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Evolution and geometries of gravitational collapse structures with examples from the Statfjord Field, northern North Sea

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Abstract

Gravitational collapse structures may range in scale from centimetres to hundreds of kilometres and affect both loose sediments and consolidated rocks. The area affected by gravitational failure will commonly be amphitheatre-like in map view, whereas a cross-sectional view will typically display a listric and concave upwards detachment surface. The degree of deformation increases in the direction of sliding. If movement of the sliding rocks is sufficiently slow, several intact slump blocks may be identified within the slide area. The movement of blocks may be translational or rotational. Two types of gravitational collapse structures are identified. In Type A, the newly-formed detachment reaches a free surface at the toe of the slide. In Type B, however, the listric detachment fault follows a weak layer and its displacement is accommodated by simultaneous slip along a major, steeper fault. This results in a ramp–flat-ramp fault geometry.

Gravitational failure is observed along the east flank of the Statfjord Field, northern North Sea. The triggering mechanisms were probably earthquakes and high fluid pressures. Listric faults detached within soft shales and are associated with several rotated slump blocks that decrease in size away from the break-away zone. The slumping occurred in several phases. First, parts of the Brent Group failed. The detachment surface was within shales of the Ness Formation. Next, the slumping cut into the Dunlin Group and detached within the lower parts of the group (shales of the Amundsen Formation). Renewed slumping of the Brent Group occurred at the new break-away zone created by the Dunlin slumping. In the final stages of gravitational failure, slumping reached into the Statfjord Formation and detached within shales at the base of the unit or within shales of the uppermost Hegre Group. The relief created at the head (break-away zone) of Statfjord slumping caused renewed slumping of the Brent and Dunlin Groups. A study of gravitational failure analogues demonstrates several similarities in geometry in spite of differences in scale, lithology, degree of consolidation, and triggering mechanism.

Keywords: Gravity collapse; Slumping; Statfjord Field

1. Introduction

Gravitational collapse structures are observed in many settings around the world and range in scale from centimetres to hundreds of kilometres. In regions influenced by extensional tectonics, gravitational instability occurs in footwalls to large rotating fault blocks. This instability may result in formation of slumps or slides along large normal faults—a development that may be of great importance during petroleum and gas exploration and exploitation. The current work will focus on the evolution and geometries of such collapse structures. Special attention will be paid to the slump structures observed on the east flank of the Statfjord Field, northern North Sea. This oil field is the largest in Europe (Kirk, 1980; Buza and Unneberg, 1986a,b) and a sound understanding of the geometries observed on the east flank of the field is of large economic importance as the oil in the relatively undisturbed main field is being drained. Structures similar to those observed on the Statfjord Field are expected, and in part observed in other oil and gas fields situated in a similar structural position. However, the high density of well data and seismic data in the Statfjord Field makes this area particularly attractive to the study of gravitational collapse structures. A study of the Statfjord Field area not only improves our understanding of the Statfjord Field itself, but also adds to our general knowledge of slumped areas in the North Sea and similar rift systems.

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2. Previous work

Many different terms have been used to describe gravity failure and related structures in past literature. Previously used expressions include slope failures (Schwarz, 1982), slide/allochton (Hauge, 1985), gravity slides (Long, 1986; Speksnijder, 1987), slumping (Jones, 1937; Morgenstern, 1967; Farrel, 1984), deep-seated rotational failures (Jones, Allison & Gilligan, 1984), rotational failures (Barnes & Lewis, 1991) earthflows (Crandell & Varnes, 1961), landslide (Hutchinson, 1973; Brunsden & Jones, 1976; Gomberg, Bodin, Savage & Jackson, 1995), slump scars (Clari & Ghibaudo, 1979), gravity gliding (Mandl & Crans, 1981; Guth, Hodges & Willemin, 1982; Schack Pedersen, 1987; Cobbold & Szatmari, 1991), landslip (Conway, 1974; Lake, Ellison, Henson & Conway, 1986), slide (Jones, 1937; Moore, Van Andel, Blow & Heath, 1970; Woodcock, 1979; Farrel, 1984; Macdonald, Moncrieff & Butterworth, 1993; Morton, 1993), sheet slides (Barnes & Lewis, 1991), rotational block slides (Schwarz, 1982), and collapse (Livera & Gdula, 1990). The use of these terms cover gravitational collapse of unconsolidated sediments as well as highly consolidated sedimentary rocks and igneous/metamorphic rocks.

In the following, we will use the definition proposed by Woodcock (1979), where slump is defined as rotational motion on a concave upwards shear plane (the definition was first proposed by Coates (1977), but the word slump has been used for a long time; Jones (1937)), and slide will be used to describe both rotational and non-rotational slope failures (often referred to as slumps in the literature). Additional descriptive definitions of gravitational collapse structures were proposed by Schwarz (1982). He suggested the term rotational block slide as an alternative to slump, whereas he used the term translational slide if movement of blocks were planar as opposed to rotational. Finally, the term gravity failure or collapse is used to describe the mechanism by which the rocks deform (i.e. a body of rock moving downslope due to its own weight).

Much is written about gravitational collapse of sediments and sedimentary rocks. The literature spans from modelling gravity failure in laboratories (Cobbold & Szatmari, 1991; Sales, 1992), via structures less than 1 m (Farrel, 1984), several metres (Hutchinson & Gostelow, 1976; Schack Pedersen, 1987), several hundred metres (Brunsden & Jones, 1972; Lake et al., 1986), several kilometres (Gomberg et al., 1995), several tens of kilometres (Davis, Anderson & Frost, 1980; Pierce, 1987; Tankard & Welsink, 1987), and finally, several hundred kilometres in scale (Woodcock, 1979; Morton, 1993).

Most of the work related to gravity failure structures describe deformation in loose sediments on the continental margins or in delta settings (Mandl & Crans, 1981; Barnes & Lewis, 1991). Other work includes deformation of lithified or partly lithified rocks in a tectonic setting (Speksnijder, 1987; Livera & Gdula, 1990). Some work has been carried out in partly lithified rocks and clay/mud along riversides and coastlines, where erosion has created unstable cliffs along which gravity failure may occur (Gossling & Bull, 1948; Conway, 1974). Finally, there is work on gravity failure structures in inland slopes (Crandell & Varnes, 1961; Brunsden & Jones, 1972).

3. Nature of gravity-influenced structures

Although the scale of gravity-related failures may vary from centimetres to hundreds of kilometres and may affect highly lithified rocks as well as unconsolidated sediments, there is still a striking similarity in the overall geometry of many of these structures. Earlier workers have also indicated that scale may not be an important factor for development of gravity failures (Gomberg et al., 1961; Suppe, 1985). Woodcock (1979) compared the scale of present submarine slides with ancient records, and indicated that the lack of large ancient examples may be because geologists attribute the geometries to tectonic mechanisms rather than to gravity alone.

The scale-independence is especially obvious when one compares real-life examples with gravity failure structures created in the laboratory (Schwarz, 1982; Sales, 1987; Fossen & Gabrielsen, 1996). Fig. 1 demonstrates the scale-independence with scales ranging from laboratory experiments to large-scale structures.

The characteristic geometry of an area affected by gravity failure is amphitheatrelike in map view (curvi-linear in profile view and spoon-shaped in three dimensions) (Fig. 2a; Hutchinson, 1973; Jones et al., 1984; Bishop & Norris, 1986; Morton, 1993). In cross-section (Fig. 2b) the main slip plane displays a concave upwards geometry where the fault detaches along a weak, typically bedding-parallel surface (Clari & Ghibaudo, 1979; Mandl & Crans, 1981; Long, 1986). This idealised geometry will not apply to settings where large reliefs cause 'avalanches' of sedimentary blocks rather than more organised and gradual deformation.

Within the slide area, several geometries may be identified (Fig. 2). The degree of deformation generally increases in the direction of sliding. This commonly results in relatively intact blocks close to the area where gravity failure starts, whereas the blocks will be broken up towards the toe (Brunsden & Jones, 1976). Even in unconsolidated sediments, a typical geometry with rotated blocks are observed at the head of the slide (Woodcock, 1979; Morton, 1993), although this will depend on relief, amount of fluids present, pore pressure, velocities and degree of consolidation. Also, unless a cliff exists at the toe of the slide, or there is no material at the bottom of a slope, the sliding sediments will be pressed against in situ sediments and compressional features may develop (Varnes, 1978; Schwarz, 1982; Macdonald et al., 1993). If a cliff exists, the slide sediments will be transported over the cliff and there is thus no need for compressional features (Livera & Gdula, 1990; Barnes & Lewis, 1991; Cobbold & Szatmari, 1991).

In general, tectonic slides are composed of an allochthonous unit (slide) that is separated from the underlying rocks by a detachment or slip surface, and where the underlying rocks are generally unaffected by the sliding-related deformation. A typical detachment (type A in Fig. 2b) reaches the surface at both the top and in the front of (or beneath) the sliding unit, and thus its formation requires a topographic high or a slope setting. Slides of this type may, for instance, occur in elevated footwalls of normal faults. However, if the detachment for mechanical reasons follows weak layers in the stratigraphic section, the detachment may not reach the free surface, but rather merge with the active fault surface of the normal fault itself (Type B in Fig. 2b). The rate of sliding is in this case controlled by the slip rate of the normal fault, and although the process is not classical gravitational sliding, it is a gravity-influenced structure that develops along side with Type A slides in extended regions.

4. Causes of gravity sliding

Gravity failure is generally associated with a triggering mechanism such as seismic shocks, rapid sedimentation, over-steepening of slopes, changes in pore pressure, or extensional deformation (Morton, 1993). Earthquakes are believed to have triggered many gravity induced failures both in lithified and unconsolidated rocks. Examples are found in the Heart Mountain region, Wyoming (Hauge, 1985), Eastern Spitsbergen (Nemec, Steel, Gjelberg, Collinson, Prestholm & Oxnevad, 1988), offshore Ireland (Moore & Shannon, 1991), New Zealand (Barnes & Lewis, 1991), and the North Sea region (Livera & Gdula, 1990). Examples of rapid sedimentation as triggering mechanism may be found, among other places, in the Mississippi Delta (Prior & Coleman, 1982; Lindsay,

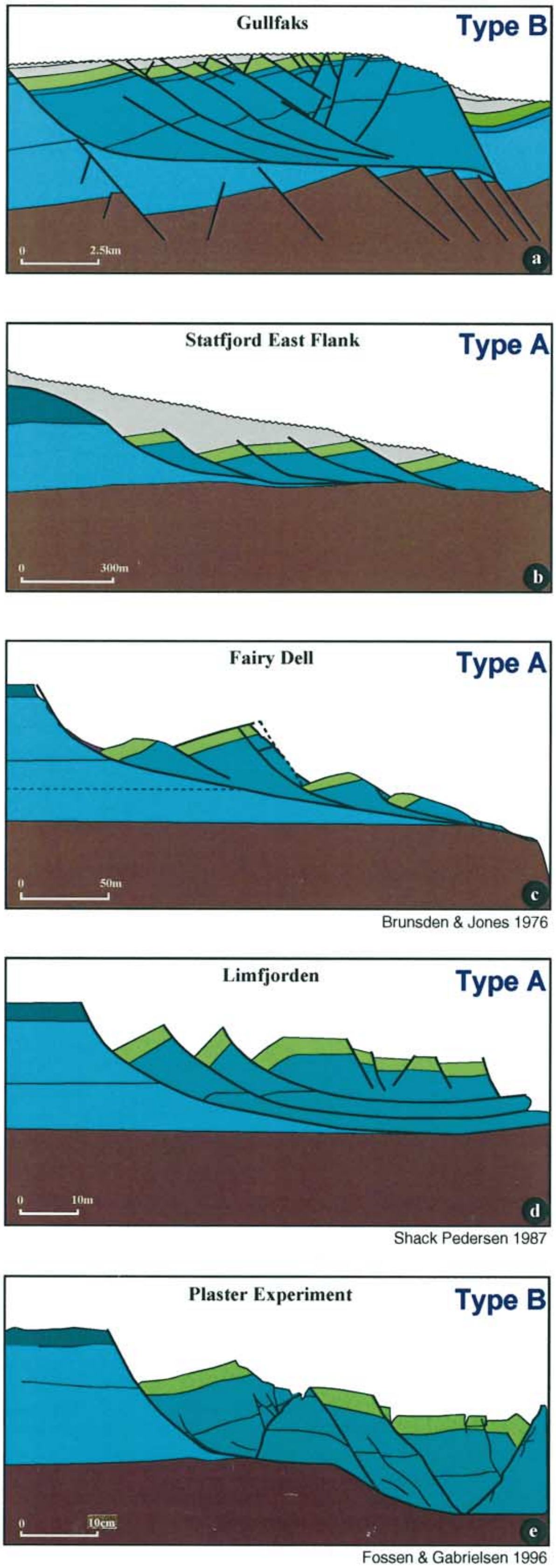


Fig. 1. Comparison of (a) the Gullfaks Field, North Sea, (b) the east flank of the Statfjord Field, North Sea, (c) Fairy Dell, S. England, (d) Limfjord region, NW Denmark, (e) plaster experiment. Although the scale is extremely different and two different mechanisms acted on the rocks (tectonic extension and gravity failure in Figs. 1a and 1e, and gravity failure alone in Figs. 1b and 1d; see Fig. 2b), all the examples exhibit the same general geometry. It does not appear that different lithologies and degree of consolidation cause any significant differences in geometry. The individual fault blocks behave relatively rigidly (a component of internal shear is expected) with a dip that is steeper than that of the undeformed rocks (a result of the listric geometry of the detachment fault).

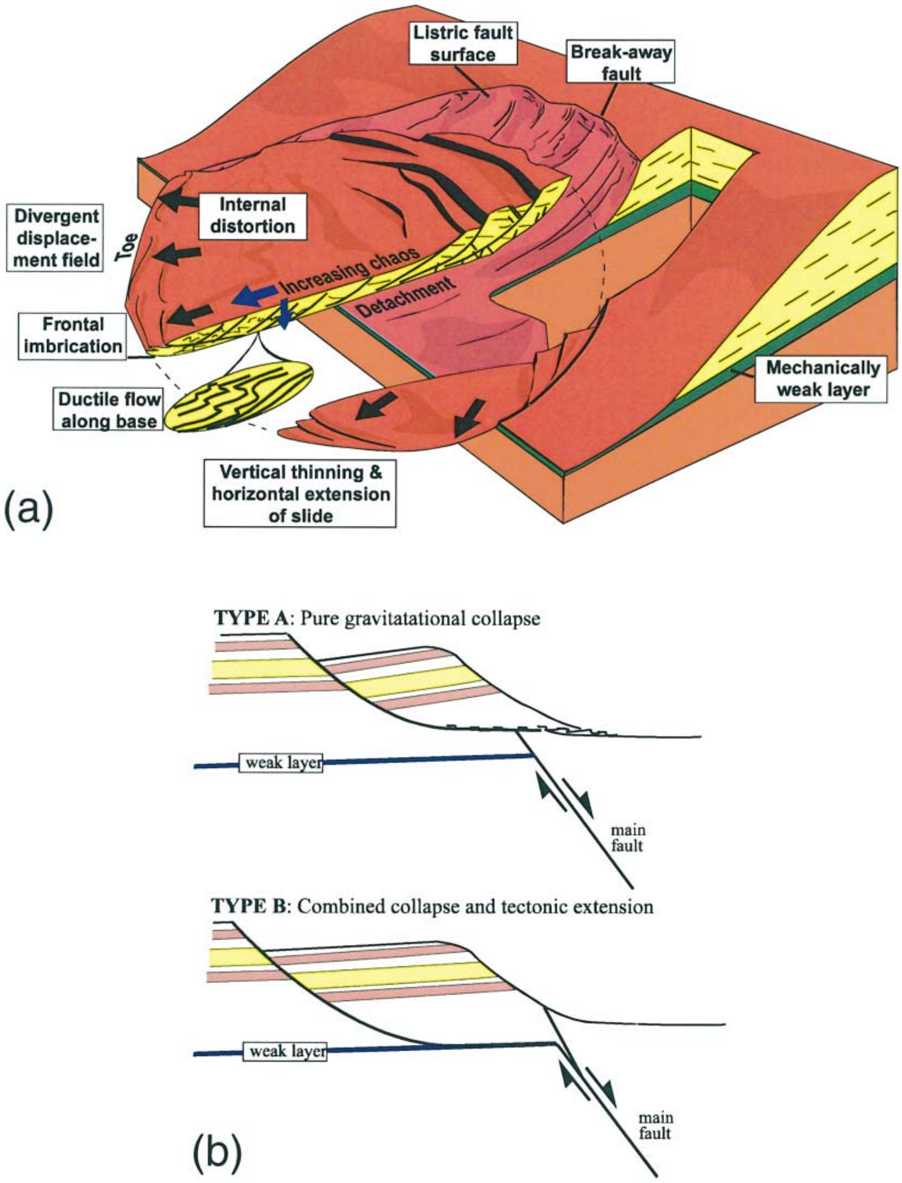


Fig. 2. (a) General characteristics of gravity collapse structures of the type discussed in the text. (b) Two types of gravitational collapse structures associated with a major normal fault. In Type A, the new-formed detachment reaches the free surface, and is therefore not dependent on active tectonism. In Type B, however, the listric detachment fault follows a weak layer and its displacement is accommodated by slip along the main, steeper fault. The result is a ramp-flat-ramp fault geometry of the type seen in several physical models (Fossen & Gabrielsen, 1996). See Fig. 1 for different examples of the two types.

Prior & Coleman, 1984) and near the mouth of the Magdalena River, Colombia (Heezen, 1956). Uplift/erosion may cause a relief such as along the coast of England (Conway, 1974; Brunsden & Jones, 1976; Hutchinson & Gostelow, 1976). Tectonic tilting may be exemplified by the Piedmont Basin, north-western Italy (Clari & Ghibaudo, 1979) and the Lobo gravity slide in South Texas (Long, 1986). Changes in pore pressure are believed to be the triggering mechanism for slides in the Gulf of Alaska (Schwab & Lee, 1988). Even melting of permafrost may, under certain conditions, be the triggering mechanism. This is considered the case in the Limfjord region in Denmark (Schack Pedersen, 1987). Basinal extension will commonly be associated with normal faulting. The faults will create a relief, and the sediments will be unstable due to the gravitational forces and start to slide. This, together with seismic activity, is thought to be the triggering mechanism for the east flank of the Brent Field (Livera & Gdula, 1990; Struijk & Green, 1991; Coutts, Larsson & Rosman, 1996), the Cormorant Field (Speksnijder, 1987), the Ninian Field (Underhill, Sawyer, Hodgson, Shallcross & Gawthorpe,

1997) and east coast of Canada (Dailly, 1975), and is also believed to be the triggering mechanism for the Statfjord Field.

5. The effect of pore fluid pressure

The effect of fluid pressure is very important in gravity failure (Hubbert & Rubey, 1959; Morgenstern, 1967; Clari & Ghibaudo, 1979). Terzaghi (1950) noted that excess pore pressure in sediments reduces the 'effective' weight of the overburden. This weight is carried by grain-to-grain contacts which gives the sediments a frictional shearing strength. The stability of a sedimentary deposit depends mostly on the shear strength and the rate with which this strength increases with depth (Moore, 1961). The role of pore pressure in gravity failure processes is discussed in detail by Mandl and Crans (1981). It is beyond the scope of this article to go in detail about the effect of pore pressure, but some of the main points from Mandl and Crans (1981) article should be emphasised. If pore pressure becomes higher than hydrostatic, the increase in shear strength with depth is reduced and failure may occur more easily. This situation is common in delta settings due to rapid sedimentation. If an impermeable layer exists, a marked increase in pore pressure is accompanied by a decrease in effective overburden stress. If the reduction is large enough, slip may start at the top of the sealed and over-pressured sequence. A gravity slide will therefore tend to detach within or immediately below an impermeable layer which acts as a decollement, thus creating a very gentle slip plane. Although it is generally agreed that impermeable layers can act as decollement surfaces (Guth et al. 1982), Lewis (1971) argues that slip planes may also form in metastable sandy-silt layers that liquefied during cyclic loading of sediments. Detachment surfaces can also develop within a stratigraphically/petrographically more or less homogeneous package. This is thought to take place in the London Clay cliffs (Hutchinson, 1973) and the Slumgullion earthflow in Colorado (Crandell & Varnes, 1961). Although gravity failure structures may detach within a lithologically homogeneous package, this is rather the exception than the rule. Throughout the literature, the detachment surface for gravity-induced slides is described as bedding planar and located within soft layers.

Mandl and Crans (1981) also suggested that within over-pressured layers, the normal faults will steepen up-dip, and thus obtain a listric shape. This is related to both the fact that high pore pressures will drastically change the direction of maximum stress as well as the effect of compaction.

6. Evolution of slides on the Statfjord Field

6.1. Location and structural setting

The Statfjord Field is located about 220 km northwest of Bergen on the western side of the North Sea Rift System (Fig. 3a and 3b) within a sub-platform area according to the terminology proposed by Gabrielsen (1986). The sub-platform area represents the most prospective play type in the North Sea and several large oil fields are identified within this structural setting (e.g. the Gullfaks, Snorre, and Brent oil fields). The Statfjord Field structurally forms the eastern part of a major (first-order) fault block along the western margin of the Viking Graben (Fig. 3a). Two other fault blocks, containing the Gullfaks, Tordis, Gullfaks Sør and Visund Fields, separate the Statfjord Field from the central part of the Viking Graben. Even though the Statfjord Field is located next to a major fault, most of the structure has undergone little deformation as compared to nearby fields located in a similar footwall position (e.g. the Gullfaks Field; Fossen & Hesthammer, 1998; Gullfaks Sør; Rouby, Fossen & Cobbold, 1996). The exception is the eastern flank of the Statfjord Field which is heavily affected by gravitational collapse structures. The Statfjord Field structure trends NE-SW, and covers an area of approximately 28 × 9 km.

The area underwent at least two major rift phases (Beach, Bird & Gibbs, 1987; Giltner, 1987; Badley, Price, Rambech Dahl & Abdestein, 1988; Thorne & Watts, 1989; Gabrielsen, Færseth, Steel, Idil & Kløvjan, 1990; Roberts, Yielding, Kusznir, Walker & Dorn-Lopez, 1995; Færseth, Sjøblom, Steel, Liljedahl, Sauar & Tjelland, 1995). The first rift phase is Permo-Triassic in age, and was early recognised from regional seismic data (Ziegler, 1978; Eynon, 1981; Badley, Egeberg & Nipen, 1984). The second phase of extension took place after deposition of the commercially important Triassic and Jurassic reservoir rocks in the North Sea and resulted in a generally E–W to NW–SE extension in the latest Middle Jurassic to earliest Cretaceous (Roberts, Yielding & Badley, 1990; Færseth, Knudsen, Liljedahl, Midbøe & Søderstrøm, 1997). Evidences for both rift phases are found on the Statfjord Field, although it is the second phase of extension that is most easily recognised in seismic and well data. The gravitational collapse structures along the eastern flank of the Statfjord Field developed during the early stages of the late Jurassic rift event. After the second rift phase, a rise in sea level resulted in a progressive burial of the Triassic and Jurassic deposits. This burial continued during the thermal subsidence in the Cretaceous to Palaeocene post-rift stage of the entire North Sea basin.

6.2. Stratigraphy

Fig. 4 shows a stratigraphic column for the Statfjord Field, from the Triassic to the Cretaceous. Gravity surveys, regional reconstructions and regional, deep-seismic lines indicate that only a thin unit of sediments exists between the Triassic sedimentary rocks and Devonian or older, metamorphic/crystalline basement in the area (Christiansson, Faleide & Berge, in press; Odinsen, Chri-

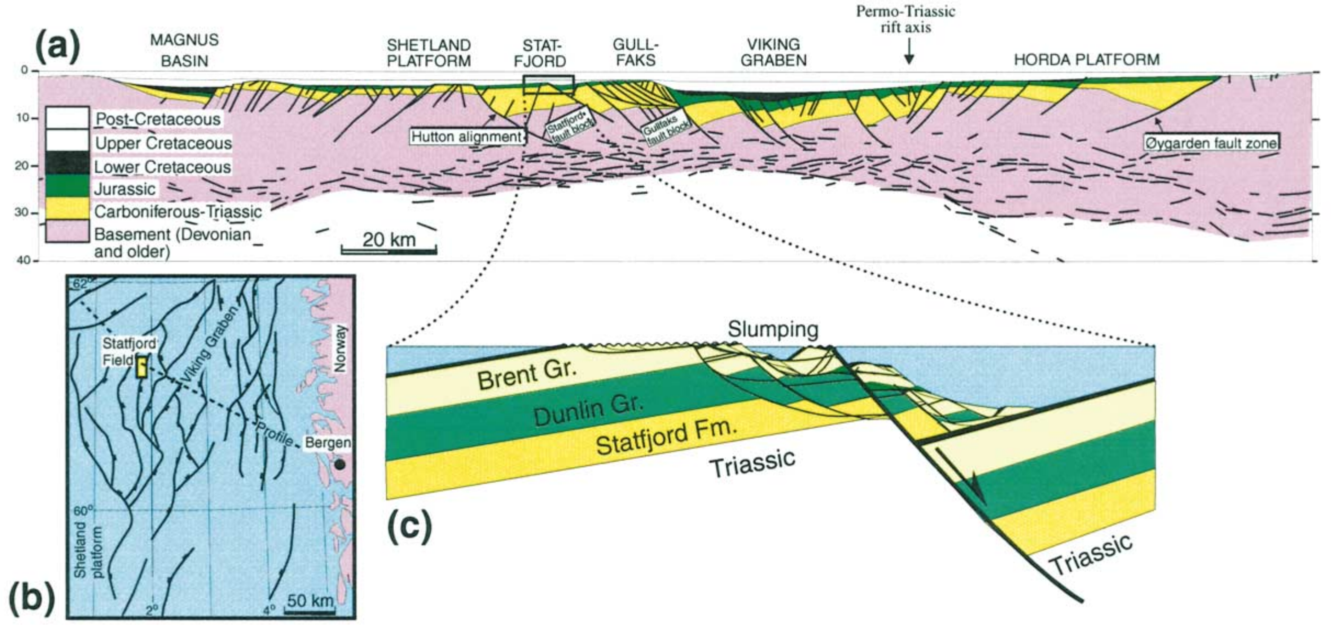


Fig. 3. (a) Regional profile across the northern North Sea and the Statfjord Field (modified from Fossen et al., 1998) and based on work by Odinsen et al., in press). See (b) for location. (b) Fault map of the North Sea Rift System with location of the Statfjord Field. (c) Detailed cross-section across the east flank of the Statfjord Field.

stiansson, Gabrielsen & Faleide, in press; Odinsen, Reemst, van der Beek, Faleide & Gabrielsen, in press).

The Triassic Hegre Group consists of interbedded intervals of sandstone, claystone and shale associated with sequences of dominantly sand or shale/claystone deposited in a continental environment. Since the base of the Hegre Group has not been reached in the Viking Graben area, the thickness of this unit remains unknown.

The late Rhaetian to Sinemurian Statfjord Formation varies from 150–300 m in thickness in the Statfjord Field. The formation consists of interlayered sandstone/siltstone and shale. The Statfjord Formation is subdivided into three members, the Raude, Eiriksson and Nansen Members. The Raude and Eiriksson Members are interpreted as fluvial deposits. The Nansen Member represents a transgressive marine sheet sand deposited on top of the alluvial flood basin. On the Statfjord Field, the three members are informally referred to as S3 (Raude Member), S2 (Eiriksson Member) and S1 (Nansen Member).

The latest Sinemurian to early Bajocian Dunlin Group consists of four formations, the Amundsen (oldest), Burton, Cook and Drake (youngest) Formations, and has a thickness in the range of 230–260 m. On the Statfjord Field, these formations are informally referred to as DIII (Amundsen and Burton Formations), DII (Cook Formation) and DI (Drake Formation). The Amundsen and Burton Formations consist of shallow marine shale, claystone and siltstone. These are overlain by silt and sandstones of the Cook Formation. The sandstones are interpreted as tidal influenced, shallow marine deposits. The Drake Formation consists of shallow marine shale and siltstone.

The early Bajocian to mid-Bathonian Brent Group is 180–250 m thick on the Statfjord Field and comprises sandstone, siltstone, shale and coal deposited in a northward prograding delta system. Together with the Statfjord Formation, the Brent Group defines the main reservoir on the Statfjord Field. The unit is divided into five formations; the Broom, Rannoch, Etive, Ness and Tarbert Formations. On the Statfjord Field, the Brent Group is also informally subdivided into six zones (B1–B6). Zones 1–3 correspond to the Ness and Tarbert Formations, whereas zones 4–6 correspond to the Etive, Rannoch and Broom Formations respectively. The lowermost unit, the Broom Formation, is interpreted as storm deposits and small distal bar build-ups on a shallow marine platform. The Rannoch Formation consists mainly of sandstone deposited in pro-delta, delta front and ebb-tidal settings. The coarser and cleaner sandstone of the Etive Formation is attributed to tidal inlet/ebb tidal, upper shoreface foreshore and lagoon barrier depositional environments. The more shaly Ness Formation is interpreted as being deposited in a delta plain setting. The unit consists of sandy channel deposits, shale and coal. The overlying Tarbert Formation comprises shallow marine sands which grade southwards into an interfingering deltaic/shallow marine sequence.

Silty shales of the mid-Bathonian to late Oxfordian Heather Formation overlie the Brent Group. The Hea-

Fig. 4. Stratigraphic column for the Statfjord Field (modified from Deegan & Scull, 1977; Vollset & Doré, 1984).

ther Formation contains several unconformities, and a hiatus (c. 6 m.y.) exists between deposition the uppermost part of the Heather Formation (late Oxfordian) and the overlying organic-rich shales of the Draupne Formation (Volgian to Ryazanian) along the crest of the Statfjord Field (Hesthammer, Jourdan, Nielsen, Ekern & Gibbons, in press). Another unconformity separates the Draupne Formation (late Ryazanian) from the Cretaceous sediments above. The unconformity is marked by a smaller (2–3? m.y.) time gap at the crest of the structure (Hesthammer et al., in press). The stratigraphic package above the base Cretaceous unconformity is marked by the general subsidence that influenced the area in Cretaceous and Tertiary times.

6.3. *Structure*

The Statfjord Field can structurally be divided into a relatively undeformed western area and an eastern flank heavily deformed by rotational block sliding. Surface and near surface degradation products (from the slump blocks) overlie most of the east flank area.

The Statfjord Field is affected by several NW–SE trending, steep-dipping normal faults that commonly offset the base of the Cretaceous. Along the crest of the structure, gravity slide structures cut into the reservoir. Rotational block slides represent the dominant geometry to the east of the crest. The shallowest detachments cut steeply into the reservoir and flatten along the shaly base of the Ness Formation/top of the Etive Formation. The next detachment cut steeply down into the Etive Formation and flattens within the shaly parts of the Cook and Amundsen Formations. The deepest detachments cut into the Statfjord Formation and flattens at the base of the unit or within shales in the uppermost part of the Hegre Group. Gravity collapse occurred all along the crest of the Statfjord Field, and can be followed northeastward into the Statfjord Øst structure, although the most extensive sliding took place in the southern parts of the Statfjord Field. Thus, the total length affected by gravity collapse is more than 25 km. The width of the area affected by rotational block slides vary between 2–4 km and widens to the south. The slumped sections can be several hundred metres thick in the easternmost part.

Only local erosion of the Brent Group reservoir along the crest of the structure and at the exposed tops of the rotated slump blocks acted prior to deposition of the Draupne Formation. The base of the Cretaceous represents another minor unconformity at the crest of the structure. On the flanks, the base Cretaceous rests conformably on underlying strata, as observed many other places in the North Sea (Rawson & Riley, 1982).

6.4. Tectonic evolution

A detailed description of the tectonic evolution of the Statfjord Field is given by Hesthammer et al. (in press). The main points can be summarised as follows:

- Immediately after deposition of the Brent Group (possibly during deposition of the Tarbert Formation), the main rifting in the Viking Graben started in late Jurassic (mid-Bathonian) times. It is likely that earlier fault activity occurred farther to the south. Upwelling of hot mantle material resulted in uplift of the graben centre, and the development of large, first order faults with kilometre-scale displacement. One of these faults defines the eastern boundary of the Statfjord Field. Movement along the fault resulted in a fault scarp with marked relief. Also in response to movement along the fault and the general doming in the centre of the Viking Graben, a westward tilting of the Statfjord Field started. It is uncertain how much of the Statfjord Field that was above sea-level at any specific time. Well data do not indicate major erosion, suggesting that the structure was mainly below or at sea level. The main uplift of the Statfjord Field took place during deposition of the uppermost part of the Heather Formation (C. A. Jourdan pers. comm.). This resulted in several erosional surfaces, identified internally in the Heather Formation.
- Rotational block sliding occurred during deposition of the uppermost part of the Heather Formation as a result of gravitational failure (this is described in detail later). Slumping prograded westward and cut into the Statfjord Formation in the final stages of gravity sliding. Little deposition of the Heather Formation took place along the top of the structure and within the slumped area after gravitational failure ceased. Only locally significant erosion acted on the Statfjord Field reservoir rocks during the erosional event in the Late Jurassic.
- The Draupne Formation was deposited after the main tectonic activity, and mainly down on the west flank and within topographic depressions on the east flank.
- A minor erosional event is defined at the base of the Cretaceous. The base Cretaceous is expected to conformably overlie the Draupne Formation down on the west flank.
- Minor tectonic activity took place along mainly NW–SE trending faults in Cretaceous time. The faults may have existed as structural lineaments prior to Cretaceous deposition.
- N–S and ENE–WSW structural trends developed in the Tertiary (post-Balder), possibly related to the opening of the Atlantic ocean. Sinistral movement probably occurred along the N–S trending faults and caused local transpression. A slight tilting of the Statfjord Field structure to the north occurred in post-Balder time. This resulted in a 130–200 m relative uplift of the structure in the northern parts. Hydrocarbons migrated into the structure in Tertiary time.

7. How slumping is identified on the Statfjord Field

In the very early phases of development on the Statfjord Field, gravity failure of the east flank of the field was yet not identified (Kirk 1980; Buza & Unneberg, 1986a,b). The first documentation of a slumped east flank on the Statfjord Field was published in 1987 (Roberts, Mathieson & Hampson, 1987) and later by Aadland, Dyrnes, Olsen and Drønen (1992). The main reasons for not recognising the slumping in the very early phase of field development were poor seismic resolution and lack of well control. As more wells were drilled, the recognition of a structurally complex east flank became obvious. Today, with more than 85 wells drilled within the slump area and better software for analysis of seismic data, it is possible to map out the detachment surface separating slumped rocks from the main field (this surface is termed the base of slope failure in this work). It is also possible many places to map the rotated slump blocks that affect the Statfjord Formation. The following section describes how the collected data have helped to interpret the geometries that resulted from gravity failure of the east flank.

7.1. Seismic data

Because slumping in the Brent Group is located immediately below the strong base Cretaceous reflection, it is generally not possible to identify individual slump blocks at this stratigraphic level. This is mainly due to the Draupne Formation, which has an abnormally low velocity, thus causing a marked acoustic impedance at the top and base of the formation. This results in a very strong seismic signal with associated peg leg multiples. Thus, where the signal is strong, reflections below are often masked. The strength of the signal is, however, controlled by the thickness of the Draupne Formation (thick Draupne Formation results in a stronger seismic signal). Thus, it is possible to identify real signals below the base Cretaceous where the Draupne reflection is weak. In addition, the top of the Statfjord Formation is commonly marked by a strong seismic signal, and it is therefore often possible to recognise the rotated slump blocks at this stratigraphic level (Fig. 5). By analysing available well data, inlines, crosslines, random lines and time slices, it is possible, to some extent, to map out the individual slump blocks.

During the seismic interpretation of slumped areas, it is important to understand what geometries are plausible and not. Fig. 6a, which is a photograph of a core from the Statfjord Formation in well 34/10-C14 on the Gullfaks Field (located 25 km to the east), clearly demonstrates that a listric fault geometry requires rotation of the strata in the hanging wall, unless internal fault block deformation is present. Fig. 6b shows a seismic section from the east flank of the Statfjord Field. The similarity between the two figures is striking and the figure clearly illustrates the relation between non-planar faults and rotated fault blocks.

At several places along the top Statfjord reflection immediately west of the slumped area, abundant small-scale horst and graben structures are identified (Fig. 7). The offset across the faults diminishes towards the base Statfjord reflection. This horst and graben system may be a pre-slumping system, i.e. structures that develop in the footwall prior to, and partly control, the slumping. Similar structures are observed in the Canyonlands National Park in Utah (Trudgill & Cartwright, 1994) and are believed related to erosion by the Colorado River. A relief map of the top Statfjord reflection from parts of the slump area clearly supports the theory of pre-slump structures in that the observed lineaments are more parallel to the onset of Statfjord slumping than the main boundary fault and occur immediately west of the onset of slumping (Fig. 8).

An azimuth map (Dalley, Gevers, Stampfli, Davies, Gastaldi, Ruijtenberg & Vermeer, 1989) of the base Cretaceous surface (Fig. 9) is useful for identifying the onset of slumping. Before gravity failure started, the sediments of the Brent Group and possibly parts of the Heather Formation were outcropping. As the structure was tilted to the west, the most elevated parts on the structure was along the main boundary fault in the east. When the crest of the rotated fault block started to slide, the highest point on the structure retrograded in a westerly direction. At all times during the gravitational failure, the highest point defined the western boundary of the slide area. Only after slumping stopped is it possible that continued tilting of the Statfjord Field caused the onset of slumping to locally be to the west of the crestal line of the field. Due to only minor erosion, the erosion line of the Brent

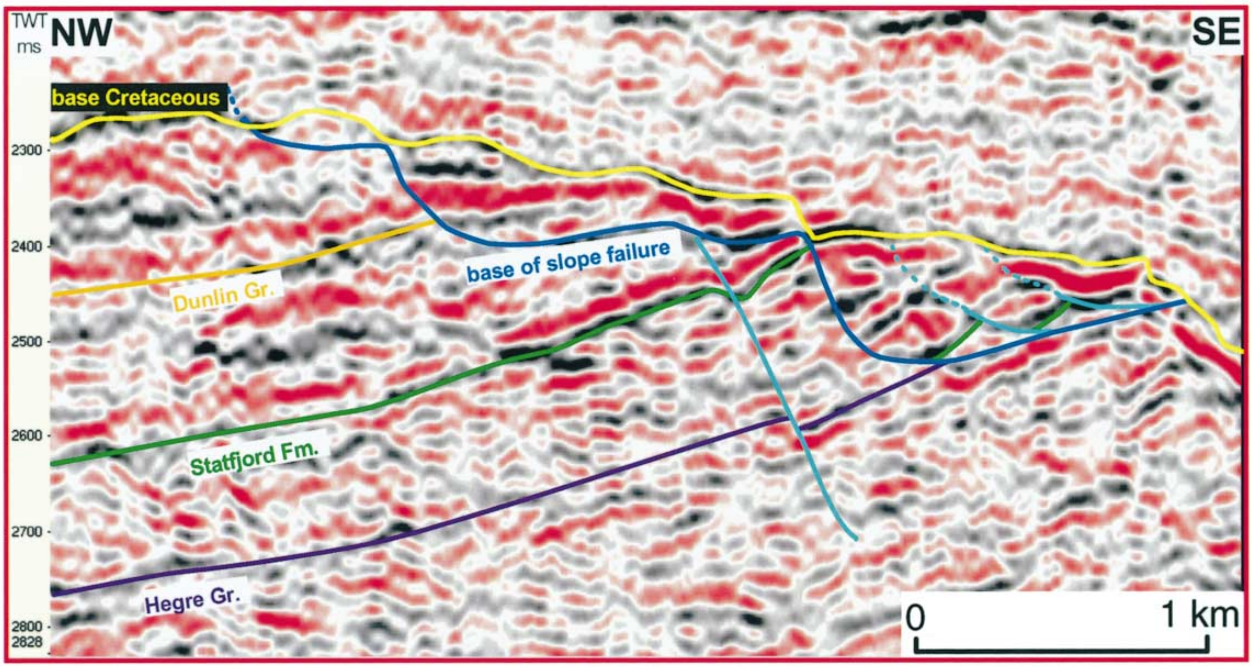


Fig. 5. Seismic profile of the slump area. Three detachment surfaces have been interpreted based mainly on well data and seismic attribute mapping. Two rotated slide blocks may be identified within the Statfjord slump area. Here, the reflections show steeper dip than on the main field, suggesting a relatively rigid block rotation. The black reflections interpreted as slumped Statfjord Formation have a steep angle with respect to the red reflection below the top Hegre Formation. The termination of the steeper dipping Statfjord reflection in the slumped area defines the base slope failure. Marked depressions of the base Cretaceous surface define onset of the main slumps. The amplitude of the base Cretaceous reflection is stronger to the east of the onset of Statfjord slumping, indicating thicker Draupne Formation in this area. Two minor deflections of the base Cretaceous surface within the area affected by Statfjord slumping may correspond to rotated slump blocks below.

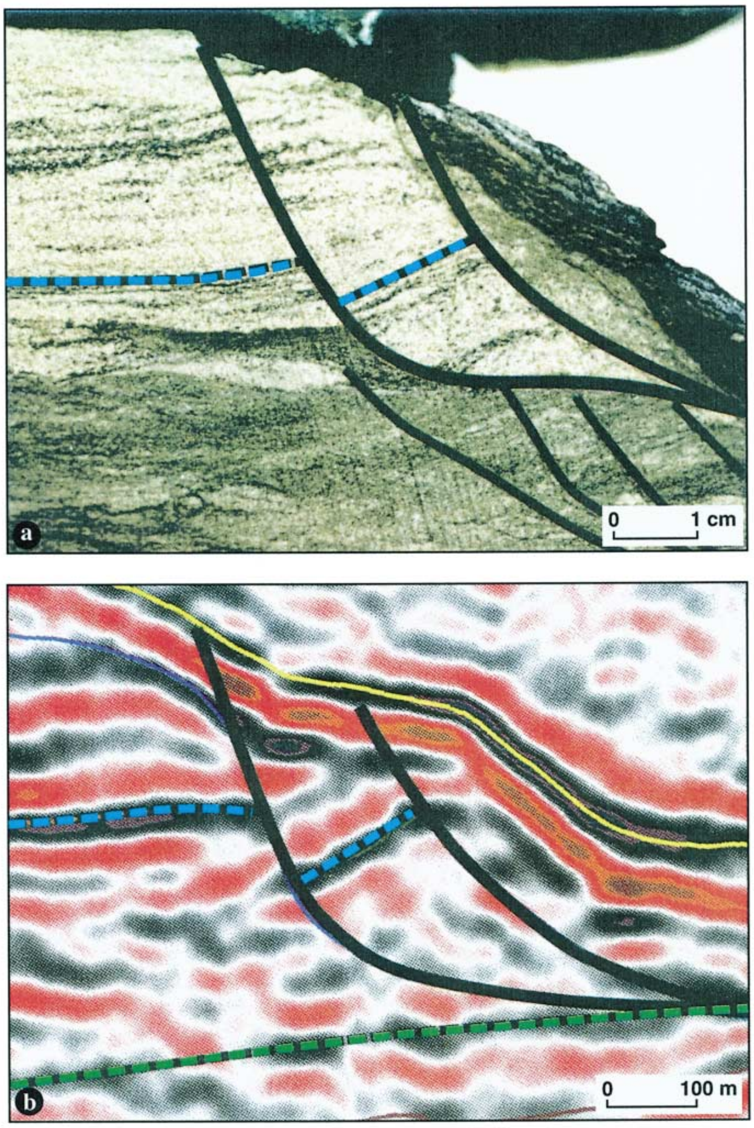


Fig. 6. (a) Core photograph from the Statfjord Formation in well 34/10-C-14 on the Gullfaks Field 25 km east of the Statfjord Field. The main structure observed is a listric fault that detaches within a more incompetent layer (shale). A rotated block is observed in the hanging wall to the listric normal fault. This geometry is a function of rigid block rotation along a listric fault. (b) A seismic inline from the east flank of the Statfjord Field. Although the fault offsetting the Statfjord Formation previously was interpreted as a planar normal fault, it is obvious how the resemblance with (a) justifies the present interpretation. Also, the top of the Hegre Group may be identified as an unbroken reflection, indicating that the fault must be listric and detach within the lowermost part of the Statfjord Formation.

Group will be located at, or close to (to the west of) the onset of slumping. An azimuth map of the base Cretaceous reflection helps distinguishing west-dipping from east-dipping strata, and therefore the line defining the break-away zone.

During slumping, and especially in the period immediately after, the topographic expression of the slump blocks were, to some extent, subdued by the erosion of the crest and degradation of the individual slump blocks. This resulted in deposition of a thin veneer of sediments that covered large areas. This degradation was, however, not capable of smoothing the topography completely, and in most places, especially above the area affected by slumping of the Statfjord Formation, much relief still existed. When the deposition of the Draupne Formation started, troughs caused by slumping as well as areas down on the flanks of the structure received most sediments. The troughs created by slumping of the Statfjord Formation had the most marked topographic expression. Thus, the Draupne Formation was thickest in these areas. Little or no Draupne was deposited along the crest of the structure. Although deposition of the Draupne Formation helped further in smoothing out the topographic relief along the east flank of the Statfjord Field, some topography remained at the beginning of the Cretaceous. The unconformity marked by the base of the Cretaceous

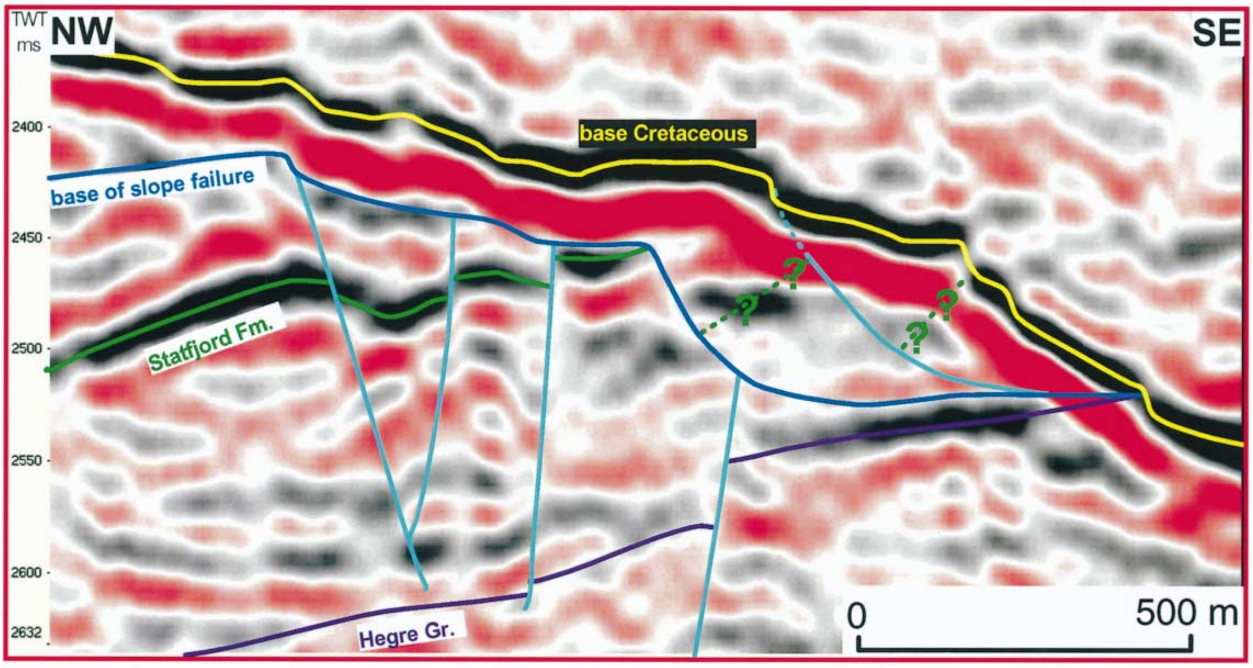


Fig. 7. A common feature observed along the top Statfjord reflection towards the area affected by Statfjord slumping is a horst and graben system. The faults appear to have significant offset of the top of the Statfjord Formation, but much less or no offset at the top of the Hegre Group. See main text for discussion. Note also how the strong base Cretaceous reflection masks the reflections within the slumped areas.

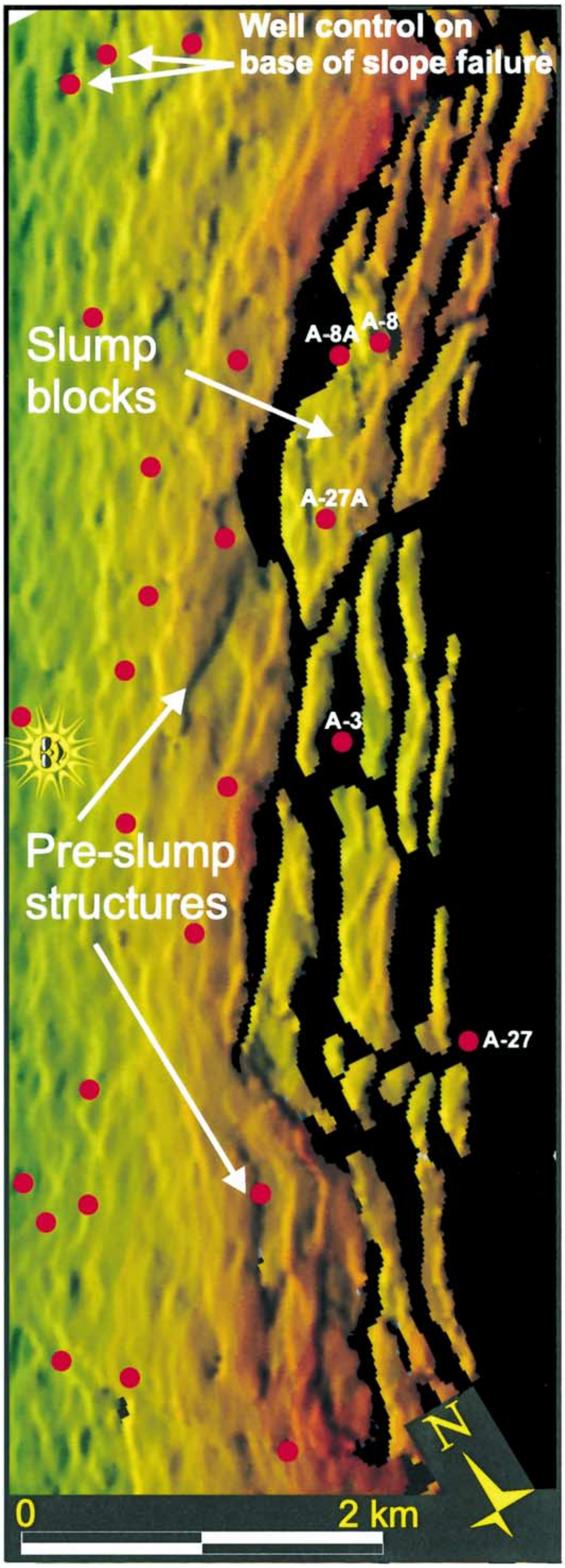
represents a relatively minor time gap (2–3? m.y.; Hesthammer et al., in press), during which some minor erosion of the top of the structure took place, and possibly of the crest of some of the rotated slide blocks. The erosion did not, however, remove the topographic expression caused by gravity failure. As sediments accumulated above the base Cretaceous surface, differential compaction of the slump area (shales of the Draupne Formation compacted more than the sandstones of the Brent Group) resulted in an enhanced topographic relief and possibly renewed movements along the listric slump faults.

An illuminated seismic timedip map (Hoetz & Watters, 1992) of the base Cretaceous surface (Fig. 10) is capable of enhancing the topographic relief that exists in the slumped areas, and provides an excellent means for mapping out the rotated slide blocks. This concept is by no means new. Brunsden and Jones (1972) mapped the topography of slopes of West Dorset by recognising breaks and changes of slope, and managed to separate several different geometries of the area below which had been affected by rotational block slides. Also, Macdonald et al. (1993) recognised that beds overlying slide blocks show a draping and ponding on the slide-produced topography. Due to the disruption of blocks as they move downslope, it may, in some cases, be difficult to define the rotated slide block boundaries with precision, but a general impression of the geometries is commonly obtained. Fig. 11 demonstrates the correspondence between slumps interpreted along the Statfjord Formation reflection and topographic relief observed along the base Cretaceous reflection. The amphitheatrelike geometry of slumps are clearly defined within the area affected by Statfjord slumping.

When analysing seismic attribute maps, it is important to try to separate seismic noise from real features (Hesthammer & Fossen, 1997b). Since noise interference features observed on seismic attribute maps commonly have a sinusoidal appearance (Hesthammer & Fossen, 1997a), it may be argued that much of what is observed on the seismic relief map of the base Cretaceous reflection is not real. While the geometry of seismic noise may have similarities with geometry resulting from rotational block slides, it is on a much smaller scale than that observed in most of the slumped area. Such noise and interference patterns are observed in areas where the Draupne Formation is thinner and thus associated with a weaker acoustic impedance and seismic signal. In most of the slumped area, however, the Draupne Formation is quite thick. This results in a very strong seismic signal of the base Cretaceous reflection. It is therefore unlikely that seismic noise and interference patterns cause significant problems in most of the slumped area, although minor structures should be investigated with care.

7.2. Well data

More than 160 wells have been drilled on the Statfjord Field. Many of these are within the area affected by gravity failure. As a result, more than 80 control points



exist for the location of the base of slope failure (Figs. 8, 10 and 11). The area affected by slumping is characterised by anomalous log signatures wich can only be explained by extensive and complex deformation (Hesthammer et al., in press). It is possible from all the well data to obtain a good idea of the general geometry of the base of slope failure. The reasoning is that more wells will penetrate the failure surface where it detaches, since this surface will be relatively shallow-dipping. Well data clearly demonstrate that the shallowest detachment surface (intra-Brent Group) is encountered farthest to the west in the area affected by gravitational failure, whereas the deepest detachment surface (at the base of the Statfjord Formation) is located next to the main boundary fault in the east (Fig. 10). The shallowest detachment surface is found from well data to be located at the base of the Ness Formation. The next level of detachment occurs within the lower Dunlin Group, but a clear bedding parallel detachment surface is not identified based on well data (Hesthammer et al., in press). The reason for this is probably two-fold. First, it appears also from seismic data that the detachment surface for the middle slump is commonly somewhat steeper than for the other slumps. Secondly, even if the detachment surface is bedding planar, seismic data indicate that several detachment surfaces exist within the Dunlin Group, although the surface that most commonly served as detachment is within the Amundsen Formation. The deepest failure surface cuts steeply into the Statfjord Formation and flattens towards the base of the formation or the uppermost parts of the Hegre Group.

Well data from the slumped areas show abundant faulting which corresponds to minor listric slump faults. A total number of 127 faults are identified within the east flank of the Statfjord Field. The cumulative missing section is estimated to 4493 m, whereas the length of drilled section is 5625 m. This gives an average missing section for each fault of 35 m, and an average fault spacing of 44 m. The average missing section for each fault in the

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Fig. 8. Colour-contoured and illuminated (from the NW) timedip map (based on seismic interpretation) of the top Statfjord reflection from the east flank area. Bright colours indicate dip to the northwest (dip towards the light source) and dark colours indicate dip in an south-easterly direction (away from the light source). Reddish colours indicate shallow depths, whereas greenish colours are located structurally deeper. Black indicates where the top of the Statfjord Formations is absent due to faulting. Locations where a well has penetrated the detachment surface (base of slope failure) are marked with red circles. These locations provide good control of reservoir characteristics both within and outside the area affected by gravitational collapse. Note the lineaments that exist immediately west of and parallel to the onset of Statfjord slumping, and which represent a horst and graben system along the top of the Statfjord Formation (Fig. 7). These structures may represent a pre-slumping system; i.e. structures that develop in the footwall prior to, and partly controls the slumping.

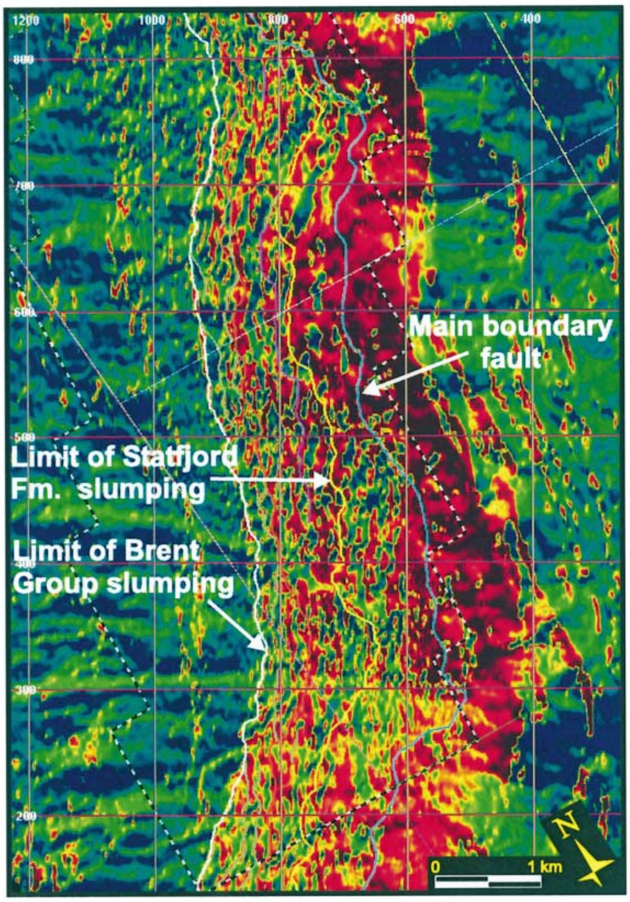

Fig. 9. Azimuth map of the base Cretaceous surface. Areas where the base Cretaceous reflection dips to the North-west are shown in green and blue colour and areas with dip to the South-east are marked with orange and red colour. The interpreted onset of slumping is marked with a white line (the Statfjord slump area is east of the yellow line, whereas the main fault is indicated by the blue line). See main text for discussion.

Brent and Dunlin Groups increases towards the south. This is consistent with the observation that the width of the area affected by gravity failure (as interpreted from both seismic and well data) increases somewhat to the south.

8. Evolution of slumping along the east flank

Three stages of slumping have been identified on the east flank of the Statfjord Field. The first phase involved rocks of the Brent Group. The second stage included collapse of the Dunlin Group, whereas the third stage cut down to the base of the Statfjord Formation. Although well data and seismic data demonstrate the presence of several detachment surfaces and increasing complexity at shallower reservoir levels, it is not possible from such data alone to resolve all details of the evolution of the area affected by gravitational failure. A sound understanding of this evolution can only be obtained through a combination of interpretation of available data and assumptions and theories that fit the observations. The following sections reflect some general ideas on how the slump structures along the eastern flank of the Statfjord Field probably evolved. The model presented is idealised and it is likely that local discrepancies from the model exist several places along the east flank.

8.1. Detachments within the Brent Group

During the tectonic activity related to the upper Jurassic rift event, the Brent Group was only weakly consolidated, whereas the Statfjord Formation was covered by ca. 500 m of sediments and thus more lithified. The rocks close to the eastern edge of the Statfjord fault block became unstable as offset along the main fault increased. Movement along faults are normally associated with seismic activity, and earthquakes were likely common on the Statfjord Field at this time. Although gravitational collapse can occur without a triggering mechanism such as an earthquake, it is likely that earthquakes caused the collapse of the gravitationally unstable Brent Group rocks in the footwall to the Statfjord Field boundary fault (Fig. 12a). The strength of the Brent Group and pore pressure beneath the detachment surface determined, to a large extent, the geometry of the slump blocks. Identification of rotated slump blocks and the fact that log correlation of the different zones in the Brent Group is possible also suggest that although abnormally high pore pressure existed, the slump blocks did not obtain enough velocity during sliding to transform into incoherent slumps (Morgenstern, 1967). Several earlier works have indicated that slide blocks may move slowly as opposed to catastrophically (Crandell & Varnes, 1961; Brunsden & Jones, 1976; Jones et al., 1984; Hauge, 1985) and thus increase the chances for preserving the initial block geometry.

The slump faults in the Brent Group detached within shales of the Ness Formation, although several minor detachment surfaces may exist at different stratigraphic levels. The shales and coal layers within this formation probably acted as seals, restricting upward movement of intergrain fluids and building up pore pressure which lowered the internal shear strength of the rocks. At some point, this led to failure. The failure surface was listric and steepened considerably towards the surface. Within the slump area, several blocks, bounded by listric faults that detached mostly along the same surface as the main failure surface, started to rotate along the listric faults. This resulted in a steepening of bedding within the slumped area. The rotation was probably slow since the blocks behaved relatively rigidly. Some internal deformation is expected in the unconsolidated sediments. Such internal deformation may occur as discrete faults, but perhaps more likely as a more widely distributed reorganisation

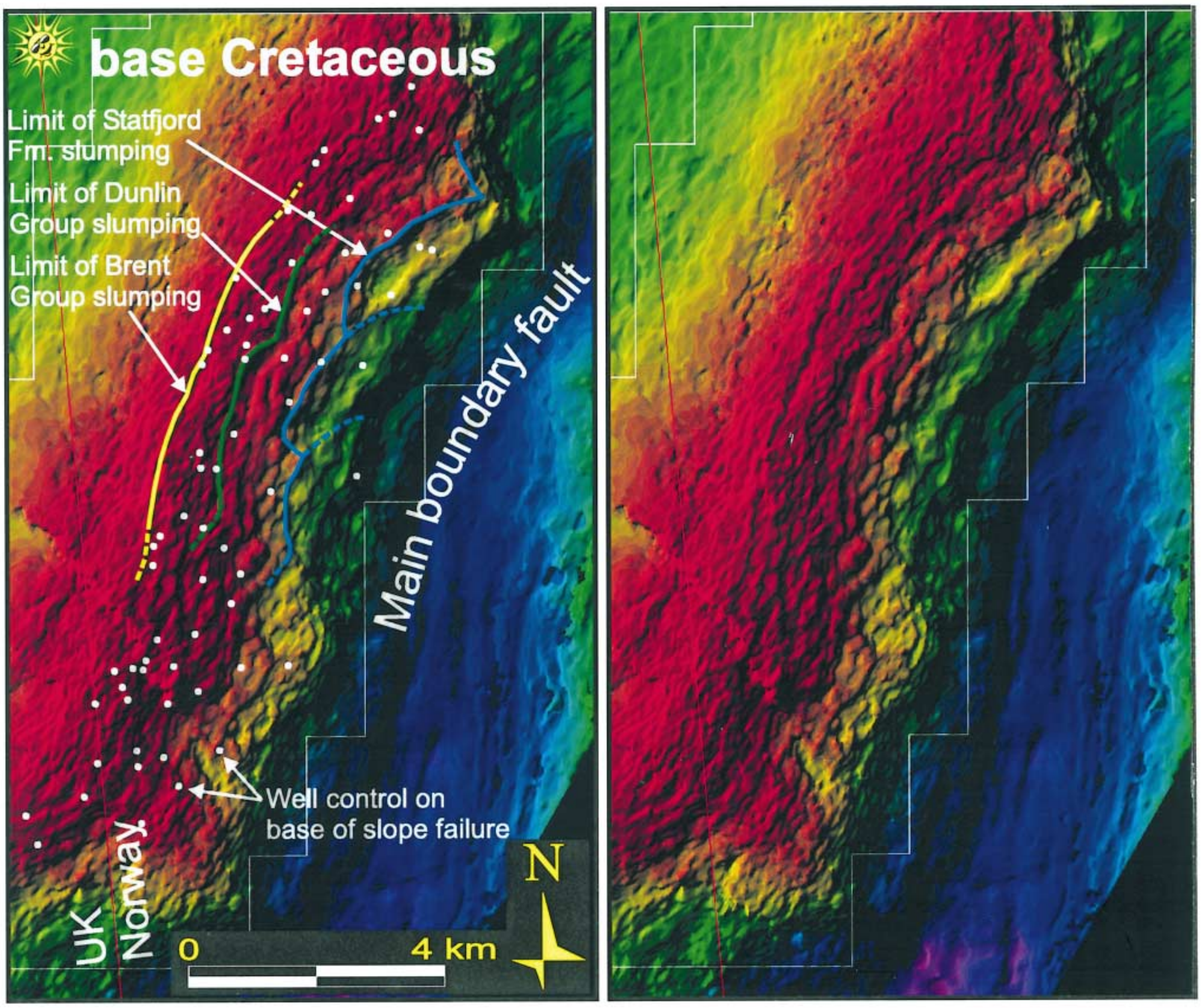

Fig. 10. Relief map of the base Cretaceous surface, 'illuminated' from the NW. The map is colour-contoured with red indicating structural highs and purple structural lows. Locations where wells have penetrated the base of slope failure are marked with white circles. The most obvious feature seen on the relief map is the depression of the base Cretaceous across the main fault. Several topographic relief structures are observed in the area immediately west of the main boundary fault, and is interpreted to reflect draping of the base Cretaceous surface over existing rotated slide blocks that developed during gravitational failure along the east flank of the Statfjord Field. The relief map indicates that slumping took place along all of the east flank.

of the grains such as observed on the Gullfaks Field to the east (Fossen & Hesthammer, 1998). The internal deformation will generally lower the dip of bedding. Thus, the shallower dip, the more internal deformation has acted on the rocks. It is quite possible, as seismic data may indicate in some places, that due to internal deformation, bedding may become shallower in the slump area than in the surrounding rocks. In a previous account (Fossen & Hesthammer, 1998), a direct relationship between dip of bedding and amount of internal deformation by grain reorganisation, and thus porosity, is suggested. The amount of internal distortion in slides is also increasing towards the toe zone. On the Statfjord Field, this effect will result in smaller slump blocks towards the east.

8.2. Detachment within the Dunlin Group

As offset along the main fault increased, the Amundsen and Burton Formations of the Dunlin Group were exposed in the footwall slope of the main fault (Fig. 12b). Perhaps as a result of high pore pressures below this stratigraphic level and seismic activity, slumping occurred at a deeper level than previously, and detached within the shales of the Amundsen Formation. Again, it is likely that several other, more minor, detachment surfaces exist at different stratigraphic levels. This gravity failure would also affect previously slumped portions of the Brent Group (Fig. 12c; shallow level slumping). The geometry of the slumped Brent Group thus became quite complex.

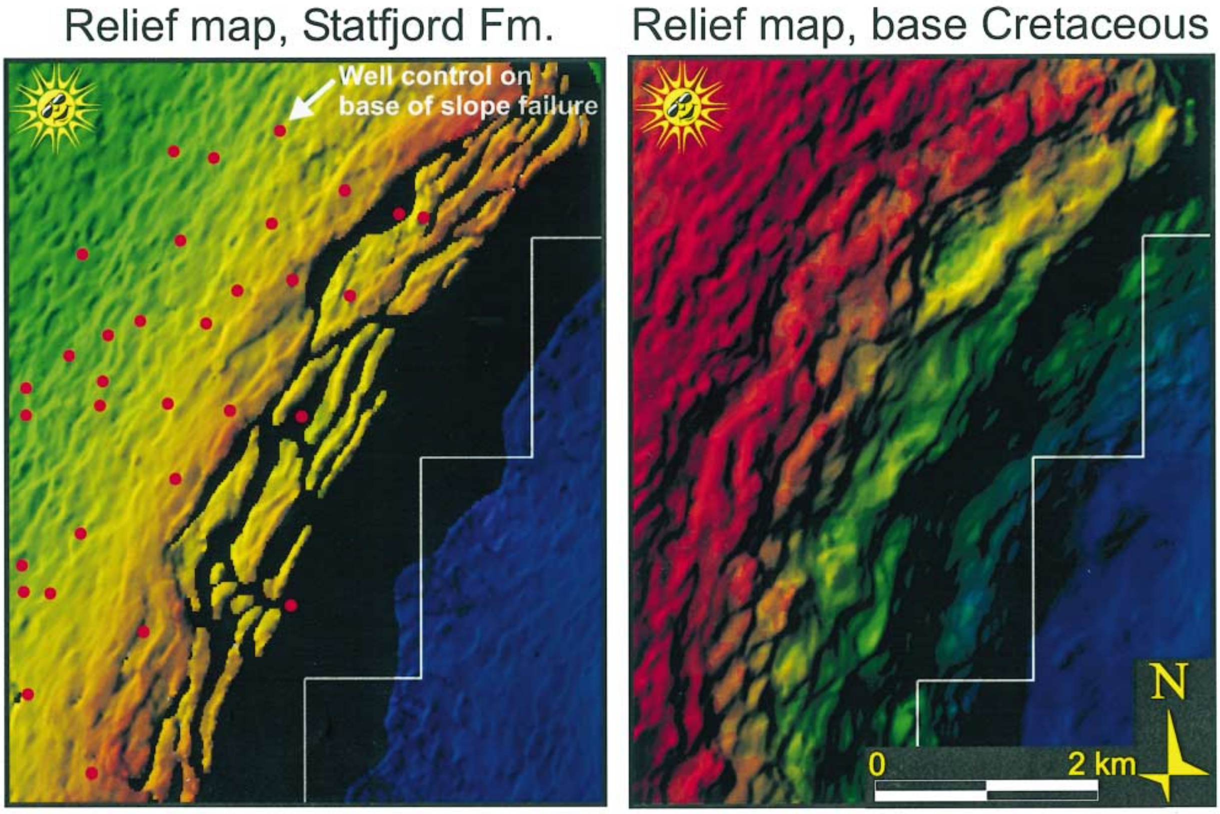

Fig. 11. (a) Relief map (based on seismic interpretation) of the Statfjord Formation from parts of the main field and east flank (Fig. 8). Areas where the top of the Statfjord Formation is absent due to faulting are marked in black. Locations where wells have penetrated the detachment surface (base of slope failure) are marked with red circles. Two major rotational slide blocks are identified, and each of them consists of several minor rotated blocks. The southern major slump block is located deeper than the northern block. (b) Relief map of the base Cretaceous surface covering the same area as (a). It is clear how the slumping of the Statfjord Formation is reflected along the base Cretaceous surface. An analogue may be found in the Dorset area (Brunsden & Jones, 1972) where today's subdued topography is thought to reflect the underlying structures.

When gravitational failure entered the Dunlin Group, a new relief developed along the new break-away zone. It is likely that this cliff was also gravitationally unstable and caused minor slumping of the Brent Group (Fig. 12c; shallow level slumping).

8.3. Detachment within the Statfjord Formation

With increasing offset along the main boundary fault, shales of the lowermost part of the Statfjord Formation and the uppermost part of the Hegre Group became exposed in the footwall to the main fault (Fig. 12d). Again, high pore pressure existed below the impermeable shale layers, thus decreasing the shear strength of the rocks at this stratigraphic level. As the rocks became unstable, sliding detached within these shales (Fig. 12e). Because the rocks of the Statfjord Formation were much more consolidated than rocks of the Brent Group, the Statfjord slump blocks behaved more rigidly and underwent less internal deformation. Some evidence of internal deformation is, however, observed (dip of layering within the slump blocks is, in some parts of the area, less than dip of layering on the main field). The slump faults that soled out at the base of the Statfjord Formation were more extensive than those which detached within the Brent and Dunlin Groups. Thus, larger slump blocks exist at this stratigraphic level.

Due to slumping of the Statfjord Formation, a new cliff face developed at the break-away zone to the Statfjord slump area. This cliff was gravitationally unstable and resulted in renewed slumping with detachment within the shales of the Amundsen Formation. This resulted in yet another cliff at the latest (westernmost) break-away zone which also became unstable and failed due to gravitational forces (Fig. 12e; shallow level slumping). Detachment related to this failure was likely within shales of the Ness Formation. Since gravity failure subsequently stepped westward, rocks at some level above the Statfjord Formation have experienced several faces of slumping, and the geometry of these rocks are very complex. Least deformation is observed in rocks that underwent only one phase of gravity failure.

During slumping, degradation (local erosion) of the protruding slump blocks smoothed the surface relief

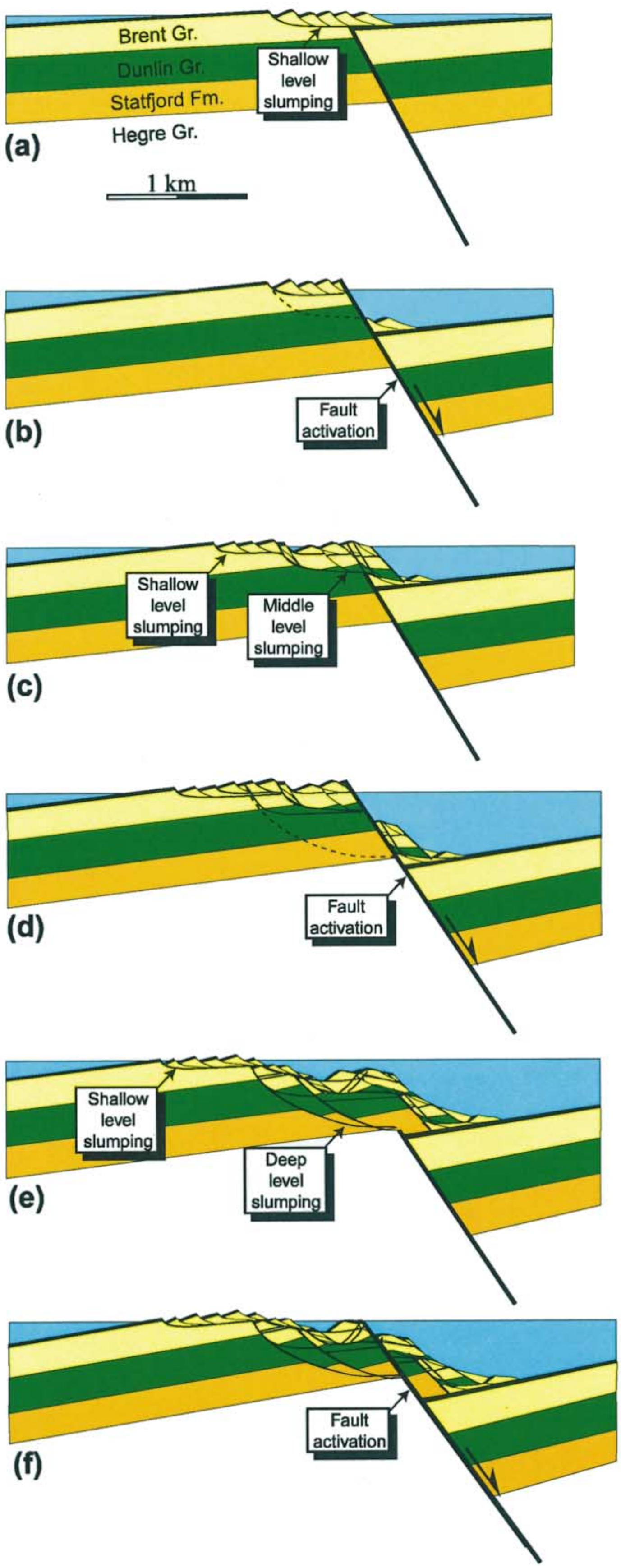

Fig. 12. Evolution of slides along the eastern margins of the Statfjord Field. See main text for detailed discussion. (a) Movement along the main fault caused a relief where the footwall was exposed to gravitational instabilities. Slumping of the Brent Group occurred when the gravitational forces overcame the frictional shear strength of the Ness Formation shales. (b, c) Further movement along the main fault exposed rocks of the Dunlin Group. This led to renewed instabilities and gravitational collapse. The detachment was located within shales of the Amundsen Formation. The break-away zone (onset of Dunlin slumps) was unstable and resulted in slumping of the Brent Group. (d, e) With increasing offset across the main fault, rocks of the Statfjord Formation became exposed to gravitational instabilities. This led to renewed failure, this time with the detachment located within shales of the lower parts of the Statfjord Formation. The new break-away zone was also unstable and led to further slumping of the Dunlin and Brent Groups. (f) When fault activity ceased, the east flank of the Statfjord Field was characterised by complex slide geometries and several detachment surfaces. Rocks that experienced only one phase of slumping may still have their initial geometries intact, whereas those rocks that underwent several phases of slumping will display extremely complicated geometries. Erosion of the slumped crest is not shown. Although only three distinct detachment surfaces are indicated in the figure, several, more localised, surfaces are identified at different stratigraphic levels along the east flank.

somewhat. Since the Brent Group normally defined the highest points in all slump blocks, it was mainly these rocks that became degraded. As a result, a thin veneer of mainly sandstone would cover the area affected by slumping.

9. Comparison of the Statfjord Field with other field examples

Multiple detachments, as identified on the Statfjord Field, are also observed on the Brent Field which is located immediately to the south of the Statfjord Field (Livera & Gdula, 1990; Struijk & Green, 1991; Coutts et al., 1996). The geometry of the slumped area is very similar to that interpreted on the east flank of the Statfjord Field (Fig. 13). Although gravity collapse is not commonly described as being a major deformation mechanism along the crestal flanks of the North Sea oil fields, with exceptions of the Statfjord Field (Roberts et al., 1987), the Brent Field (Struijk & Green, 1991), Ninian (Underhill et al., 1997), and Cormorant Field (Speksnijder, 1987), it is quite possible that this type of deformation was common along the crests of most of the oil and gas fields in the North Sea. In fact, recent well data from the Gullfaks Field and the Veslefrikk Field (Fig. 14) indicate that slumping was active in the footwall to the main boundary faults of these fields as well. Several places, erosion will have removed most evidence of gravitational collapse structures (e.g. the deeply eroded Gullfaks, Gullfaks Sør, Snorre and Visund flanks). Other places, footwall collapse structures may be attributed to tectonic processes rather than pure gravity failure (as it was in the early phases of field development on the Statfjord Field; Buza & Unneberg, 1986a, b).

The Fairy Dell area in Dorset along the south coast of England provides an excellent field analogue to the slumping observed on the Statfjord Field. A comparison of this area with parts of the east flank of the Statfjord Field reveals striking similarities (Fig. 15). Brunsden and Jones (1976) stated that early maps from the Fairy Dell area suffers from lack of later detailed revision. The early map may thus provide an analogue to seismic interpretation (Fig. 15b and 15c). The elongated blocks observed in Fig. 15b and 15c are similar both in appearance and in size. The amphitheatrelike geometry of the slumped area is also comparable. Another interesting feature is the high displacement gradients along the slump faults. Such gradients are also found associated with relay structures in sandstones in the Canyonlands National Park in Utah (Trudgill & Cartwright, 1994) where displacement changes from zero to more than one hundred metres over a distance of only 500 m. A comparison of a cross section from the Fairy Dell landslide with one through the 33/9-A3 well on the Statfjord Field (Fig. 16) further demonstrates the similarity between the two areas.

10. Summary and conclusions

Gravity collapse structures may range in scale from centimetres to hundreds of kilometres and affect both loose sediments and highly consolidated rocks. An area affected by gravity failure is commonly amphitheatrelike in map view. A cross-sectional view typically shows a listric and concave upwards geometry where the fault detaches along a bedding parallel surface. The strain increases in the direction of sliding. Thus, the fault blocks close to the break-away zone will generally be less deformed and larger in size than fault blocks at the toe of the slide. Movement of blocks within the slide area can be both translational (translational block slide) and rotational (rotational block slide). For rotational block slides with little internal block deformation, dip of bedding within the rotated blocks will typically be higher than for bedding not affected by gravity failure. If a free surface does not exist at the toe of the slide, compressional structures may develop. If the velocity of the slide blocks exceeds a certain value, the slide may not reveal a systematic geometry as described above. Instead, an avalanche with chaotic debris will result.

Causes of gravity failure may be seismic shocks, rapid sedimentation, over-steepening, or changes in pore pressure. Pore fluid pressure plays an important role in gravity failure and may affect the geometry of the detachment surface and the velocity with which the slide blocks moves. Pore pressure reduces shear strength, and generally causes the rocks to fail within impermeable soft layers such as shales. Gravitational failure took place along the east flank of the Statfjord Field when the relief along the main boundary fault reached a certain height, such that the shear strength of the rocks was exceeded. The triggering mechanisms were probably earthquakes (due to fault movement related to the late Jurassic rift event) and high fluid pressures. Pore pressure played an important role during gravity failure, in that overpressure at the boundary between porous sandstone and impermeable shale reduced the frictional shear strength of the rocks.

The gravitational collapse on the Statfjord Field took place as rotational block slides. Listric faults detached within soft shales, and several of the slump blocks developed and rotated along the listric faults. The process of slumping was polyphasal. First, parts of the Brent Group slumped. The detachment surface was within shales of the Ness Formation. Next, the slumping cut into the Dunlin Group and detached within the lower parts of the group (shales of the Amundsen Formation). Renewed slumping of the Brent Group occurred at the new break-away zone created by the Dunlin slumping. In the final stages of gravitational failure, slumping reached into the Statfjord Formation and detached within shales at the base of the unit or within shales of the uppermost Hegre Group. The relief created at the head (break-away

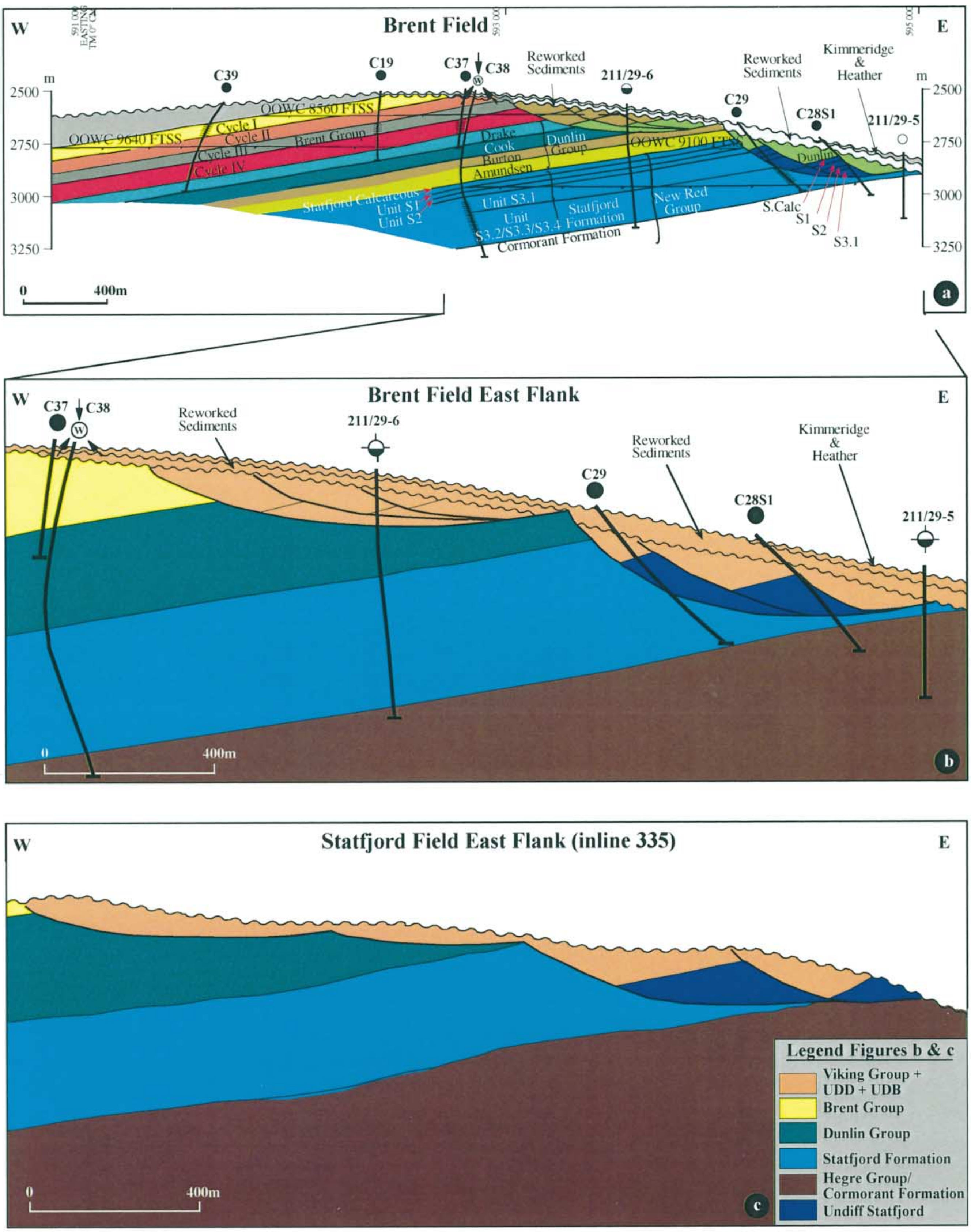

Fig. 13. (a) Detailed profile from the east flank of the Brent Field (from Struijk & Green, 1991). (b) Simplified profile based on (a). (c) Profile near well 33/9-A27 (Fig. 8) on the east flank of the Statfjord Field. The profiles from the Brent and Statfjord Fields show striking similarities, suggesting that gravity failure along the crest of the major block-bounding fault is a widespread feature in the area, that more than one phase of failure took place, and that failure affected rocks from the Brent Group and stratigraphically down through the Statfjord Formation. The rotational slumps affecting the Statfjord Formation detach near the top of the Hegre Group on both fields. No vertical exaggeration.

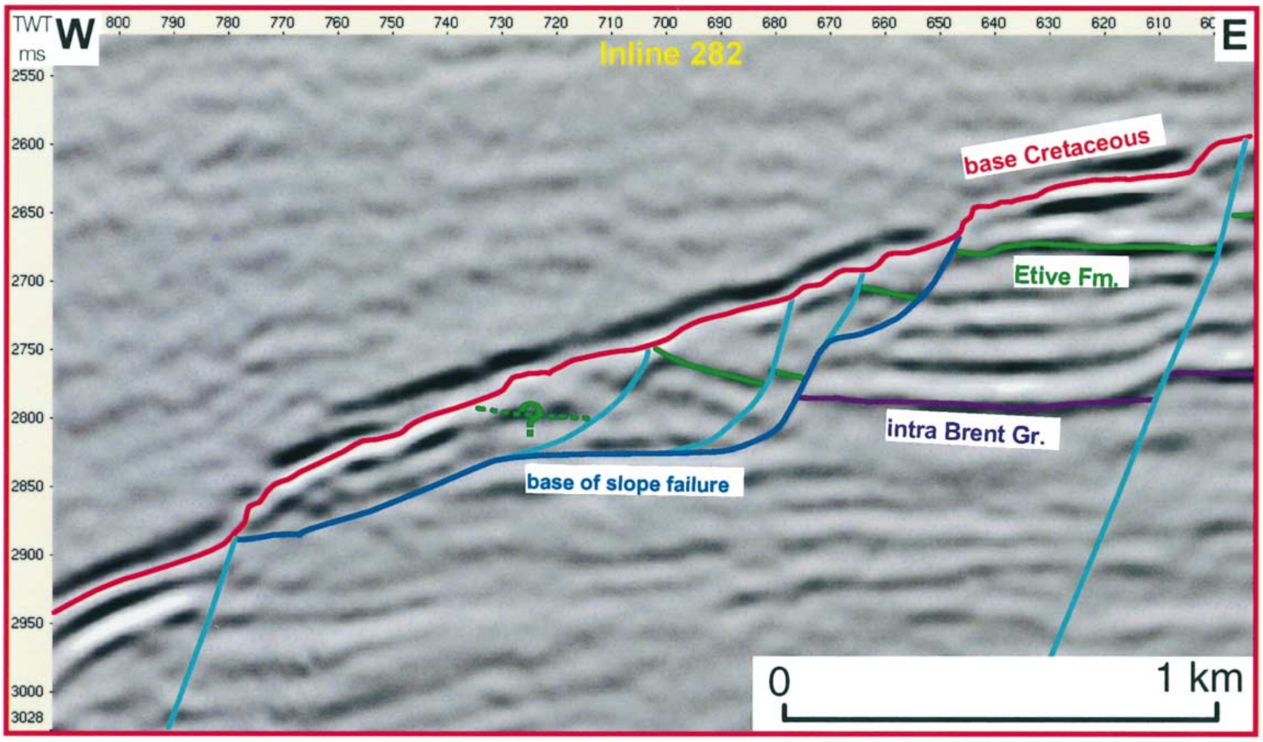

Fig. 14. Recent interpretation of seismic data from the Veslefrikk Field indicates that the western flank of the field is affected by gravitational failure. The geometries observed have many similarities to those observed along the eastern flank of the Statfjord Field (Figs. 5 and 7). The seismic interpretation have been supported by recent drilling of well 30/3-7B. Dip of bedding within the slumped area is higher than outside the area affected by gravitational failure. Similarly to that observed in Fig. 6, this indicates a listric shape of the detachment fault.

zone) of Statfjord slumping caused renewed slumping of the Brent and Dunlin Groups.

After gravitational failure ceased, the topographic highs created by the rotated slump blocks were eroded. This degradation of the slump area affected mainly the Brent Group, and resulted in a thin veneer of sandstones that draped over existing structures.

Slumping on the Statfjord Field generally occurred as rigid block rotation. Some internal deformation is, however, expected, especially within the poorly consolidated Brent Group. The movement of the individual slump blocks were probably slow. Due to break-up, the size of the slide blocks diminishes away from the breakaway zone.

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