Stratigraphy and Oil: a Review. Part 1: Exploration and Seismic Stratigraphy: Observation and Description

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Stratigraphy and Oil: A Review

Part 1

Exploration and Seismic Stratigraphy: Observation and Description

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Résumé — Stratigraphie et pétrole : bilan – Première partie : Exploration et stratigraphie sismique : observation et description — Cet article est le premier d'une série de deux articles qui porte sur l'ensemble de l'activité de recherche entreprise par l'auteur à l'*IFP* depuis 1972. Après quatre années consacrées à l'étude des marges du sud-ouest Pacifique, le fil conducteur de ses activités devient la stratigraphie, que celle-ci soit sismique ou séquentielle.

Cette série est composée de quatre chapitres résumant les résultats importants des travaux effectués, avec une attention particulière sur ceux qui ont une portée méthodologique. L'ordre chronologique a été conservé pour souligner l'évolution des idées et des méthodes.

Ce présent article comprend les trois premiers chapitres. Le premier concerne l'étude des marges actives du sud-ouest Pacifique, avec la découverte ou la précision de plusieurs traits structuraux. Ce chapitre est ici présenté car il comporte déjà les prémices de la stratigraphie sismique. Le second traite de l'introduction, en France, de l'essor et de la diffusion de la stratigraphie sismique. Le troisième porte sur l'étude des cônes détritiques sous-marins avec la large utilisation des méthodes de la stratigraphie sismique, les interactions entre les apports des travaux à terre et ceux de sismique marine, et, enfin, l'application des expériences, en canal et en cuve, destinées à l'interprétation des dépôts gravitaires. Ces résultats auront une influence importante sur le développement de la stratigraphie séquentielle.

Chacun de ces chapitres comporte une introduction qui présente l'état des connaissances à l'époque où les travaux ont été entrepris ainsi que les enjeux des recherches, un paragraphe sur les travaux réalisés et un autre dédié aux principaux résultats.

Les principales conclusions seront présentées à la fin du deuxième article.

Abstract — Stratigraphy and Oil: A Review – Part 1: Exploration and Seismic Stratigraphy: Observation and Description — *This article is the first of a series of two articles which cover all of the author's research activities at* IFP *since 1972. After four years devoted to the study of the Southwest Pacific margins, he transferred the main focus of his activities to stratigraphy, both seismic and sequence.*

This series is made up of four chapters summarizing the major results of the work done and emphasizing the studies which had a methodological impact. The chronological order is preserved to underscore the evolution of ideas and methods.

This first article has the first three chapters. The first concerns the study of the active margins of the Southwest Pacific with the discovery or clarification of several structural features. This chapter is

presented because it addresses the beginnings of seismic stratigraphy. The second deals with the introduction, growth and spread of seismic stratigraphy in France. The third concerns the study of clastic submarine fans with the broad use of seismic-stratigraphic methods, the interactions between the inputs of onshore investigations and those of marine seismic reflection, and the application of flume and tank experiments to the interpretation of gravity deposits. These results were to have a significant impact on the development of sequence stratigraphy.

Each of these chapters has an introduction that presents the state of knowledge at the time when the work was undertaken and the challenges faced by the researchers, a section on the work achieved, and another on the main results.

The main conclusions are presented at the end of the second article.

FOREWORD

The author's overall research activities were nearly always driven by stratigraphy, whether seismic or sequence, both exercising substantial mutual influences. Even the early years, during which the objective of the work was aimed at the description and understanding of active margins, served to initiate the descriptions in the sense of seismic stratigraphy by already setting questions that were only resolved later.

The work discussed in this review was achieved mainly thanks to the *IFP*'s scientific, technical and financial support. Onshore and offshore missions were made possible with the backing of various organizations: *CNEXO (Centre national d'exploitation des océans)* then *IFREMER (Institut français pour la recherche et l'exploitation de la mer), ORSTOM (Office de la recherche scientifique et technique d'Outre-Mer), FSH (Fonds de soutien aux hydrocarbures)* and *CEPM (Comité d'études pétrolières et marines*) and of oil companies *(TOTAL, SNPA (Société nationale des pétroles d'Aquitaine), SNEA-P (Société nationale Elf Aquitaine-Production) ELF*. The major projects and extensive studies conducted were also backed by several organizations (*EC (European Communities), DHYCA (Direction des hydrocarbures)* with *FSH*) and/or companies *(ELF, AGIP, GDF, MARAVEN, PETROBRAS, SAUDI ARAMCO, SONATRACH, TOTAL*, etc.). The logos of the companies and organizations mentioned are those that were in use at the time of the projects. Signification of sigla is provided at the end of the text.

Virtually all the work was done in often close cooperation with researchers of the *CNRS* ((M. Cremer, M. Deynoux, T. Jacquin, A. Mauffret, P. Patriat, etc.), *ORSTOM* (J. Dubois, G. Pascal, A. Lapouille, etc.), *CEMAGREF (Centre national du machinisme agricole, du génie rural, des eaux et forêts)* (P. Beghin, G. Brugnot), the *École nationale supérieure des mines de Paris* (A. Galli, H. Beucher, C. de Fouquet, C. Lantuéjoul, G. Le Loc'h, G. Matheron, J. Rivoirard, S. Séguret et H. Wackernagel), various universities (F. Guillocheau, JP. Loreau, P. Mechler, J. Perriaux, C. Queuille, M. Steinberg, M. Tesson, etc.) and with engineers (whose names are given with the studies) of several companies. Very early, they involved multidisciplinary groups. Also noteworthy was the active participation of numerous students of the *ENSPM* (École nationale supérieure du pétrole et des moteurs) during their final year courses, DEA diploma and PhD dissertations.

The work done at *IFP* was initiated by L. Montadert. R. Pelet contributed his sometimes critical backing. All the projects were completed in close cooperation with many *IFP* researchers: J. Letouzey, G. Jacquart, R. Vially, A. Mascle, P. Trémolières, O. de Charpal, B. Biju-Duval were the first involved. R. Eschard, B. Doligez, P. Joseph, G. Desaubliaux, O. Lerat, D. Granjeon, JC. Lecomte, Y. Mathieu, JL. Rudkiewicz, F. Van Buchem, LY. Hu, D. Guérillot are those with whom the projects of the last ten years were achieved.

1 ACTIVE MARGINS OF THE SOUTHWEST PACIFIC

This chapter discusses a part of the work done from 1972 to 1982: participation in developing the Austradec II to IV seismic surveys, participation in the Fred H. Moore (1973), Austradec II (1975), Austradec III (1979) surveys, interpretation of these surveys and dissemination of the results (reports, publications and papers).

1.1 Introduction

The late 1960s were marked by the revolution of plate tectonics (with the major contribution of Le Pichon, 1968) following a very strong interest aroused in the study of the ocean floors by several American universities. Very little was known at the time about these floors, about their nature, the processes involved in their creation (and destruction/ modification in the active margins) or the sedimentary processes that affect the different types of margin and oceanic basin. In very large areas, the knowledge of the morphology of these basins was still limited, and many structural features were discovered in the 1970s.

On highly effective means of investigation today, marine seismic reflection, was still in full development, both for signal sources and for modes of acquisition (still very often analog for acquisition by the universities and generally monotrace streamers), positioning (still in the development phase) and processing aimed to improve the signal-to-noise ratio. Migrations, first in time and then in depth, only appeared much later.

Note that the studies that were launched profited from the results of *IFP* basic studies of Verdon-sur-Mer, which was aimed to improve seismic acquisition, onshore and offshore. *IFP* had already sensed the importance of the study of the ocean floors and had devoted considerable efforts to its application, including the acquisition of the first ship: the *Florence.*

A number of problems arose concerning the renewal of the mining resources, and the oceanic domain was perceived at the time as likely to offer a reservoir for numerous resources.

In the early 1970s, *IFP, CFP (Compagnie française des pétroles), SNEA-P, ORSTOM* and *CEPM,* with the logistic support of *CNEXO,* undertook a vast project to investigate the margins of various oceans, starting with those in the French economic zones. These areas of study were soon extended to other regions. Speed was of the essence because most of the oil majors had also initiated such programs. The

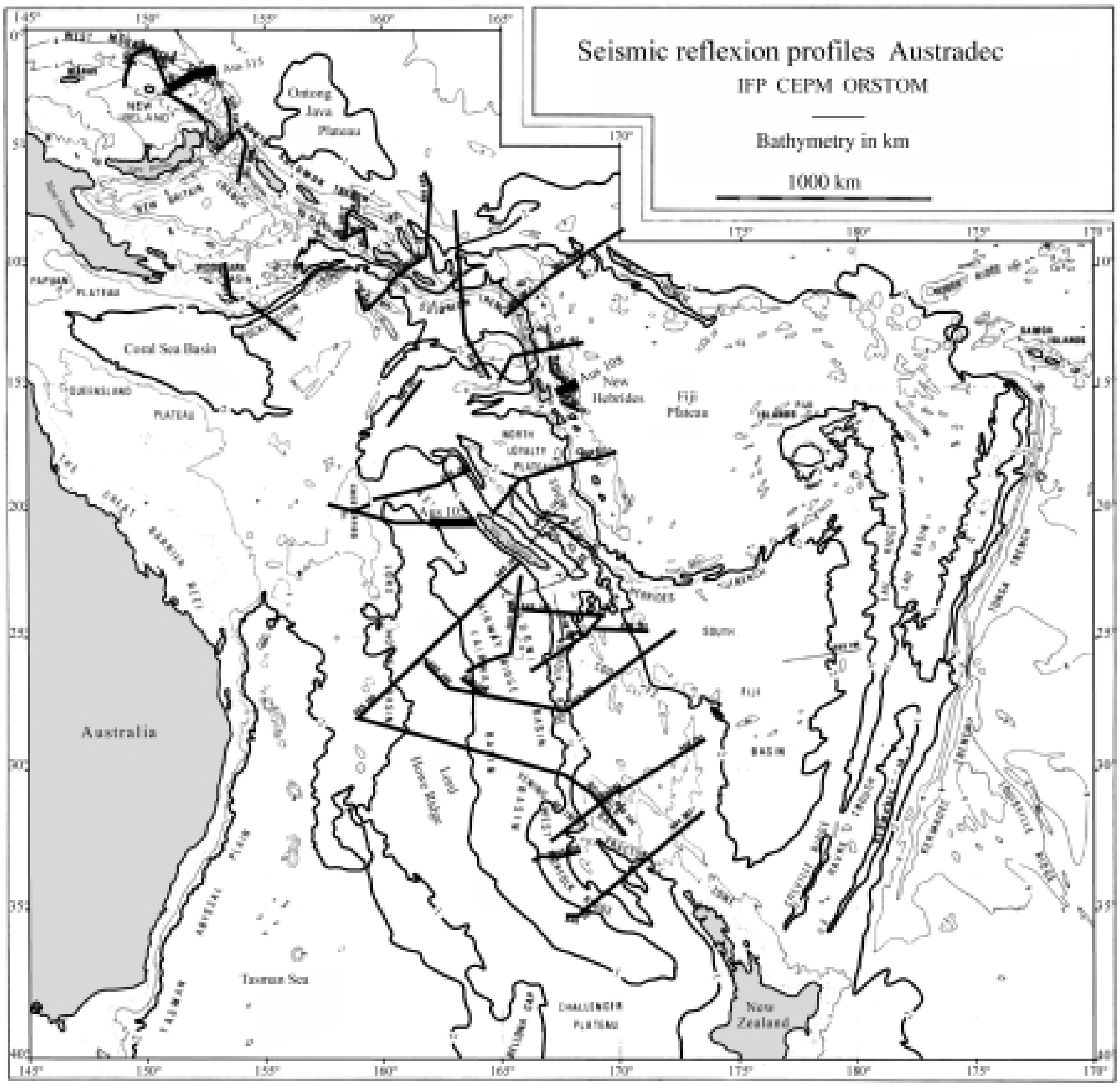

Figure 1

Southwest Pacific, position map of Austradec surveys (after Ravenne *et al.*, 1982).

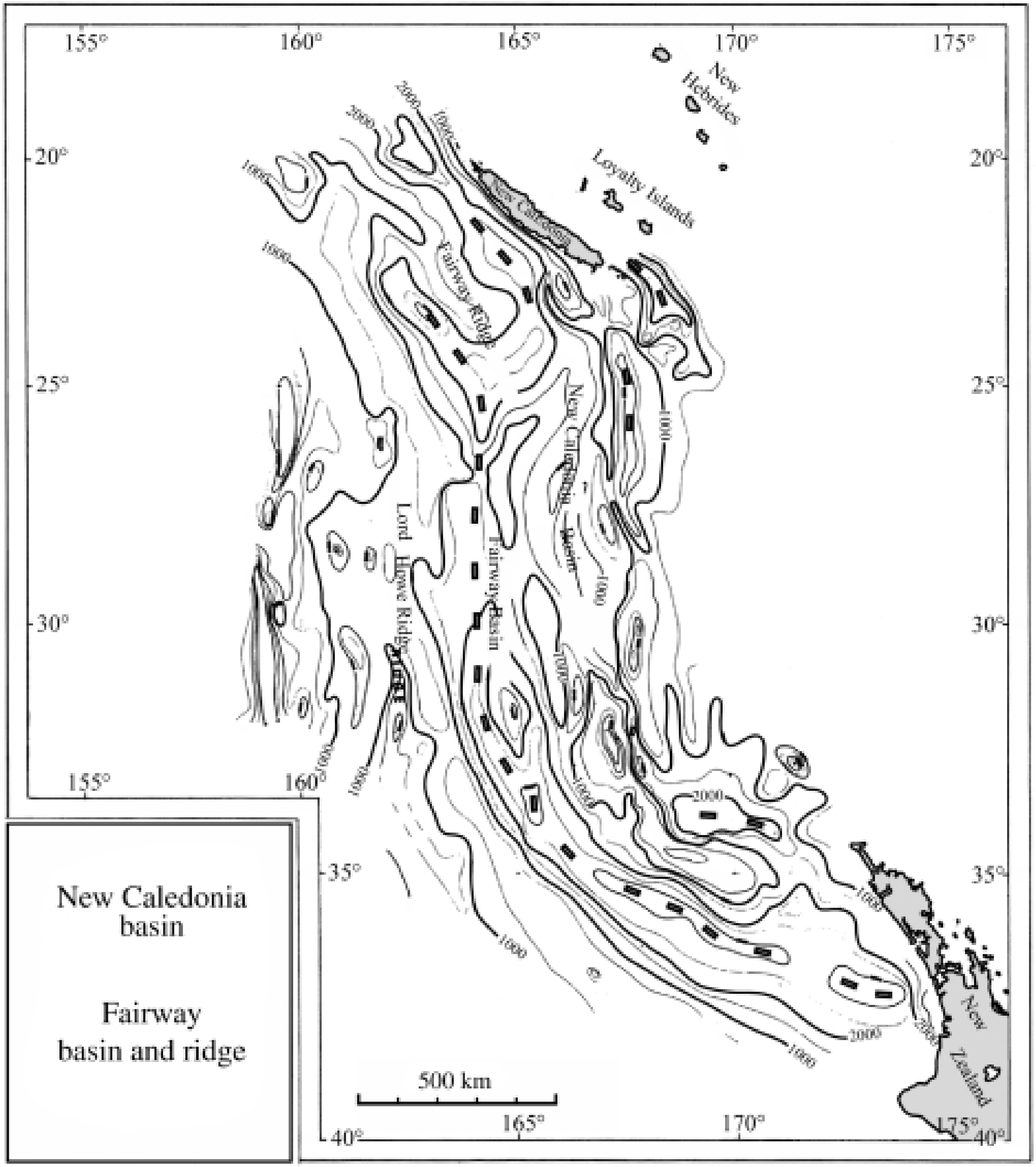

Figure 2

Isopach map of the New Caledonia and Fairway basins (after Ravenne *et al.*, 1977b).

This figure shows the subdivision of the New Caledonia basin, previously named the Fairway ridge, into the New Caledonia basin sensu stricto *(s.s.) and the Fairway basin.*

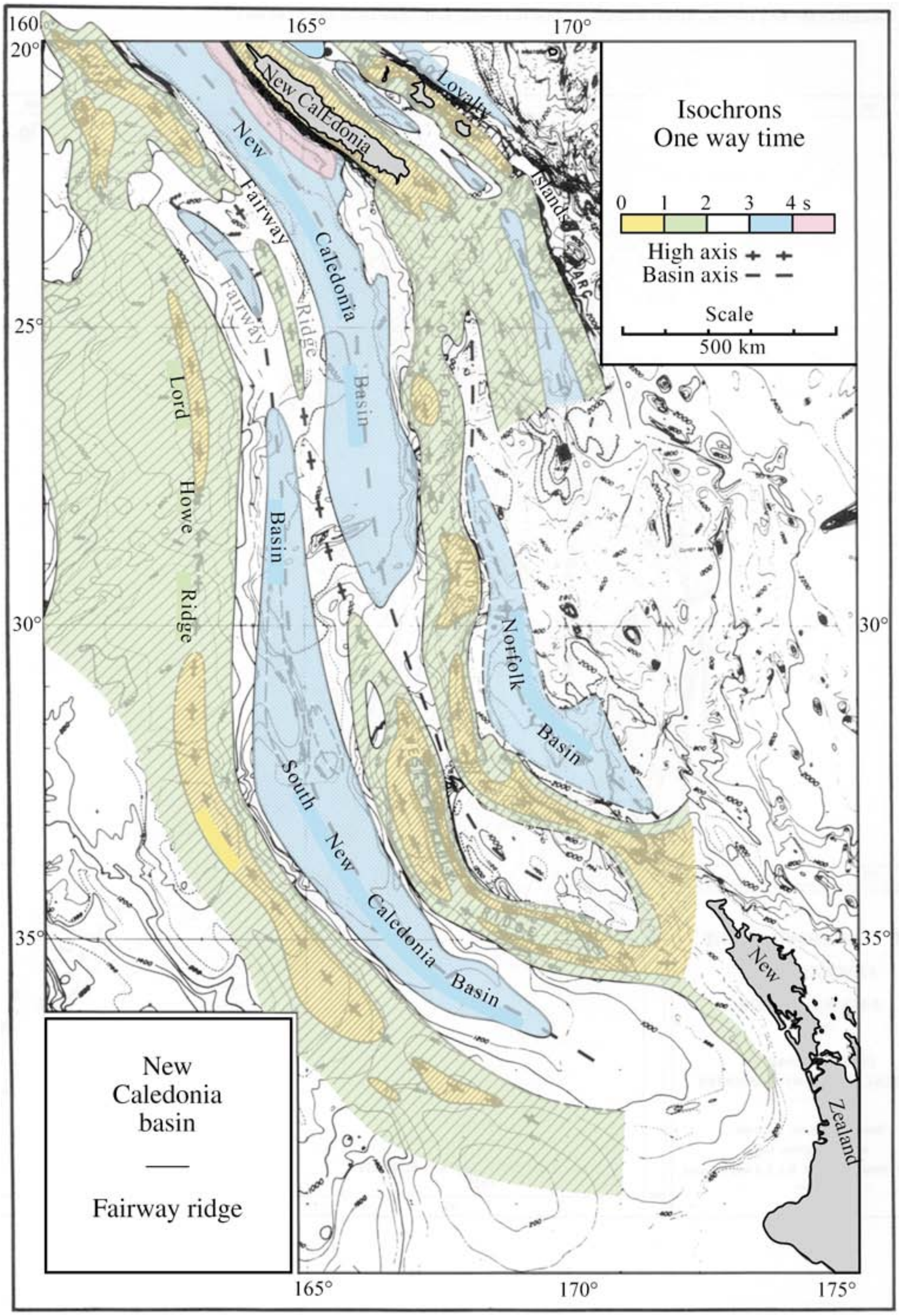

Figure 3

Structural map of Lord Howe to Norfolk ridges (after Ravenne *et al.*, 1977b).

The isochrone plot of the sedimentary cover highlights the major structural features of this region. The ridges (high axes) are shown in yellow and the basins in blue. The New Caledonia basin s.s., shown in pale purple, displays the highest thickness found in this region.

challenges were primarily economic with the search for new sedimentary accumulations, with anticipation on the possibility of exploiting them (ocean drilling was only feasible in very shallow water depths). However, the second, scientific priority, quickly revealed its potential and rapidly rose to top priority.

The Southwest Pacific economic zone (New Caledonia, the condominium of the New Hebrides and the Chesterfield Islands) was thus explored. The two principal aims were:

– the discovery of new sedimentary basins;
– the understanding and reconstruction of the history of these margins.

This scientific aspect went beyond the scope of the geological study of the Southwest Pacific and concerned the establishment of guidelines potentially valid for the deciphering of the history of more complex or more ancient margins (Mascle *et al.*, 1977).

1.2 Work Completed

Four seismic reflection surveys (Austradec I to IV) were conducted from 1972 to 1980 (*Fig. 1*). The seismic energy was supplied by a new *IFP* implosion source, the "Flexichoc" (Cholet *et al.*, 1979) which significantly improved the already high efficiency of the "Flexotir" (Cassand *et al.*, 1970). The seismic waves were collected on a 12 or 24 trace streamer and the digital recording was made by an *IFP* laboratory. All the profiles were positioned by satellite, a real achievement at the time. On the whole, adding the additional existing seismic data acquired by various foreign companies in French territorial waters, more than 100 000 km of seismic profiles were interpreted (Broin *et al.*, 1977; Ravenne *et al.*, 1977a and 1977b). Cooperative projects with *ORSTOM* researchers were conducted either on specific sectors of the geographic domain, or on specific themes. I shall mainly describe those with Dubois and Pascal which were extremely fruitful (Dubois *et al.*, 1974; Ravenne *et al.*, 1977a).

1.3 Results

These surveys identified (*Figs. 2 and 3*) the sedimentary basins and the main structures around New Caledonia, the Lord Howe ridge (Launay *et al.*, 1977) and the region extending from this ridge to the Norfolk ridge, the Solomon Islands archipelago, the area lying east of New Guinea (New Ireland, New Britain, Woodlark basin), and the Vanuatu archipelago, the site of a major project. A new structural feature, the Fairway ridge and the basin of the same name, were discovered in the New Caledonian basin. It was suggested that the Fairway ridge could be prolonged in the West Norfolk ridge.

For the first time, an interpretation was attempted in terms of seismic stratigraphy (not yet formalized at the time) by examining the lateral and vertical variations of the reflections and units consisting of several reflections in a "homogeneous sequence". It was accordingly found, from the distance to the input sources, that the north end of the New Caledonia basin, in its lower part, had a turbidite fill, whereas the Fairway basin had a pelagic fill.

Three main series were identified in the New Caledonia basin *sensu lato* (*s.l.*) (Dubois *et al.*, 1974; Ravenne *et al.*, 1977b), separated by two major unconformities (*Fig. 4*), one corresponding to an Upper Cretaceous level, and the second at the Eocene-Oligocene boundary. The mean thickness of the fill is about three kilometers. Three main types of sediment are encountered:

– clastic and terrigenous, alongside the emerged lands and hence primarily in the New Caledonia basin *s.s.* (*i.e.* the eastern part of the basin lying between the Fairway ridge and the island;
– pelagic: calcareous mud with some siliceous intercalations, especially in the Fairway basin;
– volcanoclastic.

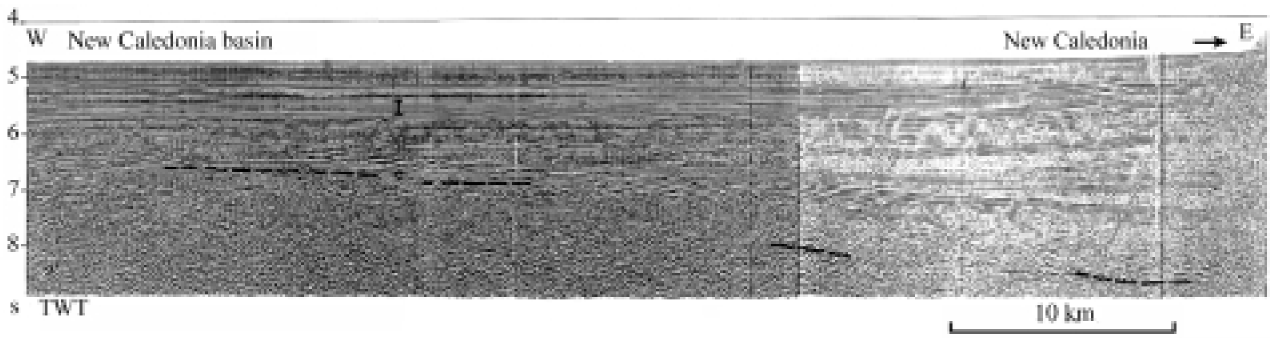

Figure 4

Southwest Pacific, Austradec 105 profile (after Dubois *et al.*, 1974).

Around 6,5 s two way time (TWT), the horizon emphasized by the dashes corresponds to the Upper Cretaceous unconformity; the limit under the I corresponds to the Eocene-Oligocene unconformity. The wedge shape that develops eastward between these two unconformities emphasizes the filling by turbidite deposits from New Caledonia.

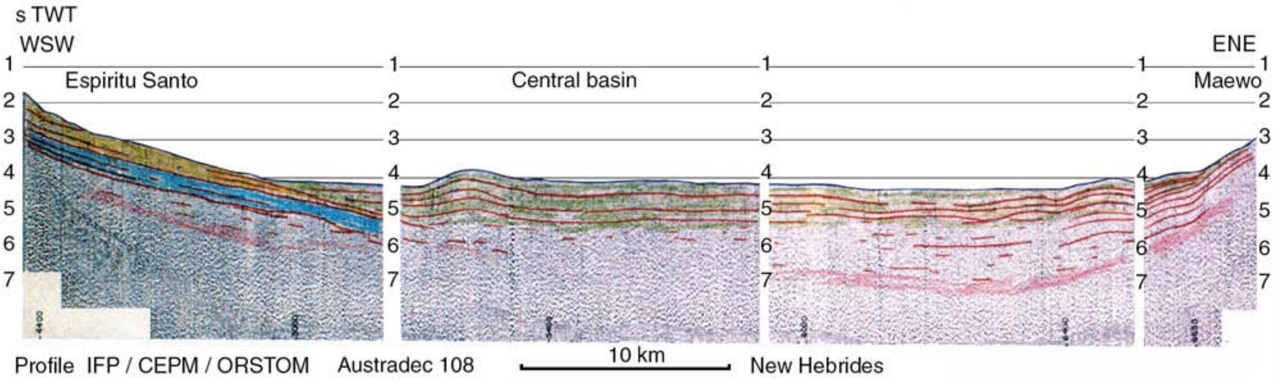

Figure 5

New Hebrides, Austradec 108 profile (after Ravenne *et al.*, 1977a).
The weak reflection definition zone between 5 and 7 s corresponds to volcanoclastic deposits. The dip of the blue and orange layers to WSW suggests the tilting associated with the arrival of the d'Entrecasteaux ridge in the subduction zone.

In the Vanuatu archipelago, the structural components of the island arc and their morphology were clarified (Ravenne *et al.*, 1977a; Dugas *et al.*, 1977) in the north and south segments of the arc, by using (after a manual anomorphosis to have comparable documents) over 20 000 km of seismic profiles (*Figs. 5 et 6*). The following were identified from west to east: the oceanic trench, an internal wall with one or two slope breaks and a suspended basin intermediate between the upper slope break and the frontal arc, the frontal arc itself, a median sedimentary basin comprising an active volcanic axis on its east limb, and finally, a complex horst-graben system separating the arc from the recent oceanic plateau, the North Fiji plateau. In this plateau, the recording of virtually horizontal reflections raised many problems: bedded crust or artifacts? This type of bedded oceanic crust is now well-known, but this appeared highly improbable at the time.

The structural features were much less easy to differentiate in the central segment of the archipelago (*Figs. 6, 7 and 8).* The internal wall of the trench is very narrow, the prolongation of the internal wall as observed in the north and south segments was occupied by the islands of Esperitu Santo and Malekula. It appears that the western part of Esperitu Santo consists of two slope breaks observed in the north segment after their uplift caused by the recent arrival of the d'Entrecasteaux fracture zone and the associated high points in the subduction zone. This interpretation was supported by two different approaches: study of the focal mechanisms of earthquakes and the seismic reflection data (Ravenne *et al*., 1977a).

It was then shown that New Ireland and the Solomon Islands archipelago had belonged *(Figs. 9 and 10)* during the major part of their history to a single island arc similar to the one of the Vanuatu archipelago in its north and south segments, displaying identical behavior and structural features (Broin *et al.*, 1977). The present active margin of the Solomon Islands archipelago is superimposed on this early island arc, without any immediate genetic relationship. The structural features of the early arc result from the ancient subduction of the Pacific plate under the Indo-Australian plate in the Middle Cenozoic. The arrival of the Ontong Java plateau in the subduction zone in the Miocene stopped this subduction and, with the continued relative movements of the plates, led to the creation of a new active margin to the south of New Britain and the Solomon Islands archipelago.

Many other scientific results were published and compiled in the International Symposium *Géodynamique du sud-ouest Pacifique*, Éditions Technip, Paris (1977), which groups most of the papers presented at the symposium (Noumea, 1977).

Finally, as shown by other articles of the work quoted, the structural features, clarified and better defined with the seismic data used in an intra-oceanic active margin domain, hence with low sedimentary cover, will participate in an understanding of the regions either with a thicker sedimentary cover or one that has undergone a more complex structural history.

Marine exploration extensively continued for nearly fifteen years. Participation in a number of acquisition surveys, in their interpretation and the dissemination of the results obtained, set the stage for the introduction and spread in France of seismic stratigraphy, a method developed by the geologists of the *Exxon* and confidential at the time.

2 SEISMIC STRATIGRAPHY

2.1 Introduction

Before and even during the 1970s, seismic data were interpreted by trained geophysicists, physicists or

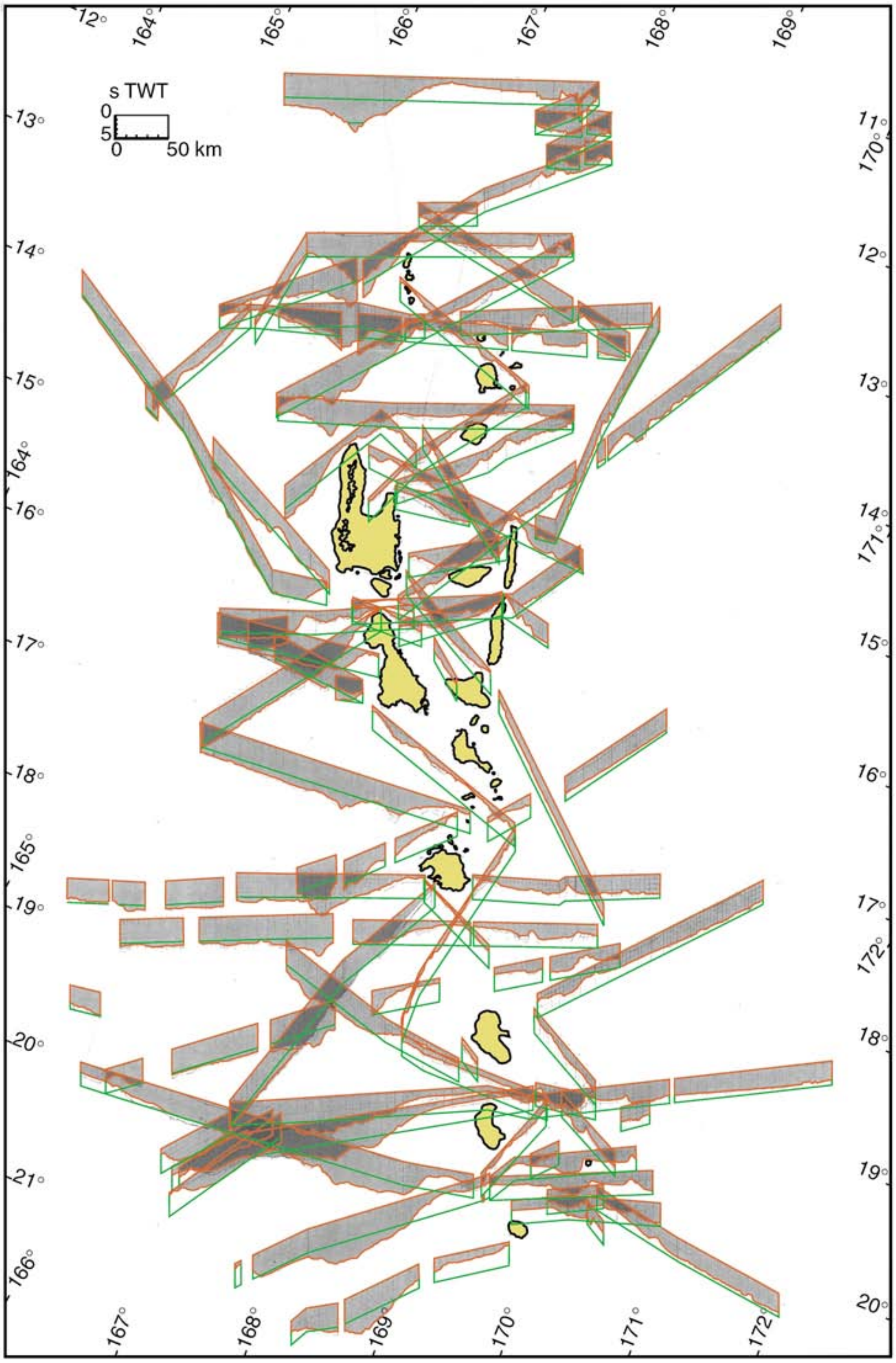

Figure 6

Serial sections in the New Hebrides arc (after Ravenne *et al.*, 1975).

This figure shows the projection of all the profiles shot in the New Hebrides region. Note particularly the morphological evolution of the internal limb of the trench (shown in the following figures) with the amplification of the intermediate basin at mid-slope going from the north and south ends towards the center.

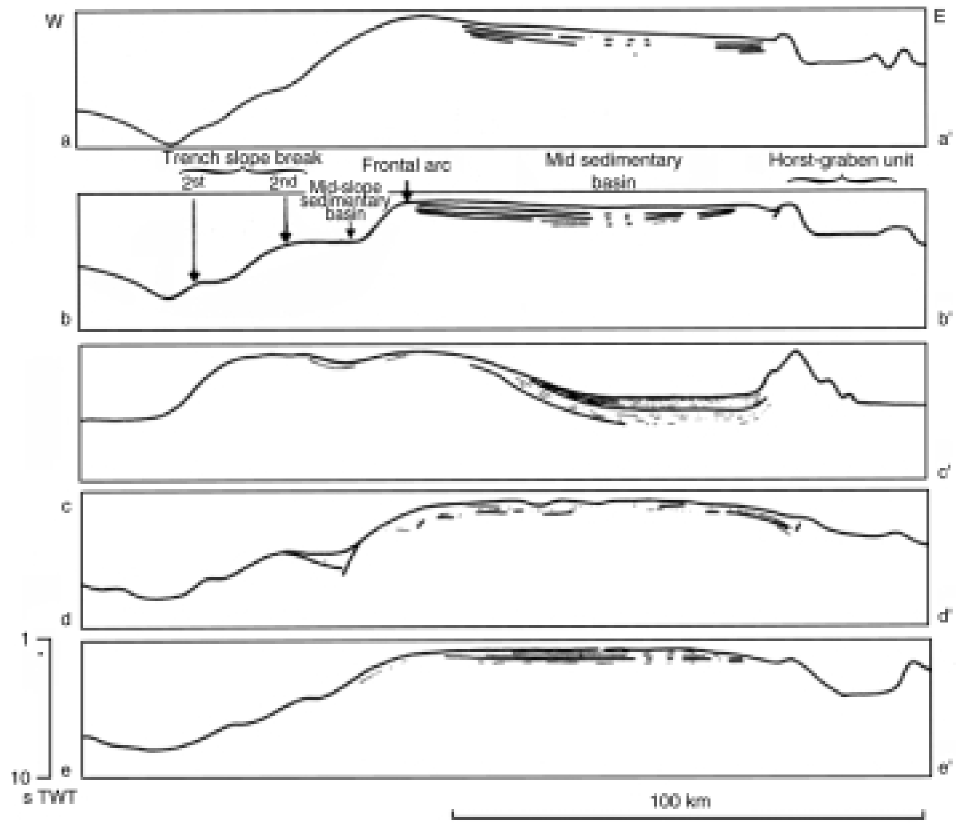

Figure 7

Profile sections at the New Hebrides arc (after Ravenne *et al.*, 1977a).

Figure showing the impact of the arrival of the d'Entrecasteaux ridge in the subduction zone to the west of section cc' on the depth of the trench and on the change in morphology of its internal limb.

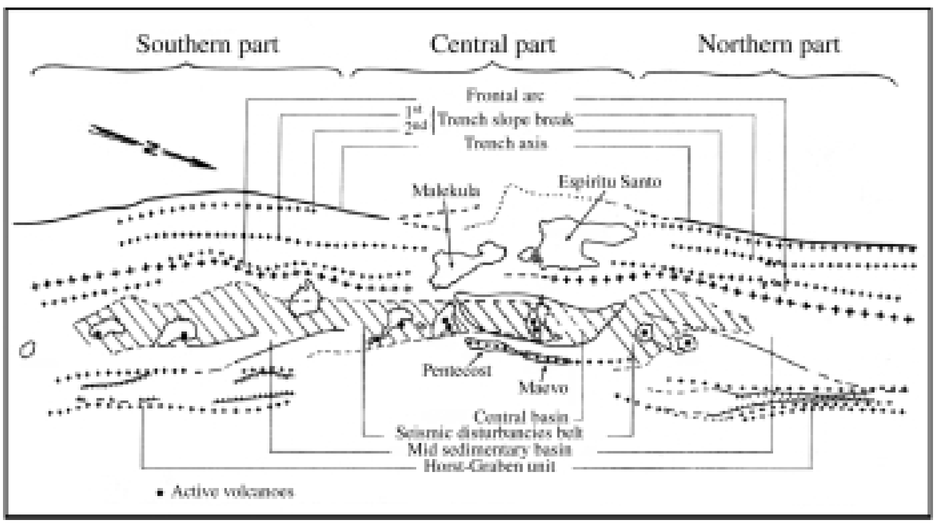

Figure 8

Structure-contour map of the Hew Hebrides (after Ravenne *et al.*, 1977a).

This structure-contour map was charted using more than 20 000 km of seismic profiles (Fig. 5). The north and south parts are very similar. The central part reveals numerous differences and shows how the two slope breaks of the northern part collide in Esperitu Santo, the result, as we suggest, of the entry of the d'Entrecasteaux fracture zone in the subduction zone.

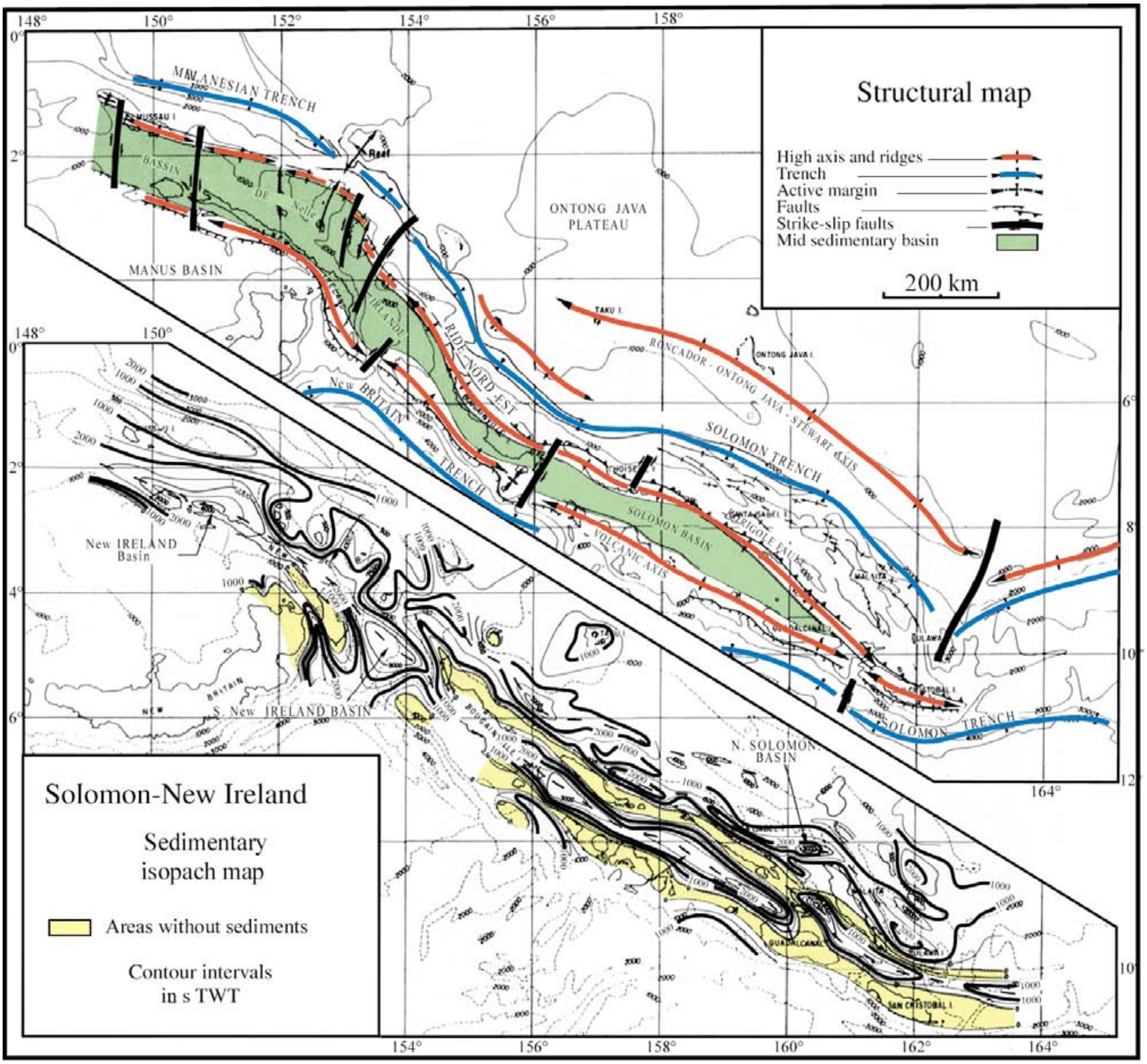

Figure 9

Structural and isopach maps of the Solomon's New Ireland region (after Broin *et al.*, 1977).

The upper part of the figure shows all the structural features framing the Solomon's basin and its prolongation into the New Ireland basin. The predominant trend is NW-SE. These structural features are affected by NNE-SSW strike slip faults. The bottom part shows the isopachs of the sedimentary deposits. The sediment-free zones correspond to the volcanic axes bordering the basins.

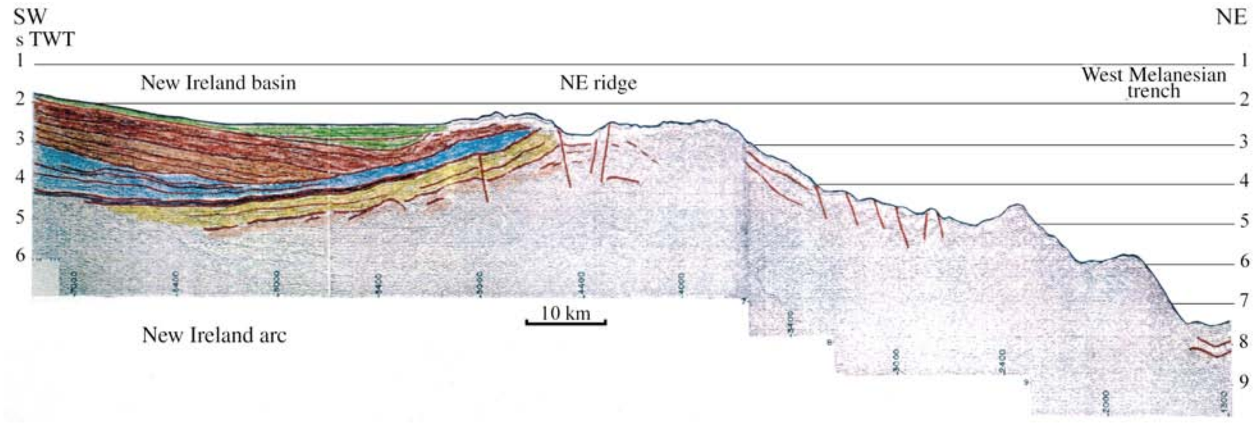

Figure 10

New Ireland: Austradec 315 profile (after Broin *et al.*, 1977).

The sedimentary fill of the New Ireland basin illustrates the complex history of this region. It can be assumed that most of the sedimentation took place in horizontal strata given the configuration of the reflections. The northeastward uplift of the yellow series and of the bottom part of the blue series is probably caused by the arrival of the Ontong Java plateau in the subduction zone. The eastward tilt of the upper part of the blue series and the red series indicates a differential uplift of the SW limb of the arc. Only the green series has not been affected by later deformations.

mathematicians, and very seldom by geologists. The first ones mainly favored treatments that served to improve and reinforce the continuity of reflections such as AMCO (coherence enhancement, « amélioration de cohérence » in French). This type of processing cancels a large part of the information and thereby led certain geophysicists to correlate platforms of Jurassic and Cretaceous age with a Quaternary fill, the erosion unconformity having been erased and the reflections on either side artificially joined! Few geologists were trained as both geologists and geophysicists, therefore able to enlist geological knowledge to interpret the profiles. The results thus obtained were nonetheless hotly debated, indeed criticized, precise because of the consideration of geological knowledge and the uncertainties suggested by the geophysicists. Even today, many geophysicists consider that the geological interpretation in terms of lithology is highly risky because a reflection results from a complex route.

The “FAGIS” research project, common to *SNEA-P* and *IFP* was created in late 1977 to improve the results of seismic interpretation. The acquisition processes of seismic data were in fact very costly, and the time allowed to interpretation very short. Besides, very few concepts were available to guide interpretation. Hence the challenges were clearly to supply the interpreters with documented and, if possible, validated guides.

2.2 Work Completed

The work began with a bibliographic synthesis based on a first course by Vail (1976) on seismic stratigraphy. This course by Vail—a former student of Sloss, who made a huge contribution to the evolution of sequence stratigraphy (Sloss *et al.*, 1949; Sloss, 1963, 1988)—was the essential factor, particularly since this first course contained all the reservations and hesitations making it a potentially very rich tool compared with the *AAPG 26 Memorandum* (1977) which came later and settled a major part of the reservations expressed. It served as a support for the drafting of four reports (Ravenne, 1978; Ravenne, 1981). The most important dealt with eustatic variations, a term that the author considered incorrect because of the knowledge available and which he converted into thickness variations of the water column on the platforms. This was certainly more lengthy and more cumbersome, but accurate and usable for setting aside conflicts of interpretation. Frequent meetings with Vail then covered points of disagreement such as excessively sudden drops (for the author) in the sea-level that he assumed. These discussions, followed by many joint field missions, always revealed a very open researcher, analyzing and testing all the hypotheses. Note that the report on thickness variations of the water column was initially the one most questioned by the industrial partner, because judged too academic, and even disregarded as a complete waste of time. Two years later, this judgment was completely reversed. The method was then widely disseminated in the academic work (courses and seminars).

Following this study, Bôt *(CFP)* and the author undertook a synthetic study of the North Sea, mainly focused on the Cenozoic. The large regional profiles available were virtually unused to analyze the sequences of this era, although they appeared extremely rich for investigating all the sequences and evolutions of the facies in this relatively shallow environment. Under the direction of the author, several students used these profiles to prepare their final year reports at *ENSPM*, or their thesis work. Noteworthy was the thesis of Le Nir (1987), which stood as a reference for many years.

2.3 Results

The main result is the widely used, disseminated and taught interpretation method, that remains a reference. This method is based on a rigorous observation of all the seismic parameters (continuity, amplitude, apparent frequency, configuration, reflection terminations, search for unconformities, etc), and on their classification within uniform units (belonging to the same depositional "sequence") to define seismic "facies" and then on the 3D analysis of their lateral and vertical variations. Interpretation only took place after these three steps were completed.

The use of this method first led to a completely new mode of interpretation, objective and predictive, checked by the trained geologists, and then to a review of a number of destructive processings of the information contained in the seismic data. Many new sedimentological and stratigraphic concepts were then developed during the application of the method to the massive exploration profiles. These profiles were in fact obtained over long distances which, in the sense of the inputs, often began near the coast and ended in the clear oceanic basins, thereby allowing the study of the evolution of the deposits. The new concepts led to the development of sequence stratigraphy.

Sequence stratigraphy was practiced at the time by two schools (roughly speaking, one based on the definition of the unconformities—*Exxon* and *Vail School*—and the second on the maximum flooding surfaces—Galloway, 1989; Cross, 1988; Cross and Lessenger, 1988). The one supported by Vail derived from seismic stratigraphy which he had rigorously formalized (Vail, 1976; Vail *et al.*, 1977a, 1977b). Most of the author's work addressed the interpretation of seismic data following the approach proposed by Vail. During the lessons given, stress was laid on the first task, which consisted in finding the terminations of the reflections in order to determine the unconformities. These unconformities and/or their prolongation helped in turn to pinpoint the depositional sequences within which the work on the seismic facies could begin. However, it soon appeared to the author that his practice was different when he interpreted sections. While he began by finding the terminations, he very quickly switched to the search for the most continuous possible high-apparent frequency reflections which helped to separate the sets of reflections he could

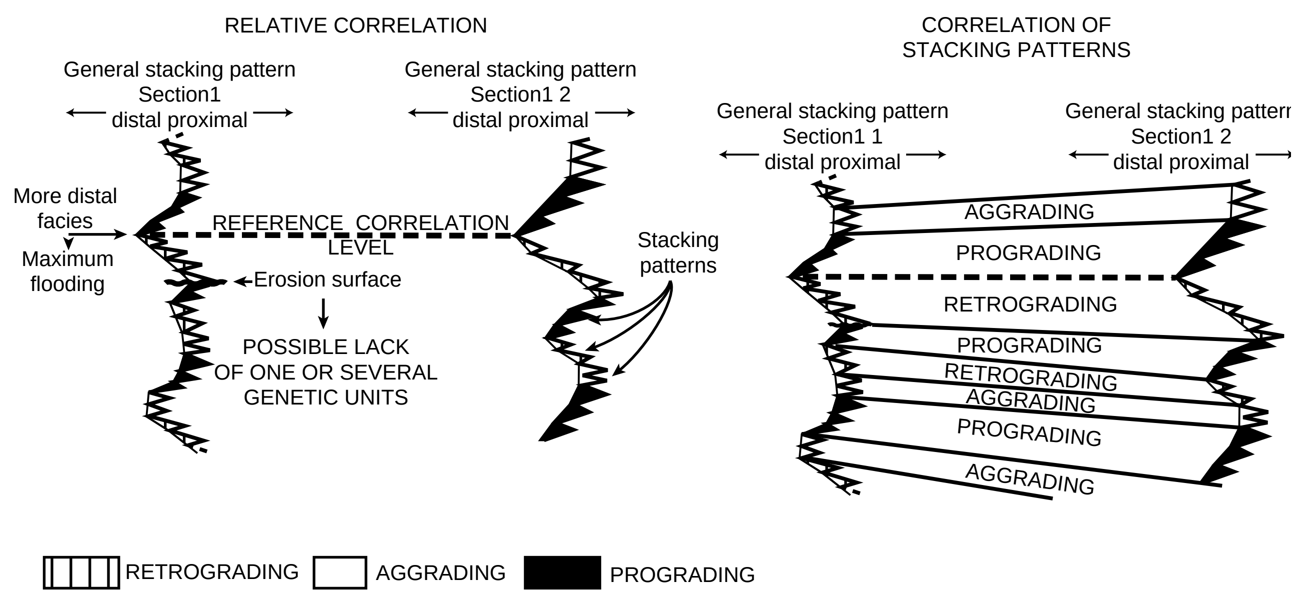

Figure 11

Sequence stratigraphy, correlation model (after Lafont, 1994).

The 1st correlation is made on the most distal facies after having reconstructed the general stacking motifs (from distal to proximal). The subsequent peaks are then correlated so as to underscore the hiatus.

resume the search for terminations. This was already in fact the simultaneous use of both types of surface and hence of both schools. This comment was subsequently incorporated in the teachings. The important factor was to decipher, understand and then predict the lateral and vertical evolution of the deposits. The definition of the sequences, in one case: a continuous succession of strata bounded by often diachronous unconformities; in the other: a succession of strata likely to be affected by internal erosion but bounded by continuous and relatively synchronous strata, did not affect the understanding of the sedimentary unit. A contrast, it was sometimes easier to recognize the unconformities or more continuous horizons. Experience showed that the determination of the flood surfaces made section-to-section correlations easier, starting with the correlation of the major episodes, then of the less pronounced episodes helping to identify the disappearance of certain units; this technique is very well illustrated (*Fig. 11*) in the thesis memorandum of Lafont (1994). In short, the results thus obtained assumed considerable importance in the interpretations of the seismic profiles because they put numerous geological interpretations and correlations into question. They also revealed the extraordinary lateral variation of the seismic facies within a given depositional sequence in marine environment, the importance of gravity mechanisms, etc. The development of seismic stratigraphy ultimately led to the development of sequence stratigraphy.

3 DEEP SEA FANS

3.1 Introduction

Towards the late 1970s, several oil companies found that many oil reservoirs presumed to be located in platform environments were (or could be) in environments of submarine clastic fans. These were relatively unknown, except onshore chiefly with the work of Mutti (Mutti, 1974a; Mutti and Ricci Lucchi, 1974b; Mutti and Ricci Lucchi, 1975), Normark (1970, 1974, 1978), Walker (Walker, 1967; Walker and Mutti, 1973; Walker, 1978), Bouma (1962), Stanley (1961, 1975; Stanley *et al.*, 1978). Experiments in analog modeling of turbiditic currents conducted by Kuenen (Kuenen, 1937; Kuenen and Migliorini, 1950; Kuenen *et al.*, 1956; Kuenen *et al.*, 1957; Kuenen, 1964) and Middleton (1966a and 1966b, 1967, 1970; Middleton and Hampton, 1973) allowed a preliminary understanding of the development of gravity deposits. The importance of gravity collapses at sea was chiefly known due to their devastating effects on telephone lines. At the time, the *Committee of Marine Petroleum Studies* launched a study program targeting deep sea fans. Certain sedimentary accumulations had already been recognized on slopes of stable margins and slope bottoms during major exploration seismic surveys (Bay of Biscay, 1969, Mediterranean, 1970, GéoManche, 1975, Cape Verde, 1980); these profiles, too widely spaced, did not allow their characterization.

At the technical level, the acquisition and processing of seismic data had advanced considerably. The Verdon-sur-Mer team that had developed the Flexichoc (Cholet *et al.*, 1979), a highly efficient implosion source for the quality of the signal produced and which avoided harmful bubble effects, had just developed a new source: the mini Flexichoc (Grau, 1981), also based on the implosion principle. This source featured a lower power, hence less penetration depth, but higher resolution power than with conventional sources. To provide an order of magnitude, a conventional source offered a resolution power of about 50 m in the sedimentary series between 1000 and 3000 m under the sea-floor, while that of the mini Flexichoc reached 10 m, a significant advantage for the precise analysis of sedimentary series. The lack of power could be offset by the simultaneous or slightly offset use of several sources.

The possibility of shifting the moment of the implosion of each of the sources was exploited shortly thereafter by Thillaye du Boullay (1977, 1979a) to obtain indications about dip in the transverse direction to the movement of the ship and thereby analyze the first profiles with controlled 3D information (Thillaye du Boullay, 1979b). This was invaluable in the study of the faulted parts of the slopes, pull-apart scars, etc., because in these cases, the sources of the reflections were diverse and only partly originated in the stratas located vertically under the line joining the emission source to the signal reception streamer, an effect that was amplified with decreasing depth. This point is often ignored, and for a preliminary and rapid interpretation, the tendency is to consider that the observed profile only contains reflections located in the same plane. Progress was subsequently achieved in the improvement of a focusing of the signal transmitted and today, the virtual generalization of 3D seismic reflection avoids this pitfall (Walton, 1972; Brown, 1986; Weimer and Davis, 1996). Seismic data processing had also advanced considerably and multiple onboard coverage immediately allowed a solid interpretation and hence the possibility of guiding the rest of the survey or re-shooting a profile.

The *CNEXO* then acquired the *Sea Beam* a multibeam depth finder. This made it possible to chart bathymetric maps of hitherto unequalled accuracy, a source highly appreciated for the improvement of the knowledge of the ocean floor, particularly with the spatial coverage provided and the possibility of identifying the evolution of the sea floor during repeated acquisitions.

The challenges were essentially economic, very close to those that had led to the launching of the generalized exploration of the ocean floor: survey of potentially favorable zones for hydrocarbon trapping and an increase in the permit area. The aim was to obtain a model or models of organization of deep sea fans and their characteristics. At the scientific level, this involved developing knowledge that was virtually nonexistent in France, indeed to discover new sedimentary units and to understand the processes responsible for their deposition.

3.2 Work Completed

Several offshore surveys were conducted:

– in the Gulf of Lion (Mediterranean Sea): HR 1 survey (Briend *et al.*, 1981), LIGO 1 survey (Gubian *et al.*, 1981), LIGO 2 survey (Briend *et al.*, 1982);
– in the Biscay Bay (Atlantic Ocean): Seafer 2 survey (Morice, 1981), CF1 survey (Coumes *et al.*, 1981, 1982; Cremer, 1983; Ravenne *et al.*, 1983b; Cremer *et al.*, 1985; Orsolini *et al.*, 1984; Nely *et al.*, 1985; Ravenne *et al.*, 1988c);
– in the Bahamas: BACAR 2 survey (Le Quellec *et al.*, 1983; Ravenne *et al.*, 1984, 1985; Ravenne *et al.*, 1988d);
– and in the Indian Ocean: Indus fan (Coumes *et al.*, 1978), Indus survey (Ravenne *et al.*, 1986; Ravenne *et al.*, 1988b).

Only the last three will be mentioned, partly because of the quality of the results obtained and also because of the author's substantial, sometimes preponderant, participation in the interpretation of their profiles. This participation gave him familiarity with all the events that affected the progress of the surveys (for example, suspended shooting, positioning errors, etc.) and to take account of them in interpretation.

To improve the interpretation of the seismic data acquired in submarine fan environments, the author initiated a long series of projects (in which he actively participated) on the Annot Sandstones *s.l.*, from 1980 to 1985. They were then extended from 1984 to 1986 to the south end of the Vercors and a part of the Vocontian domain for a better interpretation and understanding of gravity deposits of calcareous origin. The aim of these projects was not to increase the regional geological knowledge but rather to find analogues of what was described on the seismic sections, both for the unconformities, configurations of reflections, parameters enabling the definition of seismic facies, and for these facies themselves.

At the time, Beghin, a fluid mechanics specialist, and researcher at *CEMAGREF*, carried out flume experiments to model snow avalanches by triggering gravity flows of particles or dense fluids in water. The first mission conducted in the Annot Sandstones (1980) enabled Cremer and the author to identify a typical succession, a "sequence", in the bars containing their coarsest grained material and which they called "granule bars". This sequence in no way resembled the Bouma sequence, so that there was no data for deciphering the processes responsible for edification. The task involved understanding and explaining the processes responsible for its deposition, anticipating the spinoffs of the results in the exploration of these deposits, and the knowledge of the experiments arrived at the ideal moment. They offered perfect conditions for modeling the depositional processes which concerned the aim of this work, and thereby led to a collaboration that lasted more than ten years, during which the equipment (large tank, laser tracking of flows, etc.) and the flow initiation processes were improved.

Cooperation with *CEMAGREF* is expected to start again with a recent revival of interest in submarine fans, which is discussed in the chapter dealing with the characteristics of the reservoirs (2nd article).

The data acquired both offshore and onshore, and the flume and tank experiments served for diploma studies and thesis, which were directed or codirected by the author (Inglis *et al.*, 1981; Jean, 1985; Jean *et al.*, 1985; Laval, 1988; Laval *et al.*, 1988).

3.3 Results

The only results presented here are those considered significant from the methodological and scientific standpoint. Those obtained by the interpretation of the data acquired during the deep sea surveys are then described, followed by those concerning field studies and finally, those resulting from experiments. The results of these projects have been consigned to many reports (a few linear meters for Cap-Ferret!) and some of them (too few) have been published.

Some data are now less confidential, although still valid today, and could be the subject of quality theses given the progress achieved in the establishment of concepts in sequence stratigraphy (the bibliography is too large on this subject to be fully mentioned here, but certain projects are worth recalling here, including the forerunner and still valid work of Gressly (1838)—Cross and Homewood (1995)—and Walther (1894), then those of Sloss, already mentioned, Wheeler (1958 and 1964); Swifp (1968), Vail, already mentioned, the 1980s and 1990s witnessed the proliferation of a considerable number of reference publications: Goodwin and Anderson (1985), Kauffman (1986 and 1988), Jervey (1988), Posamentier *et al.* (1988), Van Wagoner *et al.* (1988 and 1990), Guillocheau et *al*. (1989), Tesson *et al*. (1990a and 1990b), Guillocheau (1990, 1991 and 1995), Goldhammer *et al.* (1990), Devine (1991), Jacquin *et al*. (1991), McDonough and Cross (1991), Mitchum *et al*. (1991), Homewood *et al.* (1992). These years also witness the publication of four unavoidable works in facies sedimentology and stratigraphy: Reineck and Singh (1980), Leeder (1982), Reading (1986) and Miall (1990). Already a thesis that the author codirected with Orszag-Sperber was carried out in this spirit (Lafont-Pétassou, 1993) presuming the data of the Indus fan. These results put into question well established concepts and were accordingly published. This thesis represents a model in terms of seismic-stratigraphic interpretation using latest sequence stratigraphy concepts at the time, in other words, those published including the theses of Proust (1990) and Merzeraud (1992) and the review nearing completion by Jacquin, those not published at the *University of Rennes* (work of Guillocheau and his team), also unpublished work under way at *IFP* (Eschard, Van Buchem) and those published in the thesis of Lafont (1994). This thesis proposes a conceptual link between the principal schools of sequence stratigraphy (Vail, 1976; Vail *et al.*, 1977a and 1977b, 1991; Cross, 1988, 1989; Galloway, 1989).

3.3.1 Sea Surveys

Cap-Ferret (France)

This site, previously surveyed by Berthois *et al.* (1969, *Fig. 12)* was the subject of two bathymetric map surveys with the *CNEXO* multibeam finder *(Fig. 13)*, three seismic acquisition surveys *(Fig. 14)* and a diving survey with the submersible *Cyana*. Cremer, for his thesis work, and the author, were the permanent interpreters of these surveys. The thesis of Cremer (1983) should have exclusively concerned the deep Cap-Ferret deposits, but was quickly extended to the study of the Annot Sandstones (directed by the author).

Engineers from the partner oil companies also participated in seismic interpretation. Thus Orsolini *(SNEA-P)* worked for several periods spread over the first two years (1980 and 1981). The rather frequent changes of industrial partners that followed was often the cause of wasted time because of the customary questioning by the new arrival of work previously done. This was not deliberate, but the survey site was very complicated and many sediment input sources were involved; the conclusions previously obtained were nearly always based on a set of tenuous observations and not on a single undeniable fact. Besides, each new arrival came with his experience and hence tried to insert the knowledge acquired elsewhere. One to two months was lost at every stage, reaching three months towards the end of the study.

This site was the subject of several years of study finalized by numerous reports, a single publication (Nely *et al.*, 1985) and the thesis of Cremer (1983). Other publications and the

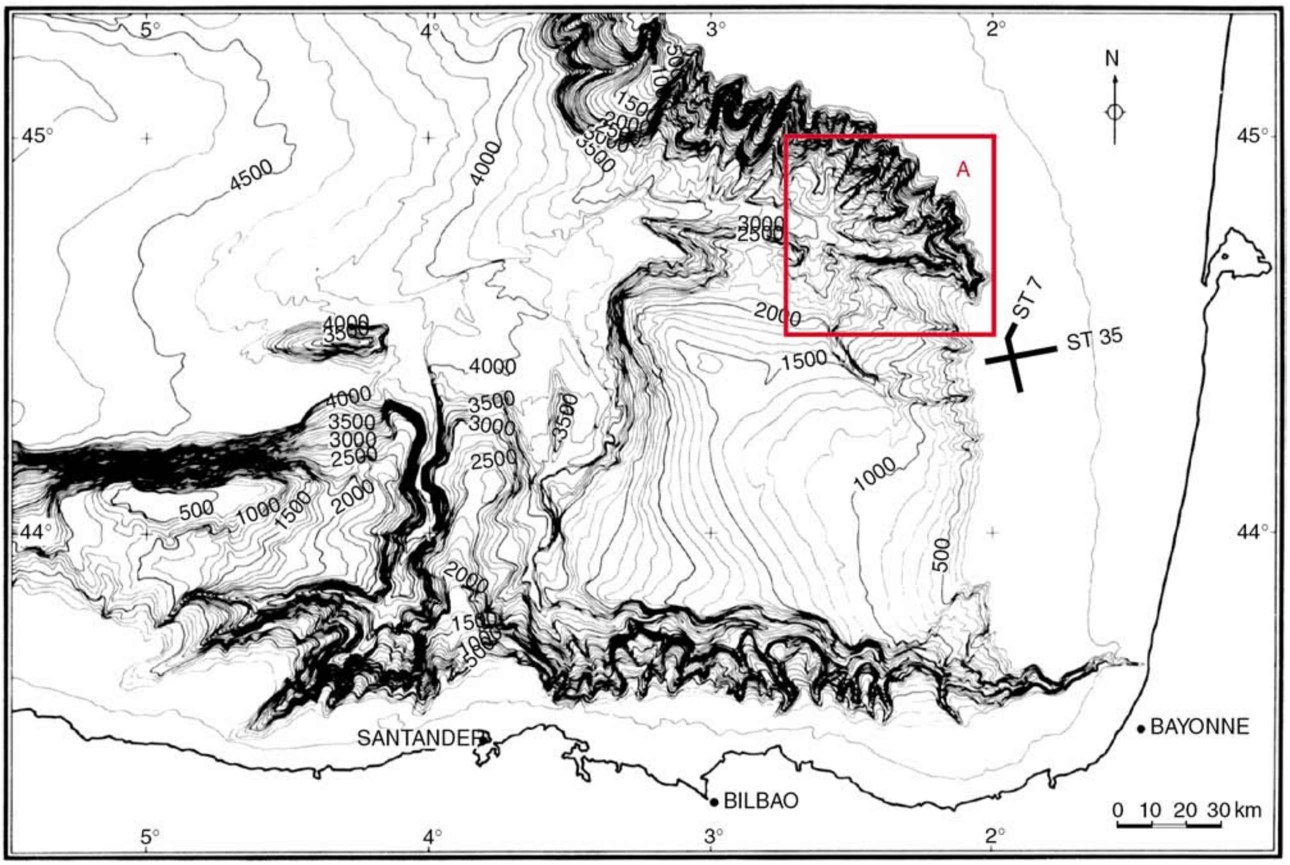

Figure 12

Cap-Ferret, main bathymetric contours extracted from the map by Berthois *et al.* (1969).

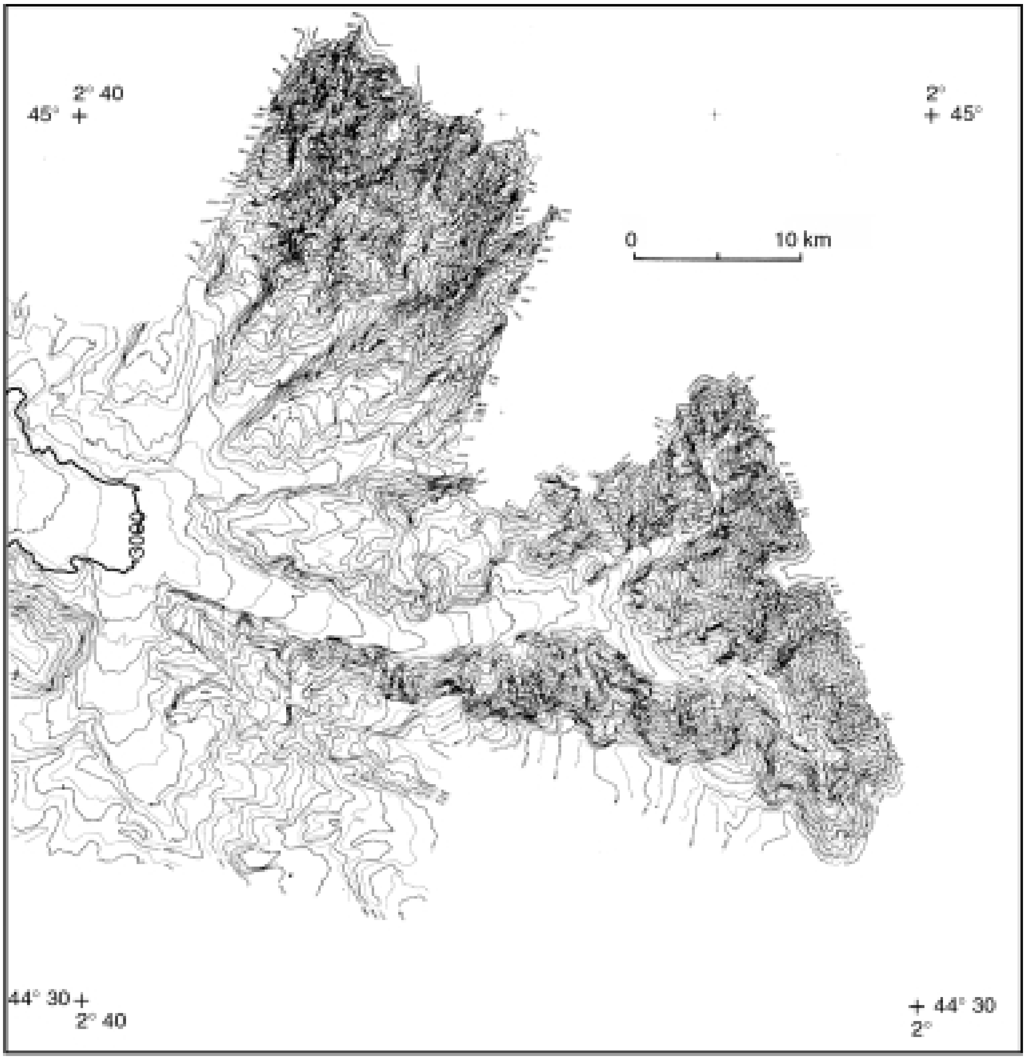

Figure 13

Cap-Ferret, main bathymetric contours extracted form the *Sea-Beam* map (after Nely *et al.*, 1985).

The zone represented here corresponds to the red inset in the previous figure. Note the considerable improvement in definition and, in the northern part particularly, the stream system of the canyons located at the position of the rather representative figures of pull-apart lobes in Figure 12. This suggests successive remobilizations, followed by active phases of erosion with the privileged emplacement of the canyons in these weakened zones.

film (*Gravity Deposits*, *IFP*, 1988) on reciprocal inputs of field and marine seismic data used a few profiles, particularly for purposes of illustration. The film was produced for pedagogical purposes for master and PhD students, and for professionals of the academic and industrial world. It is still in use today.

The choice of the Cap-Ferret site to obtain a simple and transposable deep sea fan model soon proved to be a mistake due to its complexity, but these surveys improved the knowledge of a part of the French territory. This complexity served to refine the method for analyzing gravity bodies and the knowledge of these bodies themselves, reflecting the innumerable discussions and hypotheses proposed for testing! The only results mentioned here are those of a general nature and hence able to help in the understanding of other sites, and those which illustrate specific difficulties or a lack of knowledge even today.

The first survey was conducted in the Cap-Ferret depression. This basin receives from the North episodic inputs from the starved Armorican margin mainly originating in gravity collapses affecting the slope and southern margin of the platform, to the east of the more continuous inputs that transit through the Gironde and the prolongation of the Parentis basin, to the south of the inputs which transit via the Landais marginal shelf and finally, to the southeast of the inputs from the Pyrenees and the Basco-Cantabrian margin and chiefly transiting via the Gulf of Cap-Breton and the Santander and Torre Lavega canyons. A simple scheme showing the arrangement and evolution of the components of a submarine fan is therefore impossible to obtain.

One of the salient facts is the complexity of the topography—particularly for the Armorican margin—which was very different from the image of stable margins previously proposed in numerous books still referred to at the time (Heezen *et al.*, 1959; Curray, 1966; Drake and Burk, 1974; Fischer, 1974; Heezen, 1974). The map charted by Berthois *et al.* (1969), (*Fig. 12*) previously implied this complexity, but the contours were smoothed due to the lack of data. Use of the multibeam depth finder led to the discovery of many relief scars, submarine cliffs of variable height, and the detail obtained revealed that the contours of the great semi circular pull-outs were intersected by several small canyons or were also the object of minor pull-outs (*Fig. 13*).

The sediments transported on the Armorican margin mainly accumulate on the slope and on the shelf near the slope break in unstable locations, as shown by the bathymetric map of Berthois and the one charted using the multibeam depth finder. The volumes involved in the pull-outs are enormous, ranging from the more frequent 10 to 50 km. The magnitude of these volumes and the frequency of these pull-aparts were very useful for understanding certain units of the Annot Sandstones, and were two of the analog arguments used to substantiate the plausibility of the "catastrophist" hypotheses concerning their deposition, since their volume appeared too large to correspond to turbidity currents *s.s.*

The small systems, at the seismic scale, resulting from these pull-aparts are very simple and display a morphology comparable to that of alluvial fans. The succession of seismic facies (*Figs. 14 and 15*) is nearly always the same, including in the gravity deposits of calcareous origin. Immediately after the pull-apart, a body (A) is deposited, and depending on the state of compaction and the type of original material, displays numerous characteristics (including the seismic facies) of the depositional environment of the unit pulled out, but the dip is different and the faults and fractures are abundant. The thickness of this body very often grows steadily from upstream to downstream. Observed in greater detail, the pull-apart and the body appear to be multiphase, without any possibility of estimating the duration between two phases: one hour, one day, one year? The only certainty is the number of bodies present in a seismic unit whereof the accumulation time definitely did not exceed 1 or 2 Ma given

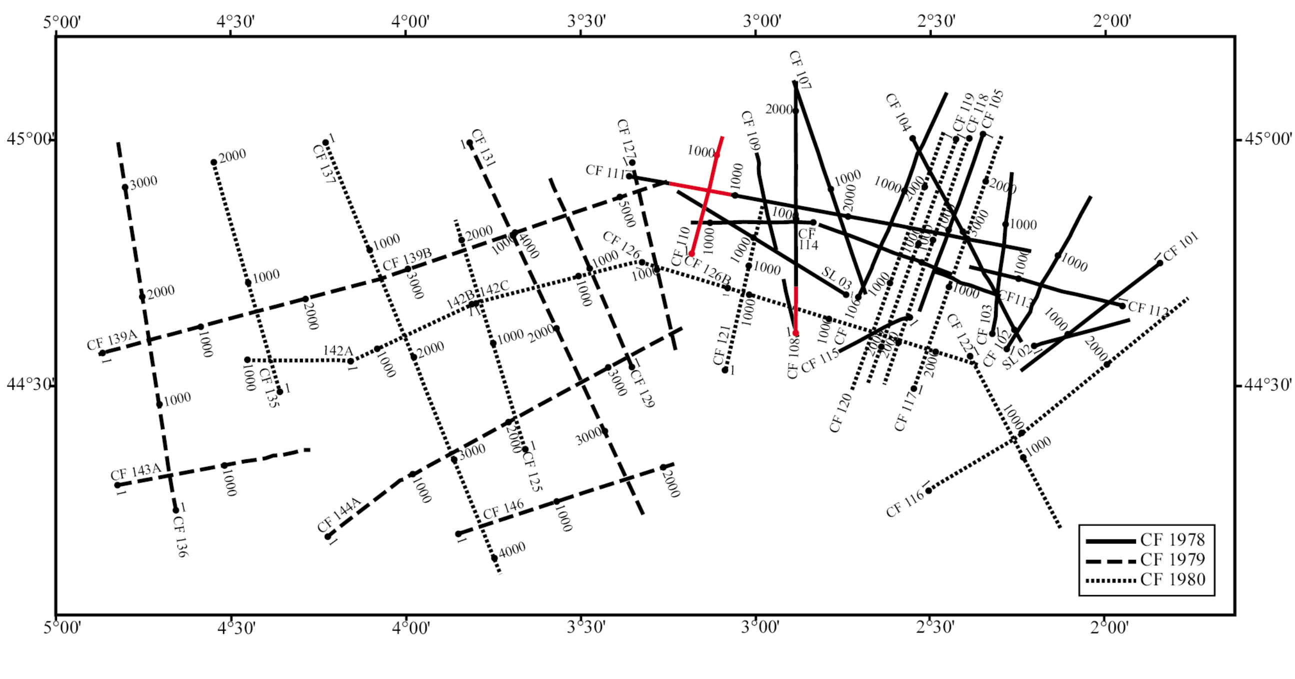

Figure 14

Cap-Ferret, position of profiles (after Nely *et al.*, 1985).
The profiles in red are discussed in the rest of the text.

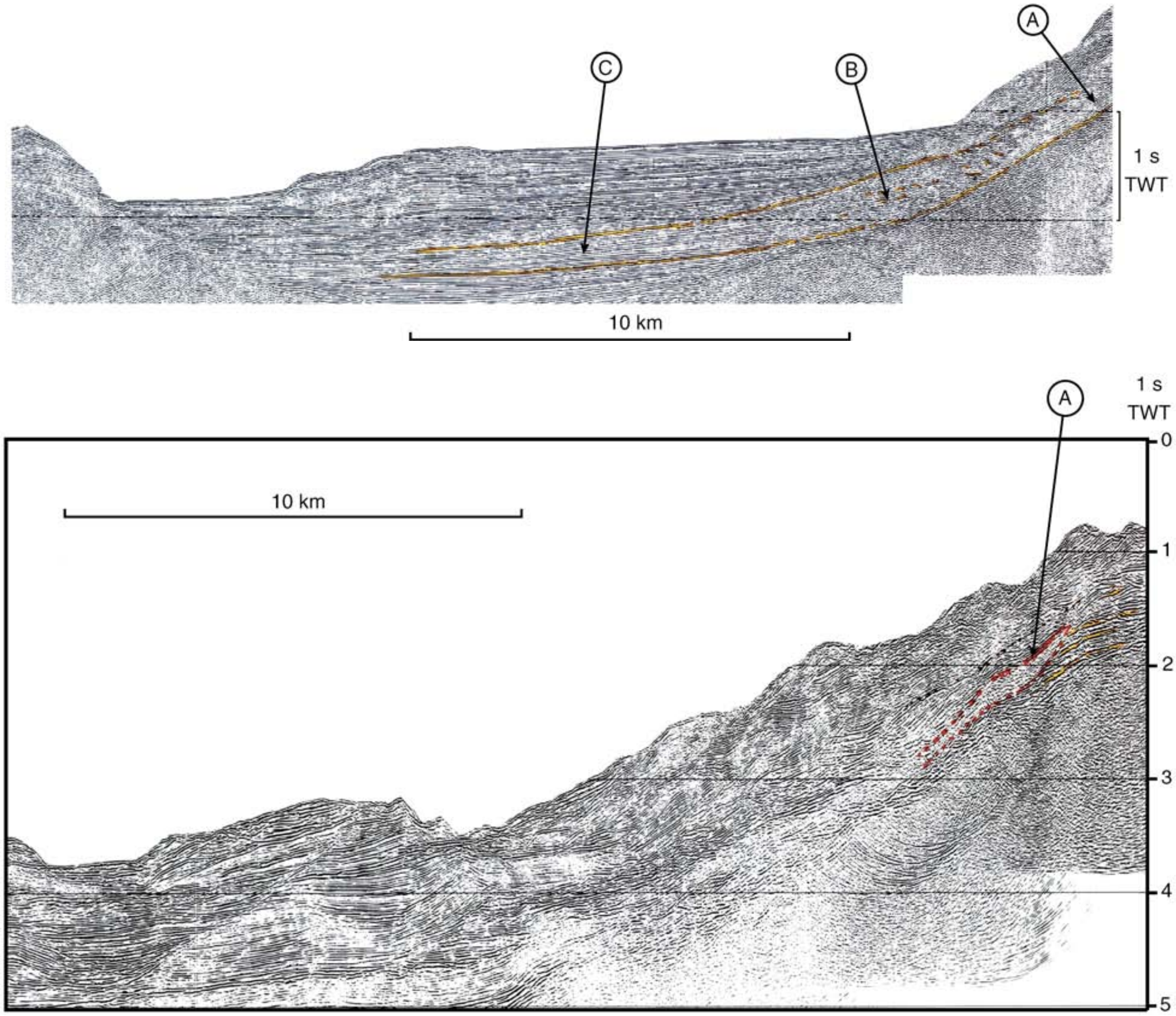

Figure 15

Cap-Ferret, succession of seismic facies observed in deposits resulting from a pull-apart (after Ravenne *et al.*, 1983b).

On the upper profile (CF 110), the unit bounded by the orange contours shows the evolution of the sedimentary dynamics after a massive pull-apart (lower profile). From upstream to downstream (or from right to the left of the figure) are successively observed a body A in which the reflection fragments are still visible attesting to the incomplete fracturing of the pull-apart body, then a body B in which only the chaotic reflections are visible, attesting to the complete remobilization of the material, and finally a body C, well organized with a fan shape in the upstream direction resulting from a sedimentation in density surge processes. This unit appears to be multiphase in detail.

The low profile shows the succession of packets pulled apart and slid in the slope. One of the pull-apart bodies is circled in red. Some original reflections of the orange platform are still discernible. These bodies can then evolve as indicated in the upper profile.

the datings carried out (Muller, 1981, unpublished report). Each of these catastrophic episodes is instantaneous at the timescale considered.

This body (A), in which the reflections of the original unit are readily recognizable, is followed by a body (B) only showing one organized reflection. This point is one of the keys to decipher the depositional mode of these deposits. A set of disorganized reflections normally reflects a mass slip. This hypothesis, once such a unit is observed, is validated or disproved by the evolutions upstream and downstream of the facies. This point is also related to the seismic processing. If a coherence enhancement is performed, the disorganized character and hence a key to interpretation disappear. This is important to note for the reexamination of old profiles, because these processings are no longer used today.

The two bodies described so far are bodies of reworked early deposits. The next (C), is a new sedimentary body in which nearly all the particles have been separated and replaced in suspension, and then deposited under the action of density surges or turbidity currents. The transition is fairly sudden with the previous body (B) since the reflections, first disorganized, very rapidly become remarkably organized, with high apparent frequency. They converge downstream, reflecting here the progressive decrease in thickness of the deposits. In the Cap-Ferret site, this evolution occurs mainly perpendicular to the Armorican margin, in a north-south direction. The first two bodies (A and B) are still located in the margin, and the second (B) can reach the foot of the margin. The last (C) is deposited in the very gently sloping, indeed horizontal part of the Cap-Ferret depression. The distal deposits of the last body can hence be remobilized after their deposition by the action of east-west directed density surges. Finally, the reflections of the distal part of the deposits originating in the pull-outs of the Armorican margin can be intercalated with those caused by deposits not having the same source.

This evolution immediately implies an attempt to identify these bodies onshore, because this would indicate that it belongs to three very different units of a single genetic unit. The difficulty is particularly great:

– since the outcrops, at the scale needed for their most reliable interpretation in the present state of knowledge, are often discontinuous, distorted by the subsequent tectonics;
– because the slope domains are generally the privileged site of inherited faults separating the platform from the basin and hence they are reactivated by the tectonics;
– and because the body displaying disorganized reflections is the most vulnerable to erosion.

The continuity of the sedimentary bodies in submarine domain helps to understand the constructions, processes and interpretations of onshore geological data which could not be formulated previously, particularly in stratigraphic terms. For example, a short time ago, some bodies were interpreted as resulting from overthrusts caused by compressive forces (thus Kerckhove (1969), proposes that the "block shales" of the Ubaye-Embrunais represent olithostromes connected with the deposition of an early submarine sheet and states that this term should be reserved for very large scale submarine slips associated with submarine overthrusts. The interpretation in terms of slip is excellent, but the initiation of these slips does not demand the involvement of a thrust sheet). In fact, many of them were merely the translation of pull-aparts often in extension domains.

One observation is important to counsel caution against hasty interpretations with an example that is often used in teachings and, as for any seismic interpretation, emphasizes the need to have a regional framework and profiles spreading substantially beyond the survey zone and, if possible, located in parallel and perpendicular to the direction of the inputs. In this example (*Fig. 16*), a profile parallel to the foot of the slope of the Armorican margin, a set of very characteristic reflections perfectly matching the underlying reflections is surmounted by a unit displaying exactly the same characteristics and separated from it by an unconformity. The observation shows an overthrust that could imply a compressive tectonics. The description of a perpendicular profile shows that this "overthrust" actually results from a decollement following a gravity pull-out super imposing the upstream part of the distal body with its downstream part, and it implies no compression.

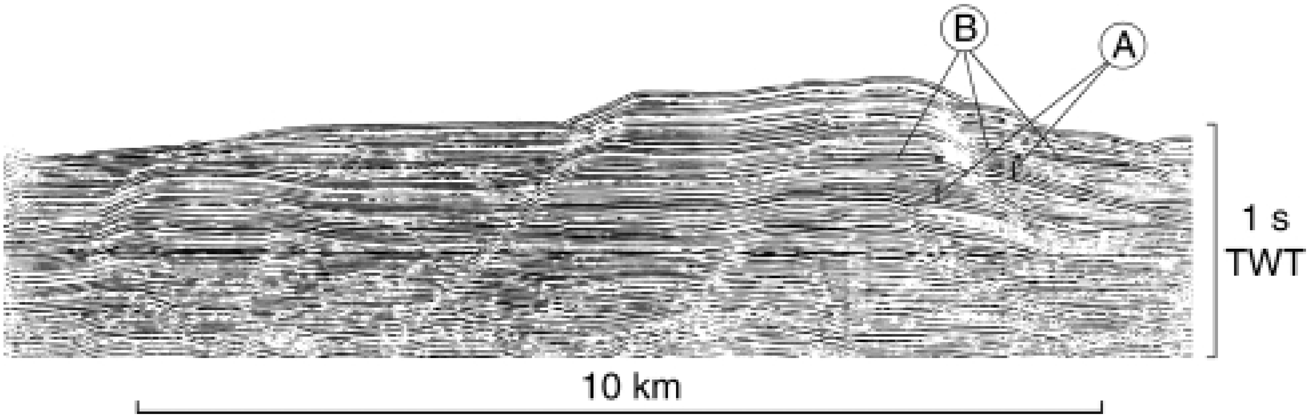

Figure 16

Cap-Ferret, profile CF 111, impression of overlap (after Ravenne *et al.*, 1983b).

This profile parallel to the foot of the Armorican margin shows the superimposition of unit A at the right on unit A located immediately to the left, giving the impression of an overlap that should not be interpreted in terms of compressive tectonics. The superimposition results from the pull-apart and slip of the upstream part of body A on its distal part.

In the Cap-Ferret depression, it was very difficult to differentiate between the major units. To improve the interpretation, a request was made that the next survey (1979) include a series of narrowly spaced profiles in comparison with the normal acquisition grid of these surveys. These new profiles were spaced by 1 km instead of the usual 10. Correlation was virtually impossible because of the many interferences between the reflections caused by deposits of different sources and the many reactivations and slips in the zone selected for this narrow grid. Mauffret, who participated in this part of the interpretation, is sure to remember this. The precise deciphering and recording requires here the acquisition of a much denser grid, *i.e.* 3D seismic profiles; the spaced profiles mainly help to distinguish the main sequences.

The distal part of the Cap-Ferret depression comprises seismic units consisting of one to three reflections which differ from those of the other units in their configuration and their seismic parameters. Minor unconformities appeared to separate the units. The most probable interpretation was that these reflections were caused by deposition lobes as described by Mutti and Ricci Lucchi (1975). Yet some aspects of these units and the usual comparison with fluviatile systems (slope bottom similar to alluvial fans, upstream network of drains converging towards a main transport axis, then logic evolution with the decrease of the slope towards a meandriform network) suggested meanders, which was confirmed by the new bathymetric map charted with the *Sea Beam* during these missions, which reveal certain meandriform aspects of the present submarine drainage system. However, the interpretation could not be substantiated since the present system functions in a period of relative high sea-level and because the deposits analyzed were mainly put in place in a low-level period. The presence of meanders in other deep submarine environments was confirmed by Kenyon (1992, oral communication) who participated in the acquisition of data in the Mediterranean using a side-scan sonar during a *UNESCO* mission (1992, N/W *Golendhzik*) in connection with the TRADMAR program, which is discussed later for the Annot Sandstones in the chapter dealing with the characterization of the reservoirs. Kenyon (oral communication, 1992) further stated that he had already identified several meandriform systems in the Atlantic Ocean with the efficient sonar available to the *IOS (Institute of Oceanographic Sciences).*

Problems of terminology connected with the complexity of the topography or with certain depositional environments clearly appeared. It is often necessary to rely on the Anglo-Saxon technical vocabulary. Thus the term slope deposits was applied to deposits observed on the slopes when they are not the prolongation of prodelta deposits. This descriptive term reflected a degree of ignorance concerning their deposition of mode. Even today, much work needs to be done on these environments to obtain the keys to their recognition in outcrops. What precise name to be given to the many platforms that succeed each other topographically and whereof the morphology evolves over time? Cap-Ferret is a fine example: the present platform was morphologically

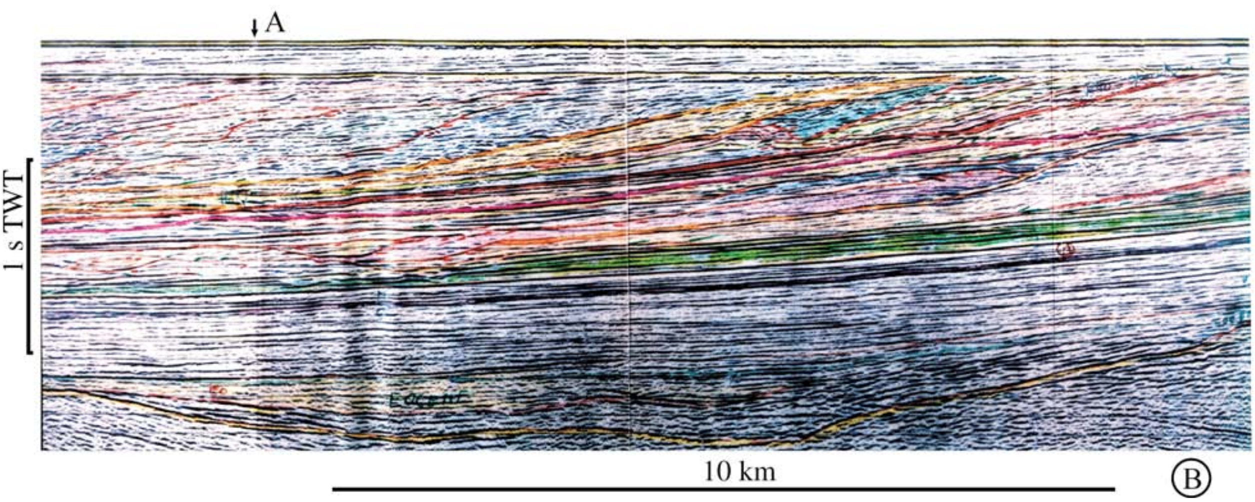

Figure 17

Cap-Ferret, profile ST 35 (after Ravenne *et al.*, 1983b).

The green unit corresponds to the distal part of the prograding series, nearly at the outcrop near the present level. Note above the complex geometries of the different prograding bodies. A rapid estimation of the depth of the deposits connected with a red marker to the left of the figure is obtained by comparing the difference in depth of this marker between the right and left ends of the profile, or nearly one second two way time (about 1000 m here).

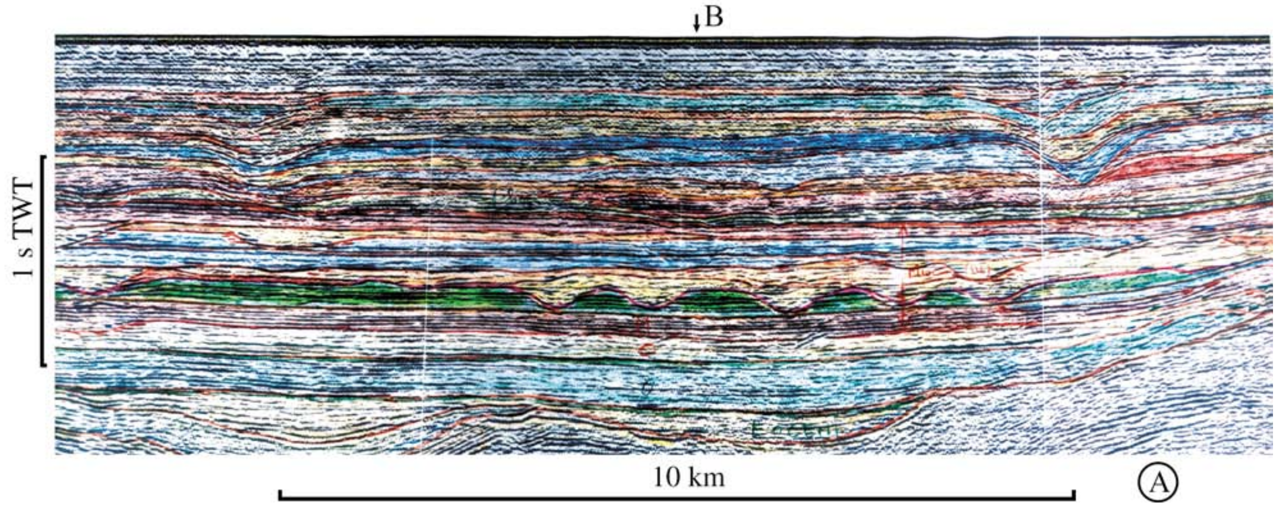

Figure 18

Cap-Ferret, profile ST 7 to be compared with Profile ST 35 *(Fig. 17)* (after Ravenne *et al.*, 1983b).

All the reflections are parallel to the ocean floor. The thickness of the water depth is small (about 100 m). A rapid examination of this section, only based on this profile, would lead to an interpretation in terms of platform with a steady subsidence of the platform. Profile ST 35 shows that this actually involves complex prograding systems. Observe the canyons which intersect the green unit and those episodically affect the underlying parts.

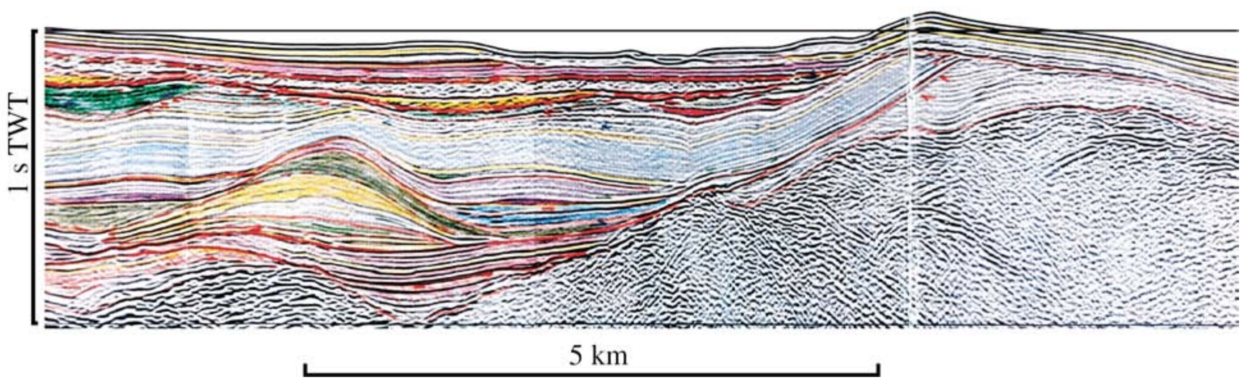

Figure 19

Cap-Ferret, profile CF 108, hydraulic dune? (after Ravenne *et al.*, 1983b).

The hummocky shape observed in the left hand part of the section was interpreted as a hydraulic dune whereof the relief is pronounced with the reinforcement of the currents on its flanks (chaotic to continuous reflections of rather high amplitude). The pale blue series overlying it reveals, on the contrary, very continuous high apparent frequency and low amplitude reflections, indicating a low energy deposit. Above channel fills are very chaotic and recent incisions affect the superficial coverage.

constructed towards the Late Eocene, by a suspended basin prolonging the Parentis basin, of which the floor was at about 1000 m, shallower than the Landais marginal shelf, itself shallower than the Cap-Ferret depression, with the latter deepening steadily towards the Bay of Biscay. This present platform was progressively filled during the succession of relative high-and low sea-level phases of many orders (or, if one prefers, of nesting phases of different durations). At all these orders, we observe *(Fig. 17)*, more or less pronounced in amplitude and in extension depending on the duration of the deposit, sets of reflections drawing large sigmoids which can be inscribed in the entire thickness of the water column when they have been engendered by strata deposited in periods of relative high sea-level in the major cycles and in the immediately preceding phase of the rise of this level. The term “relative” is employed to indicate that the thickness of the water column on the platforms does not exclusively depend on eustatism but also on the local tectonics. These units can be limited to a bottom part (about one-third of the original depth) if they have been engendered by strata deposited in periods of relative high sea-level and in the immediately previous phase of the rise of this level subsequent to the most pronounced periods of relative low-level. The latter naturally create new nesting topographies which are then draped by subsequent high-level deposits or filled by onlapping serie. The term “onlap” is only descriptive and designates termination of strata or horizontal reflections against a stratum or inclined reflection, or the termination of strata or inclined reflections against a stratum or a steeper reflection; described on a single profile, and “onlap” cannot be considered as real because it may be apparent, connected with the direction of the profile with respect to the input direction. If it is real, it often representative of strata formed in a relative low sea-level period or at the start of the sea-level rise.

Depending on the amplitude of the high or low sea-level variations and depending on the extent of the terrigeneous inputs, the sediments may or may not cross the different topographies, *i.e.* deposit more or less distant towards the open sea. Once again this a function of the available space and, in certain periods, sediments from the east can be entirely trapped at the location of the present platform. Another example pertaining to deposits underlying the present platform emphasizes the need to have regional profiles in both directions, parallel and perpendicular to the input direction. An interpreter only required to work on the outer part of this platform, without having profiles traversing it completely from the coast offshore would only have seen horizontal and parallel reflections to the bottom of the platform (*Fig. 18*). Considering this context, he would probably have attributed all these reflections to strata formed in a platform environment and invoked a steady increase in the water depth connected either with regular subsidence of an entire panel, or the elevation of the sea-level, or to the combination of both. Finally, some geometric patterns were only observed on seismic data (*Fig. 19*) and had been interpreted as hydraulic dunes.

Finally, this evocation of Cap-Ferret can be concluded by a question concerning the origin of the seismic reflections and which could be repeated on the occasion of each of the interpretations in which the author participated. The current hypothesis is that the reflections are engendered at each interface separating two units by different acoustic impedances. The reflections recorded under the platform, according to the rock fragments raised during drilling, only originate in strata composed of clay or clay-silt sediments. The impedance contrasts are very weak, and yet the reflections are highly pronounced and widely varied. Compositions of reflections, phasings, etc, reinforce them. The strongest impedance contrasts are found laterally in a single unit and are reflected there by amplitude variations. The clear reflections often mark sedimentation interruptions, hiatuses or unconformities which do not necessarily separate the strata with a significant acoustic impedance contrast.

An example supporting this remark was reported by Lecomte (1989, oral communication). On completion of the preparation of a method applied to geotechnics to examine pinchouts with very high frequency reflection and refraction tools (over 1 kHz), he prepared a mock-up of the analog modeling of a seismic acquisition. This mock-up contained a tilted wooden base on which plaster was then poured to pattern the sedimentary layers. The molding had to be interrupted temporarily and was resumed a few dozen minutes later. The first layer of plaster was nearly dry. The mock-up was then completed with the resumption of plaster pouring. The modeling was then carried out but the results were surprising. The reflections which should have originated in the base-plaster interface were weak to nonexistent. By contrast, there was a powerful reflection that raised a problem. This reflection corresponded to the interface between the two plaster layers. If there had been an acoustic impedance contrast, it would have been particularly weak, and yet a strong reflection marked the interruption in the plaster deposit.

Many studies and algorithms are based on the fact that the reflections are caused at the interfaces by acoustic impedance contrasts and the results are conclusive. However, it would be strongly advisable for research combining rock mechanics and acoustics to be conducted to clarify this origin (minor diagenetic modifications? greater influence of phasings? etc.) because this property would reinforce the seismic-stratigraphy interpretation and would open up new possibilities.

Bahamas

The survey (1982) was aimed at the identification of the characteristic features of a carbonate submarine fan. Two fans were investigated *(Fig. 20):* one located at the outlet of the Great Bahama Canyon (Eleuthera province) and the second at the outlet of the Exuma Canyon (San Salvador province). The choice of the sites was made after completing a bathymetric coverage with the *CNEXO* multibeam depth finder. The seismic acquisitions involved the same partners as for the Cap-Ferret surveys *(CEPM, IFP, SNEA-P)* and CFP) and a core survey was completed by the *University of Miami* with Schlager and Droxler.

The seismic survey (*Fig. 21*) was essentially interpreted by Le Quellec, Euriat *(CFP)* and the author, who participated actively in this interpretation in view of previous studies on other submarine clastic systems.

Only some of the major results are mentioned here, illustrating either methodological aspects or the importance of certain gravity mechanisms.

Some parts of this carbonate fan display a remarkable identity with the equivalent parts of the Cap-Ferret site both for the geometries and the configurations of the reflections

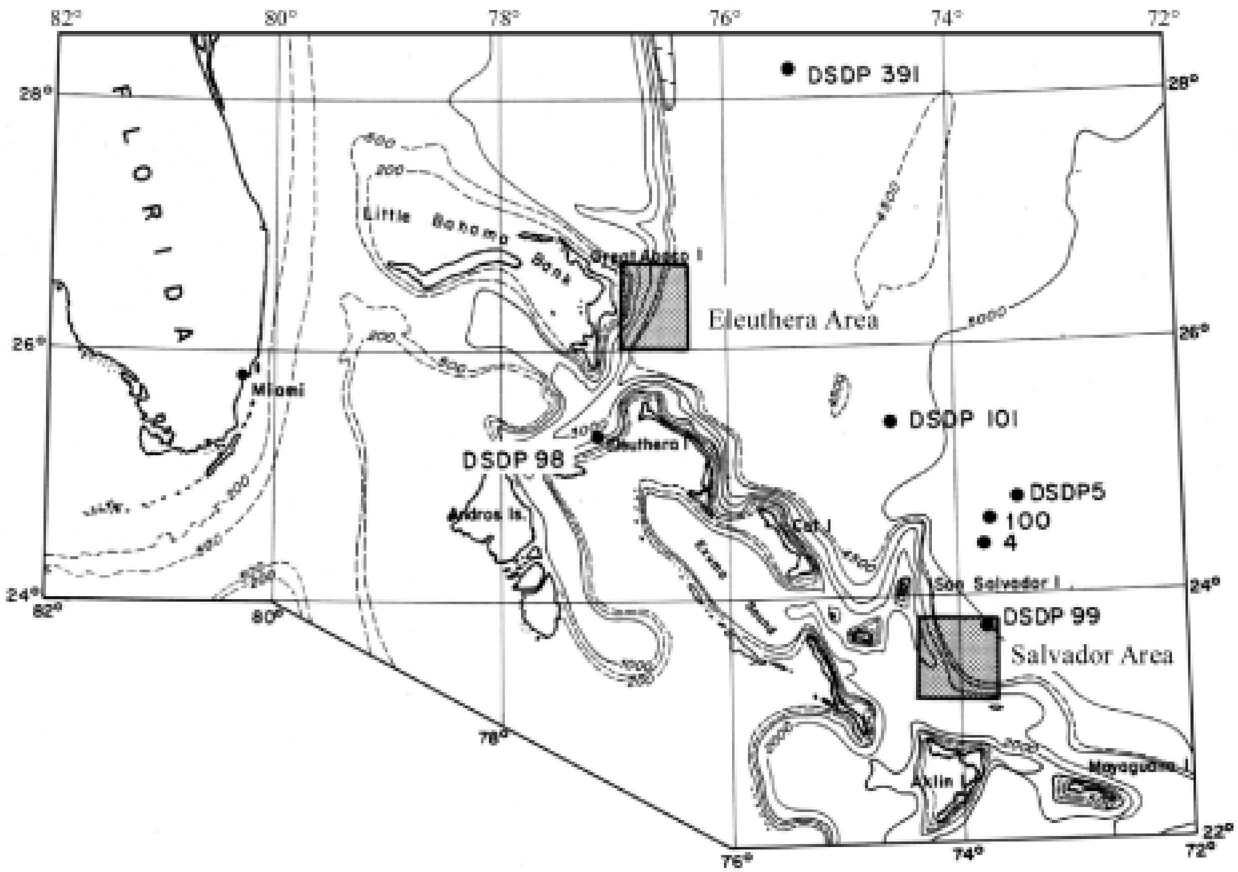

Figure 20

Bahamas, position map and bathymetry of the two survey zones (after Ravenne *et al.*, 1984; Ravenne *et al.*, 1985).
Stress must be placed here on the Eleuthera zone located at the outlet of the canyon separating the "Little Bahama Bank" from Eleuthera Island.

and for the seismic facies (*Fig. 22*). For example, it is impossible to determine the specific site connected with each of the profiles obtained on the two sites near the outlet of the canyons. The type of material does not—at the seismic scale—appear to affect the characteristics of the submarine fans; they are mainly controlled by processes specific to gravity deposits.

A series of profiles obtained perpendicular to the Eleuthera margin shows a very complex sedimentary accumulation at the slope foot, with numerous internal unconformities and many faults. A profile parallel to the margin overlapping all these profiles shows that this complex accumulation is the result of successive pull-aparts of the platform margin and of the upper part of the slope *(Figs. 23a and 23b*). This accumulation roughly forms a biconvex lens with a maximum thickness of over 1000 m and more then 10 km wide at this location. The shape of the lower part results from the erosion of the substratum by the first mass slidings. The shape of the upper part reflects a very localized origin probably with successive reactivations of a first pull-apart lobe.

The general trend of the results of these pull-aparts is comparable to that described for the slidings affecting the Armorican margin. The proximal part (*Fig. 23a*) shows sets of reflections that are still well organized, constituting the "biconvex lens" and of which the origin can be found (outer platform, slope peak) from the configuration of the reflections. Many faults affect them; the fracturing increases downstream and some units may already display a disorganization of the reflections. At the foot of the present slope, all these units are homogenized to form a unit consisting of completely disorganized reflections. It evolves towards a set of very well organized reflections, with high apparent "frequency" and converging towards the oceanic plain (*Fig. 24*).

This accumulation and its evolution are recalled to stress the importance of the volumes shifted and to hint at the difficulty of interpreting such a body observed on discontinous outcrops. Size is important. There is a juxtaposition of units whose initial characteristics are remarkably preserved with others that are much more faulted, indeed completely chaotic and, as for the Cap-Ferret systems,

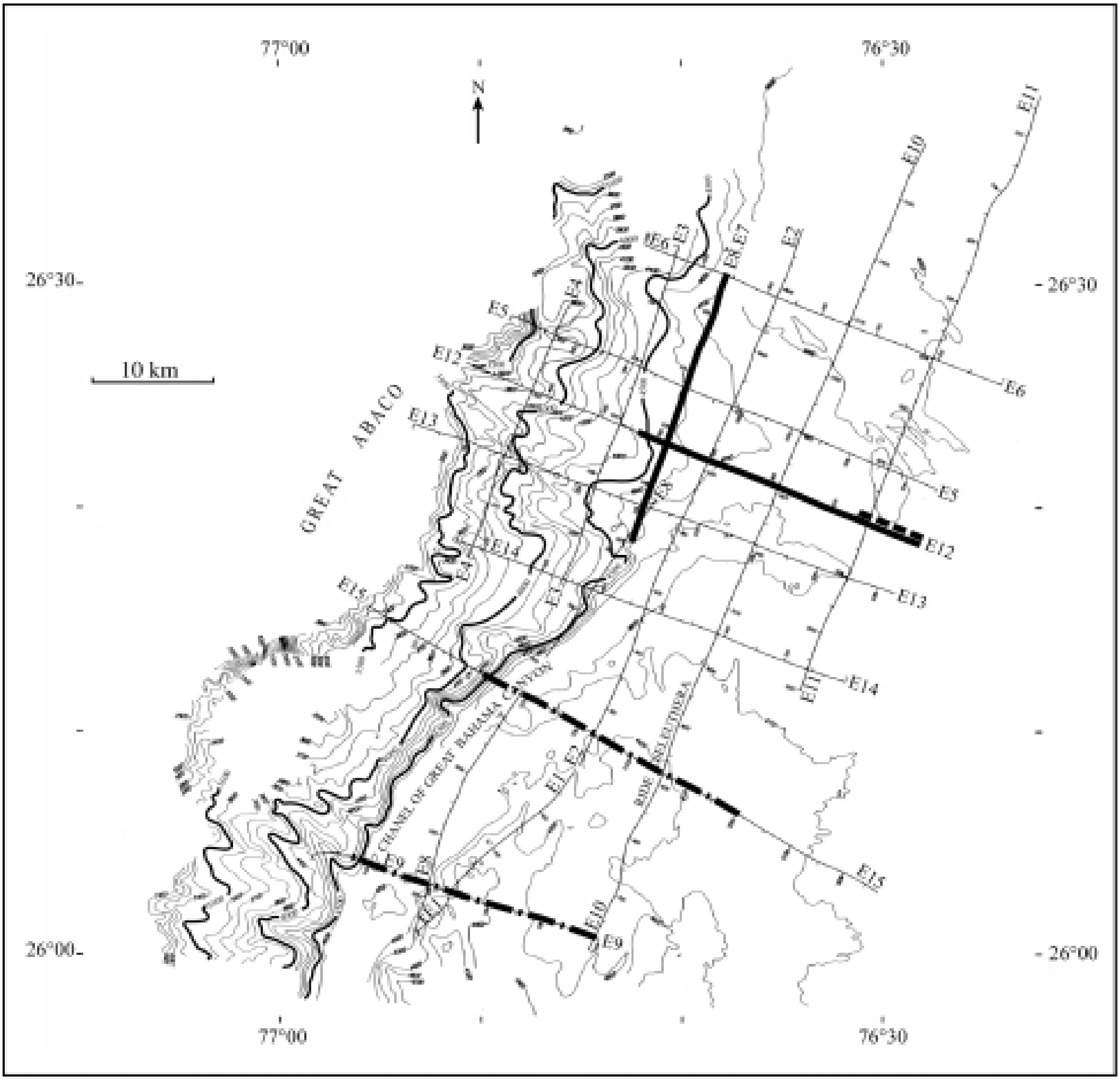

Figure 21

Bahamas, position map of seismic lines of the Eleuthera survey (after Ravenne *et al.,* 1984; Ravenne *et al.,* 1985).
The previous figure located the Eleuthera zone. The overline profiles are presented further.

how can we relate such units with certainty to the more distal very organized series?

The sequence represented by this accumulation and the associated bodies (*Figs. 23a and 23b)* corresponding to its distal evolution, was essentially deposited during the Neogene (Ravenne *et al.,* 1984). It rests in apparent conformity on a sequence with a very different seismic facies attributed by Ravenne *et al.,* (1984, 1985) to the Upper Cretaceous (see below). The hiatus between them corresponds to horizon A (Ewing and Hollister, 1972). It is overlain by a Pliocene to Quaternary sequence consisting of sediments deposited in canyon-channel systems and reworked by massive oceanic gyres along the base of the scarp. Three sequences have thus been distinguished (Upper Cretaceous, Neogene, Plio-Quaternary) (*Fig. 23a*).

The three sequences were then correlated with the DSDP boreholes ("Leg ODP" 99, 100, 101 and 391, Hollister *et al.*, 1972, Benson *et al.,* 1978) located to the east off the Blake Plateau scarp, and in the prolongation of the northeast end of the large gravity pull-aparts, with an attempt to compare the

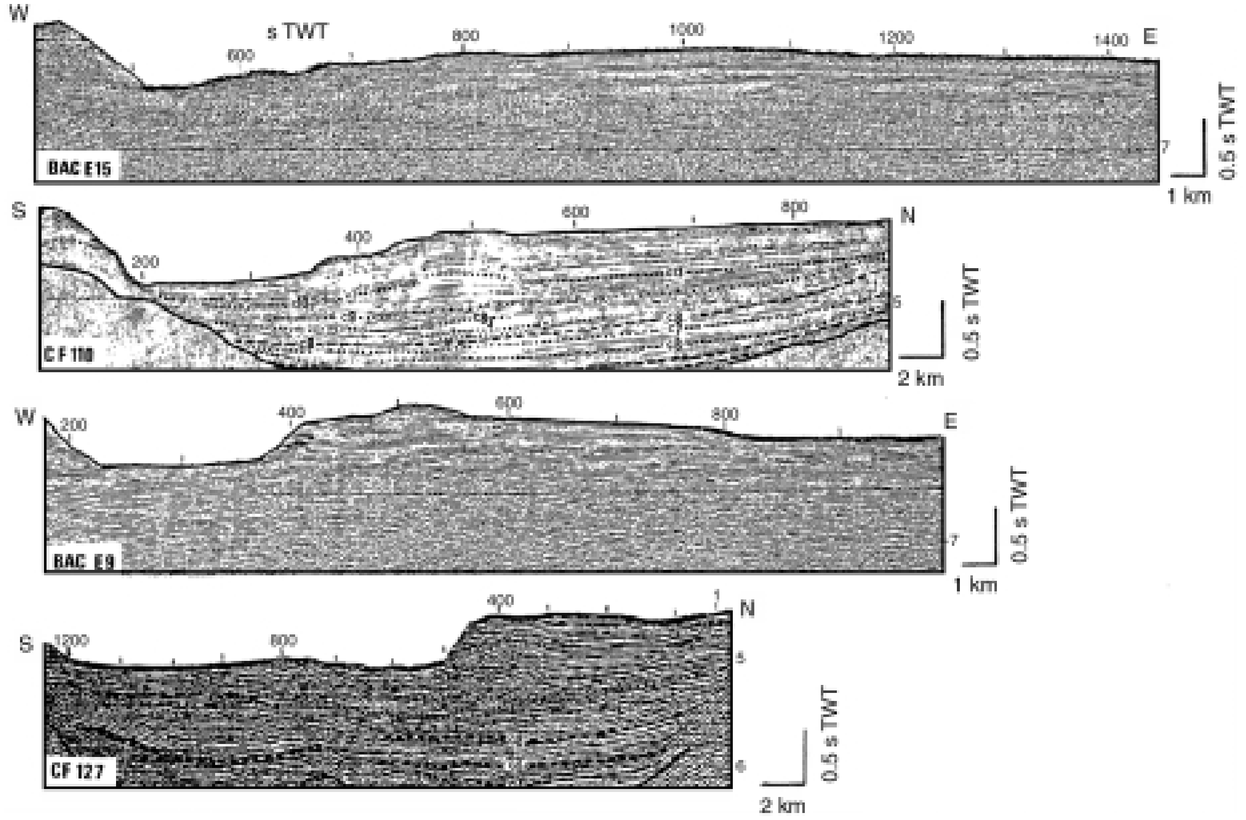

Figure 22

Bahamas, comparison of seismic signatures of a carbonate fan and a silico-clastic fan (after Ravenne *et al.*, 1984; Ravenne *et al.*, 1985).

Profiles BAC E15 and E9 were recorded in a carbonate fan, CF 110 and CF 127 in a silico-clastic fan. The morphologies of seismic signatures are similar between the two types of fan in the distal parts (BAC E15 and CF 110) and in the proximal parts (BAC E9 and CF 127). This similarity is somewhat diminished due to the difference in horizontal scale between profiles BAC and CF (ratio of 1 to 2).

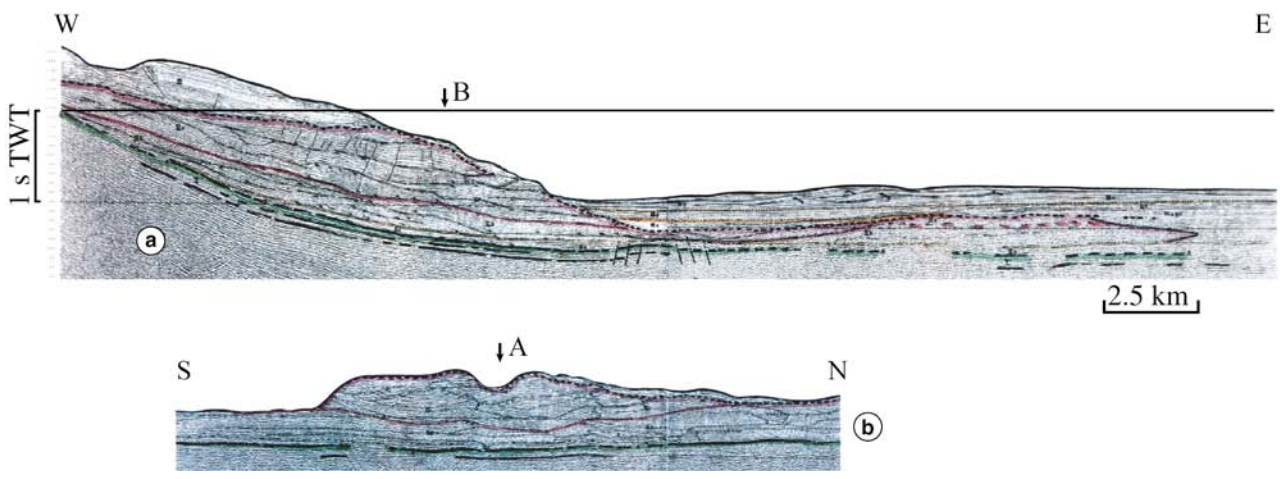

Figure 23

Bahamas, profiles BAC E7 and E12, stacking of slide bodies (after Ravenne *et al*., 1984; Ravenne *et al.*, 1985).

The upper profile (BAC E7, denote A) basically displays a slope deposition configuration. It intersects the lower profile (BAC E12, denoted B) which clearly shows that the succession of sedimentary deposits between the two red boundaries corresponds to the superimposition of deposits resulting from pull-apart lobes, of which the first strongly eroded the bottom series. The size of the lobes is considerable, reaching 10 km in width and more than 0.6 s TWT or about 1000 m in thickness.

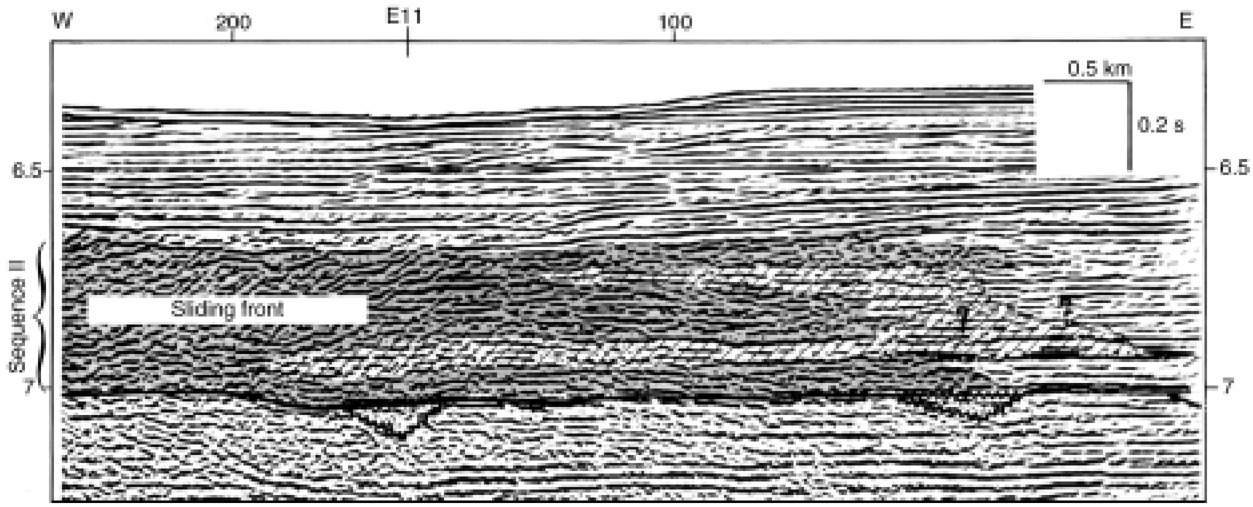

Figure 24

Bahamas, transition from a completely destructured sliding body to an organized body (after Ravenne *et al.*, 1984; Ravenne *et al.*, 1985).
The reflections are completely chaotic in the slip front, attesting to completely fractured material. These reflections are reorganized eastward, reflecting the deposition of a completely remobilized material replaced in suspension.

seismic facies and the main unconformities. A number of difficulties emerged. The cores recovered are highly fragmented and horizon A, presumed to separate the Cenozoic from the Cretaceous, was situated at the appearance of rock fragments of Cretaceous age mixed with fragments of Miocene age, interpreted as dustfalls from the drilling of the upper layers. The interpretation made here highlighted the importance of gravity mechanisms, which were relatively unknown in this region. Another interpretation of the mixture of rocks with different age has been proposed: they could belong to a sequence deposited by gravity processes in the Miocene comprising fragments of rocks of Cretaceous age originating in the pull-apart of fragments of the platform and the slope.

The interpretation of this survey served to propose drilling sites. The author accordingly participated in the ODP 101 survey with Fourcade, Droxler and Eberli, just some of those with whom his relations were prolonged. Unfortunately, a number of problems prevented the coring of the proposed sites, because the pipe lengths necessary to carry them out had not been shipped on board.

Indus

This survey *(Fig. 25)* was conducted by *CGG* (1977) and interpreted by a team under the direction of Coumes *(SNEA-P)*. The author's participation is discussed further.

The gigantic size of the channel-levee systems of the Indus is striking. A channel-levee system (*Fig. 26*) can be more than 50 km wide and a levee can be up to 1000 m high! The Indus fan belongs to the large family of fans with high transport efficiency, owing to the essentially clayey material making it up. These dimensions are no doubt very rare, but if some of them outcropped, it would be very difficult to separate the sediments deposited in the levees from those deposited by other processes in the oceanic plain, because the lithologies are very similar, the dips within each levee are low, and the dips of the layers of the base and the summit of each levee conform to those of the overlying and underlying deposits.

At the time (1978) the periods of formation of the canyons and associated submarine fans were hotly debated. Vail (1976) defended the hypothesis of the formation of the canyons in a period of low sea-level and used deposits of submarine fans as indicators of this low level in the seismic stratigraphy concepts which he had formalized. He relied for this on the vast body of petroleum data usually acquired in a stable margin setting. Brown and Fischer (1977) defended the reverse hypothesis, relying on the fans that he had investigated along the Californian coast. It subsequently turned out that Vail's hypothesis was the right one, particularly in this type of fan. However, there was some difficulty in getting the message across to the industrial partners, because Brown was recognized as one of their experts.

While Coumes and the rest of the team worked on the deep fan data, the author (Ravenne *et al.*, 1988b), examined the profiles acquired on the platform by the Wintershall Company in 1976) and only after this task was finished did

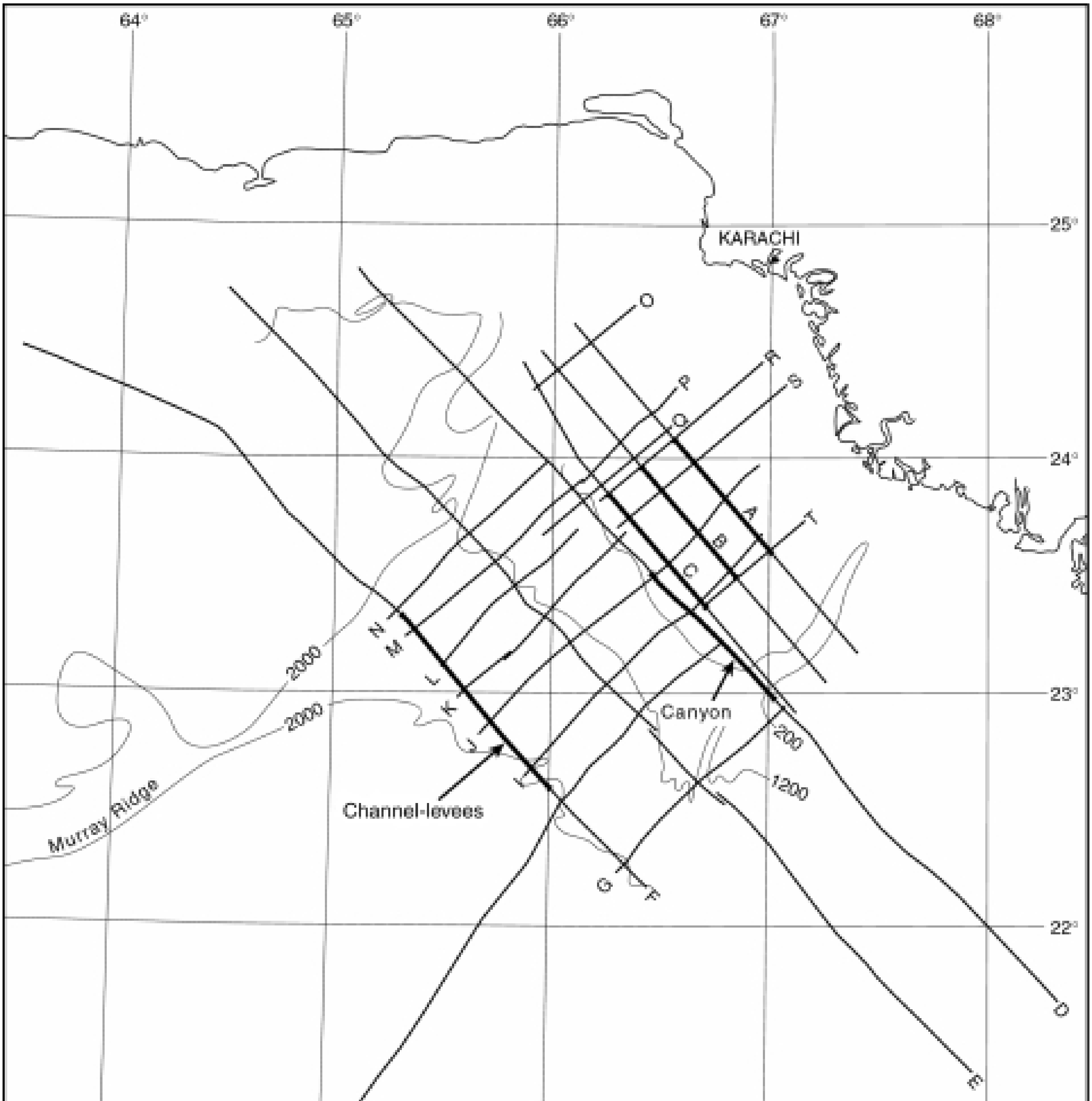

Figure 25

Indus, position plan of seismic profiles of the survey (after Coumes *et al.*, 1978).

The overlined profiles correspond to those that are discussed below to illustrate the Indus channel-levee system.

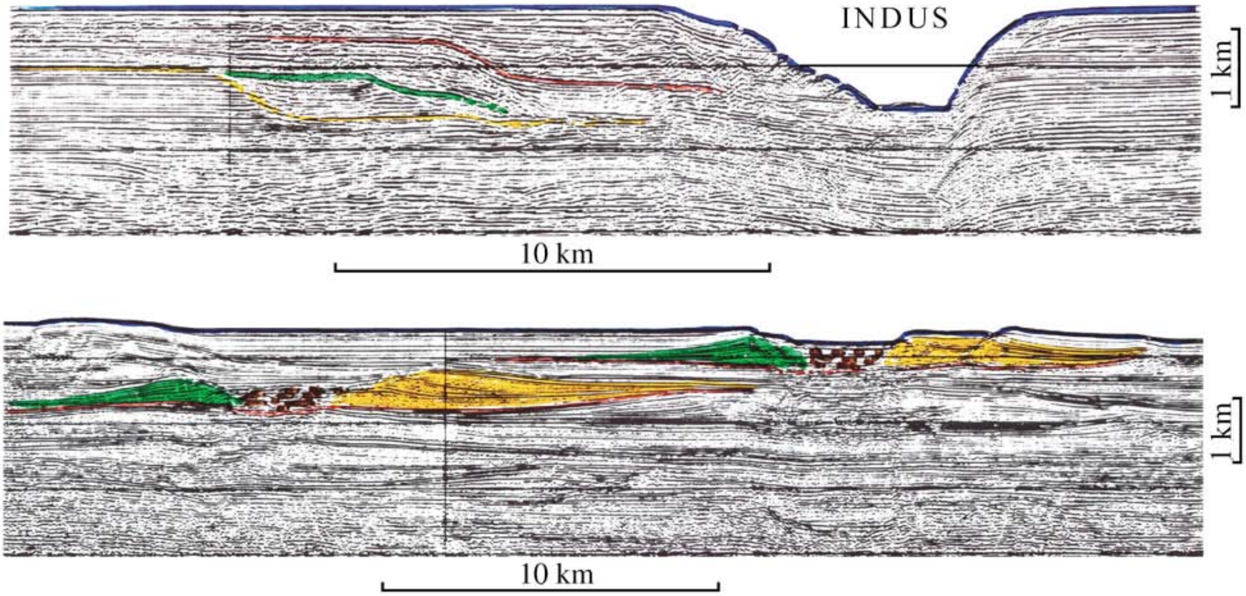

Figure 26

A channel-levee system of the Indus (after Coumes *et al.*, 1978).

It is primarily important to observe the vertical and horizontal scales. The upper profile (profile D in Fig. 25) is located just before the platform/slope break in nearly 200 m depth. The present canyon has its maximum depth at this point (about 1500 m). The three yellow, green and red pickings show the western margin of the three main systems of previous canyons which migrated from W to E (Coriolis force? impact of the uplift of the Murray ridge?). The lower profile (profile E) shows two channel- levee systems, one levee of up to 1000 m at its maximum thickness. Other channel-levee systems are visible below. Note the doublet of reflections draping each of these units and which corresponds to the period of starvation of the inputs.

he focus on the data of the Indus fan, particularly for the sequence correlations. The platform is wide (about 100 km) and always displayed a low dip during the Neogene. Five main series separated by major erosion unconformities constitute the Neogene (*Fig. 27*). Their thickness increases from the coast offshore. They mainly consist of horizontal reflections in the perpendicular direction to the inflow direction and are very slightly divergent offshore in the direction of these inputs. The seismic facies and their evolution from upstream to downstream are characteristic of silico-clastic platform deposits.

The observation of the profile parallel to the coast nearest the slope break towards the basin (*Fig. 27c*), or the one where the depth of the platform has always been the greatest, successively shows the following from the bottom upward:

– A 1st platform series (P1), very uniform whose continuity is only interrupted by three canyons (only one canyon is shown in Figure 27c), the easternmost being the precursor of the present Indus canyon.

– A 2nd platform series (P2) overlying the previous one, nearly entirely filling the three canyons. Many reflections of the layers making up this series are continuous with the platform at the fill of the canyons (*Figs. 27a and 27b*). The end of the canyon filling (confirmed for those subsequent to the next two erosion phases) is nearly always emphasized by the presence of a concave reflector upward in perfect continuity with the last reflector of the platform. This series is intersected by three new canyons located nearly precisely at the location of the previous ones. Their location differs by a slight eastward migration of their axis, allowing the preservation of the west limb of the previous ones and that of their filling. The successive phases can thus be clearly reconstructed. The new canyons, by contrast, intersect the central and eastern parts of the fill of those of the 1st platform series.

– A 3rd platform series (P3) overlying the previous one similarly fills the 2nd series of canyons. The same descriptions apply to the 3rd series of canyons.

– A 4th platform series (P4) overlying the previous one and similarly filling the 3rd series of canyons. A single change occurs during the erosion of the 4th series, where there remains only one canyon located on the west limb of the present Indus canyon. The disappearance of the other two could be attributed to the uplift of the Murray ridge, which caused a skewing of the platform and hence a modification of the drainage system.

– A 5th platform series (P5) overlies the unit and participates in the filling of the last canyon in this figure.

– Finally, a 6th platform series (P6) overlies the previous platform.

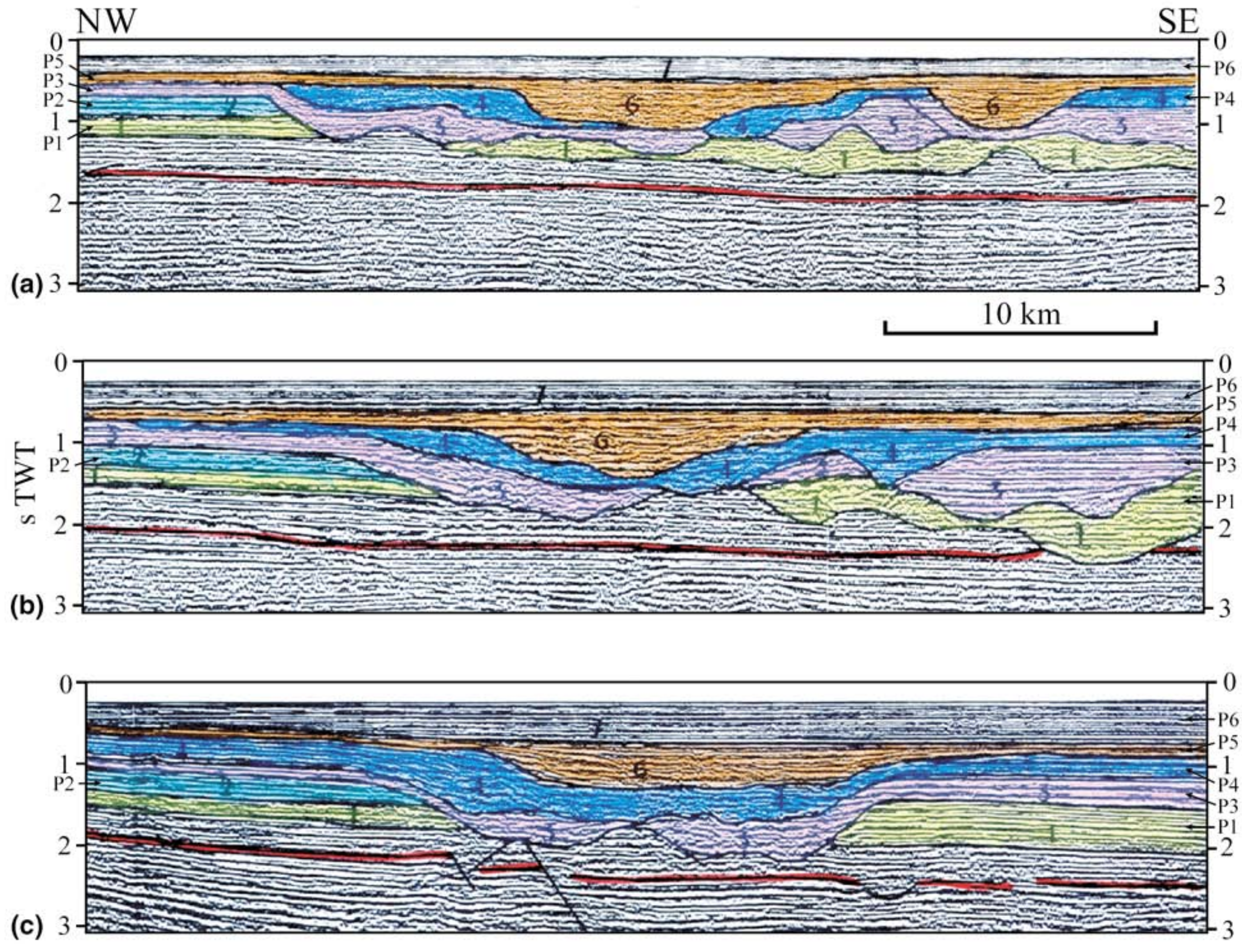

Figure 27

Indus, Profiles of series parallel to the margin showing four main series of platforms incized by the canyons (after Coumes *et al.*, 1978; Ravenne *et al.*, 1988b).

The three profiles are located parallel to the slope break. The main canyon is clearly individualized in the lower profile, the nearest to the slope break. Note the superimposition of the fossil canyons which intersect the different paleoplatforms (P1 to P). Going up along the shoreline, the canyons are less well individualized, and near the coast, correspond to a generalized erosion unconformity.

The observation of a profile parallel to the coast located at the middle of the platform (*Fig. 27b*) shows the same succession of six platform series and erosion cases. By contrast, the number of canyons created at each erosion phase is much greater, their incision depth much smaller and their width also smaller. Each of the series is very discontinuous and appears rather as a succession of canyon fills separated by outliers.

The observation of a profile parallel to the coast and very close this one (*Fig. 27a*) no longer helps to identify the horizontal and fairly regular reflections characteristic of the platform deposits. Some of them are sparse and discontinous. No clear canyon intersection is discernible, except that of the present Indus canyon. A multitude of generally discontinuous and low-amplitude erosion unconformities affects all the deposits.

These three profiles help to decipher the main evolution of the platform during the Neogene. Five platform series were deposited during the uplift and high sea-level phases. Each series is separated from the next by a major erosion phase underscored by three fossil canyons, with the exception of the phase separating the last two series where only a single canyon is present. These erosion phases clearly reflect a sea-level drop going up to the emersion near the present coastline. The increasing thickness of the deposits from the coast offshore shows that the thickness of the water depth was sufficient to permit and preserve the sediments on the platform (we would say today that the available space was sufficient and this is the term that I shall employ below) and partly reflects the increase of the available space. This was never reduced (or only slightly and, in this case, the reduction is lower than the resolution power of the seismic survey) on the part of the platform next to its transition, the slope towards the basin, as shown by the perfect succession of the different series. On the contrary, the available space was reduced in the innermost part and also probably in the central part, thereby contributing to the decrease in thickness of the series towards the coast and the input of material to the basin.

In the basin, Coumes and Estève had identified three main series composed of channel-levee systems. The profiles were widely spaced and did not permit the mapping of the systems. The first attempts to connect them to the single Indus canyon were unsatisfactory. After the work on the platform, it became possible to suggest that these systems were connected to each of the fossil canyons and the pattern thus obtained was highly conclusive. Noteworthy (following the previous work in seismic stratigraphy) is the presence of a doublet of very continuous and very high apparent "frequency" reflectors (this term characterizes the space between the reflections, its use is abusive but it has been adopted by all the interpreters) at the top of each of the series of channel-levee systems (*Fig. 26*).

All these observations suggest a deposition interpretation that confirms Vail's hypothesis (1977) for the formation of the canyons. In a period of rising sea-level and a period of high level, the available space was sufficient to permit the deposition and preservation of the platform sediments. The width of the platform was such that the available space created permitted the sedimentation virtually all the sedimentary input. Sedimentation in the basin finally amounted to the very thin film responsible for the genesis of the reflection doublet. In a period of lower sea-level, the available space on the platform was considerably reduced, even becoming negative towards the shoreline, causing the erosion of a large part of material previously deposited and the creation of the canyon system. This system conveyed towards the basin the material resulting from the erosion of the platform, which was added to the material always coming from the hinterland and no doubt in larger quantities, because of the modification of the river equilibrium profile. All these inputs allowed the edification of the channel-levee systems.

This study served to highlight the importance of the width of the platform for the evolution of the sequences. This factor, which was not at all discussed at the time, has since been widely used, and the study of its impact has been considerably intensified, particularly by Jacquin *et al.* (1991) and Jacquin and Vail (1995).

3.3.2 Field

Only the most important results of the field and seismic data are presented here for their mutual interpretation. Two sites were selected for the extraordinary quality in continuity of the outcrops. Besides, these two sites had been investigated previously, particularly by Stanley for Annot (Stanley, 1961, 1975; Stanley *et al.*,1978) and by Arnaud-Vanneau (1980) and Arnaud (1981) for the Vercors, thereby supplying a solid stratigraphic framework on which the studies could rely.

Annot

This was the most important survey site in terms of duration (1980 to 1985) and the number of students involved and led by Riché, Trémolières and the author (final year work at *ENSPM* of Albussaïdi, Inglis, Butin-Kiener, Calatayud, Laval, Lepvraud, Le Varlet, Mousset, Roy, Salim and Vially and thesis work at the *Dolomieu Institute* of Jean (1985) and Deharveng *et al.* (1987)). It also marked the start of the field missions of the author at *IFP*, since all the previous studies had been focused on the seismic exploration of the margins and oceans. This survey was justified by the need to validate the seismic interpretation. The results were highly satisfactory.

The Annot sandstones represent the upper term of the Prabonian trilogy (Eocene Lower Oligocene) (Bertrand, 1896, 1936, 1946). Previous investigations (Bouma, 1962; Lanteaume, 1962; Lanteaume *et al.*, 1967; Stanley, 1961, 1975; Stanley *et al.*, 1978) demonstrated that these sandstones were deposited in a deep sea environment by turbidite processes. The origin of the material was clearly identified first by Gubler (1958) and then by Ivaldi (1973, 1974, finalized in 1989 in his *Habilitation à diriger des recherches*). A previous inspection (1978) found that the size of the main bodies deposited was compatible with the seismic resolution power. Their study was therefore expected to improve the interpretation of the seismic sections. Three observations already justified the first mission (1980):

– the first observation of the Chalufy onlaps described as such;
– the very long continuity of the "granule bars" providing the framework of sequences compatible with the seismic resolution power *(Fig 28)*;
– the possible interpretation of "block shales" described by Kerckhove (1964, 1969) as major pull-aparts affecting the eastern edge of the basin where these sandstones were deposited.

These observations emphasized the importance of the Annot sandstones and led to the broadening and prolongation of the field work by other missions of Cremer and the author (1981 and 1982) and by the researches of the students listed at the beginning of this section.

The aggradation pinchouts were identified by seismic prospecting, but this could have involved a clear termination of strata against a slope or a subsequently progressive thinning below the seismic resolution power. How were they constituted? The observation of those of Chalufy provided answers to these questions. It was also recognized that the very continuous reflections were mainly generated by clay

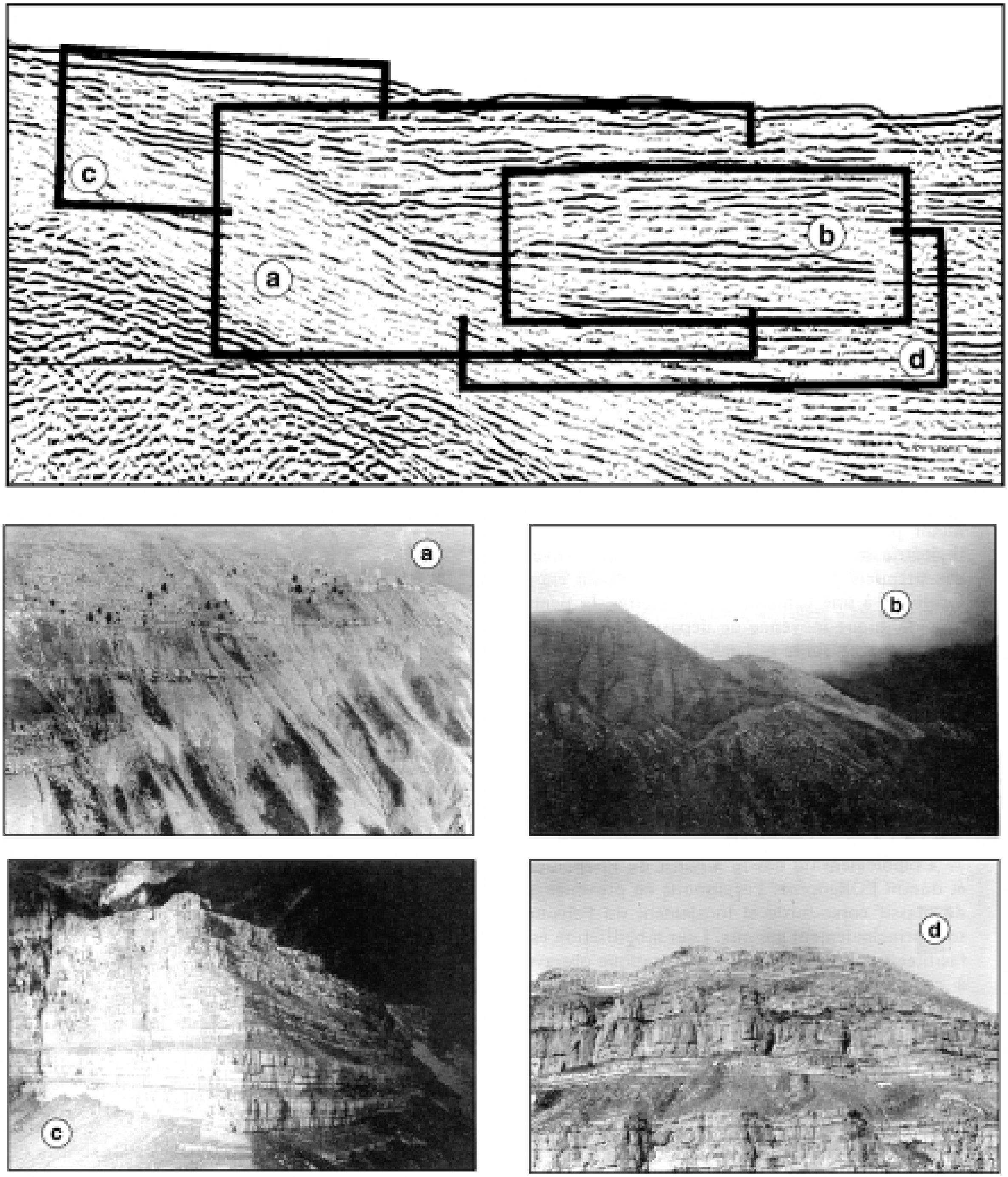

Figure 28

Gravity deposits observed on seismic marine data (Cap-Ferret) and on outcrops (Annot *s.l.)* (after Ravenne and Beghin, 1983a).

The field-seismic comparisons helped to propose possible interpretations of certain configurations (which also depends on the available material). Inset (a) in the seismic profile shows the terminations of the high amplitude, subhorizontal reflections in onlap against the inclined low-amplitude reflections. The analogy with photograph (a) (Chalufy) suggests a deposit of sandstones against slope clays. Insets (a) and (d) on the seismic profile again show high amplitude subhorizontal reflections which can be interpreted as relatively massive sandstone deposits by comparison with photographs (c) (summit of La Blanche) and (d) (avalanche mountain). Inset (b) shows high-amplitude, subhorizontal reflections eroded and overlain by chaotic reflections. The latter were normally interpreted as "high energy" deposits, and hence potentially rich in sand. The comparison with photograph (b) (black head) shows that it could be mainly argillaceous deposits and hence without any reservoir property. The vertical sizes of photographs and of the seismic profile are relatively comparable (about 500 m for inset (a), 200 m for photographs (a), (c) and (d), 400 m for photograph (b).

deposits and that the chaotic reflections reflected high energy and mainly sandy deposits (Vail, 1976, Mitchum *et al.,* 1977).

The consequences were important for oil exploration. This study demonstrated, with the great extension of the granule bars and their thickness, that these bars could generate very continuous reflections and that sediments of the block shale type could generate chaotic reflections. Hence the interpretation could be completely contradicted. It has never been written that the results of these observations constituted the rule (great continuity equals sandstones and chaotic configuration equals mixture) but attention was drawn to this other possibility. Once again, the removal of the indetermination required replacing the seismic survey zone in a broader setting with regional profiles making it possible to track the evolution of the facies and to identify the type and origin of the terrigenous material.

Another important result was the identification of the "granule bars" and especially their sequence arrangement (*Fig. 29*). These granule bars are very similar to the high density turbidite deposits described by Lowe (1982) and whereof certain characteristics had previous been clarified (Lowe, 1975, 1976). The results were the subject of a film and several publications (Jean *et al.,* 1985b; Ravenne *et al.,* 1983a, 1987, 1988c) and papers (Cremer *et al.,* 1982; Ravenne *et al.,* 1982a and 1982b, etc.). A part of them were utilized in the thesis of Cremer (1983), and especially in that of Jean (1985a) which still stands as the reference work on the Annot sandstones. Perriaux of the *University of Grenoble* often participated in the field work and helped to intensify and synthesize the deposition of these sandstones thanks to the work of two students, Jean, already mentioned, and Deharveng. Unfortunately, the latter did not complete his PhD.

Vercors

The chief aim of the study of this site was to seek analogies of sedimentary processes on the slopes and in the basins and their seismic interpretation, but in calcareous environments. The south margin of the Vercors corresponding to the paleoslope separating the platform from the basin is what permits the study of the deposits transposable to the seismic scale.

The work was done with Girard under the direction of Deynoux, Vially and the author (1984, 1985). These studies help to identify pull-aparts and gravity slips of comparable size to those observed in seismic prospecting. They were not pursued, but the preliminary studies were sufficiently significant for a research subject to be entrusted to Jacquin. Vail, with whom two missions had been conducted in the Vercors, and whose interest in this site was manifest, welcomed Jacquin at *Rice University,* where he investigated and compared the two sites of the Vercors and the Guadalupe (Texas).

The two main results acquired in company with Vially (1988) were:

- The discovery of large prograding bodies of the platform and slope margin with the physical surfaces bounding them, so extensively described on the seismic profiles but never observed in the field at this scale. Certainly, Arnaud (1981) and Arnaud-Vanneau (1980) had already identified them by the correlation of numerous serial cross-sections, but in this case, they were tangible with their surfaces and hence made a fundamental contribution to the interpretation of seismic data. The progradations of the coarsest grained strips which emphasize the paleotopography of the slope are subdivided by a lozenge shaped network of fractures does not affect the underlying and overlying marno-limestone strata. They were interpreted by one of the *Shell* geologists during the *AAPG* excursion (1988) as due to a residual and differential shift shortly after their deposition.
- The discovery of the complexity of the canyon fills of Upper Jurassic age; the slip beds observed at their base and the numerous fissures and faults affecting these fills towards the center of the canyon and downstream which developed totally after the depositions, always reflect their subsequent slips. These fills appeared by far to be formed of three units, three clearly distinct bars *(Fig. 30).* Each bar consists of a very disparate assembly of blocks and fragments of strata whereof the juxtaposition is representative of a major gravity episode like those observed in the Bahamas (Ravenne *et al.,* 1988d).

Many other types of slip were identified, their variety illustrated the original state of compaction of the layers involved. The biggest pull-apart observed is the one that led to the formation of the Gâs (or Gats), on the southeast margin of the Vercors. It is nearly comparable in size to the one that affected the Eleuthera margin. It would be advisable to resume the detailed work in this region, with up-to-date concepts, because the outcrop is spectacular by its dimensions and the evolution of its filling.

In the Dévoluy range (Ravenne and Vially, 1988e), the complicated structures observed in the more distal parts of the slope deposits appear to result from gravity processes (particularly enormous "slumps", mass slips, pull-aparts, etc.) which culminated in the edification of the units involved. These structures were then affected by the subsequent tectonic phases which amplified the deformations either in their original directions, or on the margin of the structures.

3.3.3 Experiments

These experiments conducted with Beghin and the objectives, were truly forerunners to those undertaken recently in several laboratories in the United States.

Unfortunately, all the results were not published and the unpublished work of Beghin is under completion by Brugnot.

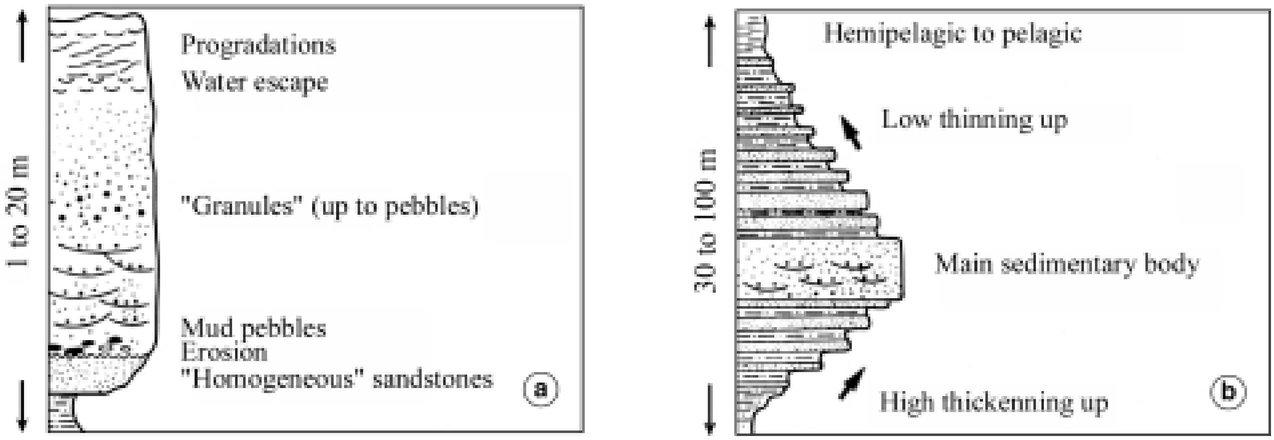

Figure 29

Annot, granule bar and typical "sequence" (after Ravenne et Beghin, 1983a).

Part (a) shows the complete superposition of the levels observed in a granule bar. This may be more complex in proximal position where several bars may be amalgamated, especially in case of fragmentation of the initial sliding body: it is accordingly not rare to observe at the base superposition of several levels with pebbles and granules, and only the last bar displays the upper levels. Part (b) shows the typical sequence with the rapid thickening-up zone often less developed than slow thinning-up zone. The central sedimentary body may consist of several bars, especially in proximal position.

Systematic and accurate experiments were then conducted by Laval as part of his PhD (1988a).

In Flume

The first experiments were performed in the early 1980s in the 10 m long flume of the *Fluid Mechanics Laboratory of the University of Grenoble.* The original idea was to model the density surges that appeared to correspond more to most of the mechanisms responsible for the deep sea fans with the many pull-aparts present upstream of these fans and the evolution of their facies. Each pull-apart produces a finite amount of material and a density surge is specifically characterized by the flow of a finite quantity of heavy fluid without a subsequent input of dense fluid from behind. The experiments previously conducted (Kuenen, 1937; Kuenen and Migliorini, 1950) concerned density currents, characterized, by a continuous supply of heavy fluid. Lüthi (1980, 1981) modeled density surges virtually at the same time: however, in his titles, he retained the current term of density, although he explained clearly in his first article that he was modeling "surge-types"; in the second, the modeling is intermediate between surge and density since he injects a continuous flow but only for 3 min. These points are important, because the surge-type and density surge are very precise and unfortunately, the use of the first usually leads to wrongful attributions.

Density surge and current have very different characteristics. They represent two extreme types of turbiditic flows hence between which many intermediate cases exist, like for example, those induced by variable flows as a function of time. One possible case is the evolution of a density surge into a density current during a part of the floor when the finite quantity is large and most of the particles have been dissociated. At this stage, the flow may appear as a continuous flow of dense fluid with supply from behind. The final phases of the flow resume a surge dynamic. On the other hand, nearly all the initial phases have this dynamic, which served to explain the sequence logic of the "granule bars" (*Fig. 31*, Ravenne and Beghin, 1983a).

Two applications are important for the deposits and erosion mechanisms:

– The importance of the hydraulic jumps created at each slope break: these slope breaks are especially frequent on the flanks of the Cap-Ferret depression and in the Bahamas scarp. The forces developed from the bottom upward are considerable. In the powdery snow avalanches, they are responsible for the tearing out and projection of larches to heights of sometimes over several tens of meters. The larches are then reinserted into the body of the avalanche. These are the only forces capable of dissociating the particles of previously consolidated units, putting them into suspension and of tearing out the clay pebbles at the slope, having in mind the powerful cohesion of the clay that is once deposited. The clay pebbles or silts are then reinserted in the dense body of the surge (where all the material has now been completely dissociated) and deposited nearly immediately above the base of the "granule bar" (*Fig. 29*). They are superimposed on the very first layer of this bar formed of

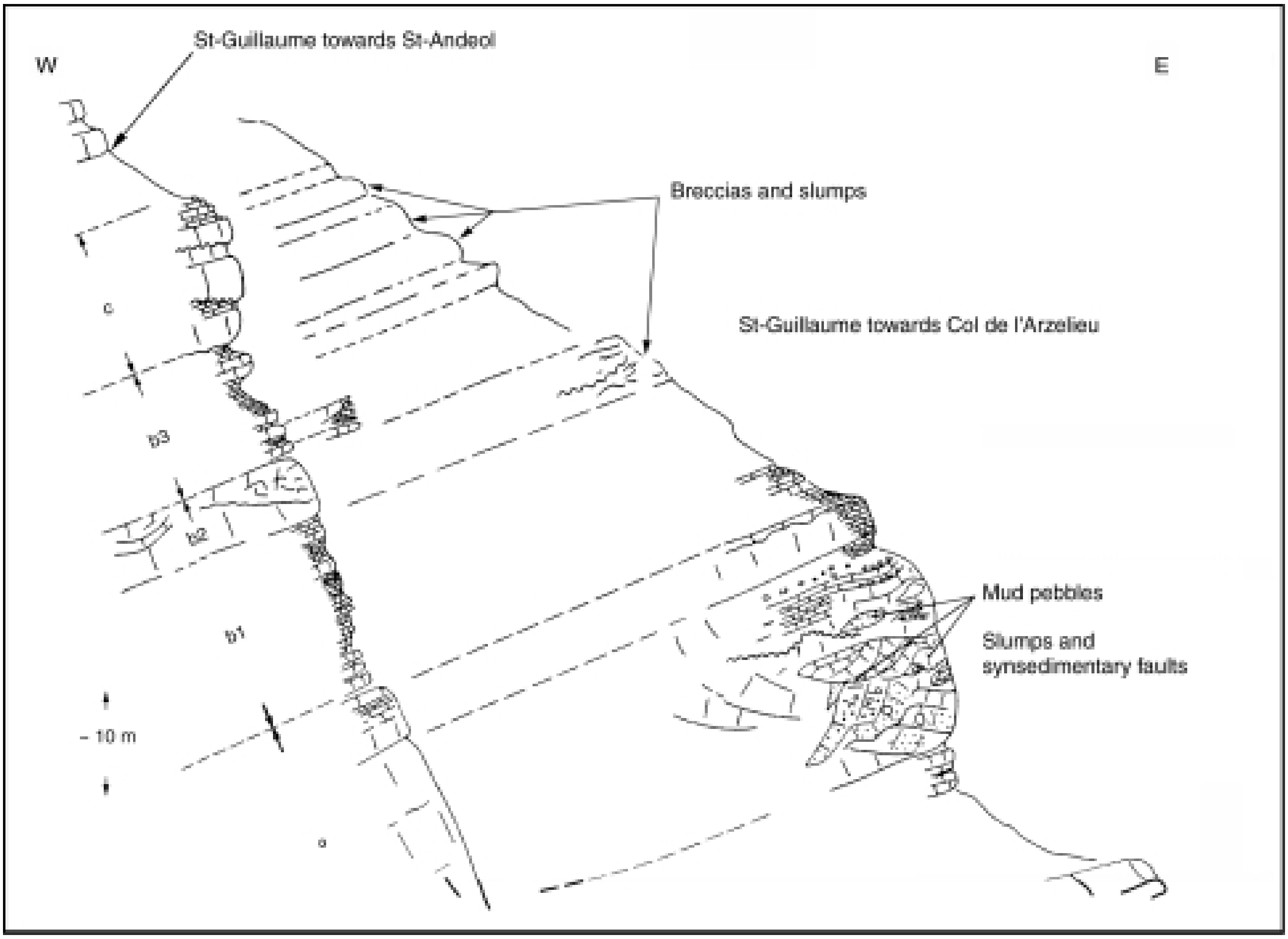

Figure 30

Vercors, complexity of three apparent bars consisting of canyon fills (after Ravenne and Vially, 1988e).

The lower bar (a) appears to be very continuous and relatively isopach. The sections surveyed in this bar reveal its internal complexity (detail to right of figure) and the fact that it results from major gravity processes.

more uniform sandstones than the subsequent ones; it generally lies without significant erosion on the underlying strata. These first sandstones are deposited by a density current process and originate in the first suspensions in the hydraulic jumps. They then represent the slip bed (very often present at the base of the more massive bars) due to the residual gravity of movement of the overall bar. The rest of the hydraulic jumps can cause the dislocation of the initial mass into several units which supply density surges that succeed each other in a more or less long interval (one hour, one day?) and cause the deposition of complex bars with the nesting of often truncated sequences except the last.

– One property of the displacement of the density surge from its formation: its front is raised above the substratum and the surge moves on a “cushion” of water that preserves the substratum from substantial erosion even under very massive sliding bodies.

Most of the experiments were conducted with perfectly calibrated silica microspheres, and some with clay. These experiments cleary showed the high and low transport efficiency aspects defined by Mutti (1975). Once the initial mixture contains more than 10% clay, the surge moves along the entire length of the flume and is stopped by the flume extremity. By contrast, with silica beads, the distance traveled by the surge is limited to a few meters, and is a function of the grain size distribution.

The importance of the distinction between density surge and current, of which Beghin, a fluid mechanics expert, had demonstrated the differences in properties and behavior, has already been emphasized. A surge can obviously function for a period as a density current, and alternations between surge and current may exist. A “granule bar” with its sequence arrangement corresponds to a generally unique event, sometimes multiphased. Its duration is very short given the total duration of about a million years, of the deposition of

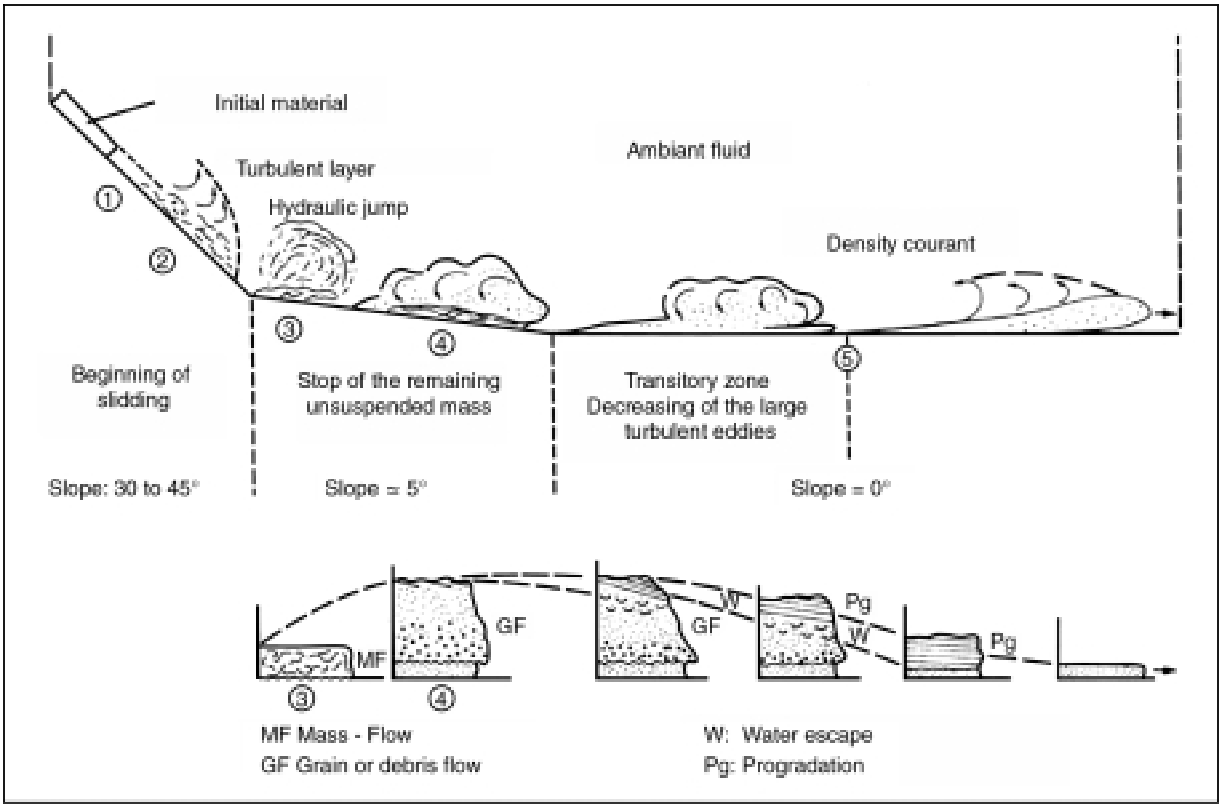

Figure 31

Evolution of a surge type and sedimentation associated with the different phases (after Ravenne and Beghin, 1983a).

The upper part shows the evolution of a surge type (characterized by the flow of a ***finite quantity*** *of dense fluid). Note the formation of the hydraulic jump at the slope break of which the energy is considerable (serves to tear off pebbles from the substratum); many slope breaks generally exist in a margin or canyon profile. Note also at 5 the presence of a fluid tongue in front of the surge and under it while protecting the substratum from erosion.*

The lower part shows the deposits corresponding to each of the flow phases.

the Annot sandstones, the number of these events and the separation of each of them by an often subsequent alternation of clay-silt and sandstone strata, whereof the deposition and the periods of intercalated nondeposition had to require fairly long intervals. The volume of material involved by the deposition of a single one of these parts can exceed 15 km^3, which is closely comparable to the volume of many pull-aparts described along the Armorican margin (Ravenne *et al.*, 1988c). The bibliography often displays a confusion between the two processes, for mainly historical reasons, connected with the first experiments and the ignorance of the major gravity pull-aparts, and because only the fluid mechanics experts had discerned this distinction. It appears that most of the thick reservoirs of deep sea fans originate in density surges, given the high frequency of catastrophic pull-aparts in the margins, and that only they are apparently capable of mobilizing large quantities of material. The deposition processes connected with surge-types have been applied successfully inter alia in the Maghrebin Oligocen basin (Baghli *et al.*, 1989).

In Tank

The most significant result is the virtually systematic succession in the bottom of the tanks, after the initiation of the surge in an inclined flume, of three consecutive vortices. This succession was observed with dense fluids and with surges consisting of silica beads of different sizes or mixtures thereof. Between each vortex a non deposition zone develops, caused by forces of aspiration towards the downstream from behind the first vortex, and those in the opposite direction in the front of the next vortex. The distal part of the deposits is characterized by a network of numerous apparent “channels” resulting mainly from zones of incorporation of ambient fluide between the lobes and fissures of the front of the surge (Ravenne and Beghin, 1983a).

CONCLUSIONS

As introduced in the foreword, the studies conducted were guided by stratigraphy. The execution was achieved within *IFP* by many joint projects conducted with the academic and industrial worlds. Considerable progress has been achieved in seismic stratigraphy and in sequence stratigraphy, and these should continue considering the scale of the work to be done and the synergies to be developed. The main results have been discussed at the end of each of the sections.

The 2nd article discusses the power of the sequence stratigraphy tool to characterize oil and gas reservoirs and the participation of group led by the author in developing concepts. This period of activity (the longest and which involve the largest number of researchers) resulted in the development of a quantitative geology and the creation of methods and software allowing the direct use of geological knowledge. It was marked by the establishment of an effective and efficient multidisciplinarity. The driving role played by IFP in the revival of sedimentology and stratigraphy in France is highlighted.

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