SEISMIC FACIES AND CLAY TECTONIC FEATURES OF THE YPRESIAN CLAY IN THE SOUTHERN NORTH SEA

by

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(with 13 figures)

ABSTRACT

High-resolution reflection seismic investigations carried out in the Southern North Sea have revealed a peculiar pattern of structural deformations in the Ieper/London clay. Many features can be correlated with land observations. As the deformations are confined to the clay body, their origin ought to be sought in the Ypresian depositional history itself.

A clue to the basic mechanism of Ypresian clay tectonics is the observation of a wave-like deformation fitting a model of a Rayleigh-Taylor gravitational instability, caused by density inversion in a self-sealing clay body. Abnormal pore fluid pressures may have contributed to the sediment flow by acting as a lubricant, decreasing the sediment shear strength. The dissipation of abnormal pore fluid pressures could have happened by a process of progressive hydraulic fracturing or locally by the development of diapiric drainage pipes over rising clay wave crests. Some brittle deformations suggest some additional processes of stress and strain evolution in such a compacting clay body.

Surface features such as diapirs piercing Quaternary palaeovalley fills and slide structures with apparent growth faulting behaviour in Quaternary times may argue in some cases for a reactivation of inherited deformations.

Key words: seismic stratigraphy, Ypresian, clay tectonics, diapirism, compaction, Rayleigh-Taylor instability.

SAMENVATTING

Door middel van hoge-resolutie reflektieseismiek werd een merkwaardig patroon van strukturele vervormingen in de Ieperse klei aan het licht gebracht. Deze vervormingen zijn nauw gebonden aan deze kleiformatie, zodat hun oorsprong naar alle waarschijnlijkheid verband houdt met de compactiegeschiedenis ervan.

De waarneming van een golfvormige struktuur in de klei kan duiden op de rol van een instabiliteit van het Rayleigh-Taylor type, ontstaan door dichtheidsinversie in een ondergecompacteerde kern. De abnormale poriëndruk (overdruk) hiermede geassocieerd moet bijgedragen hebben tot de fluïdisatie van het sediment door het sediment door verlaging van de schuifweerstand. De dissipatie van deze overdruk kan gebeurd zijn door hydraulische fracturatie van de gehele kleimassa of ook lokaal door de ontwikkeling van diapirische draineringspijpen, boven de golfkruinen. Breuken in de onderste en bovenste kleihorizonten wijzen op een bros gedrag ten gevolge van een vroege compactie.

Sommige vervormingen in de Ieperse klei kunnen gereaktiveerd geweest zijn in Kwartaire tijden, zoals blijkt uit de waarneming van kleidiapieren die in de Kwartaire opvulling van paleovalleien dringen, of nog van breuken die gedurende een zekere periode in het Kwartair doorgewerkt hebben.

Sleutelwoorden: seismische stratigrafie, Ypresien, kleitektoniek, diapirisme, compactie, Rayleigh-Taylor instabiliteit.

RESUME

Un ensemble assez remarquable de déformations de l'argile yprésienne a été mis en évidence par des profils sismiques à haute résolution. Ces déformations sont intimement liées à cette unité stratigraphique et suggèrent un lien avec l'évolution de la compaction de l'argile.

Une ondulation fort caractéristique de certains horizons porte à penser qu'une instabilité gravitationnelle du type Rayleigh-Taylor s'y est développée, probablement due à une inversion de densité par un phénomène de sous-compaction. La pression interstitielle anormale associée à cette sous-compaction peut avoir contribué à la fluidisation du sédiment en diminuant sa résistance au cisaillement. Cette pression interstitielle anormale peut s'être dissipée par fracturation hydraulique de la masse complète de l'argile, ou également localement par le développement de cheminées diapiriques au sommet des crêtes de l'onde observée. Un réseau intense de failles dans les horizons supérieur et inférieur de l'argile semble indiquer un comportement cassant dans ces couches, probablement caractérisées par une compaction précoce.

Certaines déformations de l'argile yprésienne peuvent avoir été réactivées au Quaternaire. En effet, l'on observe des diapirs d'argile pénétrant les couches de base de remblais quaternaires dans des paléovallées, ainsi que certaines failles qui en toute apparence ont fonctionné pendant un certain laps de temps au Quaternaire.

Mots-clés: stratigraphie sismique, Yprésien, tectonique des argiles, diapirisme, compaction, instabilité du type Rayleigh-Taylor.
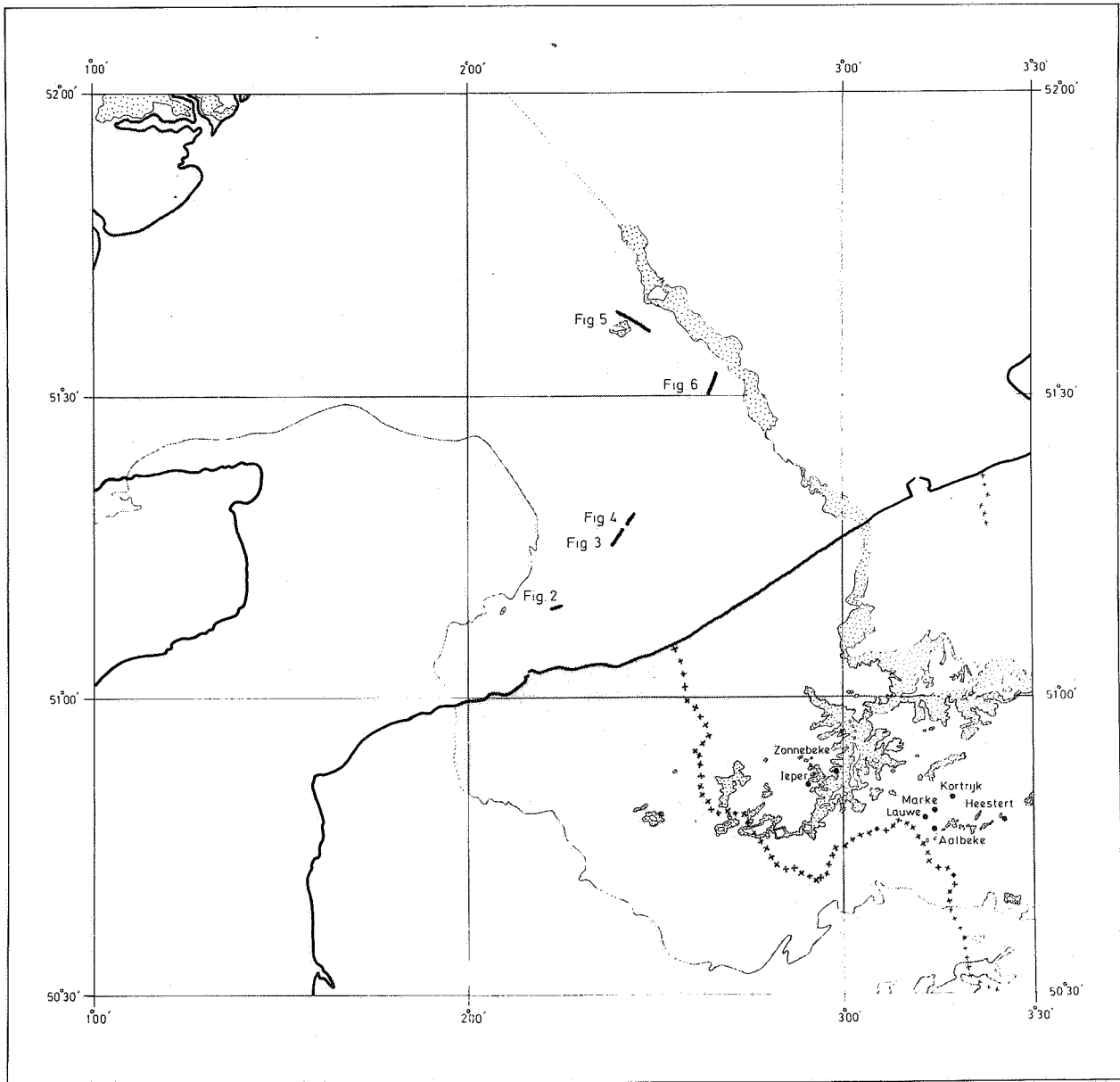
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Fig. 1
Extension of the Ieper Clay outcrops in the Southern North Sea and adjacent Belgian and British basinal areas.
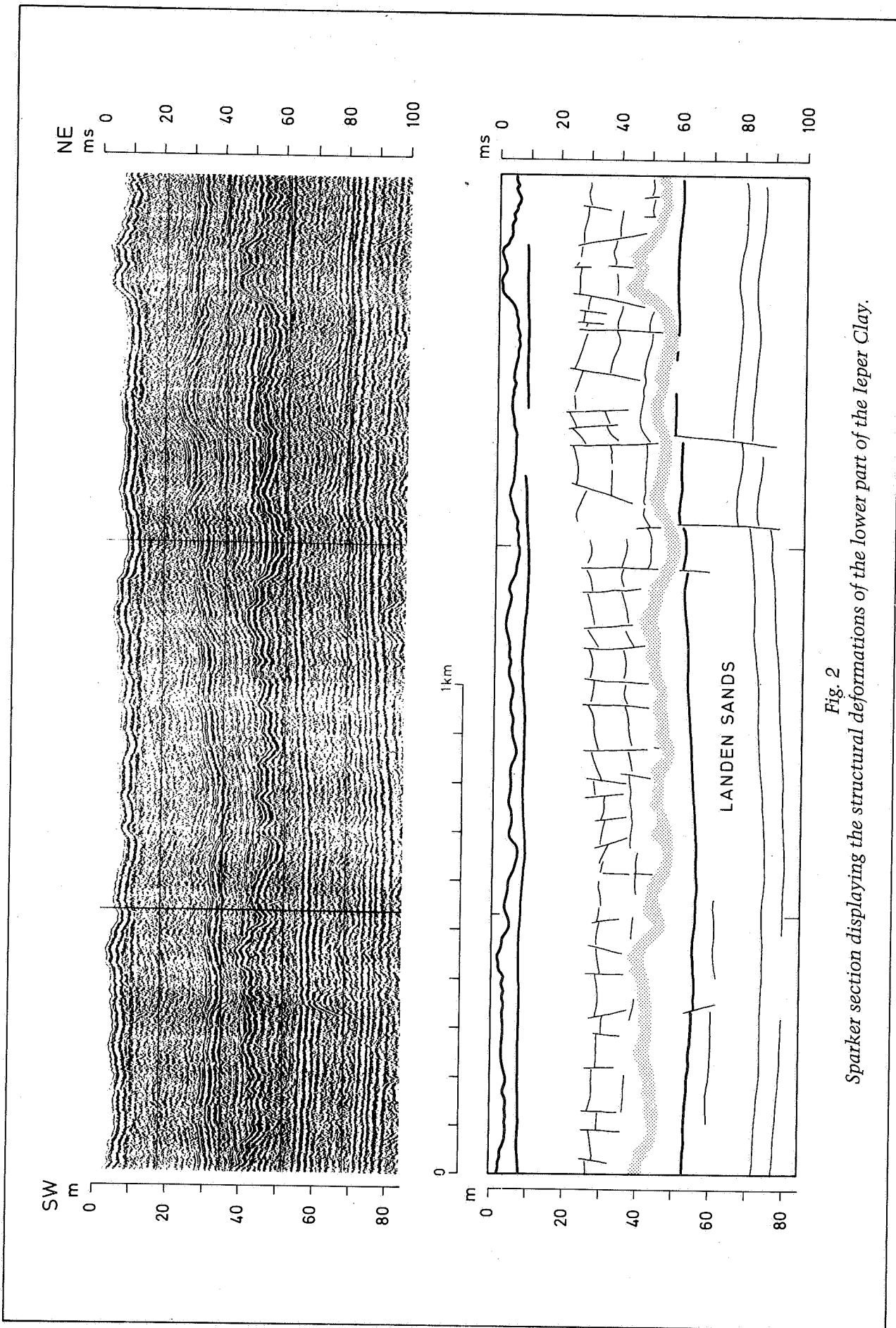
Fig. 2

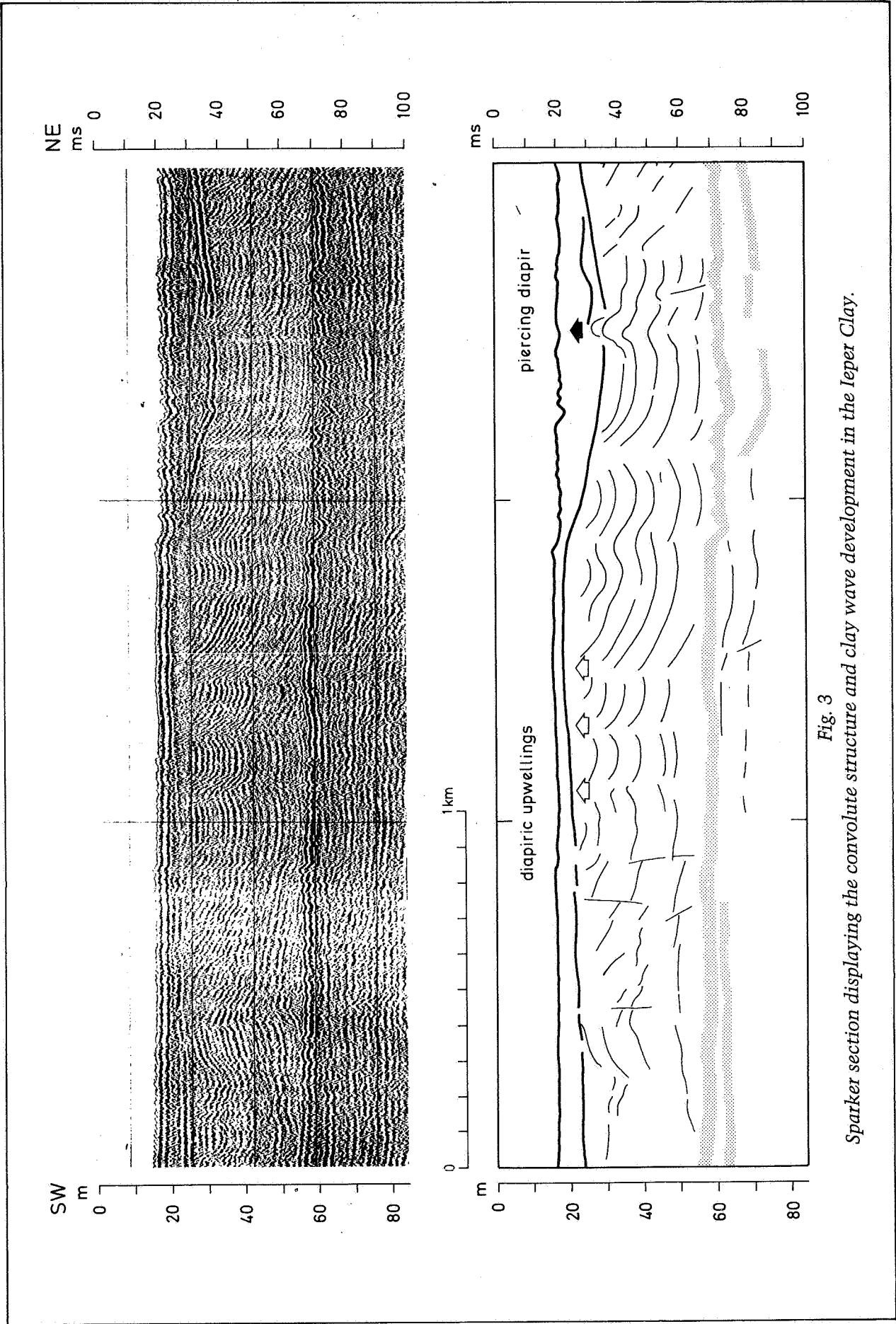*Sparker section displaying the structural deformations of the lower part of the Ieper Clay.*

Fig. 3

Sparker section displaying the convolute structure and clay wave development in the Ieper Clay.
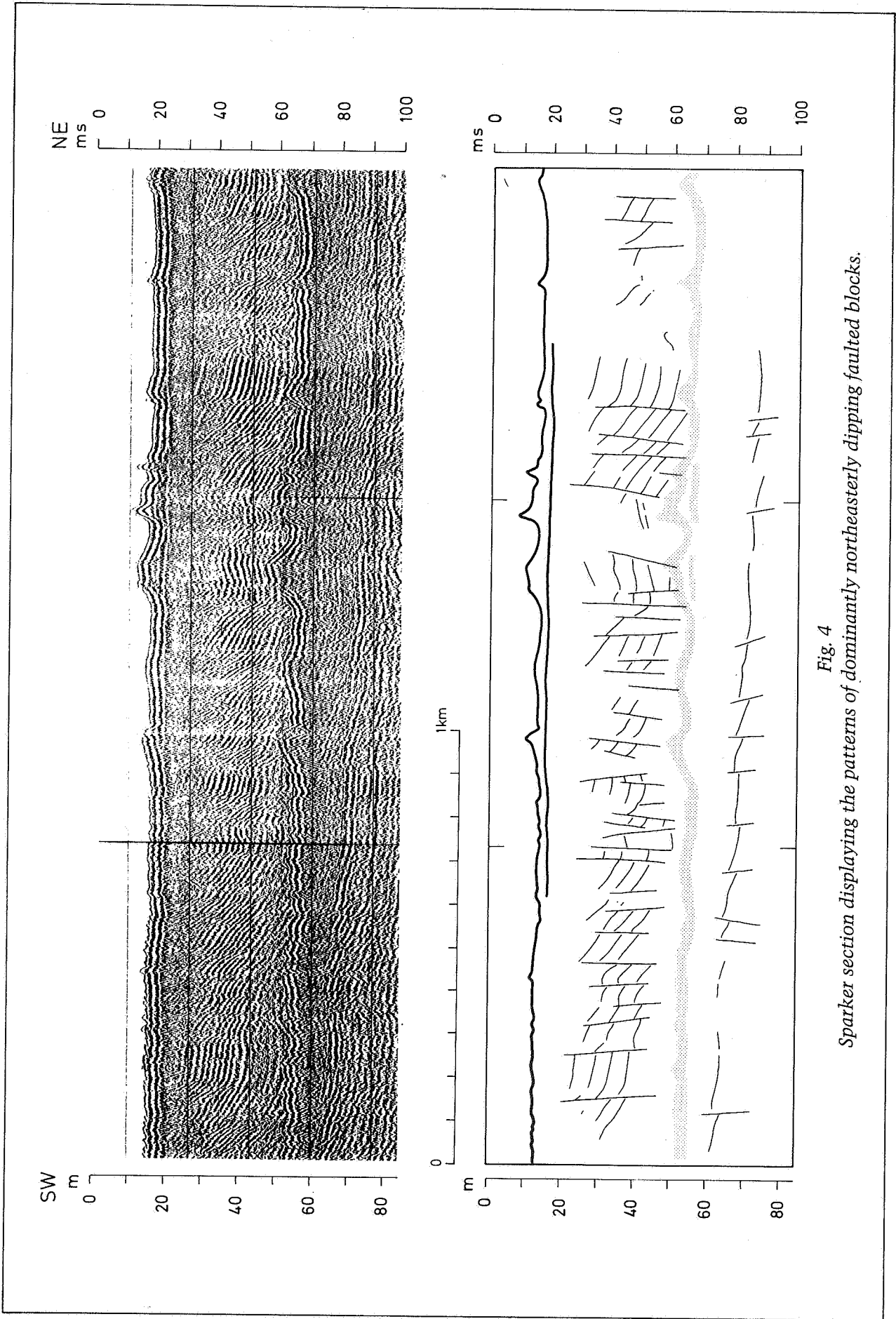
Fig. 4

Sparker section displaying the patterns of dominantly northeasterly dipping faulted blocks.
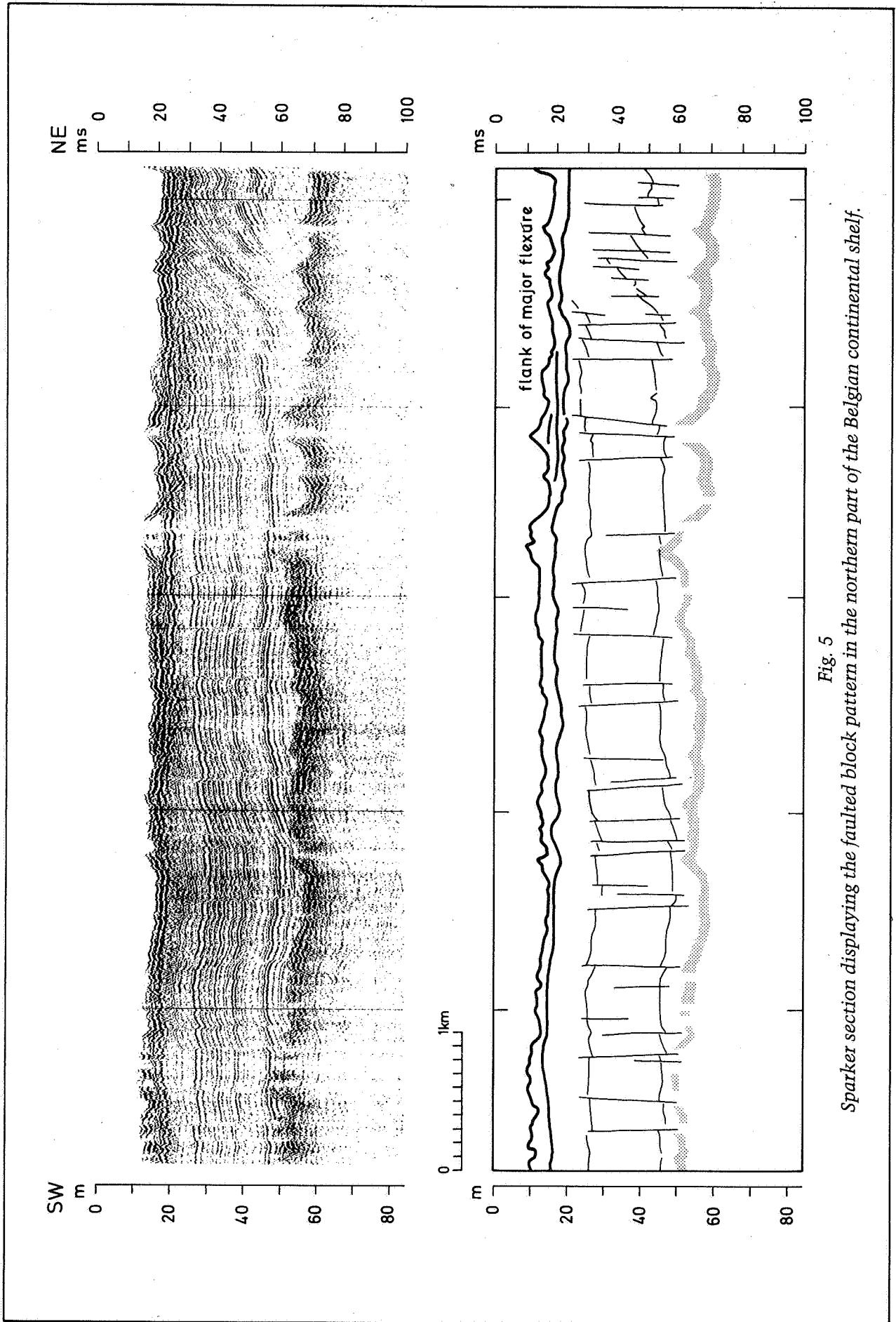
Fig. 5

Sparker section displaying the faulted block pattern in the northern part of the Belgian continental shelf.
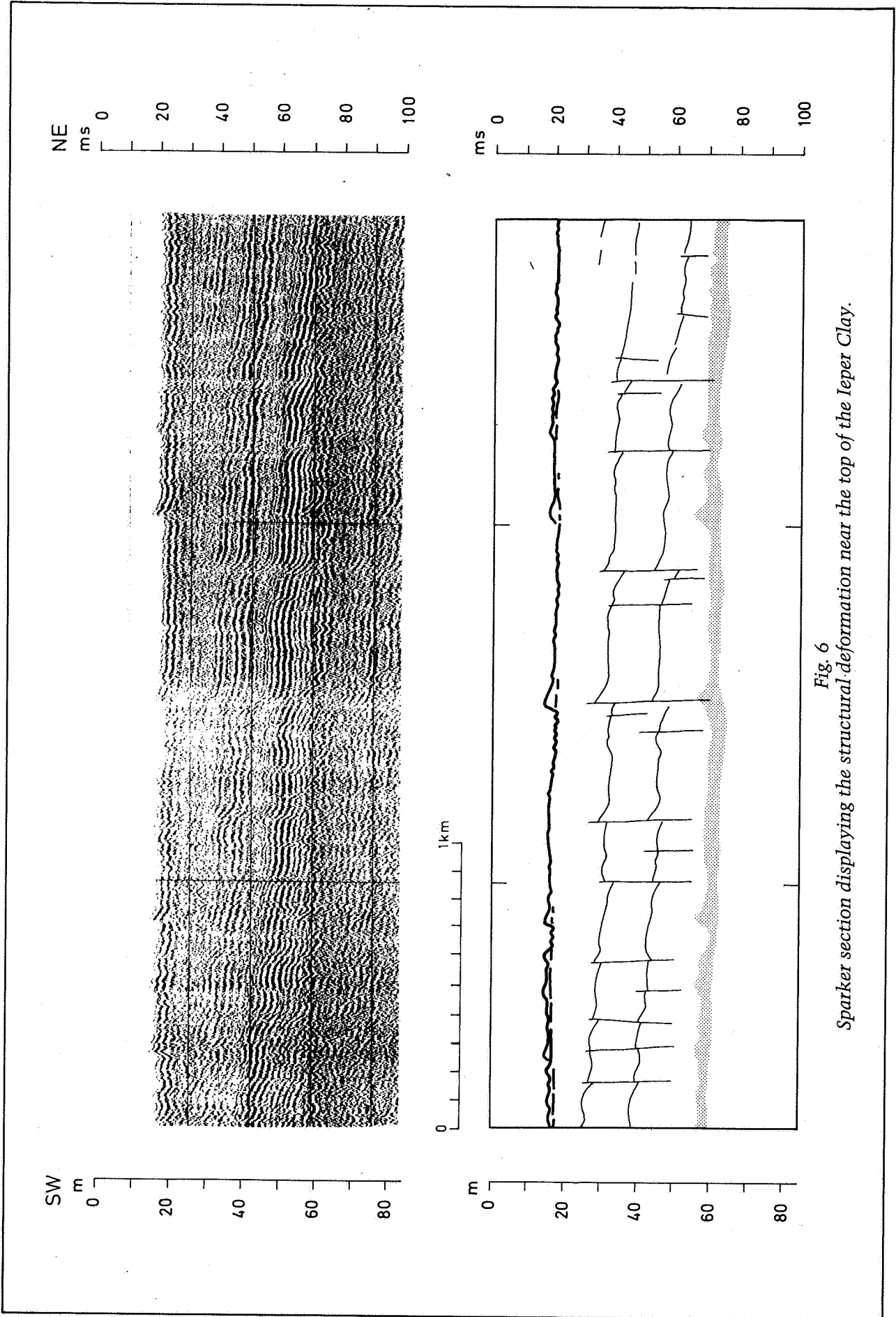
Fig. 6

Sparker section displaying the structural deformation near the top of the Ieper Clay.

INTRODUCTION

High-resolution reflection seismic investigations carried out in the past ten years in the Southern Bight of the North Sea have revealed a striking pattern of internal deformations in the Ieper or London clay.

These deformations have eluded and still do elude several seismic investigations, mainly because of a lack of strong reflectors in this clay formation. Only when seismic sources are properly tuned, in other words when the right energy is delivered in the right frequency band and when due attention is paid to pulse shaping, it is possible to observe a kind of interference composite, which represents the sum of all weak reflection responses from the many, subtle interfaces within the clay sequence. Such interference patterns closely mould the structure of the clay beds and thus reveal any deformation feature.

Deformations in the Ieper clay are widespread, having been observed all over the Southern Bight of the North Sea, from the Belgian coasts to the Thames estuary.

A striking feature is that these deformations are closely bound to the Ypresian clay: they do not affect the Palaeocene basement and fade out in the overlying Ypresian sands.

DEFORMATION STYLE

The deformation style may be different from place to place: in some areas it is chaotic, in other ones more regular, with a peculiar vertical zonation. Such a vertical zonation is illustrated by a set of four profiles (fig. 2, 3, 4, 6), shot along a southwest-northeast trending seismic track on a relatively stable part of the continental shelf (fig. 1). Owing to the gentle northeasterly dip of the Ypresian clay, successively higher horizons are brought close to the surface along such a direction, and hence within the penetration range of high-resolution seismic probing. A fifth profile (fig. 5) is situated more northly, closer to an area where basement-induced tectonics are observed, but still beyond the direct influence of such deformations.

The first profile (fig. 2) shows a lower interval in the Ieper clay, up to about 25 m above the undisturbed basal reflector, marking the Landen sands — Ieper clay boundary. Intense block faulting may be observed, with tilted and bended blocks and apparently randomly dipping fault planes. The average throw at the level of a reflector, characterized by a discrete high-frequency reflection response, amounts to about two metres.

The second profile (fig. 3) illustrates the deformation pattern in a second interval, reaching from about 25 metres up to at least 70 metres above the clay base. The movement initiated in the lower interval amplifies in upward direction and develops into a convolute sequence, consisting of a festoon-like alternation of broad, rounded synclines and narrow, cuspate anticlines.

The cuspate anticlines often develop into diapirs, one of them piercing overlying Quaternary deposits in the bottom of a buried valley (fig. 3).

The wavelength of the convolute structure varies between 200 and 300 metres along this profile, and the amplitude of these clay waves ranges from 2 to 10 metres.

Further upward in the stratigraphic sequence, the convolute structure becomes increasingly disturbed, giving way to a pattern of faulted blocks, predominantly tilting towards northeast on the considered profile (fig. 4). Further north, there is little evidence of a particular dip-related trend in this interval (fig. 5).

Approximatively at the level where the Ypresian clay should grade into the Ypresian sands, another peculiar deformation pattern is observed (fig. 6). Again some well defined reflectors are affected by faults, but the deformation consists of alternately tilting and down-warping bedding terminations, without significant tilting or displacement of the blocks themselves, between the faults. Tilting and down-warping segments associated with each fault point away from each other, in opposition with bedding deformations caused by normal drag associated with block faulting.

Although some doubt may be cast on the exact shape of a few down-warping segments, owing to a possible interference with diffractions at reflector terminations, the reality of the uplifted terminations is beyond any doubt. It thus appears that the faults and associated reversed drag have not been caused by a movement of the blocks. Our hypothesis is that bedding terminations have been dragged by some flow, propagating along the rupture planes. This idea will be developed further.

LAND EVIDENCE

Land evidence of deformations in the Ieper or London clay has been found both in England and in southwest Belgium. Furthermore, the patchwork of small tilted blocks of Ieper clay described by PAEPE (1965) in the Lys river basin in northern France might also to some extent be related to this phenomenon.

Fault planes dipping 40 to 60° have been observed in the basal interval of the London clay in the Thames basin (B. D'OLIER, personal communication). London clay diapirs piercing into Quaternary sediments in buried scour hollows, a possible analogy for the phenomenon observed on fig. 3, have been described in numerous outcrops in the London region (BERRY 1979).

Fig. 7 shows a typical example of a London clay diapir, affecting a sequence of Pleistocene sands and gravels through faulting (D'OLIER, in HENRIET e.a. 1982).

In the region of Lauwe near Kortrijk (Belgium), inclined faulted blocks have been described by MOORKENS and BRABB (1968) (fig. 8). The blocks dip about 13° north and the throw of the fault planes amounts up to 10 m. Similar faults have been observed by VAN VAERENBERGH (1987) in the "Koekelberg" quarry in Marke (fig. 9a and 9b) and in the "Kobbe" quarry in Aalbeke, near Lauwe. One of the faults in the latter quarry has a typical listric shape (fig. 10) and bears witness of activity in Quaternary times, as shown by the wedge-

shaped Quaternary fill deposits on top of the downthrow side. This suggests a possible development of a pre-existing fault into a slide with growth faulting character during Quaternary times.

STEURBAUT and NOLF (1986) reported faults with a throw of more than 10 m in a clay pit in Zonnebeke (fig. 11). Further observations of faults in the Ieper clay have been made by GEETS (unpublished), LINSTER (1975) and VAN VAERENBERGH (1987).

Many of the fault patterns described in southwest Belgium are located in the upper Roubaix Clay Member or lower Aalbeke Clay Member (stratigraphic terminology in accordance with STEURBAUT and NOLF, 1986), i.e. in the middle to upper part of the Ieper clay sequence. They might thus be correlated with the tilted block structures, shown on the seismogram of fig. 4.

One general remark should be made regarding the visual observation of faults on clay outcrops. This often proves as elusive as the observation with seismic techniques, due to the fact that colour gradings of clay beds, which facilitate the visual observation of deformation patterns, are strongly controlled by the degree of humidity of the clay wall and thus subject to seasonal variations.
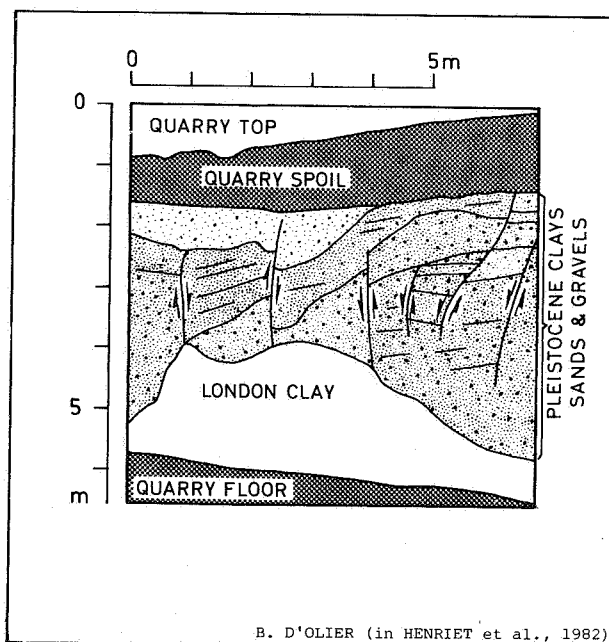

Fig. 7
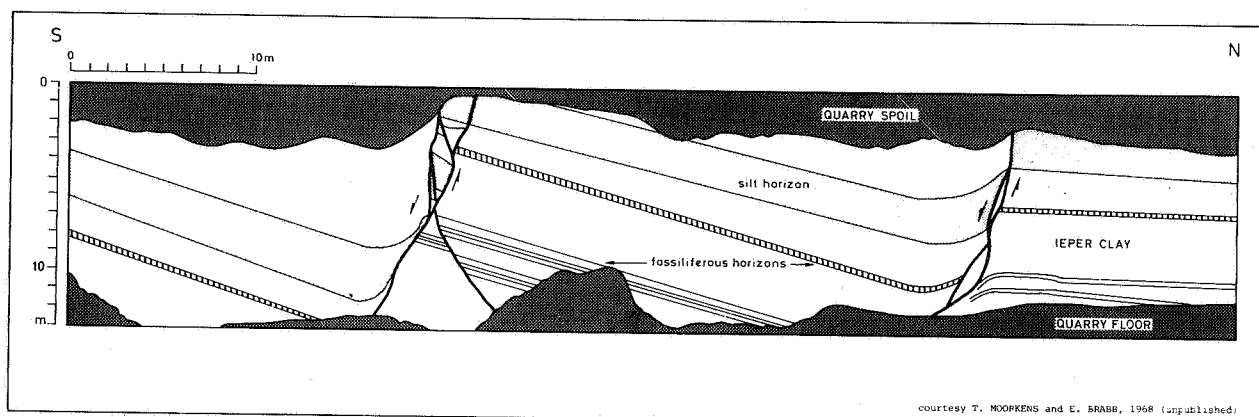*London Clay diapir at Woodham Walter (Essex, England).*

Fig. 8
Faulted blocks in the Ieper Clay, observed at Lauwe (West Flanders, Belgium).

GENETIC MODEL

The observation of such peculiar deformation patterns deserves an interpretation, a genetic model.

Clay tectonic deformations have often been associated with differential loading. This idea has been supported for instance by the observation of diapiric intrusions under prograding delta deposits (e.g. MORGAN e.a. 1968) and by model studies (RETTGER 1935). In Scandinavian countries, well developed clay tectonic features have been explained by most authors in terms of differential loading by prograding Quaternary ice sheets.

It is true that obliquely prograding sediments of probably Upper Ypresian or Lutetian age are locally found on top of the Ypresian clay off the eastern Belgian coast. Due to this local character however, they could hardly account for deformations with such a regional extent.

As to the hypothesis of a glacial origin, although some authors (e.g. KELLAWAY e.a. 1975) have argued for Quaternary ice advances down to the Channel, most Quaternary geologists stay reluctant to this idea. Anyhow, it is difficult to conceive how an advancing ice sheet could have induced the quasi-stratigraphically bound zonation of deformation patterns, observed in the dipping section of the Ieper clay.

If we further neglect for the time being some possible local, basement-induced tectonic influences and also the evidence of activity of some local structures in Quaternary times, it is clear that the origin of the bulk of the deformations, bound to the Ieper clay, ought to be explained in terms of the Ypresian depositional history itself.
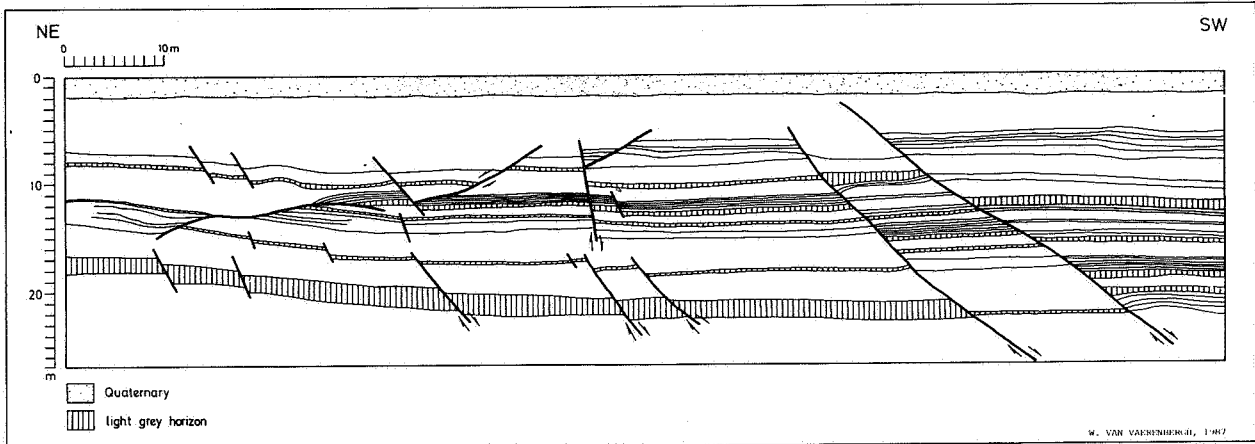
Fig. 9a
Faults in the "Koekelberg" quarry, Marke.

Fig. 9b
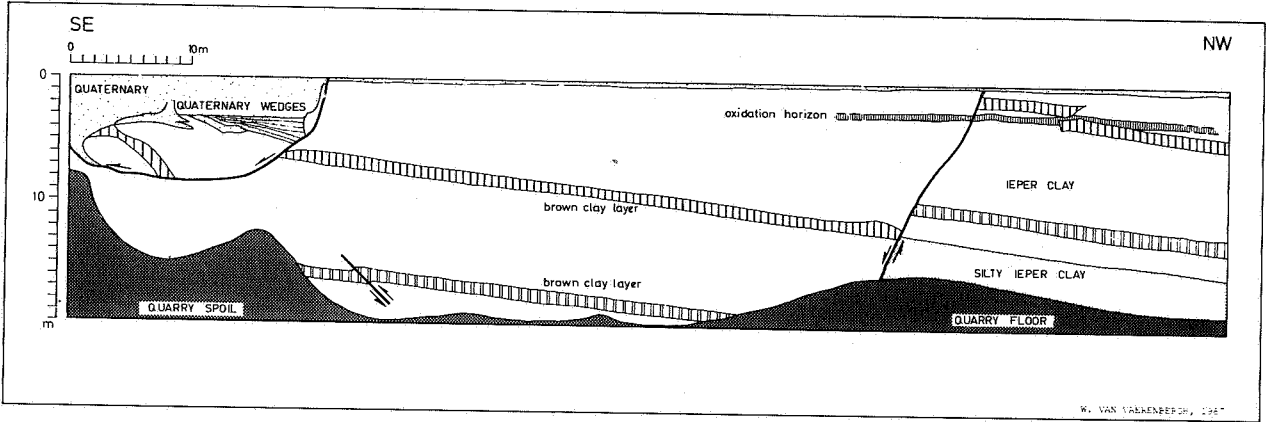Faults in the "Koekelberg" quarry, Marke,
photographic detail.

Fig. 10
Faults in the Ieper Clay observed in the "Kobbe"
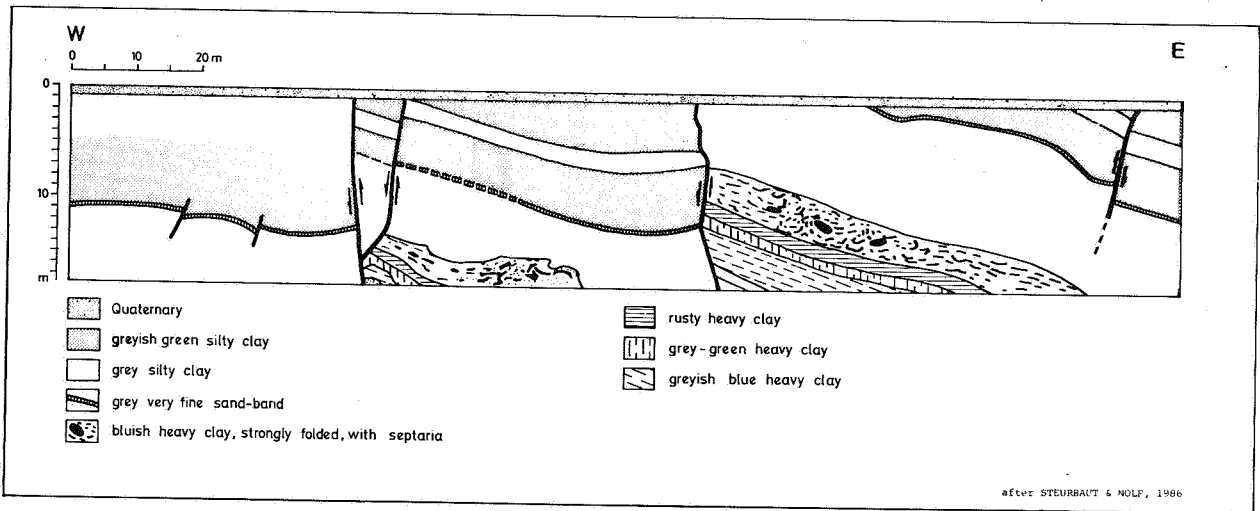*quarry at Aalbeke (West Flanders, Belgium).*

Fig. 11
Normal and inverse faulting in the "Van Biervliet"
clay pit in Zonnebeke.

a

b ↑h

c ↑h

ρ(Mg/m³)

ρ(Mg/m³)

LANDENIAN
SAND DEPOSITION

d ↑h

e ↑h

f ↑h

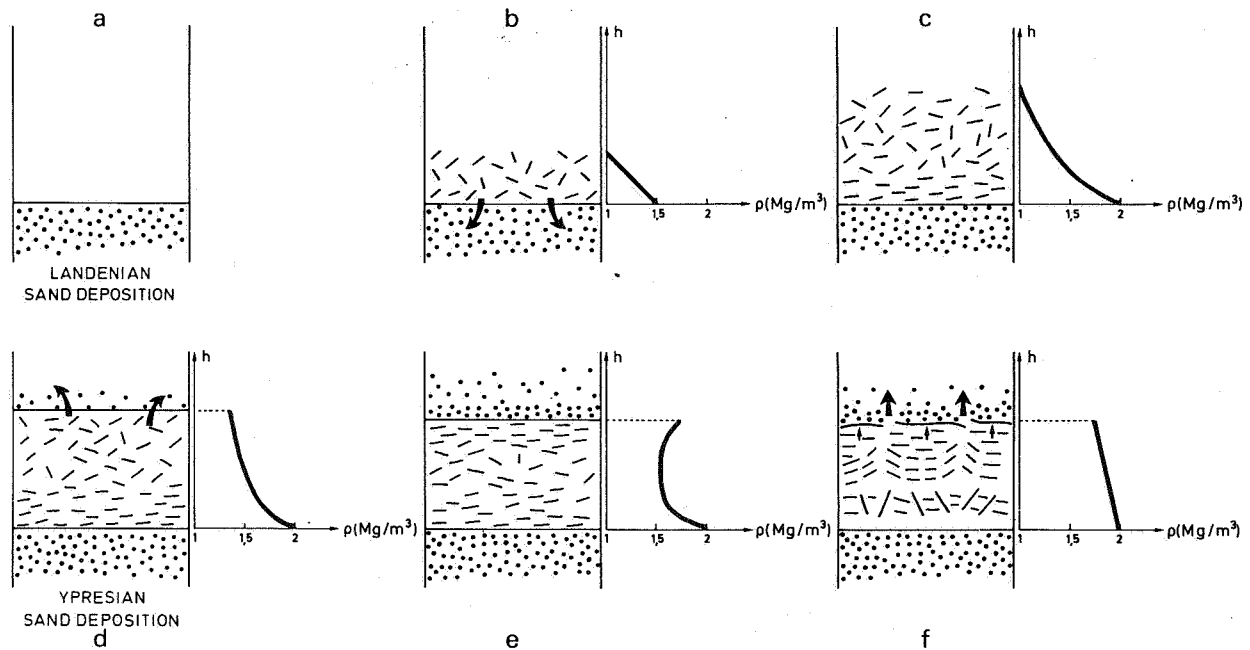ρ(Mg/m³)

ρ(Mg/m³)

ρ(Mg/m³)

YPRESIAN
SAND DEPOSITION

Fig. 12
Compaction model of the Ieper Clay.

A simple compaction model (fig. 12) might help to understand the dynamics involved.

Ypresian clays have been deposited as loose, high-porosity, water-logged muds. As sedimentation progressed and the thickness of the clay deposits increased, gradual compaction occurred, reducing pore space through the expulsion of pore water.

As long as a sediment mass can be freely drained, pore water pressure remains hydrostatic, which means that it balances the weight of the water column only. In such a situation, the interparticle contacts carry the full increase of the submerged sediment weight (the lithostatic stress).

Pore water drainage was probably maximal near the base, both due to the maximal overburden weight tending to reduce pore space and to the presence of a permeable sand substratum, the Landen sands, providing an easy path for water expelled from the base layers of the clay (fig. 12b).

The relatively quickly drained basal clay beds could thereby suffer a faster rate of compaction, soon building a permeability barrier which impeded further drainage of the clay mass through the Landen sands. The increase of compaction with depth near the clay base also involves a density gradient, schematically shown on fig. 12c.

One can imagine that a similar phenomenon may have occurred at the top of the Ieper clay sequence, when clay sedimentation gave way to the settlement of more dense sand deposits. Indeed, the provision of a permeable top layer offered a possibility of fast drainage of pore water from the top of the clay (fig. 12d). This implies that the clay could start to compact from the top down, in addition to the compaction from the bottom up.

Through this mechanism, the Ieper clay may have sealed itself, which has two major and related effects:

(1) as water has a very low compressibility, the sealed part of the clay remained undercompacted for a certain time, which means that it had a lower density than its overburden of compacted clays and sands; in other words, a density inversion was created (fig. 12e), which is a gravitationally unstable situation;

(2) as soon as drainage gets impeded in some part of the clay body and sedimentation goes on, locked pore water suffers an increased pressure due to the fact that it has to bear part of the weight of the overburden; this means that pore water pressure increases from its original hydrostatic gradient towards the lithostatic gradient, giving rise to a so-called overpressurized situation. An increase in pore pressure will proportionally decrease the effective normal stress acting on the interparticle contacts, thus decreasing the shear strength of the sediment.

Both mechanisms, jointly, may be regarded as the main agents in the development of clay tectonic deformations like those observed in the Ypresian clay. The gravitational instability may be considered as the motor, which drove the sediment flow, while the overpressurized pore water could act as a lubricant, decreasing the shear resistance at the level of the grain contacts.

RAYLEIGH-TAYLOR INSTABILITY

A clue for the role of a gravitational instability is the observation of the clay wave (fig. 3). This wave shape fits the model of a deformation of an
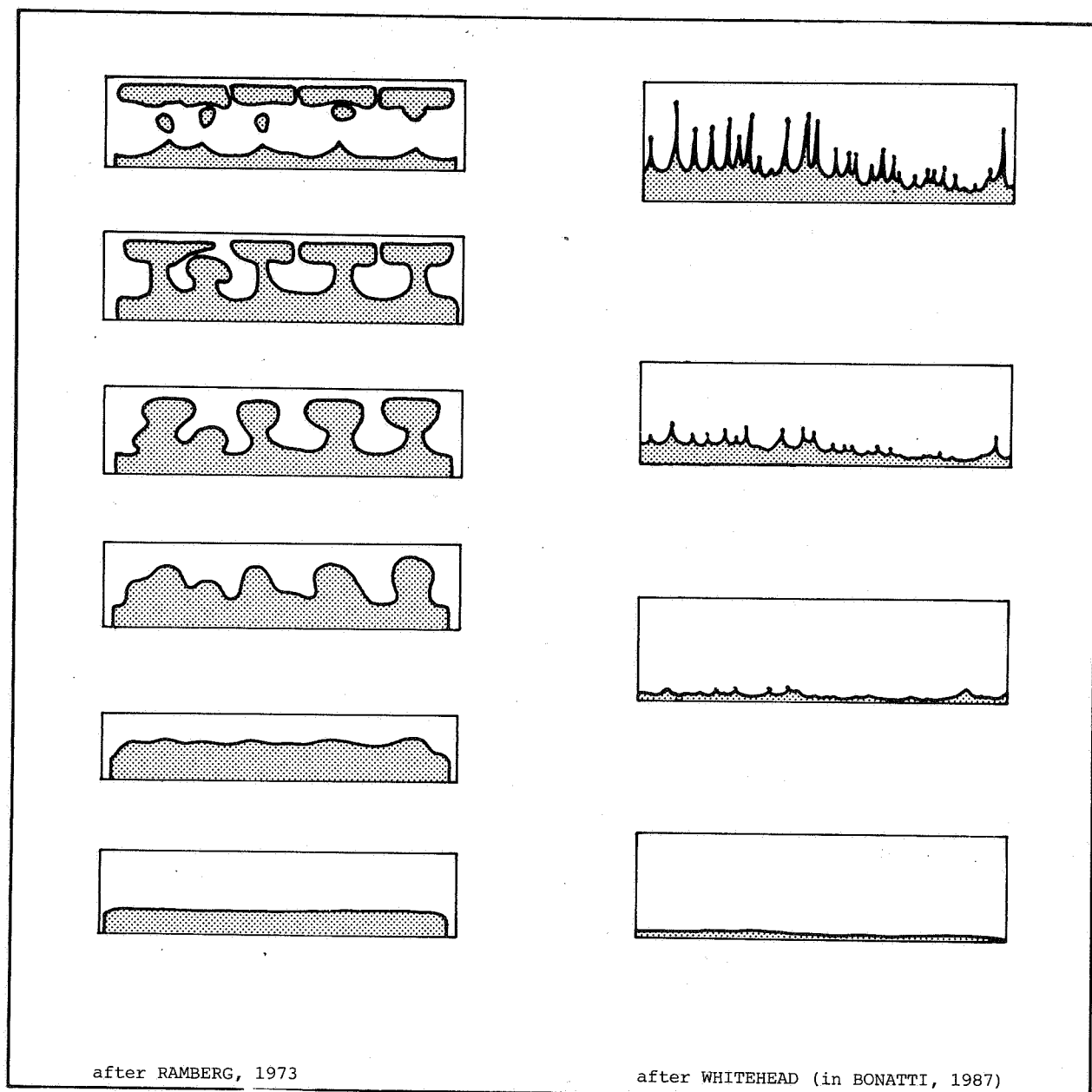
after RAMBERG, 1973

after WHITEHEAD (in BONATTI, 1987)

Fig. 13
Physical models of the development
of a Rayleigh-Taylor instability.

interface between two viscous fluids with different densities and viscosities, when the denser fluid is overlying the lighter one. Such a model is known in fluid dynamics as a Rayleigh-Taylor-type instability. The concept of the development of Rayleigh-Taylor instabilities has already successfully been applied to various geological problems such as salt tectonics (TURCOTTE & SCHUBERT 1982), diapirism in orogenic belts (RAMBERG 1968, 1972, 1973) or upwelling of magmatic material along island arcs and oceanic spreading zones (e.g. BONATTI 1985, 1987).

The Rayleigh-Taylor theory predicts that the interface between a high-density upper layer and a layer below with lower density (and possibly lower viscosity) will develop a sinusoidal instability that may evolve into a pattern of regularly spaced upwellings of the lower density fluid into the denser layer.

Theoretical results have been verified with analog models. RAMBERG (1973) used a centrifuge technique to investigate gravity-driven deformations of layer cakes in which higher density viscous fluids (syrup, oil, wax, painter's putty, plasticine) were overlying lighter fluids. More recently, WHITEHEAD (e.g. in BONATTI 1987) has been experimenting by injecting a mixture of water and glycerine into a bath of pure glycerine. Results of both RAMBERG's and WHITEHEAD's experiments are schematically drawn on fig. 13.

The spacing or wavelength of the instability is related to the ratio of the thicknesses of the upper

and lower layers and the ratio of their viscosities. It has been shown by TURCOTTE and SCHUBERT (1982) that in a simplified two-layer model where both layers do not significantly differ neither in thickness nor in viscosity, the wavelength of the interface deformation amounts to about 2.5 times the layer thickness. This is the wavelength that gives the shortest time constant and hence dominates the growth of the instability.

In a first approximation, the observed spacing of some 200 m between the upwellings in the Ypresian clay (fig. 3) is in good agreement with the above ratio, when a model is assumed with a layer thickness of about 70 m (half the total thickness of the clay).

When applying such a model to the Ypresian clay tectonic development, one should stay aware of the simplifications involved. For instance there are few arguments for postulating a true interface in a sequence which was most probably characterized by compaction gradients. However, in the authors opinion, these simplifications do not detract from the proposed model's conceptual value.

BASAL DEFORMATIONS

If the clay wave observed apparently could find a satisfactory explanation in a Rayleigh-Taylor-type instability model, the deformations of apparently pure brittle character, observed both below and above the wavy interval remain to be explained.

The faults in the lower clay interval (fig. 2) may be interpreted either independently, or as associated features of the main clay wave growth in the overlying unit. When these deformations are viewed as independent features, having developed prior to the growth of the clay wave phenomenon, two possible mechanisms could be taken into consideration.

One might be a simple process of sliding, caused by gravity pull on minor slopes, possibly related to differential compaction and draping over irregularities of the basal erosion surface. The influence of a regional slope effect should at this level be discarded, considering the apparently random orientation of fault planes. Sliding processes on very gentle slopes have been well documented by CRANS e.a. (1980). They could initiate in thin sediment stacks, already long before the above proposed phenomenon of self-sealing of the overlying clay mass occurred.

However, attention should also be paid to a simple model of stress evolution in fine-grained sediments, subject to a growing overburden weight. The mere increase in vertical load by continuous sedimentation generates in a sediment an increase in vertical compressional stress, with which the increase in horizontal stress will usually not keep pace. When viewed in terms of deviatoric stresses, a state of stress is thus created with horizontal components of extensional nature. In sediments with a low degree of cohesion, the slightest form of such

a stress state might already generate steep, normal faults, in accordance with Anderson's fault theory. The normal faults frequently observed in fine-grained pyroclastic or fluvio-glacial deposits may be caused by such a simple mechanism. Subsequent flattening of such faults in a clay sediment by progressive compaction cannot be ruled out.

When analysing the basal fault development, it may however be unjustified to overlook the possible role of the clay wave growth, which occurred in the overlying layers in later times. Any viscous flow in the central part of the clay body should indeed have exerted a drag on its basal boundary layer. Whereas the prime clay wave deformation could have been of plastic nature, the underlying more compacted beds should have behaved rather as a brittle unit, subject to fracturing. If not regarded as the prime agent in fault development in the basal horizon, the clay wave growth might at least be considered as responsible for a reactivation of pre-existing faults. In such a hypothesis, one might expect both normal reactivations under a tensional regime below the deepening, broad synclines, as well as inverse reactivations under a regime of horizontal compression, below the anticlinal axes of upwelling.

ROOF DEFORMATIONS

The deformations observed above the convolute horizon are again of truly brittle nature, argueing for a late development in already partly consolidated layers.

Two deformation styles have been identified in the upper Ypresian clay sequence: a regular block faulting (fig. 5), sometimes displaying a pronounced northeasterly dipping trend (fig. 4), and an upper deformation style with inverse drag features along quasi vertical fracture planes (fig. 6).

The block faulting directly above the convolute horizon might be a direct effect of a basal drag, exerted by the flow of the underlying sediment. Again both horizontal extensional and compressional deviatoric stress components might be expected. This time however normal slide structures caused by extensional stresses should be associated with upwelling crests, while thrust faults related to compressional stress components might be expected above the deepening synclinal troughs. The remarkable coexistence of normal and inverse faults observed in clay pits in Zonnebeke and Aalbeke might reflect such a close proximity of both extensional and compressional stress fields, associated with the growth of an underlying disturbance of sinusoidal shape. If the faults had been caused by a regional tectonic stress field, their nature would have been more homogeneously extensive (normal faults) or compressive (inverse faults). However, the northeasterly dip trend observed in fields of faulted blocks over vast areas of the Belgian continental shelf might nevertheless argue for some influence of a regional slope solicitation at the moment of fault initiation.

Finally, the fractures in the upper interval, characterized by inverse drag features on bedding

limbs on either side of the faults, deserve some special attention. On seismograms like the one displayed on fig. 6, a smooth envelope could be drawn through the fractured horizons, thus bearing witness of the absence of true block rotations or vertical translations. In a way, it appears as if the uplifted bedding terminations have been dragged by a rising flow, propagating along the rupture planes. The associated down-warpings might then represent collapse structures due to mass withdrawal. The distinct polarity of these deformations, all collapsed bedding terminations being on the same side of the faults, might again reflect the influence of an external, regional (dip?) constraint.

Although the penetration limits of the high-resolution reflection method did not allow to verify the direct superposition of such fractures and underlying upwellings, these fractures are nevertheless in this hypothesis regarded as the possible upper expression of drainage paths of excess pore water from underlying overpressure horizons.

RELAXATION OF THE CLAY DYNAMICS

Clay dynamic processes are intrinsically of transitory nature. They find their origin in delayed compaction of a clay body and terminate when conditions of hydrostatic pressure in the pore fluid are restored, either by slow seepage or by fracturation of the permeability barriers.

In the Ypresian clay, the relaxation of abnormal pore pressures may locally have taken catastrophic forms, above the rising wave crests. Such crests could indeed develop into diapiric ridges and drainage chimneys, through which a flow of excess pore water and mud searched its way towards the surface, fracturing and dragging on its way overlying, more consolidated and brittle horizons. The observation of clay breccias in Ieper clay cores in deep borings in northern Belgium (VANDENBERGHE 1980, personal communication) might support this idea. Such Ieper clay breccias could thus have a similar origin as mud volcano breccias, observed in deltaic environments (e.g. Mississippi delta).

The flow of excess pore water into the overlying permeable beds heralded the normal consolidation of the central part of the clay body and thereby the desactivation of the gravitational instability, freezing the incipient clay wave into the shape nowadays observed on seismograms.

An evaluation of the time period elapsed between the initiation of the instability (sealing of the clay body) and its desactivation (marked by the flattening of deformations in overlying strata) suggests a possible time window of about 2 million years. LEYMAN (1987) calculated that the development of a Rayleigh-Taylor instability with a wave amplitude of 10m, in a two-layered Ypresian clay model with a density contrast of $0.1\,Mg/m^3$, would request an average viscosity of about 10^{16} Pa.s, a few orders of magnitude lower than for instance values for salt (10^{18} Pa.s, TURCOTTE and SCHUBERT 1982). A careful timing of such clay

tectonic events may thus yield sediment viscosity values, of particular importance in rheologic studies of sedimentary basins.

The above hypothesis of catastrophic relaxation of abnormal pore pressures through clay diapirism should in the authors' opinion however not be considered as the unique mechanism of overpressure dissipation in the Ypresian clay. A large amount, if not the major component of overpressure dissipation probably happened through a mechanism of progressive microfracturing of the clay. The intense fissuration of the Ieper clay and of the London clay has already been described by various authors (e.g. DE BEER 1979, FOOKES & PARRISH 1969, SKEMPTON e.a. 1969), but a satisfactory explanation has hitherto not been advanced. Considering the role played by abnormal pressures in the origin of the major clay tectonic deformations, there are good reasons to believe that the general fissuration of the Ieper clay is also a direct result of such overpressures in the pore fluid, through the well-known process of hydraulic fracturing.

Progressive microfracturing may possibly be regarded as a major factor in the dewatering process of the bulk of the overpressured Ieper clay. The diapiric drainage chimneys observed in the Ieper clay should rather be regarded as singularities, which locally induced a faster, catastrophic drainage.

CLAY TECTONICS IN QUATERNARY TIMES

Different observations suggest an activation of sediment tectonics in the top zone of the Ypresian clay in Quaternary times: clay diapirs bulging into Quaternary palaeovalley fills (cfr. fig. 3 and fig. 7), listric slide structures covered with wedge-shaped Quaternary deposits (fig 10), low-angle thrust structures (Kwadestraat clay pit, Heestert), etc.

A detailed description and interpretation of these recent deformations falls beyond the scope of this paper. However, for the sake of completeness, one might argue that comparable basic mechanisms could be taken into consideration for explaining such deformations.

Abnormal pore pressures generated under permafrost conditions could be responsible for a decrease in sediment shear strength or a decrease in shear stress, resisting motion on pre-existing fault planes.

Furthermore, the appreciable amount of erosion in Quaternary times led to a significant decrease in vertical stress, leading to vertical deviatoric components of extensional nature in the top layers of the sediment. Such a stress release by erosion was probably the origin of the plane-parallel, horizontal jointing observed in many outcrops in the top zone of the Ieper clay (e.g. Kwadestraat clay pit, Heestert).

The coincidence of Quaternary clay diapirism with deeper upwellings, as observed on the seismogram of fig. 3, or the association of progressive slide structures with original Ypresian clay

tectonic features (faults, e.g. fig. 10) also suggests that many Quaternary clay tectonic deformations probably found their origin in a reactivation of inherited fractures or of fossil diapiric flow lines.

CONCLUSIONS

The clay tectonic phenomena observed on high-resolution reflection seismic sections and on several outcrops can be explained by a logical stress history of a thick, compacting clay unit, covered by coarse-grained sediments.

A fundamental observation made on seismic sections is the confinement of the deformations to the Ieper clay: faults throwing up to 10 m in the central part of the clay body do not affect the Landenian basement and fade out in the overlying sequences. The origin of such deformations is therefore to be sought in the Ypresian depositional history itself.

A clue to the basic mechanism of the clay tectonics in the Ieper clay is the observation of a festoonlike wave shape, fitting a model of a Rayleigh-Taylor instability caused by a density inversion in a self-sealing clay body. A parallel decrease in shear strength of the sediment by abnormal pore fluid pressures may have acted as a lubricant for the sediment flow. The dissipation of abnormal pore pressures probably happened throughout the bulk of the clay mass by a process of progressive hydraulic fracturing. Above the rising clay wave crests, a faster, catastrophic drainage through diapiric pipes could develop, possibly giving rise to brecciation of already consolidated, brittle horizons.

In addition to this hydrodynamically controlled stress history, some further processes could be taken into consideration: early normal fault development under an increasing burial thickness, regional slope sollicitation at the moment of maximal decrease in sediment shear strength, recent modulation of the top layers of the Ieper clay by Quaternary erosion and periglacial phenomena.

The above model should in no way be regarded as an ultimate one. Rather, it should be regarded as a first working hypothesis, subject to further revisions, refinements, validations or refutations. Many investigators of the Ieper clay have hitherto overlooked the significance of observed faults and deformations, considering them as mere local accidents. A first understanding of a phenomenon, whatever incomplete, often forms a prerequisite for the gathering of further factual evidence. It is hoped that the presented seismic evidence and the derived model might trigger new observations, leading to a better insight in the Ypresian depositional history.

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