MUD-CRACK DIAPIRISM IN THE RINGERIKE SANDSTONE OF SOUTHERN NORWAY

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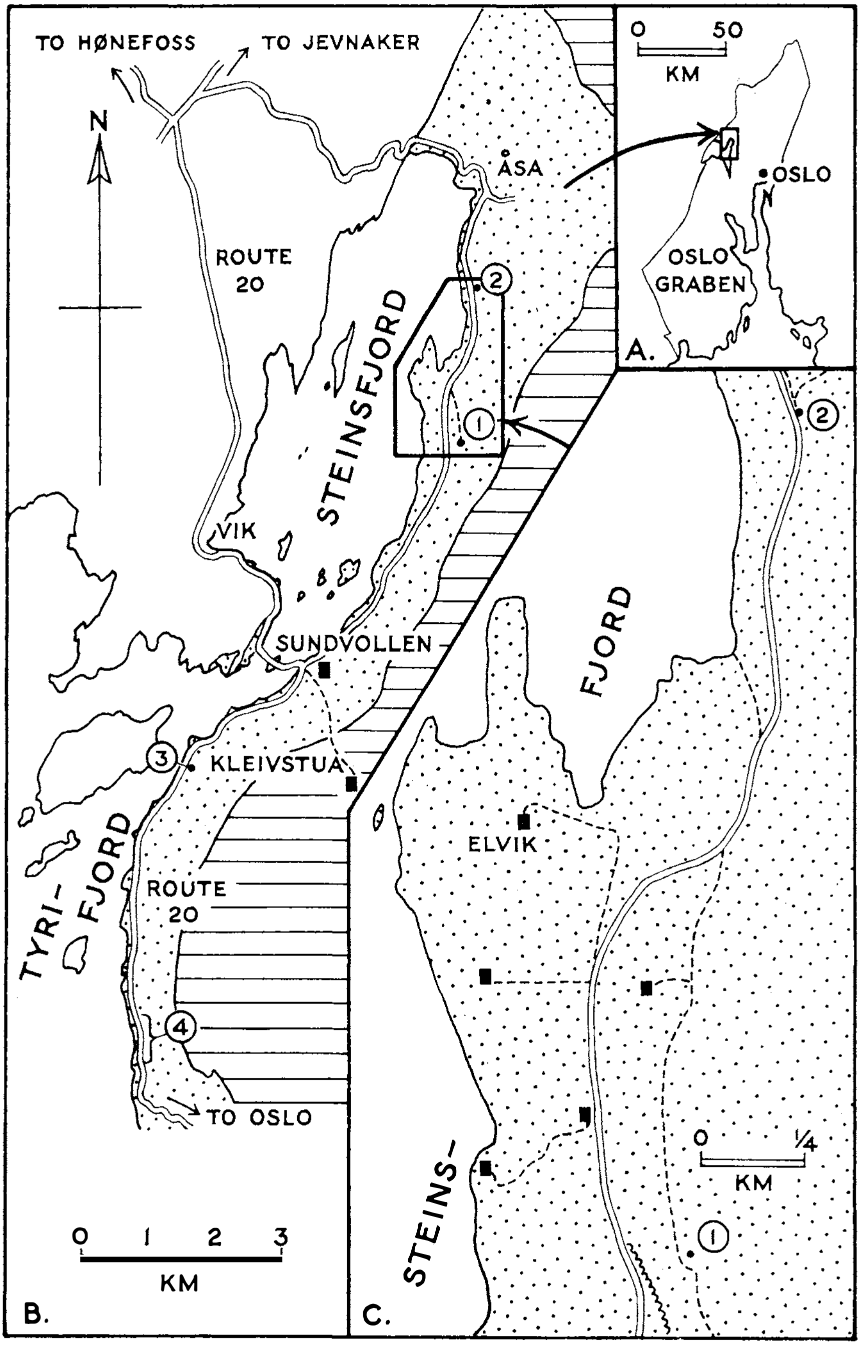
Abstract: An unusual type of small-scale diapirism is described from the Ringerike Sandstone Formation (Lower Devonian) of Ringerike, southern Norway. Polygonal mud cracks in shale are injected from below by coarse-grained siltstone which is interbedded with the shale. The possible origin of this structure is discussed, and it is thought probable that vertical and lateral pressures, aided perhaps by earthquake shocks, mobilised waterlogged silt below sun-dried and cracked mud, causing injection of silt into the cracks.

Introduction

The Ringerike Sandstone Formation (partly Ludlovian in age but mainly Downtonian) is well-exposed to the east of Tyrifjord and Steinsfjord, which are parts of a single large lake about 25 kilometers north-west of Oslo (Fig. 1A and B). This „Red-Bed'' sequence shows a number of primary sedimentary structures. Some of these are well-known, such as cross-bedding, ripple-mark, mud-crack and eurypterid trails (Kiær, 1924) while others found by the writer do not appear to have been described in detail from this area. This second group of structures includes current-lineation (Stokes, 1947 and 1953), rill-mark (Shrock, 1948, fig. 90A), ripple-drift lamination (Walker, 1963), slump structures and diapirically deformed mud cracks. The last-named are described in this paper: the others will be included in a full description of the Ringerike Sandstone Formation to be published later.


TO HØNEFOSS
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B.
0 50
KM
OSLO
OSLO GRABEN
A.
FJORD
ELVIK
STEINS-
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C.

Localities

Diapirically deformed mud cracks have been found at four localities on or near the Oslo—Sundvollen—Åsa road (Fig. 1B & C). Locality 1 (0°22' O'' W. of Oslo meridian, 60°5'30'' N)[1] is the best exposure but it is less-accessible than the others. It lies 4 km north-east of Sundvollen and 3.7 km south of Åsa. It can be approached on foot from the north end of the north-south track leading off the main road (Fig. 1C) but more directly by scrambling up the northern end of the cliff (indicated by a serrated line at the southern edge of Fig. 1C) and traversing rough ground until the track is reached. The locality is just north of a sharp bend in the track. Locality 2 (0°21'45'' W, 60°6'45'' N) lies 2.4 km north of locality 1, on the east side of the Sundvollen—Åsa road where two tracks branch off from the main road (Fig. 1C). Locality 3 (0°26'25'' W, 60°2'50'' N) is on the east side of the Oslo—Sundvollen road (Route 20, Fig. 1B) 2.5 km south-west of Sundvollen, 137 m north-east of a stream, and locality 4, (0°27'5'' W, 60°0'45'' N) on the same side of this road, extends northwards for some hundreds of meters from a point which is 145 m north of the Gomnes bus stop situated outside the telegraph office. Here, the best mud-crack diapirism is seen in a 40 m-long section directly opposite a farm which is close to the road on the west side; other examples are seen at the 38-kilometer post further north.

Description of the structures

Locality 1. At the base of a low crag (see Fig. 2) there is a well-jointed brownish-grey (5YR 4/1) fine-grained sandstone at least 90 cm thick. It is finely laminated, and these laminae develop into distinct topsets and foresets in the middle of the crag. After correcting for the small regional dip the foresets are found to dip 18° at 145°

[1] Longitude is given W. of Oslo meridian, which is 10°43'2'' E. of Greenwich meridian.

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Fig. 1. Mud-crack diapirism locality maps. Blank areas to the north-west are marine Ordovician and Silurian. Stippled areas are Ringerike Sandstone (non-marine Upper Silurian and Downtonian). Striped areas to the south-east are Permian (mainly volcanics).

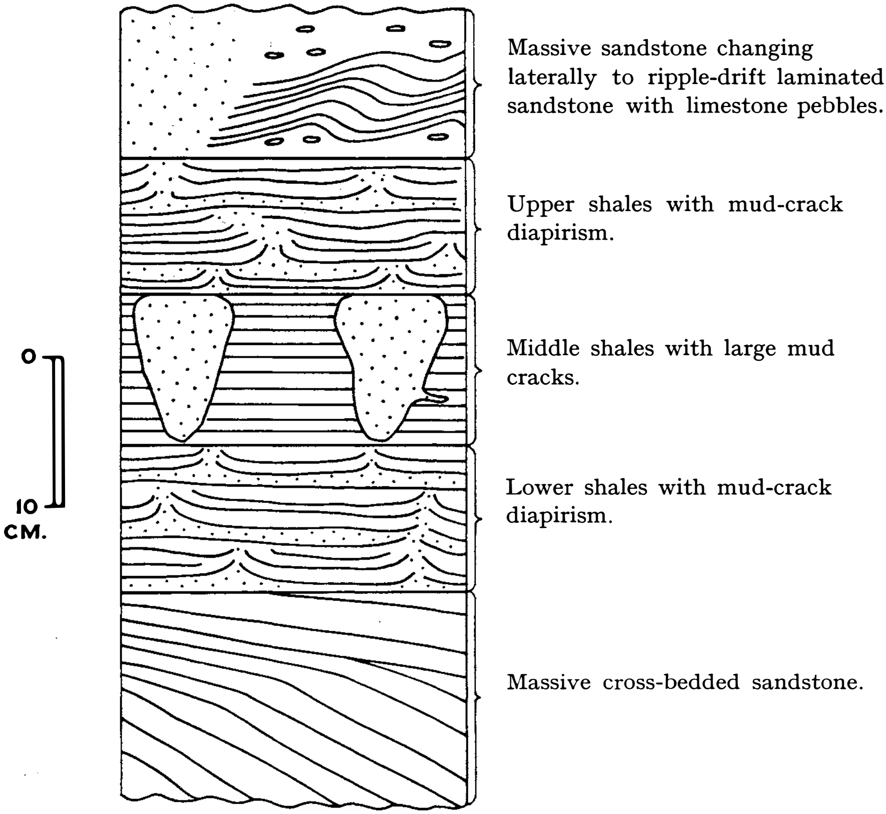

Fig. 2. Sequence of beds at locality 1.

true bearing which is typical for this area. In thin section (Leicester University Geology Department Slide NK767c), the interlocking sub-angular to angular quartz grains show diameters of between 0.06 and 0.1 mm and the rock is thus a 'very fine sandstone' of Wentworth's classification. Muscovite flakes lie approximately parallel with the bedding and felspars, chlorite and iron-ore are present. There are some compound grains of quartzite, chert and basalt. There is little pore-space and calcite cement is sparsely and irregularly distributed round the detrital grains, and there is interstitial sericite and chlorite.

The top of this thick sandstone is irregular, having three shallow channels cut into it, filled with red and green laminated shale and very fine-grained sandstone. Above come the lower shales with mud-crack

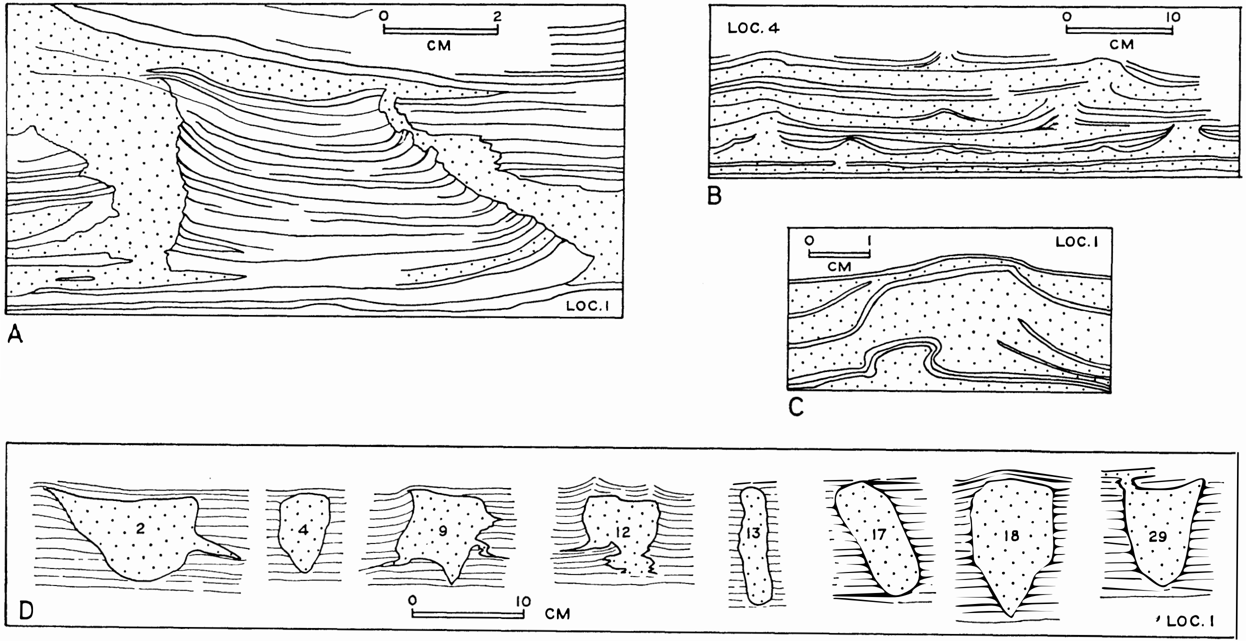

Fig. 3. A, B. Vertical sections through diapiric structures. C. Doming-up of shale by movement of sand. D. A selection of infilled mud cracks from the middle shales, locality 1. (Silt is stippled).

diapirism, between 35 and 40 cm thick. In this bed, the normal alternation of thin layers of shale and fine-grained sandstone is interrupted at intervals by miniature diapiric structures, in which fine sand or silt has pushed up (Fig. 3C) and sometimes broken through the muddy layers, often affecting several centimeters of strata. Along a single horizon exposed on the face of the crag, the diapiric injections are spaced at irregular intervals, ranging between 5 and 17 cms. Fig. 3A, drawn from field sketches and photographs, shows the appearance in vertical section of one of these structures, which resemble minute salt domes or laccoliths. The axes of the diapirs trend in various directions: by dissecting part of the exposure, they were seen to form, in plan view, a polygonal pattern of size and shape comparable with normal-sized mud cracks, about 10 cm across. Fig. 4 shows a sketch of a hand specimen taken from the junction of three cracks.

In thin section (NK767a), the silt 'intruded' through the mudstone laminae shows very angular quartz grains, with diameters ranging from 0.025 to 0.075 mm and the rock is thus mainly a siltstone of Wentworth's classification, only a little finer-grained than the sandstone (NK767c) at the base of the crag. Calcite, plagioclase felspar, chlorite, greenish-brown biotite and metaquartzite occur as detrital grains of similar size to the quartz. There is much sericite. Limonite, scattered small magnetites and a few ilmenites changing to leucoxene are also present. Calcite matrix is prominent and more conspicuous than in the underlying sandstone. The bent-up shale laminae consist of fine-grained argillaceous material with many angular quartz grains and mica.

Above part of the exposed section of the lower shales (Fig. 2), a band of mainly greyish-red (10R 5/2) shale, 7 to 10 cm thick, is interrupted by downward-tapering 'pockets' filled with medium-grained sandstone. These occur at intervals of between 2.4 and 52 cm (the average being 26 cm). 30 'pockets' are exposed: a few are sketched and numbered in Fig. 3D. Nos. 4, 13, 17 and 18 have sharp margins with the surrounding shale but Nos. 2, 9, 12 and 29 show slightly 'intrusive' relationships. Excavation of some of the pocket infillings showed that they are shallow but relatively rather wide mud cracks affecting only the middle shale layer, which it is calculated must have contracted by at least 10% in a horizontal direction on desiccation. Above this bed are the upper shales with mud-crack diapirism, similar

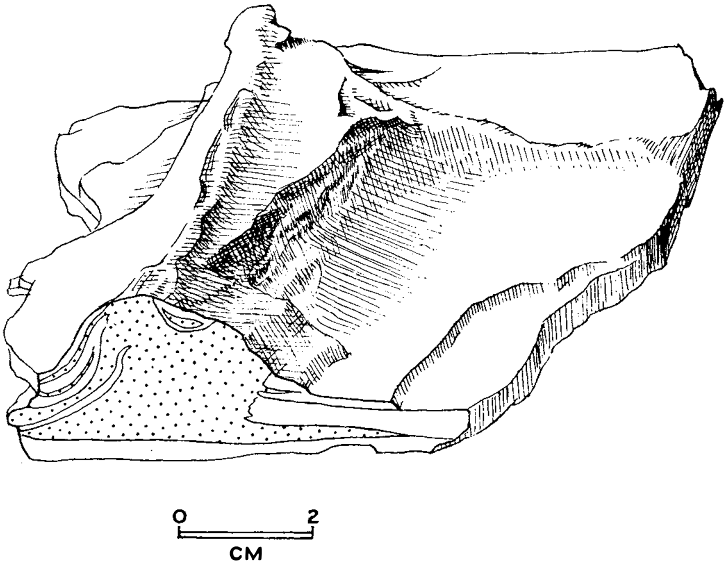

Fig. 4. Sketch of a specimen from locality 1, showing the joining of three mud cracks and diapirism in one of the cracks.

to the lower shales. The highest bed exposed in the crag is a massive sandstone which changes laterally to sandstone with ripple-drift lamination incorporating small fine-grained limestone pebbles (Fig. 2). At the southern end of the crag, a miniature slump horizon occurs above the mud cracks.

Thus at this locality there are two sets of mud cracks, the smaller scale, in the lower and upper shales, showing field relationships which indicate diapiric filling from below and the larger-scale, in the middle shales, indicating normal filling from above, but showing occasional slight 'intrusive' character.

Locality 2. Here, joint surfaces expose mud-crack diapirism. The best examples are just north of a 25 cm-wide Permian basic igneous dyke which trends at 302°. Greyish-red rather fine-grained argillaceous sandstones 10 to 40 cm thick show some ripple-drift lamination. The sun-cracked shales which are penetrated by silt often bear scattered fine-grained limestone pebbles, a feature rather characteristic of certain horizons in the lower half of the Ringerike Sandstone.

Locality 3. Here, two mud-crack horizons are exposed, the lower, just above road level, being about 10 cm thick and the upper, 16 cm thick, separated by a 16 cm-thick sandstone showing good ripple-drift lamination. The injected mud cracks are between 8 and 14 cm apart as measured on the exposed face. 18 m to the north there is a normally filled crack 26 cm deep and 7.5 cm wide at the top, tapering to a point downwards, and cutting through a well-developed horizon of ripple-drift lamination. A further 10 m to the north are more large mud cracks of similar character: these continue at the same horizon for a further 15 m. They are in all respects similar to the large cracks in the middle shales of locality 1. Higher up in this section there is broad but shallow channelling.

Locality 4. Again on the east side of the main road there are good exposures of a 45 cm-thick band of diapiric mud cracks, similar to those at the previous localities, associated with small-scale channelling and slumped laminated sandstones, some with ripple-drift structure. Small limestone pebbles are conspicuous, as at locality 2. Directly opposite the farmhouse the cracks are seen in three dimensions. A vertical section through them (Fig. 3B) shows that a lower injection may penetrate several shale laminae but does not necessarily coincide with the location of diapirism at higher horizons.

Horizon

The Ringerike Sandstone is an almost unfossiliferous formation probably about 1000 m thick (Kiær, 1924, p. 7) and it is difficult to be sure of the continuity of any horizon. At present it is not possible to say whether the diapiric structures occur on a single horizon or whether they were formed at different times.

Origin

There seems no doubt that most of the structures began as a polygonal pattern of mud cracks formed by the desiccation of thin argillaceous layers formed under water. There was the usual shrinkage and slight upturning of the edges of the laminae. What is unusual is that subsequent pressure appears to have mobilised some of the intervening silt layers and crack infillings, which then behaved like miniature salt domes or laccoliths and rose up through the cracks in the shale laminae. In the dry conditions necessary for the formation of mud cracks it would not be expected that the thin silt layers between the mudstones would be mobile. There are at least four possibilities: (1) that the silt flowed in the dry state; (2) that sufficient water was retained in the silt to allow it to flow; (3) that water came up from lower water-bearing horizons; (4) that re-submergence of the mud cracks caused the silt to become mobile before the mud had fully imbibed water (suggested by Prof. Ph. H. Kuenen, in a personal communication). Explanation (1) seems unlikely in the confined spaces between the shale laminae; (3) might apply at locality 1 where, just below the mud crack horizon, there is a subaqueously cross-bedded thick sandstone with little pore-space (see p. 22) indicating possible loss of water on close-packing. At the other localities, however, no such 'water reservoir' rocks are seen. Explanation (4) is a possibility, although in this case the sharp edges of the shale laminae might be expected to have become slightly rounded as water was absorbed. Explanation (2) is thought to be the best, having several points in its favour. The silt layers, like the shales, appear to have been water-lain, for they have ill-sorted angular quartz grains, are not dune-bedded, show in places ripple-drift lamination similar to the 'type 1' of WALKER (1963) and have miniature slump horizons of subaqueous type. The silt was porous (p. 24) and could have retained much of the interstitial water. Also, modern examples of mud-cracked surfaces overlying wet sediment are known in England. Dr. T. D. Ford (personal communication) has observed this relationship in some Derbyshire caves, where treading on the cracked surface resulted in the squeezing up of wet mud through the cracks. Mr. M. J. Hooper has seen the same phenomenon during the filling of the West Hanningfield reservoir and around the fresh-water pools behind the sea-wall at Leigh marshes (both localities being in Essex), where he observed normal-sized mud-crack polygons with wet black mud occupying the cracks (personal communication).

Assuming, then, that the Ringerike mud cracks formed rapidly in the shale layers without desiccation of the underlying silt, a cause for the 'intrusion' of the wet silt through the cracks must be postulated. Several factors may have contributed to the process: (1) vertical pressure caused by the accumulation of more sediment above the cracked horizon; (2) lateral pressure due perhaps to artesian conditions in the water-bearing silt layers; (3) shock (e.g. from earthquakes) mobilising the wet silt momentarily by thixotropic change (see DUNNINGTON, 1945, p. 247, BOSWELL, 1948 pp. 421—2, MEAD, in SHROCK, 1948, p. 214 footnote). Close comparisons with some other quicksand phenomena cannot be made, since pit-and-mound structures (SHROCK, 1948, pp. 132—6), air-heave structures (ROLFE, 1960), spring-pits (QUIRKE, 1930), spring-domes (WILLIAMSON, 1961) and sand volcanoes (NEVILL, 1957, GILL and KUENEN, 1958) are formed at sediment-water or sediment-air interfaces and not within the body of the accumulating sediment. The closest analogy is with sandstone dykes and sills injected from below (e.g. SHROCK, 1948, p. 204, fig. 163, WATERSTON, 1950, GREENSMITH, 1957). The first-named author describes a specimen of Pennsylvanian Wamsutta red-bed formation of the Norfolk Basin, Massachusetts, showing complete and incomplete sand-filled mudcracks together with a minute sandstone dyke ending upwards in shale. This dyke at least must have been injected from below, and it is possible that the mud cracks were invaded similarly. Another close comparison is with structures in the Epidotic Grits of Skye described by SUTTON and WATSON (1960, p. 117). In these Torridonian rocks, one or more sandstone layers were upheaved and injected into breaches in a mudstone cover. The mudstones were deformed and broken up, while the overlying strata were domed-up and miniature laccoliths were formed due to sand spreading out between bedding planes after being forced upward. The intruding sand is structureless and shows no relict bedding, a negative feature noticed also in the Ringerike diapirism.

Diapiric effects have been produced experimentally by SELLEY and SHEARMAN (1962). In a tank of water they laid down loose-packed fine sand, then a thin clay layer and finally a bed of coarser sand, with thin black bands to represent bedding. ,,When the tank was shaken, the fine sand below the clay fell into a tighter packing, and immediately the excess pore-water was expelled upwards to form a thin but conspicuous layer between the top of the sand and the overlying clay. Within a few seconds, the water burst through the clay at a number of points, and flowed upwards through the overlying sand, carrying some of the fine-grained underlying sand with it. The bedding of the overlying sand adjacent to these 'break-through' points was bent and transported abruptly upwards."

The author concludes that, as with so many geological phenomena, no single factor can account for the observations, and that all three factors (vertical pressure, lateral pressure and shock) may have been necessary to produce this apparently rare mud-crack diapirism.

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