Zeitschrift: Bulletin für angewandte Geologie

Herausgeber: Schweizerische Vereinigung der Petroleum-Geologen und –Ingenieure; Schweizerische Fachgruppe für Ingenieur-Geologie

Band: 4 (1999)

Heft: [1]: Geological results of a hydrocarbon exploration campaign in the southern Upper Rhine Graben

Artikel: Geological results of a hydrocarbon exploration campaign in the southern Upper Rhine Graben (Alsace Centrale, France)

Autor: Lutz, Manfred / Cleintuar, Max

DOI: https://doi.org/10.5169/seals-221515

Bull. appl. Geol.	Vol. 4	Suppl.	3 - 80	May 1999

Geological results
of a
hydrocarbon exploration campaign in the southern Upper Rhine Graben
(Alsace Centrale, France)[1]

by

MANFRED LUTZ[2,4] & MAX CLEINTUAR[3,4]

Abstract

Between 1970 and 1990 an association of Shell Française S.A. and SNEA(P)* carried out exploration for a Mesozoic play in the French part of the Upper Rhine Graben, between Strasbourg and Mulhouse. Originally, the prime exploration objectives were Triassic sandstone and carbonate reservoirs in fault- and dip-bound traps; in the late phase of the venture, the exploration efforts were mainly directed towards reservoirs of the Grand Oolithe.
Between 1970 and 1990 the Association acquired some 1700 km of seismic lines, and drilled 7 wells to the Mesozoic, two of which reached the Basement.
Geological results, comprise information on the stratigraphic and lithologic development of the Triassic, Jurassic and Paleogene in the central part of the Alsace, and on the structure of the Graben fill down to the top of the Basement. They are illustrated by a series of interpreted seismic cross sections, summary logs of the wells drilled and log correlations of the Mesozoic strata encountered.
The structural development is characterised by subsidence and block faulting during the Paleogene and Early Neogene: Faulting started during the deposition of the Saliferous formations (M. Eocene to Early Rupelian („Latdorfian")) and after a period of quiescence in the middle Oligocene (Gray Series), it reached its highest intensity in latest Chattian to Aquitanian time; this triggered movements of the Paleogene salt as from the latest Chattian, which culminated in the extrusion of diapirs in the Mulhouse Salt Basin. The faulting was followed in the latest Aquitanian and Burdigalian by uplift of the southern

---

[1] Extended and revised version of a paper presented at the annual convention of the Swiss Association of Petroleum Geologists and Engineers, held at Freiburg im Breisgau on June 12, 1993.

[2] Manfred Lutz, Geologisches Institut der Universität, Albertstr. 23B, D-79 104 Freiburg im Breisgau; formerly with Shell Internationale Petroleum Mij., The Hague, The Netherlands

[3] Max Cleintuar, Loolaan 106, NL-2271 TP Voorburg; formerly with Shell Française, Exploration Dpt., Paris

[4] Both authors were involved in Shell's exploration campaign in the Alsace, especially during the first, most active decade, M.C. as the geologist responsible for the venture with S.F. in Paris, M.L in Shell's head offices in The Hague more in the role of a critical spectator. M.C. has done most of the original geological studies and interpretations; M.L. re-interpreted many of the data and compiled the present paper.

* Societé Nationale Elf Aquitaine (Production)

part of the graben and the adjacent highs, which caused erosion of up to 1 - 1.5 km of Early Neogene and older strata in the Graben. As from the Late Burdigalian, the uplifted southern part of the Graben was onlapped from north and south by younger Neogene strata, ranging in age from Late Burdigalian in the Swiss to Alsatian Jura and the Badish Kaiserstuhl Mountains, to Late Miocene („Pontian") in the Sundgau and the northern Alsace, and Late Pliocene in the larger part of the area discussed. Quaternary subsidence amounted to 100-300 m only.

The wells drilled encountered hydrocarbon shows only. It is concluded that the reasons for the absence of hydrocarbons in economically producible quantities are:

- the difficulty in charging the Lower Triassic (M. Buntsandstein) reservoirs (originally the prime target) from the Lower Jurassic (Toarcian) source rock, and the absence of deeper (Late Paleozoic) source rocks,
- the large distance - c. 100 m - between the top of these reservoirs and the first reliable seal;
- the variability of the reservoir quality of the Grande Oolithe (the secondary objective) changing from moderate to none within the area, and, above all,
- the unfavourable temporal relation between the main phase of hydrocarbon generation during maximum burial in the Aquitanian, and the final structural development completed only after the Burdigalian uplift.

Contents

List of Figures

Abbre iations

Abbreviations used on seismic sections for stratigraphic units and important reflections.

Stratigraphic units:

Q	Quaternary (+ (?) Pliocene)	
N	Niederrœdern/Freshwater Beds (Chattian)	
G	Gray Marls Formation	
S	Saliferous (Zone) Formation	
	SU/SM/SL	Upper/Middle/Lower Saliferous Z. Formation
	F	Fossiliferous Zone (= Middle Pechelbronn Beds)
	K	Lower Potash Salt within the U. Saliferous Fm
	cross-hatched: salt within the Saliferous formations	
Eo	Eocene/basal (infra-Saliferous) Eocene	
Bt	Bathonian	
Bj	Bajocian	
GO	Grande Oolithe	
Aa	Aalenian + L. Bajocian	
JL	Liassic (excluxive basal limestones)	
Kp	Keuper (inclusive the basal limestones of the Liassic, excl. Lettenkohle: Lk)	
Mk	Upper Muschelkalk+ Lettenkohle	
Bs	Buntsandstein	

Reflections

Q	near base Quaternary
C	Séries Carbonatées (Chattian)
N	near base Niederrœdern/Freshwater Beds (Chattian)
G	base Gray Marls Formation
F	near Fossiliferous Zone (~ base SU=U. Saliferous Fm)
S	within Saliferous Formations
T	near base Tertiary (often near top Grande Oolithe, or near base Paleogene Evaporites)
O	near top Grande Oolithe
L	near top L. Liassic Limestones
M	near top Muschelkalk-Lettenkohle carbonates
B	within Middle Buntsandstein

1. Introduction

1.1 Regional setting (Fig. 1)

The Upper Rhine Graben is the most conspicuous part of the west European Tertiary rift system. Extending for some 300 km in a NNE direction between the Jura Mountains near Basel and the Rhenish Schiefergebirge NW of Frankfurt, it cuts at an acute angle several NE striking units of Variscan basement and of its mainly Mesozoic cover. The system is continued to the south and the north by the Bresse Graben and the Hessian depression, respectively, the individual elements being dextrally offset en échelon with respect to each other.

The Upper Rhine Graben is situated at the southern flank of a major structural feature, the Rhenish Massif (Ziegler 1982) or Rhenish Shield (Cloos 1939) which was uplifted as from the Late Jurassic. In the basement of the present graben shoulders, sinistral wrench faults of Late Paleozoic age are known to lie parallel to the graben edges. A sinistral shift of magnetic anomalies crossing the graben was observed (Edel & Lauer 1974). These observations suggest that an old, inherited zone of weakness exists in the basement under the present graben. The thickness and facies of the Triassic and Jurassic cover are not affected by this zone, but it most probably controlled the location of Cretaceous and Tertiary igneous activity mentioned below, as well as the location of the graben, once it was suitably oriented with respect to the regional stress field. Volcanic activity in the form of igneous dykes of mantle origin, started as early as 100 Ma b.p., i.e. around the boundary between the Albian and the Cenomanian. These dykes and related volcanic phenomena are said to bear witness to the growth of a mantle diapir and a mantle cushion within the lithosphere, assumed in turn to be related to the origin of the Upper Rhine Graben. The graben subsided as from the Middle Eocene. Most authors appear to agree that the graben-forming processes are related to the Alpine deformation, although the mechanism of this relation is still in dispute.

Graben subsidence started in the M. Eocene with the formation of a chain of lakes marking the location of the later graben. Subsidence continued from the Late Eocene to the Late Aquitanian, accompanied by intense faulting from the Chattian. It was accompanied and/or followed since the latest Aquitanian or earliest Burdigalian by a general uplift and erosion of the southern part of the graben (south of the latitude of Karlsruhe) and its shoulders. The extrusion of the Kaiserstuhl volcanics is dated as Burdigalian. Deposition resumed towards the end of the Miocene („Pontian“) in the north as well as in the south, but subsidence up to the present was significant only in the northern part of the graben. Differential uplift of the graben shoulders, mainly during the Quaternary and stronger in the south than in the north, is responsible for the morphological expression of the Graben.

1.2 Hydrocarbons and hydrocarbon exploration in central and southern Alsace before 1970

In the southern part of the Rhine Graben, surface hydrocarbon occurrences have been exploited since the Middle Ages in the Pechelbronn area north of Strasbourg. But also south of the latitude of Strasbourg, hydrocarbon seepages and indications have long been known from both sides of the Rhine river (Fig. 2; Sittler 1972, 1985; Albiez 1935). The most remarkable of all are the seepages and oil-impregnated Late Oligocene sandstones of the so-called Alsatian Molasse in the Oelbach valley

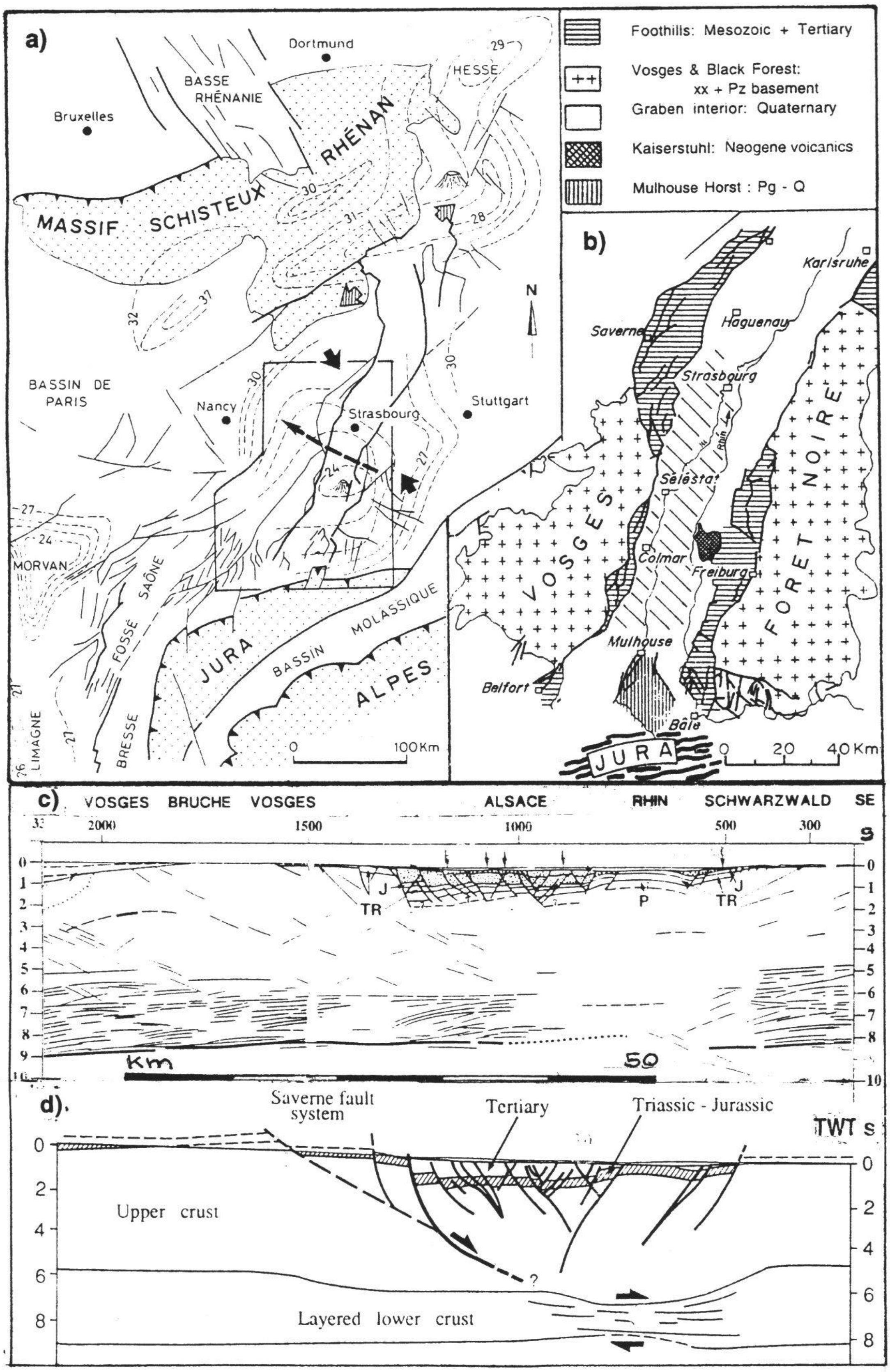


Fig. 1: Southern Upper Rhine Graben: Geographic and geological/structural setting:
a) Regional frame (from Sittler 1992: Fig. 5, after Larroque et al. 1987, amended); depth contours of MOHO in km; inset: position of b); dashed arrow S of Strasbourg: location of c) and d).
b) Southern Graben and adjacent areas (Duringer & Gall 1993: Fig. 1); obliquely hatched: area discussed in this paper.
c)-d) ECORS-DEKORP seismic reflection profile, line drawing and interpretation (Brun et al. 1991: Fig. 2b and 5)

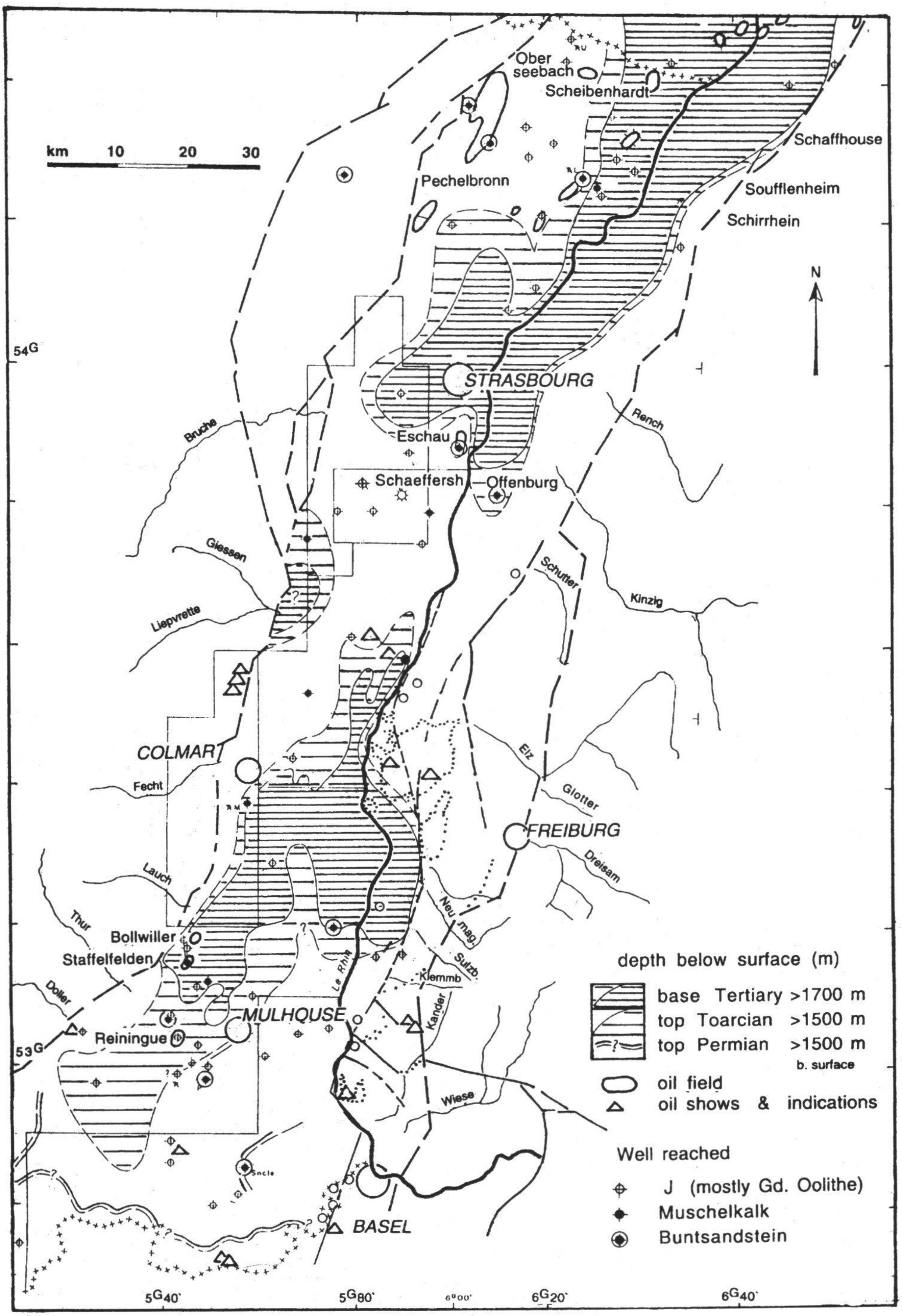


Fig. 2: Southern Upper Rhine Graben: Oil and gas fields, shows and kitchens; wells to the Mesozoic (1970).

near Hirtzbach, some 20 km SSW of Mulhouse (Sittler 1972; Vonderschmitt 1942). These surface shows triggered some drilling activity in the last century as well as between 1928-1939, as did the shows in the Doller valley at the margin of the Vosges west of Mulhouse and in the Sundhouse area E of Séléstat. In 1951, MDPA[1], the Alsatian potash mining company, discovered by serendipity an oil accumulation in the Grande Oolithe, a Middle Jurassic reservoir, near Staffelfelden, some 10 km NW of Mulhouse. This initiated a period of active exploration in the southern Rhine Graben for hydrocarbons trapped in Mesozoic reservoirs, in particular in the Grande Oolithe. During the decade that followed, large areas were surveyed by reflection seismic and some 66 wells were drilled in the Alsatian part of the Rhine Graben south of Strasbourg. Two more small oil accumulations were discovered in the Greater Mulhouse area, viz. Bollwiller (Grande Oolithe, 1951) and Reiningue (Upper Jurassic Rauracian limestones, 1957). In the area south of Strasbourg, the Grande Oolithe was found to be oil-bearing in Eschau (1955), gas-bearing in Schæffersheim (1955), and with good oil- and gas-shows in Meistratzheim-1 (1962).

A similarly intense exploration effort on the eastern, Badish side of the southern Rhine Graben during the fifties and early sixties was not rewarded with success.

As from 1960, exploration activity was drastically reduced for technical and economic reasons. Geological results of the previous period, however, become published or otherwise accessible. They confirmed and improved the general picture of the thickness and facies distribution of the Tertiary fill known from the earlier

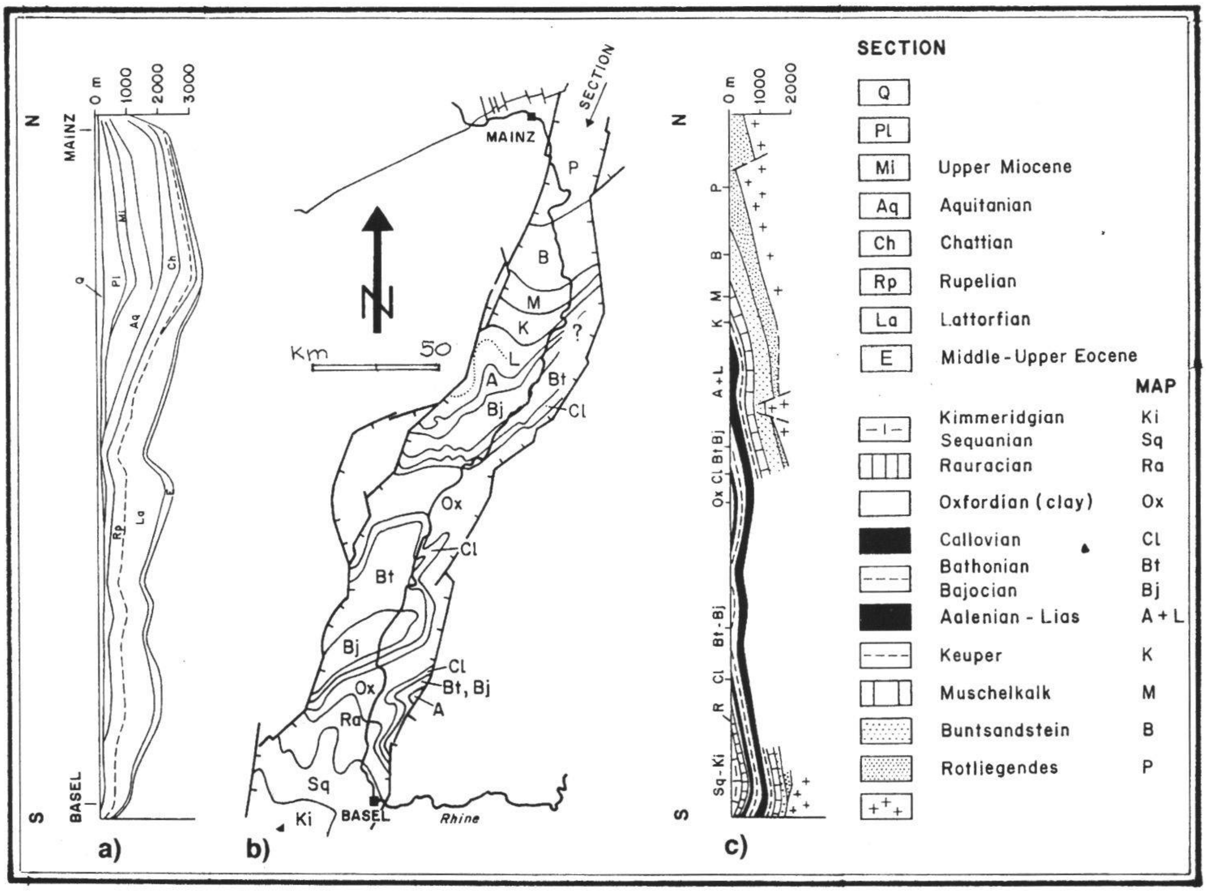


Fig. 3: U. Rhine Graben: **a)** Tertiary sedimentary fill. **b)** subcrop below Tertiary. **c)** Mesozoic preserved below Tertiary (Diebold 1972 (unpublished) after Sittler 1965, 1969).

potash exploration activities (Fig. 3a, 4; Maikovsky 1952) and permitted mapping of the subcrop of the Mesozoic strata below the base of the Tertiary (Fig. 3b, c; Sittler 1965). At the same time, advances in seismic technology based on digital recording and processing improved seismic resolution and seismic penetration, thus opening up new depth ranges to exploration and allowing the elucidation of even more complex structures. Also, the relation of organic maturation and hydrocarbon generation (Tissot & Welte 1978), and the importance of the relation in time and space between hydrocarbon generation and trap formation became better understood.

1.3 Mesozoic plays in central and southern Alsace

In the late sixties, geologists of Shell (and of SNEA(P), we assume) realized that in the southern Rhine Graben and the adjoining Swiss and French Jura mountains, the Lower Triassic Buntsandstein and the carbonates of the M. Triassic Upper Muschelkalk and Lettenkohle had been hardly drilled, but could form exploration objectives, where adequately sealed and having access to an active hydrocarbon kitchen. A play concept was developed, which assumed:

- Lower Triassic sandstones and Middle Triassic carbonates as *reser oirs;*
- *sealed* by Middle and/or Upper Triassic evaporites and claystones;
- fault- and dip-bound *traps;*
- filled with hydrocarbons being generated from either of two conceivable *source rocks:*

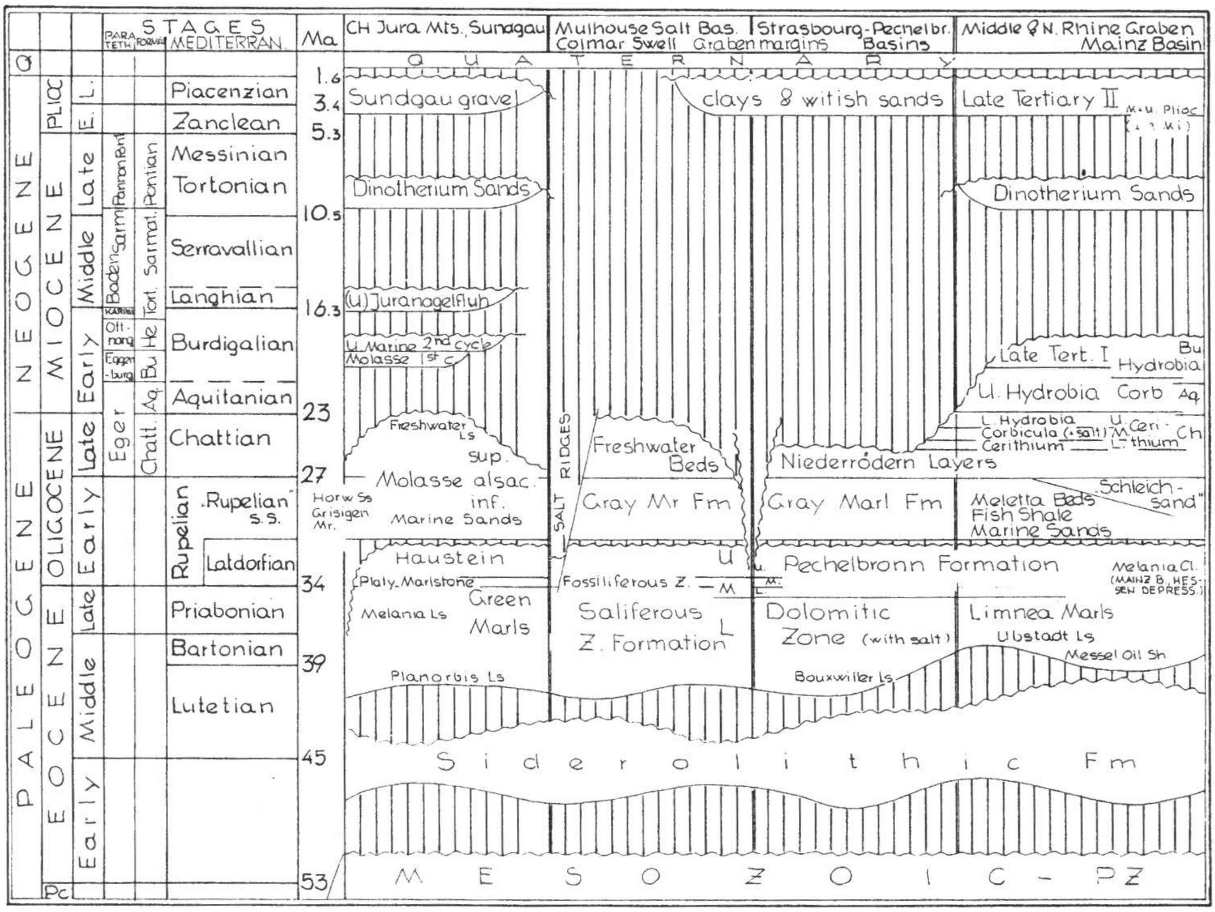
a) Upper Carboniferous - Lower Permian coals and bituminous shales, deposited and preserved in Variscan (Hercynian) post-orogenic troughs or grabens; or
b) Lower Jurassic (Toarcian) bituminous shales generating oil in deeply buried fault blocks, and juxtaposed by major faults to the Triassic reservoirs in adjacent high blocks.

The concept appeared encouraging enough to justify the acquisition of large acreage tracts in the French and Swiss Jura Mountains, where concealed Permo-Carboniferous grabens were expected (Bitterli 1972; Beck 1975: Fig. 12).
In the Alsace, the interest was mainly directed towards the little explored central and southern part south of Strasbourg. The northern part, with the famous Pechelbronn oilfield, had already been intensely explored and was partially covered by exploration or production permits. It was therefore less attractive.

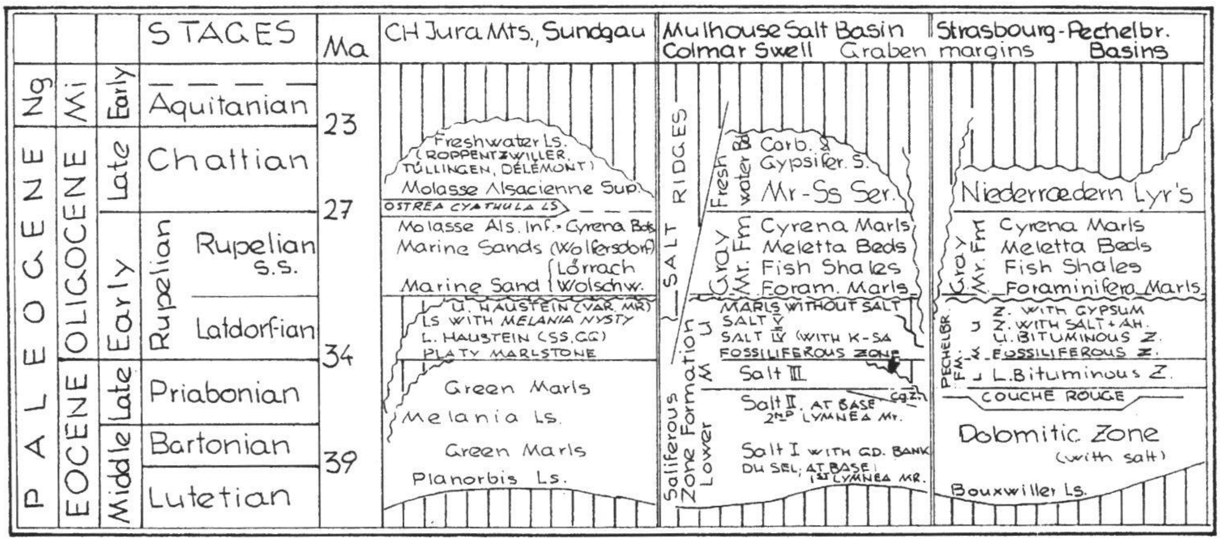
Primary objectives in this area south of Strasbourg were reservoirs in the clastic sequence of the Buntsandstein, and within the carbonates of the U. Muschelkalk and Lettenkohle. They had been penetrated by only few wells: 3 wells had penetrated the whole Buntsandstein, 6 more had just reached its upper part, and some 15 wells had penetrated the Lettenkohle-U. Muschelkalk reservoirs (Fig. 2). Both formations were, however, well known from outcrops at the Graben margins. The M. Jurassic Grande Oolithe was regarded as a secondary target only, as its reservoir properties had been shown earlier to be highly variable and of often poor to moderate quality.

Marls and evaporites of the Lower and Middle Muschelkalk and of the Keuper were assumed to provide seals for the Triassic reservoirs, Upper Dogger marls and Paleogene claystones and evaporites for the Grande Oolithe.

The Lower Jurassic (Toarcian) Posidonia Shale was regarded as the main potential source rock, generating hydrocarbons in the deepest part of the graben, i.e. in the



a)



b)

Fig. 4: Stratigraphy of the Tertiary of the U. Rhine Graben:
a) overview; **b)** Southern U. Rhine Graben: detailed stratigraphy of the Paleogene. After Sittler & Schuler in Vinken (1988: 41-47); ages (Ma) from Grahmann (in Vinken 1988: Fig. 267); position of Central Paratethys and formerly used, stages adapted from Doppler (1989: Tab. 1) after Roegl & Steininger (1983).

Mulhouse, Séléstat, and Strasbourg (Zorn) depressions (hatched area in Fig. 2). Wherever the mature source rock and the Triassic reservoirs were juxtaposed by major faults, hydrocarbons would be able to migrate into the stratigraphically older reservoirs; the structural relation between Triassic hydrocarbon accumulations and the presumed Toarcian source rock in the Greater Pechelbronn area was taken as a model (Schnæbelé 1948: Plate IX (section 4); Blumenrœder 1962: Fig. 12). Fault throws needed to juxtapose the Lower and Middle Triassic reservoirs with the Toarcian source rock, would be some 550 m and 300 m, respectively.
In the Sundgau area, south of Mulhouse, a possibly source-rock-bearing Permo-Carboniferous trough or graben was expected to be present between the well Wintersingen (some 20 km E of Basel), which had drilled oil-shale-bearing Autunian, and the outcropping Stephanian coal measures, mined in the Ronchamp area on the SW slope of the Vosges. Further north, the occurrence of Late Paleozoic source rocks was regarded less likely, except possibly in a NE-trending belt crossing the Rhinegraben between Séléstat and Offenburg, connecting scattered occurrences of Late Paleozoic strata west and east of the Rhine Graben (Fluck & Weil 1975: Fig. 26). In the Vosges (Fluck in BRGM 1972b: 6-7, 24, 32-36), isolated patches of Westphalian west of St. Hyppolyte (6 km SW of Séléstat) contain uraniferous bituminous shales (0-50 m thick) and coal lenses; while Stephanian and Autunian coal was mined near Villé at the edges of the Permian Villé Basin. Here, as in the Permo-Carboniferous trough of northern Switzerland, the faulted Autunian is overstepped by less deformed Saxonian strata, thus recording the so-called Saalian movements. Comparable and possibly related occurrences of Lower Permian to Upper Carboniferous strata are found in the Black Forest near Offenburg (anthracite-bearing Westphalian of Diersburg-Berghaupten, and Stephanian of the Geroldseck near Lahr) and near Baden-Baden (Geyer & Gwinner 1991: 49).
Minor source rocks were assumed to exist in the Lettenkohle and the Lower Muschelkalk.

Traps were expected to resemble known structural traps like Staffelfelden in the south, and Eschau, near Strasbourg, in the north: These comprise eastward-tilted fault blocks, bounded by major antithetic faults in the west, and dip-bounded in the east (Blumenrœder 1962: Fig. 14, 18).

Blumenrœder (1962: 43) had discerned in the area of interest two regional highs, the „dorsale de Colmar-Gerstheim“ and the „seuil d'Erstein“ which he assumed to have been positive features at the beginning of the Tertiary deposition. As a rule, oil accumulations in Mesozoic reservoirs in the Alsace had been found in structures, that existed already in or before early Tertiary time (Blumenrœder 1962: 45), so these two highs, and in particular the hardly investigated Colmar-Gerstheim swell, were regarded as particularly prospective.

2. Summary and results of Shell-SNEA(P)'s exploration activities 1970-1990

In order to explore the play described, Shell Française applied in 1970 for large permits in the southern and central part of the Alsace, and SNEA(P) in the central and

[1] 1^G = 1 gon = 100` = 0.9°; on French official maps, geographical coordinates are given in gons, with the Paris Meridian as origin for longitudes

northern part. Subsequently, both companies decided to join forces in the central area between the latitudes of Guebwiller (S. of Colmar) and Marmoutier (NW of Strasbourg) called „Périmètre d'Association Shell-ERAP 'Alsace Centrale'", Shell Française being operator south of 53^{G} 60` N[1] (just south of Séléstat) and SNEA(P) north of that line (Fig. 2).
In 1974, the well Meistratzheim-2 was drilled by Shell Française (in compensation of earlier activities of SNEA(P) within the northern part of the jointly explored area) on a well defined high where an earlier well had found good oil and gas shows in the Grande Oolithe. The new well confirmed the presence of thick, porous and permeable sandstone reservoirs in the Buntsandstein, but failed to find any hydrocarbons in the Triassic.

Between 1974 and 1980 the Association then acquired some 1200 km of seismic lines. This permitted to study the structural style of the entire jointly explored area and the delineation of the structural pattern of both the Tertiary and the Mesozoic formations.

Five more wells were drilled in the period 1978-1980, two in the north, adjacent to the Schæffersheim gas field south of Strasbourg, and three in the south, between Colmar and the Kaiserstuhl. None of them encountered any hydrocarbons in the Triassic. Only one, Artzenheim-1, encountered significant oil shows, but no reservoir, in the higher part of the Grande Oolithe (see chap. 3.2.3).

A critical review of this first drilling campaign showed that:

- the Triassic reservoirs drilled were essentially devoid of hydrocarbons. This could mean that the charge mechanism envisaged -migration from the L. Jurassic source rock in a low block into juxtaposed Triassic reservoirs of the high block- did not work (although fault throws appeared to be sufficient), or that insufficient hydrocarbons had been generated to charge the Triassic reservoirs;
- whereas one of the expected source rocks, the Toarcian bituminous shales, proved to be regionally present, no indications for Late Paleozoic deposits were seen between Strasbourg and Mulhouse, in either wells or in the seismic records;
- the reservoir quality of the Grande Oolithe proved (as expected) to be highly variable; and in the southern wells much poorer than in the north (MEI-2);
- the increasing thickness of Paleogene salt towards the Mulhouse Potash Basin led to the formation of salt ridges on top of, and triggered by, faults in the Mesozoic-basal Tertiary substrate;
- the definition of trap geometry proved difficult due to rapid lateral variations of sound velocity, and to the difficulty, if not impossibility of correctly migrating the 2D-seismic lines in areas of intense faulting and salt tectonics; and most important of all,
- the southern part of the Rhine Graben had limited hydrocarbon generation potential. Hydrocarbon kitchens appeared to be restricted to the deepest parts of the Potash Basin and its SW continuation (Dannemarie Graben). There was apparently no Recent widespread hydrocarbon generation, and long range migration did not appear to occur.

In consequence, interest became focussed on traps *within* the assumed kitchens, with the Grande Oolithe as the main objective - notwithstanding its highly variable reservoir properties. The Association therefore applied for, and was awarded in 1979 and 1987, respectively, the permits „Neuf-Brisach" and „Munchhouse" adja-

cent to the old acreage and covering the deepest part of the graben east and south of Colmar (Fig. 2). The old permits covering the Colmar-Gerstheim Swell were allowed to expire.
Seismic surveys in the new permits confirmed the presence of large, N-S trending tilted blocks below a thick, halotectonically deformed Tertiary overburden. A well, Ste-Croix-en-Plaine-101 D (deviated as SCR-101 G) was drilled in 1989 in the deep Mulhouse Salt Basin SSE of Colmar on the culmination of a tilted block with access to a deep kitchen. The Grande Oolithe, the prime target, was, however, not encountered, probably due to fault cut-out. The well also failed to find any hydrocarbons in the deeper reservoirs of the Lettenkohle-U. Muschelkalk, and the Buntsandstein. The Association therefore decided to terminate the exploration activities in the area. Twenty years after Shell Française's first application, the last two permits were allowed to lapse at the end of their respective periods of validity in 1990.

3. Interpretation of seismic and well data (by area)

3.1 Strasbourg - Séléstat area

3.1.1 Operational aspects

The area discussed (Fig. 5) comprised the SNEA(P)-operated part of the „Périmètre d'Association“ between Lat. $53^{G}60`$ (just S of Séléstat) and $54^{G}10`$ (see chap. 2). Nearby hydrocarbon accumulations and indications in the Mesozoic reservoirs (Triassic and Dogger) appeared to confirm the play concept: Mesozoic (Jurassic and Triassic) reservoirs were present, and migration of hydrocarbons from potential Toarcian source rock into the reservoirs across antithetic faults appeared possible where source rock and reservoir were juxtaposed.

Within the area, SNEA(P)'s Schæffersheim Field is located (with producible gas, and oil shows in the Grande Oolithe). In the Meistratzheim-1 well (MEI-1), good oil and gas shows were encountered. Oil shows were also reported in the Sundhouse area E of Séléstat, from shallow water wells and the well Sundhouse-P1 (SHP-1; Gachot 1936).
3 km NE of the permit, an oil accumulation in the Grande Oolithe had been found in the Eschau structure, an eastward tilted block, bounded in the west by an antithetic fault (Blumenrœder 1962: Fig. 7, 8). Eschau-1 (PREPA[1] 1955) drilled 40 m into the Buntsandstein, and tested 13 m3/h salt water with gas shows.
7 km W of Eschau, the well Lipsheim-1 (LIP; PREPA 1957) had tested within the permit a similar structure, but found only oil shows in the Grande Oolithe.
On the Wittisheim structure, some 14 km NE of Colmar, PREPA had drilled the well Wittisheim-1 (WIS) to the Grande Oolithe in 1955 (BRGM 1972b: 38, 40), but tested only salt water.

After preliminary studies, exploration activity in the permits of the Association started in this northern part, where Shell Française drilled in 1974 the well Meistratzheim-2 (MEI-2), based on seismic acquired before by ERAP. Later on, the Association acquired more than 700 km of new seismic lines in the area and drilled two more wells, Grunsbuhl-1 (GRB, Fig. 5) and Binnenweg-1 (BWG, Fig. 5), in 1979.

[1] Societé de prospection et exploitations pétrolières en Alsace

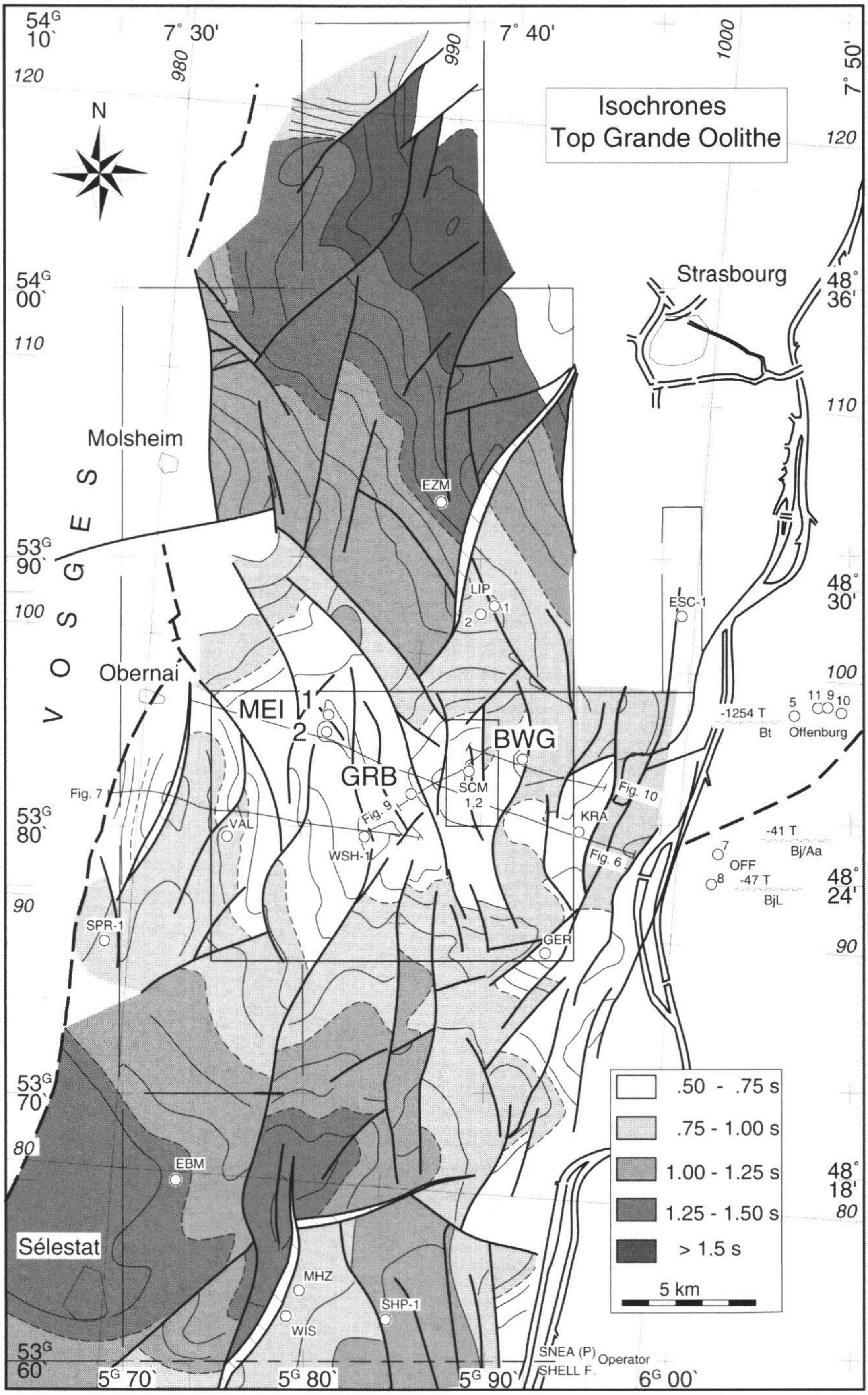


Fig. 5: Strasbourg-Séléstat area: Isochrones top Grande Oolithe. Note: the geographical coordinates indicated on the margins of Figs. 5, 12, 20, 21, delimit the sheets of the official French maps 1/50'000 (^{G}),and German maps 1/25'000 (^{0}). Wells: EBM Ebersheim, EZM Entzheim.

3.1.2 *Structural interpretation*

The main structural features of the area are shown on Fig. 5. They comprise a prominent high between Obernai and the well Krafft (KRA), just E of Erstein, called here the Meistratzheim high; and the Tertiary Sélestat and Strasbourg basins, south and north of the high, respectively.

The high had been drilled earlier by the wells Meistratzheim-1 (MEI-1, 1962), Schæffersheim-1 (SCM-1, 1955), and Westhouse-1 (WSH-1, 1961). Of these, Schæffersheim found the Grande Oolithe gas-bearing, and Meistratzheim-1 encountered good gas- and oil-shows. The high strikes ESE and is well expressed at the base Tertiary unconformity and at top Grande Oolithe. On strike with this Tertiary uplift, a pre-Tertiary high is indicated by the subcrop of the ?Grande Oolithe and the L. Bathonian west and north of Obernai (Schirardin 1953: 1807; Théobald 1955: Fig. 2) whereas to the south and further north, Callovian and Oxfordian strata subcrop below the Paleogene in the foothills of the Vosges.

This ESE striking structural high has sometimes been called the Erstein Swell (BRGM 1987: 50, Fig. 10). However, it is situated down the NW flank of the gravimetric and magnetic Erstein Swell first revealed by the gravity surveys of MDPA. The latter strikes NE through the village of Erstein, c. 20 km S of Strasbourg (Maïkovsky 1952: 34 and Fig. 8). This geophysical anomaly has been shown by Edel & Lauer (1974) to continue as a magnetic anomaly into the basement of the Vosges (Champ-du-Feu, Hohwald - Epinal) and (be it slightly sinistrally displaced) the Black Forest (Baden-Baden). They suggested that it may correspond in the graben to a higher position of the basement. This was not confirmed, either seismically or by drilling: the well St-Pierre-R1, drilled just northwest of the axis of the Erstein Swell, found base Tertiary/ top Callovian at a depth of 1273 m bsl. (BRGM 1972b), i.e. 810 m deeper than in the wells Meistratzheim-1 and -2, drilled on the deeper flank of the magnetic high. Magnetic basement can here not be correlated directly with geologic (crystalline) basement.

A seismic line (Fig. 6), running from the Rhine River near the well Krafft-1 (c. 18 km S of Strasbourg) towards Obernai gives an impression of the structural style of the area: numerous submeridional (NNW to NNE) faults cut the Graben fill into a series of horsts, grabens and westward tilted blocks bounded by antithetic (E-throwing) faults. As shown in Fig. 5, this deformation style affects high and low areas equally.

A number of fault- and dip-bound trap geometries can be recognized, especially the two horsts at the E. and W. end of the line (on which the wells Meistratzheim and Krafft were drilled), and in between several tilted blocks, bounded by antithetic faults, such as the gas-bearing Schæffersheim block, and the Grunsbuhl and Binnenweg structures (Fig. 9, 10, 11).

Note that northeast and north of the Meistratzheim high, the Eschau and Lipsheim structures (Fig. 5) and the fault blocks in the Greater Pechelbronn area (Schnæbelé 1948: Pl. IX-XI; Sittler 1985: Fig. 8) all dip towards the east and are bounded by west-throwing faults.

A seismic section crossing the Grunsbuhl and Schæffersheim structures (Fig. 9), shows the structural style in some more detail: westward-tilted blocks of some 1-3 km width are bounded by east-dipping faults with throws of some 100 ms at the level of the Rupelian Fish Shale as well as at the top of the Grande Oolithe reflectors. Some of these faults, for instance the one at the eastern flank of the Schæffersheim structure, are complex, being composed of several parallel antithetic, and secondary synthetic faults, forming little grabens in front of the high block.

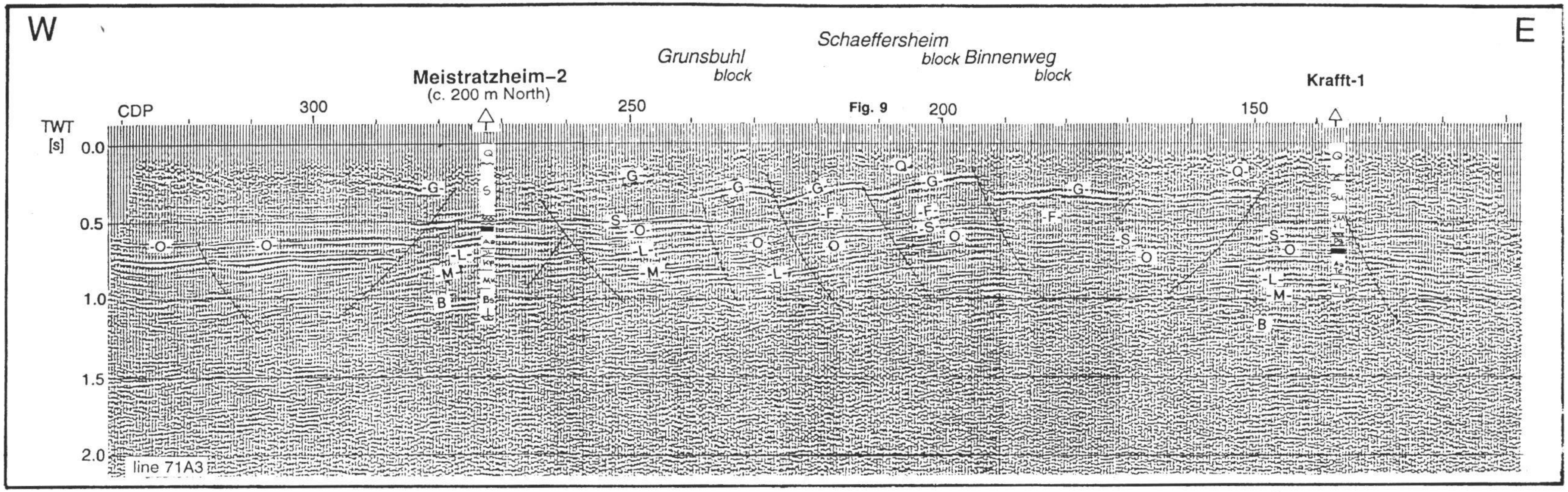


Fig. 6: Seismic W-E section Meistratzheim - Krafft; location on Fig. 5; for abbreviations of reflexions and stratigraphic units, see listing before main text.

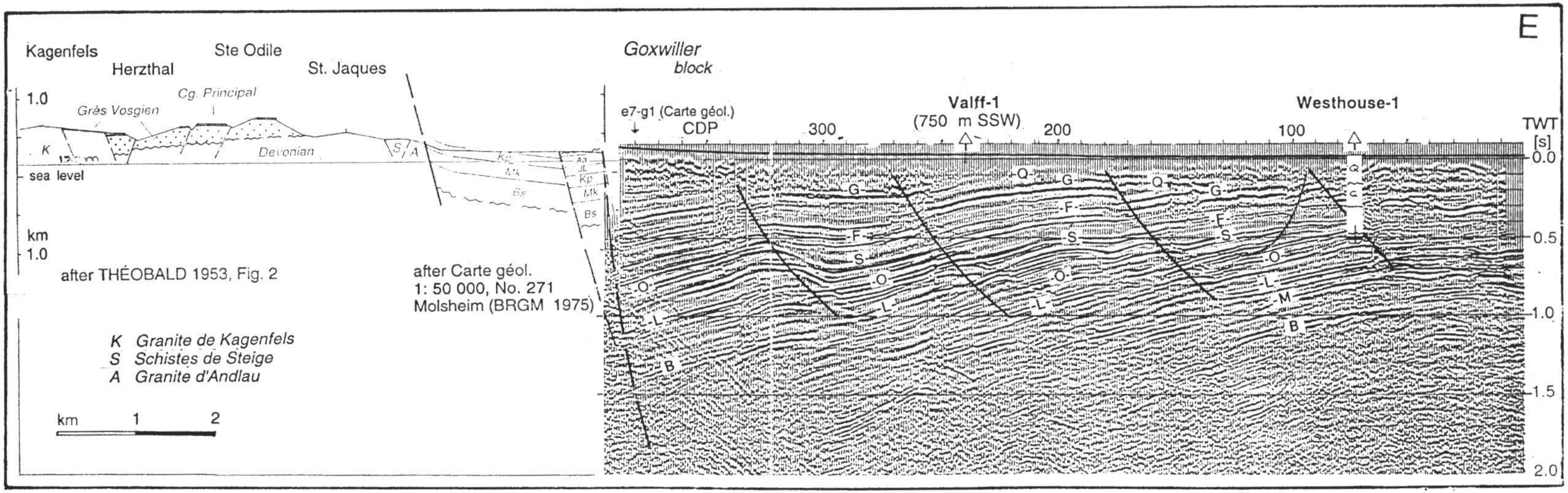


Fig. 7: Geol.- seismic W-E section Ste-Odile - Westhouse; location on Fig. 5.

Fig. 7 illustrates the relation between the Rhine Graben and the uplifted Vosges Mountains. The seismic line, which starts in the east in the deep part of the tilted Grunsbuhl block, runs through the well Westhouse-1 (PREPA 1961; see Walgenwitz et al. 1979: annexe 1), passes 0.7 km north of the well Valff-1 (BRGM 1972b: 38, 40) and ends some 1.5 km W of the village of Goxwiller. On this line, the base Plio-Pleistocene ("base Q") unconformity in the three eastern blocks dips slightly to the east and is clearly affected by the two antithetic faults in the east of this line. The throw at base Plio-Pleistocene level may be estimated at not more than 20 ms. The underlying Gray Series (G) dips to the west and is truncated by the base Plio-Pleistocene unconformity, so that in the westernmost block, the Gray Series is completely absent. The geological map (BRGM 1975, sheet 271 Molsheim) shows patchy outcrops of the „Latdorfien/Sannoisien (e7-g1)" in the midst of the Quaternary cover in this part of the section. Note that in the well Hilsenheim-1 (DPXV) some 15 km south of this line, more than 600 m of M.-U. Oligocene strata (Gray Series and Chattian Niederroedern Beds) are preserved (Maikovsky 1941: Tab. 16). The underlying Saliferous formations (Zones Salifères = Lymnea Marls Mbr. and Dolomitic Zone, respectively, and Pechelbronn formations; see Fig. 4 for strat. nomenclature) corresponding to the interval between the reflections G and O (Fig. 7) all show a thickness increase within each block in a downdip direction, from east to west; and in the same direction, from block to block: e.g. from 280 ms at the updip, eastern side of the Westhouse block, to 420 ms at its downdip, western side, and to > 800 ms (corresponding to some 1400 m, with the velocities measured in St-Pierre-R1) at the western end of the seismic section, at a distance of only 500 m from the strongly faulted Vosges border zone (Rhine Fault = faille rhénane) where intensily faulted Jurassic and Triassic strata are crop out (Théobald 1953, BRGM 1975). Similar fault-controlled thickness variations are seen on a geological section through the Pechelbronn oil field (Sittler 1965: Fig. 34).

No significant variations in two-way traveltime of the interval between the reflections from the Fish Shale and from the top of the Grande Oolithe can be observed between the Grunsbuhl, Schæffersheim and Binnenweg blocks in Fig. 9. The bounding faults, therefore, are of post-Early Oligocene age. We do not see, however, an obvious difference in direction between faults which were active in the older part of the Paleogene, the Saliferous formations, and those which came into existence only after the deposition of the Gray Series (but before the Plio-Pleistocene).

The throw of most faults within the northern part of the Périmètre d'Alsace Centrale, is less than 200 ms (Fig. 5), i.e. not sufficient to juxtapose the assumed Toarcian source rock and the clastic reservoirs of the Buntsandstein. Nevertheless, a fault throw > 300 ms is seen on the eastern flank of the Goxwiller structure; while some 9 km north of the well Sundhouse-P1 (SPH-1) and also at the western margin of the Wittisheim structure (E of Séléstat, well WIS-1) and of a structure NW of Lipsheim (wells LIP-1, -2), the fault throw reaches 750-1000 ms.

3.1.3 Drilling results

Meistratzheim-2 (MEI-2), Fig. 8

The well Meistratzheim-2 was drilled in 1974 in the centre of a horst block, as the first test of the Middle and Lower Triassic reservoirs. The well encountered the Grande Oolithe developed as an oolitic packstone to grainstone with a thickness of

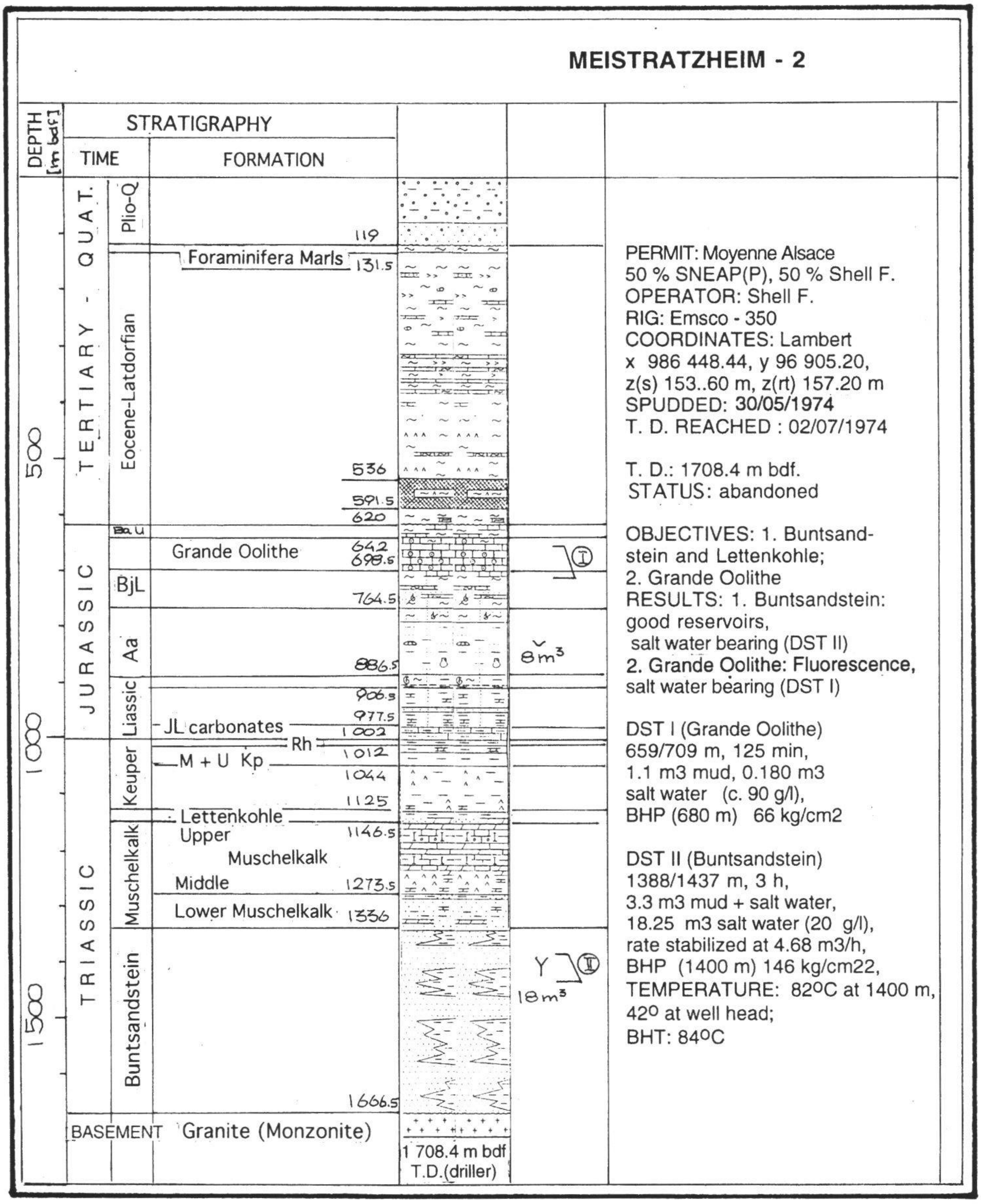


Fig. 8: Meistratzheim-2: Well summary; well location on Fig. 5.

56.5 m. Good reservoirs were seen in the Grande Oolithe (sonic log porosities of 16-32 % over 38 m), in the dolomites and limestones of the Lettenkohle and Upper Muschelkalk ($\varnothing_{SL}$ = 4 - 1%) and clastic reservoirs of the Buntsandstein ($\varnothing$ = 4 - 17% on sonic log; $\varnothing$ = 12 - 35% and K = 57 - 1524 mD on sidewall samples). Hydrocarbon indications were observed whilst drilling through the Dogger and the Liassic (gas indications and fluorescence on cuttings). The Toarcian paper shales, however, were not seen in cuttings and are not recognizable on logs. In the Buntsandstein,

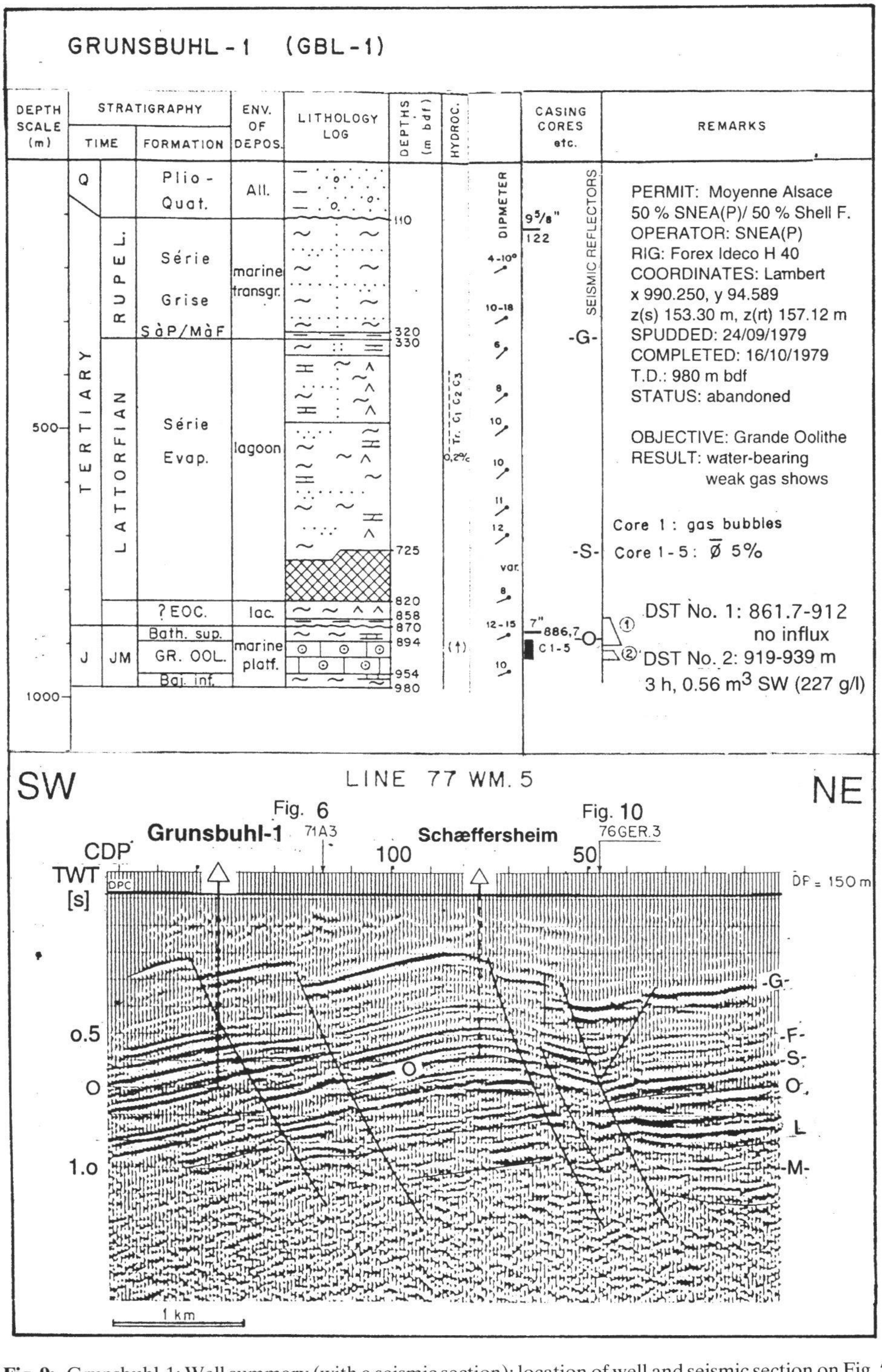


Fig. 9: Grunsbuhl-1: Well summary (with a seismic section); location of well and seismic section on Fig. 5.

minute gas traces only were measured over a restricted interval. Mud losses (c. 8 m^3) occurred when drilling in the Aalenian around 850 m, presumably in the Grande Oolithe; while another 18 m^3 were lost in the higher part of the Buntsandstein. They confirmed the reservoir qualities of these intervals as interpreted from logs, but both reservoirs produced salt water only in drill stem tests.

Grunsbuhl-1 (GBL-1), Fig. 9

On a small fault block west of their Schæffersheim gas field, SNEA(P) drilled the well Grunsbuhl-1 in 1979. It found the objective, the Grande Oolithe, about 95 m deeper than in the gas field, and much more compact: core porosities averaged 5 %, and no influx was achieved during the 1st drillstem test over an interval covering marly Bathonian and the top 18 m of the Grande Oolithe. Apart from some gas bubbles in fissures on cores, no hydrocarbons were encountered. In a 2nd DST, the well produced in 3 hours 560 l of rather concentrated (227 g/l) saltwater from the central part of the Grande Oolithe.

Binnenweg-1 (BWG-1), Fig. 10, 11

E of the Schæffersheim field, well Binnenweg-1 was drilled in 1979 on behalf of the association by SNEA(P) as operator. The target of the well, the Grande Oolithe, was cut out by an unexpected fault. SNEA(P) then deepened the well on their own account to a T.D. of 1822 m. After having reached the Buntsandstein without hydrocarbon shows, the well was plugged back and drilling was resumed for common account to reach the Grande Oolithe reservoir by controlled deviation in the high block to the west. The side-tracked well, Binnenweg 1-bis, penetrated 75 m of Grande Oolithe of which only the middle part contained effective porosity and permeability. The Grande Oolithe was found c. 210 m lower than in the gas field. The dipmeter indicates southwesterly dips of about 10°. No hydrocarbon shows were found in the well which was abandoned at a T.D. of 1125 m (1097 m vertical depth).

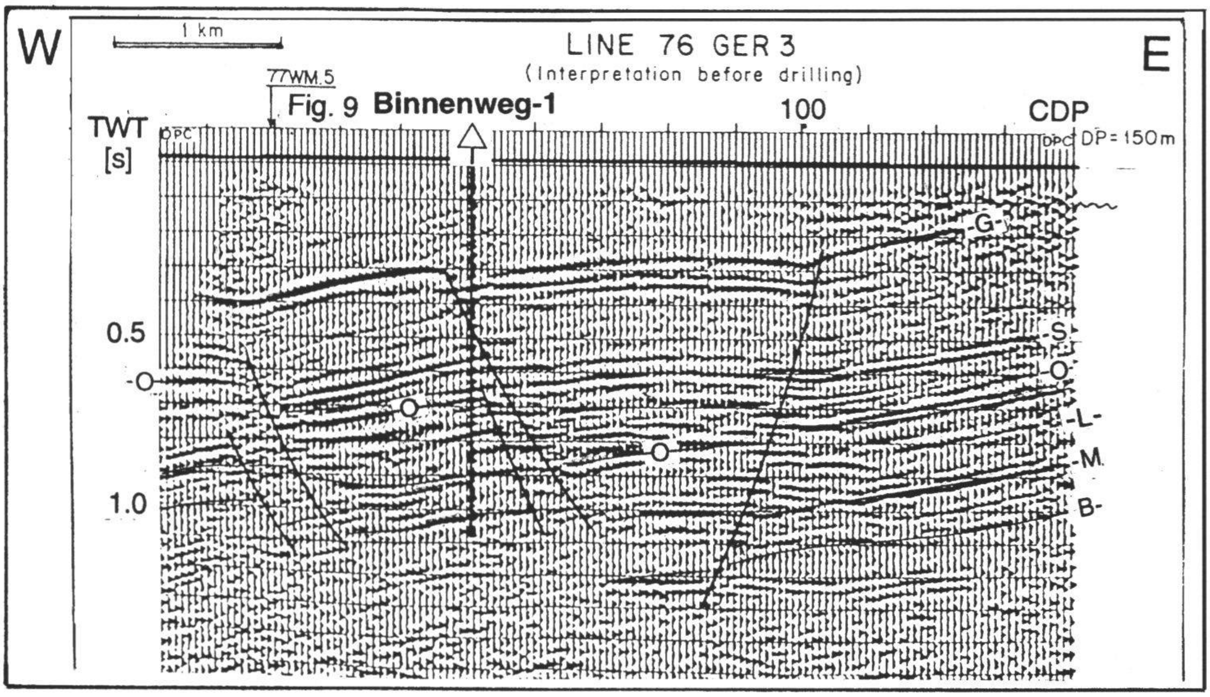


Fig. 10: Seismic section through well Binnenweg-1; location on Fig. 5.

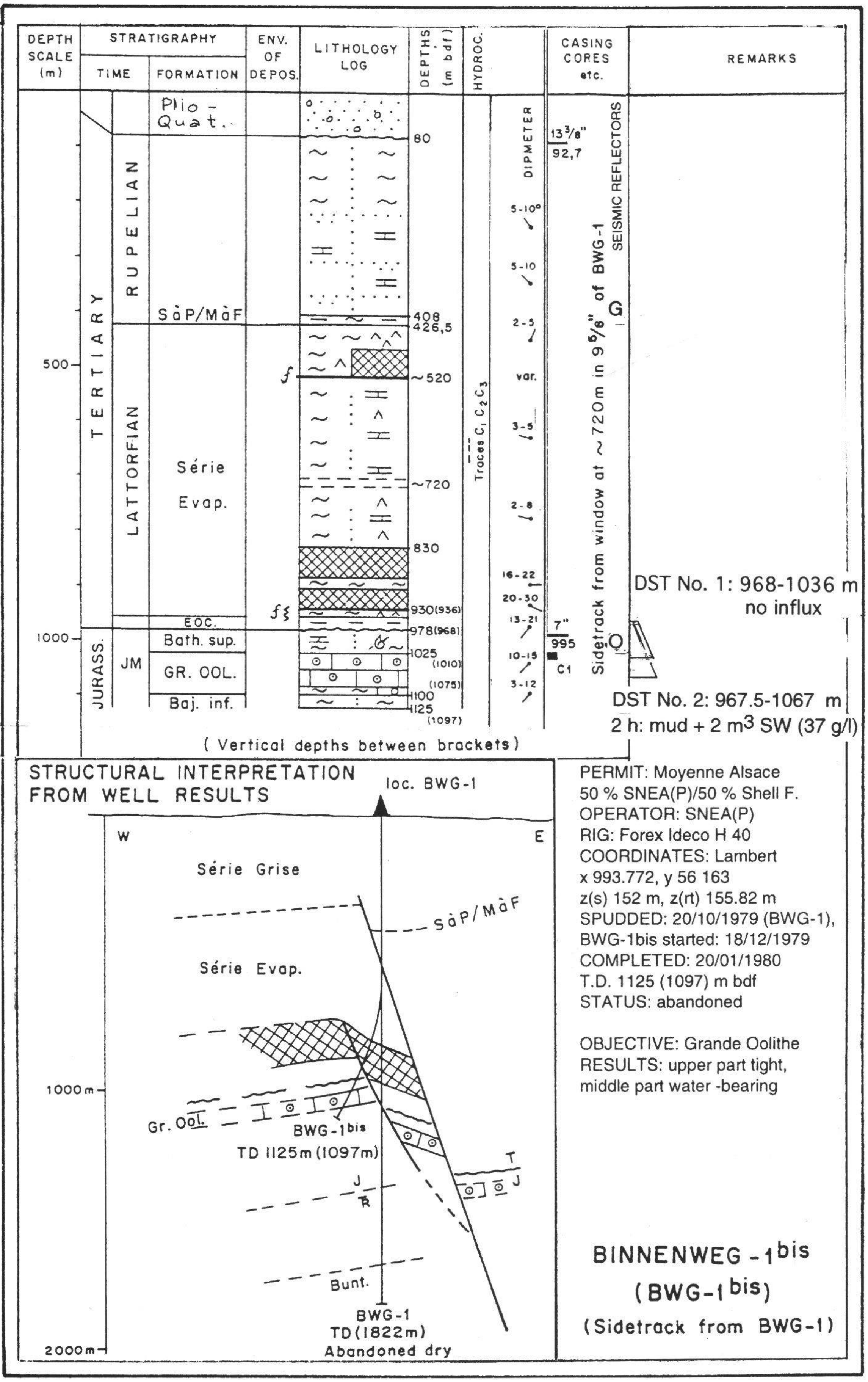


Fig. 11: Binnenweg-1 and -1bis: well summary; well location on Fig. 5.

Rele ant competitor wells

After the relinquishment of the permit by the Association, some more wells were drilled within or just north of the area discussed. The results of these are relevant for the final evaluation of the play.

A group of companies (Total, Essorep, DSM) drilled the well Muttersholtz-1 (MHZ-1) on the Wittisheim structure, some 7.5 km ENE of Séléstat to the Buntsandstein; reportedly it was abandoned as a dry hole; the Grande Oolithe of the same structure had been tested without success by PREPA's well Wittisheim-1 (WIS-1) in 1954. Similarly, the reservoirs of the Buntsandstein were tested in the Lipsheim structure by dry well Lipsheim-2 (SNEA(P)-Essorep, 1986; T.D. 1815 m in Lower Triassic); and in the Schæffersheim structure by Schæffersheim-101 (SNEA(P)-Essorep-Total, 1989). Apparently, none of these wells met with economic success.

3.2 Séléstat-Colmar area

3.2.1 Operational aspects

This area comprises essentially the Shell Française operated southern part of the Strasbourg-Sud permit, and the westerly adjoining northern part of Shell Française's permit Rhin, between Colmar and Séléstat, both between $53^{G}60$` and $53^{G}40$` N. latitude (Fig. 12).

This part of the permit had been investigated, mainly between the wars, by geophysical (electrical) surveys and by a number of wells drilled for the exploration of potash salt. Two of these wells were drilled in a structurally deep position down to the Mesozoic substrate, Ostheim (OSM), some 8 km north of Colmar, and Bischwihr (BSW), c. 900 m W of Muntzenheim-1 (Foerster 1911; BRGM 1972a: 56, Tab. 1); Bischwihr could be used for reflection identification and calibration, as could the two deep hydrocarbon exploration wells drilled earlier on the Colmar Swell, Illhæusern-1 (ILH-1) and Sundhouse-P3 (SHP-3).

Surface hydrocarbon indications have been reported from within the area and from several localities near its western and eastern boundaries; they include asphalt veins in the Muschelkalk at the border of the Vosges between Ribeauvillé and St. Hippolyte (Van Werveke 1913: 96). East of the Rhine river, in the Kaiserstuhl, oil is reported from the Oberschaffhausen and Niederrotweil phonolites as impregnations or in fractures (Pfannenstiel 1933: 37-38; Wimmenauer 1951: 22). A sudden occurrence of oil shows in water wells of the Sundhouse-Schoenau area (E and ESE of Séléstat) in 1924 caused the drilling of the Sundhouse wells (SDH-P1-3) in 1925, 1938 and 1939, respectively (Gachot 1936, BRGM 1972a: 56, Tab. 1). Another oil exploration well, Illhæusern-1, was drilled in 1955 by PREPA to a depth of 1518 m (Fig. 12; BRGM 1972a: 56).

Between 1974 and 1979, the Association covered the southern part of the Strasbourg Sud permit with a regular seismic grid with a line distance of 1-3 km, for a total length of some 360 km. Three wells were drilled in 1979 on the most promising structures. As none of them was successful and all obligations were fulfilled, the Association ceased its activities in the area.

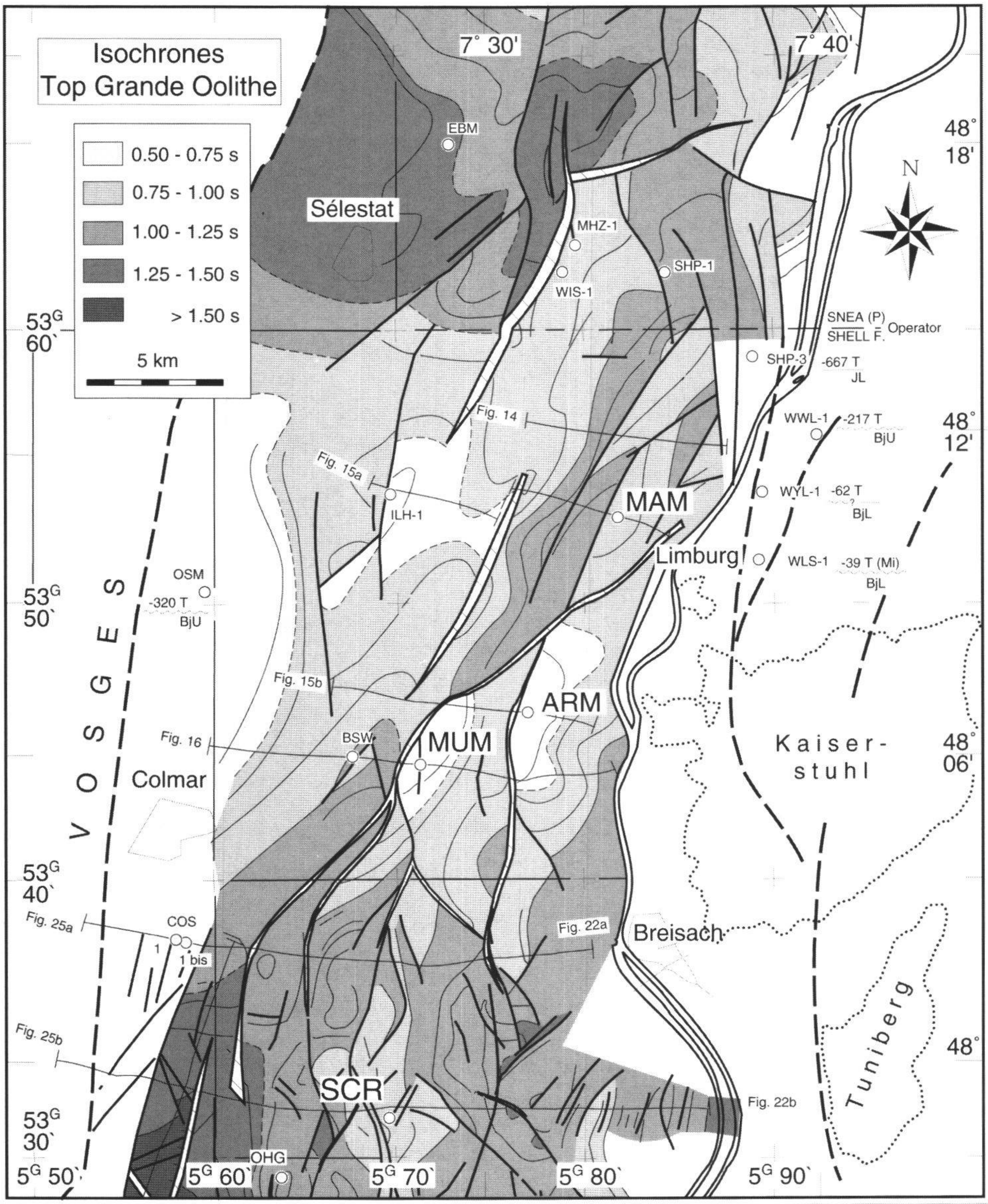


Fig. 12: Séléstat - Colmar area: Isochrones top Grande Oolithe.

3.2.2 *Structural interpretation*

Reflections in the area were identified in the pre-drilling period with help of stratigraphic and lithologic data from the older wells and interval velocities measured in the well Meistratzheim-2. A synthetic seismogram of the Mesozoic penetrated in that well (shown on Fig. 14) was particularly helpful in interpreting infra-Tertiary reflections. The interpretation was refined using stratigraphy, sonic velocities and

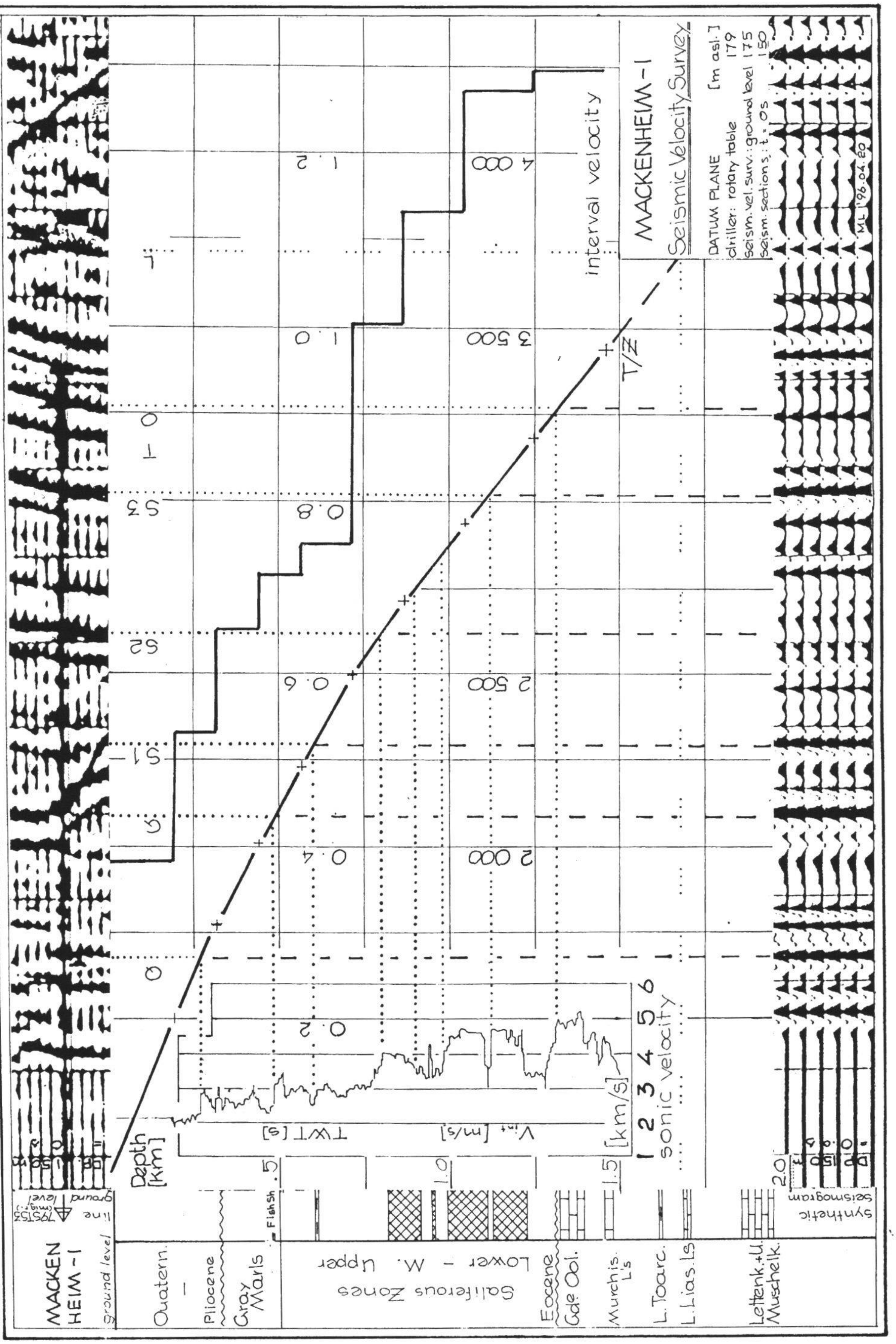


Fig. 13: Mackenheim-1: Well velocity survey, with synthetic seismogram and part of seismic line 79STS3 at well location (Fig. 15a).

formation densities from the wells drilled in the area itself. As an example, a velocity survey in the well MAM-1 allowed the identification of the main reflectors down to the Aalenian (Fig. 13, 15a). The highest of the three reflections within the Paleogene Saliferous formations marked S1 is apparently caused by a low acoustic velocity interval (595-610 m) which is described as a light gray plastic marl with intercalations of bioclastic limestones. With respect to the base of the Gray Series (reflection "G"), this reflection is in a similar position as the one designated "F", e.g. on Fig. 22a. At the location of the well Appenwihr-1 it originates near to the Fossiliferous Zone.

In Fig. 13, one recognizes on the sonic interval velocity log (next to the litholog) a regular and contuinuous increase of the sonic velocities of the shale intervals with depth from the (?) Pliocene down to 980 m. Deeper Paleogene shales, intercalated within (1105-1121 m) or underlying thick salt layers, show constant or even decreasing sonic velocities, indicating undercompaction - they may, consequently, be expected to be overpressured. Such overpressuring of shales within the Saliferous Zone formations is assumed to have occurred widely before (and eventually prompting) halokinetic deformation in the deeper parts of the salt basin.

The isochrone map of the top of the Grande Oolithe (Fig. 12) shows a roughly NE trending high zone, subdivided by N to NNE striking faults into a number of eastward tilted blocks between Colmar in the west and the Kaiserstuhl Mountains in the east. It is bounded in the north by the Séléstat depression, and in the south by the Mulhouse Basin, both of Tertiary age.
This high zone coincides with a marked SW-NE trending pre-Tertiary high between the Colmar-Sud (COS), and the Wyhl (WYL-1) and Wyhl-Süd (WLS-1) wells E of the Rhine river at the latitude of Marckolsheim, as shown by the base Tertiary subcrop map (Fig. 3). It overlaps only partially, however, with the W-E or WNW-ESE striking, positive anomaly between the area just north of Colmar and the Kaiserstuhl seen on the gravity map of MDPA (Maikovsky1952: Fig. 8). As discussed for the Erstein swell (chap. 3.1.1), the positive gravimetric anomaly, and the recent high zone partially coincide, but have different trends.

Blumenrœder (1962) had connected the western end of this early (or pre-) Tertiary to Recent high zone (with the well Colmar-Sud) with the high on which the well Gerstheim was drilled. He called this NNE directed high axis „dorsal de Colmar - Gerstheim" and suggested that, by analogy with the Erstein swell, it was an „old" structural feature.

In the northern part of the area discussed, both the Mesozoic and the Paleogene strata are dissected by N to NE striking faults into elongated, eastward tilted fault blocks, as in the northerly adjoining area (chap. 3.1.2). Towards the south, the thickness of the Paleogene salt increases. Concomitant with and caused by this increase, the Paleogene is more and more halokinetically deformed, the salt being concentrated in mostly N-S elongated ridges, separated by depressed salt-withdrawal zones.

Jung and C. & M. Schlumberger (1936: 79) were the first to recognize that one of the prominent salt structures of the Mulhouse Basin (see chap. 3.3.1) continues for more than 35 km towards the north, onto the Colmar swell. They called it „anticlinal de Rustenhart-Marckolsheim". The existence of this salt ridge was proven by a number of wells which, in the search for potassium salt of the Upper Saliferous Zone, were drilled on this feature down to a depth of 400-600 m into the Middle or Lower Saliferous Zone, viz. Fortschwihr-1 and -2, Elsenheim and Ohnenheim (BRGM 1972a: 56, Tab. 1). They all met, below less than 200 m of Pliocene-Quaternary strata, the U. Saliferous Zone Formation of L. Oligocene age (so-called „Lattorfien“ or „Sannoisien“), the younger, M. Oligocene, Gray Series not being preserved below the Plio-Pleistocene unconformity.

Line 78STS2 (Fig. 14) crosses the northern end of the Marckolsheim salt ridge some 6 km south of the latitude of Séléstat. In this section, the ridge is just an anticline, caused by thickening of the deeper part of the Paleogene strata (the Lower (and ?Middle) Saliferous Formation), above which the U. Saliferous Fm and Gray Series are domed up, the crest being somewhat faulted. The salt ridge overlies a flexure of the Mesozoic and older substrate, the position of which changes from horizontal to an easterly dip.

Towards the south, the amplitude of the Marckolsheim ridge increases, as shown by a composite seismic W-E line through the wells Illhæusern, Ohnenheim and Mackenheim (Fig. 15a), only 3 km to the south of the section (Fig. 14) discussed above. In this more southern line, the post-Saliferous strata on the eastern flank of the ridge are bent up and eroded over the crest, as shown by the reflection configuration and confirmed by the well Ohnenheim (which encountered the U. Saliferous Formation below the Plio-Pleistocene cover). On the Eastern flank, the higher part of the Saliferous formations (between the Fish Shale and the S2 reflections) thins towards the salt ridge, whereas the deeper part (between reflections S2 to O) thickens. We assume the thinning of the higher part to be caused by fault movements and block tilting during deposition of the M. and U. Saliferous formations. The thickening of the deeper interval and, especially, of the interval S3 - O reflects the withdrawal of salt from the deeper part of that tilted block towards the Marckolsheim ridge. Faint reflections within the Gray Series appear to be parallel to the reflection at its base and are cut unconformably by the base Plio-Pleistocene reflection, indicating that

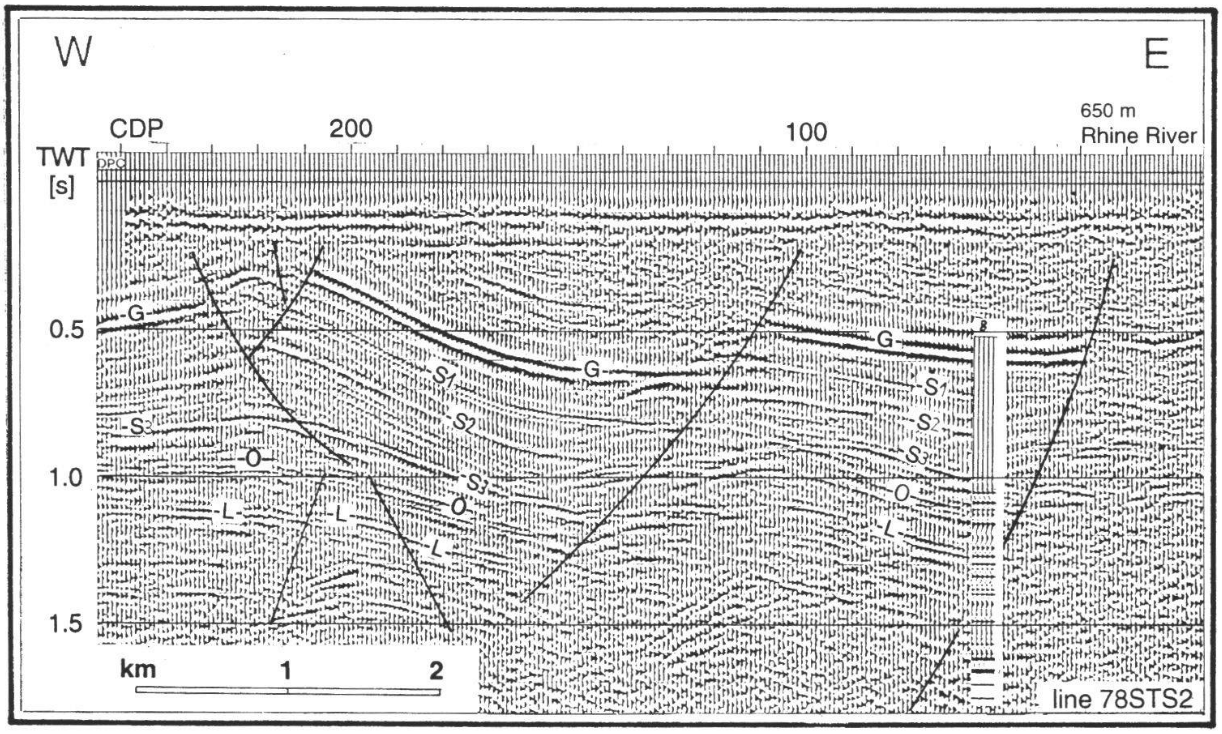


Fig. 14: Seismic W-E section N of Mackenheim, just S of a line connecting Artolsheim (F) and Weisweil (D); below CDP 60, synthetic seismogram of the Mesozoic of well MEI-2 used for reflexion identification; location of section on Fig. 12.

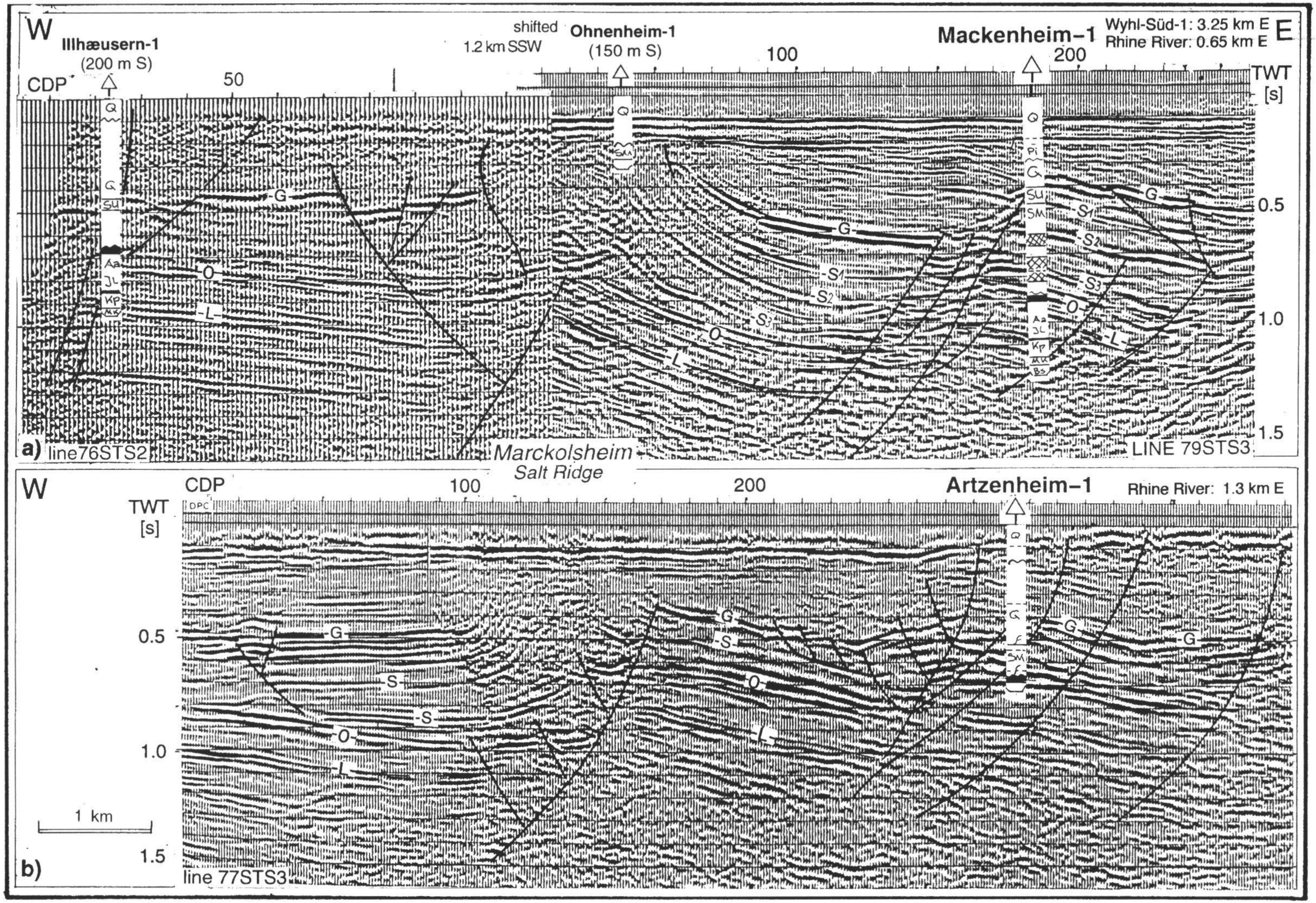


Fig. 15: **a)** Seismic W-E section through Illhæusern and Mackenheim-1;
b) seismic W-E section through Artzenheim-1; location of sections on Fig. 12.

the movement of the salt and the substrate blocks was post-Rupelian and pre-Plio-Pleistocene.
On the W flank, the Gray Series abuts abruptly against the Saliferous formations which here apparently broke diapirically through their roof.
On the E side of the line, the Paleogene of the Mackenheim structure has been faulted and tilted together with its substrate. Yet, some movement of the salt is suggested by a wavy deformation of the reflections S3 and S2 between the regularly straight or curved reflections O and S1; the same is observed for the reflection S3 on the E flank of the Marckolsheim ridge.

More to the south, the substrate continues to be cut by sub-meridional, west-throwing faults which bound eastward tilted blocks (Fig. 15b through the well Artzenheim-1 and Fig. 16 through the well Muntzenheim-1). The deformation of the saliferous and the supra-saliferous Paleogene, however, is on this section clearly independent of that of the substrate. The interpretation in detail of Fig. 16 east of the Muntzenheim-1 well is difficult, if not impossible; it appears, however, that below the Plio-Pleistocene unconformity predominantly younger Paleogene strata (Gray Series and Freshwater Beds) subcrop; these strata are strongly faulted, apparently by listric faults: the deformation style suggests intense salt movements, and, probably, extrusion of salt to the surface.

On the W half of Fig. 16, the substrate rises towards the edge of the graben; this rise is interrupted by numerous, but minor antithetic (W-throwing) faults. The reflection-configuration of the Saliferous and supra-saliferous Paleogene is interpreted as being caused by the extrusion of an earlier salt pillow below CDP 50-70.

Jung and C. & M. Schlumberger (1936: 80), observing the parallelism between the Rustenhart-Marckolsheim (and other) salt ridges, on one side, and of the regionally prevailing fault direction (known at the time from the Graben margins mainly), concluded that „the subdivision (découpage) in compartments (by the salt ridges) must be due to faults which have triggered the diapirism“.

The seismic sections on Fig. 14, 15 and 16 indeed all show a flexure (Fig. 14) or fault (Fig. 15, 16) at base Tertiary level below the Rustenhart-Marckolsheim salt ridge; the amount *and* the direction of throw of this fault change, however, from south to north: in the south, around the Muntzenheim-1 well, the fault is antithetic and throws to the west, separating east-dipping blocks; whereas from the well Elsenheim (between Fig. 15b and 15a), the throw as well as the dip of the faulted strata is towards the east; on the northernmost line (Fig. 14), hardly any fault-throw can be recognized anymore; the fault appears to be replaced by a flexure.

Whether or not the fault below this salt ridge is continuous, is an open question. M. Flandin of Shell Française (who interpreted the seismic sections at the time) didn't think so: he connected the west-throwing boundary fault of the Muntzenheim block with a disturbed zone which emerges some 2 km north of the Muntzenheim-1 well and runs in NE direction towards the Rhine River (Fig. 12). We prefer to assume that the cause for the remarkably straight and continuous salt ridge (Fig. 21) is a similarly straight and continuous fault in the substrate of the Paleogene evaporites.
The faulted and halokinetically deformed Oligocene is unconformably overlain by Plio-Pleistocene cover. At the top of the Mackenheim structure, however, one of the western boundary faults appears to continue into the basal Plio-Pleistocene, though with a minor throw (10-20 ms) only.

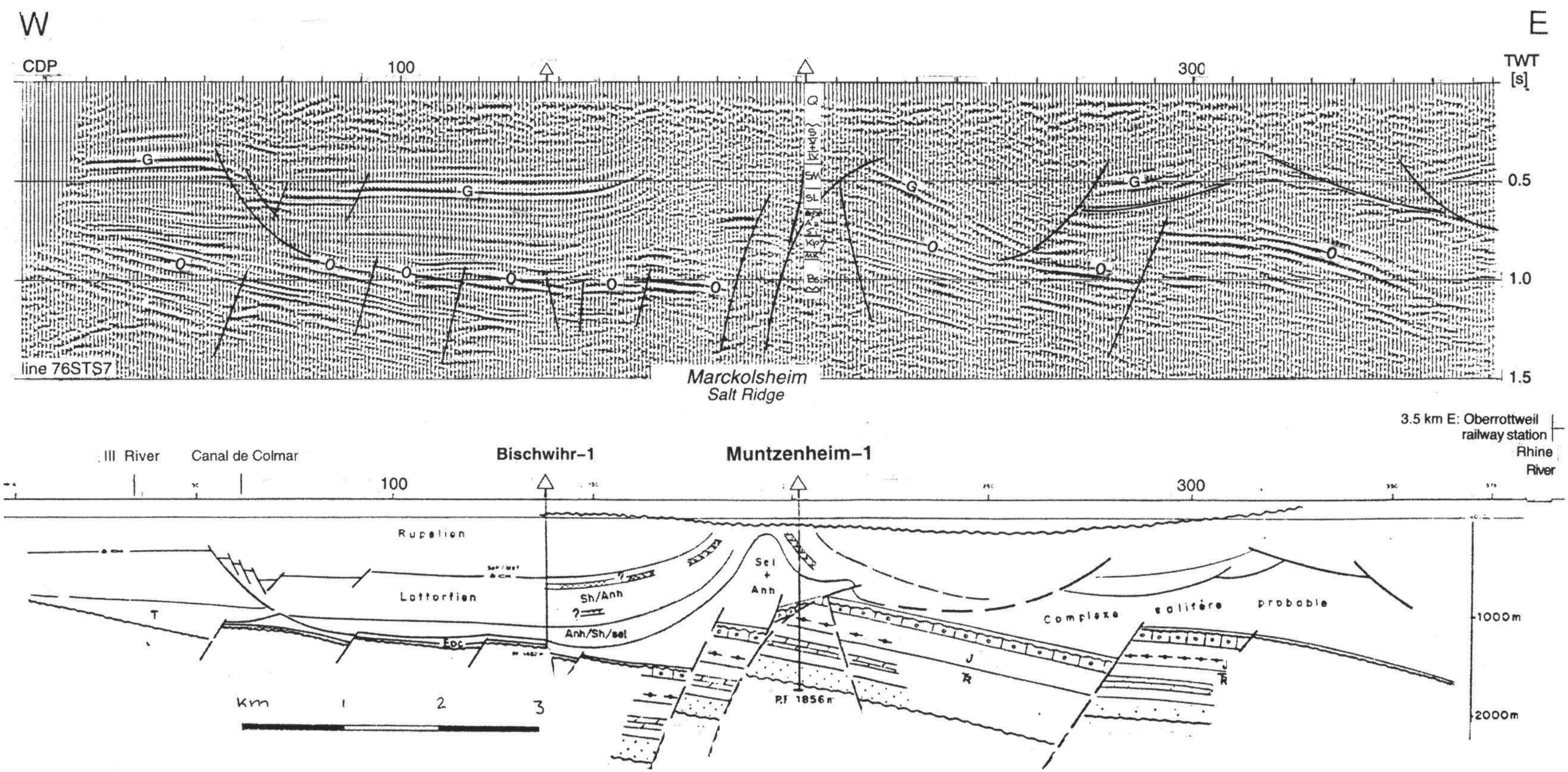


Fig. 16: a) Seismic W-E section through Muntzenheim-1;
b) interpreted geological section; location on Fig. 12.

The seismic surveys of the Association identified 4 undrilled dip- and fault-closed structures at base Tertiary level, all east-dipping, and bounded on the high, western side by antithetic faults with several 100 m of throw. The three larger ones were drilled, Muntzenheim (MUM-1) to the basement, Mackenheim (MAM-1) to the Buntsandstein, and Artzenheim (ARM-1) through the Grande Oolithe only. None of them discovered hydrocarbons in economic quantities, although the stratigraphy and the depth of the target horizons were largely found as prognosed, thus indicating that the structural interpretation shown in Fig. 12 is probably essentially correct.

3.2.3 Drilling results

Muntzenheim-1 (MUM-1), Fig. 16, 17

The well Muntzenheim-1 was drilled in 1978 by Shell Française on the eastern flank of the Rustenhart-Marckolsheim salt ridge. It was planned to test the reservoir potential of the Buntsandstein and the Upper Muschelkalk/ Lettenkohle, and, as a secondary objective, the Middle Jurassic Grande Oolithe, on the (assumed) culmination of an eastward tilted block, closed in the west by an antithetic fault (Fig. 16). Seismic resolution at base Tertiary/top Grande Oolithe level (Refl. O, Fig. 16) was rather poor at the drilling location. Results are summarized on Fig. 17. Below base Tertiary, encountered at 1062.5 m bdf, the larger part of the Grande Oolithe and all of the underlying sandy limestones of the deeper Bajocian to Upper Aalenian were absent. This fact could be explained in various ways, (i) the well drilled through a fault which cut out the most interesting part of the M. Jurassic section; or (ii) the top part of the M. Jurassic has been eroded, and the oolithic limestone seen at the Tertiary/Jurassic boundary is of L. Tertiary, or of Aalenian age. Paleontological dating of cutting samples by SNEA(P) revealed an Upper Eocene-Oligocene microflora in the mudstones and shales of the interval 1050-1065 m, foraminifera and other microfossils of Bathonian (down to 1077 m) and possibly Bajocian age (1080-1083 m) in the oolithic wacke- to packstones from the interval 1071-1083 m, and an Aalenian microflora from 1095 m downwards; these observations as well as log correlation with neighbouring wells and dipmeter results (Fig. 17) suggests fault cut-out rather than erosion.
The remnant section of the Grande Oolithe showed fluorescence, but proved to be impermeable in two drillstem tests.

In the Toarcian, at least 6.5 m of excellent oil source rocks were identified between 1199-1205.5 m bdf from geochemical analysis of sidewall samples and from log interpretation; the organic maturity corresponds to a vitrinite reflectance of 0.6 % i. e. to the beginning of the oil window.

An apparently undisturbed sequence of the Lower Liassic and of the entire Triassic was drilled, which could be essentially well correlated with the section drilled before in Meistratzheim-2, and with the sequence observed at the surface at the western edge of the graben (BRGM 1972a: Fig. 1 and 2, p. 10, 14). The Buntsandstein contains porous intervals as suggested by mudlosses whilst drilling and shown by log interpretation; on test, however, it proved to be waterbearing.
The well bottomed at 1856 m bdf, in a „biotite granite with rose feldspars“.

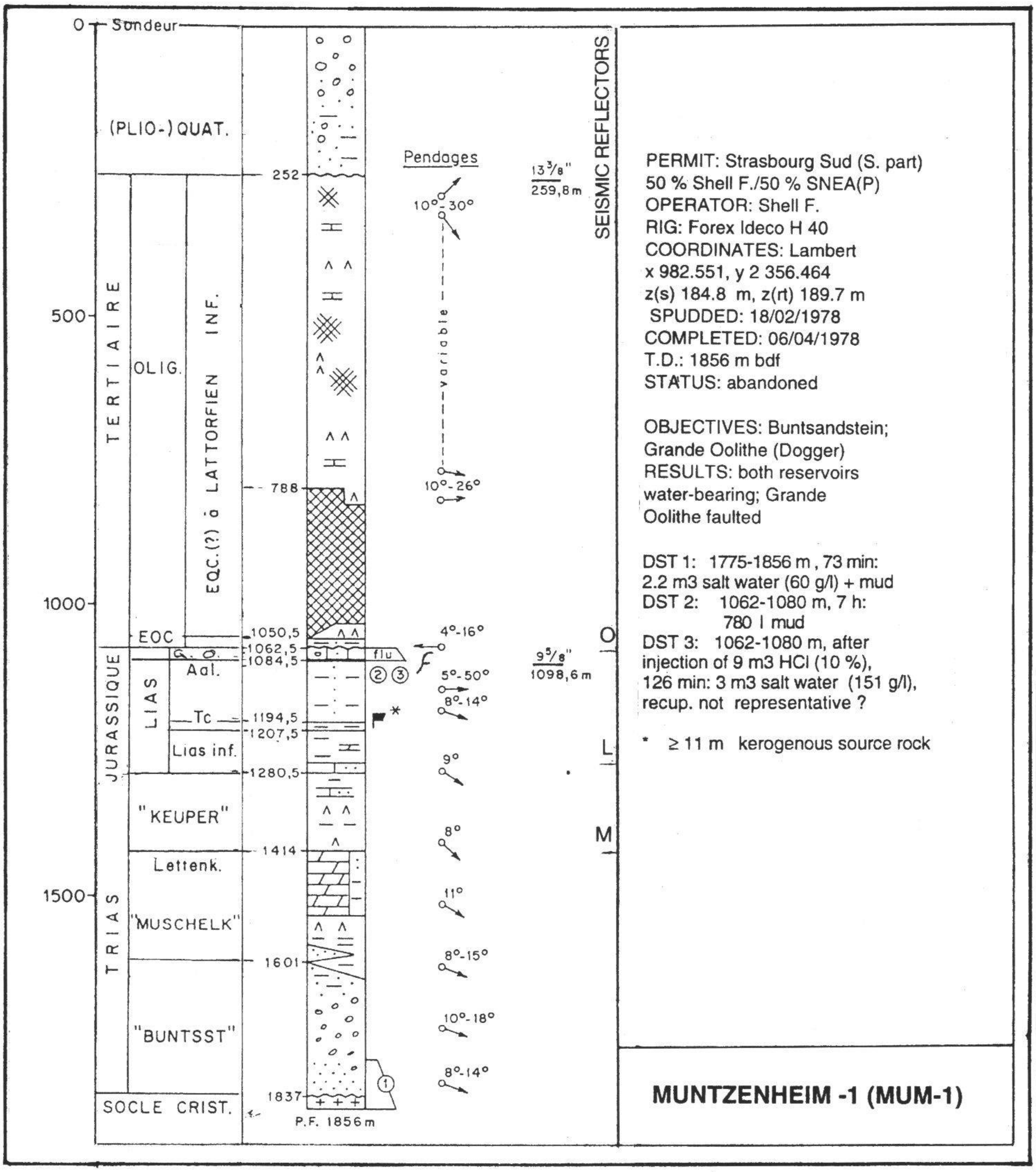


Fig. 17: Muntzenheim-1: Well summary; well location on Fig. 12.

Artzenheim-1 (ARM-1), Fig. 15b, 18

The second well drilled by Shell Française in the southern part of the Strasbourg-Sud permit encountered a Grande Oolithe section of 51 m thickness. Porous intervals and fine fissures were found oil impregnated, but tests proved the upper part of the reservoir to be tight, while deeper down only water with oil traces was tested. Core data and log analysis showed the oolithe reservoirs to have porosities of 3-11%; petrophysical data, supported by geochemical analysis of the oilshows by SNEA(P), indicate an oil saturation of up to 30 % over the larger part of the oolithe

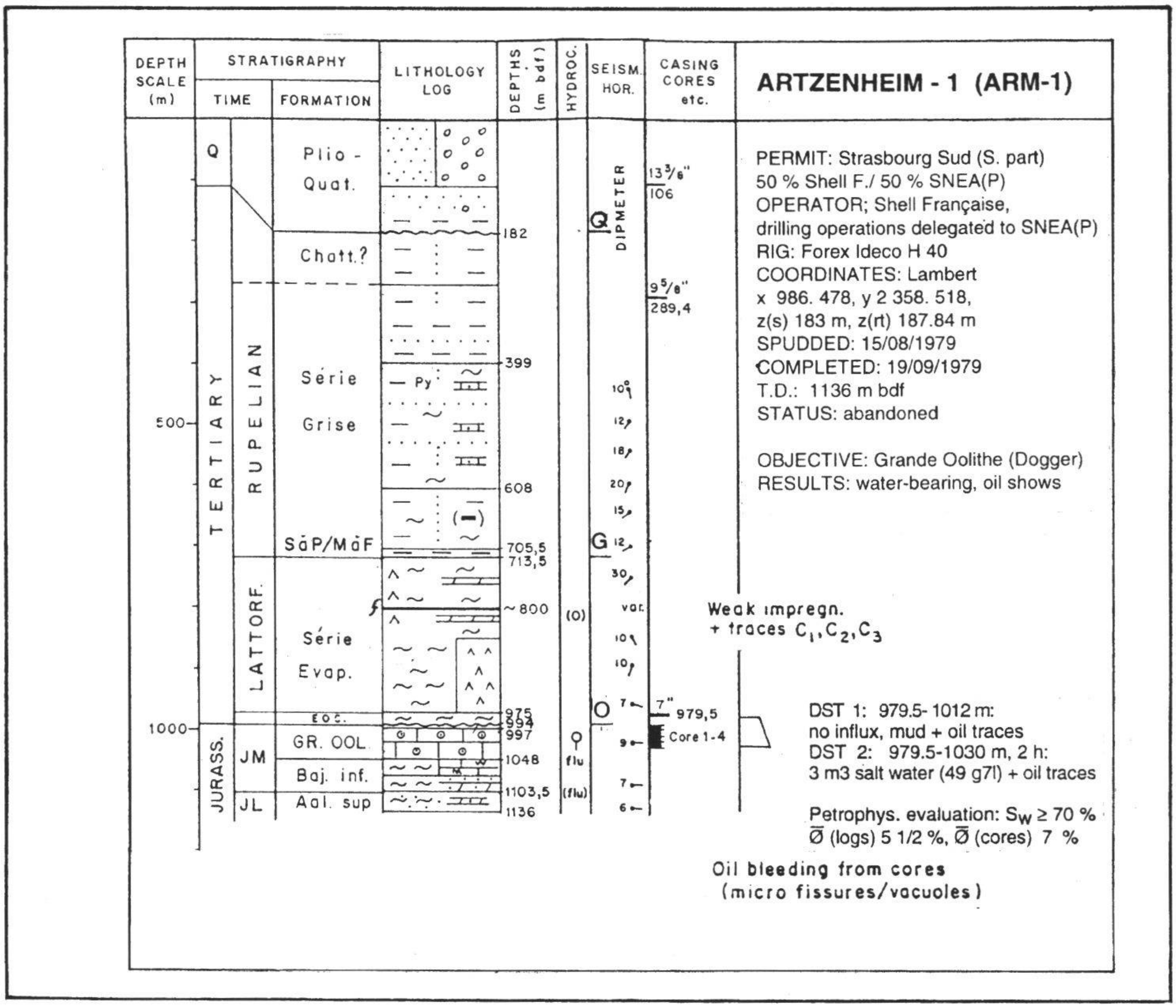


Fig. 18: Artzenheim-1: Well summary; well location on Fig. 12.

interval. Drilling was terminated at T.D. 1136 m within the Aalenian; after a conclusive water test in the Grande Oolithe, the well was plugged and abandoned. The presence of a small oil accumulation updip is still possible.

Mackenheim-1 (MAM-1), Fig. 15a, 19

The last of the wells drilled by the Association in the Strasbourg-Sud permit, Mackenheim-1, was drilled some 2.5 km NW of Marckolsheim, and nearly on the same latitude as the German well Wyhl-1, situated 5 km to the east. Although located on a structure with better seismic definition and assumed better sealing quality than the two earlier wells MUM-1 and ARM-1, it was considered second choice because of its small drainage area and its more distant position with regard to the assumed oil kitchen. Drilling confirmed the good seal quality: a massive sequence of Paleogene salt, even thicker than expected, was found above the Dogger objective; but no hydrocarbon shows whatsoever were seen in the 84 m thick Grande Oolithe section.

The well was deepened to the Triassic for the sole account of SNEA(P); it was abandoned after having reached a T.D. of 2096 m bdf in water-bearing Buntsandstein.

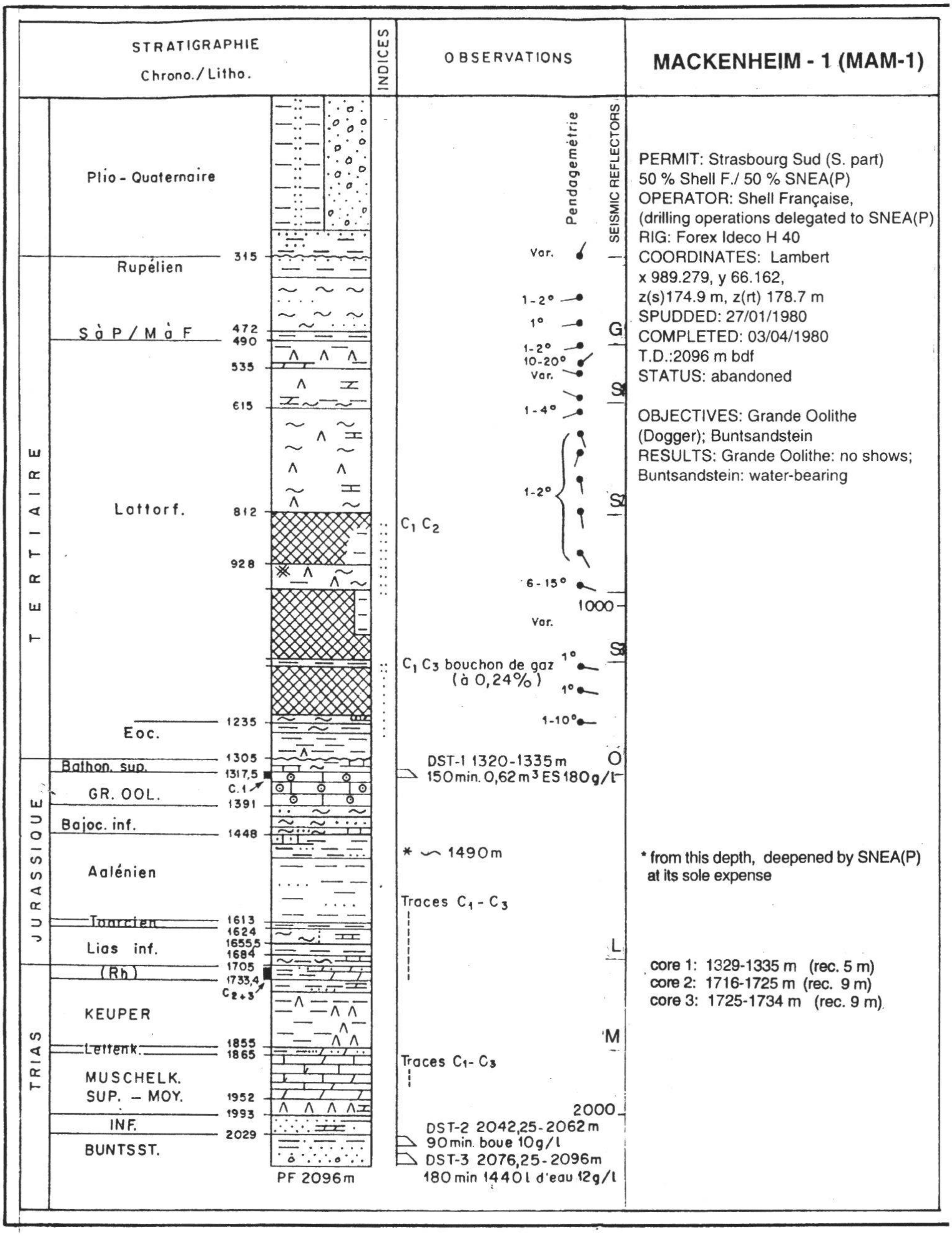


Fig. 19: Mackenheim-1: Well summary; well location on Fig. 12.

3.3 Colmar-Mulhouse area

3.3.1 Operational aspects

We discuss in this paragraph the former permits „Neuf-Brisach", „Munchhouse", and „Rhin" (southern part), covering large parts of the Mulhouse salt basin between the Colmar swell in the north and the Mulhouse horst in the south, the Graben margins between Colmar and Guebwiller in the W, and the Rhine river in the E, respectively (Fig. 20). This area which is adjacent to the Mulhouse potash mining district, had earlier been intensively explored down to the top of the Middle Saliferous Formation in search for potassium salts. The thick Paleogene salt section is halokinetically deformed into elongated ridges and a circular dome (Fig. 21).

Salt structures in this area were recognized in the 1920's from electric surveys and confirmed by wells, and first described by Friedel (1927) and C. & M. Schlumberger (1928).
J. Jung and C. & M. Schlumberger (1936: 79) mapped the top of the Paleogene salt all over the Mulhouse Basin with the help of electric soundings, making use of the marked resitivity contrasts between the fresh-water filled Quaternary cover, the Paleogene shales, and the massive evaporites of the Paleogene Saliferous Formations, with intermediate, low, and very high resistivities, respectively. They recognized (and named) all the salt structures developed in the area.

Until the late 60's, reflection seismic surveys could not penetrate the thick sequences and accumulations of Paleogene salt which, thus, concealed the structure of the underlying Mesozoic.

Only a few wells, therefore, had investigated the Mesozoic for hydrocarbons in the area discussed: The well Oberhergheim-1 (OHG-1, PREPA 1956; BRGM 1978) drilled ~ 150 m of Mesozoic strata (Oxfordian marls - Bajocian Grande Oolithe), and the well Blodelsheim-1 (BDM-1, PREPA 1953/54; BRGM 1978) penetrated below a Paleogene salt dome a Mesozoic sequence of 770 m comprising Oxfordian marls to Early Triassic Upper Buntsandstein. These two wells were located on top of near surface salt structures (Meyenheim ridge and Blodelsheim dome, respectively) which were visible on the old seismic. In the NW corner of the area discussed, PREPA's well Colmar Sud-1 (COS-1: BRGM 1962) drilled in 1957, encountered oil shows in a fault structure below a thick salt-bearing section on the margin of the Graben.

Of the three permits held by the Association between 1974 and 1990 within the area, the permit „Rhin" (southern part) covered the graben margin between Colmar and Soultz (Ht. Rhin); it was granted to Shell Française in 1972 and was part of the jointly explored area as from the beginning. As c. 140 km of new seismic lines did not show any prospective structures, the permit was relinquished in 1980.

As the seismic acquired in the southern part of the Strasbourg-Sud permit NW of Neuf-Brisach allowed the mapping of the top of the Mesozoic even below a thick salt cover, the Association applied for an exploration permit covering the free acreage to the south, down to the latitude of Mulhouse. The permit, called Neuf-Brisach was granted in 1979. After the unsuccessful drilling campaign in Strasbourg-Sud and the subsequent prospect review (see chap. 2), the exploration effort of the Association concentrated on this southern area, which was in 1987 enlarged to the West by a new permit Munchhouse, and which then comprised the larger part of the Mulhouse salt basin. It was expected that with modern seismic surveys the structure of the Mesozoic strata below the Paleogene section would be elucidat-

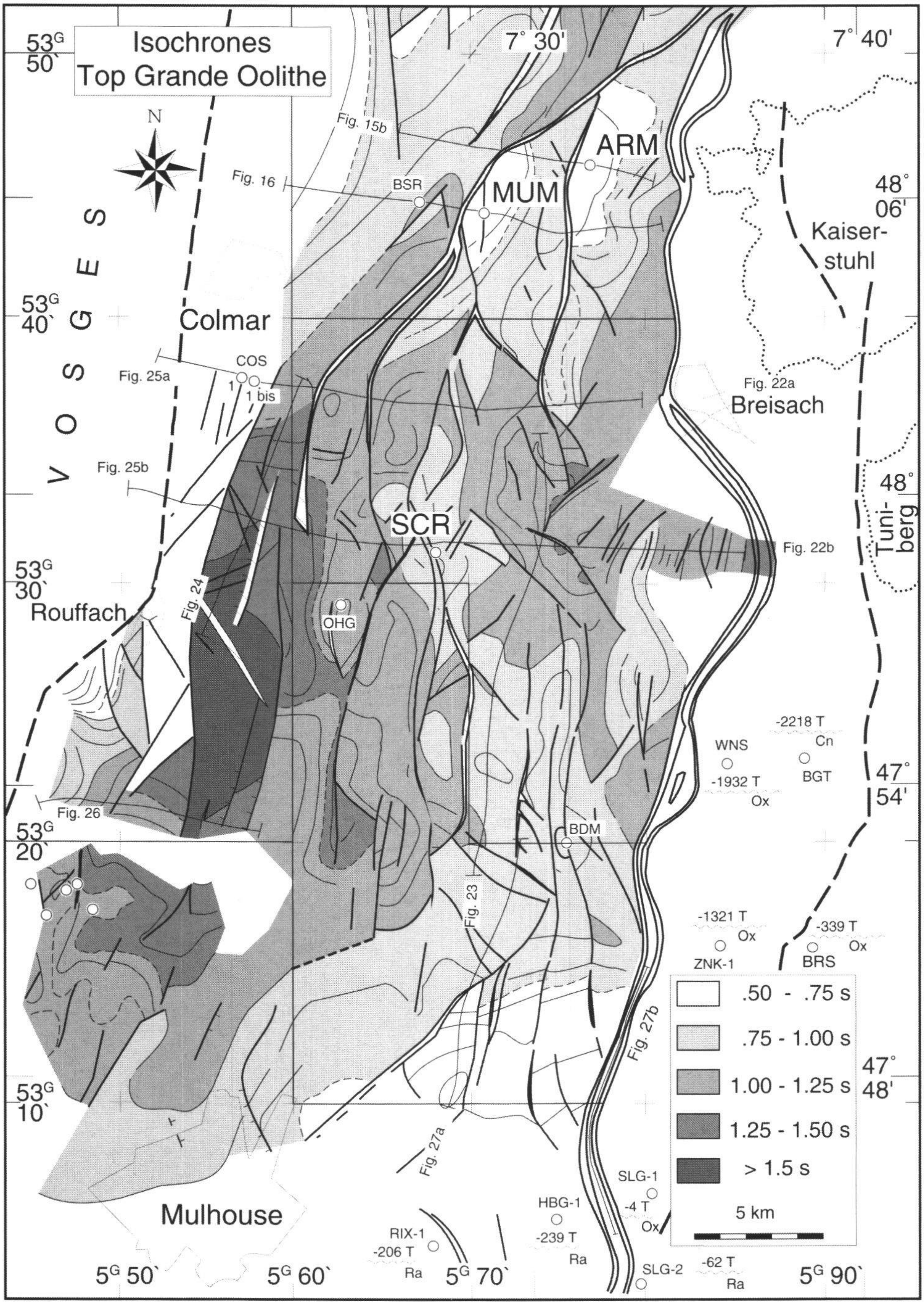


Fig. 20: Colmar - Mulhouse area: Isochrones base Tertiary/top Grande Oolithe.

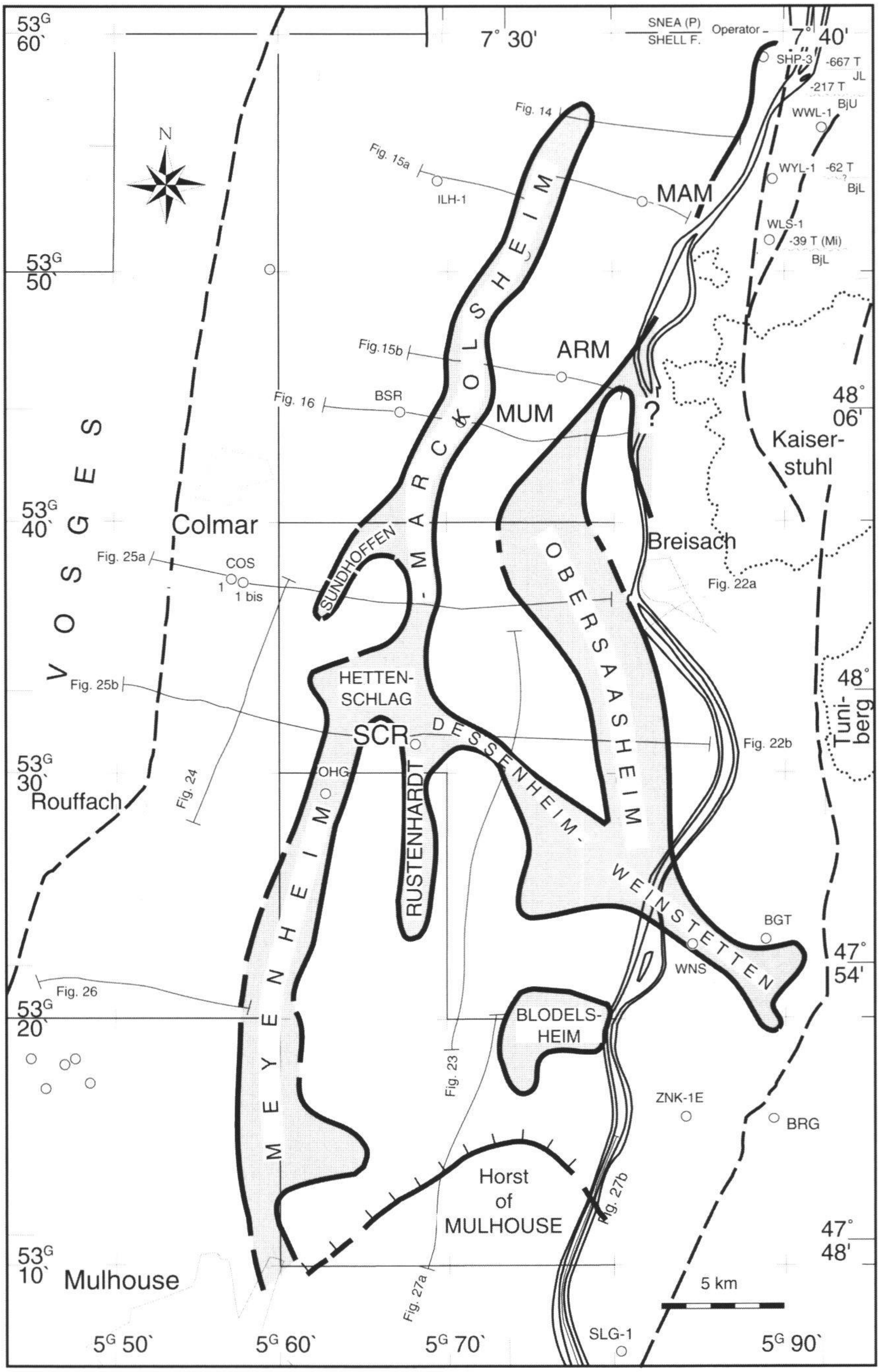


Fig. 21: Colmar - Mulhouse area: Subcrop of the Tertiary salt ridges and domes below the Plio- Pleistocene unconformity

ed. It was assumed that the substrate of the Saliferous formations was cut by predominantly submeridional faults into antithetically tilted blocks in a similar way as found in the north (e.g. Muntzenheim-1, Fig. 16) and known in the SW of the area discussed from the Staffelfelden and Hirtzbach structures (Blumenrœder 1962; Orgeval 1939 in Vonderschmitt 1942).

Between 1979 and 1986 the Association acquired some 460 km of seismic lines in the permits Neuf-Brisach and Munchhouse. They also drilled one well, Ste-Croix-en-Plaine, in 1989.

3.3.2 Seismic interpretation

Stratigraphic aspects

In the halokinetic sinks of the area, the M. Oligocene Gray Series and the Chattian Freshwater Beds are more completely preserved than in more northerly areas. This is shown e.g. in Fig. 23 north; this N-S line runs obliquely through the central part of the depression between the Obersaasheim and Dessenheim salt structures. In this salt withdrawal zone, an undisturbed section of the post-saliferous Middle and Upper Oligocene, some 800 ms (approx. 1200 m) thick, is preserved. Its stratigraphy has been interpreted with the help of the well DP-034 (Heiteren-2) from which the bases of the Gray Series and of the Chattian Freshwater Beds are known. In the higher parts of the Freshwater Beds, an interval with characteristic high frequency reflections is seen, e.g. at CDP 160 around 400 ms (Refl. C) and 200 ms. These reflections have been recognized elsewhere; in Fig. 23 south, at the location of the well DP 209 (Hirtzfelden III; BRGM 1978: 37) they could be identified with the help of lithologic data from Courtot et al. (1972: 79) as corresponding to the lower and upper Série Carbonatée of the Freshwater Beds which enclose a gypsum-bearing interval. As thicknesses vary only slightly in these Late Paleogene strata, the sequence of the post-Saliferous Paleogene may be recognized elsewhere by its reflection character even without well control.

Structure

Between the Colmar Swell in the North and the Horst of Mulhouse in the south, the Mesozoic and the base of the Tertiary are depressed and form the so-called Mulhouse Basin, filled with thick Paleogene strata (Fig. 20). As shown earlier by Sittler (1972a: Fig. 4) and Daessle (in Risler 1991: Fig. 1) a central, north-south trending row of higher blocks at base Tertiary level, the „central highs", subdivides this depression into two parts; the deeper and larger western part runs northward from the Staffelfelden area (NW of Mulhouse), in front of the inner Graben border fault, the Faille Rhénane. South of Colmar its axis begins to rise and to turn to the NNE, into the half-graben west of the Muntzenheim and Mackenheim structures (Fig. 12). The smaller Blodelsheim-Buggingen sub-basin extends between Blodelsheim (BDM) and Artzenheim (ARM) eastward over the Rhine River (Fig. 20).

The present-day structural base Tertiary configuration (a mayor depression subdivided by a series of intervening highs) was already in existence during deposition of the Paleogene Saliferous Zones, as Blanc-Valleron & Gannat (1985) have shown. The Paleogene depositional basin was, thus, subdivided into a western

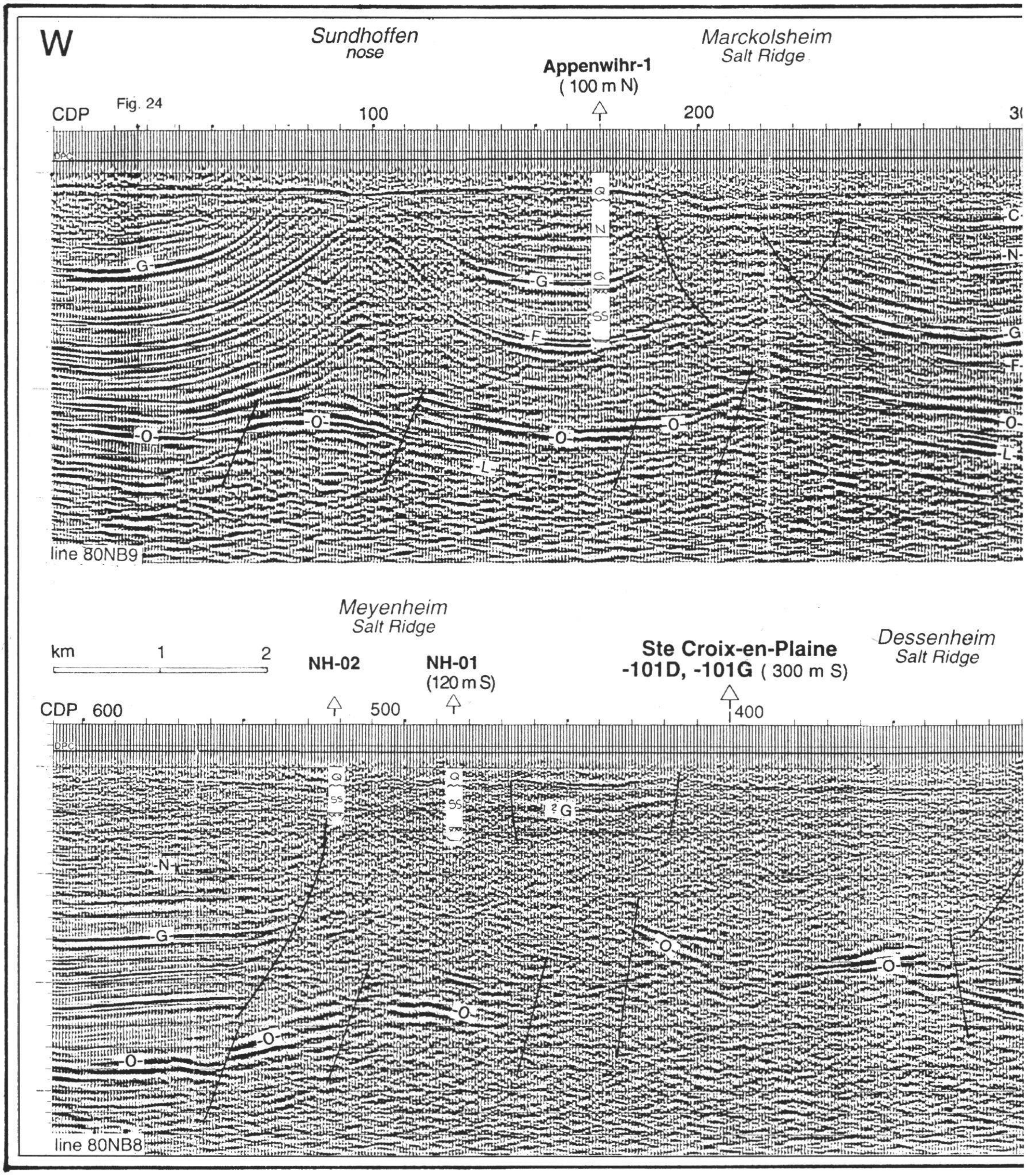
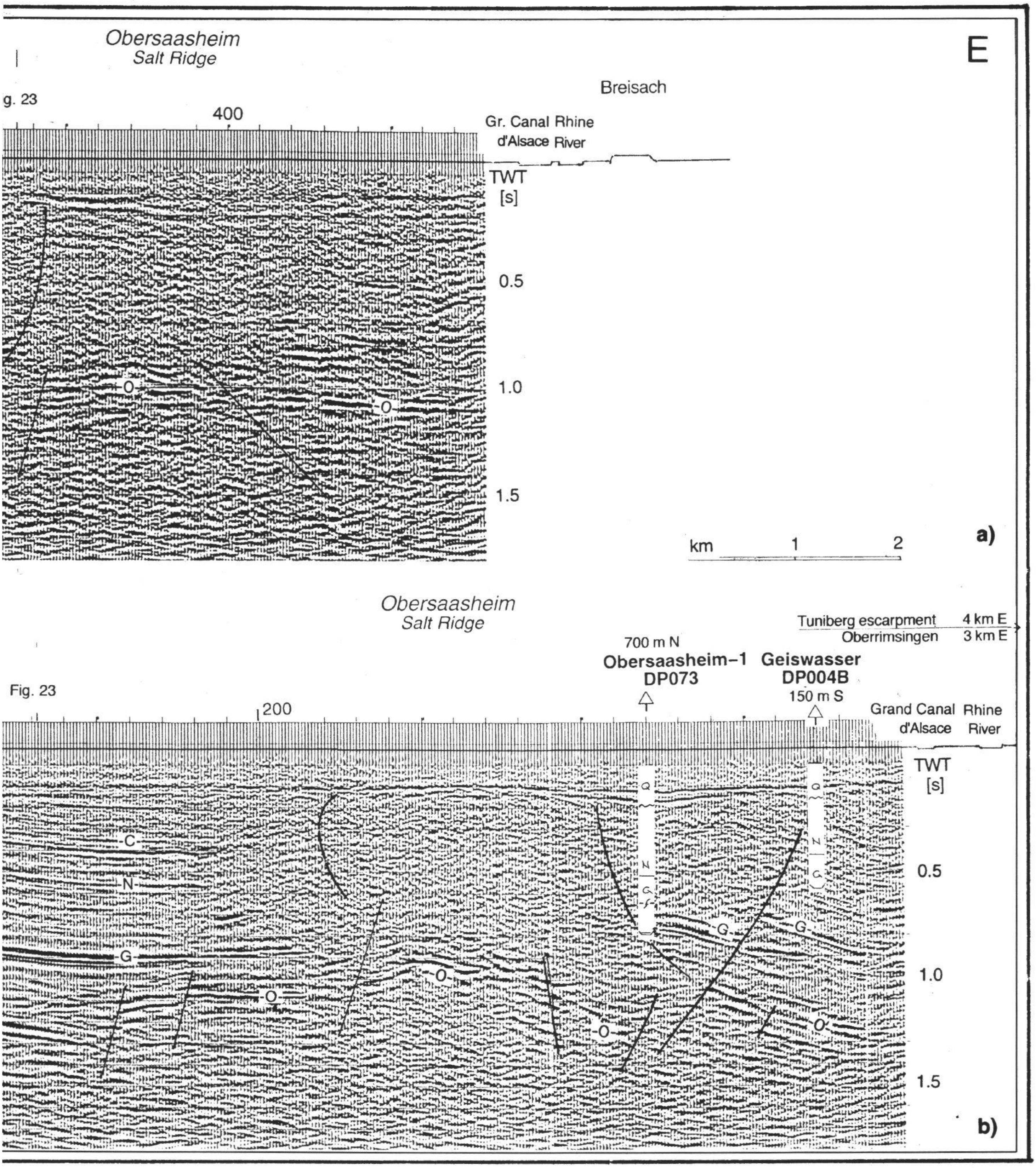


Fig. 22: **a)** Seismic W-E section Sundhoffen - N of Neuf-Brisach;
b) Seismic W-E section through Ste-Croix-en-Plaine-101 to Geiswasser; location of sections on Figs. 20 and



Obersaasheim
Salt Ridge
E
Breisach
g. 23
400
Gr. Canal Rhine
d'Alsace River
TWT
[s]
0.5
1.0
1.5
O
km 1 2
a)
Obersaasheim
Salt Ridge
Tuniberg escarpment 4 km E
Oberrimsingen 3 km E
700 m N
Obersaasheim-1
DP073
Geiswasser
DP004B
150 m S
Fig. 23
200
Grand Canal Rhine
d'Alsace River
TWT
[s]
C
N
G
O
0.5
1.0
1.5
b)

Staffelfelden-Niederentzen (or Wittelsheim) and an eastern Buggingen part. The Meyenheim-Marckolsheim salt ridge appears to have been formed just E of the axis of maximum salt deposition in the Wittelsheim subbasin and its northern continuation, whereas the Weinstetten and Obersaasheim ridges trace roughly the axis of the eastern Buggingen subbasin.

Two superimposed levels with different deformation styles may be recognised already in the SE corner of the Sélestat-Colmar area E and SE of the wells MUM-1 and ARM-1 (chap. 3.2). This difference is more strongly expressed to the south between Neuf-Brisach and the N flank of the Mulhouse Horst, as the seismic sections of Fig. 22 to 27 illustrate.

The lower level, comprising the basement and the overlying cover rocks of mainly Mesozoic age, up to and including the basal, pre-Saliferous Early Tertiary, is cut by submeridional faults into a number of N-S striking and mostly E dipping panels as we described them before from the adjacent northerly area. Major variations of thickness and facies of the Paleogene coincide with the main marginal faults of the graben (Courtot et al. 1972: 88) and with the NW. and N. margin of the Mulhouse Horst (Fig. 27b). Late Eocene - Early Oligocene basement-controlled movements are thus indicated.

The higher, mainly Paleogene, level below the shallow Pliocene-Quaternary cover, encompasses the Saliferous formations of the Upper Eocene and Lower Oligocene („Sannoisien", „Latdorfian") and the overlying Gray Series and Freshwater Beds of Middle and Late Oligocene age. This level is dominated by mainly NNE striking salt ridges with the Upper Saliferous Formation generally subcropping below the Plio-Pleistocene unconformity (Fig. 21). In inter-ridge areas thick sequences of the Gray Series and the overlying Freshwater Beds are preserved (Fig. 22a, b, 23north). In the areas of most intense diapiric salt movements, the fill of the sinks between the salt ridges is dissected into rotated blocks by listric faults which apparently sole out in the underlying Saliferous Formations (Fig. 23 south, 26). The NNE-striking ridges of Meyenheim, Rustenhart-Marckolsheim, and Obersaasheim (south of Neuf-Brisach) are connected to each other by the Hettenschlag dome, and the NW-SE trending Dessenheim Ridge which continues to the SE over the Rhine River to the eastern, Badish side of the Graben, where it is known as the Weinstetten salt structure (Breusse & Astier 1961, Gunzert 1962, Schreiner in GLA 1977).

In the south of the area, the basal Tertiary-Mesozoic substrate rises quickly towards the Mulhouse Horst, subsidence of which was reduced already during the Paleogene (Fig. 27a, b); no Paleogene salt was deposited on this high. The separation into two structural levels with a different deformation style therefore terminates at the edge of this old high.

To demonstrate deformation style and age relations within the Mulhouse salt basin, we discuss in some detail two seismic W - E sections (Fig. 22a, b). Fig. 22a , a W-E line (80 NB9) 1.3 km N of the latitude of Neuf-Brisach shows three salt ridges in different stages of development. In the west (left), a simple fold, the Sundhoffen nose, is developed. The top of the anticline is eroded at the Plio-Pleistocene unconformity ("Q") down to the Upper Saliferous Formation. The base Gray Series reflection ("G"), clearly developed in the sinks E and W of the ridge, subcrops on its flanks. The reflection "F", originating near the top of the M. Saliferous Formation, may be followed almost to the culmination of the structure. The interval between reflec-

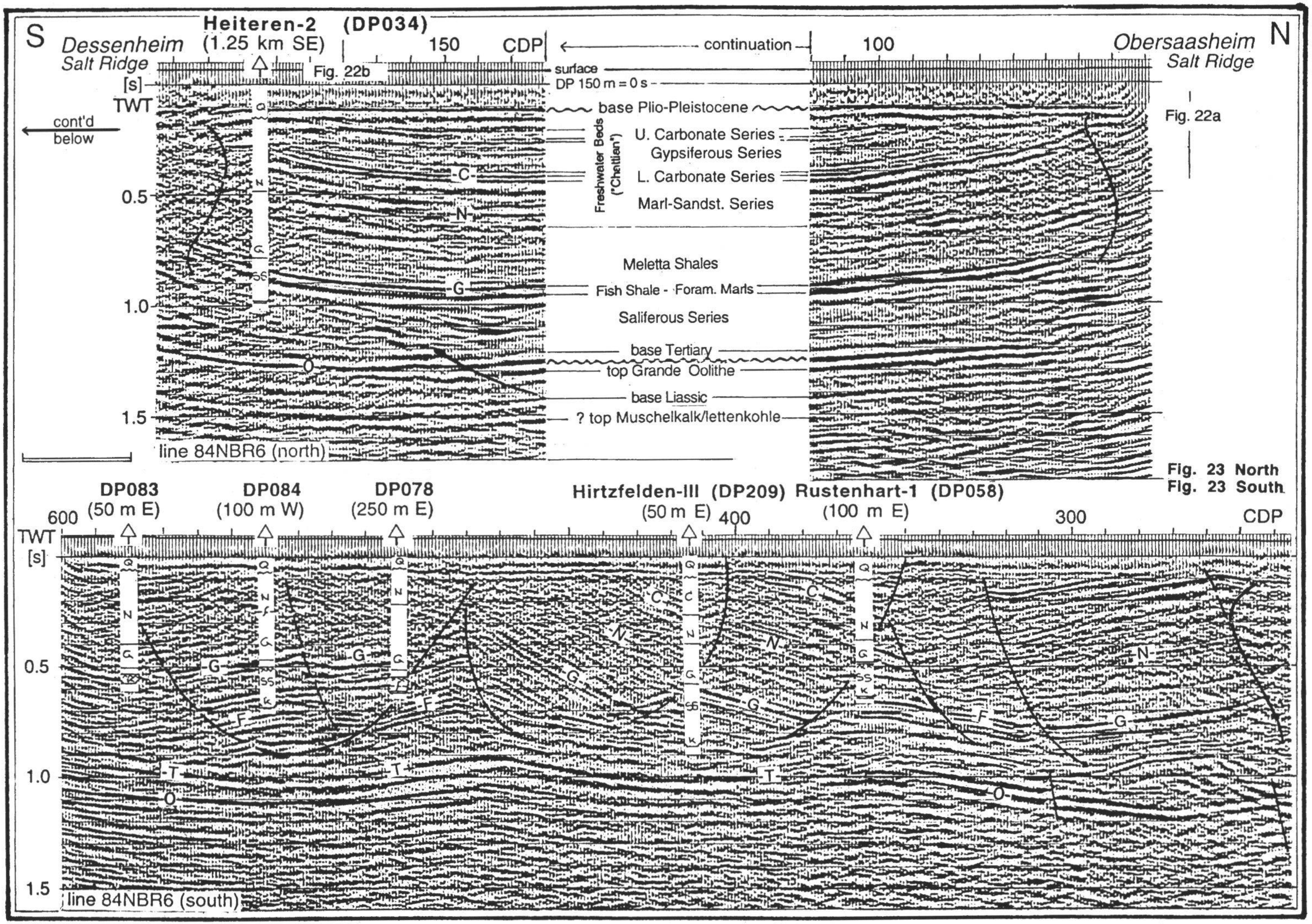


Fig. 23: Seismic N-S section from the Obersaasheim Salt Ridge through wells Rustenhart and Hirtzfelden III; location on Figs. 20, 21.

tions G (base Gray Series) and F thins up the eastern flank, but thickens up the western flank. We conclude that these thickness changes are not caused by the growing salt accumulation, but by earlier movements along the underlying fault that separates two eastward tilted blocks of the substrate. At a deeper level, around 1 s TWT, one can recognize a triangular opening of the reflections of the deeper Paleogene above the basal Tertiary and the Mesozoic into the salt accumulation. From this, we conclude that the material accumulated in the core of the structure originates essentially from the deepest part of the salt-bearing section, i.e. from the so-called Salt 2 and, especially, Salt 1 (Grand Banc du Sel) of the Lower Saliferous Formation (Blanc-Valleron & Gannat 1985), as Larroque & Ansart (1985: 839) observed earlier.

The Marckolsheim ridge below CDPs 180-230 is clearly more strongly deformed: on both sides, the flanking strata are bent upward, but reflections appear to be cut by an oblique westward rising „chimney“ with chaotic reflections only. We regard this ridge as a real diapir.
Inspection of the sink E of this structure shows again a parallelism (i.e. no strong thickness variations) down to the base of the Gray Series (identified by reflection character). The underlying interval down to what we interpret tentatively as the top Middle Saliferous Formation reflection ("F") thickens into the eastern adjacent salt structure; in the highest part of the interval, above the reflection F, this thickening may be depositional (as on the western end of the line). On the eastern edge of this sink, the reflections from the Paleogene terminate abruptly against a practically reflection-free area between the base Plio-Pleistocene reflection, and that near base Tertiary. This area, extending from CDP 320 to the end of the section some 5 km E, is again interpreted as a diapiric salt accumulation, viz. the Obersaasheim ridge of Jung and C. & M. Schlumberger (1936).

Below each of the three salt structures discussed, and only there, the substrate of the Saliferous Formations is cut by one or more important faults with throws of 100-200 ms.

Throughout the seismic line, the base Plio-Pleistocene unconformity ("Q") appears to be somewhat disturbed and is depressed in top of the salt structures, probably by solution processes. Elsewhere, e.g. on Fig. 22b between SP 350-520, this reflection appears slightly uplifted in top of the Meyenheim and Rustenhart salt ridges. An anomalously high position of the top of the Saliferous Formations (10 m below surface; top salt at 100 m) was found by a well drilled on the crest of the Hettenschlag salt dome (Schlumberger 1928: 445). Jung and C. & M. Schlumberger (1936) recognized this young deformation by mapping a slight uplift of Late Quaternary (Würmian) terraces (Basse Terrasse, Niederterrasse) in top of the salt ridges discussed.

Essentially the observations made on line Fig. 22a may be made on Fig. 22b (80NB8). Again the reflections from the fill of the sinks between the salt ridges terminate abruptly against the subvertical boundaries of the practically reflection-free ridges; and again, these are underlain by faults and high blocks (horsts) of the substrate. If our interpretation of the base Tertiary reflection between CDP 325-250, and further to CDP 185 is correct, the difference in thickness and reflection character of the Saliferous formations in this part of the section, and on its western end, W of the Meyenheim Ridge (between CDP 560-600) is remarkable - 180 and 300 ms vs 550 ms.

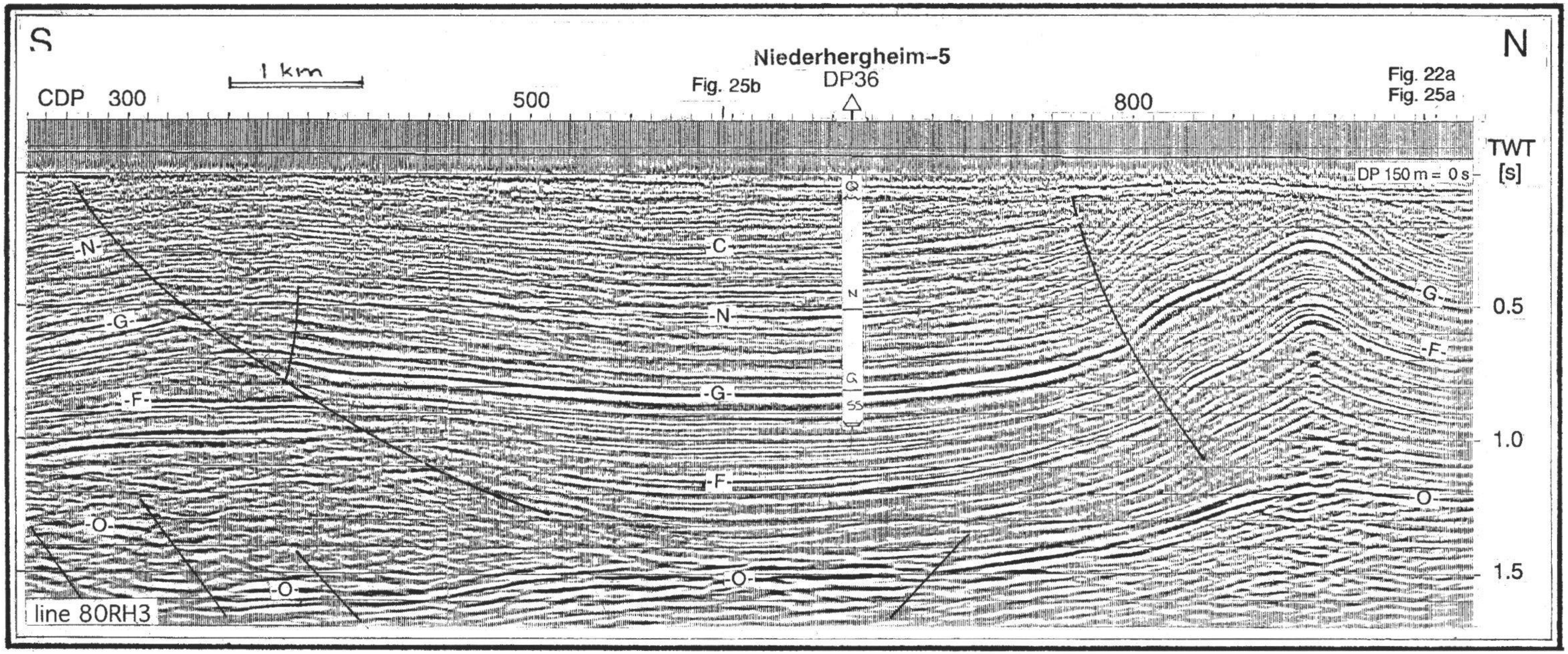


Fig. 24: Seismic N-S section through the well Niederhergheim-5; location on Figs. 20, 21.

In the central part of the line, the high, which separates the Wittelsheim from the Buggingen subbasin is seen; the well Ste-Croix-en-Plaine-101 was drilled just south of this line, on the culmination of one of the tilted blocks which form the Central High. Going south along the N-S line 84NBR6 (Fig. 23south), after crossing the narrow Dessenheim Salt Ridge, the supra-Saliferous strata (Gray Series and Freshwater Beds) are dissected into numerous strongly tilted blocks (we count six at base Gray Series on this line) rotated along listric faults which apparently sole out within the 250-500 ms occupied by the Saliferous formations. Its top part, however, (sometimes, e.g. at CDP 530-560, down to the top Middle Saliferous reflection “F”) has been deformed together with the overlying strata as one competent package. Only the lower part apparently was highly mobile and acted as a detachment horizon between the two structural levels. The Mesozoic and basal Tertiary substrate is much less disturbed.

We noted earlier that the Paleogene strata above the Saliferous formations (Gray Series and Chattian Freshwater Beds) in general do not record thickness variations which may be linked to the growth of the adjacent salt ridges; these salt structures, therefore, are younger than the youngest strata preserved in the intermediate sinks, and older than the Pliocene-Quaternary cover which overlies these strata unconformably.

However, marked thickness variations of the Paleogene interpreted to be depositional have been seen near to the basin margins, viz. in the depression W of the Meyenheim salt ridge, and - less clearly - in sinks S and W of the Blodelsheim salt dome.
Fig. 24, a seismic line (80RH3) running N-S near to the Graben margin shows a Paleogene section which is well comparable with that of Fig. 23north.

At the location of the well DP 36 (Niederhergheim 5), the prominent reflection G betweeen 700-800 ms corresponds to the basal part of the Gray Series (Fish Shales to Foraminifera Marls). Base Chattian (as known from the well section) coincides here as elsewhere (Fig. 23north) with a rather weak low frequent reflection (“N”) just at and below 500 ms. A 2-3 loop high frequency band can be recognized some 200 ms higher (Refl. C). It is more clearly expressed west of the well location, between CDP 600-610). It has the same appearance and the same distance to the base Chattian and base Gray series reflections as the reflection which we interpreted in Fig. 23north as originating from the Série carbonatée inférieur of Courtot et al. (1972: 79). The bundle of deeper reflections between 1140 and 1200 ms (“F”) can be followed directly to Colmar Sud 1 and jump-correlated to Appenwihr-1 (Fig. 22a). They are identified as originating near to the top of the Middle Saliferous Formation (Zone fossilifère). The deepest reflection (“O”) at approx. 1.5 s may be correlated by character and geometry (unconformable to the overlying Saliferous Paleogene) with the top of the substrate near to the base Tertiary or the top of the Grande Oolithe.

Fig. 25a and b (lines 80RH7 and 80RH1), continuing Fig. 22a and b, respectively, show the development of this sequence towards the west, towards the Rhine fault: In Fig. 25b, the deepest part of the Saliferous Formations, just above the approx. horizontal base Tertiary/top Mesozoic reflection (“O”) shows a rapid *thickening,* towards the west, into the Rhine fault, presumably due to halokinetic movements. This is compensated by a marked *thinning* of the Upper Saliferous Formation (interval “F” to “G”) and of the immediately underlying strata west of the crossing with line Fig. 24. We assume this thinning to be depositional and to reflect the growth of a salt accumulation near the Rhine Fault which was triggered by extensional movements along the latter. In Fig. 25a, the thinning of the interval between reflections F and G is also seen; the deeper part, however, is more strongly faulted and cannot be interpreted unequivocally.

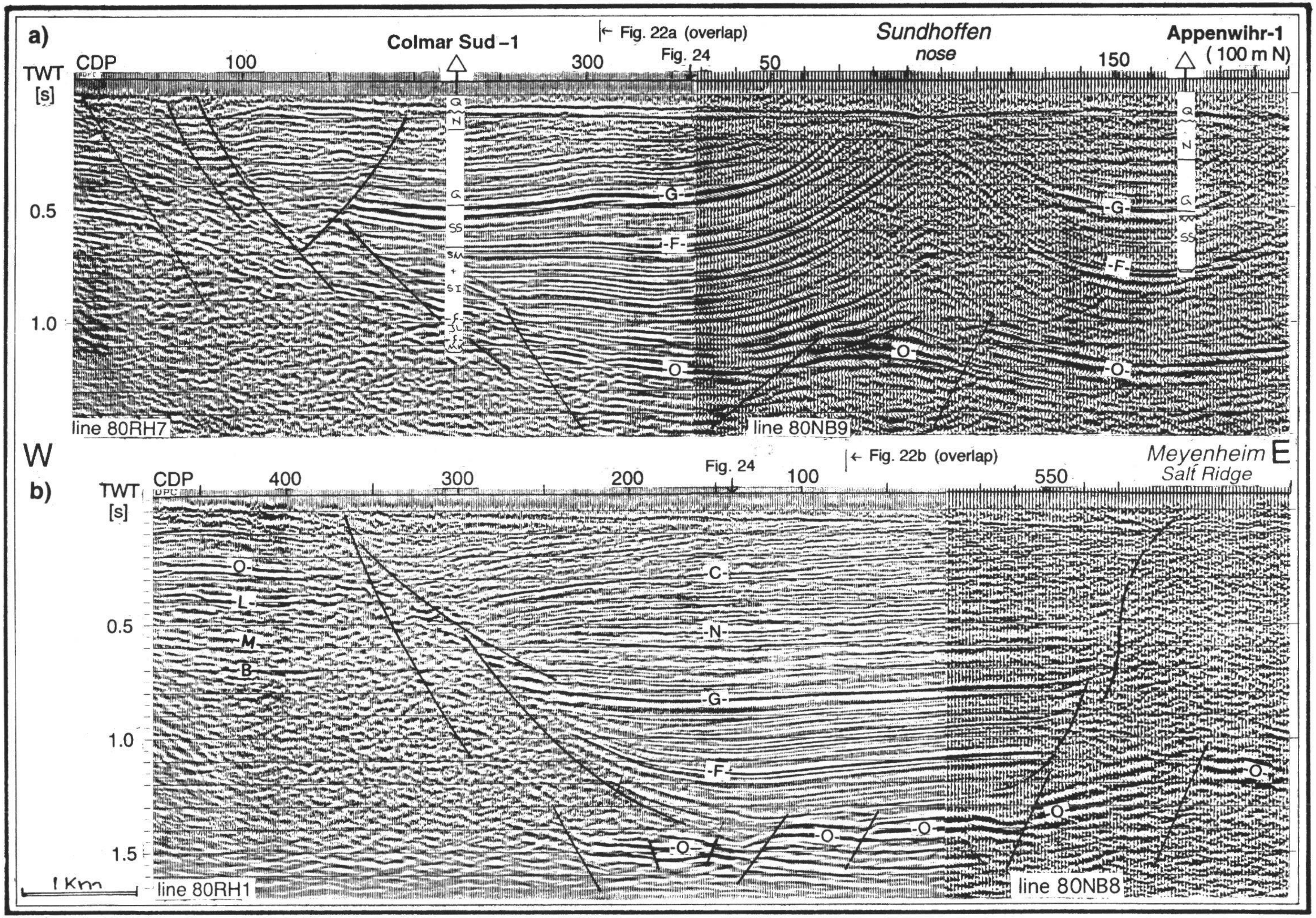


Fig. 25: Seismic W-E sections at the western Graben margin:
a) through the well Colmar-South, continuation of Fig. 22a;
b) 5 km South of a), continuation of Fig. 22b; location of sections on Figs. 20, 21.

Duringer (1988: 191-204) has interpreted 3 seismic sections from the W. Graben margin; his lines no. 2 and 3 resemble our Fig. 25a and b. He also assumes that the thinning observed is depositional.

Within the M.-U. Oligocene interval, the approximately horizontal Gray series shows a uniform thickness on the seismic sections. Above the base Chattian level ("N"), however, strata dip to the west, into the fault and are clearly thinning from E to W (Fig. 25b). This thinning records a continuation of the growth of the salt accumulation (pillow) along the Rhine fault as from the Early Chattian, affecting most of the higher section preserved below the Plio-Pleistocene unconformity. The deepest, westward thickening interval is assumed to consist essentially of salt of the Lower Saliferous Formation; the higher strata above the salt represent the remaining part of the Paleogene; these are mainly clastics and may be assumed to have been deposited horizontally or with an easterly dip. The observed reflection geometry, thus, suggests control of the thickness of these strata by a salt accumulation which started growing near the Rhine fault during deposition of the M. Saliferous Formation, triggered by extensional movements along the Rhine fault. After a period of quiescence in the Middle Oligocene (Gray Series), it continued its growth during depositon of the Chattian Freshwater Beds and possibly thereafter. Some time after the deposition of the latest Freshwater Beds and before the resumption of the deposition on top of the Neogene-Quaternary unconformity, the accumulation extruded. The collapse of its eastern flank is recorded by the western dip of these Chattian strata (Fig. 25a, b), at places enhanced by W throwing Y-faults (Fig. 25a). Similar observations can be made on other E-W lines situated somewhat more to the south and in between the lines discussed. We assume these thickness variations to be halokinetic. The thickness increase of the basal part of the Saliferous formations W of, say, CDP150 (Fig. 25b), thus, is thought to be the remnant of an extruded salt pillow.

The evacuation of the primary salt accumulation, the pillow, creates accomodation space at the surface, a so-called secondary peripheral sink. This sink may be expected to be filled with sediments, thickening towards the diapir in the west. Such a secondary peripheral sink, however, is not recorded in the geometry of the preserved strata. Even in the highest part of the Chattian strata, on top of what we believe to be the reflection originating from the Série carbonatée inférieur, the west dipping reflections are parallel or westward converging. The sedimentary record of the salt extrusion is not preserved, but the chaotic reflections of the youngest interval below the Plio-Pleistocene unconformity between CDP 370-300 (Fig. 25b) may be interpreted as solution remnants of a dissolved diapir.

The Rhine fault strikes almost N-S from Colmar to Rouffach. More to the south, it continues to the SW (Fig. 20). The deepest part of the sink west of the Meyenheim salt ridge is located immediately adjacent to the meridionally striking segment of the Rhine fault. Where the fault turns off to the SW, the axis of this depression continues to the south as may be seen on Fig. 26 (line 76RH2). On this cross section, the pillow was not formed against the basin margin, but within the basin. It is underlain by a fault in the substrate (in fact the continuation of the Faille Rhénane of more northerly transsects) which is assumed to have controlled its location. Here, the eastern and the western flank have collapsed.

The center of this depression itself is characterised by rather chaotic reflections; the deeper Gray Series and Saliferous formations are cut by listric faults soling out

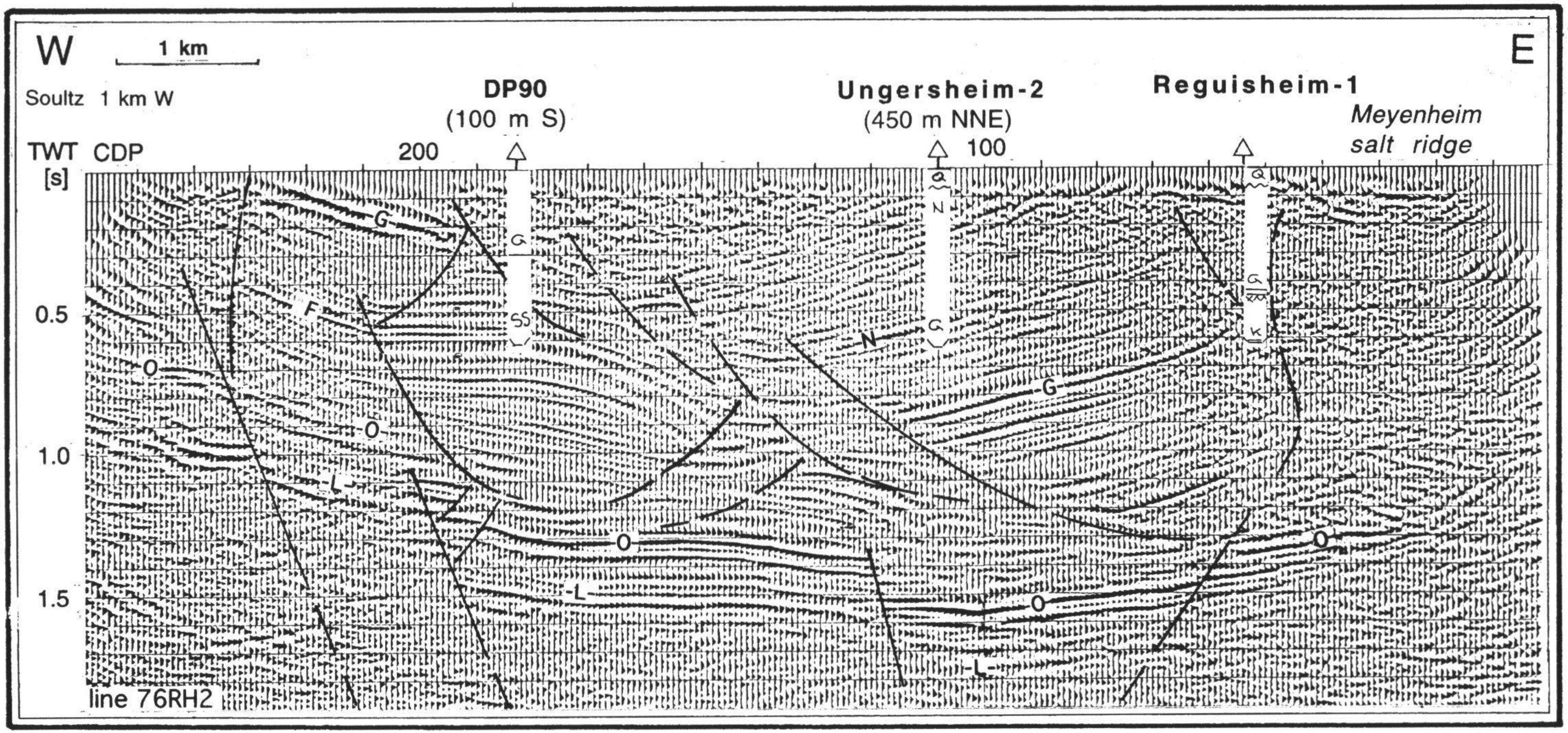


Fig. 26: Seismic W-E section E of Soultz (Ht. Rhin). location on Figs. 20, 21.

within the deeper part of the Tertiary interval, i.e. presumably in the Lower Saliferous Formation. The depression mentioned thus represents a sort of a secondary peripheral sink sensu Trusheim and Sannemann (Trusheim 1957, 1960), although the corresponding diapir is not preserved, but has been extruded to the surface and has dissolved. Trusheim himself figured in his classical paper a similar feature (1957: 144, Fig. 14, left side).

Salt movements (halokinesis) within the Mulhouse Salt Basin were, thus, initiated along the western Graben margin possibly already during deposition of the Middle Saliferous Zone Formation and continued vigorously here (and also near to the N. edge of the Mulhouse Horst, around the Blodelsheim salt dome) during the deposition of the Chattian Freshwater Beds.

The sedimentary record of most if not all of latest Paleogene to Neogene time is eroded below the Plio-Pleistocene unconformity (see chap. 4.2). Therefore, we cannot study the development in space and time of these salt structures. Elsewhere, however, the depositional record of the growth and extrusion of salt accumulations is preserved and from this the mechanism of these processes can be deduced, e.g. in NW Germany (Trusheim 1960) or East Texas (Seni & Jackson 1983). From these studies, it is known that growth and extrusion of salt accumulations creates space for the accomodation of sediments in the salt withdrawal areas. This space is immediately filled with sediments; in fact, once salt starts moving and accumulating, further growth and extrusion of such an accumulation is generally a response to continuing deposition in the salt withdrawal areas.

In our area domains are seen which are reflexion-free or contain only chaotic reflections; these domains are known from the numerous potash exploration wells to be filled with the Eocene to Lower Oligocene Saliferous formations, and are interpreted as diapirs. Next to them, but separated by apparently sharp, subvertical boundaries reflective packages occur (Fig. 22b) which may be stratigraphically identified by the prominent base Middle Oligocene reflection ("G"), which subdivides this package; the higher part, corresponding to the Middle Oligocene ("Rupelian") Gray Series and the Chattian Freshwater Beds is often flat lying and undisturbed. The distances between individual reflections are everywere rather similar (cf. Fig. 22b at CDP 600 and CDP 250, W of the Meyenheim and E of the Rustenhart-Marckolsheim salt ridges, respectively). This suggests uniform deposition in one and the same basin, i.e. before the start of the salt movements. The thickness of the deeper part of the package, the Saliferous formations, is variable in the sinks. It is, particularly, clearly different west and east of the Meyenheim Salt Ridge (see also Blanc-Valleron & Gannat 1985: 825-826): Well expressed, mostly parallel reflections, some 600 ms thick, are observed at CDP 600 W of the Meyenheim ridge (thickness variations only near to the Rhine fault: see above); but there is only 300-100 ms between base Middle Oligocene and base Tertiary between the Dessenheim and Obersaasheim Ridges with only irregular, rather short reflections. Further south in the same inter-ridge low (Fig. 23south), where the supra-Saliferous (above the reflection G) is broken and rotated along listric faults which appear to sole out in the Saliferous formations, the two-way travel time of the interval base Middle Oligocene- to base T-reflections amounts only to 300-400 ms.

Both diapirs and intermediate sinks are unconformably overlain by the mostly undisturbed Plio-Pleistocene cover.
Fig. 27a and b are two N-S lines across the northern margin of the Mulhouse Horst. This edge is not formed by major faults (as the W margin towards the Dannemarie Graben) but by a northward tilt of the Mesozoic and Paleogene strata. Note on the high flank of the horst the clear reflection from the Eocene Melania Limestone ("Ml"), which was identified by a crosssection connecting the Hombourg-1 and the Schliengen-1 wells drilled 2 km W and 1.8 km E of Fig. 27b, respectively, and the reflection marked "F", assumed to originate near the Fossiliferous Zone; both change character or disappear downflank. The overlaying strata show downdip a marked thickening and updip onlap.

3.3.3 Drilling results

Ste-Croix-en-Plaine-101 D, -101 G (de iated well) (SCR-101 d, G)[1], Fig. 22b, 28, 29

The well Ste-Croix-en-Plaine-101 D was intended to investigate infra-Saliferous strata at the culmination of a faulted monocline within the N-S trending high zone separating the Wittelsheim Subbasin from the Buggingen Subbasin (Fig. 20).

Well results are summarized on Fig. 28. The interval between base Tertiary at 1641 m bdf, and the top of the Liassic around 1900 m, could not be correlated with nearby wells either by logs or by lithology. The characteristic sequence from the deep Oxfordian to the Aalenian strata, and in particular the Grande Oolithe could not be identified in the well, neither in cuttings nor on wireline logs; instead, some 60 m of marls, dated palynologically as Oxfordian, and 160 m of a variegated, argillaceous microbreccia were encounterd; it is assumed that the microbreccia is a fault gauge, and that the Dogger series with the Grande Oolithe is cut out by a fault. From the top of the Toarcian to T.D., correlation with neighbouring wells, e.g. MUM-1, is straightforward. The U. Muschelkalk-Lettenkohle was found tight and unfractured, without any reservoir properties. The Buntsandstein was encountered at the depth predicted; 160 m of the formation were drilled without any hydrocarbon indications. The strata on top of the Conglomérat Principale with a thickness of some 50 m were devoid of reservoirs, as expected; in the Conglomérat Principal and the underlying Grès Vosgien, average porosities of 3-5 %, and max. values of 4-8 % were evaluated from the sonic log.

In order to penetrate the Grande Oolithe on the high block, the well was sidetracked from a window cut in the 9 5/8" casing between 1101-1104 m bdf; drilled in an easterly direction, it met essentially the same sequence as the first hole below base Tertiary, i.e. first Oxfordian marls, followed by the microbreccia mentioned down to 1930 m; as the first hole was at this depth already clearly within the Toarcian of the low block, drilling was terminated. After several unsuccessful attempts to lower the logging sondes, the well was plugged and abandoned. It is assumed that the deviated well drilled into the same fault zone which had been hit before by the first well; this fault (which is not recognizable on the seismic) would, thus, strike E-W. Note that the correlation between SCR-101D and the deviated well SCR-101G (Fig. 29) is based on results of a palynological study of cuttings by SNEA(P).

[1] largely based on data from SNEA(P), viz. the Final Well Report (author G. Mabunda), and a note by P. Moreau & JM. Moron on the correlation between SCR-101D and -101G

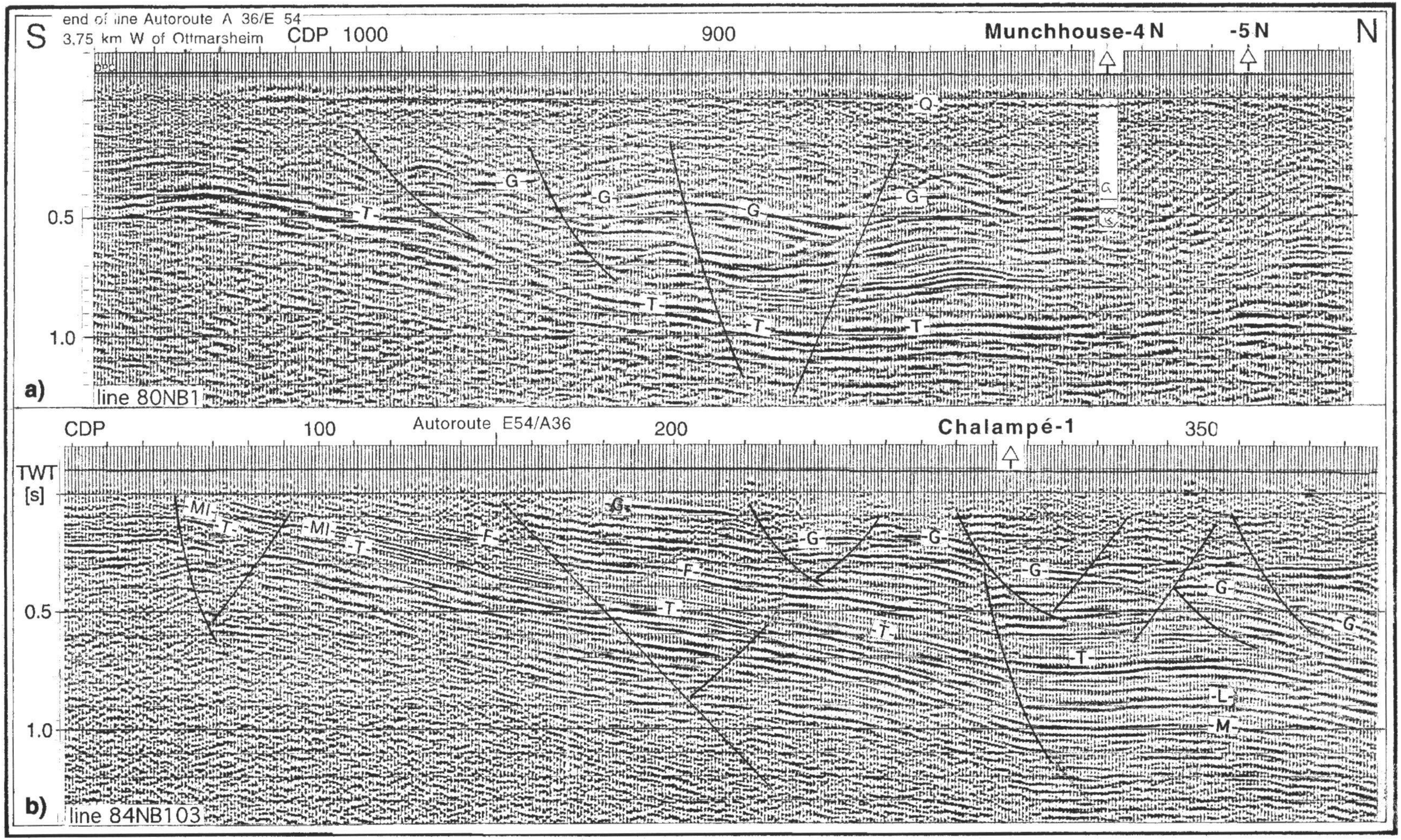


Fig. 27: Seismic N-S sections from Salt Basin to Mulhouse Horst:
a) W of Blodelsheim and Ottmarsheim.
b) from Chalampé southward along the Rhine River; location of sections on Figs. 20, 21.
MI = near Melania limestone

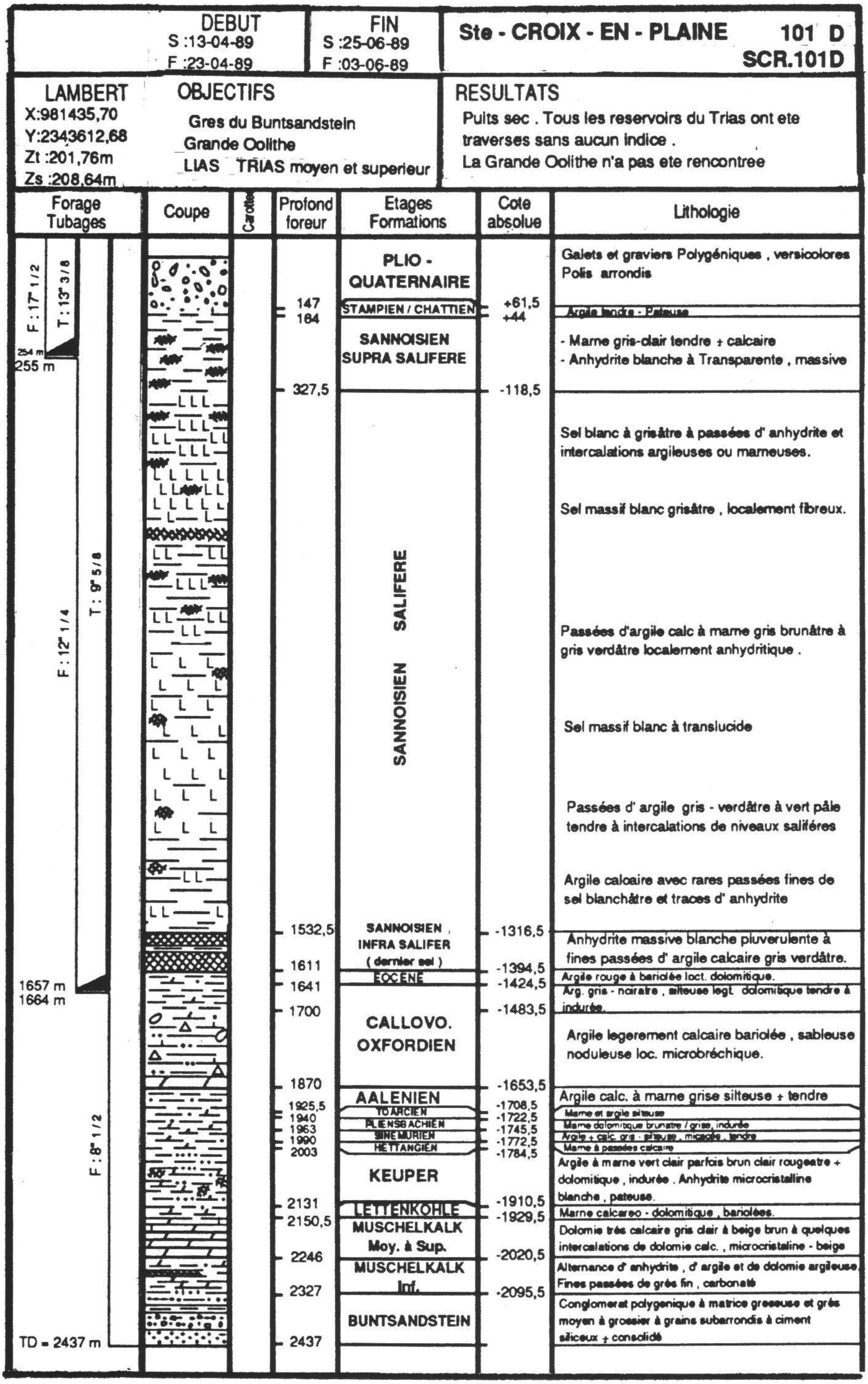


Fig. 28: Ste-Croix-en-Plaine 101 D: Well summary (author: SNEA(P)); well location on Figs. 20, 21.

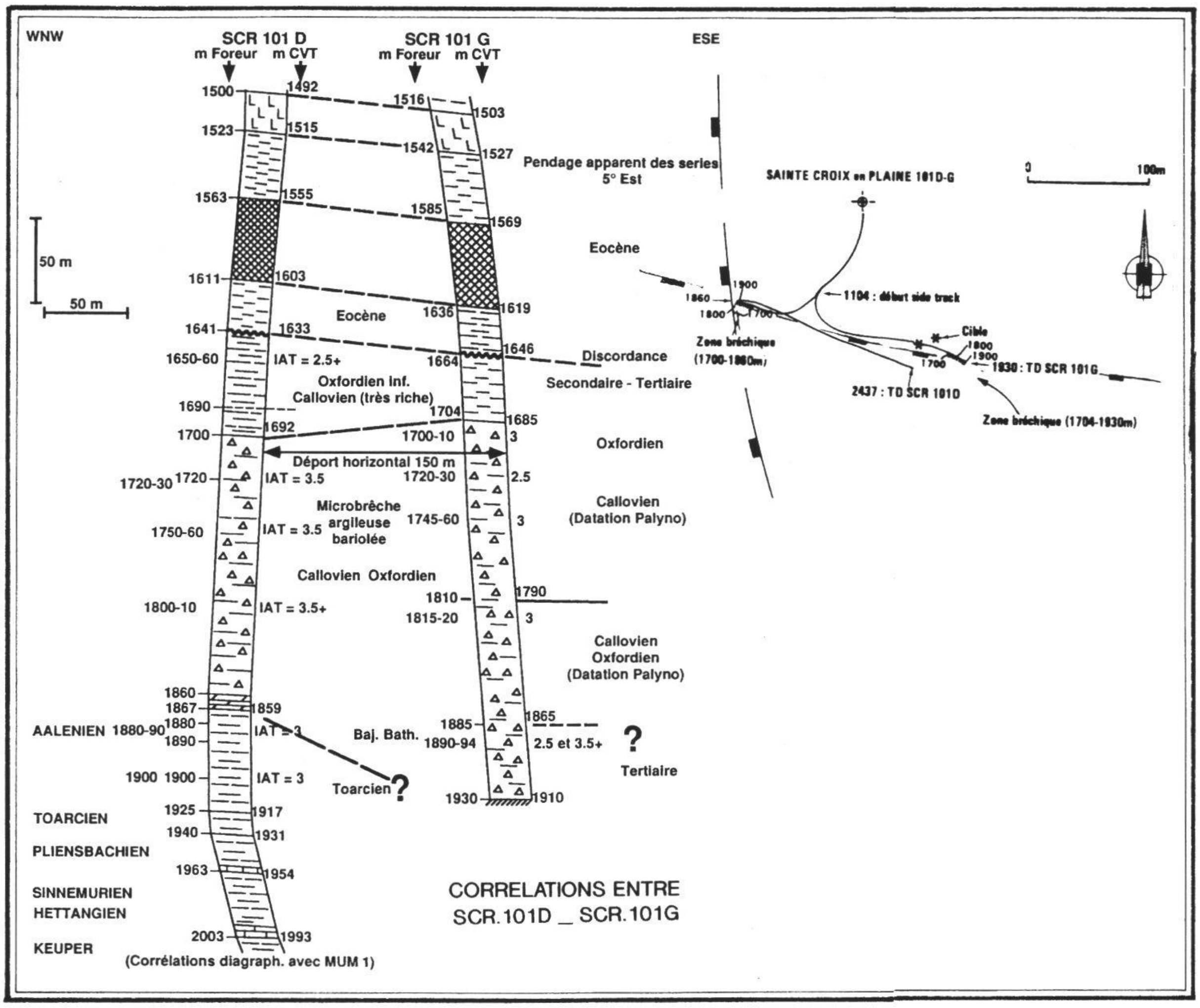


Fig. 29: Correlation between Ste-Croix-en-Plaine 101 D and 101 G (deviation) (author: SNEA(P)).

4. Discussion of results

4.1 Scientific results

4.1.1 Stratigraphy

Basement

Two of the wells discussed, MEI-2 and MUM-1, drilled into the crystalline basement. Both encountered acid to intermediate magmatites, similar to rock types encountered in the basement of the neighbouring Vosges.

Paleozoic

No sedimentary Paleozoic rocks were found between the crystalline basement and the Lower Triassic, nor were any indications for their presence recognized in the seismic sections.

Mesozoic

The stratigraphic record on top of the basement, thus, starts with Mesozoic strata, viz. the Buntsandstein. A detailed discussion of the Mesozoic sequence in the subsurface as seen mainly on logs and seismic records, in particular the exact correlation of the well expressed log units (Fig. 30 to 34) with biostratigraphic units and the mapping units of the Geological Surveys, should include all relevant wells drilled on both sides of the Rhine river. It would, thus, exceed the aim of this paper.

In the well summary figures (e.g. Fig. 8 etc.) we therefore have kept the original stratigraphic interpretations and boundaries of the Mesozoic as well as of the Tertiary as given by the operators, even if a different correlation, a shift of boundaries or a change of the stratigraphic terms used is suggested by log comparison or more recent literature, respectively.

Nevertheless, we have documented the Mesozoic sequences drilled in the wells of the Association by their respective gamma-ray, and sonic or density logs, and show possible correlations with the lithological sequences of nearby surface sections or wells as recorded in the explanatory notes of the respective geological maps 1 : 50'000 of the Geological Survey (sheets Colmar, Neuf-Brisach, and Molsheim, BRGM 1972a, 1978, 1975) and with logs of other nearby wells available. Figs. 30 to 34 show that the individual units of Lower Triassic to Upper Jurassic age are generally well correlatable between the wells discussed, and with the surface sections described from the edge of the Graben, be it that thicknesses, particularly of thick shale units, may have been underestimated if derived from surface data only.

The correlation between the Buntsandstein/Muschelkalk boundary in outcrops e.g. on the sheets Colmar and Neuf-Brisach, and on the logs is still somewhat problematic mainly due to rather poor surface sections, which in general do not allow the definition of the boundary in sufficient detail to correlate it with the rather well expressed log configuration in the boundary region. However, we attempted a correlation of the log of MAM-1 with the section described by GLA (1977: 91-92) some 10 km to the E; if the correlation is correct, the Muschelkalk as defined there, would start with the log unit numbered 19 on Fig. 30 and 31.

Here as elsewhere on Fig. 30 to 34, the numbering of log units serves only a purely descriptive purpose, to show which peaks (or, more important, which sequences of peaks) were correlated between neighbouring wells. No further stratigraphic meaning is implied.

The log correlation of the Lower, Middle and Upper Muschelkalk and the overlaying Lettenkohle is rather straightforward (Fig. 31). Very characteristic are the low gamma-radiation units marked G, H and I in the Lower and Middle Muschelkalk. Density, sonic velocity and cuttings prove the presence of anhydrite in these intervals. The lowest, marked G, may be equated to the Geislingen Bank E of the Black Forest (Simon 1982, Becker et al. 1997), situated within or at the base of the so-called Orbicularis-Marls; the Geislingen Bank is generally still regarded as Lower Muschelkalk, but represents the first cycle of the Muschelkalk evaporites. The two higher units I and H are assumed to correspond to the two evaporite cycles of the M. Muschelkalk described from the Heidelberg region and from more eastern areas by Friedel & Schweizer (1989).
The Upper Muschelkalk is c. 80 m thick in MAM-1, MUM-1, SCR-101, and MEI-1. The gamma ray logs from this unit appear to be well comparable. Comparison to the surface section described N of Freiburg (Leiber in GLA 1977) is less straightforward. We could not identify with certainty on the well logs the units discerned at the surface. The thickness of the Upper Muschelkalk at the surface is said to be 50-65 m on the relevant sheets of the geological map in the Alsace, and 56 m near Freiburg, whereas in the subsurface it is constantly 80 m or more.
The logs of the Lettenkohle of the southern wells are easily correlatable between

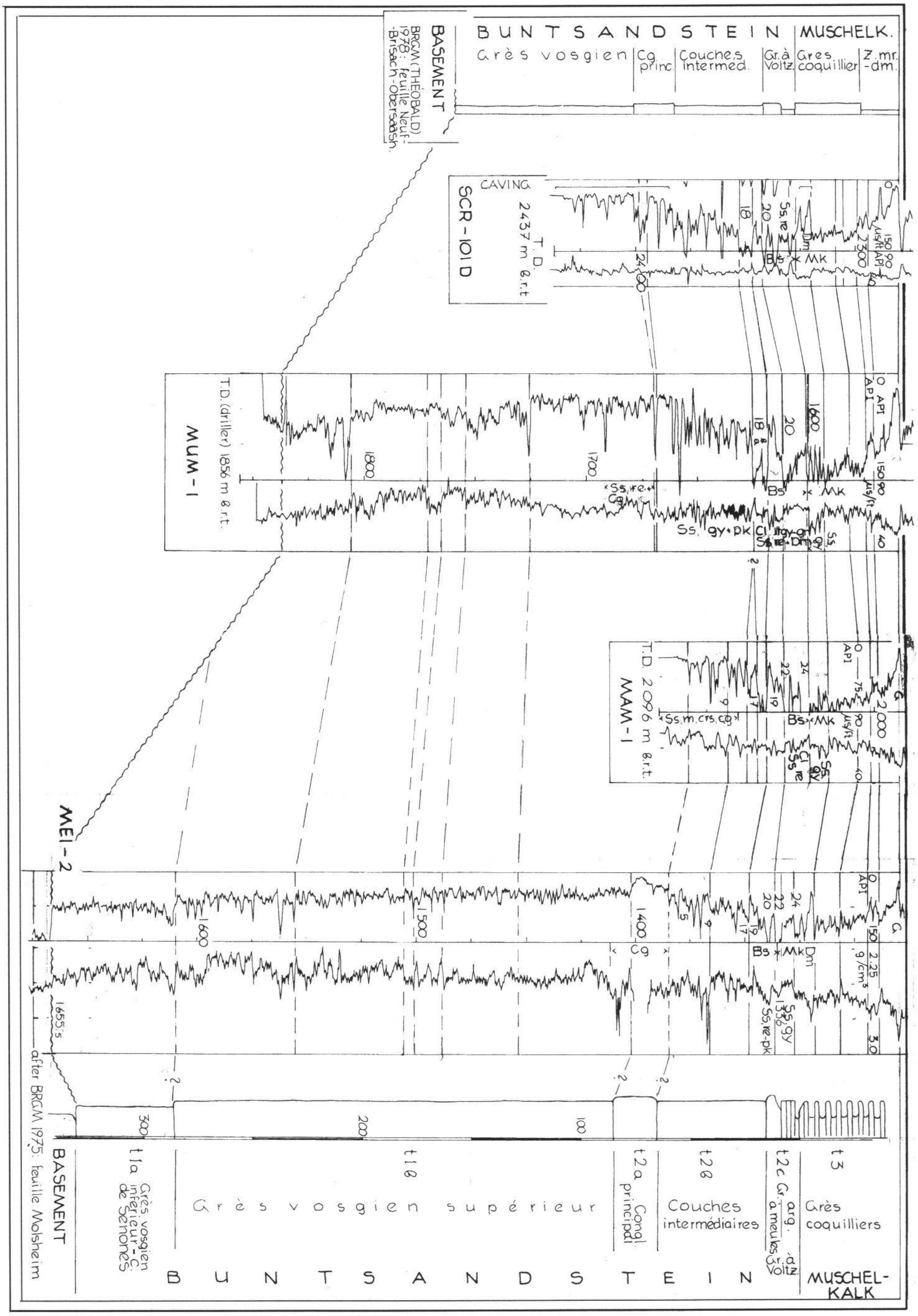


Fig. 30: Log correlation: *Buntsandstein;* Bs/Mk-boundary (indicated along vertical mid-line of logs) and lithologies: from final well logs wells Meistratzheim-2 (MEI-2), Mackenheim-1 (MAM-1), Muntzenheim-1 (MUM-1), Ste-Croix-en-Plaine-101D (SCR-101D); well locations on Figs. 5, 12, 20.

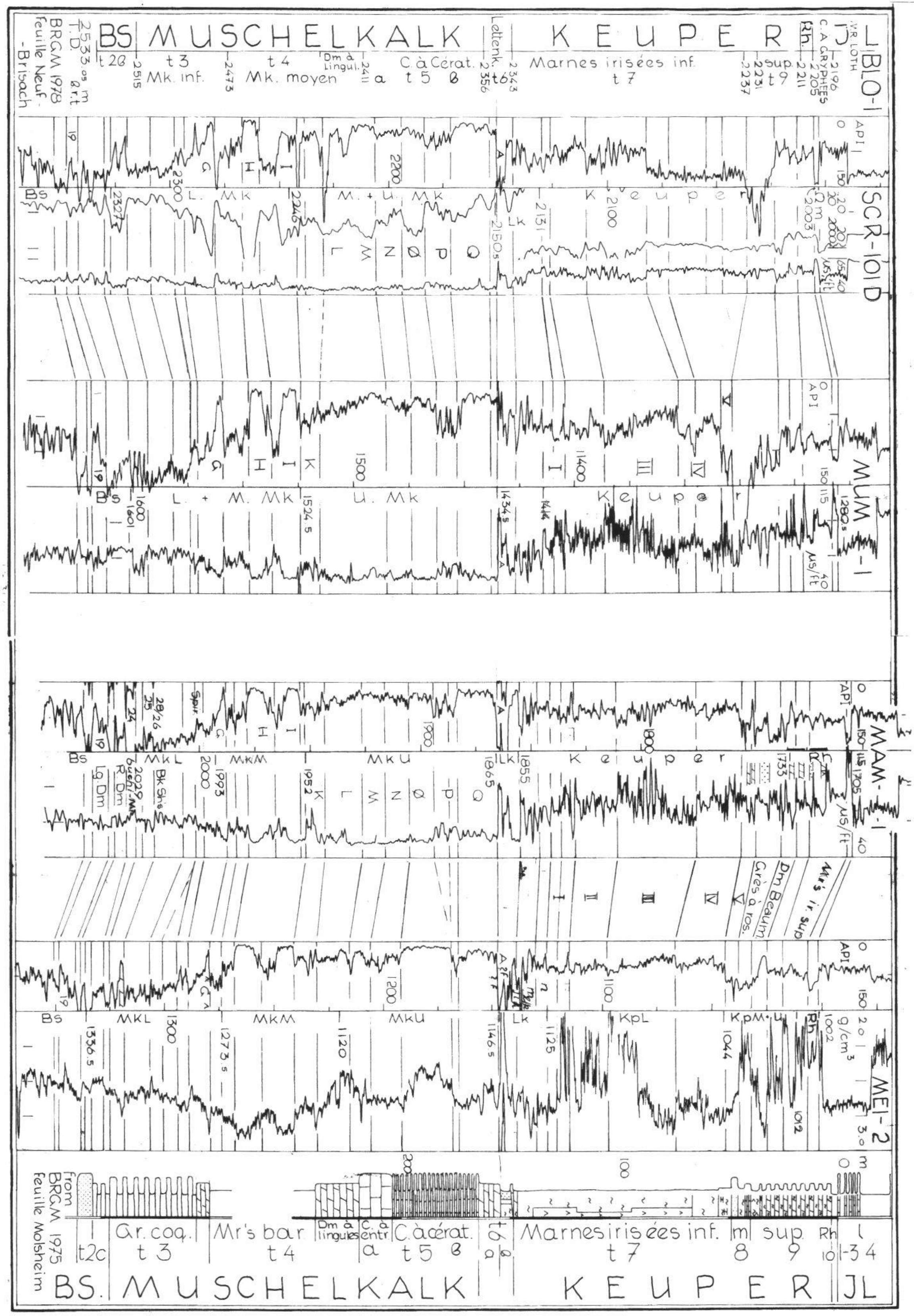


Fig. 31: Log correlation: *Muschelkalk - Keuper;* along vertical midline of logs: stratigraphic units from final well logs; MAM-1: Keuper - M. Muschelkalk acc. to BRGM (1972b); L. Muschelkalk: correlation with GLA 1977: 91, Fig. 7 - Lg. Dm = Liegende Dolomite, R. Dm. = Rauhe Dolomite, Bk.Sh's = shales in top of Deckplatten, Spir = Spiriferina-Bank; MEI-2: U. Muschelkalk-Lettenkohle - letters a-n = assumed equivalents of the bancs répères of Duringer (1982, Fig. 11a+b); wells as on Fig. 30 and Blodelsheim-1 (BLO-1); well locations Figs. 5, 12, 20.

each other and with the surface sections described from sheets Colmar and Neuf-Brisach (BRGM 1972a, 1978) and the area near Freiburg E of the Rhine river (GLA 1977: 102-103).

It should be noted that E of the Rhine River the top of the Muschelkalk is traditionally placed higher than in Eastern France. The dolomites of some 10 m thickness between the Couches à Cératites of the U. Muschelkalk and the shales of the Lettenkohle are included in the Lettenkohle as Dolomie inférieur by French geologists, whereas in SW Germany all but the top meter or so is called Trigonodusdolomit and regarded as part of the Upper Muschelkalk. Trümpy (in Théobald & Laugier 1963: 72) suggested that earlier, and Duringer (1996) confirmed it for the area W of Strasbourg.

The thin peak numbered "A" in MAM-1 and the wells south of it, corresponds to the so-called Alberti-Bank of Badish geologists; cuttings in MAM-1 and a sidewall core in MUM-1 indicate that it is overlain by a thin (c. 1 m) layer of dark brown, very fine sand to silt, as known also from outcrops in the Freiburg area.
Between Mackenheim and Meistratzheim an unequivocal correlation is not yet possible; even the connection of the Lettenkohle of Meistratzheim to the surface exposures near Wasselonne described by Duringer (1982) is doubtful in detail. Nevertheless, we indicated assumed equivalents of Duringer's bancs repères on the log of MEI-2 (Fig. 31) and suggested a possible correlation between MEI-2 and MAM-1.

The Keuper interval is well bracketed between the shales and dolomites of the Lettenkohle at the base, and the claystones of the Rhétien at the top. It may be subdivided into a number of log units and correlated from Meistratzheim to Ste-Croix-en-Plaine (Fig. 31).

The sequence of the Marnes Irisées Inférieures in the well Mackenheim-1 may be compared with the equivalent Gipskeuper on the eastern, Badish side of the Rhine river in the wells Wyhl-1 and Wyhl-Süd-1, which was recently correlated with the well known sequence in the Kraichgau depression, E of the graben between Karlsruhe and Heidelberg (Lutz & Etzold 1998). This comparison shows that the larger part of our unit I (Fig. 31) corresponds to the Grundgips of the Badish subdivision. The high sonic velocity/low gamma radiation interval in the upper part of unit III corresponds to the middle sulphate horizon (Mittlerer Gipshorizont), and a similar interval in unit IV to the upper sulphate horizon (Untere Bunte Estherienschichten).

In Mackenheim-1, two cores were taken from the interval 1716-1734 m (recovery 100 %) in what was originally interpreted as Rhétien. According to the lithological description of the cores and cuttings, however, it appears to be Upper Keuper (corresponding to the higher Middle Keuper of German authors): over- and underlain by variegated (mostly red and purple) clays and claystones with intercalations of clayey dolomites, a fine-grained, light gray sandstone was recovered from 1722.60 - 1723.80 m, and clayey dolomites from 1726.70 - 1728.20 and 1730.90 - 1734.40 m. The lower of these dolomites may be identified by its position on top of the strong gamma radiation interval of the Grès à Roseaux and the Marnes Irisées Moyennes as belonging to the Dolomie de Beaumont. In the well Muntzenheim-1, a thin (c. 1 m) sandstone has also been identified from the cuttings in the same stratigraphic position. Sandstones are rare in the Upper Keuper of the southern Upper Rhine Graben; this was possibly the reason why the interval was originally assigned to the Rhétien. Yet, similar thin sandstone layers are known in the same stratigraphic position in the north of the Alsace, e.g. as described on the sheets Bouxwiller, Haguenau, Saverne, Brumath and Molsheim of the geological map 1/50'000 (BRGM;

Schnæbelé 1948). In the Kraichgau depression and the adjacent part of the Upper Rhine Graben between Heidelberg and Karlsruhe, rather thin Sandstones are common in the equivalents of the Marnes Irisées Supérieures, and are correlated with the 4 subunits of the Stubensandstein in northern Württemberg. In that area, the 3rd and, in particular, the 4th Stubensandstein are the most prominent of these sandstones, and they spread far to the west (Schweizer & Kraatz 1982: 65). We, therefore, tentatively correlate the sandstone in the uppermost part of the Keuper in the wells Mackenheim and Muntzenheim with the upper (?4th) Stubensandstein of the Kraichgau depression.

An interval, a few meters thick and consisting of variegated clay, marks in all our logs the boundary between the Keuper and the Liassic; as in the well Illhæusern (BRGM 1972a: 13), we call it Rhétien. In top of this clay, 1-2 m of sandstone are reported from Meistratzheim-2 and Muntzenheim-1: in MUM-1, a sidewall sample from this interval is described as a fine- to medium-grained, micaceous sandstone.

The following intervals of the Liassic and the Aalenian are perfectly correlatable throughout the area (Fig. 33). We attempted also to correlate and interpret stratigraphically the remainder of the Mesozoic section, comprising in the wells of the Association essentially strata of the Dogger (Bajocian and Bathonian) (Fig. 34). Considering the facies variations regionally known from this interval, this correlation should be regarded as tentative only.

Tertiary

The lithostratigraphy of the Rhinegraben Tertiary has recently been reviewed by Sittler & Schuler (1988). In the same volume (Vinken 1988) the biostratigraphic dating of these units was discussed by various authors. In the exploration campaign reported, which was directed towards Mesozoic targets, no new insights into the stratigraphy of the Tertiary were gained except for local data on thickness and lithology at the well locations and, in part, by the seismic records reported upon above. An overview of lithostratigraphic mapping, log and chronostratigraphic units is given in Fig. 4.

In central and southern Alsace, south of Strasbourg, the main part of the Tertiary section was deposited during the Paleogene. Within this interval, lateral and vertical facies changes are largely controlled by the subsidence history of the southern Rhine Graben and by base level variations within the rift. They are also partially controlled by external factors, especially by climate and variations of sea level in adjacent or related marine domains. The subdivision and correlation of the Paleogene sequence is essentially based on graben-wide flooding events which are recorded by lacustrine and/or marine transgressive strata on the graben margins, and condensed deposits in its central parts (representing possibly somewhat larger time intervals than the transgressive strata at the basin margin). We mention the Planorbis- and the Melania- (Brunstatt-) Limestones of the Sundgau and adjacent graben margin areas, and what we regard as their approximately synchronous or slightly younger basinal equivalents, the Marnes Vertes à Limnées I and II (Courtot et al. 1972: 72); the basinal Zone Fossilifère (M. Pechelbronn Formation) and its marginal equivalents; and the basal units of the M. Rupelian Gray Series, the Foraminifera Marls, Fish Shales and transgressive marine sands and conglomerates (e.g. „sables marins“ of Éguisheim SW of Colmar (Sittler 1965; BRGM 1972: 16); „Meeressand“ of the greater Basel area (Wittmann 1952, Fischer 1965)), as well as

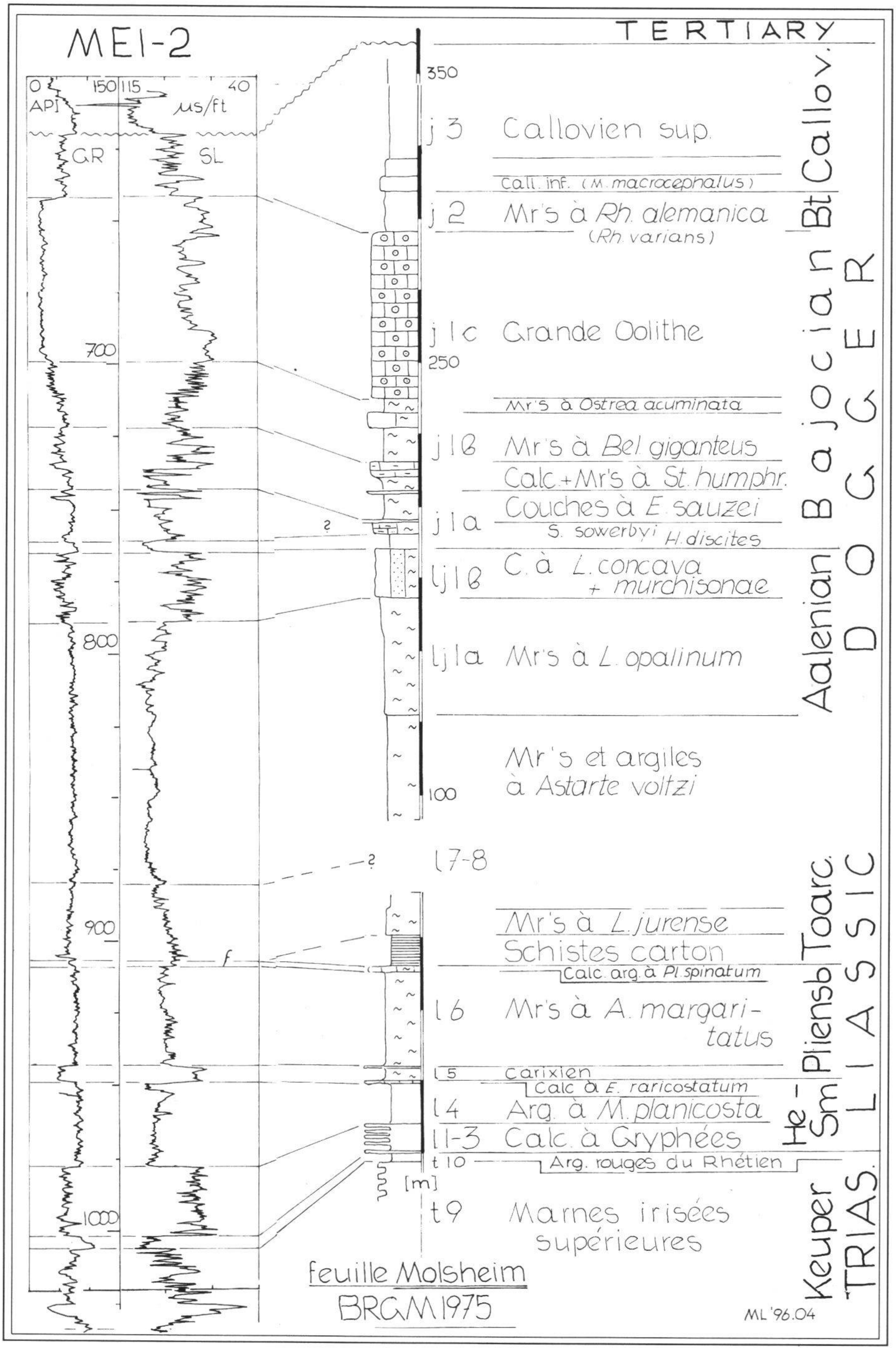


Fig. 32: Correlation gamma ray/sonic log of the *Jurassic* interval of Meistratzheim-2, and a composite surface section from geol. map 1:50'000, sheet Molsheim (BRGM 1975); well location on Fig. 5.

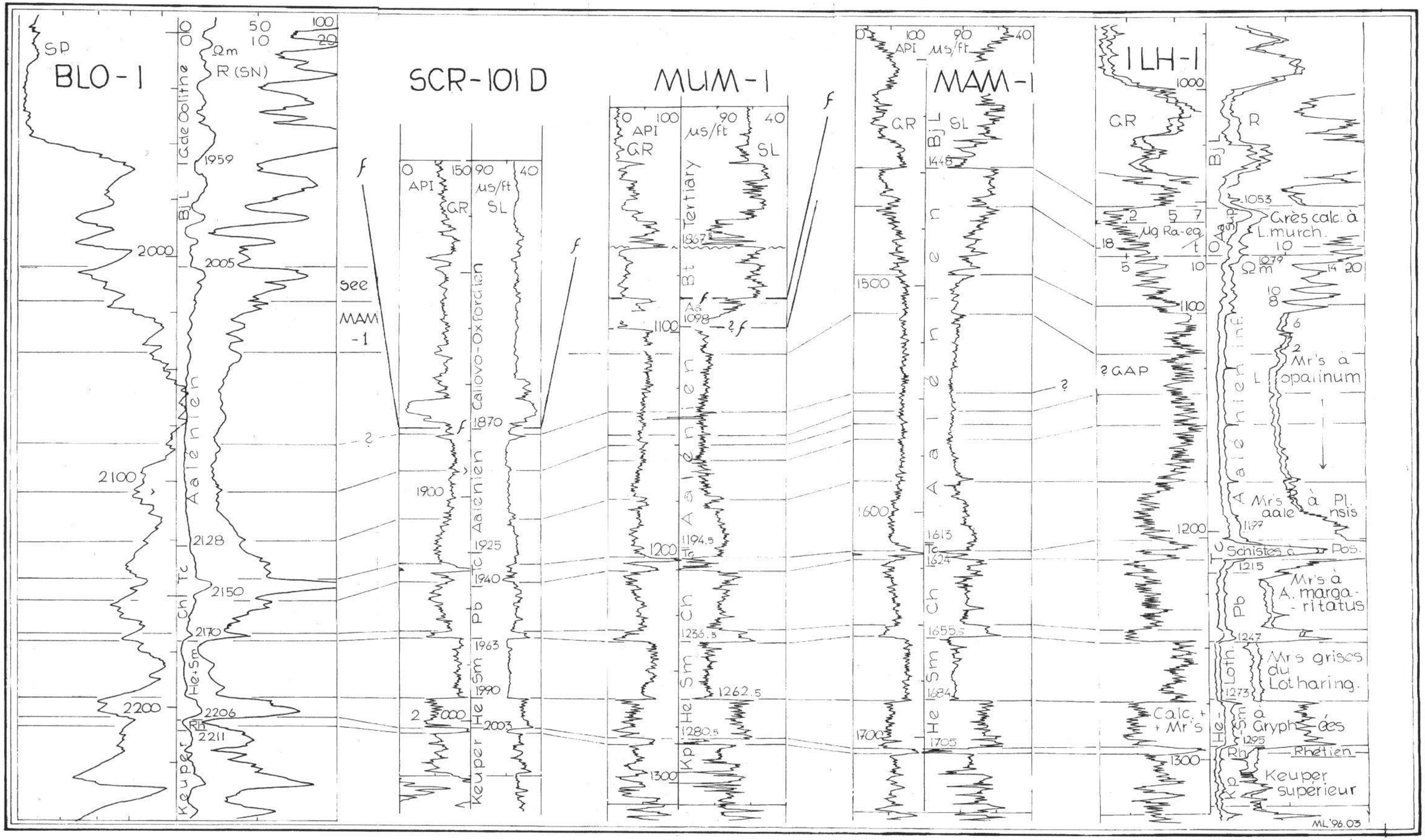


Fig. 33: Log correlation: *Liassic* and *Aalenian;* along vertical mid-line of logs: stratigraphy from final well logs; strat. units in ILH-1 from BRGM 1972b; wells as on Fig. 30, and Blodelsheim-1 (BLO-1), Illhæusern-1; well locations on Figs. 5, 12, 20.

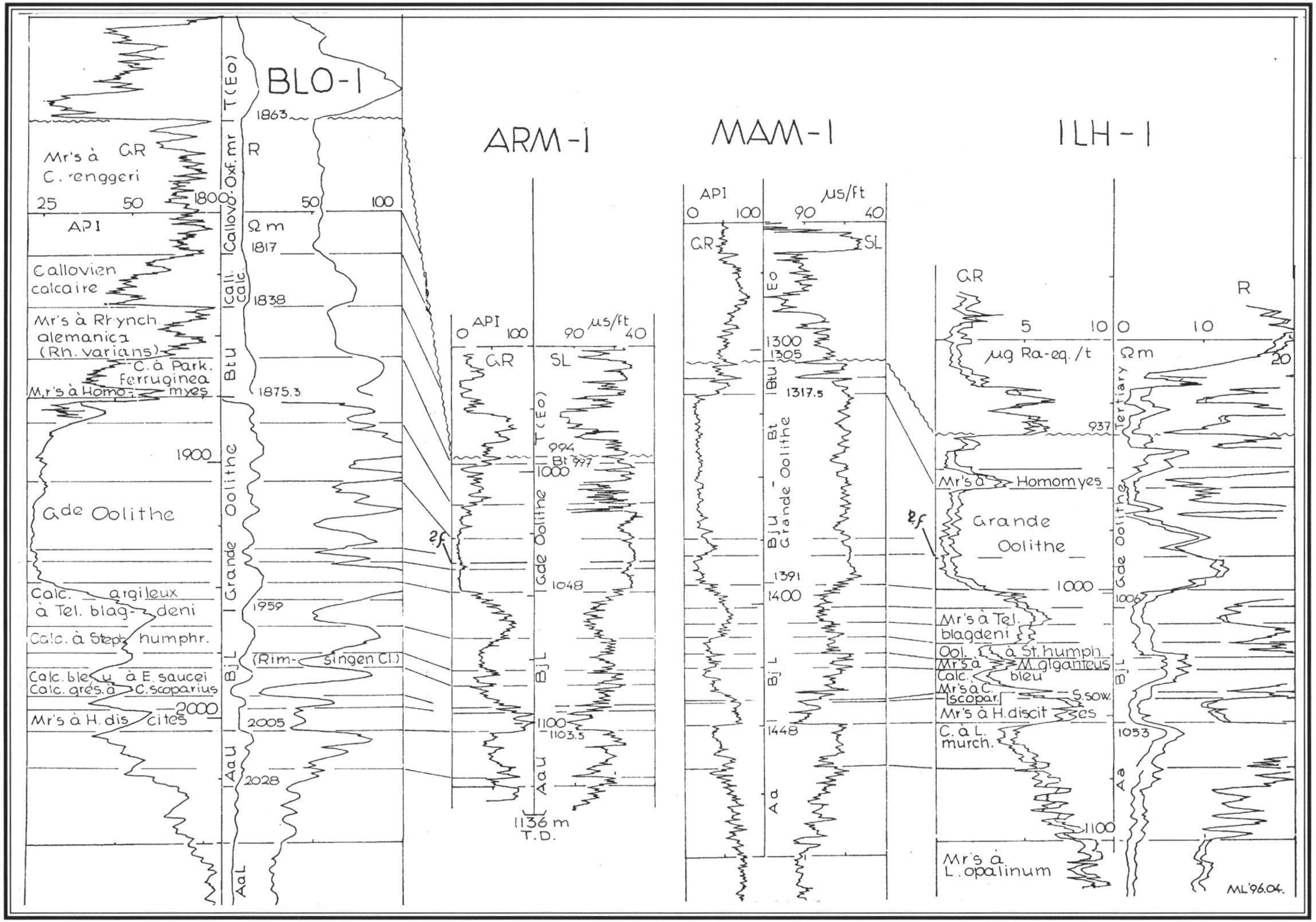


Fig. 34: Log correlation: *Bajocian-Bathonian* to *base Tertiary* unconformity; along vertical mid-line of logs: stratigraphy from final well logs; strat. subdivision in ILH-1 and BLO-1 acc. to BRGM 1972b and 1978; wells Illhæusern-1 (ILH-1), Mackenheim-1 (MAM-1), Artzenheim-1 (ARM-1, Blodelsheim-1 (BLO-1); well locations on Figs. 12, 20.

the „Couches à Ostrea cyathula" near to the Rupelian/Chattian boundary (BRGM 1976b: 11).

The youngest strata of the Paleogene preserved below the Neogene-Quaternary unconformity in the area discussed are the Chattian Freshwater Beds. In their upper part, a marked flooding event is recorded by the Lower and Upper Série Carbonatée and the intercalated Série Gypseuse (Courtot et al., 1972: 79). We have shown above, that this unit may be recognized seismically in the main halokinetic sinks of the Mulhouse Salt Basin west of the Obersaasheim, Dessenheim, Blodelsheim and Meyenheim salt structures. It is generally correlated with the Roppentzwiller, Tüllingen and Délémont Freshwater Limestones of the Sundgau, the Greater Basel area, and the Swiss Jura Mountains, respectively (Sittler 1972a: 114).

If one compares the Chattian sequence of the area discussed with that of the Upper Rhine Graben north of Strasbourg, and with that of the Molasse Basin of western Switzerland, one observes a flooding event within the uppermost Chattian deposits of all three regions. In the middle and northern Upper Rhine Graben, the marine to lagoonal Cerithium Beds overly the non-marine Niederroedern Formation. The Cerithium Beds subcrop N of Strasbourg (near Haguenau) below the Neogene-Quaternary unconformity. Sittler & Schuler (1988: 45) suggest time equivalence of this unit with the upper part of the Freshwater Beds of the southernmost graben, i.e. the Séries Carbonatées et Gypseuse. In the Lower Freshwater Molasse of the northern Alpine foreland basin of western Switzerland, a flooding event near the Chattian/Aquitanian boundary is recorded by freshwater carbonates and gypsiferous marls, under- and overlain by apparently terrestrial sandstones and variegated marls (Jordi 1955: 39-53). Büchi (1983: 222) suggested that a connection exists between this brackish to lacustrine intercalation and the Upper Cyrena Layers of the South-German Lower Freshwater Molasse, whereas Lemcke (1973: 14) assumes a marine ingression from the Rhone valley. Irrespective of the paleogeographic interpretation, however, one sees that these flooding events are of similar age. We suggest that they have a common cause, viz. a regional base level rise which was felt both in the terrestrial western Molasse Basin and southern Rhine Graben, as well as in the marine domain, i.e. the eastern Molasse Basin and the middle and northern Upper Rhine Graben. This flooding event may, therefore, be used for regional correlation within the graben and beyond, to the Alpine foreland.

In the area discussed between Strasbourg and Mulhouse, whitish sands and clays have been described in numerous wells at the base of the mostly Quaternary cover which unconformably overlies the faulted Paleogene. They are very similar to the strata cropping out N of Séléstat between Epfig and Dambach-la-Ville (Frohnhoff and Plettig hills, BRGM 1972b: 18). These, in turn, are correlated by lithological character with the sands of Riedseltz (S. of Wissembourg) which contain in places Upper Pliocene plant remains (Siat 1954: 81).

4.1.2 Structure

The seismic lines discussed indicate that faulting of both the Mesozoic and its Paleogene cover started during the deposition of the Saliferous formations and their equivalents in Late Eocene to Early Oligocene (Priabonian to Latdorfian) time. After a period of relative tectonic quiescence during the deposition of the Gray Series and the Chattian Freshwater Beds, intense block faulting occurred following deposition of the Chattian Niederroedern and Freshwater Beds, respectively, but before the resumption of the sedimentation in the Pliocene (Courtot et al. 1972) in a time interval for which a sedimentary record is missing in the area reviewed. Circumstantial evidence shows that the age of this faulting period is mainly Latest Chattian to Aquitanian (see below).

Within the Mulhouse Salt Basin, the Saliferous formations and the post-Saliferous Paleogene are halokinetically deformed. The seismic lines permit us only to date the beginning of the salt movements along or near to the faille Rhénane and S and W of the Blodelsheim Dome; it is contemporaneous with the deposition of the Freshwater Beds and, thus, Chattian. Most of the salt movements, however, appear to be younger than the deposition of the carbonate/sulphate units in the highest part of the Freshwater Beds. They started in the latest Chattian only, and possibly continued into the Early Miocene (Aquitanian) from which we have, however, no direct record in the southern graben.

The systematic positioning of the main salt ridges over major faults and horsts of the substrate as shown by the seismic lines (Fig. 14 - 16, 22) and the dating of both the salt movements and the block-faulting as essentially post-Chattian and pre-Plio/Pleistocene, is a clear indication that the Neogene extensional tectonics and the movements of the salt are related.
We assume that pressure gradients created by the opening of extensional faults and by overburden pressure differences due to the tilting of individual blocks or/and lateral facies changes initiated the flow of salt, and its accumulation in areas of lower overburden pressure once it had became unstable due to compaction of the overburden to densities above that of the salt. These salt movements led to the formation of elongated salt anticlines or salt pillows (sensu Trusheim 1957: 120, 1960: 1524) in the Mulhouse Potash basin, as well as in parts of the Strasbourg-Sud permit and in the Buggingen subbasin on the eastern side of the Rhine river. In the central part of the Mulhouse Basin, salt structures continued growing and intruded diapirically into the overlying strata. The presence in the areas outside the central part of the Mulhouse Basin of salt pillows and anticlines, with an often faulted, but essentially preserved roof, is assumed to have resulted from restricted volumes of salt being available for accumulation and/or the restricted movability of the salt-clay formations due to insufficient overburden or overburden gradient.

Following this episode of faulting and diapirism, the whole of the southern graben was uplifted together with its shoulders, i.e. the area of the present-day Schwarzwald and Vosges basement massifs („Black Forest-Vosges dome“ of Laubscher 1987). This uplift is marked within the Graben by the Neogene-Quaternary unconformity (reflection "Q"). The upper boundary of this unconformity can be dated within the area discussed only as pre-(?)Upper Pliocene.

The overlying Late Neogene - Quaternary cover within the central part of the graben, but outside the area of salt movements, is only locally affected by the faults dissecting the Mesozoic and Paleogene. Where such (mostly minor) dislocations of the Late Neogene - Quaternary unconformity reflection occur (e.g. Fig. 7; chap. 3.1.2), they may be due to differential compaction of the underlying older Tertiary, the preserved thicknesses of which may strongly differ from one block to the other.

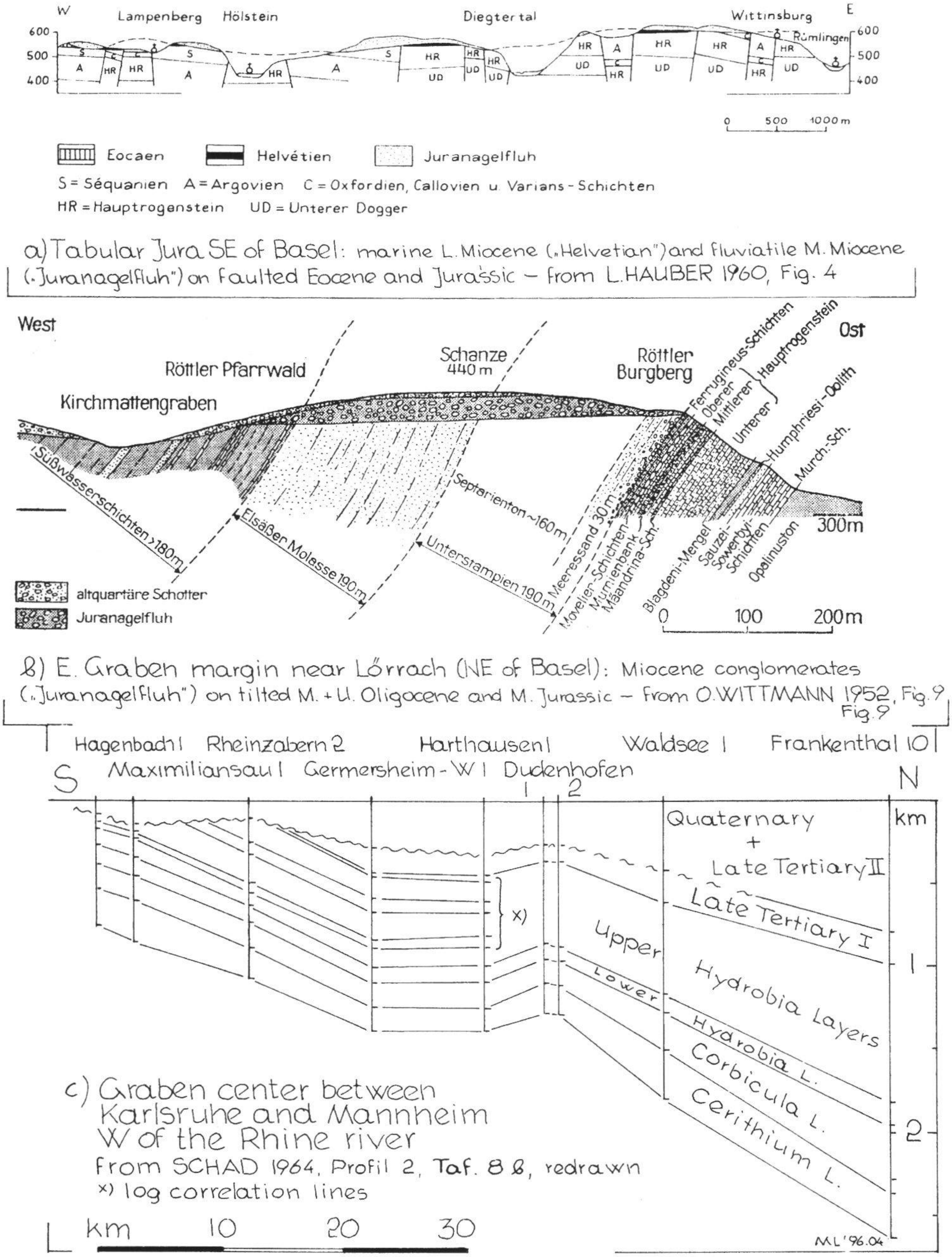


Fig. 35: The Neogene unconformity in the S. Rhine Graben: Structural cross sections:
a) Tabular Jura SE of Basel: marine L. Miocene ("Helvetian") and fluviatile M. Miocene ("Juranagelfluh") on faulted Eocene and Jurassic.- From Hauber (1960: Fig. 4).
b) Eastern graben margin near Lörrach (NE of Basel): Miocene conglomerates ("Juranagelfluh") on tilted Middle - Upper Oligocene and Middle Jurassic.- From Wittmann (1952: Fig. 9).
c) Graben center between Karlsruhe and Mannheim, W of the Rhine River.- From Schad (1964: Taf. 8b), redrawn.

Within the area of halokinetic deformation, continuing rise of the salt is indicated at places by an uplift of the base Quaternary to very shallow positions, e.g. near Hettenschlag. Dissolution is indicated by minor depressions (Fig. 22a, b; chap. 3.3.2).

The faulting of the older Tertiary and its Mesozoic substrate, as well as the uplift and erosion of the fill of the southern Graben is, thus, older than the Late Neogene-Quaternary, and younger than the Rupelian or (in most cases) Chattian. The timing of these events may be bracketed even closer by observations from nearby areas, viz. by surface and subsurface data from the graben N of Strasbourg, and surface observations from the Kaiserstuhl, the Lörrach area E of Basel, the Swiss Jura Mountains, and the southern and southeastern margin of the Black Forest (Fig. 35).

In the middle and northern Rhine Graben, Schad (1964, 1965) has shown by detailed log correlation that intensive synsedimentary faulting took place in post-Rupelian time, mainly during the deposition of the Chattian-Aquitanian Cerithium-, Corbicula- and Hydrobia-Beds. He also recognized that the so-called Late Tertiary II („Jungtertiär II“) rests unconformably on the underlying strata south of Landau and Bruchsal (N of Karlsruhe) (Fig. 35c). The youngest of these, the „Late Tertiary I“, may reach the Aquitanian/Burdigalian boundary (Sittler & Schuler 1988; Brelie 1974). The stratigraphic gap widens to the south so that successively older beds subcrop below the Upper Miocene to Pliocene strata above the unconformity. Near Haguenau (N of Strasbourg), the Chattian marine Cerithium Beds subcrop below the Neogene-Quaternary cover (BRGM 1976a). The eroded sequence S of Strasbourg, thus, comprises strata from the Burdigalian/Aquitanian boundary to the Chattian, and may reach, especially in the Mulhouse Basin, into the Gray Series and the Upper Saliferous Formation.
In the middle and northern part of the Rhine Graben, the oldest strata on top of the unconformity are the deposits of the „Late Tertiary II“ of Upper Miocene („Sarmatian“ to „Pontian“) to Pliocene age (Brelie 1974, Sittler & Schuler 1988). In the Mainz Basin, on the northern borders of the Graben, and in several wells between Lauterbourg and Haguenau (Boenigk 1987), the first strata in top of the unconformity are the „Dinotherium Sands“, fluviatile deposits of southern provenance (Vosges and Black Forest, Boenigk 1987: 390) and of Late Miocene („Pontian“) age (Sittler & Schuler 1988: 47).

In the eastern Kaiserstuhl, east of the area discussed, volcanic tuffs rest on a slightly westward tilted erosion surface over faulted Paleogene (Lower Pechelbronn = M. Saliferous Formation to Chattian Cyrena Marls) (Wimmenauer in GLA 1977: 163-164; Schreiner in GLA 1959: 99).

The age of the Kaiserstuhl volcanism has been dated radiometrically as 16-18 Ma (Lippolt, Gentner & Wimmenauer 1963, G.A. Wagner 1976, Schleicher 1986), i.e. late Early to earliest Middle Miocene (Snelling 1985), corresponding to the former „Helvetian“ and „Tortonian“ (deepest part only) stages.

Within the youngest part of the Kaiserstuhl volcanic complex, a mammal fauna has been found in volcanic tuffs of the Limberg just E of the Rhine river at the latitude of Marckolsheim. According to Tobien (gla 1959), this fauna is of younger „Burdigalian“ or, less probably, „Helvetian“ age, but is certainly pre-„Tortonian“. Tobien (Fig. 239 in Vinken 1988) indicated for this strata a radiometric age of 16.5 Ma, which would correspond to the top of the Burdigalian (Snelling 1985, in Vinken 1988, Fig. 267) or of the former „Helvetian“.

The volcano-sedimentary rocks of the Limberg at the NW corner of the Kaiserstuhl near the Rhine River are regarded as the youngest part of the volcanic complex of the Kaiserstuhl (Wimmenauer in GLA 1959). These rocks were affected during the volcanism by SE striking Early Miocene faults which form a small graben. These faults are younger than the main faults of the Graben fill (seen to be pre-volcanic in the eastern Kaiserstuhl) and are oblique or normal to the prevailing fault direction in the westerly adjoining area (Fig. 12); we assume that they are linked to the volcanism.

In the Sundgau, in the southernmost part of the Rhine Graben, south of the area discussed, and in the adjoining Ajoie (Swiss Jura Mts.), the basal parts of the alluvial cover - the Late Miocene Dinotherium Sands and/or Vosges Gravels and Sands (Sittler 1972; Liniger 1966) - are derived from the north, from the Vosges.

At the very edge of the Graben, within the Rhine Graben flexure near Lörrach (E of Basel), fluviatile conglomerates cover unconformably and horizontally the strongly west-dipping strata of the Dogger, the Rupelian Gray Series and the Chattian Freshwater Beds (Fig. 35b); these conglomerates, correlated with the „Tortonian“ Juranagelfluh of N. Switzerland, are, in turn, overlain by flat lying, early Quaternary gravels (Wittmann 1952).

In the Tabular Jura of Baselland, pre-„Helvetian“ („Paleogene“) structures are covered unconformably by the younger, so-called „Helvetian“ parts (= higher Burdigalian of modern Mediterranean stratigraphy) of the Upper Marine Molasse (Fig. 35a, from Hauber 1960) which in turn are overlain by the Juranagelfluh, fluviatile conglomerates of essentially „Tortonian“, i.e. topmost Burdigalian to Serravallian, age. The northernmost occurrence of this marine Miocene was found by Fischer (1965: 42) in the Alsatian Jura, at Kiffis.

The strong extensional faulting, the halokinesis and the inferred concomitant deposition in salt-withdrawal areas in the inner part of the southern graben may be dated by analogy as mainly Late Chattian-Aquitanian. The occurrence of salt deposits in the Late Chattian Corbicula Beds in the Worms region of the middle graben was related by Sittler & Schuler (1988: 46) to „the dissolution of former salt-bearing formations“ elsewhere. We assume that these dissolved salt-bearing formations are the Paleogene Saliferous formations of the southern graben, which were mobilized by the Late Chattian-Aquitanian block faulting and exposed to dissolution, either by uplift and erosion in fault blocks and domal or anticlinal accumulations (salt ridges), or by diapiric ascent of salt and (?overpressured) shale formations, as was suggested earlier by W. Wagner (1955).

These movements were followed in the Aquitanian by a vigorous uplift of the Southern Graben and its shoulders (Black Forest-Vosges Dome: Laubscher 1987). The extent of the erosion in the southern graben is difficult to quantifiy as we have no density or sonic velocity data from wells in the more northerly, continuously subsiding parts of the graben to estimate the thickness of the removed overburden.

An order of magnitude of the overburden missing below the Neogene-Quarternary unconformity may be estimated, however, from the lack of a sedimentary record of the growth and the extrusion of the salt structures over most of the Mulhouse Salt Basin s. l. (cf. chap. 3.3.2). Observing that the Chattian Freshwater Beds do not show thickness variations related to the salt structures present, we assume that they were uniformly deposited over the central part of the Graben, and that the halokinesis started only after the deposition of these strata. Consequently, at least the Freshwater Beds were eroded in top of the growing salt pillows and the extruding diapirs. In the intermediate salt-withdrawal areas, the peripheral sinks, the Freshwater Beds are preserved; younger strata (topmost Chattian to Aquitanian) have to be assumed to have been deposited in primary and secondary peripheral sinks in volumes equal to those of the salt evacuated and equal to or greater than those of the Freshwater Beds eroded over the diapirs.

Most of these younger strata deposited in primary and secondary peripheral sinks has been removed by erosion which, thus, records the period of the mainly Burdigalian uplift. With a thickness of the Freshwater Beds of up to 800 ms corresponding to some 1000 - 1200 m in the wells DP 207 (Niederhergheim 5) and DP 34 (Heiteren), and a roughly equal area (and consequently volume) occupied in the central part of the Mulhouse Salt Basin by diapirs and sinks, the volume eroded from the top of the diapirs is equivalent to an erosion over the whole area of roughly 500 - 600 m. That is a minimum value for a closed system where all material eroded on top of the growing salt structures was deposited in the adjacent sinks. It does not take into account any volumes of sediment carried out of the system or of salt removed by solution.

An order of magnitude of 1000 m for the thickness of the strata eroded in the Mulhouse Basin below the Neogene-Quaternary unconformity may, then, be a reasonable assumption. We assume that a similar erosion affected also the more northerly areas between the Mulhouse and the Strasbourg Basins. Roll (1979: 40; Tab. 1), Laubscher (1987: 297) and Sittler (1985: 354) also estimated Miocene uplift and erosion of the southern Graben at about 0.1 - 0.7 km, 1 - 2 km, and 1 - 1.5 km, respectively.

Roll (1979) was the first to stress the importance of this period of Neogene uplift, whose climax he dated as Early Pliocene; he illustrated it (1979: Fig. 19) by mapping the subcrop below the Plio-Pleistocene and the thickness of the eroded Paleogene.

The dating of this uplift as Aquitanian is corroborated at the southeastern and southern edge of the Black Forest by Miocene conglomerates, the so-called Juranagelfluh, which record uplift and erosion of the Mesozoic cover of the Black Forest from the Late Aquitanian onwards.
In the Late Miocene and Pliocene, a slow onlap from north and south is observed towards the high formed by the uplift of the southern graben during the Neogene. This high controlled the drainage of the area for the remainder of the Tertiary. The „Kaiserstuhl watershed“ (Levy 1921; Bartz 1936) caused drainage to the south in the southernmost Alsace, the Sundgau, and the adjoining Swiss Jura Mountains, and to the north in more northerly regions. Its position may still be recognized by the direction of the main tributaries of the Rhine river within the Vosges and the Black Forest (Fig. 2): SW-, S- and SE-directed south of a line connecting the Hohneck and the Petit Ballon in the Vosges, with Badenweiler, and the Belchen and Feldberg mountains in the Schwarzwald, and northward flowing north of that line. Only in the Early Pleistocene, the Rhine River could overcome this obstacle and extend its drainage area to the south (Bartz 1961, Lininger 1966).

The apparent K/Ar age of the Early Oligocene potash salts in the Mulhouse Basin of 19.8 Ma (Lippolt et al. 1963: 535), i.e. basal Burdigalian (Harland et al. 1990), is clearly younger than the Early Oligocene depositional age (> 32 Ma) of these strata. It may indicate the time of the final recrystallisation of these salts after the Early Miocene tectonism (Sittler & Schuler 1988: 44).

The Late Oligocene to Early Miocene faulting and halokinesis that is seen on the seismic sections is obviously correlated with the strong E-W extension, slightly oblique to the main Graben direction (N20°E) and vertical sigma1 (maximum principal stress), revealed by measurements of the direction of salt fibres in tension gashes within marl layers of the U. Saliferous Formation in the Mulhouse potash mining district (Larroque & Ansart (1984, 1985); and by microtectonic studies on the western and southern margin of the graben (Larroque & Laurent 1988).
The persistence of this stress field with a vigorous E-W extension into the later Early Miocene is suggested by the occurrence of numerous esentially N-S (NW-NNE) striking volcanic dykes in the central Kaiserstuhl which show an aggregate extension of „several hundreds of meters“ on an E-W distance of some 3 km (Wimmenauer in GLA 1959).

In summary, we see the following main stages in the structural development of the Rhine Graben between Strasbourg and Mulhouse:

- ESE-WNW rifting and subsidence along predominantly NNE striking faults during the Late Eocene to Early Oligocene;

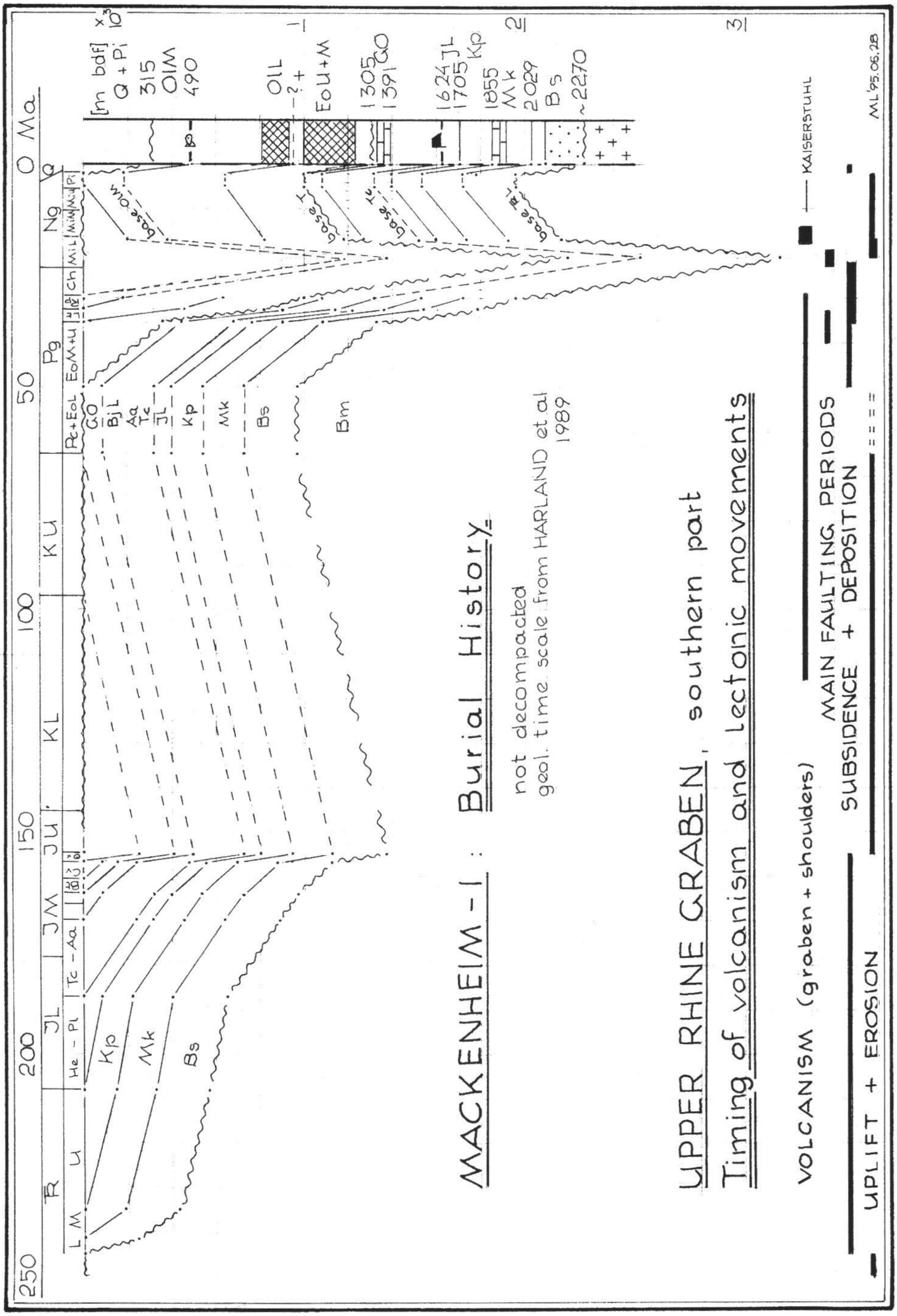


Fig. 36: Mackenheim-1: Burial graph.

- anticlockwise rotation of the regional stress field;
- maximum burial in early Miocene time, immediately preceding or concomitant with
- E-W to ENE-WSW extension („rifting“), causing intense faulting of the graben fill, and triggering the salt movements in the southern part of the area, possibly combined with some transpression or wrench movement along older, NNE to NE striking faults;
- contemporaneous with, or immediately followed by strong uplift and erosion of the whole of the southern Graben, say, south of Strasbourg, up to Middle or Late Miocene time. Maximum erosion is assumed to be 500 m (Roll 1979) to 1000-1500 m (Sittler 1985: 354).

The structural development of the area as summarized above, is illustrated by Fig. 36, which shows the burial history at the location of the well Mackenheim-1, and the timing of the main tectonic movements and the volcanism.

Note that the burial graph of MAM-1 does not take into account decompaction. As part of the Paleogene sequence in MAM-1 is undercompacted, and as we assume that undercompaction of the shaly and evaporitic sequences of the Paleogene of the southern Rhinegraben was a widespread phenomenon through large parts of their history (see chap. 3.2.2.), the use of common compaction/depth relations would not effectively increase the accuracy of the burial graph which, although being quantitatively incorrect, is assumed to depict qualitatively well the burial history.

4.2 Petroleum-geological aspects

The exploration campaign discussed came to an end without economic success after drilling seven wells on what appeared to be the most prospective structures. To understand the causes of this failure, we will compare the original assumptions on which the venture was based, with the corresponding results.

The main *source rock* expected, the Toarcian Paper Shales, was identified in Muntzenheim-1 with a thickness of 13 m of which 6.5 m proved by log interpretation and sidewall samples to be bituminous shales of good source rock quality. The interval could also be recognized in cuttings and by its characteristic log readings (high gamma ray, resistivity, and sonic transit time) in Mackenheim-1 and Ste-Croix-en-Plaine-101. In Meistratzheim, however, no Paper Shales were seen; they are possibly cut out by a fault.

Indications for source-rock-prone Late Paleozoic strata were neither found in the wells nor seen in seismic records.

Reser oirs were found as expected. In the wells drilled by the Association through the Buntsandstein (MEI-2, MUM-1), thick, porous and permeable sandstones were encountered in the Middle Buntsandstein, but without hydrocarbons. Also the wells Grunsbuhl-1 and Mackenheim-1, deepened by SNEA(P), did not find any production in the Buntsandstein.

The carbonates of the Upper Muschelkalk-Lettenkohle showed variable reservoir properties in these wells: $\varnothing_{SL}$ in MEI-2 = 4 - 18 %; in MUM-1 = 2 - 7.5 % in the deeper, calcareous part, and 5 - 8 % in the dolomitic top part (interval “Q” of Fig. 31); in SCR-101, they were found rather tight (<5%).

In the Grande Oolithe, good porosities were only encountered in two of the northern wells, viz. MEI-2 (16 - 32 % over a net thickness of 38 m) and GBL-1 (average $\varnothing_{SL}$ = 15 %). Comparable good porosities were also reported from other wells near the northeastern edge of the Grande Oolithe platform, e.g. in the Schæffersheim, Eschau and Offenburg fields. Variable, and mostly poorer porosities were found in wells farther away from the platform edge, e.g. E of Colmar in ARM-1 ($\varnothing$av. 5.5 % on logs and 7 % from cores), MAM-1(estimated from the sonic log as 5 - 17 (av. 12)%), and MUM-1 (5 - 16 (av. <10) %).

Top seals for the M. Jurassic Grande Oolithe are formed in most cases by Paleogene strata consisting in all wells of claystones, marls, anhydrite and a salt sequence. In MEI-2, MAM-1 and ARM-1, between the base of the Paleogene seal and the top of the Dogger reservoir, an interval of marls and carbonates of the Bathonian and of the basal Tertiary is intercalated. This interval, although no reservoir, may be somewhat porous and permeable. Such non-sealing non-reservoir intervals („waste zones“) reduce the effective height of a structural closure and, in consequence, of the trap volume; moreover, as the total hydrocarbon column height is the sum of the thickness of the hydrocarbon-filled effective reservoirs and of the waste zone, the pressure differential through the final seal may be larger than expected from the producible hydrocarbon column height alone.

The *seal* in top of the Buntsandstein reservoir is less well defined. The final seal is formed by the first anhydrite layer of the Muschelkalk evaporites, some 105 m and 95 m, respectively, above the massive sandstones of the Middle Buntsandstein in the wells MEI-2 and MUM-1. The intervening strata are characterised by high gamma-radiation. According to the cutting description they consist of some silt and shales, but mainly of fine- to medium-grained sandstones, often clayey or carbonate cemented. Mud losses in MUM-1 (23 m^3 between 1615 - 1640 m) suggest that porous and permeable beds are present in this interval and we doubt whether this interval can be regarded as a seal at all.

Lateral seals to the tilted fault blocks, may be formed by impermeable formations in the downthrown blocks, juxtaposed to the possible reservoirs, and/or by an impermeable fault plane.

The *structures* drilled were all dip- and/or fault-bounded, i.e. either fault-bound horsts (Meistratzheim), or tilted blocks bounded on the high side by antithetic faults, as in Muntzenheim, Mackenheim, Artzenheim, or Ste-Croix-en-Plaine. Across the bounding faults, the Grande Oolithe reservoir in the high block was juxtaposed to the clay-/evaporite-sequences of the Paleogene; in addition, a clayey fault gauge may be present. It appears probable that such faults are generally sealing. For the Buntsandstein reservoirs it is more difficult to evaluate the fault-seal quality.

The play model foresaw charging of the Buntsandstein reservoirs with hydrocarbons generated from the Toarcian source rock in fault contact with the reservoir. Overpressured hydrocarbons (the overpressures resulting from the hydrocarbon generating process itself) would break the fault seal temporarily, and would be expelled into the (hydropressured) reservoirs of the adjacent (high) block; after the pressure release, the fault would close again and keep the hydrocarbons trapped in the high block. The process, resembling the „seismic pumping“ and „fault valve“

mechanisms proposed by Sibson (1981, 1990), could have occurred repeatedly in pulses during the hydrocarbon generating phase. It is obvious that the trapping process is rather complex. Whether and where it has been realized is difficult to predict; a throw of the structure-bounding fault at the time of generation equal to the distance sourcerock/reservoir, i.e. of 450 - 475 m, corresponding to 250 - 300 ms TWT, would facilitate the migration of hydrocarbons into the adjacent Buntsandstein reservoirs. Places where this condition is fullfilled at the present time are, according to the seismic maps the Illhæusern, Goxwiller and Lipsheim structures (see chap. 3.1.2). We do not know, however, whether the bounding faults discussed were active again after the main hydrocarbon generation period. In structures bounded by faults with a smaller throw, migration of hydrocarbons from the Toarcian source to the Buntsandstein reservoir had to be downward, through the fault zones, which were assumed to be temporarily permeable during fault reactivation, and had to compete with an upward escape into higher reservoirs (e.g. the Grande Oolithe) or to the surface.
Seismic pumping and fault valving controlled by hydrocarbon generation appears to be a valid process, but we believe now that in the area discussed, the chances of charging Buntsandstein reservoirs by this process are small.

Besides the parameters discussed above, a knowledge of the timing and temporal relation between the processes of hydrocarbon generation/migration and of structuration is needed for the prediction of hydrocarbon accumulations.
Hydrocarbon generation is essentially a temperature-controlled process. Present-day temperatures in the southern part of the Upper Rhine Graben are only slightly elevated and do not show the strong lateral variations known from more northerly areas, e.g. in the northern Alsace (Delattre et al. 1970: Fig. 2). A heat flow value of some 72 mW/m^2 was measured in the Buggingen potash mine, on the Badish side of the graben, E. of the well Ste-Croix-en-Plaine (Kappelmayer 1967: 101), i.e. only some 15 % higher than the average terrestrial heat flow. Average temperature gradients evaluated from corrected bottom hole temperatures measured in the wells drilled by the Association are all below 40 °C/km, i.e. only slightly elevated (Fig. 37).

Bottom hole temperatures (BHT) measured in repeated log runs were corrected for the cooling effect of the drilling process according to a solution proposed by Lachenbruch & Brewer (1959), figured by Gretener (1981: Fig. 5.31-4) and applied to North Sea data by Evans & Coleman (1974). This correction takes into account the time of cooling the formation by the circulating mud, the time of warming up between the cessation of the circulation, and the measurement of the BHT in at least two consecutive log runs. As cooling times were not reported in the available data, we assumed some technically reasonable values. We think this to be permissible as variations of the cooling time within reasonable limits (e.g. 3 - 10 h) only moderately (< 5%) change the final result.

As M. & R. Teichmüller (1979) have shown, the heat flow during the formation of the Upper Rhine Graben was not uniform. Their study of the organic metamorphism of Mesozoic and Tertiary strata of the Graben revealed the existence of two heat pulses during its history, one in the Paleogene, and another one in the Late Neogene-Quaternary. Villemin et al. (1986) arrived at the same conclusion for the southern Graben by modelling the rifting process. From the observations discussed above, it appears, however, that the influence of the second pulse on the temperatures of the prime source rock in the southern Graben is more than outweighted by the erosion caused by the Neogene uplift of the Graben fill.

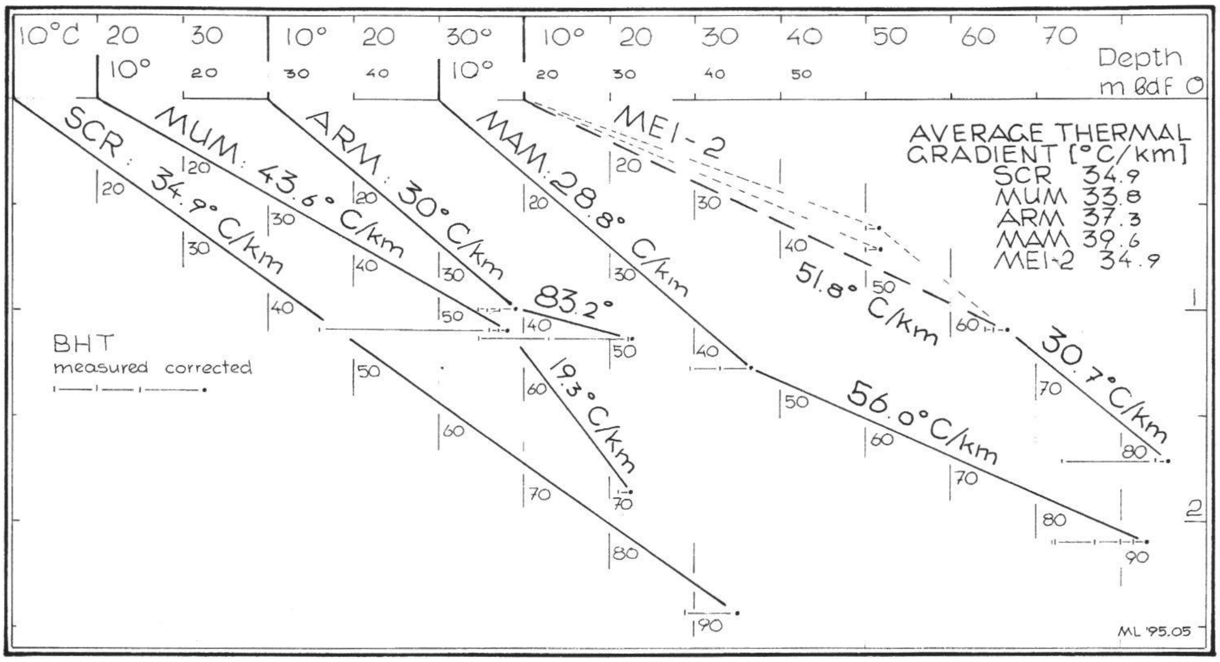


Fig. 37: Temperatures and temperature gradients in the wells drilled.

We therefore assume that in the area discussed, the maximum temperature of the prime source rock, the Toarcian bituminous shale, was controlled by the maximum depth of burial, and was, therefore, reached before the final structuration of the target horizons by the Neogene inversion. As hydrocarbon generation is temperature-controlled, main generation is assumed to have occurred also during maximum burial, i.e. in Late Aquitanian to Early Burdigalian time. Any oil and gas generated would have been trapped in the culminations of the structures then present.

The present-day structural configuration was determined by the latest Aquitanian-Burdigalian uplift and simultaneous late faulting (if any). It is, therefore, younger than the time of maximum burial, corresponding to the max. temperature of, and main hydrocarbon generation from the potential source rock(s). With further faulting and tilting of the graben fill during the Neogene uplift, any hydrocarbons originally trapped either escaped through reactivated or newly formed faults to the surface or remigrated to new traps along paths which cannot be predicted.

Highly prospective for oil, therefore, are only „old" structures which were present not later than the Late Paleogene and remained high throughout the Neogene to the present time.

Blumenrœder (1962) already pointed out that oil accumulations in Mesozoic reservoirs are „essentially linked to paleostructural elements"; he mentioned as examples Staffelfelden, and Eschau (S. of Strasbourg), both producing from the Grande Oolithe.

Our original exploration effort in the Meistratzheim and the east of Colmar areas was, therefore, directed towards regional paleostructural elements, viz. the Colmar Swell and the Meistratzheim High; but as individual paleostructural culminations could not be identified on the data available, it appears now likely that the largest of the small discoveries of the southern Graben, Staffelfelden, was discovered rather accidentally. Similarly, hydrocarbon generation during the maximum burial in latest Paleogene-Early Neogene time and migration in a structural setting different of that of today, may have caused the wide, but haphazard distribution of hydrocarbon shows in places which have no easy access to present-day kitchens: asphalt or heavy oil in Mesozoic limestones in the Vosges and Schwarzwald foothills, the heavy oil accumulation in basal Eocene limestones of the Allschwil-1 well W of Basel; and, most relevant, the find of an oil-impregnated fragment of Liassic in a probably Middle Miocene tuff breccia by Sauer et al. (1955: 365) in the foothills of the southern Black Forest:

They describe a tuff breccia filling a volcanic pipe, from a well drilled near Müllheim, in which they found a fragment of Liassic rock which showed, when smashed, droplets of oil. On circumstantial evidence, the volcanic explosion was dated as younger than the regional uplift and erosion of the Paleogene discussed above, and older than latest Miocene, viz. as probably Middle Miocene. Other fragments indicate that the pipe pierced a sequence reaching from the Paleozoic to the basal Tertiary. We regard the presence of live oil in that fragment as a strong indication for oil generation before the Neogene inversion viz. during the max. burial in the (?) Aquitanian.

Summarizing we see that in the Upper Rhine graben between Strasbourg and Mulhouse

- no Late Paleozoic source rocks are present;
- migration paths from the Toarcian source rock into Buntsandstein reservoirs, the original main target, are complex , so that it is difficult to predict whether and eventually where it could materialize;
- most of of the strata overlying the Buntsandstein are permeable, a reliable seal only occurring c. 100 m above the top of the Middle Buntsandstein reservoirs;
- the reservoir quality of the Grande Oolithe, our main target in the later phase of the venture, is highly variable; porosities range from porous (Meistratzheim-1) to tight (Artzenheim-1);
- hydrocarbon generation most probably occurred before final structuration; during and after the Neogene uplift, early accumulations may have escaped to the surface or remigrated to new traps along paths which hardly can be predicted.

Adding up these negative elements for the Mesozoic play in the southern Rhine Graben, it becomes now clear, that exploration for hydrocarbons in the Mesozoic of the southern Graben was fraught with a very high risk. The fact that hydrocarbon generation apparently preceeded the final structuration, makes a systematic search for, and the prediction of, hydrocarbon-filled traps difficult, in particular as the depositional record of the structural development is partially removed by erosion and, in a large part of the area discussed, is blurred by halokinesis.

Acknowledgements

The authors thank Shell Française S.A., Paris, and Shell International Exploration and Production B.V., The Hague, as well as Societé Nationale Elf Aquitaine (P), Paris, the partners in the exploration venture discussed, for their permission to use the data which became available through their joint activities, and to publish the present article. Peter Lehner, Peter Heizmann and Roland Wyss reviewed various versions of the manuscript; their critical comments and suggestions improved the final paper. The efforts of Harry Doust to improve our English are gratefully acknowledged. All interpretations, however, are the sole responsability of the authors.

References quoted

ALBIEZ, G. 1935: Erdöl am Oberrhein. Naturforschende Gesellschaft Freiburg i. Br., Berichte 34(2), 345-358.

BARTZ, J. 1936: Das Unterpliozän in Rheinhessen. Oberrheinischer geologischer Verein, Jahresberichte und Mitteilungen, N. F. 25, 119-226.

BARTZ, J. 1961: Die Entwicklung des Flussnetzes in Südwestdeutschland. Geologisches Landesamt Baden-Württemberg, Jahreshefte 4, 127-135.

BECK, R. H. 1975: Die Deckung des Erdölbedarfs West-Europas aus eigenen Quellen. Bull. Schweiz. Ver. Petrol.-Geol. u. -Ing., 42/101, 14-36.

BECKER, F., LUTZ, M., HOPPE, A. & ETZOLD, A. 1997: Der Untere Muschelkalk am Südostrand des Schwarzwaldes. Oberrheinischer geologischer Verein, Jahresberichte und Mitteilungen, N. F. 79, 91-109.

BITTERLI, P. 1972: Erdölgeologische Forschungen im Jura. Bull. Schweiz. Ver. Petrol.-Geol. u. -Ing., 39/95, 13-28, 5.

BLANC-VALLERON, M.-M., & GANNAT, É. 1985: Cartographie de subsurface du Salifère supérieur du bassin potassique de Mulhouse (Oligocène, Alsace). Societé géologique de France, Bulletin (8) 1(6), 823-836.

BLUMENRŒDER, J. 1962: Le pétrole en Alsace. Geologisches Landesamt Baden-Württemberg, Abhandlungen 4, 41-62.

BOENIGK, W. 1987: Petrographische Untersuchungen jungtertiärer und quartärer Sedimente am linken Oberrhein. Oberrheinischer geologischer Verein, Jahresberichte und Mitteilungen, N. F. 69, 357-394.

BRELIE, G. v. d. 1974: Mikrofloristische Untersuchungen zur Altersstellung der jungtertiären Ablagerungen im mittleren und nördlichen Oberrheingraben. In: FUCHS, H. J. & ILLIES, K. (eds.): Approaches to taphrogenesis. Schweizerbart. Stuttgart, 72-78.

BREUSSE, J.J. & ASTIER, J.-L. 1961: Étude des diapirs en Alsace et Baden-Wurtemberg par la méthode de rectangle de résistivité. Geophys. Prosp. 9, 444-458.

BRGM (BLANALT, J. G. et al.) 1972 - 1972 a: Carte géologique de la France à 1/50'000, feuille 342 Colmar - Artolsheim (37-18), map and explanatory note (59 p.).,BRGM, SGN, Orléans.

BRGM (BLANALT, J. G. et al.) 1972 - 1972 b: Carte géologique de la France à 1/50'000, feuille 307 Séléstat (37-17), map and explanatory note (47 p.), BRGM, SGN, Orléans.

BRGM (BOUDOT, J. P. et al.) 1987: Carte géologique de la France à 1/50'000, feuille 308 Benfeld (38-17), map and explanatory note (74 p.), BRGM, SGN, Orléans.

BRGM (DUBOIS, C., coordinator) 1962: Carte géologique de la France à 1/80'000, feuille Colmar. BRGM.

BRGM (GEISSERT, F. et al.) 1976: Carte géologique de la France à 1/50'000, feuille 199-169 Seltz-Wissembourg (39-13-14), map and explanatory note (59 p.), BRGM, SGN, Orléans.

BRGM (MÉNILLET, F., THÉOBALD, N. & VOGT, H.) 1975: Carte géologique de la France à 1/50'000, feuille 271 Molsheim (37-16), map and explanatory note (82 p.), BRGM, SGN, Orléans.

BRGM (THÉOBALD, N.). 1976b: Carte géologique de la France à 1/50'000, feuille 413 Mulhouse - Mullheim (37-38-20), map and explanatory note (27 p.), BRGM, SGN, Orléans.

BRGM (THÉOBALD, N.). 1978: Carte géologique de la France à 1/50'000, feuille 378-379 Neuf-Brisach - Obersaasheim (37-38-19), map and explanatory note (43 p.), BRGM, SGN, Orléans.

BRUN, J. P., WENZEL, F. & ECORS-DEKORP team 1991: Crustal structure of the southern Rhinegraben from ECORS-DEKORP seismic reflection data. Geology 19, 758-762.

BÜCHI, U. 1983: Zur Frage der Meeresverbindung zwischen der alpinen Vorlandsenke und dem Rheintalgraben zur Zeit des Rupelian. Oberrheinischer geologischer Verein, Jahresberichte und Mitteilungen, N. F. 65, 213-222.

CLOOS, H. 1939: Hebung, Spaltung, Vulkanismus. Geologische Rundschau 30, 401-527.

COURTOT, C., GANNAT, É. & WENDLING, É. 1972: Le bassin potassique de Mulhouse et ses environs - Étude du Tértiaire. Sciences Géologiques (Strasbourg), Bulletin 25(2-3), 69-91.

DELATTRE, J.N., HENTINGER, R. & LAUER, J.P. 1970: A provisional geothermal map of the Rhinegraben (Alsatian part). In: ILLIES, J.H. & MUELLER, St. (eds.): Graben problems, 107-110, Schweizerbart, Stuttgart.

DOPPLER, G. 1989: Zur Stratigraphie der nördlichen Vorlandmolasse in Bayerisch-Schwaben. Geologica Bavarica 94, 83-133.

DURINGER, P. 1982: Sédimentologie et paléoécologie du Muschelkalk supérieur et de la Lettenkohle (Trias germanique) de l'est de la France. Diachronie des Facies et reconstitution des paléoenvironnements. Thèse Dr. de spécialité (3ème cycle) en Géol., 96 p., Université Louis Pasteur, Strasbourg.

DURINGER, P. 1988: Les conglomérats des bordures du rift cénozoïque rhénan - Dynamique sédimentaire et contrôle climatique. Thèse Dr. ès Sc. naturelles, 278 p, Université Louis Pasteur, Strasbourg.

DURINGER, P. & GALL, J.-C. 1993: Les écosystèmes microbiens marqueurs des variations des niveaux lacustres en contexte de fan-deltas. Exemple du rift rhénan méridional (Europe occidentale). Geologische Rundschau 82(1), 30-41.

DURINGER, P. 1995: Dynamik der detritischen Ablagerungen am Rande des Oberrheingrabens (Obereozän- Unteroligozän) (Exkursion G am 21. April 1995). Oberrheinischer geologischer Verein, Jahresberichte und Mitteilungen, N. F. 77, 167-200.

DURINGER, P. 1996: Muschelkalk and Lettenkohle of eastern France. Université Louis Pasteur, Strasbourg, Inst. de Géologie, excursion-hand-out, june 1997.

EDEL, J. B. &. Lauer, J.P. 1974: Magnetic anomalies, thermal metamorphism and tectonics in the Rhinegraben area. In: FUCHS, K. & ILLIES, J.H. (eds.): Approaches to taphrogenesis. 155-160, Schweizerbart Stuttgart.

EVANS, T. R. & COLEMAN, N. C. 1974: North Sea geothermal gradients. Nature 274 (1974/01/04): 28-30.

FISCHER, H. 1965: Geologie des Gebietes zwischen Blauen und Pfirter Jura (SW Basel). Beiträge zur geologischen Karte der Schweiz, N.F. 122, 106 p.

FLUCK, P. &. WEIL, R. 1975: Géologie des gites minéraux des Vosges et des régions limitrophes (Vosges s.s., Fossé rhénan, Lorraine). Bureau de recherches géologiques et minières, Mémoires, 87 (II), 189 p.

FÖRSTER, B. 1911: Ergebnisse der Untersuchung von Bohrproben aus den seit 1904 im Gange befindlichen, zur Aufsuchung von Steinsalz und Kalisalzen ausgeführten Tiefbohrungen im Tertiär des Oberelsass. Geologische Landesanstalt von Elsass-Lothringen, Mitteilungen 7(4), 349-524.

FRIEDEL, M. G. 1927: Sur l'existence d'un dome de sel dans le bassin potassique oligocène du Haut-Rhin. Académie des Sciences (Paris), Comptes Rendues 184, 1028-1031.

FRIEDEL, G. &. SCHWEIZER, V. 1989: Zur Stratigraphie der Sulfatfazies im Mittleren Muschelkalk von Baden-Württemberg (Süddeutschland). Geologisches Landesamt Baden-Württemberg, Jahreshefte 31, 69-88.

GACHOT, H. 1936: Les sondages de Sundhouse et de Molsheim. Service de la carte géologique d'Alsace et de Lorraine, Mémoires 3, 91-98.

GEISSERT, F. 1987: Aus fernen und nahen Zeiten. Geologie aus nah und fern. Editeur Etablissement Geissert, F 67770 Sessenheim, 128 p.

Geologisches Landesamt Baden-Württemberg (GLA) 1959: Erläuterungen zur geologischen Exkursionskarte des Kaiserstuhls 1:25'000.

Geologisches Landesamt Baden-Württemberg (GLA) (GROSCHOPF et al.) 1977: Erläuterungen zur Geologischen Karte von Freiburg im Breisgau und Umgebung 1:50'000, 351 p.

GEYER, O. F. & GWINNER, M. P. 1991: Geologie von Baden-Württemberg.- 4th ed., Schweizerbart Stuttgart, 482 p.

GRETENER, P. E. 1981: Geothermics: Using temperature in hydrocabon exploration. AAPG, Education Course Note Series No. 17, Tulsa Ok. (USA).

GUNZERT, G. 1962: Zur Frage des Diapirismus in der tertiären Salzlagerstätte des südlichen Oberrheintals. Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen 116(1), 69-88.

HARLAND, W. B., ARMSTRONG, R.L., COX, A.V., CRAIG, L.E., SMITH, A.G. & SMITH, D.G. 1990: A geologic time scale 1989. Cambridge University Press,.Cambridge.

HAUBER, L. 1960: Über das Tertiär im nordschweizerischen Tafeljura.- Eclogae geologicae Helvetiae 53/2: 656-663.

ILLIES, H. 1962a: Oberrheinisches Grundgebirge und Rheingraben. Geologische Rundschau 52(1), 317-332.

ILLIES, H. 1962b: Prinzipien der Entwicklung des Rheingrabens, dargestellt am Grabenabschnitt von Karlsruhe. Geologisches Staatsinstitut Hamburg, Mitteilungen 31, 58-122.

ILLIES, J. H. &. FUCHS., K. (eds.) 1974: Approaches to taphrogenesis. Stuttgart: Schweizerbart, 460 p.

ILLIES, J. H. &. MUELLER, St. (eds.) 1970: Graben Problems. Karlsruhe: E. Schweizerbart (Stuttgart), 316 p.

JORDI, H. A. 1955: Geologie der Umgebung von Yverdon, Jurafuss und mittelländische Molasse. - Beiträge zur geologischen Karte der Schweiz, N.F., 99, XIII+85 p.

JUNG, J. &. SCHLUMBERGER, C. et M. 1936: Soulèvement des alluvions du Rhin par les intrusions salines diapires de la Haute Alsace. Service de la carte géologique d'Alsace et de Lorraine, Bulletin 3, 77-86.

KAPPELMEYER, O. 1967: The geothermal field of the Upper Rhinegraben. In: ROTHE, J.P. & SAUER, K. (eds): The Rhinegraben progress report 1967, Serv. Carte géol. Alsace Lorraine, Mém. 26, Geologisches Landesamt Baden-Württemberg, Abhandlungen 6, 101-103.

LACHENBRUCH, Arthur. H. &. BREWER, Max C. 1959: Dissipation of the temperature effect of drilling a well in Arctic Alaska. U.S. Geological Survey, Bulletin 1083C, 73-109.

LARROQUE, J.-M. &. ANSART, M. 1984: Étude des fentes d'extension liées à la tectonique distensive du bassin potassique oligocène de Mulhouse. Académie des Sciences (Paris), Comptes Rendues 299, série II, No. 20, 1419-1424.

LARROQUE, J.-M. &. ANSART, M. 1985: Les déformations liées à la tectonique distensive du bassin potassique oligocène de Mulhouse: cas du secteur minier. Societé géologique de France, Bulletin, (8) 1(6), 837-847.

LARROQUE, J. M., ETCHECOPAR, A. & PHILIP, H. 1987: Evidence for the permutation of stresses sigma1 and sigma2 in the Alpine foreland: the example of the Rhine graben. Tectonophysics 144, 315-322.

LARROQUE, J. M. &. LAURENT, PH. 1988: Evolution of the stress field pattern in the south of the Rhine Graben from the Eocene to the Present. Tectonophysics 148, 41-58.

LAUBSCHER, H. 1987: Die tektonische Entwicklung der Nordschweiz. Eclogae geol. Helv. 80(2), 287-303.

LEMCKE, K. 1973: Zur nachpermischen Geschichte des nördlichen Alpenvorlandes. Geologica Bavarica 69, 5-48.

LEVY, F. 1921: Die Entwicklung des Rhein- und Maassystemes seit dem jüngeren Tertiär. Naturforschende Gesellschaft Freiburg i. Br., Berichte 23(1), 9-85.

LININGER, H. 1966: Das plio-altpleistozäne Flussnetz der Nordschweiz. Regio Basiliensis 7, 158-177.

LIPPOLT, H. J., GENTNER, W. & WIMMENAUER, W. 1963: Altersbestimmungen nach der Kalium-Argon-Methode an tertiären Eruptivgesteinen Südwestdeutschlands. Geologisches Landesamt Baden-Württemberg, Jahreshefte 6, 507-538.

LUTZ, M. & ETZOLD, A. 1998: The Keuper in the Rhinegraben between Heidelberg and Basel: a log correlation exercise. International symposium on the epicontinental Triassic, Halle (Saale, Germany), 1998/09/21-23, Poster presentation; abstract in Hallesches Jb. Geowiss., B, Beih. 5: 111 (full paper in preparation)

MAIKOVSKY, V. 1941: Contribution à l'étude paléontologique et stratigraphique du bassin potassique d'Alsace. Service de la carte géologique d'Alsace et de Lorraine, Mémoires,6, XIV+192.

MAIKOVSKY, V. 1952: Le pétrole dans le Haut-Rhin: le sondage Staffelfelden IV - DP 25. Soc. industrielle Mulhouse, Bull. 1952(1), 25-34.

PFANNENSTIEL, M. 1933: Die Geologie des Kaiserstuhls. In: LAIS, R. (ed.): Der Kaiserstuhl, 18-127, Freiburg i. Br.

PFLUG, R. 1982: Bau und Entwicklung des Oberrheingrabens. X+145,Wissenschaftliche Buchgesellschaft, Darmstadt.

RICOUR, J. 1962: Contribution à une révision du Trias Français. Service Carte géol. France, Mémoir, 471 p.

RISLER, J.-J. 1991: Untersuchungen am Hauptrogenstein des Mittleren Jura (Dogger) im Oberelsaß (Département Haut-Rhin). Geologisches Jahrbuch (Hannover) E 48 (Homilius-Festschrift), 83-93.

ROLL, A. 1979: Versuch einer Volumenbilanz des Oberrheintalgrabens und seiner Schultern. Geologisches Jahrbuch (Hannover) A 52, 3-82.

ROTHE, J. P., & SAUER, K. (ed.) 1967: The Rhinegraben progress report 1967. Geologisches Landesamt Baden-Württemberg, Abhandlungen 6, 1-146, Freiburg i. Br.

SAUER, K. (ed) 1962: Erdöl am Oberrhein - Ein Heidelberger Kolloqium. Geologisches Landesamt Baden-Württemberg, Abhandlungen 4, 1-136.

SAUER, K., SÖLL, H., WIMMENAUER, W. & WITTMANN, O. 1955: Ein tertiärer Tuffschlot auf der Röthe südlich Müllheim (Südbaden). Geologisches Landesamt Baden-Württemberg, Jahreshefte 1, 361-366.

SCHAD, A. 1964: Feingliederung des Miozäns und Deutung der nacholigozänen Bewegungen im Mittleren Rheingraben. - Eine Auswertung erdölgeologischer Arbeiten. Geologisches Landesamt Baden-Württemberg, Abhandlungen 5, 1-56.

SCHAD, A. 1965: Abtragungserscheinungen an der Grenze Jungtertiär I/Jungtertiär II im Inneren des mittleren Rheingrabens. Senckenbergiana Lethaea (Frankfurt a. M.) 46a (Weiler-Festschrift), 363-376.

SCHIRARDIN, J. 1953: Les surfaces prétertiaires dans la vallée du Rhin en Alsace. Académie des Sciences, Paris, Comptes Rendues 236, 1806-1808.

SCHLEICHER, H. 1986: Isotopengeochemie der Alkalivulkanite des Kaiserstuhls (Ein Beitrag zu ihrer Genese mit Hilfe radiogener Isotope). Habilitationsschrift, Universität Freiburg i. Br.

SCHLUMBERGER, C. &. M. 1928: Découverte, près de Hettenschlag, d'un deuxième dome de sel sous la plaine d'Alsace. Académie des Sciences, Paris, Comptes Rendues 186, 445-446.

SCHNÆBELÉ, R. 1948: Monographie géologique du champ pétrolifère de Pechelbronn. Service de la carte géologique d'Alsace et de Lorraine, Mémoires 7, 254 p.

SCHWEIZER, V. & KRAATZ, R. 1982: Kraichgau und südlicher Odenwald. Sammlung geol. Führer, 42, XI, 203 p, Bornträger, Berlin-Stuttgart.

SENI, S. J. &. JACKSON, M.P.A. 1983a: Evolution of salt structures, East Texas diapir province, Part 1: Sedimentary record of halokinesis. American Association of Petroleum Geologists, Bulletin 67(8), 1219-1244.

SENI, S. J. &. JACKSON, M.P.A. 1983b: Evolution of salt structures, East Texas diapir province, Part 2: Patterns and rates of halokinesis. American Association of Petroleum Geologists, Bulletin 67(8), 1245-1274.

SIAT, A. 1954: Observations pétrographiques sur les sables argileux blancs de Dambach-Epfig. Service de la carte géologique d'Alsace et de Lorraine, Bulletin 7, 81-84.

SIBSON, R.H. 1981: Fluid flow accompanying faulting: Field evidence and models. In SIMPSON D.W. & RICHARDS (eds.): Earthquake predictions: An international review. Amer. geophys. Union, Maurice Ewing Series, 4: 593-603.

SIBSON, R.H. 1990: Conditions for fault-valve behaviour. In: KNIPE R.J. & RUTTER, E.H. (eds.): Deformation mechanisms. Rheology and tectonics. Geol. Soc. (London) Spec. Publ., 54: 15-28.

SIMON, T. 1982: Zur Fazies der orbicularis-Schichten im nördlichen Baden-Württemberg und eine neue Festlegung der Grenze zum Mittleren Muschelkalk. Oberrheinischer geologischer Verein, Jahresberichte und Mitteilungen, N.F. 64, 117-133.

SITTLER, C. 1965: Le Paléogène des fossés rhénan et rhodanien. Études sédimentologiques et paléoclimatiques. Service de la carte géologique d'Alsace et de Lorraine, Mémoires 24, 392 p.

SITTLER, C. 1969: Le fossé Rhénan en Alsace. Aspect structural et histoire géologique. Rev. Géographie physique Géol. dynamique, (2) 11(5), 465-494.

SITTLER, C. 1972a: Le Sundgau, aspect géologique et structural. Sciences Géologiques (Strasbourg), Bulletin 25(2-3), 93-118.

SITTLER, C. 1972b: Le pétrole dans le Département du Haut-Rhin. Sciences Géologiques (Strasbourg), Bulletin 25(2-3), 151-161.

SITTLER, C. 1985: Les hydrocarbures d'Alsace dans le context historique et géodynamique du Fossé Rhénan. - [The case history of oil occurrence in the Rhine rift valley of Alsace]. Centre Rech.Explor.-Prod. Elf-Aquitaine, Bull., 9(2), 335-371, Pau.

SITTLER, C. 1992: Illustration de l'histoire géologique du Fossée rhénan et de l'Alsace - [Recording the Rhine Graben and Alsace history by sketched cross sections]. Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen 186(3), 255-282.

SITTLER, C. 1995: Das Erdöl im Elsass. - p. 49-69, Fig. 1-8, Tab. 1-3, in: SITTLER, C. et al. (eds): Natürliche Energiegewinnung im Unter-Elsass (Frankreich): Erdöl, Erdwärme und Wasserkraftwerke am Rhein. Jber. Mitt. oberrhein. geol. Verein, N.F. 77, 47-102

SITTLER, C. &. SCHULER, M. 1988: The description of the regional lithostratigraphy: France - The Federal Republic of Germany: The Rhine Graben. - 41-47, Fig. 10, in: VINKEN, R. (ed): The Northwest European Tertiary Basin. Geologisches Jahrbuch, A 100

TEICHMÜLLER, M. &. TEICHMÜLLER, Rolf. 1979: Zur geothermischen Geschichte des Oberrhein-Grabens. Zusammenfassung und Auswertung eines Symposiums. Fortschritte der Geologie von Rheinland und Westfalen, 27, 109-120, 4 Abb., Krefeld.

THÉOBALD, N. 1953: Le Massif du Mont Sainte Odile et ses environs. Annales Univ. saraviensis, Wiss.-Sc. 2(1-2), 3-38, Saarbrücken.

THÉOBALD, N. 1955: Description géologique du Mont National et du Bischenberg au Nord d'Obernai. Service de la carte géologique d'Alsace et de Lorraine, Bulletin, 8(1), 61-82, Strasbourg.

THÉOBALD, N. &. LAUGIER, R. 1963: Trias des abords sud du Massif Vosgien, du Jura, de la Bresse et de la périphérie du Massif Central. Bureau de recherches géologiques et minières, Mémoire 15, 66-72.

TISSOT, B.P. &. WELTE, D.H. 1978: Petroleum formation and occurrence. Springer Berlin etc.

TRUSHEIM, F. 1957: Über Halokinese und ihre Bedeutung für die strukturelle Entwicklung Norddeutschlands. Deutsche Geologische Gesellschaft, Zeitschrift 109(1), 111-158.

TRUSHEIM, F. 1960: Mechanism of salt migration in northern Germany. American Association of Petroleum Geologists, Bulletin 44(9), 1519-1540.

VILLEMIN, T., ALVAREZ, F. & ANGELIER, J. 1986: The Rhinegraben: Extension, subsidence and shoulder uplift. Tectonophysics 128(1/2), 47-59.

VINKEN, R. (compilator) 1988: The northwest European Tertiary Basin. Geol. Jahrbuch A100, 7-508.

VONDERSCHMITT, L. 1942: Die geologischen Ergebnisse der Bohrungen von Hirtzbach bei Altkirch (Ober-Elsass). Eclogae geol. Helv. 35, 67-99.

WAGNER, G. A. 1976: Spaltspurendatierung an Apatit und Titanit aus den Subvulkaniten des Kaiserstuhls. - [Fission track dating on apatite and sphene from the subvolcanics of the Kaiserstuhl (Germany)]. Neues Jahrbuch für Mineralogie, Monatshefte 1976(9), 389-393.

WAGNER, W. 1955: Die tertiären Salzlagerstätten im Oberrheintal-Graben. Deutsche Geologische Gesellschaft, Zeitschrift 105 (1953)(4), 706-728.

WALGENWITZ, F. &. MAGET, PH.; TIETZE, R. & NEEB, I. 1979: Synthèse géothermique du Fossé Rhénan Supérieur (état des connaissances). Geothermische Synthese des Oberrheingrabens (Bestandsaufnahme). BRGM, Serv. géol. régional (Alsace)/Geol. L.A. Baden-Württemberg/Comm. Europ. Community, Dir. Gen. Res. Sc. Educ; Programme on geothermal energy, 51 p., 4 Annex., 23 Encl., Strasbourg/Freiburg i.Br.

WERVEKE, L. v. 1913: Bitumenvorkommen in mesozoischen Schichten des Rheintals. Geologische Landesanstalt von Elsaß-Lothringen, Mitteilungen 8(1), 95-100.

WIMMENAUER, W. 1951: Neue Mineralfunde vom Kaiserstuhl. Bad. geol. Landesanstalt, Mitteilungsblatt 1950, 20-22, Freiburg i.Br.

WIRTH, E. 1962: Die geologischen Ergebnisse der Erdölexploration in der Rheinebene zwischen Offenburg und Lahr. Erdöl und Kohle 15 (9): 684-692.

WITTMANN, O. 1952: Erläuterungen zu Blatt Lörrach (Nr. 152) und Blatt Weil (Deutscher Anteil; Nr. 164). - 163 p., Geol. Spezialkarte von Baden 1 : 25'000 (Bad. geol. Landesanstalt - ed.), Freiburg i.Br.

ZIEGLER, P. A. 1982: Geological atlas of western and central Europe. Shell Internationale Petroleum Mij. B.V., The Hague.