SEISMIC TRACKING OF GEOLOGICAL HAZARDS RELATED TO CLAY TECTONICS IN THE SOUTHERN BIGHT OF THE NORTH SEA

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ABSTRACT

A joint seismic exploration programme, carried out in recent years by Belgian, British, French and Danish university laboratories in the southern North Sea and Schelde estuary, has revealed various styles of clay tectonics in Eocene and Oligocene deposits.

In this paper, particular attention is drawn on the remarkable deformation features observed in the Ieper or London clay, which forms the subsoil of the major part of the Thames estuary and the Belgian shelf sector.

Those clay structures have eluded many previous investigations, mainly due to a lack of interfaces with large reflection coefficients. When however a seismic source is adequately tuned, the sum of reflection responses from the many subtle interfaces within the clay sequence may construct an interference composite, which closely moulds the structure of the clay beds.

The deformations thus revealed are closely bound to the London Clay itself, fading out in overlying sands and not affecting the Paleocene basement.

Some main observed deformation features are : imbricated fault systems with tilted blocks and inclined fault planes, throwing up to 5-10 m, collapse structures and festoonlike sequences of cuspate anticlines, often developing into diapirlike escape pipes which locally pierce into the Quaternary cover.

Some of these features have already occasionally been observed on land, both in the Thames valley and in south-west Belgium. The seismic records however present a first picture of their general structural context.

Regarding their origin, different mechanisms have to be taken into consideration, including pore pressure - induced shear strength reduction and gravitational solicitation on gentle slopes at an early stage of compaction, overpressure relaxation, microseismic activation at the end of Ypresian times and glacitectonic stresses in Quaternary times.

The presence of such slip planes in Tertiary clays might represent potential hazards, especially for sea-floor gravity structures, and should be truely evaluated.

Anyhow, the further development of tunable seismic profiling systems might turn out a powerful tool for the investigation of clay dynamics in offshore work.

INTRODUCTION

A number of seismic exploration programmes carried out in recent years in the Southern Bight of the North Sea, the Thames and Schelde estuaries and the Channel have progressively revealed several styles of bedding deformations in Eocene and Oligocene clay deposits.

These seismic investigations have been carried out with broadband, high-resolution seismic sources (boomer, sparker) and single-channel recording and processing. The depth of investigation ranged from a few tens up to a few hundreds of meters below the sea-floor. A concise review of such techniques may be found in an earlier paper (HENRIET, BASTIN and DE ROUCK, 1978) though there have been a number of advances in recent years.

The observed disturbances of the internal bedding of Tertiary clay formations are closely bound to the clay layers, flattening out both downward and upward in adjacent formations. This phenomenon is referred to as clay tectonics or clay dynamics. All the principal Eocene and Oligocene clay deposits of the southern rim of the North Sea basin appear to be affected, though these deformations differ in extent, style and intensity.

The least affected deposits are the Rupelian clays (Boom clay, of Oligocene age), investigated along profiles in the Schelde estuary and the north-eastern part of the investigated shelf sector. These are generally characterized by a sequence of strong, even and parallel reflectors, due to an alternation of clay and silt horizons and the presence of carbonate concretion levels (septaria). Only the top horizons, close to an erosion surface, are seen to be locally affected by diapiric deformations, locally piercing into overlying sands.

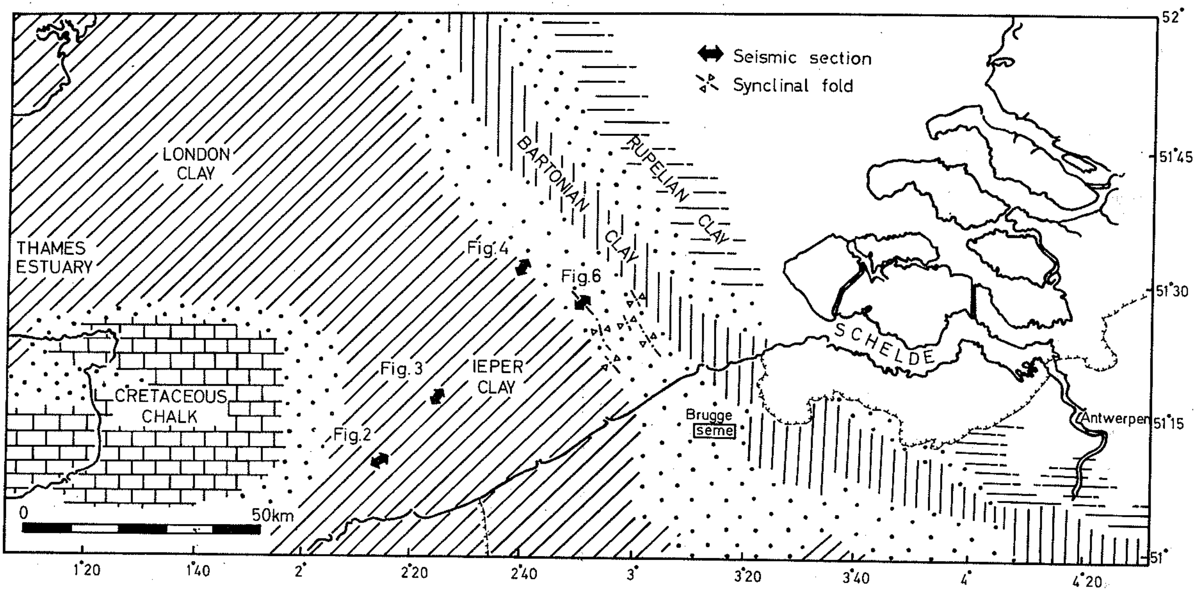


Fig. 1 : Extension of the main Tertiary clay outcrops on the southern rim of the North Sea basin. Marine data based on preliminary results of 'Project Seismic Stratigraphy, Southern Bight, North Sea'. Belgian land data based on MARECHAL and DE BREUCK (1979).

Another type of deformation is found within the Kallo Formation, a series of Upper Eocene (Bartonian) and Lower Oligocene (Tongrian) clays with associated silts and sands. These have been investigated by seismic profiling off Zeebrugge harbour and in the central to north-eastern part of the offshore area. This formation consists of three distinct seismic facies. A lower interval consists of parallel reflections, with an upper boundary of east-northeasterly dipping, sigmoidal, prograding reflection segments. This interval grades into a middle layer, consisting of convex upward, sometimes faulted, hummocky coalescing mounds. This layer finally is draped by an upper layer of continuous undulating reflections, flattening upwards.

Another, maybe extreme expression of clay dynamics might be found in some deep, steep-sided, closed pits, eroded down to the base of Rupelian clays (Schelde estuary) or Bartonian clays (central part of the shelf sector). These might be caused by the relaxation and erosion of abnormally pressured zones (cfr. further).

The above mentioned phenomena will be further described in some forthcoming papers. In this paper however, particular attention is drawn to the most striking clay deformation pattern hitherto observed - striking both by its amplitude and general extent - which has been discovered in the Ieper or London clay.

From some earlier seismic investigations in the Thames estuary, the Hampshire - Dieppe basin (Channel) and off the Belgian coast, an internal corrugation of the Ieper/London clay bedding had already been suggested by the chaotic and ill-defined reflection configuration. However, somes lines shot on a particularly stable and tectonically quiet shelf zone in the Belgian sector yielded unusually sharp pictures of a complete vertical sequence of deformations.

The high quality of many of such profiles, shot within the framework of a joint Belgian - British - French exploration programme (Project 'Seismic Stratigraphy, Southern Bight, North Sea'), resulted from favourable weather conditions and the application of a suited seismic probing technology.

GEOLOGICAL SETTING

The Ieper or London clay forms the subsoil of the major part of the Thames estuary and the Belgian shelf sector, as shown on fig. 1. It gently dips in a north-easterly direction, though not uniformly, there being a number of fold patterns superimposed upon this regional dip.

It is a fairly uniform marine silty clay, with a stratigraphic thickness of 120 to 140 meters in the Belgian coastal area and reaching a maximum thickness of 150 meters in the Thames estuary. The base is at times sharply defined by an erosion plane and basal pebble bed.

Earlier deposits are Late Paleocene marine and continental sands, with some intercalations of clays, limestone, sandstone and lignite horizons. They are subdivided into the Thanet and Woolwich and Reading Beds in the Thames region and are known as the Landen

Formation in Belgian stratigraphy. These sands are directly resting on Cretaceous chalk and reach thicknesses ranging from 40 or 50 meters (Belgian coastal area) to 60 meters (Thames region).
The Ieper/London clay generally grades upward into fine sands.

In the Thames estuary, a hard horizon of volcanic ash is found at about 6.5 meters above the base of the clay and is called the Harwich stone band. This ash marker is a prominent seismic reflector that can be traced over much of the North Sea basin.

TUNING ON CLAY

The origin of a seismic reflection is a contrast in acoustic impedance between two media. Major lithologic boundaries yield discrete reflection responses, with no significant variability in position when signal characteristics are altered.

Clay sediments, which often appear homogeneous in borings and outcrops, usually consist of a stack of laminae and thin beds with subtlely variable grain size

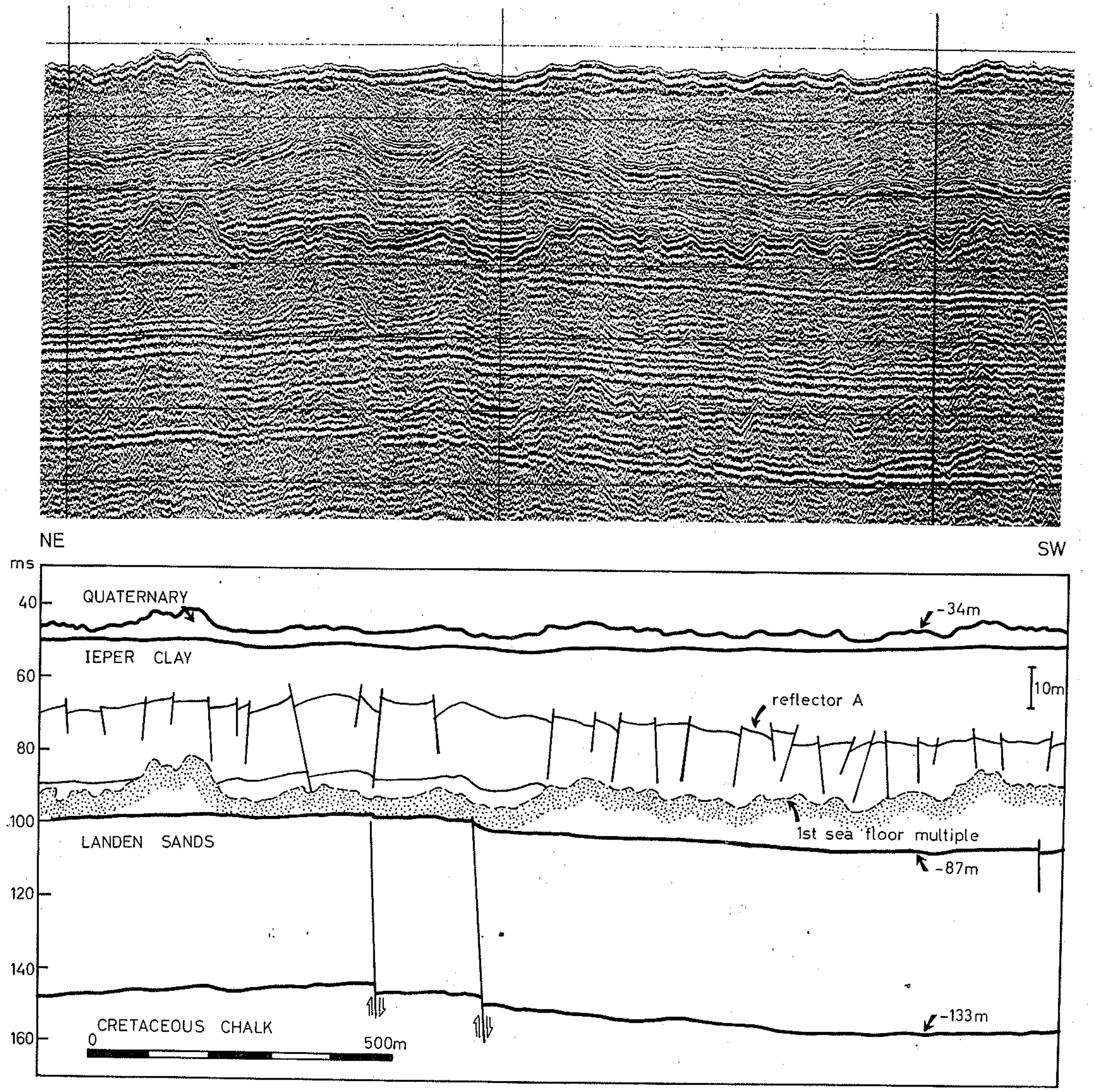


Fig. 2 : Sparker section displaying the structural deformations of the lower part of the Ieper clay

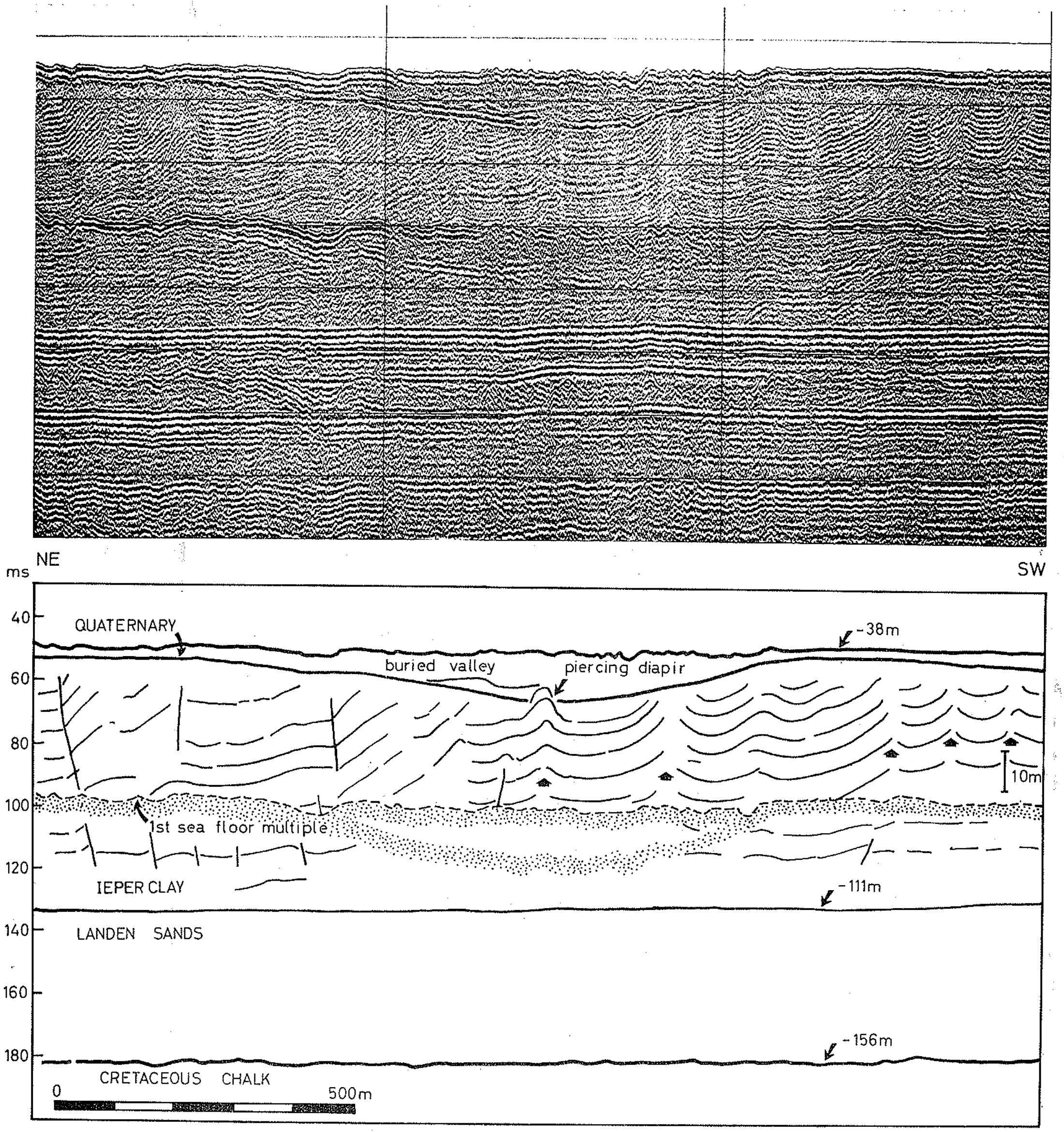


Fig. 3 : Sparker section displaying the contorted structures in the Ieper clay

and compaction characteristics. When the spacing of interfaces is of the order of magnitude of the dominant wavelength of the seismic pulse, the sum of the reflection responses may result in an interference composite with a build-up of amplitude through constructive interference. These interference composites hence do not necessarily correspond with discrete geological boundaries but they do closely follow the general trend of the bedding planes and thus mirror any structural deformation pattern.

Revealing the internal structure of such apparently homogeneous clays hence largely depends on the possibility of matching the seismic signal with the clay bedding rhythm. This means shaping the outgoing seismic pulse until an optimum response of the clay sediment is obtained. This shaping primarily depends on the seismic source configuration and the applied energy. Shorter pulses can be obtained by lowering the energy level and - when a sparker source is used - by multiplying the discharge points. The decrease in amplitude caused by lowering the energy level has to be adequately compensated by enhanced amplification techniques.

IEPER/LONDON CLAY TECTONIC STYLE

Three profiles shot on a relatively stable part of the shelf area illustrate some particular tectonic styles developed within the Ieper/London clay and the vertical zonation in deformation pattern.

Owing to the gentle north-easterly dip of the formation, successively higher horizons are brought closer to the surface - and hence within reach of high-resolution probing - along a track running southwest-northeast. The presented profiles have been shot along such a track, running from north of Dyck Bank (France) to south of East Hinder Bank (Belgian sector).

The first profile (about 51°9.5′ north, 2° 15′ east) shows a lower interval, reaching to approximately 25 meters above the normally undisturbed clay base (fig. 2). Intense block-faulting may be observed, with tilted and bended blocks and apparently randomly dipping fault planes. The average vertical throw at the level of reflector A, characterized by a discrete high-frequency reflection response, amounts to about two meters. Clay reflector segments situated over basement faults (such as those shown on fig. 2, which extend through the Paleocene and Cretaceous basement) show some additional warping.

The second profile (about 51° 17′ north, 2° 25′ east, running north of Oost Dyck Bank), illustrates the deformation pattern in a second interval, reaching from about 25 meters up to at least 70 meters above the clay base (fig. 3). The movement initiated in the lower interval amplifies in upward direction and develops into a convolute structure, consisting of a festoon-like alternation of narrow, cuspate anticlines and broad, rounded synclines.

The cuspate anticlines often develop into diapirs or drainage chimneys, which locally pierce overlying Quaternary sands. Such a situation may be observed on fig. 3, where a clay diapir pierces the bottom of a buried valley.

The average wavelength of the convolute structure amounts to between 100 and 200 meters and the amplitude between the troughs and the uplifted flanks of the diapirs ranges from 2 meters to at least 10 meters.

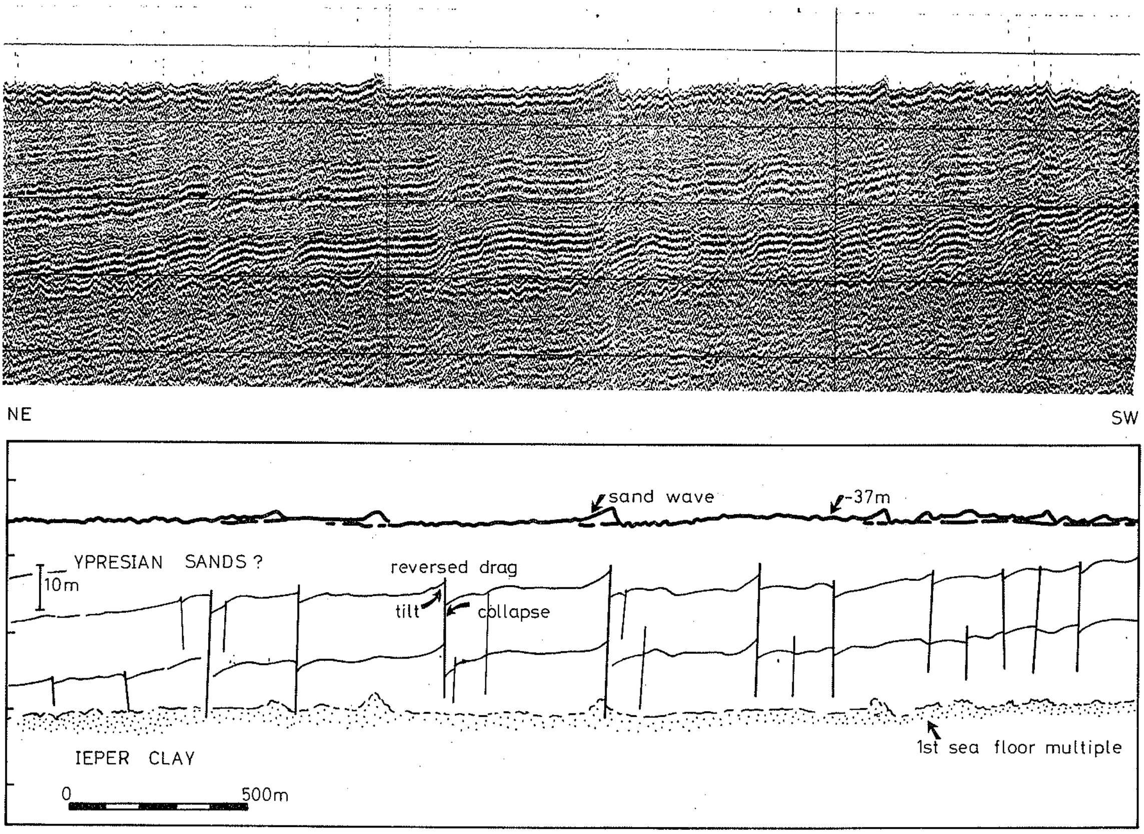
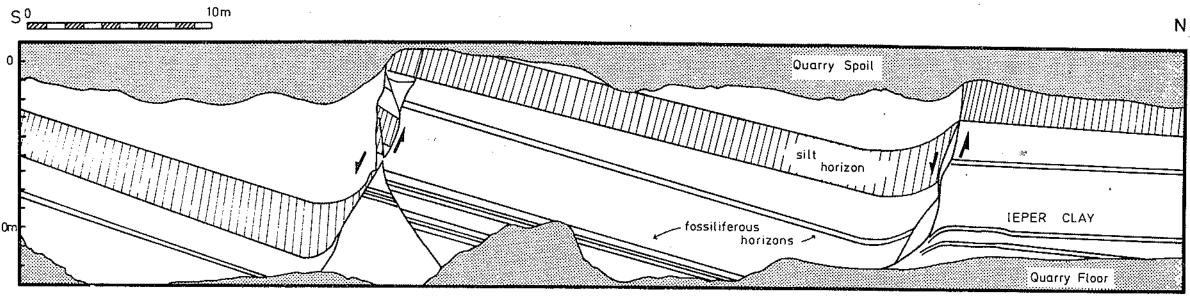


Fig. 4 : Sparker section displaying the structural deformation near the top of the Ieper clay



Courtesy T.MOORKENS and E.BRABB ,1968 , unpublished

Fig. 5a : Block-faulting in Ieper clay, observed in Lauwe (West Flanders, Belgium)

Further north-east it is observed that the convolute second interval becomes more highly disturbed, with faulted blocks dominantly tilted towards north-east. The presence of obliquely prograding sediment sets might not be ruled out, but this observation requires further control.

At approximately the level where the Ieper clay should grade into the fine sands, another, highly peculiar deformation pattern is found (profile on fig. 4, located about 51° 32′ north, 2° 40′ east). Again some well-defined reflectors are affected by a system of faults, but the deformation consists of alternately tilting and down-warping bedding terminations on either side of the faults, apparently without significant tilting or displacement of the blocks between the faults. Moreover, alternate deformations point away from each other, as opposed to the deformation of bedding terminations caused by the normal drag associated with block faulting (pointing towards each other, cfr. fig. 5a).

Although strictly speaking some doubt might be cast on the exact shape of a few down-warping segments, owing to a possible interference with diffracted events at reflector terminations, the reality of the uplifted terminations is beyond any doubt. In a way, it appears as if the faults and the associated reversed drag have not been caused by a movement of the blocks, but rather that bedding terminations have been dragged by some flow, propagating along the rupture planes. This idea will be developed further.

LAND EVIDENCE

A few deformation features of the Ieper/London clay already have been observed on land outcrops. The relative scarcity of direct observations however is probably related to the relatively small extent of such outcrops, compared to the scale of deformations observed, and to the homogeneous aspect of the clay, often impeding the observation of bedding and bedding corrugation.

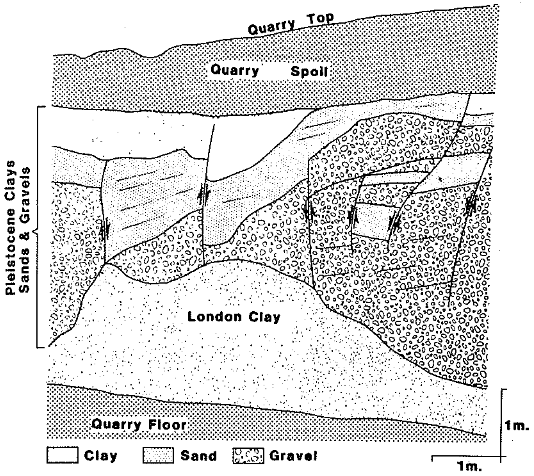


Fig. 5b : London clay diapir, Woodham Walter, Essex, England

Deformations have been reported in some former clay excavation pits in south-west Flanders, between Kortrijk and the French border. Fig. 5a shows a typical example of block-faulting, described in Lauwe (MOORKENS and BRABB, 1968). The presence of a few marker beds (silt beds and fossiliferous horizons) allowed the identification of tilted blocks, dipping up to 13° north, separated by inclined faults, throwing up to 10 meters.

More to the west, the subsoil of part of the Lys river basin in northern France has been described as a patchwork of small tilted blocks of Ieper clay (PAEPE, 1965).

London clay diapirs piercing into Quaternary sediments, a possible analogy for the phenomenon observed on fig. 3, have been observed on numerous outcrops in the Thames valley. Fig. 5b shows a typical example of a clay diapir, affecting through faulting a series of Pleistocene sands and gravels. Generally, such diapirs are grouped into swarms, of similar trend and amplitude. It cannot be ruled out that diapirism was active during the deposition of the Quaternary sands.

MECHANISMS OF CLAY TECTONICS

A simple compaction model might help to understand the dynamics observed in the Ieper/London clay.

This sediment has been deposited as a loose, high-porosity, water-logged mud. As sedimentation continued and the thickness of the layer increased, gradual compaction occured, reducing pore space through the expulsion of pore water.

As long as a sediment mass can be freely drained, pore water pressure remains hydrostatic, i.e. balancing 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 pressure).

Pore water drainage rate in the Ieper/London clay probably was maximal near the base, both due to the maximal overburden weight and to the presence of a permeable sand substratum, providing an easy path for water to leave the base of the clay. This fastly drained clay layer progressively compacted, building a permeability barrier which impeded further drainage of the clay mass through the Paleocene sands.

One could imagine that, when clay sedimentation progressively gave way to the deposition of more dense sand layers, a similar phenomenon could have occured at the top of the clay mass. For the provision of an easy path for the water to leave the top of the clay meant that the clay started to compact from the top down, in addition to the compaction from the bottom up. Through this mechanism, the Ieper/London clay may have sealed itself.

As soon as drainage gets impeded in some part of a clay body and sedimentation goes on, pore water in the sealed regions begins to suffer increased compression, having to contribute to the support of the overburden. This means that the pressure in the water of the pores rises from its normal hydrostatic value towards the lithostatic value, giving rise to a so-called overpressured or undercompacted condition.

Overpressured conditions have been encountered in sedimentary sequences on all continents, down to depths exceeding 6,000 m. They have a profound impact on the oil industry, greatly affecting exploratory activities, drilling and well completing efforts, production operations and associated reservoir engineering (BRADLEY, 1975 - FERTL, 1976 - MAGARA, 1978).

Recent studies dealing with the mechanical properties of delta sediments have shown that overpressure can start already at very shallow depths, of the order of a few meters (SHEPHARD, BRYANT and DUNLAP, 1978).

Overpressured conditions strongly affect the strength parameters of clay layers. Loose or slightly consolidated sediments owe their shearing strength to friction at the contacts between the individual particles, the sediment 'strengthening' as the interparticle contact pressures rise. Excess pore pressures in fine-grained sediments reduce the 'effective' weight of the overburden, which is carried by the intergranular contacts, hence reducing sediment strength. Such low-strength sediment masses may easily be mobilized.

Initiation and further development of Ieper/London clay mobilization may have been controlled by :

- a gravitational 'pull' on a gentle slope,
- a gravitational instability bound to density inversion,
- microseismic activity,
- differential loading,

or a combination of such factors.

The mechanism of gravity sliding of overpressured clays and silts on very gentle slopes (less than 3^0) has recently been well documented by model studies of growth faulting in deltaic sediments (MANDL and CRANS, 1979 - CRANS, MANDL and HAREMBOURE, 1980 - CRANS and MANDL, 1980) and thrust sheet gliding (HUBERT and RUBEY, 1959 - MANDL and SHIPPAM, 1979). It is probable that such gravity sliding has played a major role at several stages of the Ieper/London clay dynamic crisis, but it is difficult to rate on account of the seismic sections whether or not it might have induced significant true growth faulting.

A gravitational instability caused by the burial of an undercompacted clay mass under denser, compacted clay and sand layers may force clay to rise in crests, separated by deepening troughs, and sediment will start sliding downwards along the steepening flanks of the clay waves. As pointed out by CRANS e.a. (1980), gravity sliding on gentle slopes can occur in rather thin sediment packets, long before the clay layer has been buried by a heavier layer, and thus clay bulging and diapirism may be created later than gravity faults. MAGARA (1978) too states that buoyancy may become effective in the later stages of diapirism, but is not important in the earlier stages.

The role of a microseismic agitation, which could have triggered and enhanced the mobilization of the overpressured Ieper/London clay, deserves some attention too. A tectonic activity of the Weald - Artois dome, possibly already at the end of Ypresian times (CAVELIER and POMEROL, 1979) might have shaken instable clay masses, even in remote areas. The idea however that the Ieper/London clay deformations would directly be controlled by basement tectonics is definitely invalidated by the seismic records, which give clear evidence of the independent clay deformation pattern over often undisturbed basement areas.

The influence of local excess loading on overpressured sediments traditionally has been regarded as a main factor of clay tectonics. This idea has been supported for instance by the study of the diapiric intrusions under prograding delta deposits (e.g. MORGAN, COLEMAN

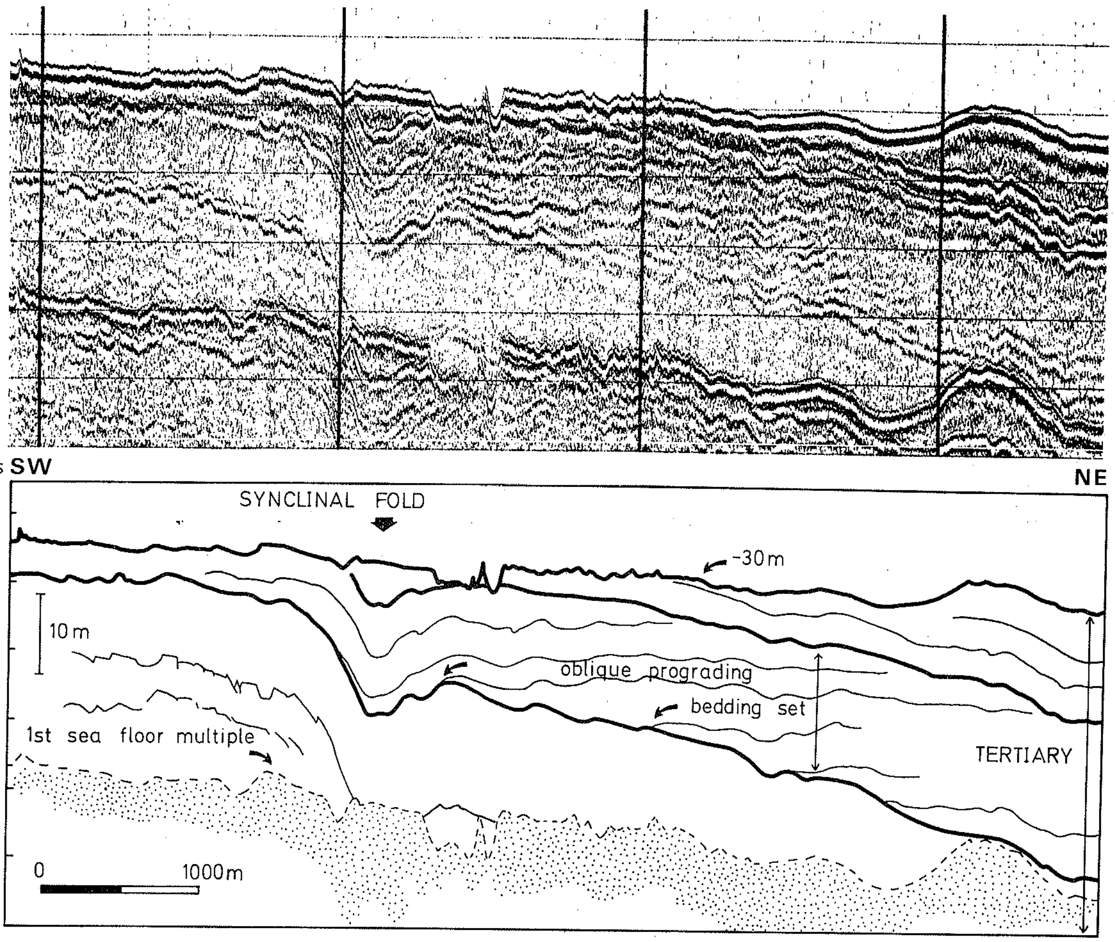


Fig. 6 : Synclinal fold and oblique stratification in Tertiary deposits

and GAGLIANO, 1965) and model studies (e.g. RETTGER, 1935). KING (1981) has described a progressively shoaling and coarsening - upwards tendency of the deposits in the upper sedimentary cycles of the London clay. This might reflect the progradation of coarser sediments from the basin margins into a regressive sea. Furthermore, clearly defined obliquely prograding bedding sets have been observed in higher sequences , of Lutetian (Middle Eocene) age (fig. 6). Local overloading by such prograding sediment masses could have generated deformations in the undercompacted clay layers.

For the sake of completeness, the possible influence of local excess loading by prograding ice sheets in Quaternary times should be evaluated too. The hypothesis of Quaternary glaciations in the Channel has been raised by KELLAWAY e.a. (1975), but many investigators keep reluctant to such an 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. The influence of Quaternary events on the reactivation of clay dynamic features however should not be underrated, as is clearly demonstrated by the swarms of diapirs, piercing Quaternary deposits.

Interpreting the seismic pictures with the above mechanisms in mind, one might suggest the following deformation scheme.

The lower, more compacted and thus more brittle interval (fig. 2) has been affected by faulting, which possibly initiated at an early stage of sediment accumulation by simple gravity sliding, controlled by local or regional slope gradients.

A progressive coarsening of the upper part of the sediment stack and the subsequent burial under a sand cover caused a compaction from the top down, the central part of the clay sealing itself into an overpressured situation. Differential loading, which might be expected in a regressive sea, caused the overpressured clay to flow, draping into clay waves which - partly by a buoyancy effect - developed into diapirs. A triggering effect and an enhancement of the clay movement through microseismic agitation should not be ruled out. The basal drag exerted by the clay flow induced further faulting and bending of the faulted blocks in the lower interval.

Clay waves developed into ridges, diapirs and drainage chimneys, through which a flow of excess pore water and mud searched its way towards the surface, fracturing overlying, more compacted and brittle horizons. The observation of clay breccias in Ieper clay cores from a deep boring in northern Belgium (VANDENBERGHE, 1980, personal communication) might support this idea (they might be considered as mud vulcano breccias).

The fractures in the upper interval (fig. 4), flanked by alternating tilted and collapsed bedding terminations, could be regarded as the uppermost expression of these drainage paths, after which the excess pore water further diffused into the permeable overburden. The constant orientation of those uppermost deformations might be the consequence of a superimposed effect of the regional dip (all collapsed segments pointing downslope).

REACTIVATION PROCESSES

Two observations suggest a reactivation of Ieper/London clay deformation in younger geological times. The first clue is the discovery (HENRIET, BASTIN and DE ROUCK, 1978) of narrow (a few hundreds of meters) and elongated (up to at least 15 kilometers in one case) synclinal depressions, with an average fold amplitude of 5 to 10 meters (fig. 6, recorded about 51° 28′ north, 2° 50′ east). They are confined to Upper Ypresian and Lutetian sand outcrops, between the Ieper clay and the Bartonian clay (fig. 1), and their axis rigourously parallels the strike of the Tertiary layers.

By their discrete presence in an otherwise unfolded region, such structures ought to be considered as the surface expression of deeper, elongated collapsed depressions, striking perpendicularly to the plane of maximum dip of the Tertiary beds. The first and most likely subsurface plane in which such groove- of furrow-shaped depressions could have developed appears to be the top of the Ieper clay.

Open ended slide structures, such as those described in models of gravity sliding in overpressured clays (CRANS, MANDL and HAREMBOURE, 1980), might well apply here, as they are able to generate elongated, strike-parallel collapsed tensional depressions at the upslope end of the slide structure. In accordance with such models, sliding may have occured along slope-parallel, rotational normal faults, which would curve down to terminate as bedding-parallel basal slip planes in clay horizons with residual overpressure (fig. 7). These slip planes should have died out downslope, the creeping sediment progressively compacting in dip-parallel direction and thus activating a buttressing force tending to restore static equilibrium. Offsets of the axis of the folds (fig. 1) might suggest the presence of transverse faults, separating neighbouring slide structures (fig. 7). The upslope part of such slide structures probably would most easily have initiated at pre-existing fractures in the top of the clay.

A plausible origin for this possible form of reactivation of clay deformations might be an increase in gravitational 'pull' through a steepening of the paleo-slope, responding to the accelerating subsidence of the huge North Sea basin further north. As shown by PERRIER and QUIBLIER (1974), the subsidence rate in the North Sea basin was moderate during the Paleocene and the Eocene, then increased during the Oligocene up to the Middle Miocene, accelerating again greatly in Pliocene and Pleistocene times after an apparent interruption in the Late Miocene.

A second clue to 'modern' (in a geological sense) reactivations of clay deformations are the diapir swarms, piercing into Quaternary deposits. As concerns the southern rim of the North Sea basin, diapirs of Tertiary clays piercing into much younger deposits have mainly been observed in the vicinity of some major valleys : Ieper/London clay diapirs near the Thames valley and in the buried valley shown on fig. 3, Rupelian clay diapirs in the Schelde valley near Antwerpen.

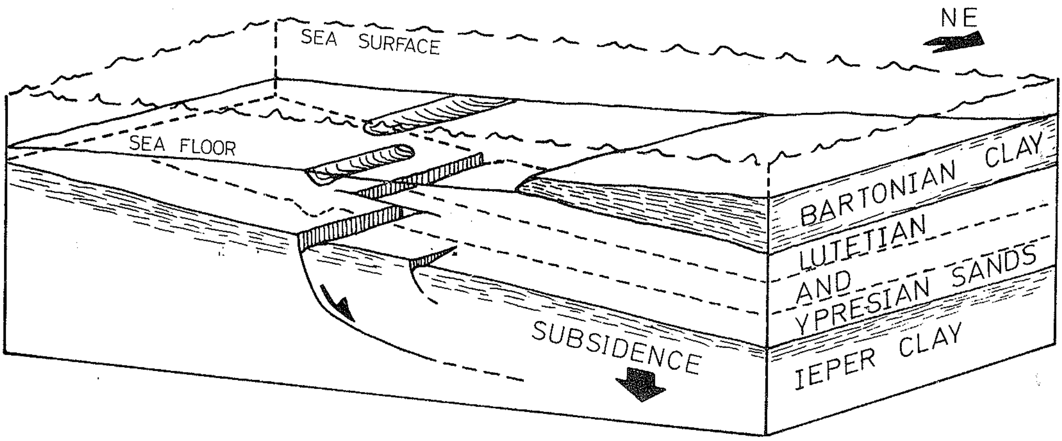


Fig. 7 : Gravity sliding hypothesis for the origin of the elongated synclinal folds observed in Tertiary layers (schematic)

Even though most of the 'original' overpressures might have dissipated as a result of the clay dynamic processes, a removal of a sediment slab by erosion in 'modern' times may have raised inherited pressures within sealed clay zones again to pore pressure levels, exceeding those required to equilibrate the new overburden conditions. Such 'new' overpressures may again have activated a clay mobilization process, which apparently preferentially developed over former, deeper drainage pipes, as suggested by the section on fig. 3.

It should be understood that clay dynamic processes and their reactivation are normally not to be considered as rapid or catastrophic events. As pointed out by CRANS e.a. (1980), gravity sliding in overpressured clays proceeds slowly and it only gradually affects larger parts of the slope. When it proceeds contemporaneously with sedimentation - the usual case - deposits at the downthrown side of the fault are often thicker than the correlative deposits at the opposite side of the fault, which in such case is known as a growth fault. This implies that average deformation rates are of a similar order of magnitude as sedimentation rates.

The observation that London clay diapirs would have been active during the deposition of the Quaternary sands, as suggested by thickening of strata across the tensional faults over the diapirs (fig. 5b), also supports the idea of slow, long-term creep movements.

DISCUSSION

RELEVANCE TO MARINE ENGINEERING

The larger part of the Belgian shelf sector and the British sector off the Thames estuary are - often directly - underlaid with Tertiary clays displaying different styles and intensities of internal deformations. The most extensively disturbed unit is the Ieper or London clay.

Such deformations probably initiated at an early stage of deposition and amplified as sediment thickness increased.

The basic mechanism of clay tectonics is the relaxation of excess pore pressures, a process further modulated by internal and external stresses and constraints. Overpressures in the Ieper/London clay probably have been generated by the retarded drainage of the low-permeability clay and by a sealing of inner parts of the clay mass, as compaction proceeded both from the base up and from the top down.

Of main concern for marine geotechnical projects is the observation of numerous faults and slip planes, some of which throw up to 10 meters. Major changes in load over such deformations, either by excavation or construction of gravity structures, might result in some displacement response - either short- or long-term - through reactivation of pre-existing weakness planes. The same holds for onshore engineering projects involving major subsurface excavation works. Consciousness of the above described deformations may contribute to safer design approaches.

Considering the scale of the deformations and the apparent homogeneity of those clay masses, classical geotechnical investigation techniques such as boring, cone-penetration sounding and sample testing usually are of little value for evaluating the general clay dynamic structures. High-resolution seismic reflection profiling may yield valuable data, but only with carefully balanced signal characteristics. In recent years, a fair amount of progress has been realized in single-channel seismic data quality through the application of digital techniques in data acquisition units. Varying the configuration of a sparker source and the level of signal energy however still requires time consuming manipulations and unavoidable data loss.

With regard to the importance of seismic pulse shaping for the detection of clay dynamics - a phenomenon of major concern in offshore site investigations - more attention ought to be paid to the development of flexible signal source systems, which could be scaled in a semi-continuous way through simple shipboard manipulation.

Finally, it should be realized that the Ieper/London clay may provide - by its variety of clay dynamic features, all within easy reach of detailed high-resolution seismic investigations and further land control - a valuable small-scale model, which might contribute to a better knowledge of clay tectonic structures which - at a larger scale - play a prime role in controlling the distribution of reservoirs in some major hydrocarbon provinces.

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REFERENCES

BRADLEY, JOHN S. - Abnormal Formation Pressure - Amer. Assoc. Petr. Geol. Bull., 59, June 1975, 957-973

CAVELIER, C. et POMEROL, C. - Chronologie et interprétation des évènements tectoniques cénozoiques dans le Bassin de Paris - Bull. Soc. Géol. France, 21, 1979, 33-48

CRANS, W., MANDL, G. and HAREMBOURE, J. - On the Theory of Growth Faulting : A geomechanical Delta Model based on Gravity Sliding - Journ. Petr. Geol., 2, 3, 1980, 265-307

CRANS, W. and MANDL, G. - On the Theory of Growth Faulting - Part II (a) : Genesis of the 'Unit' - Journ. Petr. Geol., 3, 2, 1980, 209-236

FERTL, W.H. - Abnormal Formation Pressures Elsevier Scient. Publ. Cy., Developments in Petroleum Science, 2, 1976, 382 p.

HENRIET, J.P., BASTIN, A. and DE ROUCK, J. - Integration of Continuous Seismic Profiling in Geotechnical Investigations off the Belgian Coast - Proc. 7th. Intern. Harbour Congress, Roy. Soc. Flemish Eng. (K.VIV), Antwerp, 1978, 1.18/1-1.18/13

HUBBERT, M.K. and RUBEY, W.W. - Role of Fluid Pressure in Mechanics of Overthrust Faulting - Part I. Bull. Geol. Soc. Am., 70, 1959, 116-166

KELLAWAY, G.A., REDDING, J.H., SHEPHARD-THORN, E.R. and DESTOMBES, J.P. - The Quaternary History of the English Channel - Phil. Trans. Roy. Soc. Lond., A.279, 1975, 189-218

KING, C. - The Stratigraphy of the London Clay and Associated Deposits - Backhuys, Publisher, Rotterdam, 1981, 158 p.

MAGARA, K. - Compaction and Fluid Migration - Practical Petroleum Geology - Elsevier Scient. Publ. Cy., Developments in Petroleum Science, 9, 1978, 319 p.

MANDL, G. and CRANS, W. - Gravitational Gliding in Deltas - in Thrust and Nappe Tectonics - Spec. Publ. Geol. Soc. 9, Ed. K.R. McClay and N.J. Price. Blackwell Scient. Publ., 1981, 41-55

MANDL, G. and SHIPPAM, G.K. - Mechanical Model of Thrust Sheet Gliding and Imbrication - in Thrust and Nappe Tectonics. Spec. Publ. Geol. Soc., 9, Ed. K.R. McClay and N.J. Price. Blackwell Scient. Publ., 1981, 79-98

MARECHAL, R. and DE BREUCK, W. - Geologie van Vlaanderen - in Twintig Eeuwen Vlaanderen, 7, 1979, 13-34

MOORKENS, T.L. et BRABB, E.E. - Structures de glissement dans un profil Yprésien à Lauwe (Fl. Occ.). Unpublished manuscript, 1968

MORGAN, J.P., COLEMAN, J.M. and GAGLIANO, S.M. - Mudlumps : Diapiric Structures in Mississippi Delta Sediments - in Diapirism and Diapirs. Memoir 8, Amer. Assoc. Petr. Geol., 1968, 145-161

PAEPE, R. - Evolution morphologique de la Plaine de la Lys et des Monts de Flandre - Bull. Soc. Belge Géol. Pal. Hydr., 74, 2, 1965, 1-18

PERRIER, R. and QUIBLIER, J. - Thickness Changes in Sedimentary Layers during Compaction History ; Methods for Quantitative Evaluation - Amer. Assoc. Petr. Geol. Bull., 58, 1974, 507-520

RETTGER, R.E. - Experiments on Soft Rock Deformation - Amer. Assoc. Petr. Geol. Bull., 19, 1935, 271-292

SHEPHARD, L.E., BRYANT, W.R. and DUNLAP, W.A. - Consolidation characteristics and Excess Pore Water Pressures of Mississippi Delta Sediments - Proc. 10th Offshore Techn. Conf., Houston 1978, paper OTC 3167, 1037-1048