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Growth Faults in Upper Triassic Deltaic Sediments, Svalbard[1]

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Abstract Growth faults, rollovers, and shale anticlines affecting Upper Triassic deltaic coarsening-upward sequences are excellently exposed in coastal cliffs on Edgeoya in southeast Svalbard. Study of photographs of the cliffs shows fault configuration, reservoir variations, and internal features of shale anticlines.

On downthrown blocks the strata were tilted and rollovers were formed. Beneath the concave-upward growth faults shale anticlines developed and relative uplift of the upthrown block resulted in erosion of some of the newly deposited sands. Subsequent shale deposition formed a local angular unconformity.

The faulting may have been initiated by a combination of (1) denser sands overlying less dense clays with excess pore-fluid pressure, (2) a southward prodelta slope and/or regional paleoslope, (3) differential loading associated with deltaic progradation, and (4) a triggering mechanism such as earthquakes.

These structures serve as a model for the larger Gulf Coast and Nigerian structures and provide criteria for the recognition of growth faulting in other exposures of ancient deltaic sediments.

Introduction

Growth faults develop by contemporaneous faulting and sedimentation and are characterized by the abrupt increase in thickness of corresponding strata across the fault on the downthrown block (e.g., Hardin and Hardin, 1961). Their importance in controlling the structure, facies distribution, and sandstone-reservoir geometry in deltaic sediments has been demonstrated in the Tertiary of the northwestern Gulf of Mexico (Ocamb, 1961; Curtis, 1970) and Nigeria (Short and Stäuble, 1967; Weber, 1971). Large-scale deformation structures associated with mudlumps also have been described from the modern Mississippi delta (Morgan et al, 1968; Coleman et al, 1974). However, growth faults and associated structures have not been described from exposed ancient deltaic sediments despite many detailed sedimentologic studies of such rocks. This paper documents growth faults and associated structures exposed in nearly horizontal Upper Triassic sedimentary rocks near Kvalpynten, Edgeoya, Svalbard (Fig. 1). As landing was impossible at this site, only photographic data could be obtained, but field observations on the strata have been made at other localities in Svalbard and also are included in the following account.

The Mesozoic deposits of Svalbard are terrigenous platform sedimentary rocks as much as 2 km thick and show a fairly uniform regional facies development (Harland, 1973; Livsic, 1974). Lower, Middle, and Upper Triassic marine shales and siltstones (Fig. 2) are overlain by Upper Triassic deltaic and continental coal-bearing sandstones and shales of the De Geerdalen Formation (Buchan et al, 1965; Flood et al, 1971). Sandstones and shales in the lower part of the De Geerdalen Formation are arranged in repetitive coarsening-upward sequences.

Sequences commence with a marine shale, which grades upward into a cross-laminated fa-

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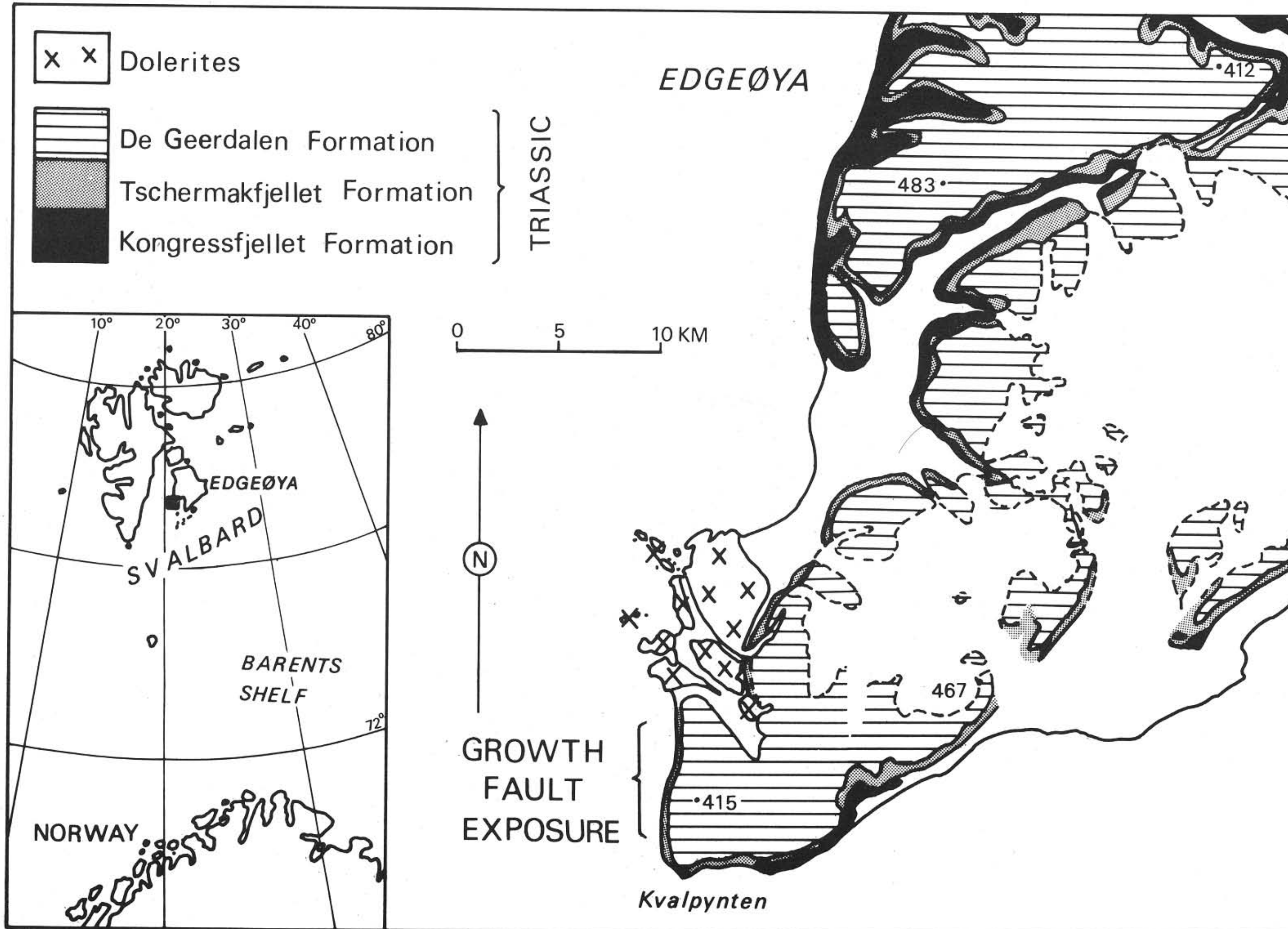


FIG. 1—Location and geologic map, based on Flood et al, 1971.

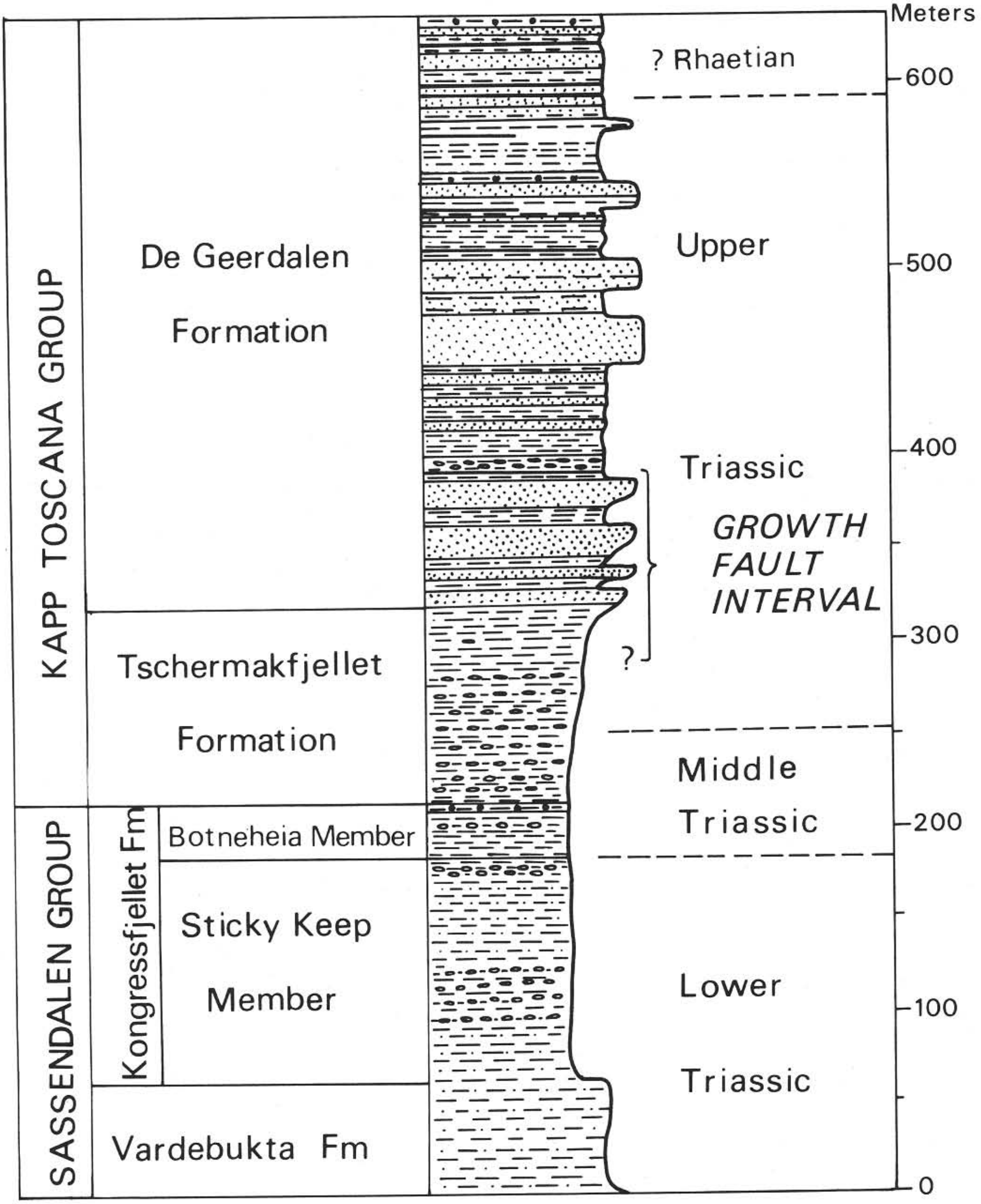


FIG. 2—Composite stratigraphic section of Triassic of Edgeoya, modified after Flood et al, 1971. Growth-fault interval is in series of deltaic coarsening-upward sequences which overlies marine shales and is overlain by predominantly continental deposits.

cies with indications of both wave and current activity. Sandstones in the upper part show medium-scale cross-stratification and ripple marks, and large-scale cross-stratification is present in photographs of many of the sandstone units at Kvalpynten. At the top of some coarsening-upward sequences are thin shelly sandstones, or a strongly erosive sandstone unit, which in turn may fine upward into shale.

The sequences are interpreted to be the result of a relative shallowing of the sea due to deltaic progradation. Deposition is considered to have occurred in delta-front and prodelta environments, with the sandstones representing coastal-barrier and/or distributary-mouth bar deposits (e.g., Allen, 1970; Oomkens, 1970). The sandstone unit at the top, which is deposited on an erosion surface may be a delta-plain channel deposit, whereas the shelly sandstone may be a transgressive deposit associated with delta abandonment (e.g., Weber, 1971; Elliott, 1974).

In thin section, the sandstones are fine to medium grained and moderately sorted. Locally a coarse sparry calcite cement is present. Rock fragments and feldspars often predominate over quartz grains (Flood et al, 1971; Edwards, 1975).

Although pertinent paleocurrent data and paleogeographic reconstructions have not been published, large-scale cross-stratification visible on the cliff face indicates that the dominant component of flow was southward.

This study is based on observations and photographs from the expedition boat, a helicopter flyby in 1974, and oblique aerial photographs by the Norsk Polarinstitutt in 1936. Vertical and horizontal distances cited in the text are based on a detailed topographic map constructed from vertical aerial photographs at the Norsk Polarinstitutt.

Sediments

Four coarsening-upward deltaic sequences are present in the part of the succession affected by growth faulting (Figs. 3, 4). A fifth sequence and dark shale above are continuous over the entire cliff section and thus serve as a datum for correlation of the older strata between the fault blocks. Individual sequences are generally 25 to 50 m thick, but locally some are as much as 60 m thick.

The sequences are made up of three sedimentary facies (Figs. 4, 5): shale, stratified sandstone, and massive sandstone. The lower fine-grained unit of each sequence is composed of a shale facies which is parallel stratified and probably consists of fissile clayey and silty mudstone. This shale grades upward into the stratified-sandstone facies which constitutes most of the upper coarse-grained unit of the sequence and shows several stratification types. Horizontal bedding is the dominant internal sedimentary structure. Large-scale cross-stratification, in sets as much as 10 m thick, is common in the sandstone units, especially on the north within individual fault blocks (Figs. 4, 5). Some sets are composed almost entirely of sandstone, whereas others are composed of interbedded sandstone and shale. Deformed stratification is present in convoluted bedding as much as several meters high, generally involving interbedded sandstone and shale. The shale and stratified sandstone facies are present elsewhere in Svalbard. The massive sandstone facies, without recognizable internal structures, is present as wedge-shaped units in the uppermost parts of some sequences, on the downthrown sides of growth faults.

Both sandstone and shale units are sheet and wedge shaped. In some areas, soft-sediment deformation has led to a more complex shape. More than half of the sandstone units terminate southward before reaching the next growth fault.

Three kinds of depositional contacts are present (Figs. 4, 6): (1) a sharp depositional contact where shale overlies sandstone in the absence of any apparent erosion; (2) a gradational contact where shale passes gradually upward into sandstone; (3) an erosional contact truncates the underlying beds, and is overlain conformably by younger beds. Contacts are erosional at the top of more than half of the sandstone units at their southern termination. Toward the south, dips on these surfaces generally increase and the surfaces apparently merge into a main growth fault (Fig. 6), suggesting erosion of a fault scarp. Northward, the surfaces appear to continue as normal sharp depositional contacts.

Growth Faults and Other Structures

Ten growth faults are exposed, affecting four coarsening-upward sequences which make up about 120 m of the stratigraphic column visible in the cliffs. A fifth thin sequence is faulted postdepositionally in one place by reactivation of a growth fault.

The growth faults are curved, concave up, and appear to flatten out southward in the shale of the Tschermakfjellet Formation, although how deep they extend is not known. The upper parts of the faults commonly flatten out gradually, imparting a sigmoidal shape (Fig. 6), but one fault terminates nearly vertically (Fig. 7). In cross section, faults dip at 20 to 50°; gentler dips may be the result of oblique profiles. Some faults show irregularities in dip magnitude and an en-echelon pattern in cross section. Others are accompanied by subsidiary faults, deformed stratification, and

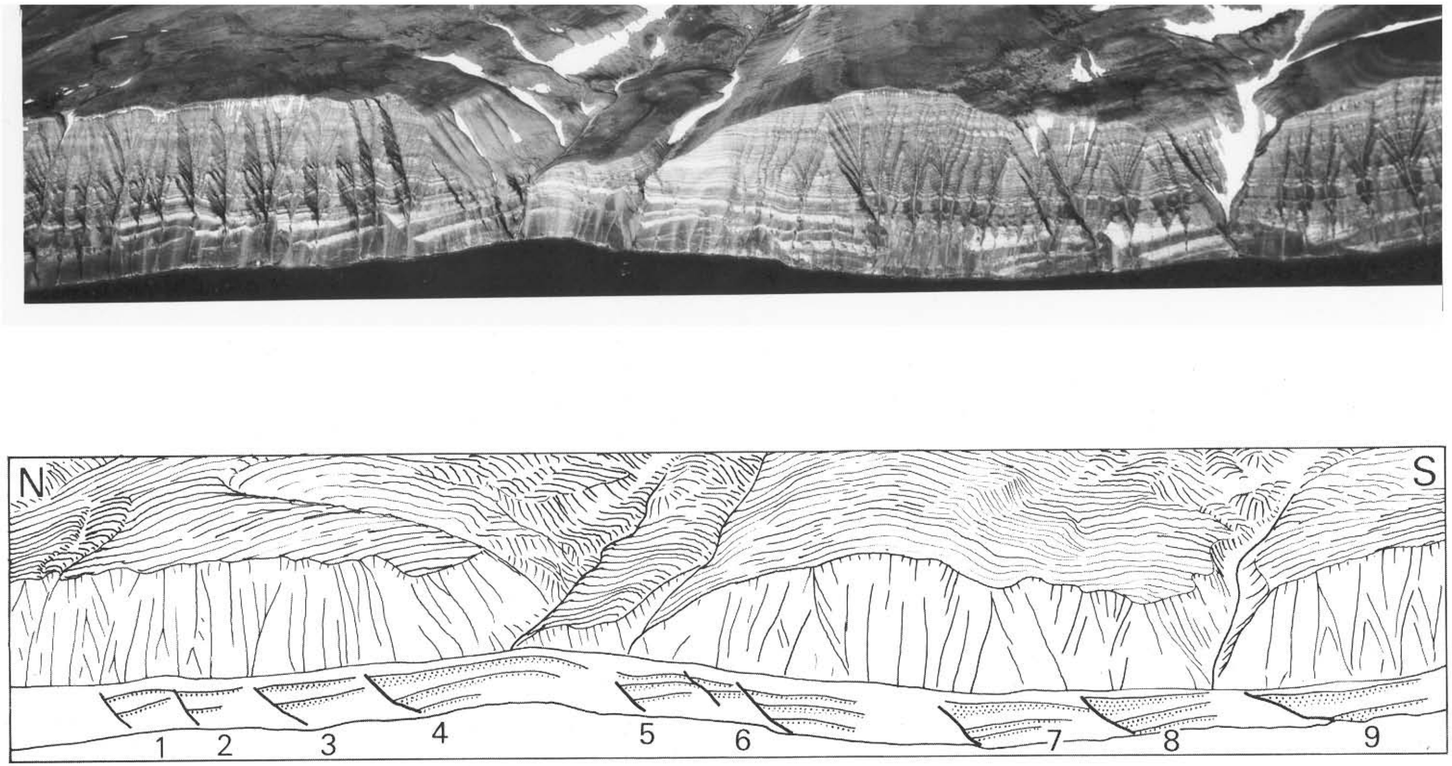


Fig. 3—Oblique aerial view and sketch of cliff at Kvalpynten, showing wedge-shaped sandstones tilted north, truncated by south-dipping growth faults which decrease in dip downward. In sketch, upper continuous line is top of fourth coarsening-upward sequence, and numbers refer to growth fault and adjacent downthrown block. Cliff is 4,200 m wide and as much as 380 m high (photo by B. Luncke, S36 3570, 1936).

Fig. 4—Sketch of structures, facies, and contacts in growth-faulted interval at Kvalpynten, based on study o photographs taken during helicopter flyby. Numbers as in Figure 3. In addition to features described in text, not antithetic growth faults, *10*.

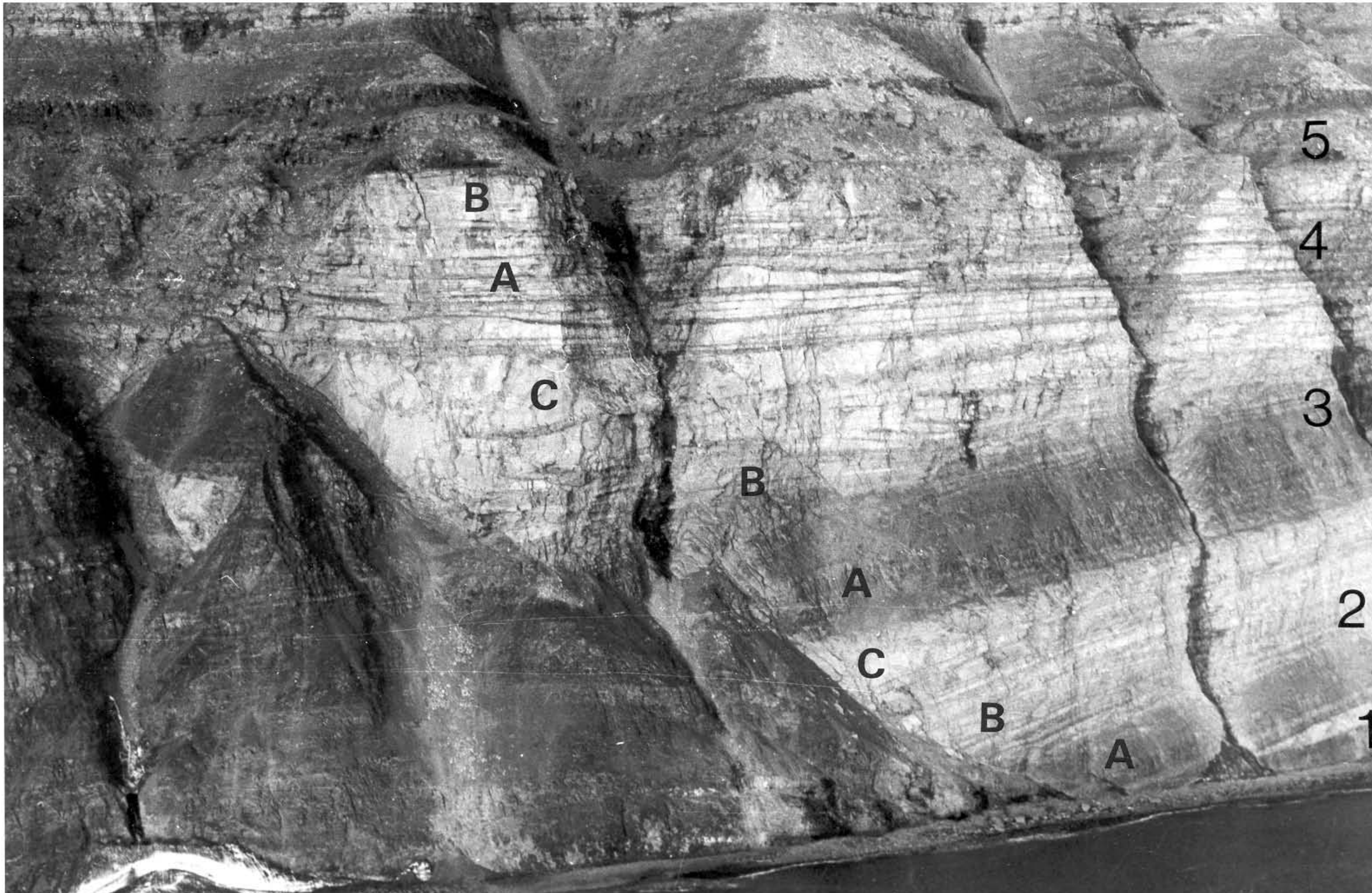


FIG. 5—Sedimentary facies in regressive coarsening-upward sequences (numbered 1 to 5 as in Fig. 4): *A*, shale; *B*, stratified sandstone; *C*, massive sandstone, forming sandstone wedges in second and third sequences adjacent to growth fault *8*. Note also large-scale cross-stratification in third sequence, and high sandstone content of shale unit of sequence *4*.

breccias. One growth fault dips toward the north (block 10, Fig. 4).

The distance between faults ranges from 260 to 860 m, and averages about 500 m, although the true strike of the faults is uncertain. Persistent southward paleocurrents parallel with the apparent dip direction of the faults and nearly ubiquitous downdip thinning of sandstone units suggest that the strike departs substantially from that of the cliff face.

In several cases, the strata of individual coarsening-upward sequences have been offset by small-scale growth faults (Figs. 4, 8).

In association with growth faults, tilting of the strata is a widespread feature. Older strata on the downthrown side of the faults dip as much as 20° north, with dips decreasing steadily upward and away from the faults. Gentle southward dips are present near the southern margin of some blocks, forming anticlinal features (rollovers; Fig. 4). A minor feature is the draping of beds (drag) along the downthrown side of growth faults (Figs. 5, 6).

Additional deformational structures include postdepositional faults which offset strata following deposition. These faults are present both in the shales at the top of the Tschermakfjellet Formation, often in association with tilting and folding, and in the overlying deltaic sequences, including one case where they are present near the crest of a rollover in fault block 4 (Fig. 4). A relatively common feature is the updoming of shale stratification just below several growth faults in the shales of the Tschermakfjellet Formation.

History of Sedimentation and Growth Faulting

Deltaic sedimentation can be divided into a prograding phase with high rates of deposition and an abandonment phase associated with reworking and minimal sedimentation (Scruton, 1960). Growth faulting occurs during progradation and produces lateral variations in sandstone thickness which may, in turn, cause corresponding variations in local rates of compaction and subsidence, as well as shale flowage. Following delta abandonment, areas underlain by thick sands will continue to subside, whereas areas with thin sands may be uplifted in a relative sense.

Whether faulting had begun during the deposition of the first sequence cannot be established, as changes in thickness of the sandstone are present in association with deformation (e.g., block 7, Fig. 4). Pronounced lateral thickness changes in the sandstones of the second and third sequences indicate that growth faulting was most active during this time.

Three factors contributing to sandstone thinning are: (1) thinning of individual sedimentation units (e.g., beds, cross-sets) controlled by lateral variations in the local subsidence rate; (2) lateral and downward termination of individual sandstone units into the underlying shale unit, a normal feature of prograding foresets, accentuated where variations exist in the subsidence rate; and (3) erosion of the upper part of the sandstone units on the south, within a fault block, apparently the result of uplift of the sediment above base level. Erosion is responsible for the southward termination of the sandstones. Southward thinning of both stratified sandstone and shale away from erosion surfaces indicates the independent effect of lateral variations in the subsidence rate, related to growth faulting (Fig. 9A).

The mutual presence of erosion surfaces and wedge-shaped massive sandstones indicates late-stage movements along the growth faults, after the main progradation of the delta. These movements led to the formation of a rising scarp protruding above base level, which provided sand to the adjacent subsiding trough below base level (Fig. 9B). These late-stage modifications suggest a high-energy environment which probably prevailed along the delta margin soon after abandonment.

Slight variations in height and thickness of the fourth sequence indicate that growth faulting virtually ceased before or during the fourth regression, although differential subsidence had continued (Fig. 9C). Thinning of this shale unit over highs on the topographic surface formed after late-stage tilting and resedimentation evidently reflects the control of irregular topography on sediment thickness. Variations in thickness of the fifth sequence are relatively minor.

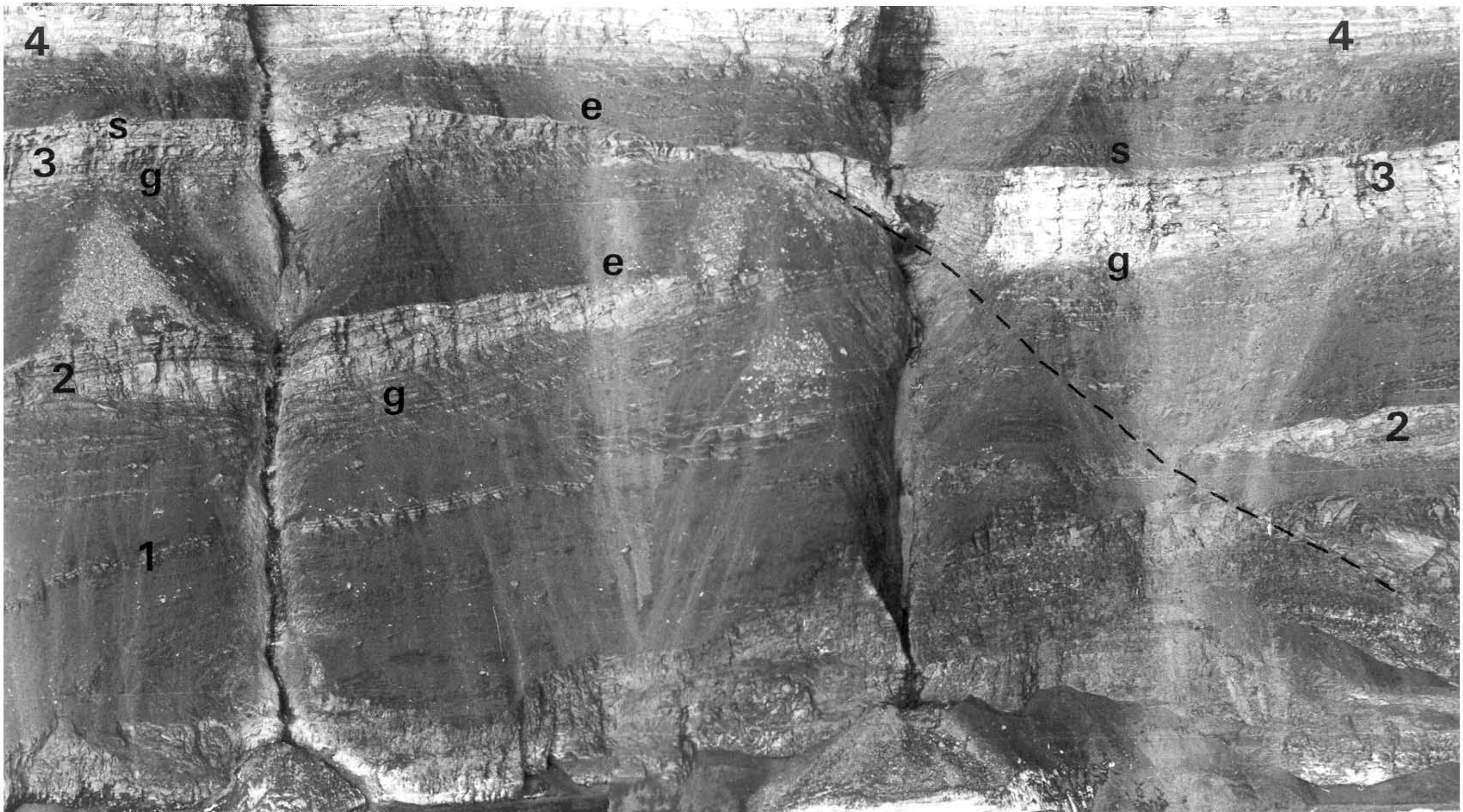
Prodelta clay (shale units) deposited on eroded sand bodies forms traps over local angular unconformities (Fig. 9C,2).

Discussion

Comparison

In common with other deltaic complexes (e.g., Short and Stäuble, 1967), the growth faults have developed in sections distinguished by coarsening-upward sequences formed during deltaic progradation. Apart from the flattening dip of the upper part of the growth faults, the overall inclination and shape are similar to those reported in other areas (e.g., Ocamb, 1961; Weber, 1971). Fault-surface irregularities are little known from the subsurface because of control spacing.

The sedimentary thicknesses affected by growth faulting and the displacements along the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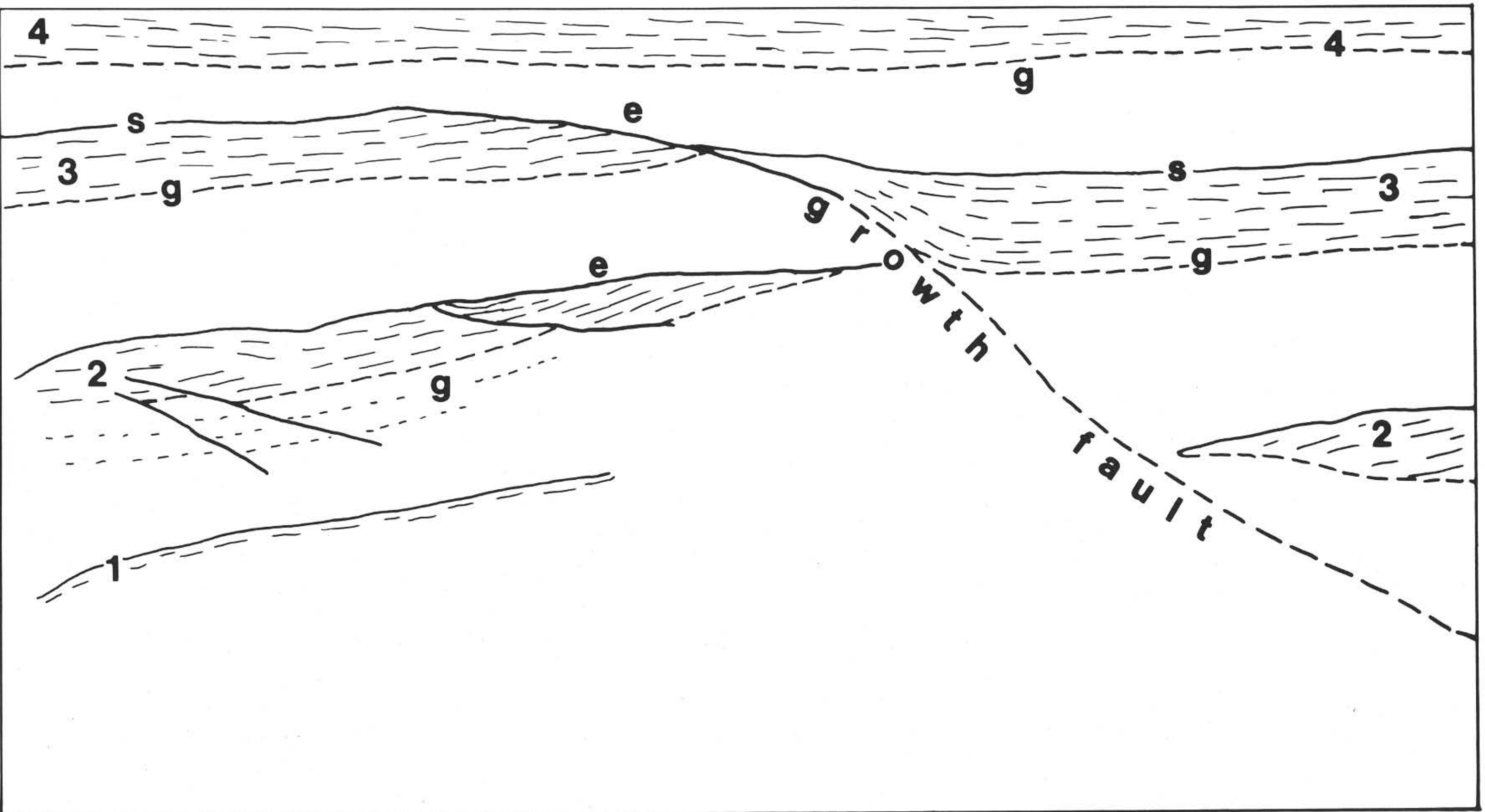

FIG. 6—Typical growth fault, *2* in Figure 4, showing decreasing dip in upper part, merging into an erosion surface *e*, which becomes a sharp contact *s* on top of third sequence. Numbers as in Figure 4, *g* = gradational contact.

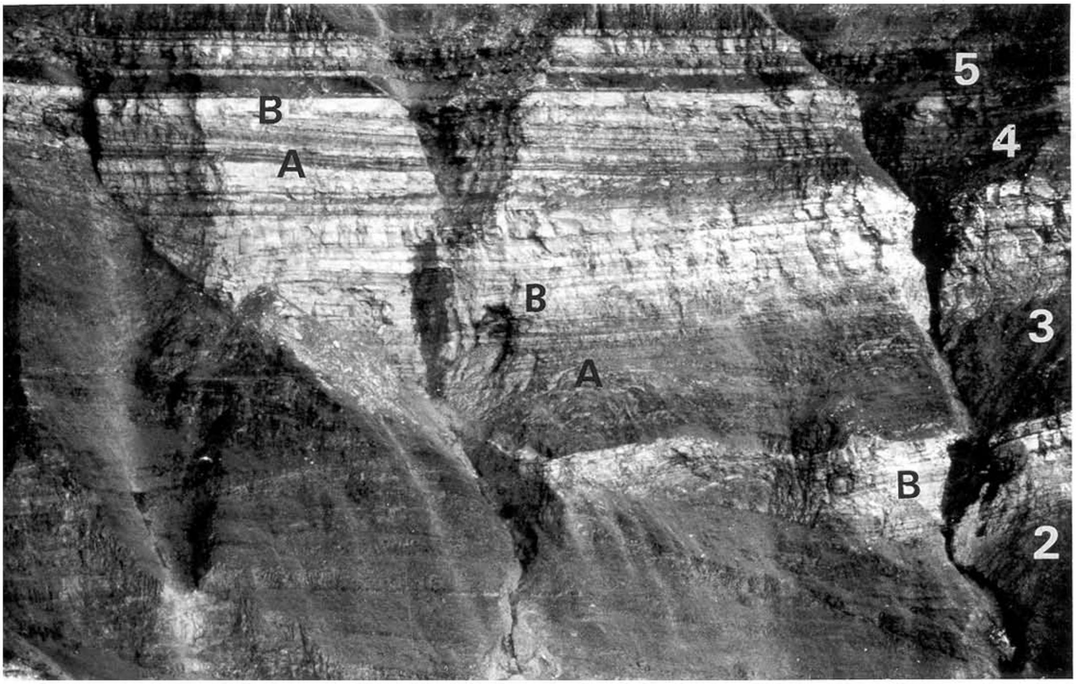

FIG. 7—Growth fault *3*, showing steep upper termination. Strata in fourth sequence are offset slightly, and fifth sequence is flexured gently. Note in sequence *4, A*, increase in sandstone across fault into downthrown block, development of sandstone interbedded with shale as large-scale cross-stratification, and dying out of sandstones away from fault further south. Numbers and letters as in Figure 5.

faults are much smaller than those reported from other deltas. In the Gulf Coast, as much as 13,000 m of sedimentary rock is offset by faults (Shelton, 1968) with throws as much as 1,500 m (Ocamb, 1961). Spacing between major faults ranges from about 2 to 10 km. In the Niger delta, as much as 3,000 m of section is involved in faulting (Weber, 1971). The Edgeoya sequence is about 120 m thick; throws along growth faults are about 50 to 75 m, and fault spacing averages approximately ½ km.

The pattern of sedimentation and growth faulting is similar to subsurface examples described by Walters (1959), Bornhauser (1960), and Ocamb (1961) where erosion occurred on the upthrown block with contemporaneous deposition on the downthrown side. According to Ocamb (1961), scarps were formed by a large initial offset with subsequent offset relatively slow and even and with net deposition on both sides of the fault. The formation of fault scarps in two phases of delta advance and retreat on Edgeoya suggests that this phenomenon was related genetically to the pattern of deltaic cyclic sedimentation.

Origin

Down-basin dipping growth faults indicate a bulk horizontal component of mass movement southward. The combined features of shale updoming below growth faults and sandstone subsidence above growth faults indicate that the relative vertical movements of these materials was a function of their density contrast.

Neither the prodelta slope (less than 1°) nor the gentler regional paleoslope is thought to be capable of leading to growth faulting. Extremely low shear strengths in the underlying shales may have developed because of excess pore-fluid pressures, generated during rapid deposition and early compaction of clay (Bruce, 1973).

On such a weak foundation, shear stresses set up in the sediments by unequal loading on the prodelta slope and regional variations in the subsidence rate may lead to failure, particularly if the sediments were affected by some kind of shock or disturbance. Ocamb (1961) has suggested the importance of microseisms in maintaining growth-fault movement. The Late Triassic regression in

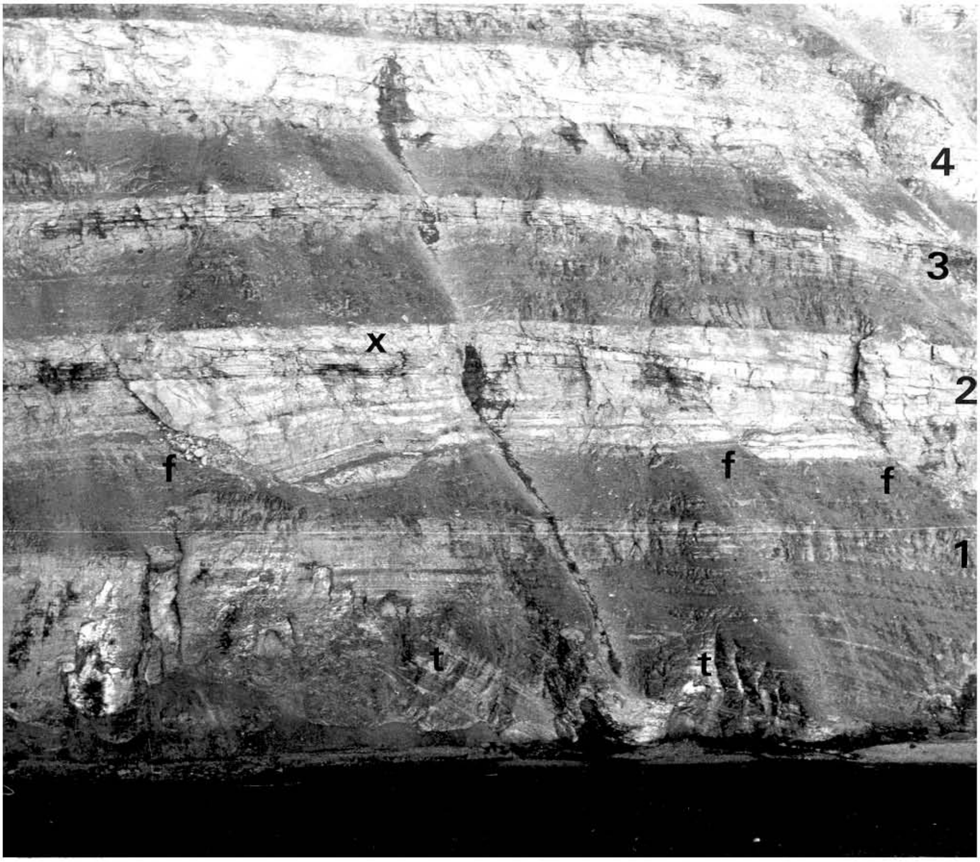

FIG. 8—Minor growth faults *f* in sequence *2,* fault block *6.* Large-scale cross-stratification *x* is developed at top of sequence. Near bottom of exposure, southward dipping shales *t* of Tschermakfjellet Formation are visible. Numbers refer to sequence.

Svalbard required the uplift of a new source area which may have been associated with some earthquake activity.

Various types of mass movements have been described from the modern Mississippi delta (Morgan et al, 1968; Coleman et al, 1974), but growth faulting has not been identified. Mass movement in the Mississippi delta involves syndepositional differential loading and diapirism, and deep-seated clay flowage, processes which apparently occurred during the Late Triassic phase of deltaic sedimentation at Edgeoya.

CONCLUSIONS

The growth faults and reservoir distribution in the Upper Triassic deltaic sedimentary rocks of Svalbard are analogous to large-scale examples from the Niger delta and the Gulf Coast Tertiary deposits.

Growth faults have not been described previously in the many sedimentologic studies of exposed ancient deltaic sequences. This could be due to scarcity, poor exposure, or confusion with tectonic faults and depositional features such as channelling and lateral facies changes.

Where growth faults cannot be observed directly, their presence may be indicated by (1) local tilting of strata compared to adjacent beds, (2) local or extensive areas of deformed prodelta shale sequences, (3) fold or fault structures not apparently related to regional tectonic trends, and (4) anomalous lateral changes in facies and thickness.

Growth faults may be distributed more widely in exposed ancient deltaic sequences than presently is considered. Evaluating the sedimentologic aspects of deltaic sequences influenced by growth faulting is important in determining both

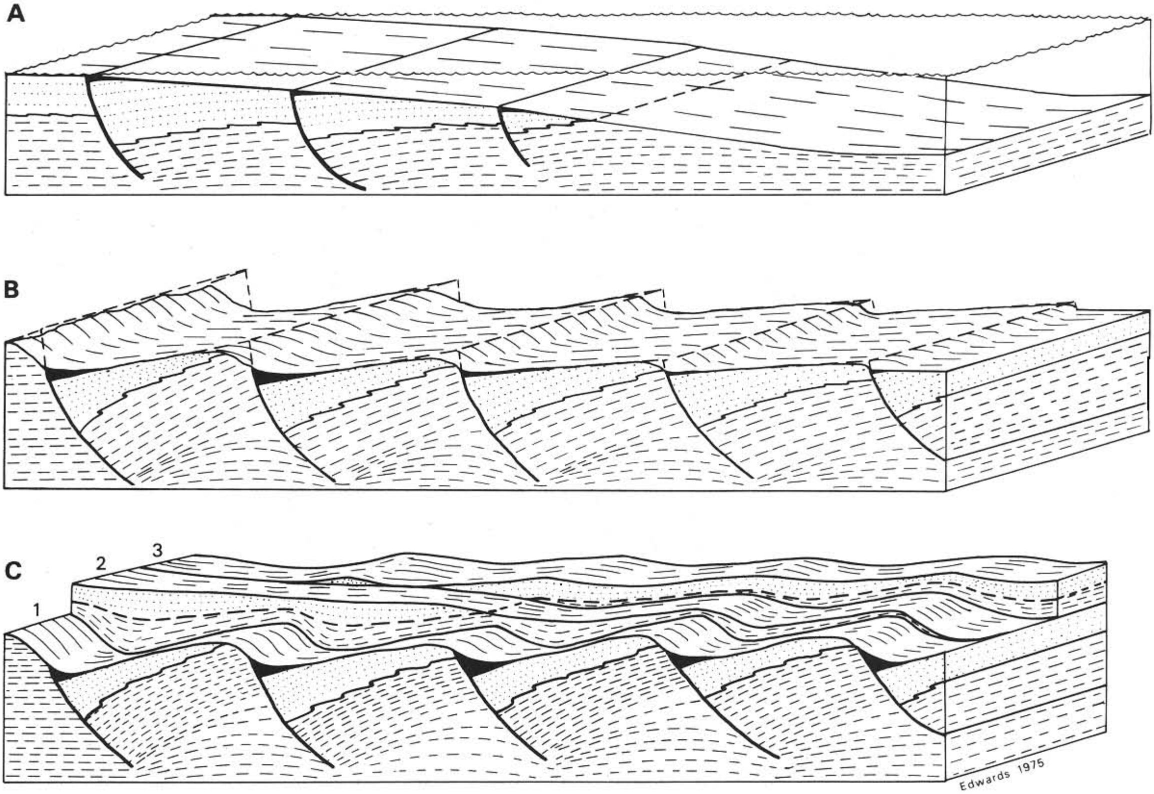

FIG. 9—Model of deltaic sedimentation during growth faulting, with some vertical exaggeration. **A**, Initiation of growth faulting during first major regression. **B**, Late-stage tilting on delta top, associated with underlying shale diapirism, forms scarps and scarp debris and erosion surfaces. Progressively less tilting is present on right toward delta margin. Black represents massive sandstone. **C**, Irregular delta top *1* is buried by prograding delta equivalent to fourth sequence *2,* which in turn is deformed by differential compaction *3.*

the features critical for the recognition of growth faulting, as well as the role of growth faulting in ancient deltaic sedimentation.

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