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SHORT NOTES

Hydrocarbon generation—a possible cause of elevated pore pressures in the Osen–Røa thrust sheet, Norway

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Abstract—The Osen–Røa thrust is very large (275 km wide in the thrust transport direction), thin (1–4 km thick) and internally shortened by 270 km. Over much of its extent the thrust sheet has moved over autochthonous or para-autochthonous Alum Shales (Cambrian). Such a large and thin thrust sheet is difficult to move as a coherent unit. High pore-fluid pressures are commonly invoked to help explain such problems. The Alum Shales are very rich in organic carbon (5–20 weight percent). They are capable of generating large volumes of hydrocarbons which could have periodically caused elevated pore-fluid pressures. The first event that was likely to have buried the Alum Shales to oil-generating depths was overthrusting during the Caledonian orogeny. Consequently, overpressuring in the Alum Shales due to hydrocarbon generation may help to explain the size of the Osen–Røa thrust sheet.

INTRODUCTION

THE Cambrian (age) Alum Shales of the southern Norwegian Caledonides provide one of the most spectacular examples of a detachment zone in the world. They comprise a thin (about 50 m), very widespread unit that rests on top of autochthonous Precambrian basement or thin Precambrian clastic rocks. The Alum Shales crop out along the external zones of the thrust belt and in windows within the thrust belt. They underlie the external southern Norwegian Caledonides from the thrust front in the Oslo Graben to about 250 km northwestwards in the thrust transport direction (Figs. 1 and 2).

The Osen–Røa thrust sheet overlies the autochthonous–para-autochthonous Alum Shales. At the trailing edge, older Precambrian clastic rocks (sparagmite) are thrust over younger Precambrian clastic rocks (also sparagmites). About 50 km further towards the foreland the Precambrian clastics are thrust over Alum Shales, while in the Oslo Graben (towards the leading edge) the Alum Shales form a detachment zone above which Ordovician and Silurian sedimentary rocks are folded and imbricated (Brøgger 1890, Bockelie & Nystuen 1985, Morley 1986b, 1987). The dimensions of the Osen–Røa thrust sheet are remarkable; from the buried thrust front to the trailing edge the thrust sheet is about 275 km, and shortening within the thrust sheet is about 270 km (Oftedahl 1943, Nystuen 1981, Morley 1986a). Such shortening is similar to the total shortening estimated for the external Western Alps (e.g. Ménard *et al.* 1991). In the main part of the Precambrian basin the stratigraphic thickness reaches 3–4 km (Nystuen 1982, 1983), but it thins to less than 1 km to the west and south (Hossack *et al.* 1985). In the Oslo Graben the Cambro-Silurian section is only about 2 km thick (Bockelie &

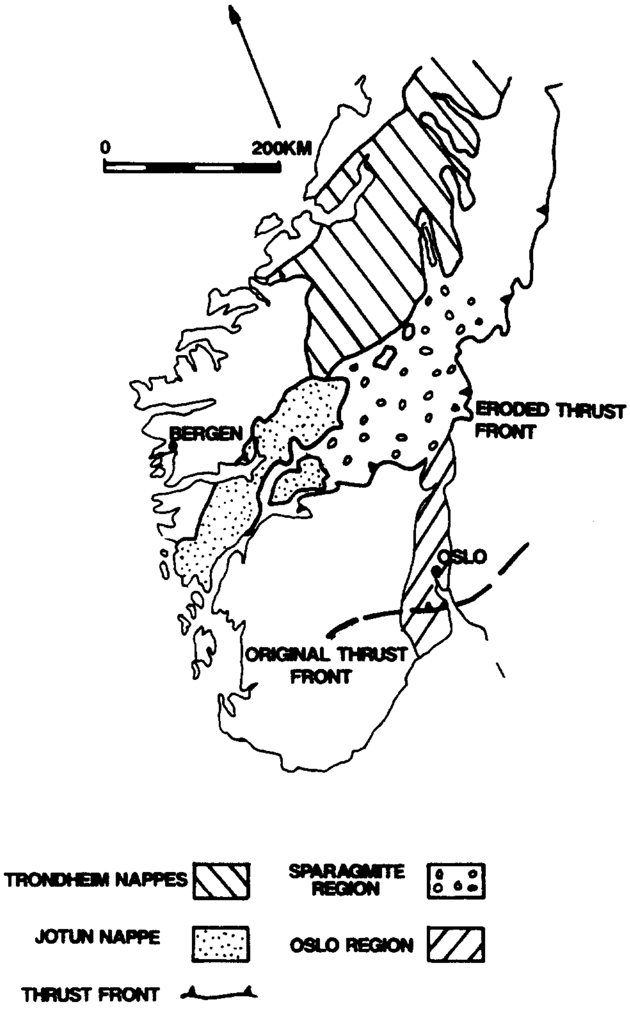

Fig. 1. Location map of the southern Norwegian Caledonides.

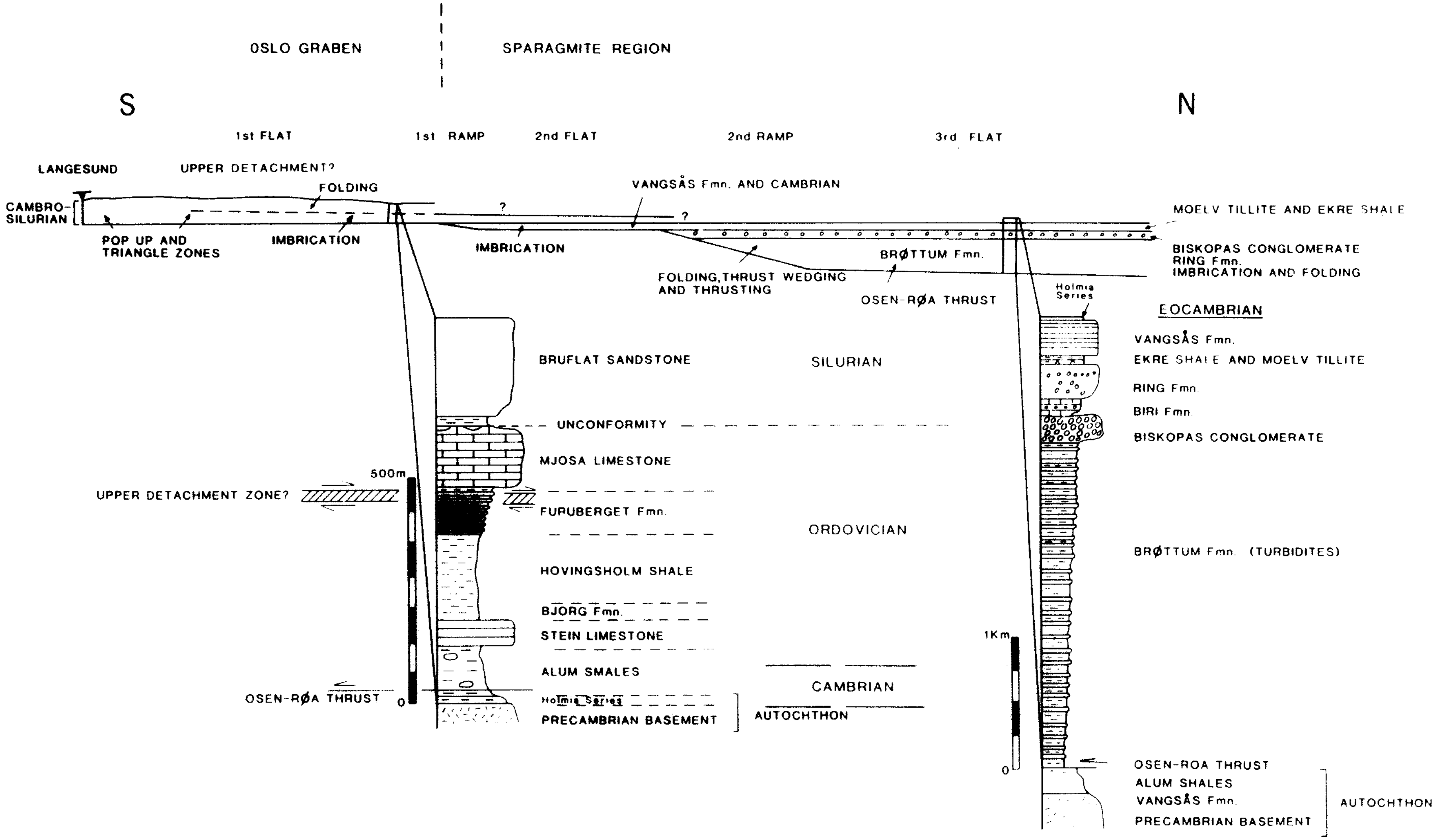

Fig. 2. Schematic cross-section illustrating the structural style of the Osen–Røa thrust sheet and the location of the Alum Shales (after Morley 1986b).

Nystuen 1985). Thus a very long and thin thrust sheet has been moved over a thin shale detachment zone. This paper examines the probable reasons why such a thrust sheet was able to develop. The thrust sheet has been extensively deformed internally by minor imbricates, detachments and folds, and it is overlain by other wide, thin thrust sheets (the Synnfjell, Aurdal, Valdres, Kvitvola and Jotun).

Factors contributing to thrust sheet dimensions

The main factors controlling thrust sheet size and amount of overthrusting are well known (e.g. Smoluchowski 1909, Hubbert & Rubey 1959, Chapple 1978, Price 1988). They are: (1) the thickness of the thrust sheet (including the overburden of overlying tectonic units and sedimentary basins); (2) the strength of the rocks comprising the thrust sheet; (3) the strength of rocks in the detachment zone; and (4) the dip of the detachment zone. In addition to these factors the geographical distribution of the unit forming the detachment zone is critical. In Scandinavia the Alum Shales transgressed over a broad flat continental platform that was little affected by faulting. Consequently, the Alum Shales form an almost ideal, widespread, relatively uniform uninterrupted unit over which the thrust sheet could move.

In order to permit the movement of a thrust sheet over large distances the strength of the detachment zone needs to be very low. This can be accomplished by a weak detachment zone exhibiting ductile behavior (e.g. salt or shale; Kehle 1970, Chapple 1978). Alternatively, in more brittle rock the shearing resistance of the detachment zone could be reduced by decreasing the normal stress due to an increase in pore-fluid pressure (e.g. Hubbert & Rubey 1959, Handin *et al.* 1963, Davis *et al.* 1983). There is a marked mechanical contrast at the base of the Osen–Røa thrust sheet between the crystalline Precambrian basement and the overlying Alum Shales. The incompetent nature of the Alum Shales and its stratigraphic position made it a likely detachment horizon. Elevated pore-fluid pressures would have made the Alum Shales an exceptionally favorable décollement zone.

One of the problems with generating high pore-fluid pressures is to have sufficient fluids in the rock at the time of thrusting, and to sustain fluids in the detachment zone during the rupturing that accompanies the thrusting. One way these problems could have been overcome in the Alum Shales was by the generation of liquid hydrocarbons during overthrusting.

Deformation within the Alum Shales

In the Oslo Region the Osen–Røa detachment forms a broad zone of deformation within the Alum Shales. Numerous sub-horizontal minor slip planes up to a few meters long are present throughout the shales. These frequently display shiny, graphitic surfaces in the carbon-rich shales. Other slip surfaces are hard, polished and porcellaneous, and tend to be developed in the lighter colored and laminated portions of the shales where the carbon content of the shales is lower. Thin sections of the highly cleaved and graphitized portions of the shales display well-developed low-angle (30–50°) anastomosing seams a few centimeters long. The seams may be fractures associated with oil generation that have become closed and re-used as slip planes, and in some cases as solution planes. Sparry calcite (probably the product of pressure-solution) is deposited in high-angle (to bed-parallel fissility) veins and conjugate sets of veins. Folding within the Alum Shales ranges from tight chevron-style puckering near the slip-horizon to broader disharmonic, asymmetrical folds within the main body of the shales. In outcrop the larger folds have wavelengths up to 4 m and amplitudes up to 3 m. Some imbricate thrusts that form discrete slip-planes higher in the section pass into broad zones, several meters wide, of disharmonic folding and locally intense bed-parallel fissility within the Alum Shales (Morley 1983).

Generation of hydrocarbons in the Alum Shales

The Alum Shales are dark brown to black, very organic-rich and laminated. Organic carbon forms between 5 and 20 weight percent of the rock, and it was retorted for oil in Sweden from 1923 to 1969 (Lewan & Buchardt 1989). Skjeseth (1957) described the Alum Shales in Oslo as containing calcite, pyrite, small amounts of uranium and 15% carbon. The Alum Shales of the Oslo Graben have undergone burial and contact metamorphism from Permian volcanism (Bergstrom 1980, Buchardt & Lewan 1990), consequently any generated oil is likely to have been destroyed. The stratigraphic thickness of the Cambro-Silurian sequence in the Oslo Graben is less than 2 km, therefore, unless geothermal gradients were very high, the Alum Shales could not have been sufficiently buried by deposition and subsidence alone to generate hydrocarbons in significant quantities (Fig. 3). About 3.5 km burial, given a crustal geothermal gradient of 27°C km^{-1} (1.5°F/100 ft), will initiate significant hydrocarbon generation (Fig. 3). Consequently, the first event likely to cause burial of the Alum Shales to such depths would have been Caledonian thrusting, both by overthrusting of higher tectonic units (e.g. the Jotun and Valdres thrust sheets) and by internal thickening of the Osen–Røa thrust sheet.

Given 5% Type II total organic carbon (Lewan & Buchardt 1989), the amount of oil expelled from the source rock is approximately 212 barrels per acre-ft. Assuming a 50 m thickness for the unit and an area of 120,000 km^2, approximately 950 billion barrels of oil may have been generated and expelled from the Alum Shales. The initial development of overpressure is the overall volume increase that accompanies the reaction of kerogen to produce more mature kerogen plus hydrocarbons and a decrease in density of the products (Meissner 1984, Spencer 1987, Buhrig 1989). Later volume changes associated with the generation of hydro-

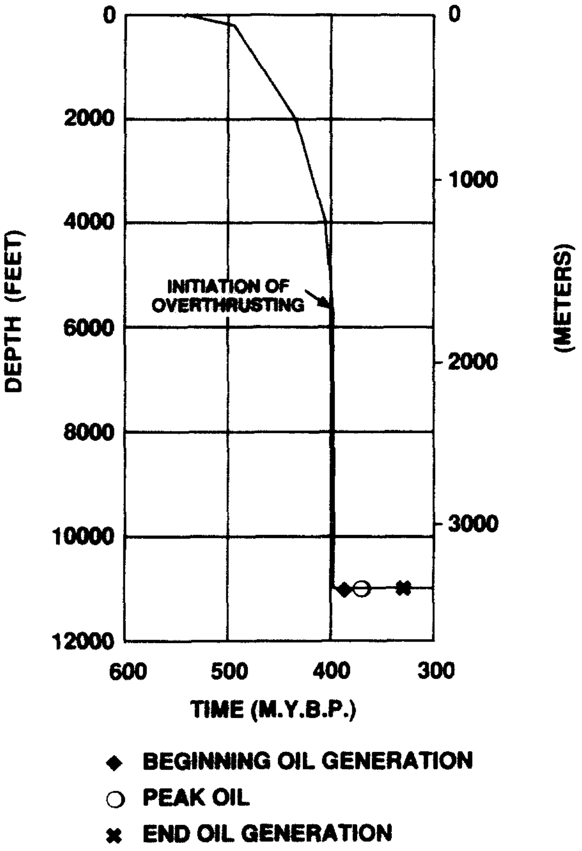

Fig. 3. Subsidence curve for the Alum Shales in the Oslo Graben (with a geothermal gradient of 1.5°F/100 ft), using the Lopatin method of calculating the timing of oil generation (Lopatin 1971, Waples 1980). Thrusting is shown as early Devonian in age for the Oslo Graben area. Further towards the hinterland the onset of overthrusting was of Silurian age, consequently maturation of the Alum Shales would have occurred earlier passing northwestwards.

carbons are to be expected because as temperature increases the density of the hydrocarbons decreases (e.g. McNab *et al.* 1952, Orr 1974). During refining cracking of hydrocarbons can produce volume increases of 10–20%. This magnitude of volume increase is probably a reasonable assumption for processes in source rocks (Ungerer *et al.* 1981, M. Lewan personal communication 1991). When hydrocarbons are generated in large quantities the source rock is subject to intense fracturing, and hydrocarbons are able to migrate from the source rock via the fractures into the surrounding rock (Lewan 1987). Bitumen-filled fractures have been noted in the Alum Shales (Buchardt & Lewan 1990). These fractures are indicative of fluid pressures temporarily approaching and exceeding the confining pressures. Consequently just prior to fracturing the shear strength of the rock would have been significantly lowered. Source rocks can generate hydrocarbons over periods measured in millions of years, provided that burial does not metamorphose the organic carbon. In addition to overpressuring caused by the initial generation of oil during burial, cracking of oil to thermal gas will cause overpressuring (Barker 1990), approximately 85 m^3 (3000 ft^3) of gas can be generated from each barrel of oil. Barker (1990) calculated that in an isolated system cracking of 1% of the oil-saturated rock would generate sufficient gas to exceed the lithostatic gradient and fracture the rock. Thrusting within the shales and mineral precipitation may subsequently have sealed up the fractures and started another cycle of overpressuring. Therefore, a detachment zone that is a source rock could periodically internally generate high pore-fluid pressures throughout the active period of a thrust sheet.

DISCUSSION AND CONCLUSIONS

The Alum Shales formed a very effective detachment horizon due to a number of factors, including lateral extent, stratigraphic position and mechanical weakness in addition to high pore-fluid pressures. Elevated pore pressures in shales are commonly due to overpressured aqueous fluids; burial could cause overpressuring by loading and by illitization of smectite, which releases water (Smith & Thomas 1971, Gretener 1976). These mechanisms probably operated in the Alum Shales. Generation of hydrocarbons is an additional factor that could cause overpressuring. The initial loading of the Alum Shales by thrust sheets during Caledonian deformation probably triggered massive overpressuring and fracturing of shales due to the generation and expulsion of liquid hydrocarbons. The generation history of hydrocarbons probably varied depending upon location within the thrust sheet. Towards the trailing edge of the Osen–Røa thrust sheet a thick pile of nappes was present. These would have resulted in the metamorphism of organic material and the cessation of hydrocarbon generation relatively early in the deformation history of the thrust sheet. Consequently, other, more ductile processes would have operated in order to sustain displacement towards the trailing edge. At the leading edge of the Osen–Røa thrust sheet, for about 150 km in the transport direction, there was relatively little overburden (Hossack & Cooper 1986) and high pore-fluids associated with hydrocarbon expulsion may have been sustained for much of the deformation history (probably a few million years). During thrusting, over 950 billion barrels of oil may have been generated and expelled from the Alum Shales. The widespread extent of the Alum Shale and its ability to generate large quantities of fluid help to explain the enormous size and massive amounts of shortening that are associated with a single thrust sheet in the Norwegian Caledonides. The pore fluid story is only a partial answer since extensive imbrication and folding within the thrust sheet indicates the thrust sheet may not have moved as a single unit. Instead, only parts of the thrust sheet may have been active at any one time (Price 1988). The ability to generate hydrocarbons may have a significant effect on the effective strength of detachment zones where source rocks are present in other thrust belts.

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