen, 2003; Deynoux & Ghienne, 2004). In contrast to grooves that are made in a soft bottom by, for instance, objects that are carried along by submarine mass flows, continental glacial grooves are rarely associated with some upward push of the sediment just beside; the reason is that the subglacial grooves are made under conditions where a hard ice mass rests on the substratum, so that soft sediments are not easily pressed upwards, apart from transport through shear planes.

The ice movement can also result in the 'streamlining' of topographic highs consisting of unconsolidated material that become overridden by the ice. If both the affected sedimentary highs are large enough and the ice cover is powerful enough, not only does the streamlining involve erosion and redeposition, but also deformation (Clark et al., 2009). This streamlining process results in tear-shaped highs that become visible after retreat of the ice and that have by called 'drumlins' in geomorphology (McCabe, 2008).

Although subglacial deformations, including those in drumlins, have been studied in fairly much detail, much more is known about the glaciturbations that were formed in front of the ice. Most common is glacial push (e.g. Van Loon et al., 1984; Eyles et al., 1999), resulting in push moraines (Bennett, 2001) that may be tens of metres high and that consist commonly of deformed proglacial fluvial and lacustrine sediments (Fig. 23A); alternating phases of ice retreat and ice re-advance can cause inclusion of till in the push moraines, and the overriding of previously deformed sediments during a re-advance tends to cause extremely complicated deformations.

It may be true that most glaciturbations must be ascribed to pressure, but tension-induced glaciturbations are also common. The main reason is that an essential component of the glacial environment, viz. the ice, disappears at a certain moment. This affects sediments in several ways, the most important being the melting of buried dead-ice blocks and the melting of ice beside a sediment. In the case of melting dead-ice within a sediment, a cavity is created, and this will eventually cause collapse, commonly in the form of a graben structure (Fig. 23C) that is termed a 'dead-ice structure'. The formation of a cavity induces de facto a negative pressure at its top, so that this structure may be considered as a result of tension tectonics. It might, however, also be considered as due to compaction (and thus represent a compagoturbation) or to gravity (and this represent an inclinoturbation); this only emphasizes once more that many processes may be involved in the genesis of a specific structure, and that it depends on the interpretation of the researcher which process(es) he thinks ultimately responsible for the deformation as an entity. The second case in which tension occurs, viz. if ice surrounding a sedimentary succession melts away, occurs, for instance, when an ice cap retreats and tunnel-mouth or tunnel deposits are set free as long ridges (morphologically indicated as eskers). The esker sediments will eventually not only collapse to fill up the previous tunnel space, but also move sideward, which tends to result in normal faulting (Fig. 23B).

A special type of glaciturbations is due to dropstones; these fall on the sea or lake bottom if a debris-laden iceberg or raft passes while melting, or when it tumbles over. Large dropstones (Fig. 23D) may cause strong deformations (Fig. 23E), whereas small stones commonly result only in relatively slight loading (Fig. 23F).

In addition, shore ice may induce deformations (Dionne, 1998), and floating icebergs reaching the bottom of a glacial lake (Eyles & Meulendyk, 2008) or the seafloor may also cause large-scale SSDS (Longva & Bakkejord, 1990; Eden & Eyles, 2001; Mokhtari Fard & Van Loon, 2004).

5.3.3. Changes in temperature and thermoturbations

Unconsolidated sediments tend to contain water, often in considerable quantities. Particularly the behaviour of water during temperature changes around its freezing point can induce intense deformation. The freezing/thawing alternations during the Pleistocene glacials affected many sediments, resulting in numerous convolutions and other structures (Murton, 2001). Such conditions prevail in the periglacial environment. Theories about the origin of typically periglacial SSDS, such as blocks of soft sediment that have been transported by a glaciofluvial stream and that therefore are assumed to have been in frozen condition (Fig. 24A), were put forth in the early fifties (Black, 1952; Schmidt, 1953; Dylik, 1956) although there is also important earlier work on this topic (Weinberger, 1944). The search for hydrocarbons in periglacial areas has given rise to much recent research, which is reflected in numerous recent works on periglacial SSDS and their genesis (Vanneste et al., 1999; Van Vliet-Lanoë et al., 2004; Antoine et al., 2005; Williams et al., 2008). This is not only due to the economic value of hydrocarbons, but also to the insight that the periglacial environment is very vulnerable and may be severely affected by global warming, with the possible consequence of dissociation of huge amounts of clathrates, which might contribute to a further rise of the global temperature.

Some SSDS are considered by various authors (Jahn, 1975; Clapperton, 1993; French, 2007) as characteristic of periglacial processes. Frost fissures (Fig. 24B), frost wedges (Fig. 24C) and associated structures may, indeed, be the only group that needs no other processes as well; a proposal by Jahn (1977) to classify fossil ice wedges is considered as being easily applicable in Pleistocene field studies (Eissmann, 1981). Cryoturbation (due to ice pressure and fluidisation of the sediment after ice melting) (see Fig. 5B) must, however, be considered as a result of typically periglacial processes in combination with much more common deformational processes such as loading and liquefaction (Jahn & Czerwiński, 1965; Benedict, 1976; Jary, 2009). It is interesting in this context that even experienced researchers cannot always be sure of the periglacial origin of a specific SSDS (see the discussion in Van Vliet-Lanoë et al., 2004).

Some other SSDS related to temperature conditions (e.g. imprints of ice flowers: Reineck & Singh, 1973; Van Loon, 1990) may also be considered as induced by temperature changes (Fig. 24D).

5.3.4. Movement of water and hydroturbations

Hydroturbations can take different forms, due to the variety of processes in which water movement plays a deformational role (Folkestad & Steel, 2001). Fairly common are desiccation cracks, which are the result of water movement from clayey sediment towards the surface where it evaporates, with the result that the clay shrinks and cracks are formed to solve the space problem (Fig. 25A; see also Fig. 6C). Desiccation cracks are therefore comparable in structure with the shrinkage cracks of cooling basaltic lava. Desiccation cracks should not be confused with the still fairly enigmatic synaeresis cracks, which are interpreted by most researchers as SSDS that are here included in the group of chemoturbations.

Another common example of hydroturbation are breccias that are formed as a result of waves affecting an unconsolidated sedimentary surface. The waves are commonly due to storm activity, but may also result from a subaqueous slide or an earthquake. Earthquakes themselves may also directly cause breccias if the shock waves affect surficial slightly consolidated sediments (Gruszka & Van Loon, 2007), but such breccias should rather be considered as endogenic SSDS. An intriguing hydroturbation is mentioned by Bouchette et al. (2001),

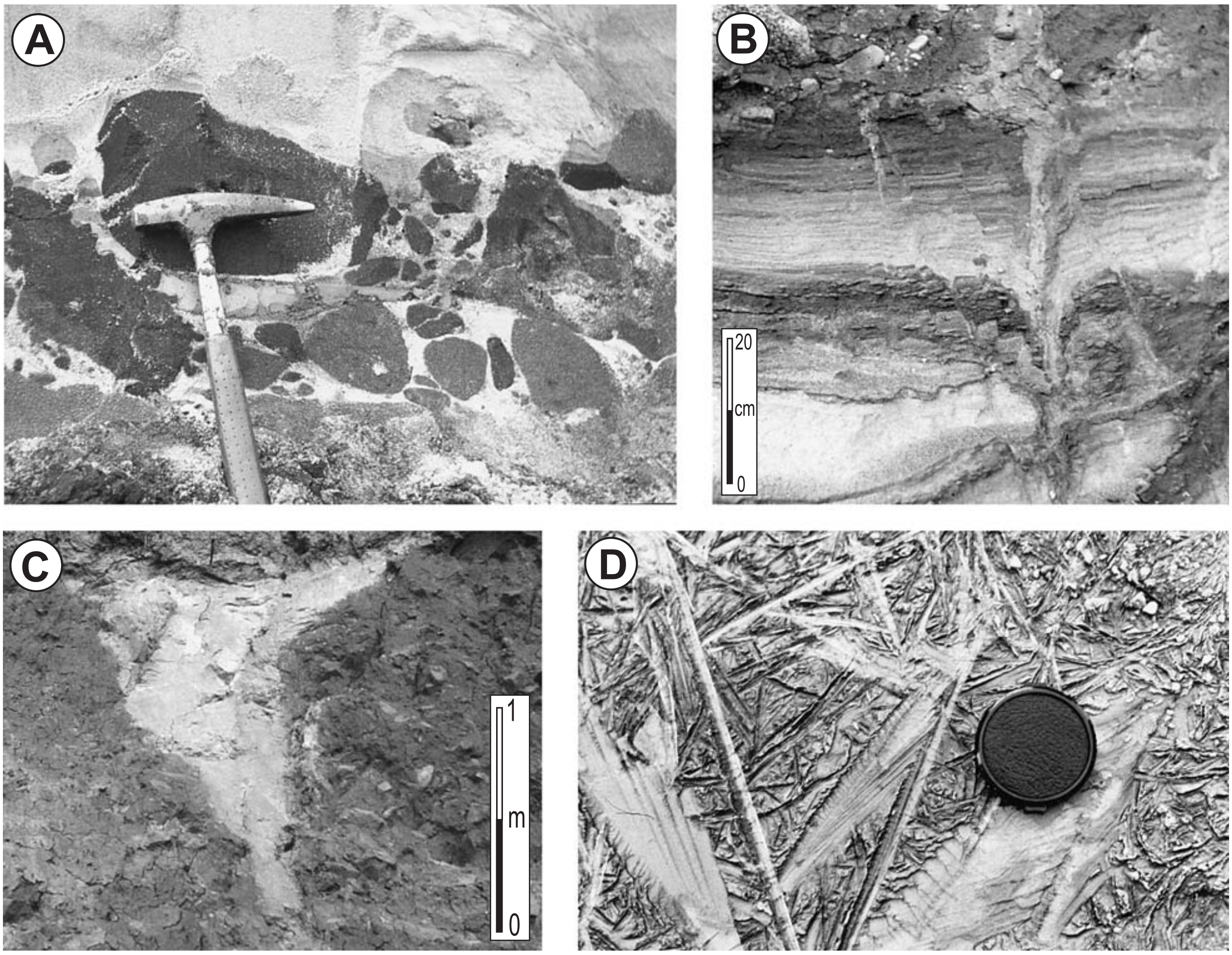
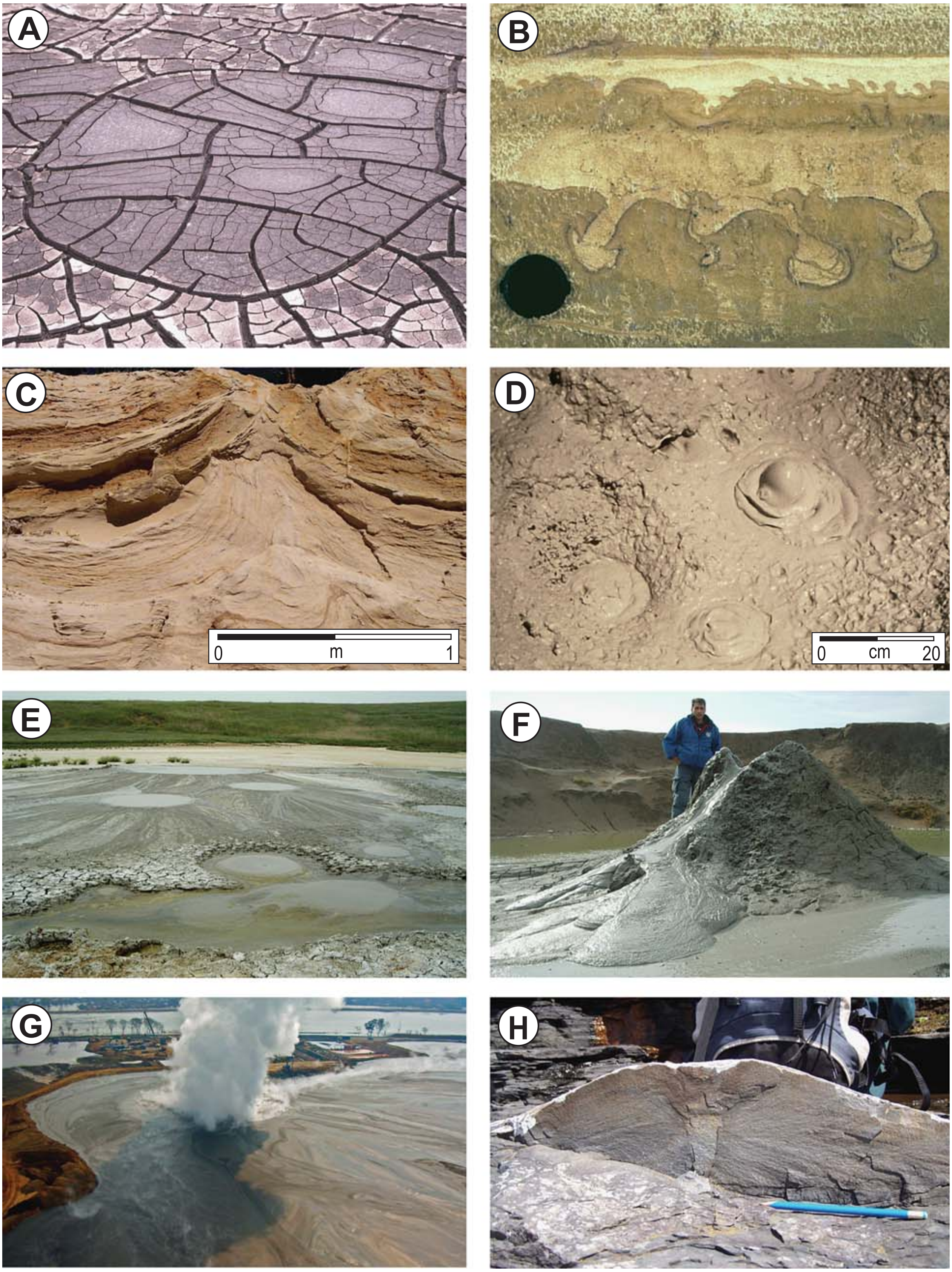


Fig. 24. Thermoturbations. A: Rounded pebbles of Miocene browncoal in the Neurather Sand, formed by transport in frozen condition during the Pleistocene. Morken open-cast browncoal mine (W Germany). B: Frost fissure in the Beuningen Layer at Getelo (Germany). C: Frost wedge in Weichselian sediments at Ścinawka Średnia (Poland). D: Imprints of ice crystals (view from above) in a muddy soil near Ginzling (Austria).

who ascribe the formation of breccias to water-wave cyclic loading.

Fine-grained sediments such as loesses (which are rare in the sedimentary record because they have hardly been preserved from the pre-Saalian glaciations: Van Loon, 2006c) and other deposits with a relatively high amount of silt are characterized by a different type of water escape. Particularly lacustrine (including glaciolacustrine) and lagoonal sediments have often relatively high concentrations of silt, and they frequently show abundant SSDS (Fig. 25B), which may point at brittle (Van Loon & Wiggers, 1976b; Gruszka & Van Loon, 2007), plastic (Van Loon & Wiggers, 1975a,b,c, 1976a,b; Collo & Giardino, 1997; Bennett et al., 2000), and liquid (Van Loon & Wiggers, 1975a,b, 1976b; Owen, 1996) behaviour.

In the case that fresh, sandy subaqueous sediments become covered by younger deposits, the resulting pressure forces some of the pore water out between the grains. Depending on the horizontal and vertical anisotropy of the sediment, the water may move in a horizontal and/or vertical direction, commonly in a non-linear way. Water-escape structures (Fig. 25C), dish structures, pillar structures and sand volcanoes (Fig. 25H) may be formed during this process (Reineck and Singh, 1973; Lowe and LoPiccolo, 1974; Lowe, 1975; Rautman and Dott, 1977; McManus and Bajabaa, 1998; Molgatt & Arnott, 2001; Neuwerth et al., 2006; Rodríguez-López et al., 2007); the escape of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pore gases (commonly trapped air) commonly results in similar SSDS. Closely related are the structures formed due to the near-surface circulation of hot fluids and/or gases (commonly as a result of hydrothermal activity) that result in mud bubbles if the fluids/gases escape through a mud layer (Fig. 25D, 25G).

Closely related but much more spectacular structures can result from water and/or gas migration (see, among others, Hansen et al., 2005) if the source of the gas and water is large enough. The gas and water under pressure may be pushed upwards, and erode mud and/or sand from the layers that they pass. The mud/water/gas mixture may flow out at the sedimentary surface, forming sedimentary volcanoes (Davies et al., 2007, 2008; Mazzini et al., 2007, in press; Kopf et al., in press). Two main types exist: mud volcanoes (that have a shield-volcano-like shape) and sand volcanoes (that tend to have a stratovolcano-like shape) (Van Loon, in press). Mud volcanoes can reach huge sizes: the Dashgil mud volcano in Azerbaijan (Fig. 25E) has a crater of over 200 m in diameter. Secondary mud volcanoes in this crater (so-called gryphons: Fig. 25F) are still active, although the Dashgil volcano itself is considered as dormant (Kopf et al., in press). An active mud volcano on Java (Indonesia), which has been baptised 'Lusi' (Fig. 25G), has probably been caused by nearby drilling activities. The volcanic activity in the neighbourhood causes high groundwater temperatures, so that the water ejected by Lusi forms clouds of steam. The outflow of huge amounts of mud has required the evacuation of some 30,000 people. Sand volcanoes (Fig. 25H) are, as a rule, much less catastrophic and their sizes rarely exceed a few metres.

In deep-marine sediments, the mud volcanoes resulting from water escape may be even larger: with sizes of several hundreds of metres

Fig. 26. Parabola-shaped, upstream directed folds in the alluvial plane of the Waal River between Oosterhout and Slijk-Ewijk (The Netherlands), formed due to a local, extremely energy-rich countercurrent that could form due to a combination of exceptionally high discharge, an exceptionally heavy storm, and an uncommon local topography (from Van Loon, 2006a).

high and kilometres wide at their base. They result from the escape of deep-seated gases (commonly hydrocarbons, possibly due to the dissociation of clathrates) that are set free in the subsoil (Aslan et al., 2001). So-called pockmarks on the sea-floor, resembling impact craters, are commonly considered as the collapse remnants of such mud volcanoes and may act for a long time as producers of water (Trincardi et al., 2004).

A special SSDS that had not previously been described and that was essentially due to flowing water and thus should be regarded as a form of hydroturbation, was detailed by Van Loon (2006a). The structures, which became visible after the Waal river (The Netherlands) had flooded the alluvial plain during a high-discharge phase, consisted of parabola-shaped, upstream-directed folds with amplitudes up to several decimeters (Fig. 26). The structures were ascribed to a rare combination of an extremely high discharge, an exceptionally heavy storm and the special local topography, which all contributed to a relatively shallow countercurrent that dragged the grass-covered topsoil over a few metres.

Fig. 25. Hydroturbations. A: Five generations of desiccation cracks, formed by continued drying of a clayey soil. B: Flame structures and load casts in Weichselian glaciolacustrine silty clays in a quarry near Skydebjerg Torp (Denmark). C: Large escape-structure (seen in cross-section) in sands from the Yoldia Sea in a quarry near Olivegrund (S Sweden). D: Mud bubbles formed by air escape through a muddy layer on Java (Indonesia). Photo J.D. de Jong (deceased). E: Mud volcanoes in the Crimea area, formed by the expulsion of gas-rich water. Photo Adriano Mazzini (Oslo). F: A gryphon: a secondary mud volcano in the center of the Dashgil mud volcano (Azerbaijan), showing characteristic lobes of mud that flow out continuously. Photo Achim Kopf (Bremen).

5.3.5. Chemical processes and chemoturbations

Most chemoturbations take place in chemical sediments. They are therefore not dealt with here in any detail. An example is the continuous growth of salt plates in playa-like conditions if salt water evaporates. The salt crystals grow gradually, not only vertically but also laterally, which results in internal stress systems if two salt plates come in contact with each other (Goodall et al., 2000) (Fig. 27). Some deformations in chemical sediments are well comparable with those in clastic sediments, however, such as the formation of salt domes or diapirs as a result of the vertical pressure exerted by the overburden. The resulting structures are in many respects comparable to clastic diapirs.

Chemoturbations in clastic sediments have hardly been studied, probably because their genetic interpretation is commonly difficult, and because little can be deduced from them. The most commonly studied chemoturbations are synaeresis cracks (Fig. 28), which at first sight look like desiccation cracks. They have, however, different characteristics, among others in cross-section and in their pattern (they do not form the more or less regular polygons that characterize desiccation cracks). They seem also restricted to one sedimentary layer, whereas desiccation cracks can affect several layers. On the basis of both field observations and experiments, it is commonly believed that synaeresis cracks form under subaqueous conditions, but the precise genesis is still a matter of debate. The most likely is that the clay minerals decrease in volume due to changes in salinity of the water (Collinson & Thompson, 1982), but McLane (1995) explains them by expulsion of fluids from colloidal suspensions (which would imply that these cracks are no chemoturbations but rather hydroturbations). The ongoing debate is one more proof that SSDS will remain a challenging study object for many more years to come.

Some SSDS may be formed when crystals grow inside a sediment, widening already existing cracks, or leaving imprints if they are solved afterwards. Crystals may also grow at the sedimentary surface under the influence of ions in evaporating pore waters, sometimes forming delicate imprints in the soft surface, but their preservation potential under subaerial conditions is practically nil.

Fig. 27. Salt plates with boundaries that are pushed up (some 1.5 cm) by ongoing salt precipitation. Salt flat between Kebili and Tozeur (Tunesia).

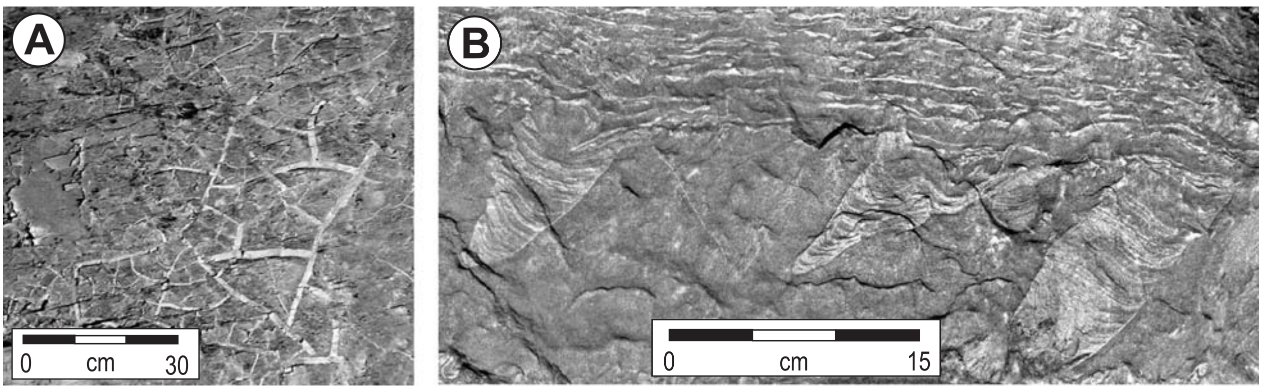

Fig. 28. Presumed synaeresis cracks. A: Bedding plain in rocks of unknown age in Peru, showing cracks that form irregular patterns that do not resemble desiccation cracks and that are ascribed to synaeresis. Photo G.R. Morton. B: Cross-section through infilled irregular cracks in the shallow-marine part of the Palaeoproterozoic Chaibasa Fm. (Singhbhum area, India) that might represent synaeresis cracks.

5.3.6. Wind activity and eoloturbations

It is commonly difficult to distinguish SSDS formed due to specific atmospheric processes from SSDS due to the normal reworking that affects exposed sediments. When wind deforms an eolian dune, this is generally considered as part of the overall (net) depositional process. There are, however, also wind-induced deformations produced by living plants that are true SSDS. Unfortunately, these structures have hardly any preservation potential. Examples are the more or less circular striations that may formed at a sedimentary surface if the wind bends a plant and forces it to move to and fro over the bottom (Fig. 29). Vegetation in deserts and semi-deserts is well known to produce such structures, but – as far as could be traced – no such deformations have ever been described from the bedding planes of lithified continental sediments; it seems likely, however, that such structures in lithified rock are easily overlooked when they are not specifically searched for. This implies that attention for such structures (which might also be considered as atmoturbations) in modern environments may help to recognise them in lithified sediments as well.

An interesting type of an SSDS that might be considered as an eoloturbation (although phytoturbation played also an essential role has been described by Semeniuk (1986). He found a brecciated caliche that he interpreted as being caused by a storm that made trees fall down. The tree roots were pulled out from the caliche with much force during the tree fall, during which process the caliche became partially brecciated.

Fig. 29. Eoloturbations (without much preservation potential) on the surface of inland dunes caused by wind-moved plants (White Sand Dunes National Park, near Alamogordo, NM, U.S.A.).

6. Relevance for the earth sciences

SSDS are now commonly considered as features that can help both to understand the development of the area in which they occur, and to facilitate the exploitation of unconsolidated sediments in which they are present. This is largely due to the fact that analyses of SSDS have drawn attention, particularly since the 1980s, of workers in geological disciplines other than sedimentology. It has now been recognized, for instance, that specific types of deformation are not restricted to hard rock or even to crystals, but can also occur in unconsolidated, even water-saturated, deposits. A characteristic example of such SSDS are kink bands; these were considered only half a century ago as a phenomenon that could occur only within crystals and foliated rocks. Descriptions of kink structures from both unconsolidated Pleistocene sands and Holocene muds (Van Loon et al., 1984, 1985) have distinctly proven, however, that conditions that result in deformations that were earlier considered as typical of hard rock can be present also in soft sediments.

The recognition that SSDS include all types of deformations known from hard rock has led to the insight that deformations in hard-rock do not necessarily reflect endogenic forces (see Fig. 3) (Van Loon, 2003), but that they may be due to exogenic processes affecting the sediments while still in an unconsolidated state. It has consequently become clear that the reconstruction of the structural development of an area cannot be based on the mere structural analysis of deformations, but that it has first to be established whether the structures involved have a sedimentary or a tectonic origin. This insight has led in many cases to adaptation of the reconstruction of the geological history of

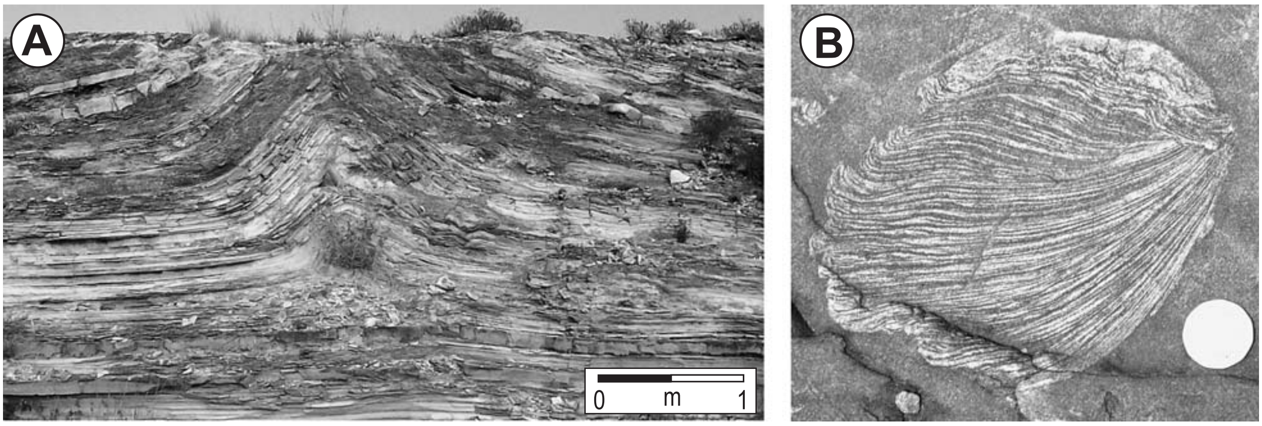

Fig. 30. SSDS of enigmatic origin. A: Structures in the Late Cretaceous Boquillas Fm., along Highway I–90 in the neighbourhood of Del Rio (Texas, U.S.A.). The structures have been described as tepee structures (Johnston, 1983) and later as a result of expansion due to recent caliche forming (Lock et al., 2001), but none of these explanations is convincing. B: More or less rounded structures occur fairly frequently as isolated 'balls' in the Palaeoproterozoic Chaibasa Fm. near Dhalbhum Gar (E India), but their shapes do not support an interpretation as unconsolidated fragments that became rounded by rolling over the bottom of the shallow sea. The internal structure of the various individual balls is identical. No satisfactory explanation of their genesis has been put forward so far.

specific areas, for instance because structural units may be characterized by different types of SSDS (Brodzikowski & Van Loon, 1985a). It must therefore be deduced that SSDS, however small they often are in comparison to main tectonic structures, have contributed significantly to the understanding of the Earth's history.

An important aspect of SSDS is that they may help to reconstruct palaeocurrent directions (and thus commonly also help to reconstruct the palaeogeography). This can be achieved by determining the pebble fabric in outcropping parts of pebbly mudstones (Van Loon, 1983), but is more commonly done by determining the fold directions in mass-flow deposits (Strachan & Alsop, 2006) or measuring the directions of flute casts, groove casts or other sole marks (Van Loon, 1972; Draganits et al., 2008). In a more general way, the flow direction of continental ice sheets can be determined on the basis of the (glacitectonic) SSDS in sediments that were positioned under moving ice or, more commonly, were pushed forward by the ice. Periglacial SSDS are, in addition, frequently used as a tool to establish a stratigraphy in otherwise difficult to correlate units; simultaneously, such periglacial SSDS help to establish a first framework for climatostratigraphy.

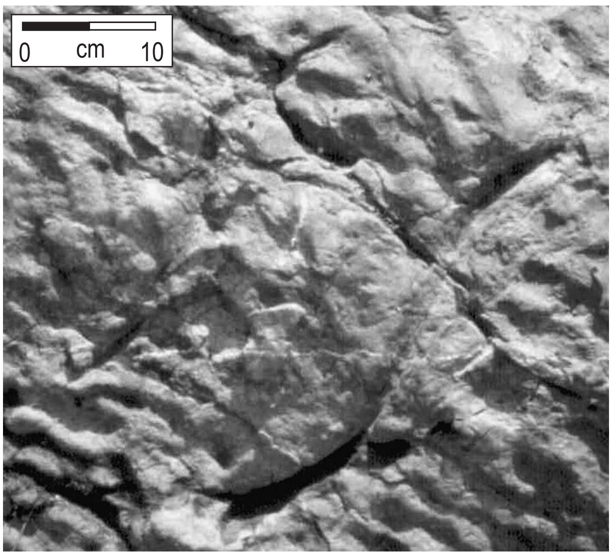

Fig. 31. Scratches in lacustrine sediments of the Early Cretaceous Cameros Basin (Rioja, Spain), ascribed to the claws of a dinosaur that was unintentionally swimming. Photo Loïc Costeur (Nantes).

It should also be realized that analysis of SSDS can contribute to hazard evaluation. The finding by Van Loon (2006a), on the basis of SSDS in an alluvial plain of the Waal river (The Netherlands), that extremely powerful counter-currents may occur in the outermost parts of the alluvial plain of the Waal river (The Netherlands), is a strong argument against the decision of Dutch authorities to allow building of new houses in the alluvial plain. Not only would these houses be at great risk during conditions similar to those that led to the formation of large folds in the alluvial plain, but such constructions would also act as obstacles for the current, thus contributing to even more powerful water movements.

In addition, it turns out that SSDS, if they reach sizes of the order of several metres, can pose significant risks. A correct interpretation of the conditions under which SSDS are formed can lead to the correct prediction of where similar or related SSDS may occur in a specific area. Such prediction may help to prevent damage to equipment or other inconveniences (e.g. large-scale sliding of walls) during exploitation, including casualties and financial losses. This has been shown convincingly for the open-cast browncoal mine of Bełchatów in central Poland, where the Quaternary overburden must be removed. This overburden contains levels with huge erratics, that sometimes occur in levels with specific large-scale SSDS. Prediction of the places where such structures might occur has prevented potential damage, indeed (Brodzikowski and Van Loon, 1990; Van Loon & Brodzikowski, 1994). Early recognition of horizons in which huge diapirs can be found has helped elsewhere in the Bełchatów mine, too, to work cost-effectively.

SSDS in the form of bioturbations can give important information about the environmental conditions in which the responsible organisms lived. A completely bioturbated horizon commonly points at a phase of very slow sedimentation or even a real hiatus (Gruszczyński et al., 2008). On the other hand, a scarcity of bioturbations in sediments that were apparently (for instance, because of the common occurrence of specific other fossils) deposited in an environment that was well suitable for life, such as a well-aerated shallow-marine environment, commonly indicates a high sedimentation rate, which implies a large supply of particles, which, in turn, has consequences for the interpretation of the palaeogeography.

Finally, it should be stressed that specific SSDS can give much more information than commonly thought. To achieve such information, it is not only necessary to unravel the deformational process (or processes), but also to reconstruct what underlying situations did cause those processes to become active. Such a reconstruction is commonly neglected, as most researchers only want to know what caused the SSDS, rather than why specific processes were active. This opens a new approach to the research into SSDS: now that the processes involved in the genesis of SSDS have, for the majority of deformations, been relatively well established (but enigmatic structures remain: Fig. 30), the unravelling of the underlying conditions as done by Van Loon (2008c) for the interpretation of dinosaur behaviour on the basis of SSDS in lacustrine sediments (Fig. 31) should be considered as the new challenge in SSDS research for the time to come.

Taken all the above together, it must be deduced that careful analysis of SSDS can provide highly valuable data for both fundamental and applied research in the earth sciences.

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