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Early fracturing of Palaeogene clays, southernmost North Sea: relevance to mechanisms of primary hydrocarbon migration

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ABSTRACT

Argillaceous petroleum source-rocks often show evidence of fracturing, which is considered to be an important factor for the primary migration of hydrocarbons. Several authors consider overpressuring of the enclosed pore fluids at great burial depths as a major factor for the generation of microfractures, through the mechanism of hydrofracturing.

Various scales of fracture networks have been observed in Palaeogene clays which have never reached burial depths, greater than a few hundreds of metres. High-resolution seismic reflection investigations carried out in the southern North Sea have revealed large-scale fracturing patterns, confined to the London/Ieper clays. Equivalent deformation and microfracturing have been observed at outcrops on land.

Field evidence suggests an early fracturing of these clays by overpressuring of the pore water at relatively shallow depths and at an early stage of the clay diagenesis. A locally observed wave-like deformation pattern may prove a relict form of a Rayleigh–Taylor instability, related to a temporary density inversion caused by undercompaction. The observed deformations can to some extent be compared with sand-box models, developed at Rennes University in France.

Argillaceous potential source-rocks, having perhaps already undergone general hydrofracturing at shallow depths may thus have reached the depths required for catagenesis in a pre-fractured state. This would have a bearing on the timing of the onset of primary migration.

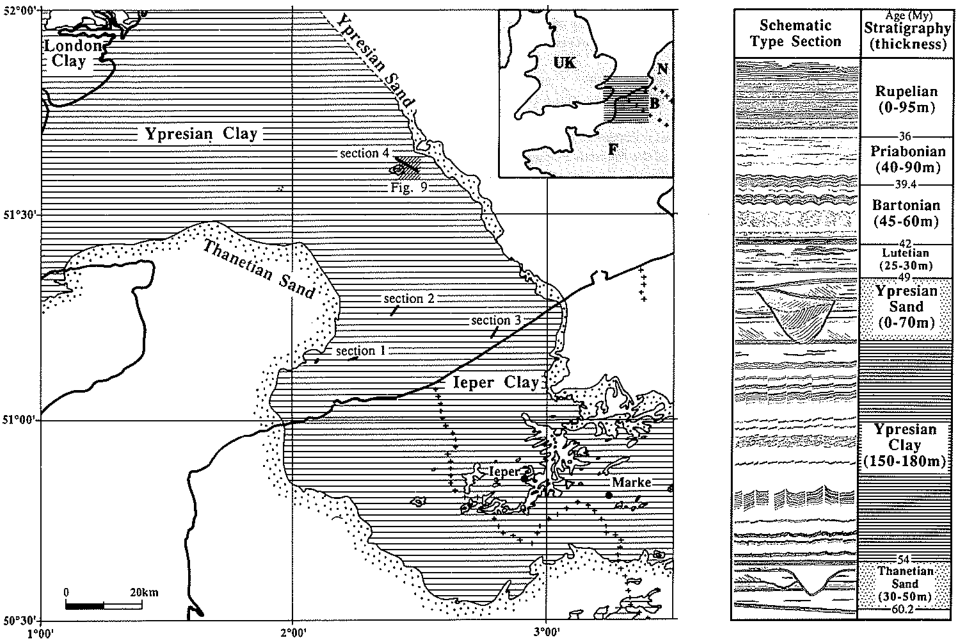

Fig. 16.1. **(a)** Study area with outcrop map of the London/Ieper Clay in the southern North Sea and adjacent land areas in Belgium and France; **(b)** stratigraphical colum, with schematic illustration of the seismic reflector pattern in each stratigraphical unit. Section 1, see Fig. 16.4; for Section 2, Fig. 16.5; for section 3, Fig. 16.6; for section 4, Fig. 16.7. For detail of study site, see Fig. 16.9.

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INTRODUCTION

High-resolution seismic reflection investigations have been carried out over the past twelve years in the southernmost North Sea (Fig. 16.1) by the Renard Centre of Marine Geology (State University of Ghent) in various contexts: students' education and training, regional geological mapping, fundamental sequence-stratigraphic research, harbour-development projects, and test programmes for survey equipment to be used in polar-margin studies. As a result, a high-density grid of more than 15 000 km of lines shot both in the single- and multi-channel mode with a variety of seismic sources became available over a relatively thin but complete Palaeogene sequence, closely tying the classical Belgian Tertiary basin to its many Palaeogene type localities (Ypres, the Rupel, etc.).

This data-base soon revealed remarkable patterns of deformations, confined to the Palaeogene clays, and permitted a systematic analysis of both the structural style and the spatial extent of these deformations. The marine observations triggered a search for such features on land, which soon proved that well-developed intraformational fault patterns could also be observed in several clay quarries. Such faults and fractures on clay walls often elude observation due to the relatively uniform nature of the clays, but some had already been observed in detailed stratigraphical studies where their significance had either been overlooked or had been attributed to very local basement-induced deformations or Quaternary effects.

The Palaeogene clay deformation in the southern North Sea thus progressively turned from an accidental observation into a subject of proper interest, in the first instance in view of its possible bearing on the stability of harbour-development structures and of offshore sites (Henriet *et al.* 1982). Such deformation, however, recently engaged the interest of the geotechnical sector, where Palaeogene clays are evaluated as potential underground storage sites for nuclear waste (for example, in the Mol underground laboratory, Belgium) or for liquefied natural gas. The evident concern in such cases is that the fractures could develop into preferential fluid migration paths under long-term thermal stresses.

The significance of such fractures as potential fluid migration paths however exceeds the geotechnical domain and may well also be of importance in petroleum geology, as discussed in this paper.

DEEP HYDRAULIC FRACTURING

Potential petroleum-source rocks, such as shales, often show evidence of intense microfracturing, which is considered to be an important factor for the 'primary' migration of hydrocarbons. Evidence of early oil migration through a network of fractures has been reported by Schnaebele (1948) from the oil mines of Pechelbronn (France), where fractures crossing marl beds were found to be lined by oil films or by a greenish halo (cited in Mandl and Harkness 1987).

Several authors consider that the microfracturing of source-rocks is mainly caused by overpressuring of the enclosed pore fluids; the basic idea is that a large increase

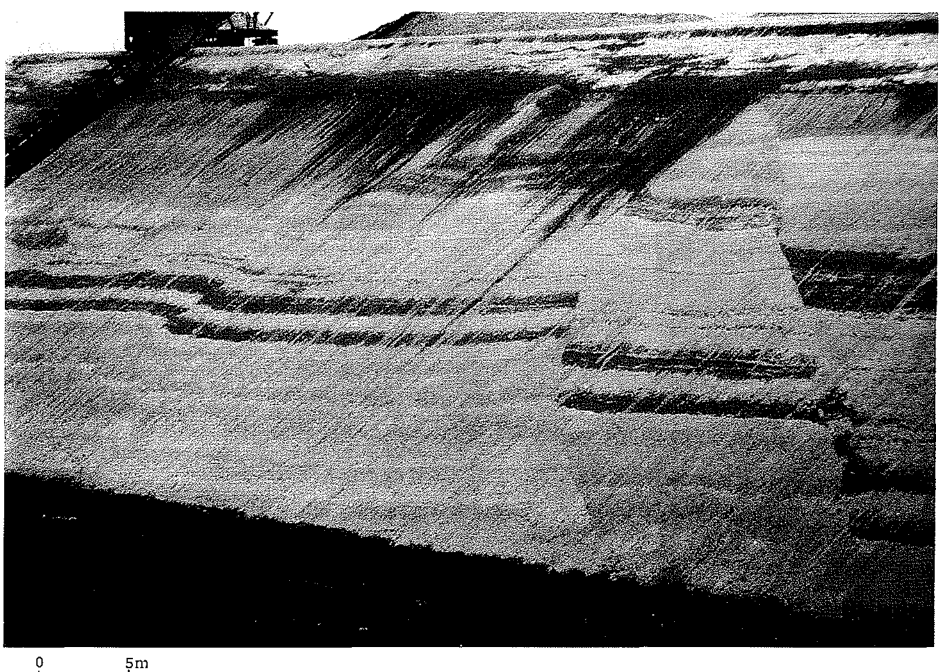


Fig. 16.2. Faulting in Ieper Clay, Koekelberg Quarry (Marke, Belgium). Note that the striations are due to extraction practices,

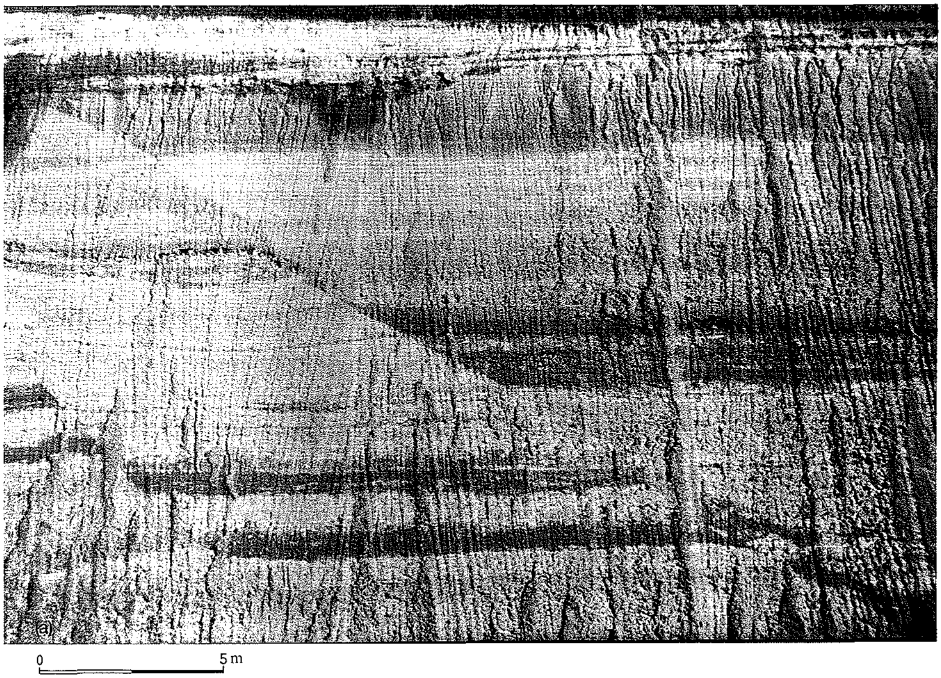


Fig. 16.3 (**a**) Faulting in Ieper Clay, Koekelberg Quarry, detail (Marke, Belgium). (**b**) Detail of a cleared surface (1) with fault mirror, striae, and the black fault gouge. (2) Black fault gouge in cross-section along the fault trace.

in pore pressure may exceed the tensile strength of the rock and induce microfacturing (Snarsky 1962; Tissot and Pelet 1971). Such a process of hydraulic fracturing is also proposed as a major agent of 'secondary' migration of hydrocarbons through shale cap rocks (Mandl and Harkness 1987).

Most investigators in the oil exploration world consider that the formation of significant microfractures by local centres of high fluid or gas pressure is restricted to relatively deeply buried, low permeability rocks such as shales or tight carbonates. According to Tissot and Welte (1984), microfracturing will be initiated beyond a depth of 3000 to 4000 m in dense rocks. The main factors responsible for pressure build-up in such circumstances are:

- the thermal expansion of water (Barker 1972);
- the specific volume increase of organic matter by generation of gaseous and liquid hydrocarbons from kerogen (Snarsky 1962; Tissot and Pelet 1971);
- the partial transfer of the geostatic stress field from the solid rock matrix to the enclosed pore fluids, as a result of the conversion of part of the solid kerogen to liquid or gaseous components (du Rouchet 1981).

EVIDENCE OF SHALLOW HYDRAULIC FRACTURING

Our results raise doubts about the hypothesis that shales are normally buried in a non-fractured state down to such large depths. Fracture networks of various scales have been observed in Palaeogene clays in the southern North Sea basin which have never reached burial depths larger than a few hundreds of metres.

The microfracturing of the Eocene London or Ieper Clay and of the Oligocene Boom Clay has been well known to soil mechanics engineers for more than a century. Some authors (Fookes and Parrish 1969) have related the miroc-fracturing of the London Clay to local basement-induced tectonics. This hypothesis seems to be invalidated because microfracturing in the equivalent Ieper Clay is also observed in areas in Belgium where no basement-induced tectonic deformations are known.

In addition, high-resolution seismic reflection investigations have revealed large-scale intraformational fault patterns in the London or Ieper Clay over their full extent in the southern North Sea. Such patterns involve faults with a throw of several metres, sometimes up to 10 m, which, however, are confined to the clay layer and fade away towards its base and top boundary. Detecting such faults in the relatively homogeneous clay mass is not straightforward and requires ideal sea-state conditions and adequate seismic source selection and tuning (Henriet *et al.* 1982). The best images have hitherto been obtained with multi-electrode sparkers, fired at relatively low energy levels.

Fault patterns have also been observed (with difficulty) on quarry profiles in South Flanders: they only show up clearly during a relatively short time interval when the quarry face is drying, thanks to the colour contrast between moist and dry beds (Figs. 16.2, 16.3). In some working quarries such as the Koekelberg pit in Marke (Fig. 16.1), the 3-D distribution of these faults is presently analysed by sequential surveys of the quarry face in the course of exploitation.

Some preliminary observations of faults in the Koekelberg quarry reveal three major fault sets. The major faults [Figs. 16.2, 16.3(a)], which apparently are similar to those observed on seismograms, display throws of up to several metres, and dips ranging between 80 and 45 degrees, although one has been observed flattening to a horizontal position in the quarry cut. The fault surface is generally characterized by a well-developed fault mirror with striae and a black fault gouge, from some fractions of a millimetre up to 15 mm thick [Fig. 16.3(b)]. Geochemical, textural, structural, and mineralogical analyses of the fault gouge material are planned or current work.

These major faults are regularly offset by a second and more dense set of faults, with relative displacements in the centimetre to decimetre scale, often in strike-slip mode. They are characterized by the absence of any well-developed fault mirror, striae, or fault gouge. They are probably to be considered as decompaction features, which occurred after uplift and erosion of the Palaeogene sequence.

At the top of the quarry, a few faults seem to have been reactivated by periglacial phenomena in Quaternary times. Locally, some of these affected the basal Quaternary beds in a growth fault mode. Permafrost deformations affecting both the top few metres of the Ieper Clay and the overlying Quaternary deposits have also been described in other quarries (Van Vaerenbergh 1987).

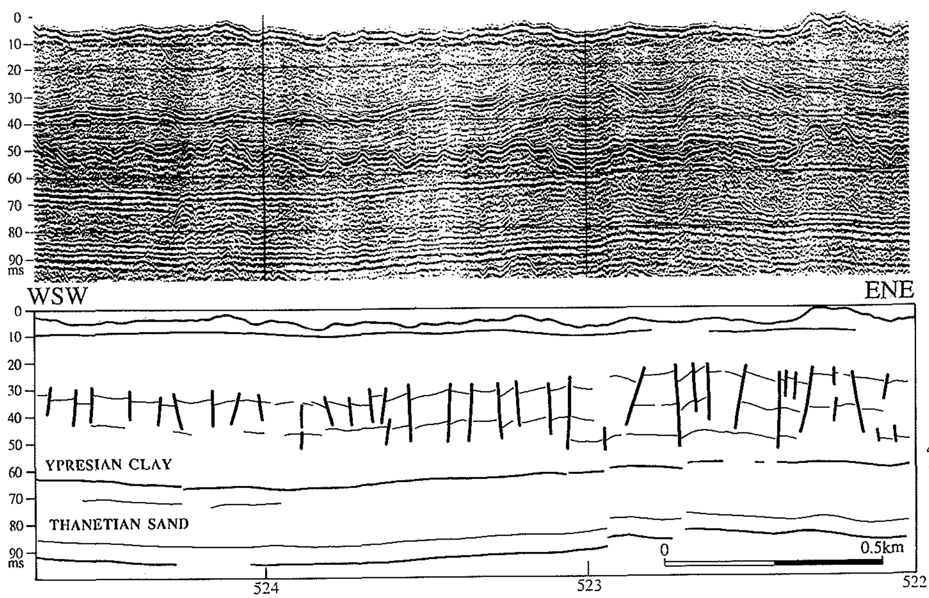


Fig. 16.4. Faulted and tilted blocks in the basal interval of the Ieper Clay (Fig. 16.1, section 1, multi-electrode sparker, 300 J). The wavy reflector at about 50 ms is the first sea-bed multiple.

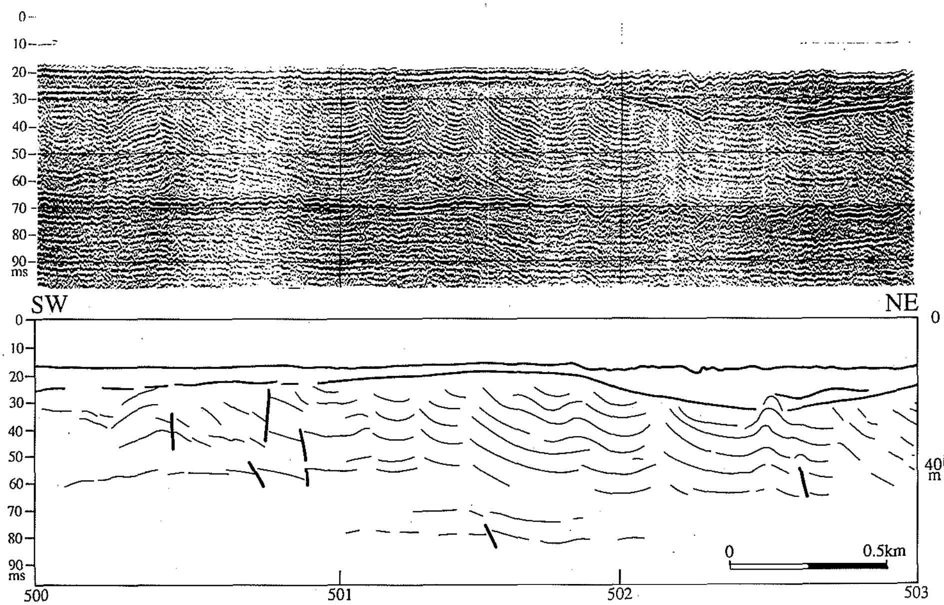


Fig. 16.5. Wavy deformation pattern in the Ieper Clay (Fig. 16.1, section 2, multi-electrode sparker, 300 J). The flat reflector at about 70 ms is the first sea-bed multiple. On the right, the base of a palaeovalley is pierced by a diapiric clay ridge, probably the consequence of a Quaternary reactivation of a pre-existing deformation.

LONDON/IEPER CLAY DEFORMATION STYLES

A few examples of these large-scale deformations on multi-electrode sparker profiles are shown on Figs. 16.4, 16.5, 16.6, and 16.7. These sections, which are located in the general outcrop or subcrop area of the London or Ieper Clay in the southern North Sea (Fig. 16.1), illustrate different deformation styles. The results of a first attempt to map the regional zonation in deformation styles is shown on Fig. 16.8.

The lower interval of the Ieper Clay, up to about 25 metres above the undisturbed basal reflector of the clay, is generally characterized by a dense pattern of block faulting, with tilted and arched blocks and apparently randomly dipping fault planes (Fig. 16.4). The average throw at the level of a reflector with a discrete high-frequency response is about 2 m.

In a second interval, from about 25 m up to at least 70 m above the clay base, one may locally observe a well-preserved wavy deformation pattern (Figs. 16.5, 16.6), consisting of a festoon-like alternation of broad, rounded synclines and narrow, cuspate anticlines. These anticlines seem to develop locally into diapiric structures. The average (apparent) wavelength of the wave-shaped deformations amounts to a few hundreds of metres, and the amplitude ranges from 2 to 10 m.

The most general deformation style observed however is a pattern of faulted and often tilted blocks, sometimes with a dominant tilt direction. This pattern has the largest distribution in the deformed zones of the Ieper Clay in the southern North Sea. The surface density of the faults has recently been investigated with a high-density seismic grid in a test zone near North Hinder Bank. The resulting map (Fig. 16.9) shows a pattern of more or less parallel, moderately curved faults, some of them lying en échelon, other ones branching or crossing each other. Small faults, with a throw of only a few metres and a length of only 200 m, can be mapped. The dominance of a certain fault orientation may have been caused either by an early local stress field related to the deformation of an underlying undercompacted horizon, as discussed later, or by any contemporaneous regional stress field. It should however be mentioned that the general fault pattern interpreted here may also be biased by the unidirectional orientation of the seismic lines, which was necessitated by traffic lane regulations. Forthcoming efforts will consequently focus on a more rigorous three-dimensional analysis of these patterns.

Approximately where the Ypresian Clay grades into the overlying Ypresian sands, about 140 m above the clay base, another peculiar deformation pattern is observed, involving faulted blocks without noticeable block movement but with inverse drag features along the fault-planes. Indeed, in contrast with bedding deformation caused by normal drag associated with block faulting, the tilting and down-warping bedding terminations point away from each other (Henriet *et al.* 1989, Fig. 6).

The deformation observed on seismograms in the roof zone of the Ieper Clay progressively fades away in the sands. On land, Ypresian sands directly overlying Ieper Clay display dense and intersecting patterns of generally normal faults with decimetric throw, associated with flow structures in clay-rich intercalations.

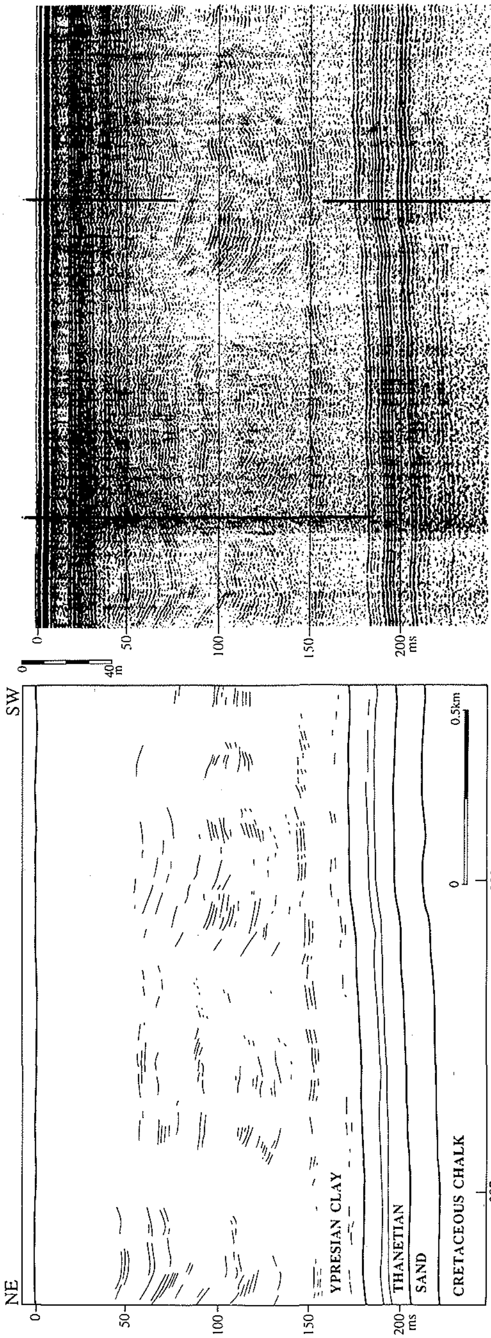


Fig. 16.6. Wavy deformation pattern in the Ieper Clay in a nearshore profile (Fig. 16.1, section 3, multi-electrode sparker, 1000 J).

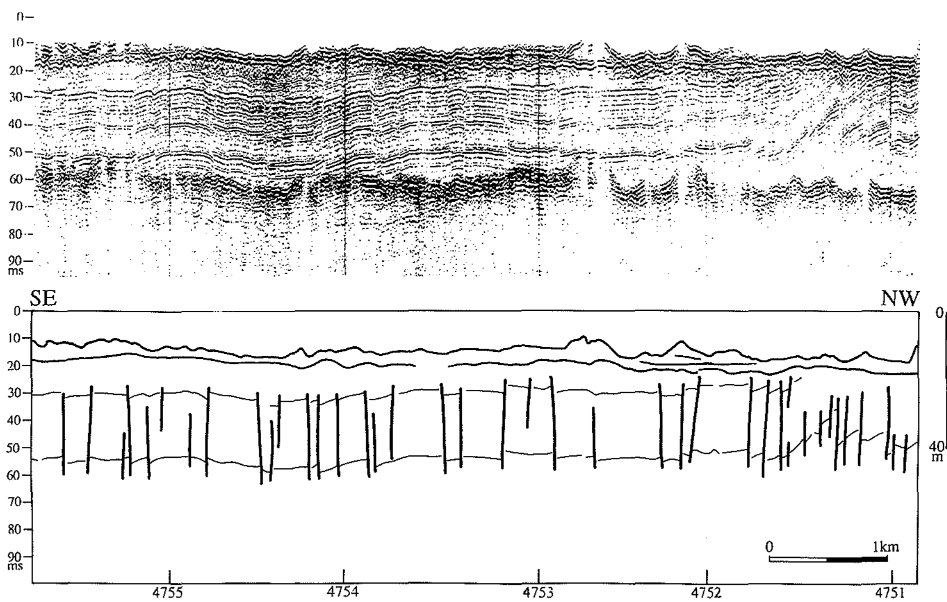


Fig. 16.7. Block-faulting in the middle to upper interval of the Ieper Clay (Fig. 16.1, section 4, multi-electrode sparker, 300 J). The wavy reflector at about 60 ms is the first sea-bed multiple. The deformation on the right is partly basement-induced.

GENETIC MODEL

A genetic model for these features has been proposed (Henriet *et al.* 1989), involving a build-up of undercompaction phenomena and, consequently, a density inversion as a result of self-sealing of the compacting clay body (Fig. 16.10).

The Ypresian clays were probably deposited as soft, high-porosity, waterlogged muds (Fig. 16.10a). As sedimentation progressed and the thickness of the clay deposits increased, pore space gradually decreased through the expulsion of pore water. Pore water drainage was probably greatest near the base, due to overburden weight tending to reduce pore space most there and to the presence of a permeable sand substratum (Thanet sands in the UK, sands of the Landen Group in Belgium) which may have provided an easy escape path for the water expelled from the basal layers of the clay. The relatively quickly-drained basal clay beds could thereby experience a faster rate of compaction, soon building a permeability barrier which gradually impeded the further basal drainage of the clay beds. The increased compaction near the clay base will have resulted in a density increase, as shown schematically on Fig. 16.10(b).

Clay sedimentation ceased and gave way to the deposition of Ypresian fine-grained and dense sands. One might consequently imagine that a similar sealing phenomenon occurred at the top of the Ieper Clay sequence. Rapid drainage through the permeable sand cover could have induced compaction from the top down, as well as from the bottom up [Figs. 16.10(c), 16.10(d)].

As a result, the clay may have sealed itself. Such a situation has two related consequences:

(1) as water has a low compressibility, the sealed part of the clay will have remained undercompacted for a time with a lower density than its overburden of compacted clays and sands [Fig. 16.10(d)]; this density inversion is gravitationally unstable;

(2) as soon as drainage was impeded in some part of the clay body, continued sedimentation meant that the locked pore water became overpressured; the resulting decrease in effective normal stress acting on the inter-particle contacts decreased the shear strength of the sediment.

Both mechanisms together may be regarded as principal agents in the development of clay tectonic deformation such as that observed in the Ypresian Clay, and especially the clay waves. The gravitational instability probably acted as the motor, which drove the sediment flow, while the overpressurized pore water acted as a lubricant, decreasing the shear resistance at the grain contacts.

The observed wave shape fits a model of deformation of an interface between two viscous fluids with different densities and viscosities, with the denser fluid resting on the lighter one. Such a model is known in fluid dynamics as a Rayleigh–Taylor instability. It predicts that the interface between a high-density upper layer and an underlying layer with lower density (and possibly lower viscosity) develops a sinusoidal instability that may evolve into a pattern of regularly-spaced upwellings of the lower-density fluid into the denser layer. This may have been the case in the Ypresian Clay [Fig. 16.10(e)].

Overpressure in shallow horizons is however intrinsically

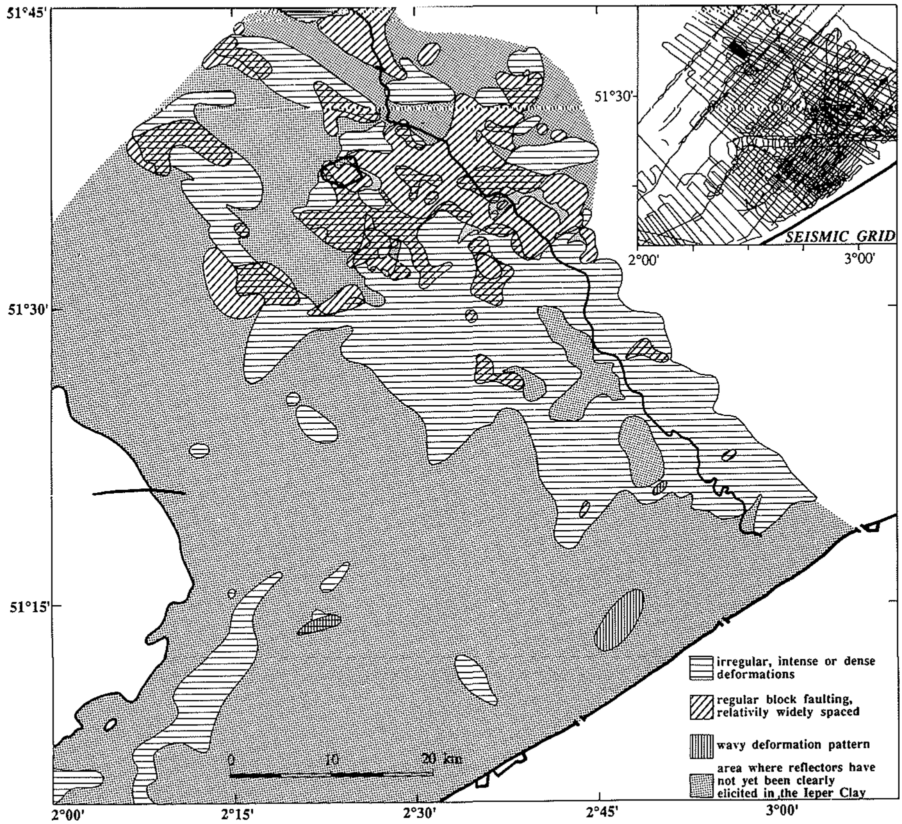


Fig. 16.8. Survey grid and regional zonation of deformation styles in the offshore extension of the Ieper Clay.

transitory. It has its origin in the delayed compaction of a clay body and disappears when conditions of hydrostatic pressure in the pore fluid are restored, either by slow seepage or by fracturing of the permeability barriers. The fracturing of the compacted (and hence more brittle) clay beds above the main undercompacted horizon could have taken place both by progressive hydrofracturing and by local fault developments, induced by the buoyant force of the upwelling clay wave crests.

As pore pressure relaxed, the upper, brittle horizons underwent faulting and tilting while progressively sagging into the initially undercompacted horizon, thus destroying the initial wave shape [Fig. 16.10(f)]. The relict wave shapes observed at a few places on the Belgian continental shelf have probably been 'frozen' by local regimes of pore water relaxation (faster, slower?) which differed from those governing the compaction over the major part of the continental shelf.

SAND BOX ANALOGUES

The observed deformation presents striking analogies with some sand-box models of extensional deformations, prepared at Rennes University, France (Vendeville, 1987; Vendeville and Cobbold 1987). In these experiments, the authors investigated the behaviour of sand layers (with density 1.3 Mg/m^3) on top of a silicone putty layer (with density 1.16 Mg/m^3), allowed to flow in one direction on a very gentle slope, and this under different loading regimes (Fig. 16.11).

There are obvious differences between the experimental conditions applied by the Rennes research team and the model for the Ypresian Clay described above. A major difference is that the development of Rayleigh–Taylor instability in our model (and in general) does not require lateral flow and hence neither a slope effect nor a basal stretch. A second difference is that the Rennes team simulated synsedimentary growth faulting by step-wise addition of sediment over progressively tilting and rotating blocks. The Ypresian block-faulting is considered to have taken place shortly after deposition and consequently does not involve any growth faulting.

What then are the analogies demonstrated by this experiment? One is that between the clay wave shapes observed in the Ypresian Clay and the silicone deformations gener-

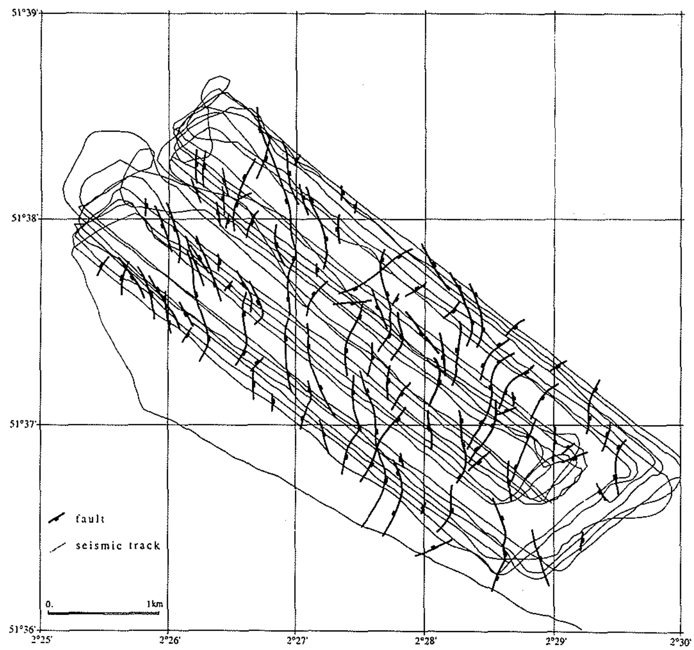


Fig. 16.9. Surface distribution of faults on a detailed study site north of North Hinder Bank (for location, see Fig. 16.1).

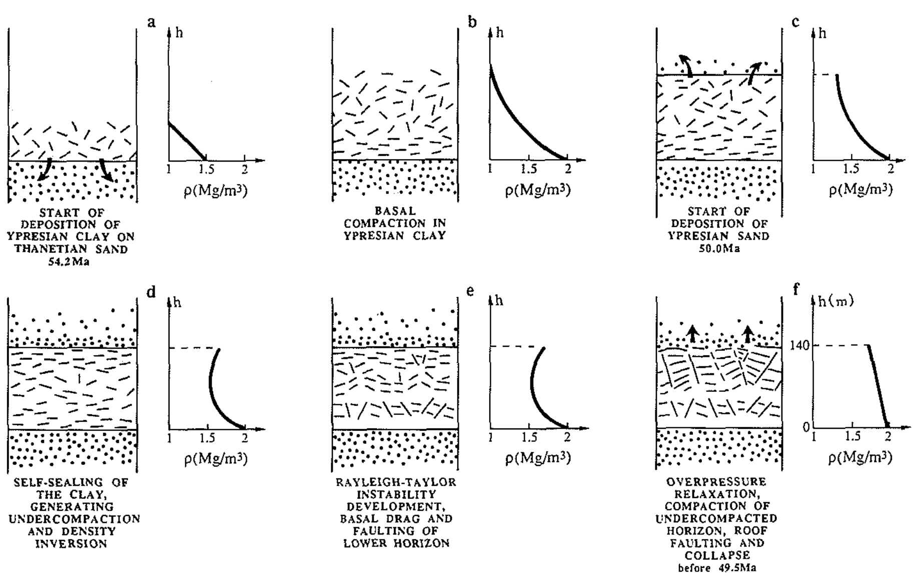
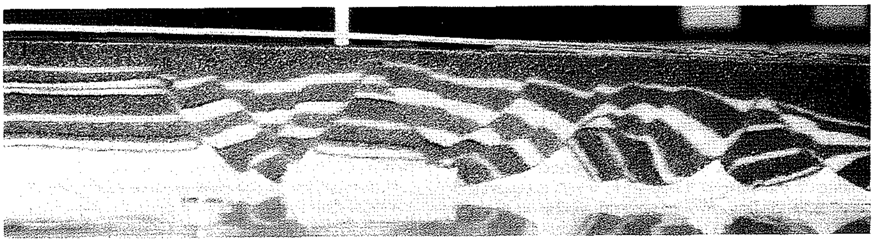
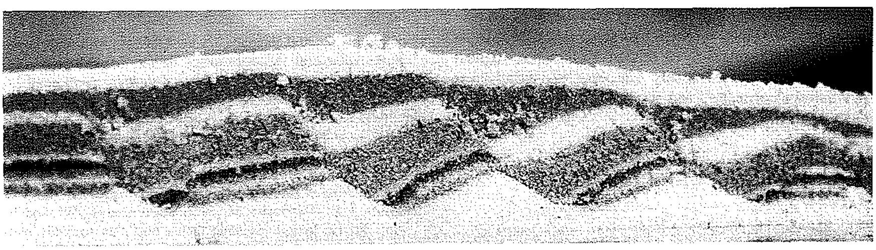


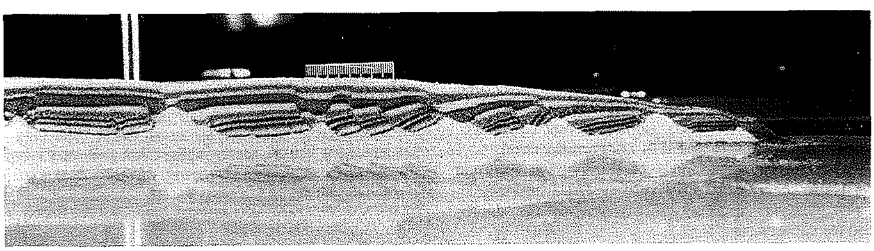
Fig. 16.10. Genetic model of the deformation in the Ypresian Clay. Arrows indicate de-watering direction. The graphs give density/depth variations of the clay.



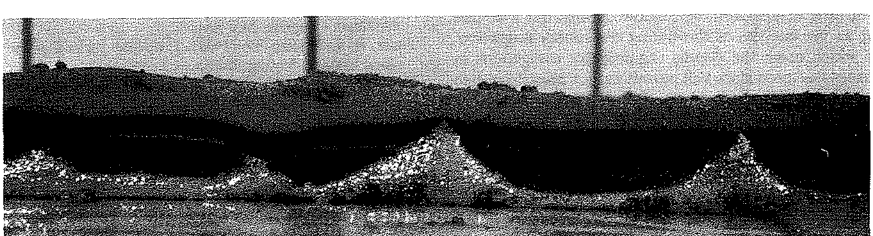
(d) non-uniform fast sedimentation



(c) non-uniform slow sedimentation



(b) fast uniform sedimentation



(a) slow uniform sedimentation

Fig. 16.11. Sand box models of deformations in sand layers (higher density) overlying silicone putty (lower density), for different loading regimes (Vendeville 1987). (a) slow uniform sedimentation; (b) fast uniform sedimentation; (c) non-uniform, slow sedimentation; (d) non-uniform, fast sedimentation.

ated under a regime of slow, uniform loading [Fig. 16.11(a)]. These deformations are beautiful examples of Rayleigh–Taylor instabilities, although not explicitly recognized as such by the authors. Their illustrative value for our model is superior to that of other published analogue models, such as those of Ramberg (1973) or Whitehead (described in Bonatti 1987). The most appealing analogy, however, is the progressive corrugation of the wave shape by rotating and tilting fault-blocks in the brittle cover when loading becomes faster and non-uniform [Fig.16.11(b),(c), and (d)]. Relaxation of the overpressure in the Ypresian Clay also resulted in an increase of the effective normal stress acting on the mineral framework, which is equivalent to an increased loading, to some extent similar to the one created in the sand box. Drainage of the excess pore water through fractures and faults must no doubt have led to relatively fast and non-uniform loading, like in the sand box experiment. However, this is over-generalization of the analogy, which is really intended as a conceptual aid. It might however be rewarding to design a sand box experiment which would more closely simulate the conditions which we believe controlled the generation of the deformation observed in the Ypresian Clay.

CONCLUDING COMMENTS: TIME OF MIGRATION

The deformation and fractures of the London/Ieper Clay are by no means unique to the Palaeogene clays of the southern North Sea basin. The Bartonian clays also show a characteristic, although quite different, internal fault development and deformation style (Fig. 16.1). Fracturing has also been observed in the Oligocene Boom Clay. The deformations of the Ieper Clay however probably owe their amplitude to the large thickness (about 150 m in the compacted state) of this relatively homogeneous clay mass, which favoured the development of undercompaction.

These clays have a certain amount of organic matter, and could possibly have developed into hydrocarbon-source-rocks (of whatever quality), if brought to the depths required for catagenesis.

The idea that potential petroleum-source-rocks may have been subjected to a general hydraulic fracturing at an early stage of their compaction, at shallow depths, has a certain impact on the analysis of the timing of primary migration. Rocks which reach the depths required for catagenesis in an already fractured state will permit earlier migration than those which still have to be fractured. Field evidence of early fracturing of potential source-rocks consequently deserves further attention.

ACKNOWLEDGEMENTS

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REFERENCES

Barker, C. (1972). Aquathermal pressuring—role of temperature in development of abnormal-pressure zones, *American Association of Petroleum Geologists Bulletin*, **56**, 2068–71.

Bonatti, E. (1987). The rifting of continents, *Scientific American*, **254**(3), 75–81.

du Rouchet, J. (1981). Stress fields, a key to oil migration. *American Association of Petroleum Geologists Bulletin*, **65**, 74–85.

Fookes, P. G. and Parrish, D. G. (1969). Observations on small-scale structural discontinuities in the London Clay and their relationship to regional geology, *Quarterly Journal of Engineering Geology*, **1**, 217–40.

Henriet, J. P., D'Olier, B., Auffret, J. P., and Andersen, H. L. (1982). Seismic tracking of geological hazards related to clay tectonics in the Southern Bight of the North Sea. *Koninklijke Vlaamse Ingenieursvereniging, Proceedings of the Symposium on Engineering in Marine Environment*, Brugge, 1.5–1.15.

Henriet, J. P., De Batist, M., Van Vaerenbergh, W., and Verschuren, M. (in press). Seismic facies and clay tectonic features of the Ypresian clay in the southern North Sea. *Bulletin van de Belgische Vereniging voor Geologie*, **98**.

Mandl, G. and Harkness, R. M. (1987). Hydrocarbon migration by hydraulic fracturing. In *Deformation of sediments and sedimentary rocks*, (ed. M. E. Jones and R. M. F. Preston). *Geological Society of London, Special publication*, No. 29, pp. 39–53.

Ramberg, H. (1973). Model studies of gravity-controlled tectonics by the centrifuge technique. In *Gravity and tectonics*. (ed. K. A. De Jong and R. Scholten), pp. 49–66. Wiley, New York.

Schnaebele, R. (1948). Monographie Géologique du Champ Pétrolifère de Pechelbronn, Strasbourg, *Mémoire de la Carte Géologique d'Alsace et de Lorraine*, **7**.

Snarsky, A. N. (1962). Die primäre Migration des Erdöls. *Freiberger Forschungshefte*, **C123**.

Tissot, B. and Pelet, R. (1971). Nouvelles données sur les mécanismes de genèse et de migration du pétrole, simulation mathématique et applications à la prospection. *Proceedings 8th World Petroleum Congress*, Moscow.

Tissot, B. and Welte, D. (1984). *Petroleum formation and occurrence*. Springer Verlag, Berlin.

Van Vaerenbergh, W. (1987). Struktuurgeologische studie van de Ieperse Klei. Licentiate Thesis, State University of Ghent, RCMG, Ghent.

Vendeville, B. (1987). Champs de failles et tectonique en extension. Modélisation expérimentale. *Mémoires et Documents du Centre Armoricain d'Etude Structurale des Socles*. No. 15, Rennes.

Vendeville, B. and Cobbold, P. R. (1987). Glissements gravitaires synsédimentaires et failles normales listriques: modèles expérimentaux, *Comptes Rendus de l'Académie des Sciences, Paris*, **305**, Série II, 1313–19.