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)

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Kapitel: 3: Interpretation of seismic and well data (by area)

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

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

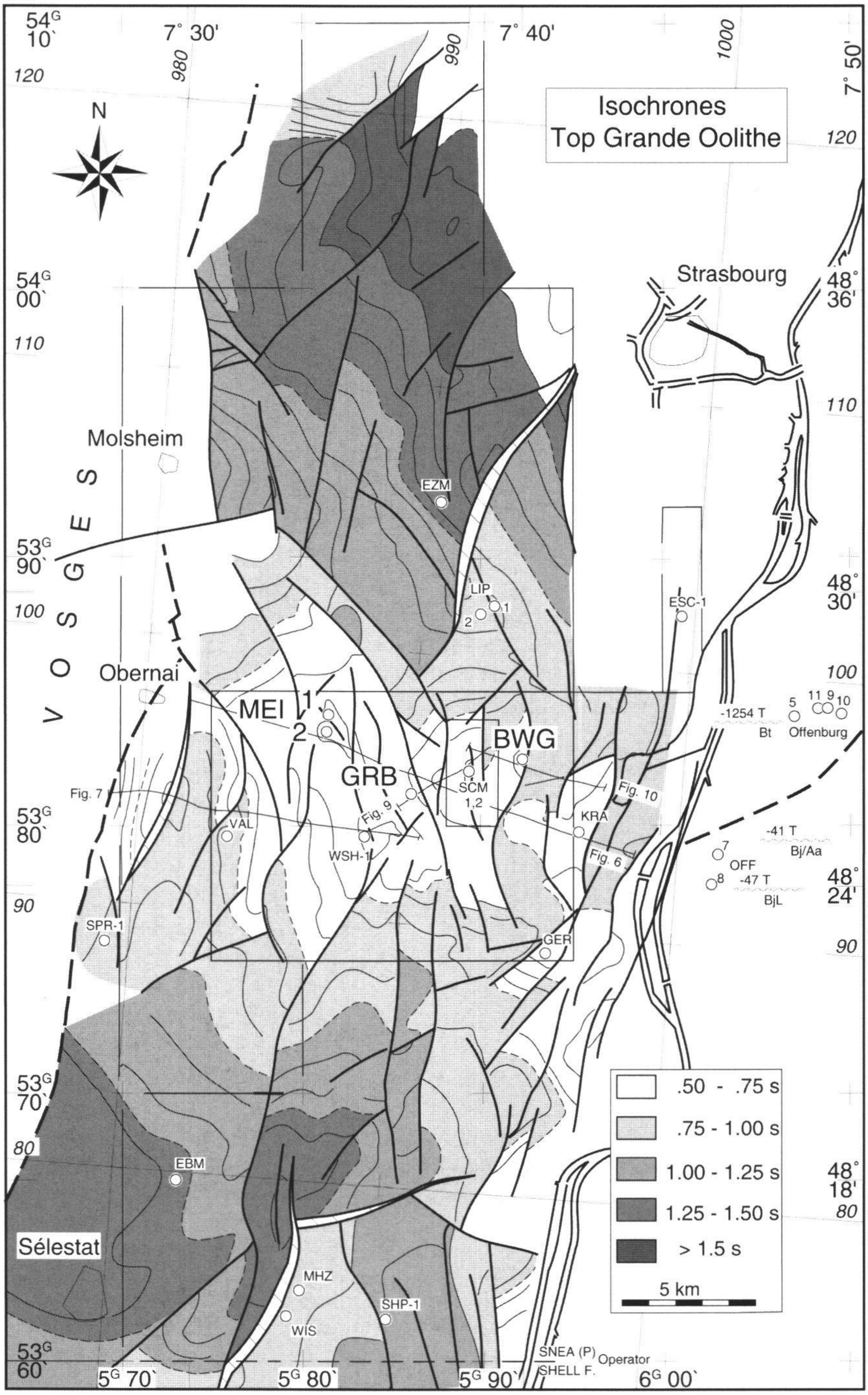


Fig. 5: Strasbourg-Séléstat area: Isochrones top Grande Oolithe. Note: the geographical coordinates indicated on the margins of Figs. 5, 12, 20, 21, delimit the sheets of the official French maps 1/50'000 (G), and German maps 1/25'000 (0). Wells: EBM Ebersheim, EZM Entzheim.

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.

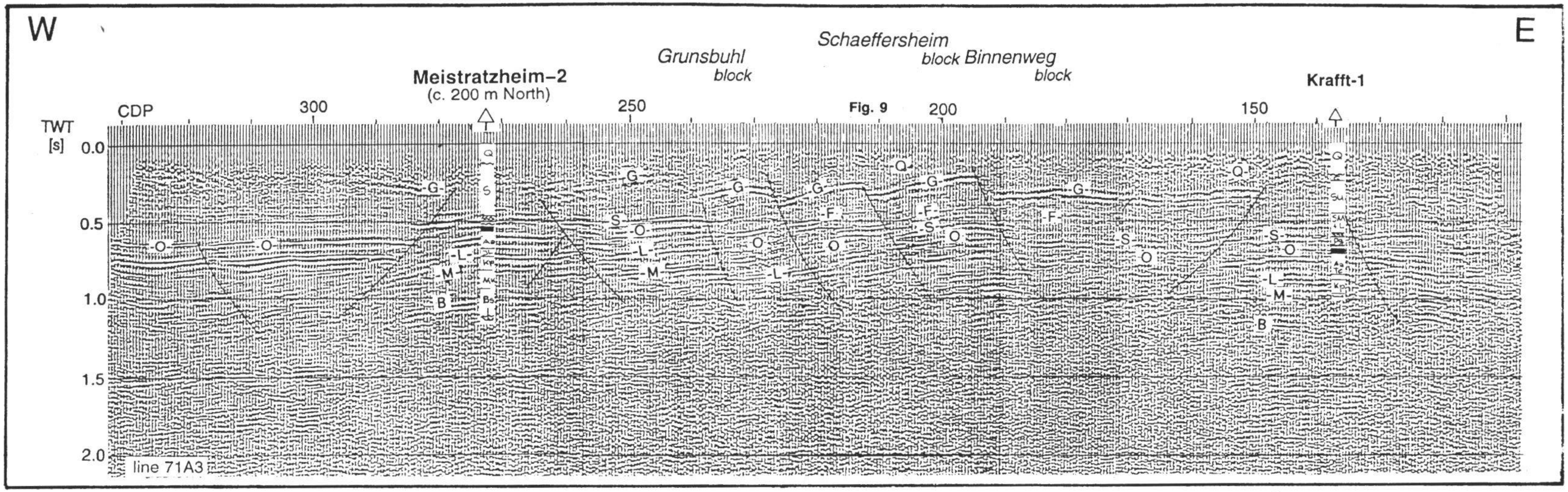


Fig. 6: Seismic W-E section Meistratzheim - Krafft; location on Fig. 5; for abbreviations of reflexions and stratigraphic units, see listing before main text.

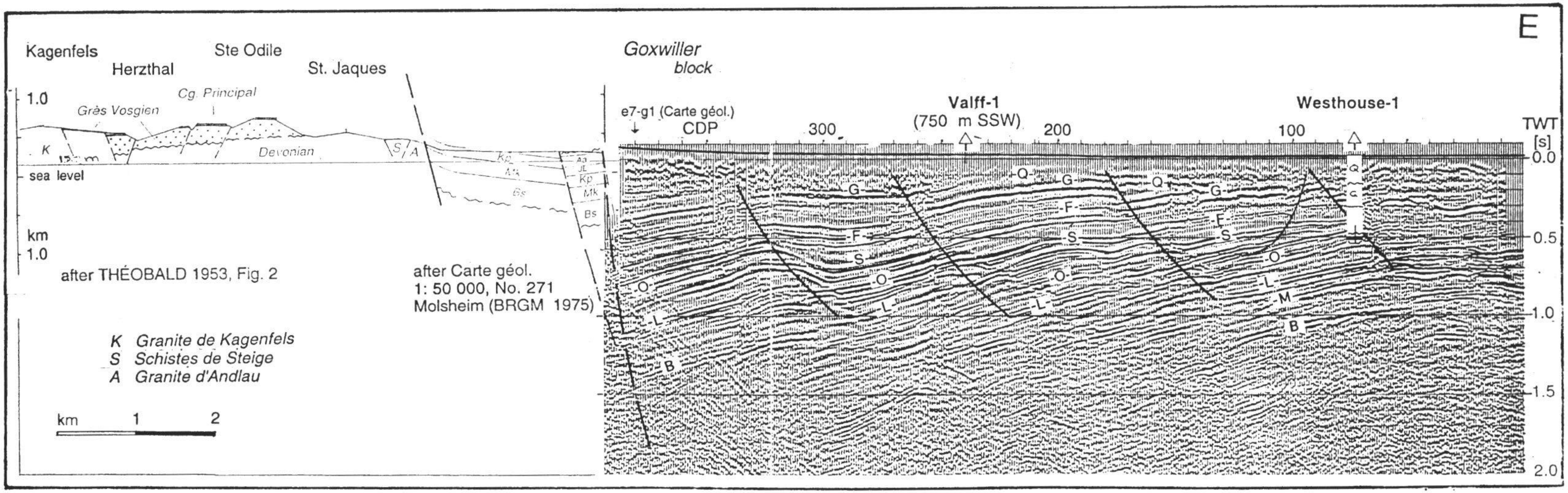


Fig. 7: Geol.- seismic W-E section Ste-Odile - Westhouse; location on Fig. 5.

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

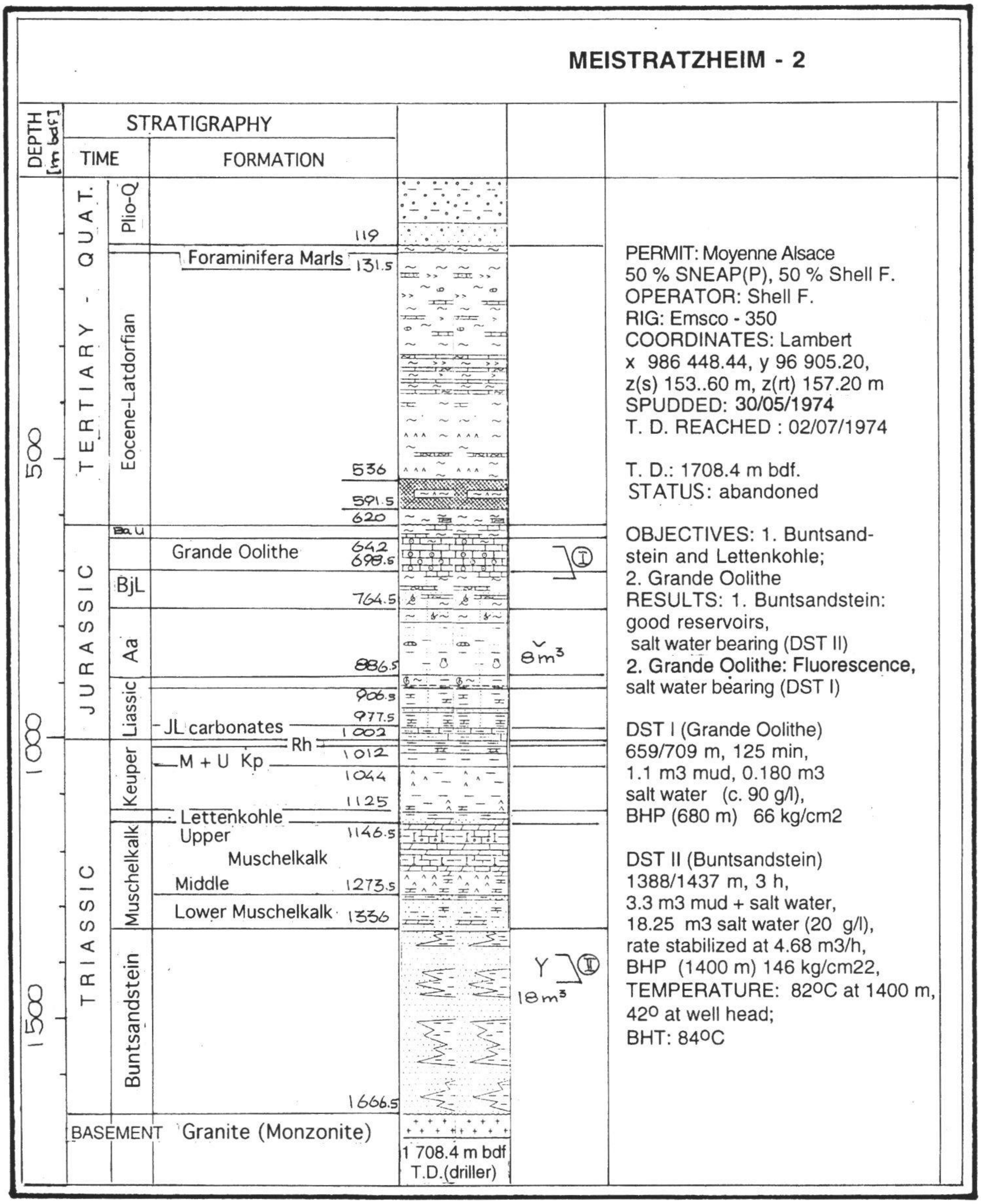


Fig. 8: Meistratzheim-2: Well summary; well location on Fig. 5.

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,

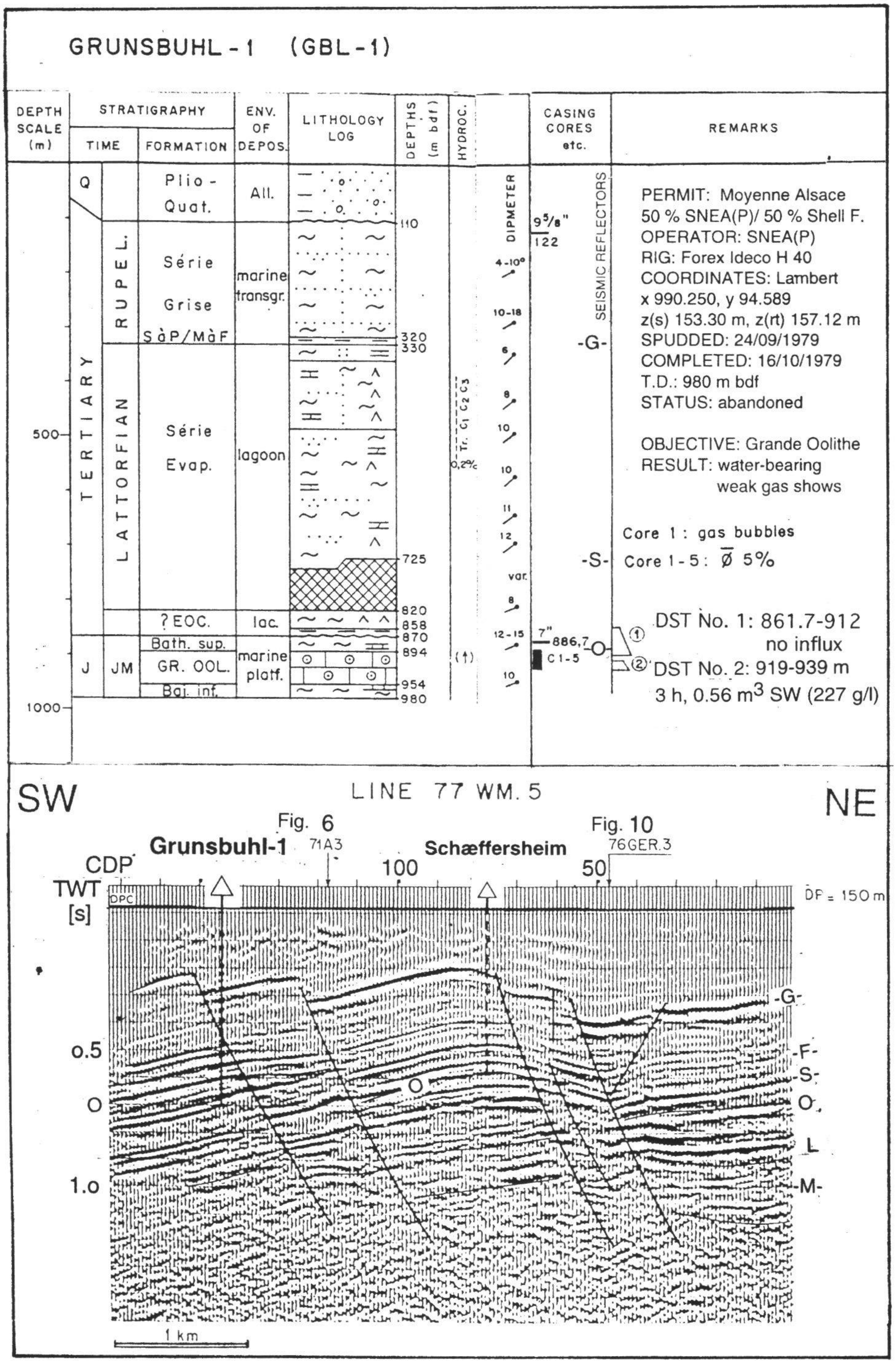


Fig. 9: Grunsbuhl-1: Well summary (with a seismic section); location of well and seismic section on Fig. 5.

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).

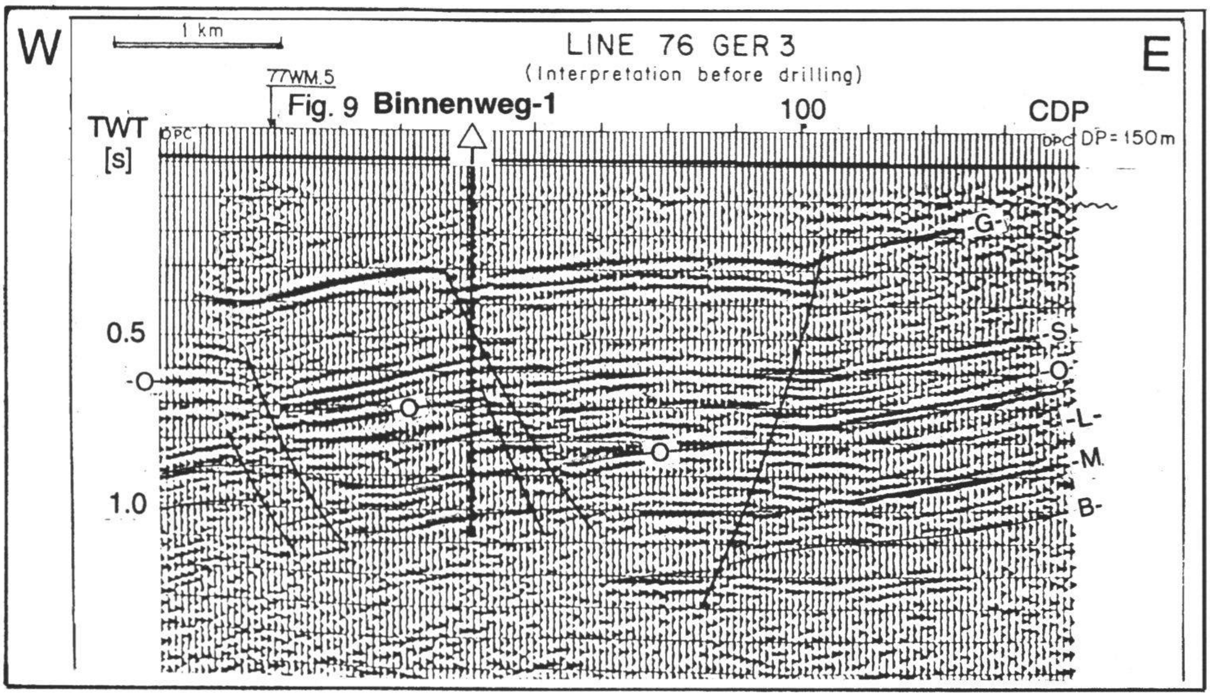


Fig. 10: Seismic section through well Binnenweg-1; location on Fig. 5.

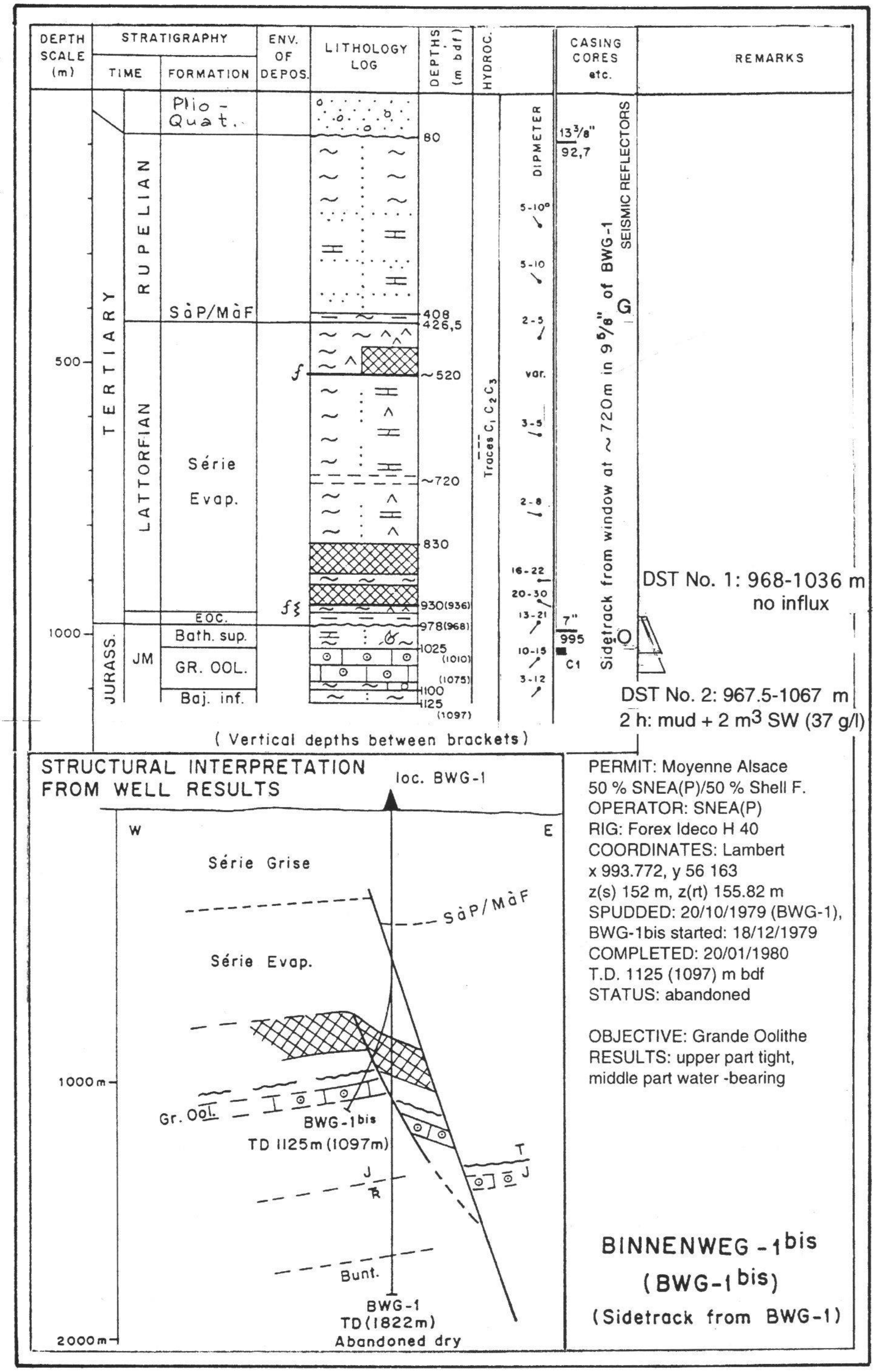


Fig. 11: Binnenweg-1 and -1bis: well summary; well location on Fig. 5.

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.

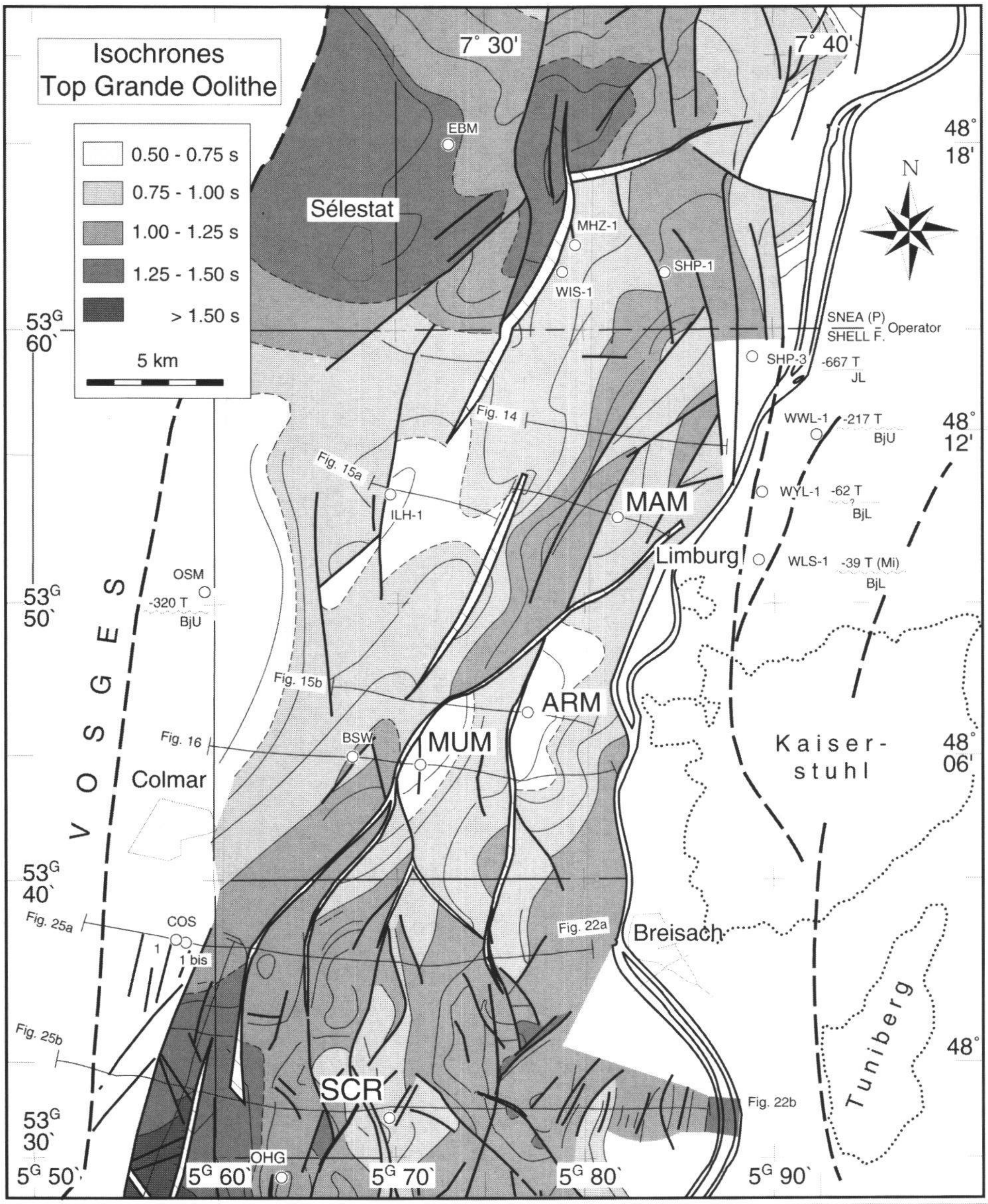


Fig. 12: Séléstat - Colmar area: Isochrones top Grande Oolithe.

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

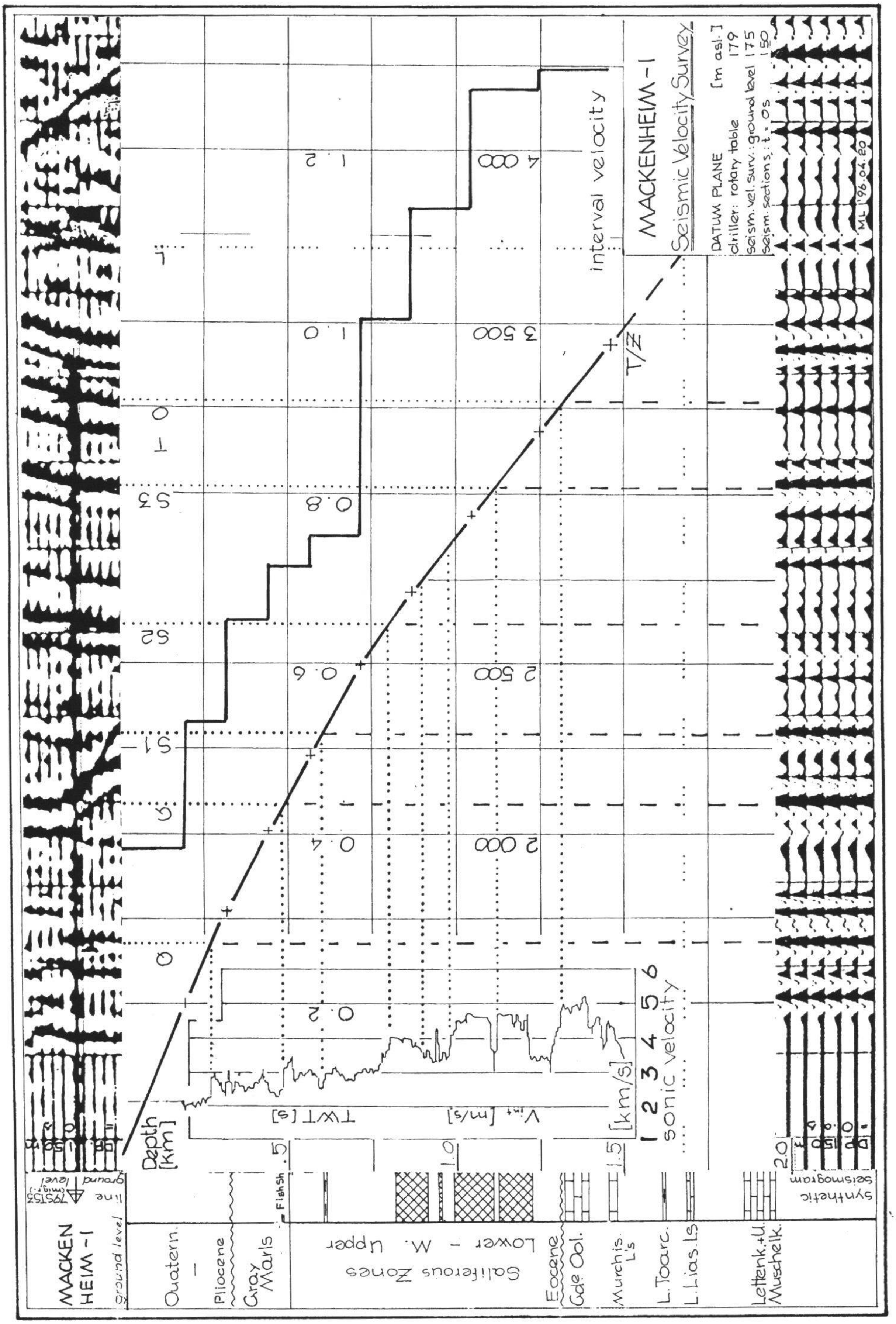


Fig. 13: Mackenheim-1: Well velocity survey, with synthetic seismogram and part of seismic line 79STS3 at well location (Fig. 15a).

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 Sélestat 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

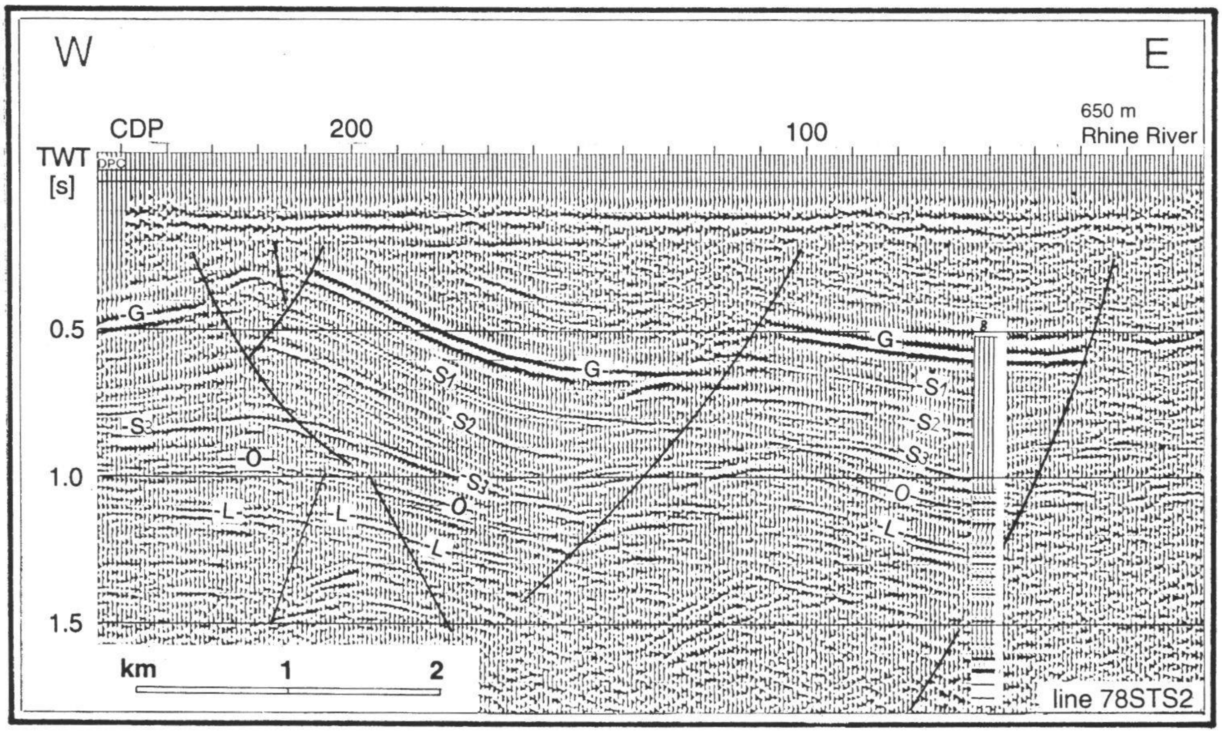


Fig. 14: Seismic W-E section N of Mackenheim, just S of a line connecting Artolsheim (F) and Weisweil (D); below CDP 60, synthetic seismogram of the Mesozoic of well MEI-2 used for reflexion identification; location of section on Fig. 12.

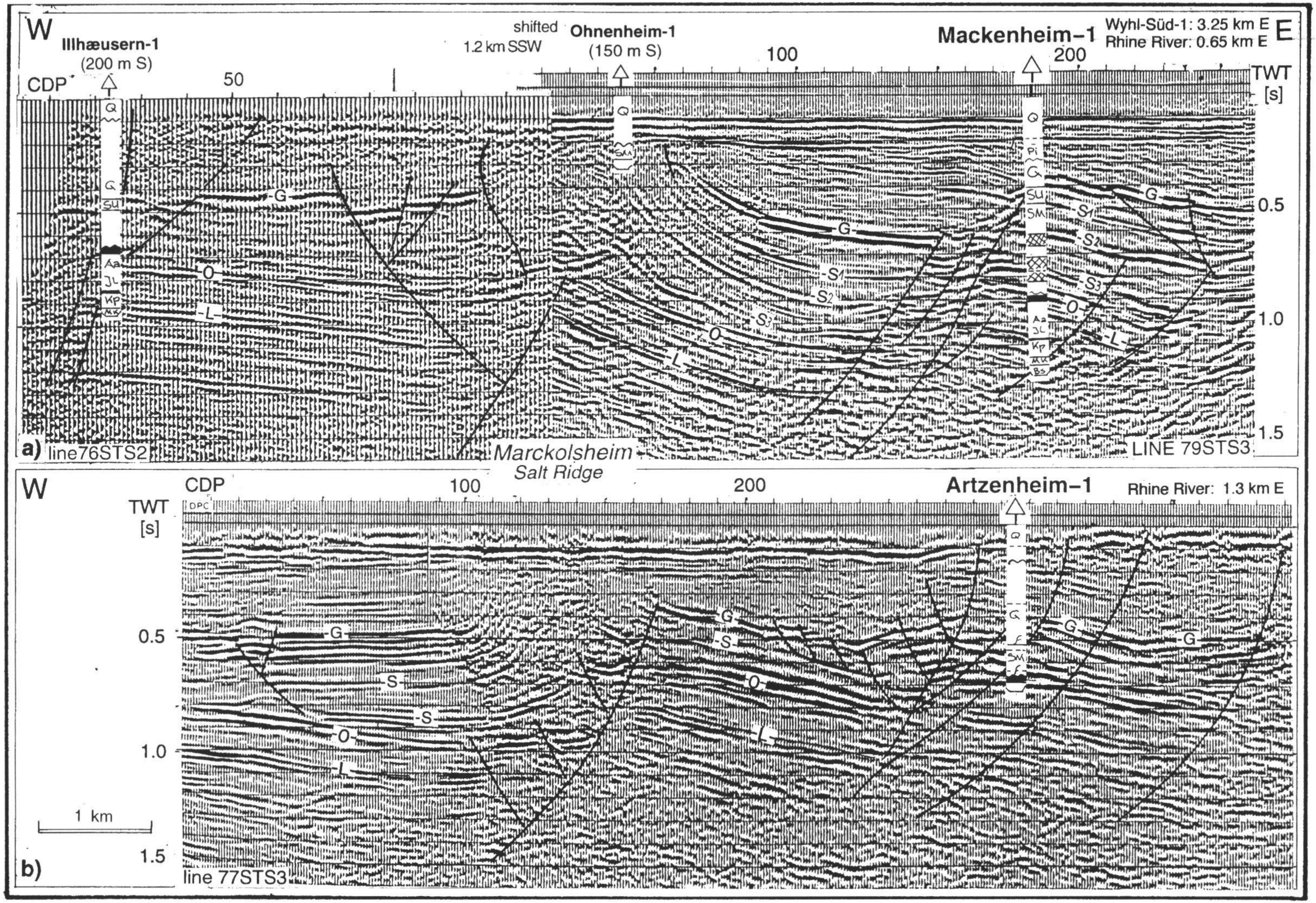


Fig. 15: **a)** Seismic W-E section through Illhæusern and Mackenheim-1;
b) seismic W-E section through Artzenheim-1; location of sections on Fig. 12.

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.

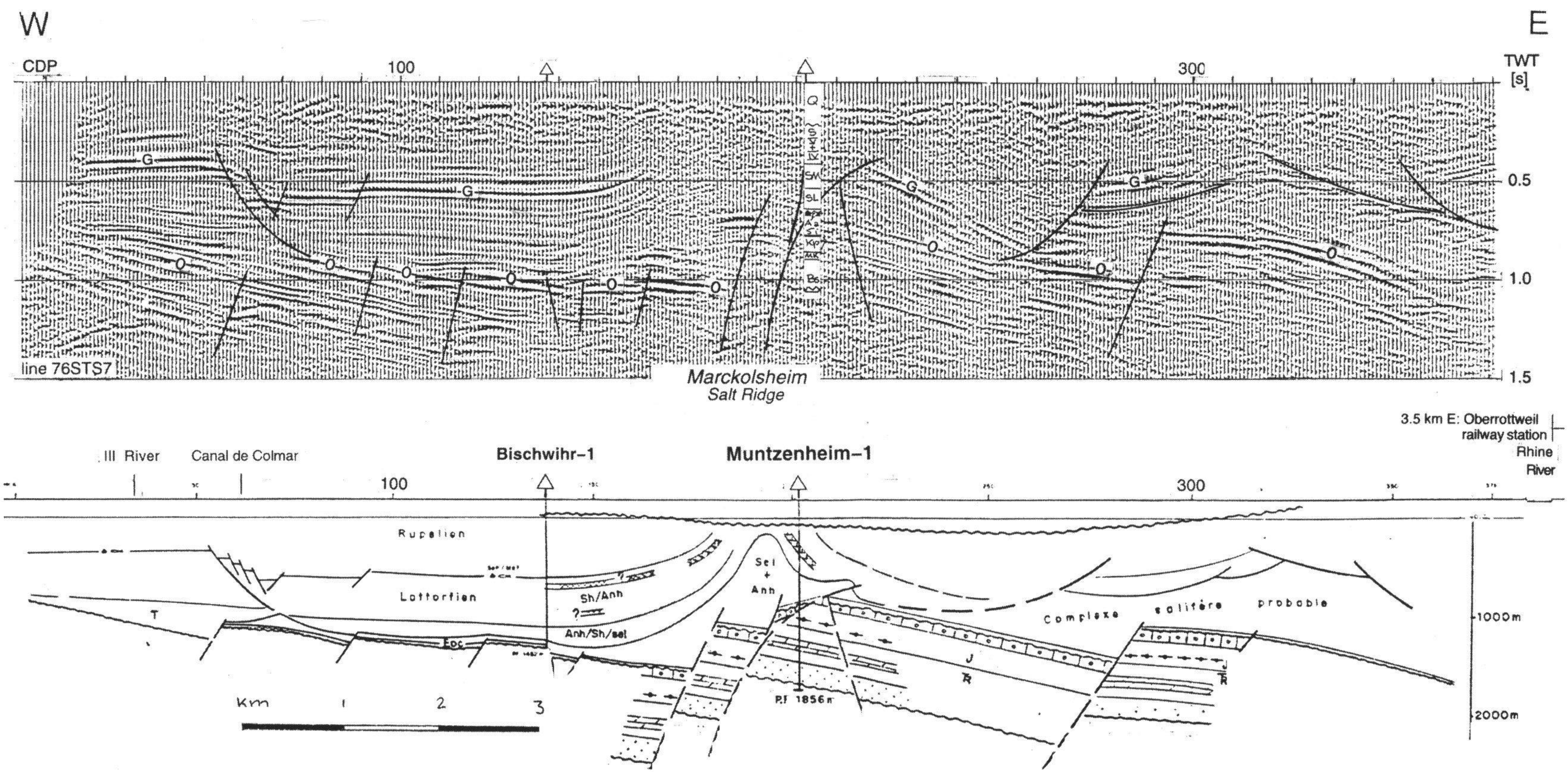


Fig. 16: **a)** Seismic W-E section through Muntzenheim-1;
b) interpreted geological section; location on Fig. 12.

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“.

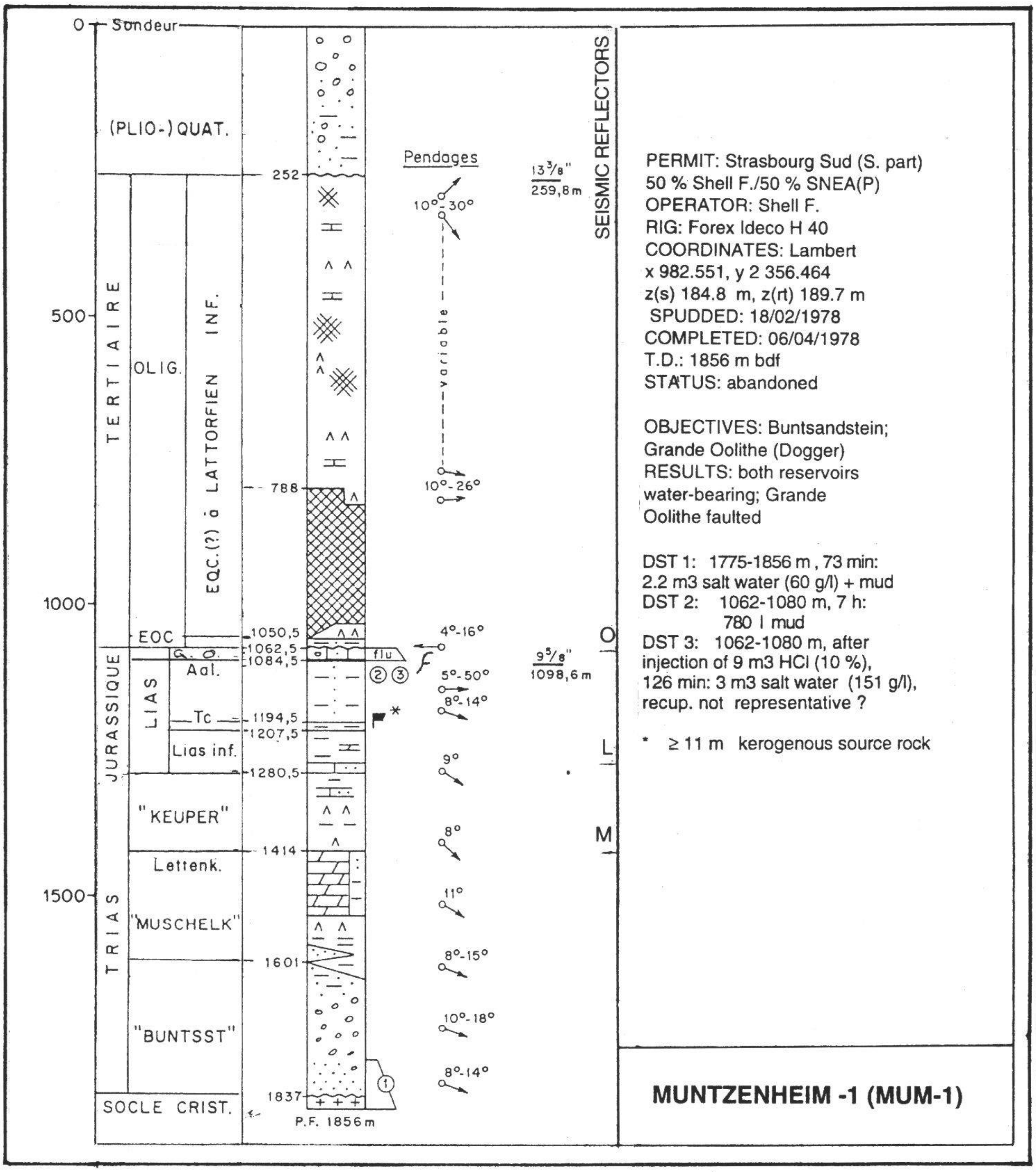


Fig. 17: Muntzenheim-1: Well summary; well location on Fig. 12.

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

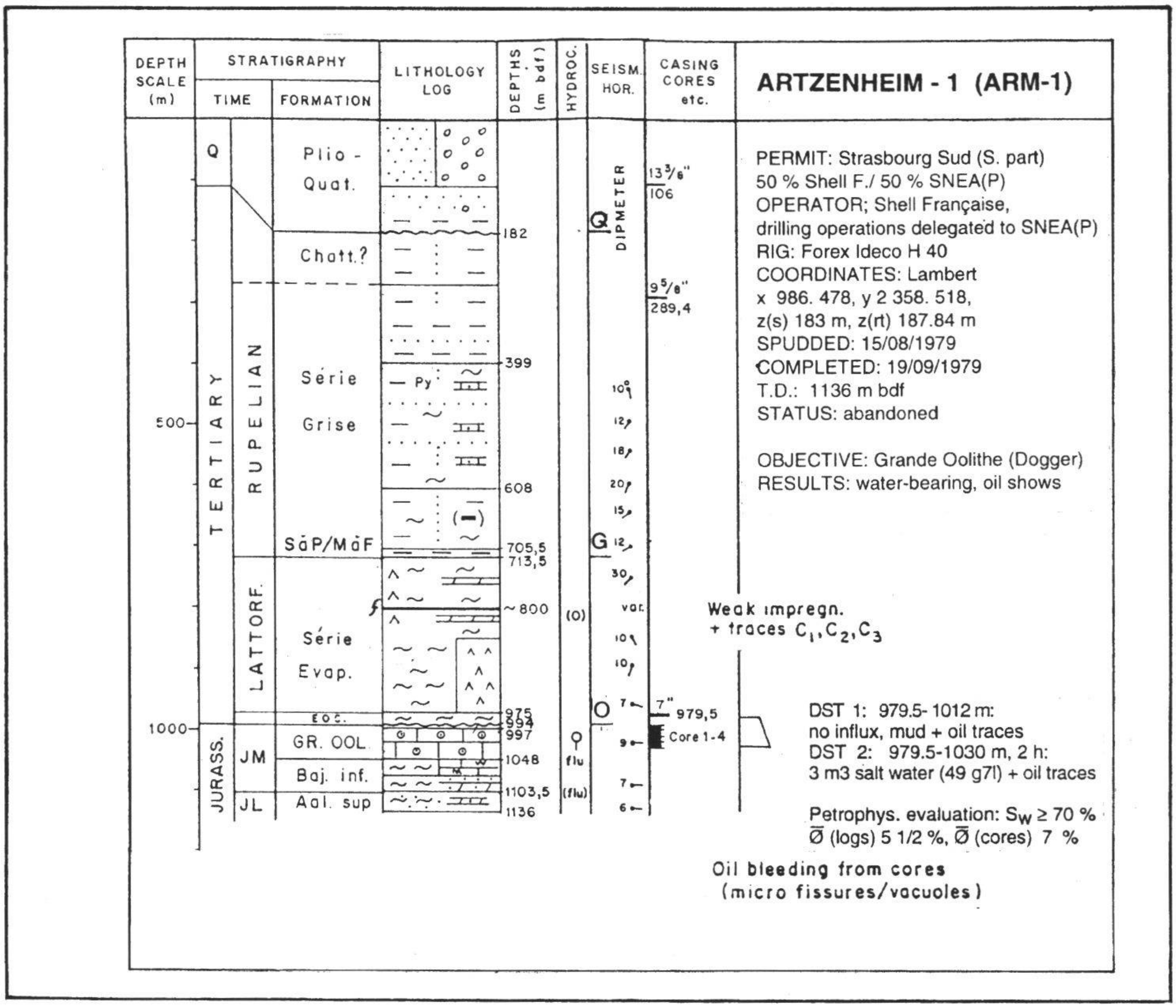


Fig. 18: Artzenheim-1: Well summary; well location on Fig. 12.

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.

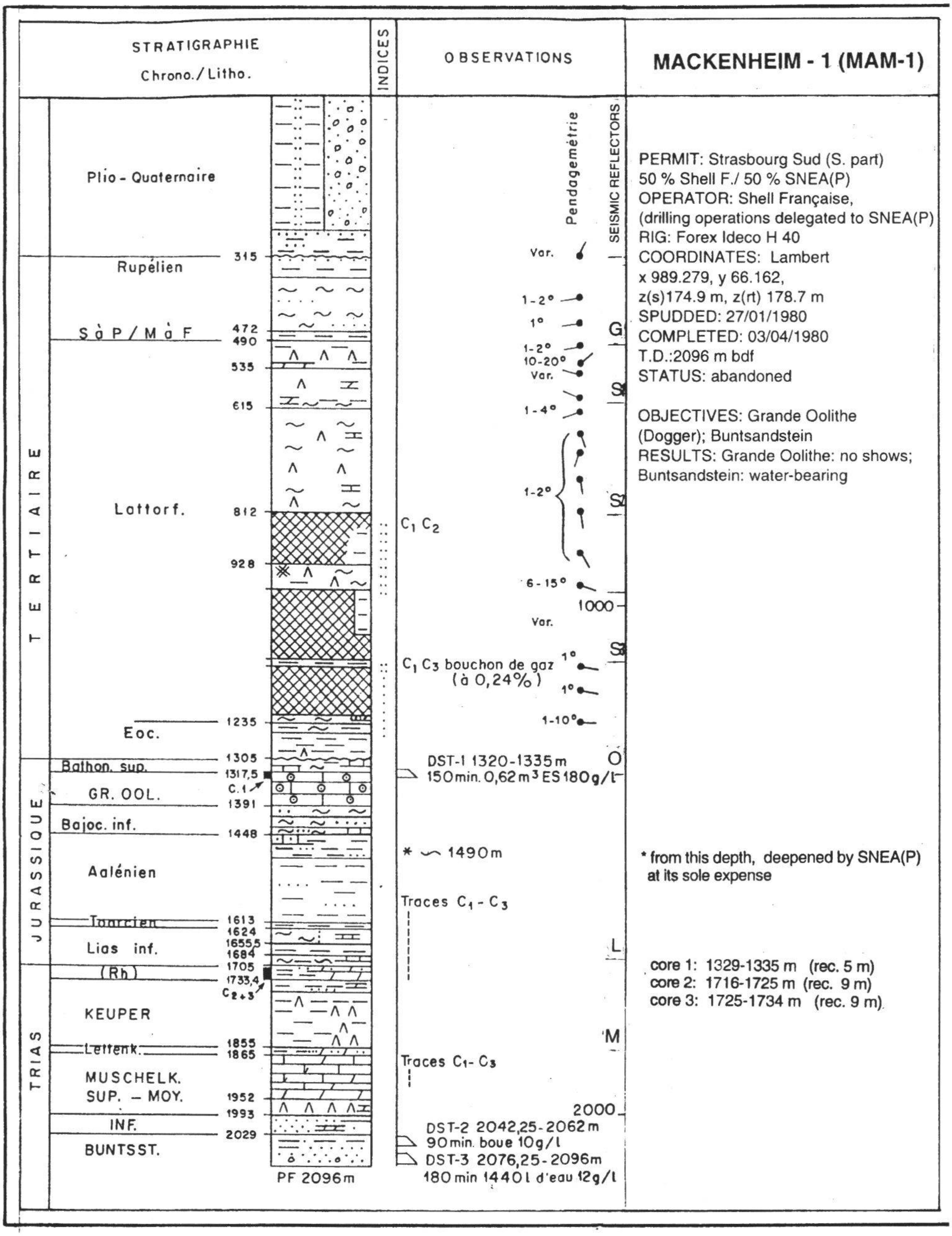


Fig. 19: Mackenheim-1: Well summary; well location on Fig. 12.

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-

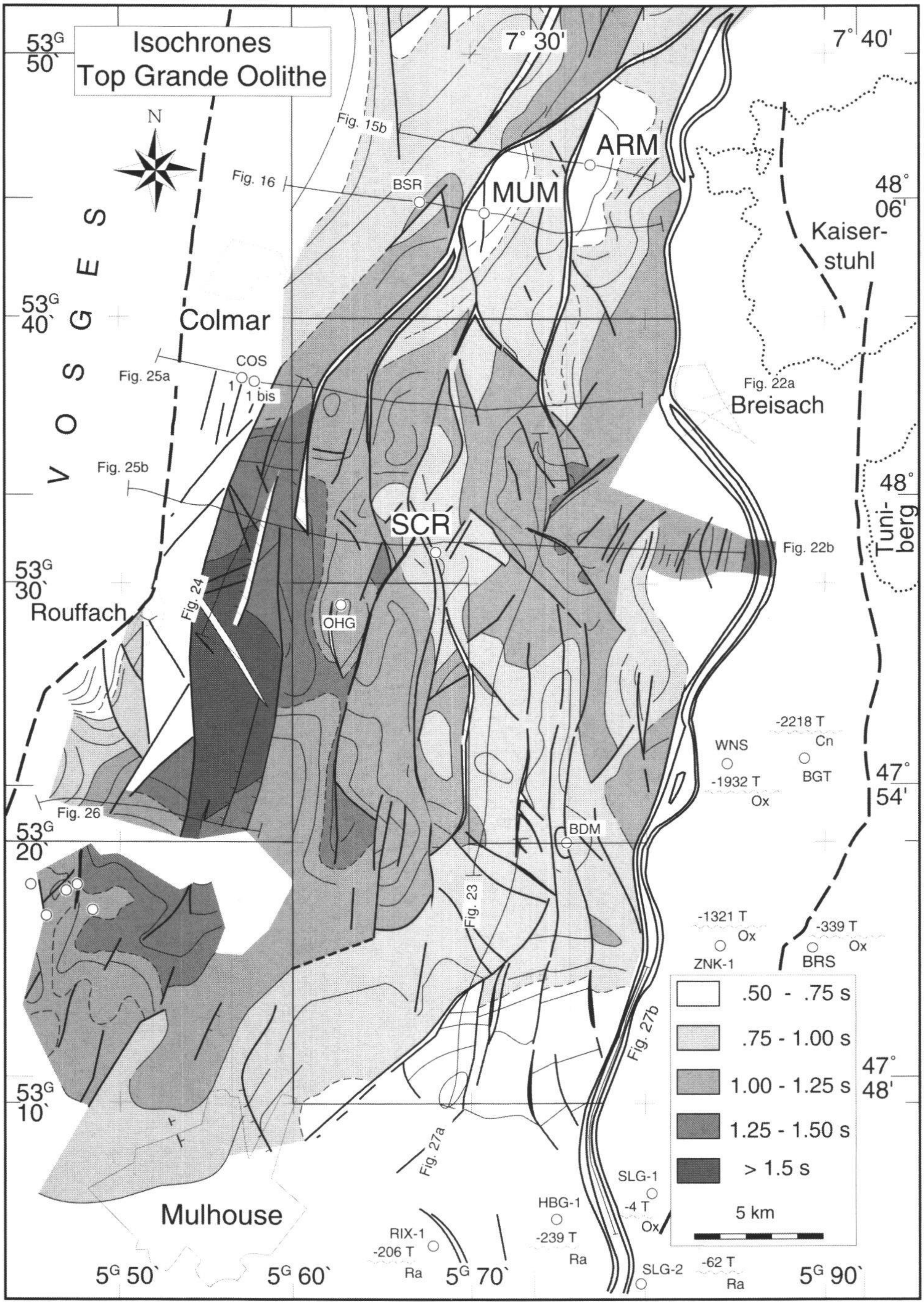


Fig. 20: Colmar - Mulhouse area: Isochrones base Tertiary/top Grande Oolithe.

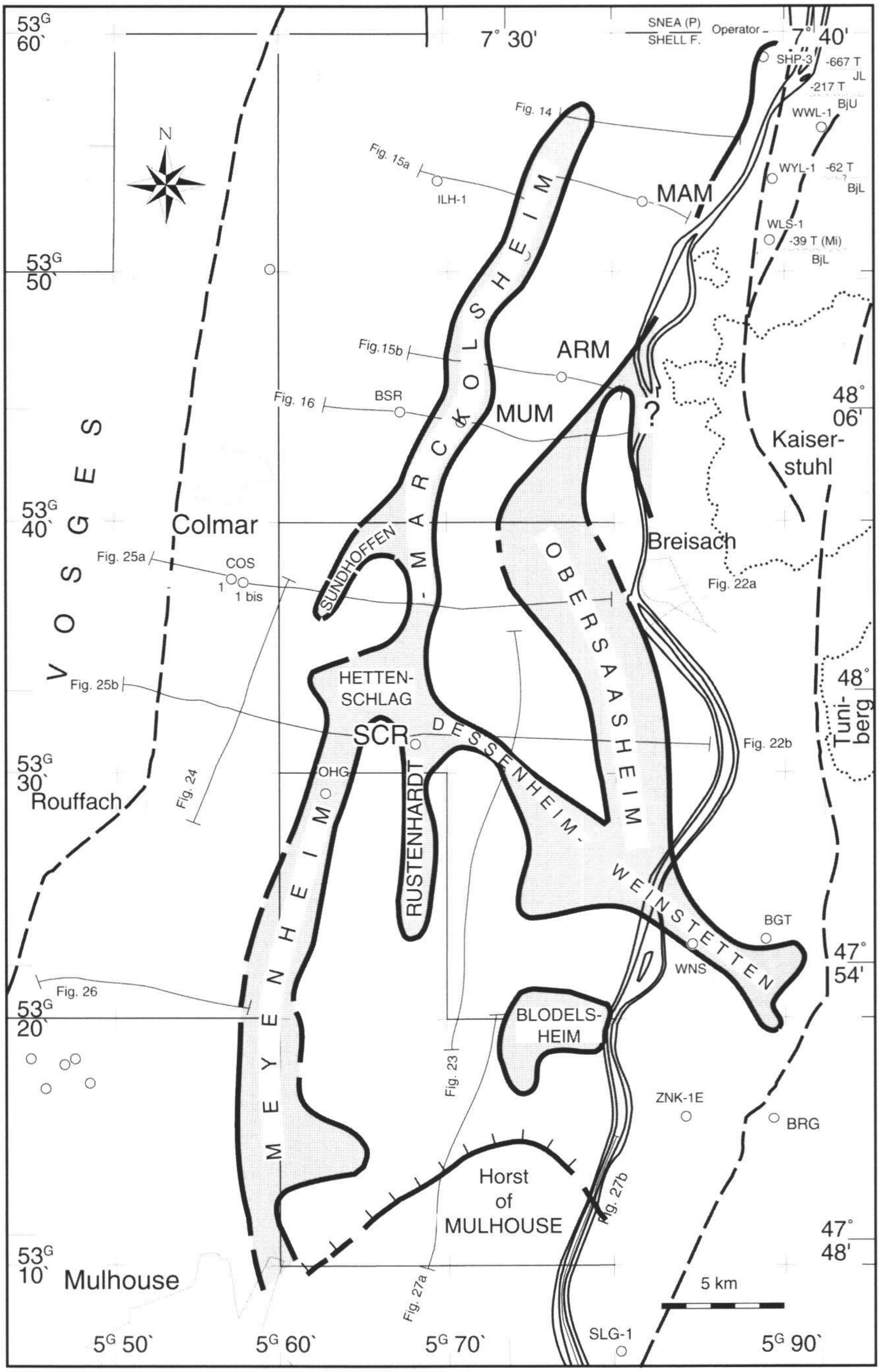


Fig. 21: Colmar - Mulhouse area: Subcrop of the Tertiary salt ridges and domes below the Plio- Pleistocene unconformity

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

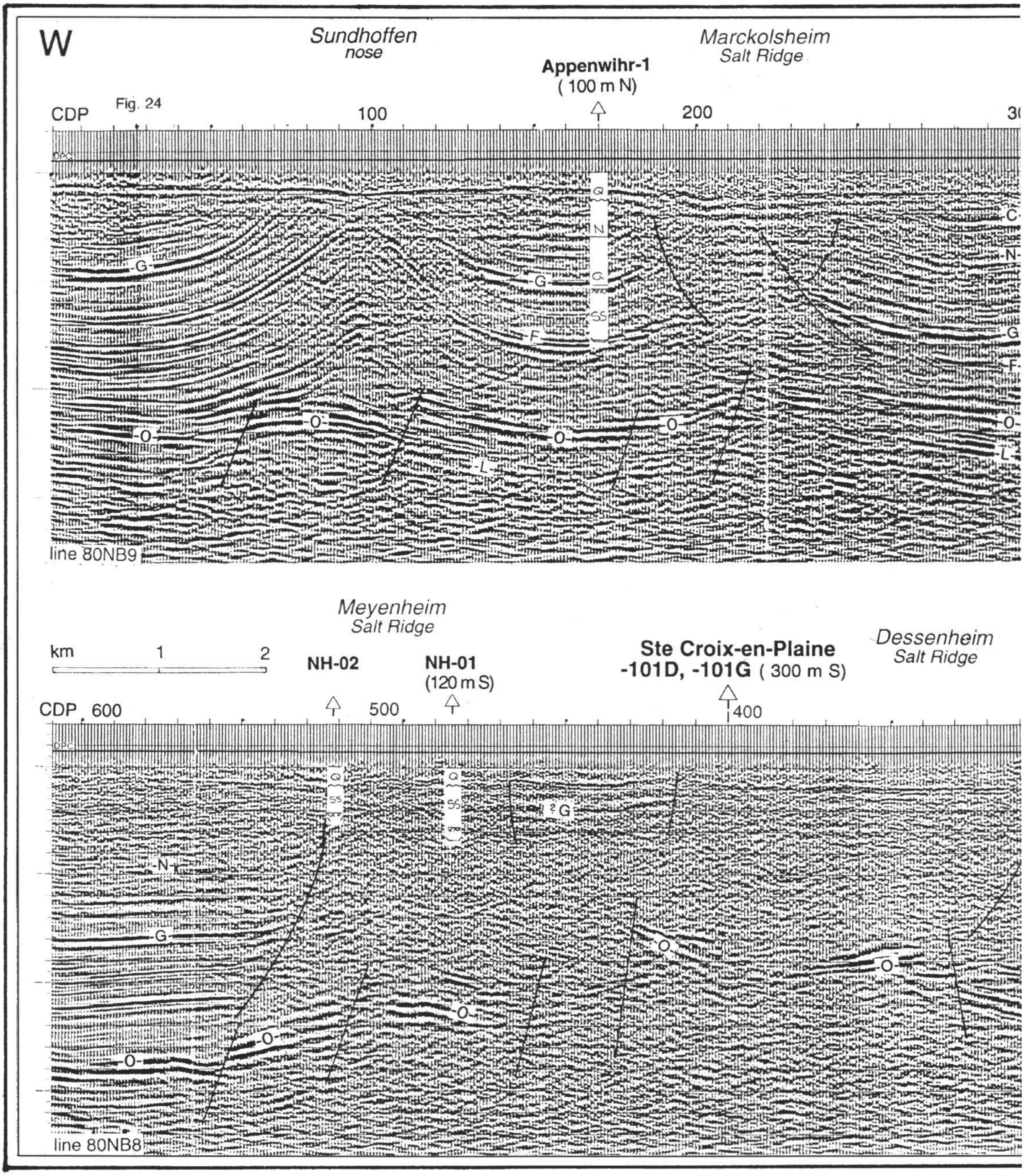
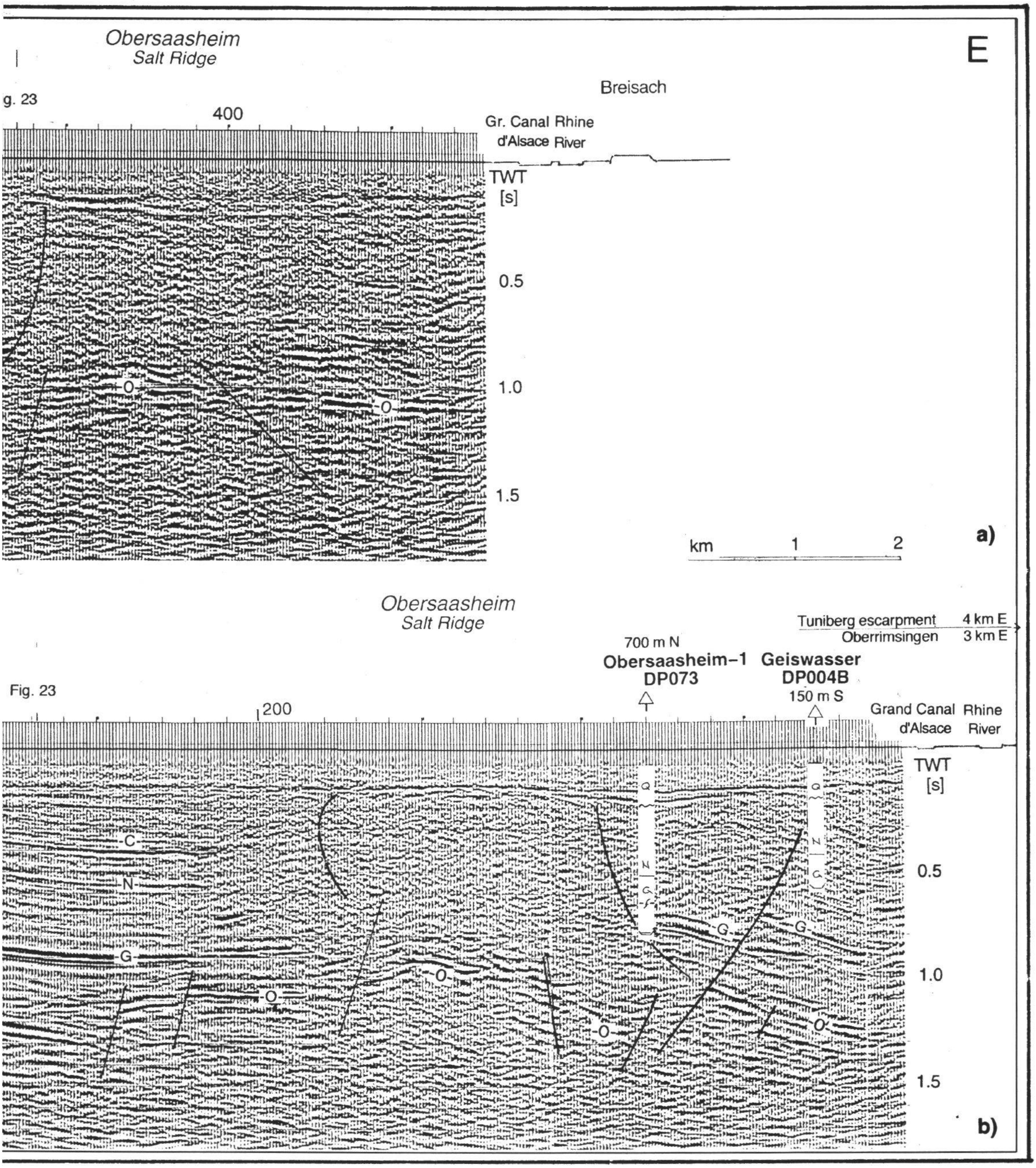


Fig. 22: **a)** Seismic W-E section Sundhoffen - N of Neuf-Brisach;
b) Seismic W-E section through Ste-Croix-en-Plaine-101 to Geiswasser; location of sections on Figs. 20 and


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

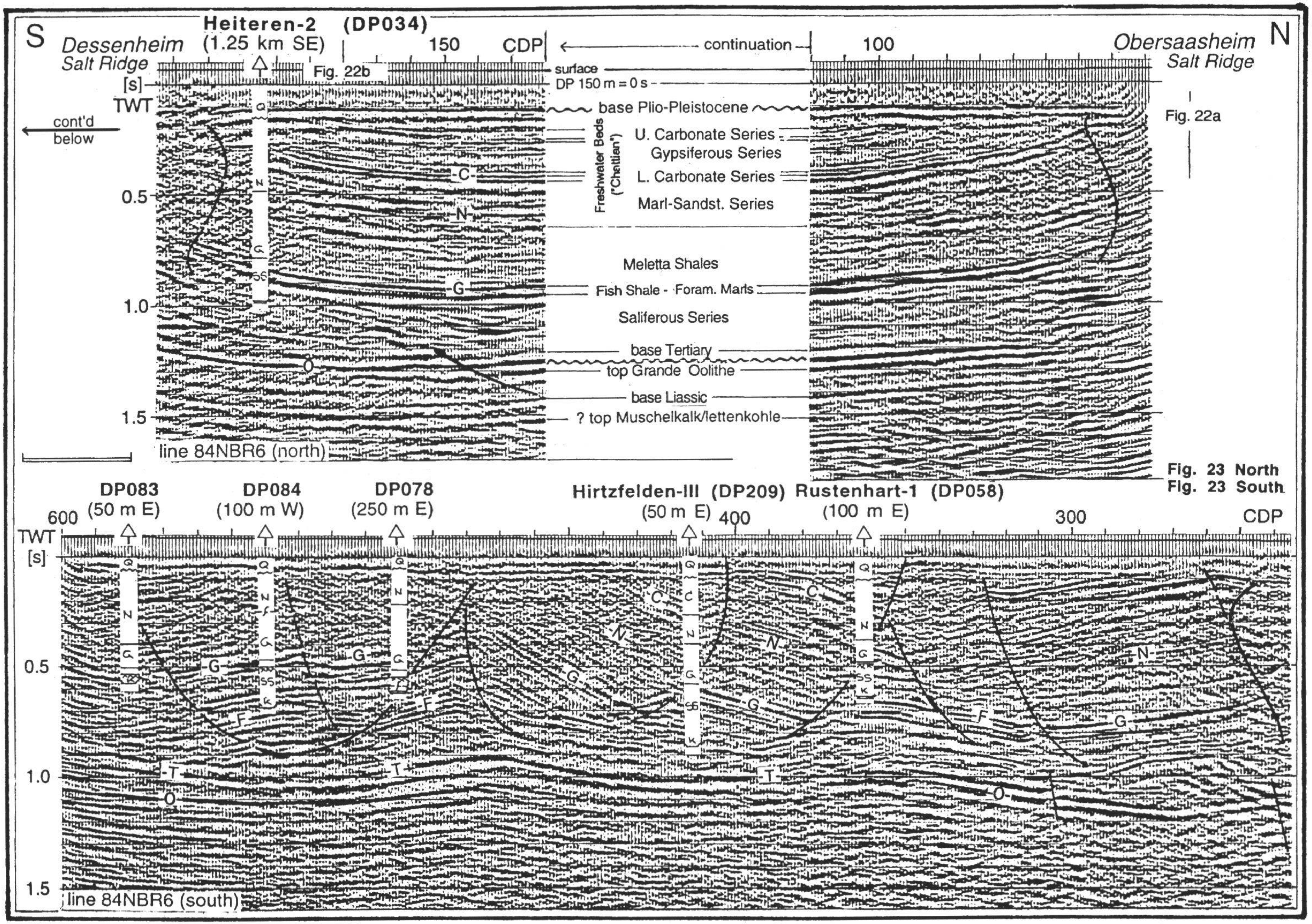

Fig. 23: Seismic N-S section from the Obersaasheim Salt Ridge through wells Rustenhart and Hirtzfelden III; location on Figs. 20, 21.

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.

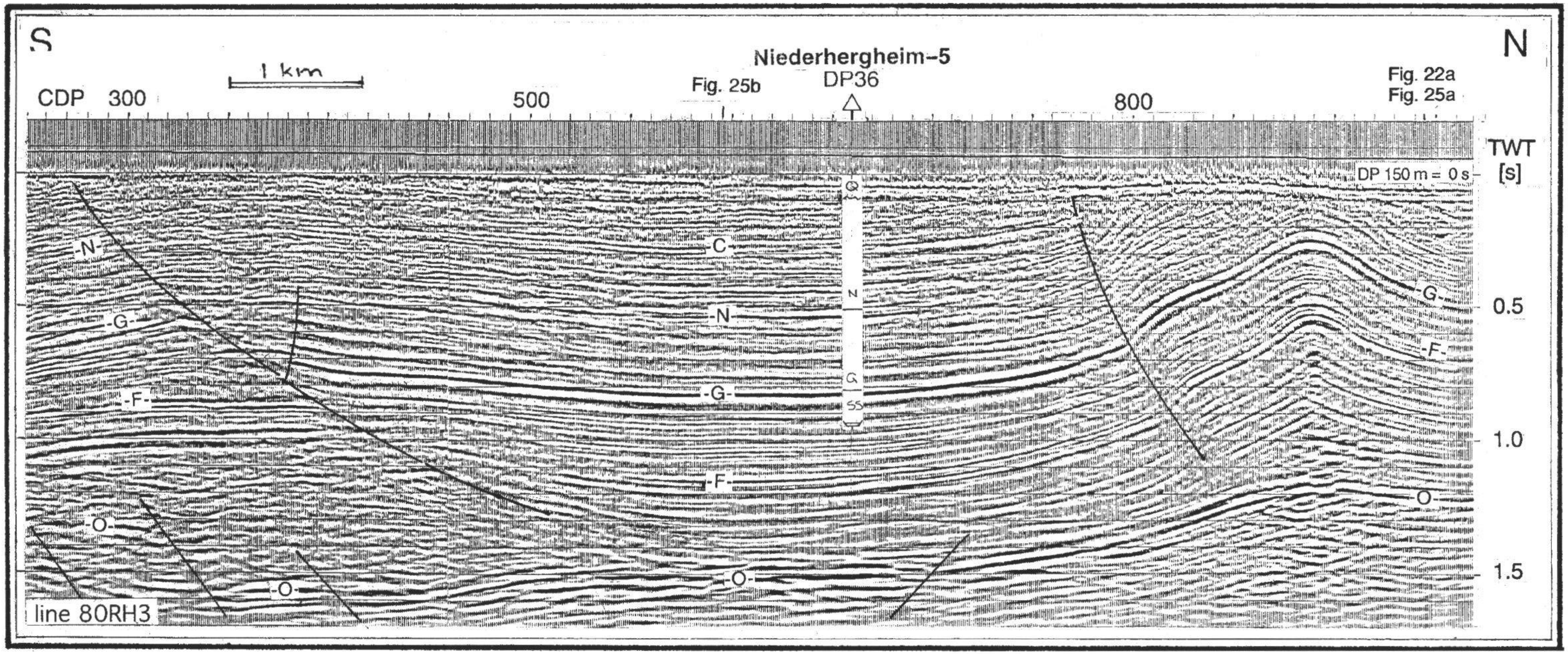

Fig. 24: Seismic N-S section through the well Niederhergheim-5; location on Figs. 20, 21.

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.

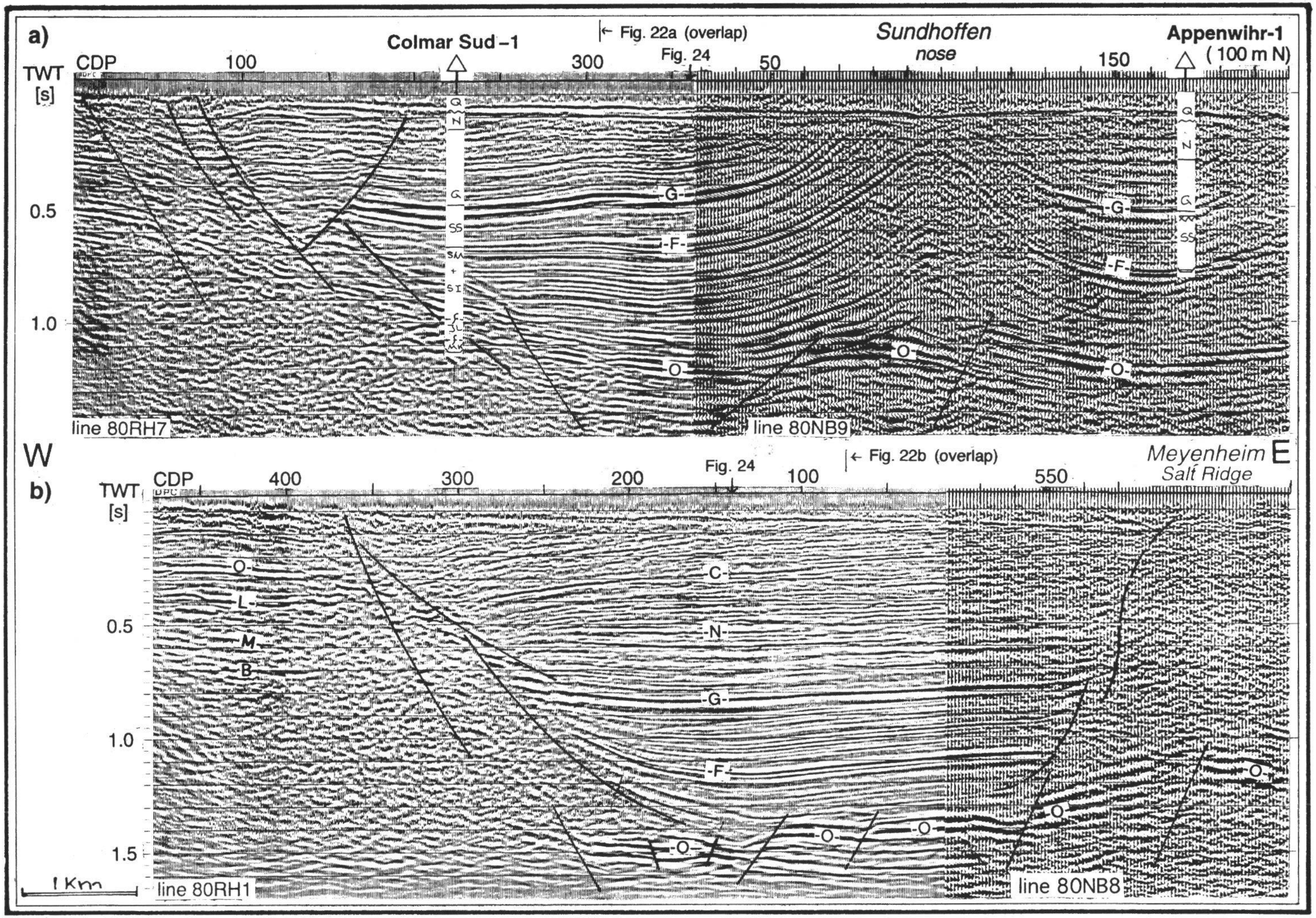

Fig. 25: Seismic W-E sections at the western Graben margin:
a) through the well Colmar-South, continuation of Fig. 22a;
b) 5 km South of a), continuation of Fig. 22b; location of sections on Figs. 20, 21.

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

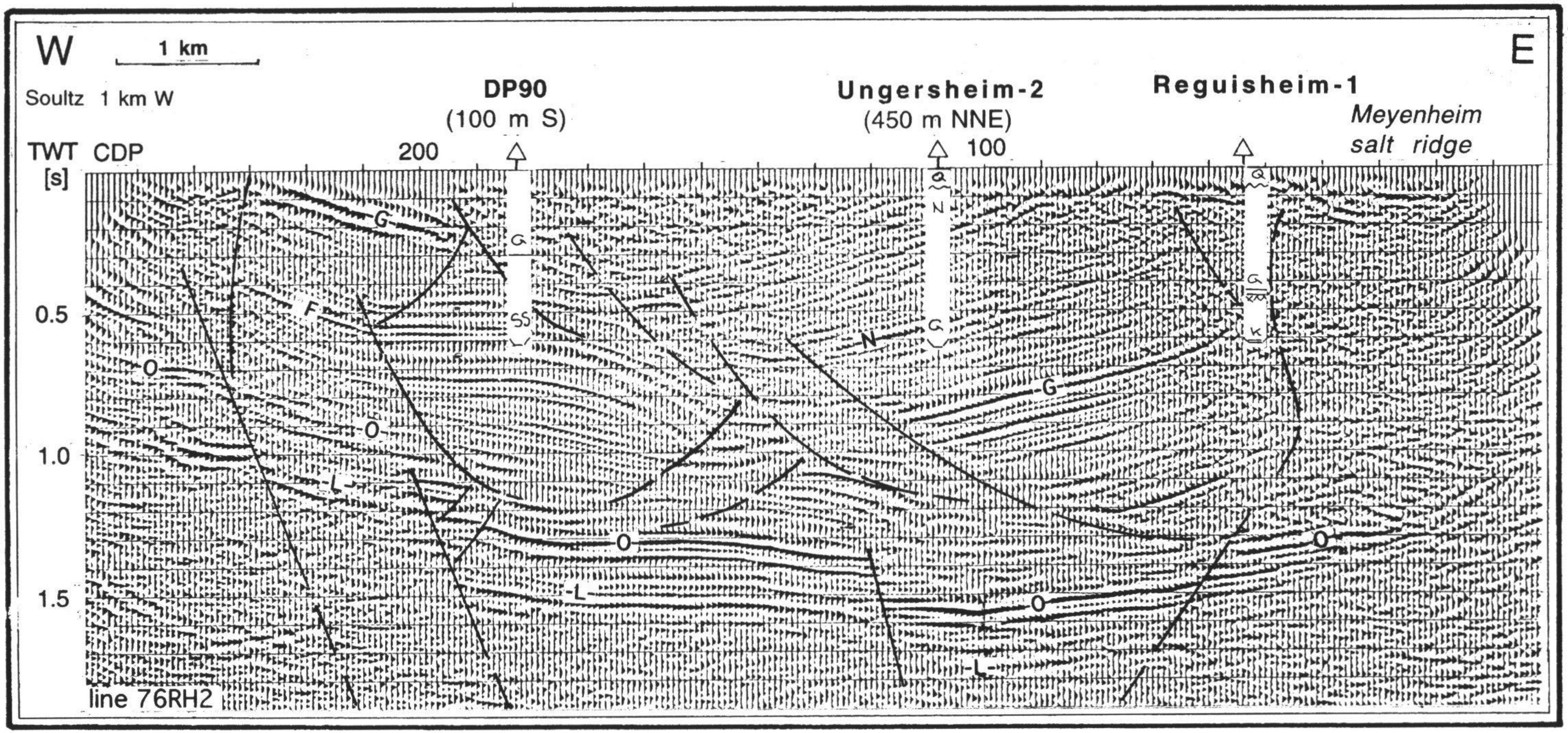

Fig. 26: Seismic W-E section E of Soultz (Ht. Rhin). location on Figs. 20, 21.

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

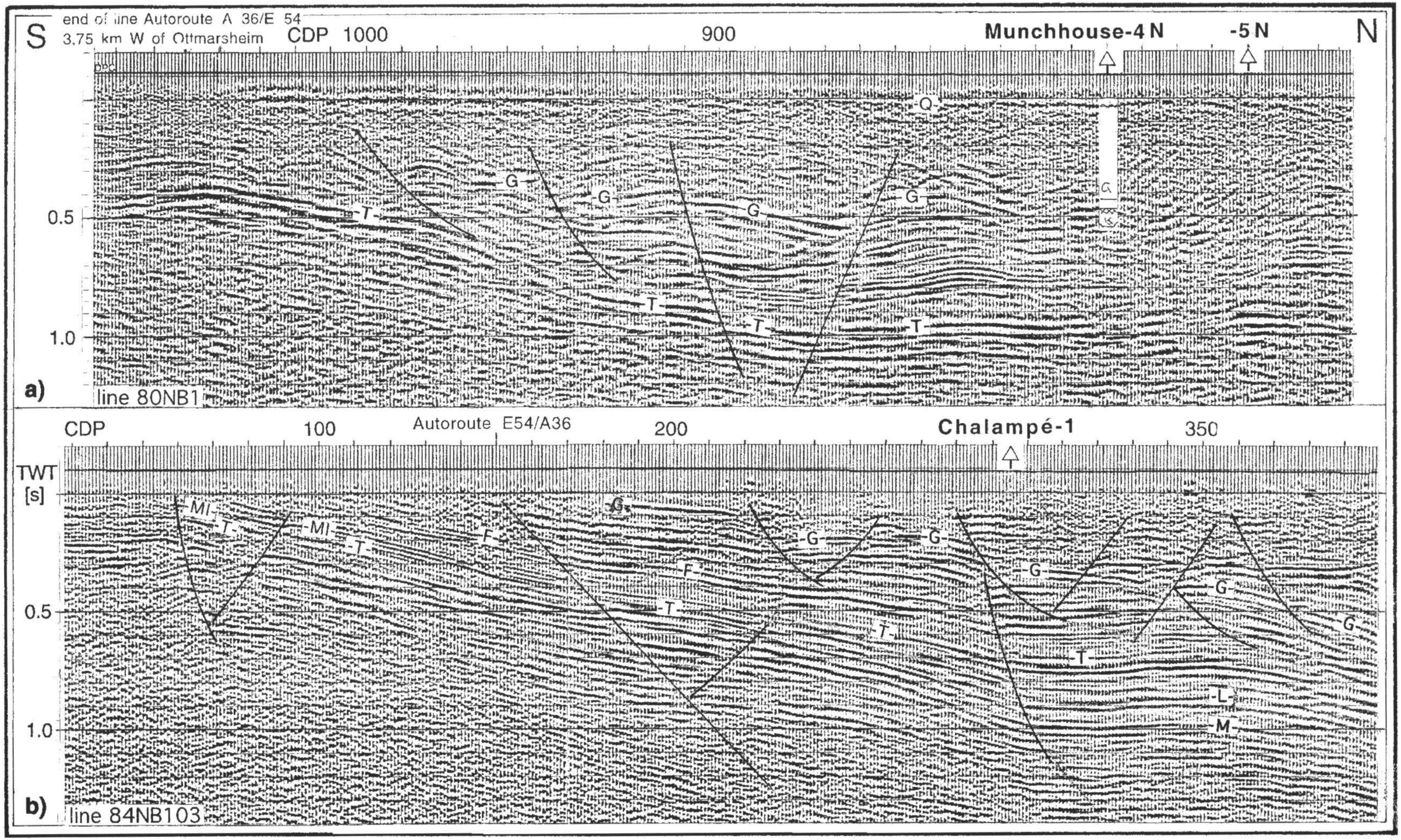

Fig. 27: Seismic N-S sections from Salt Basin to Mulhouse Horst:
a) W of Blodelsheim and Ottmarsheim.
b) from Chalampé southward along the Rhine River; location of sections on Figs. 20, 21.
MI = near Melania limestone

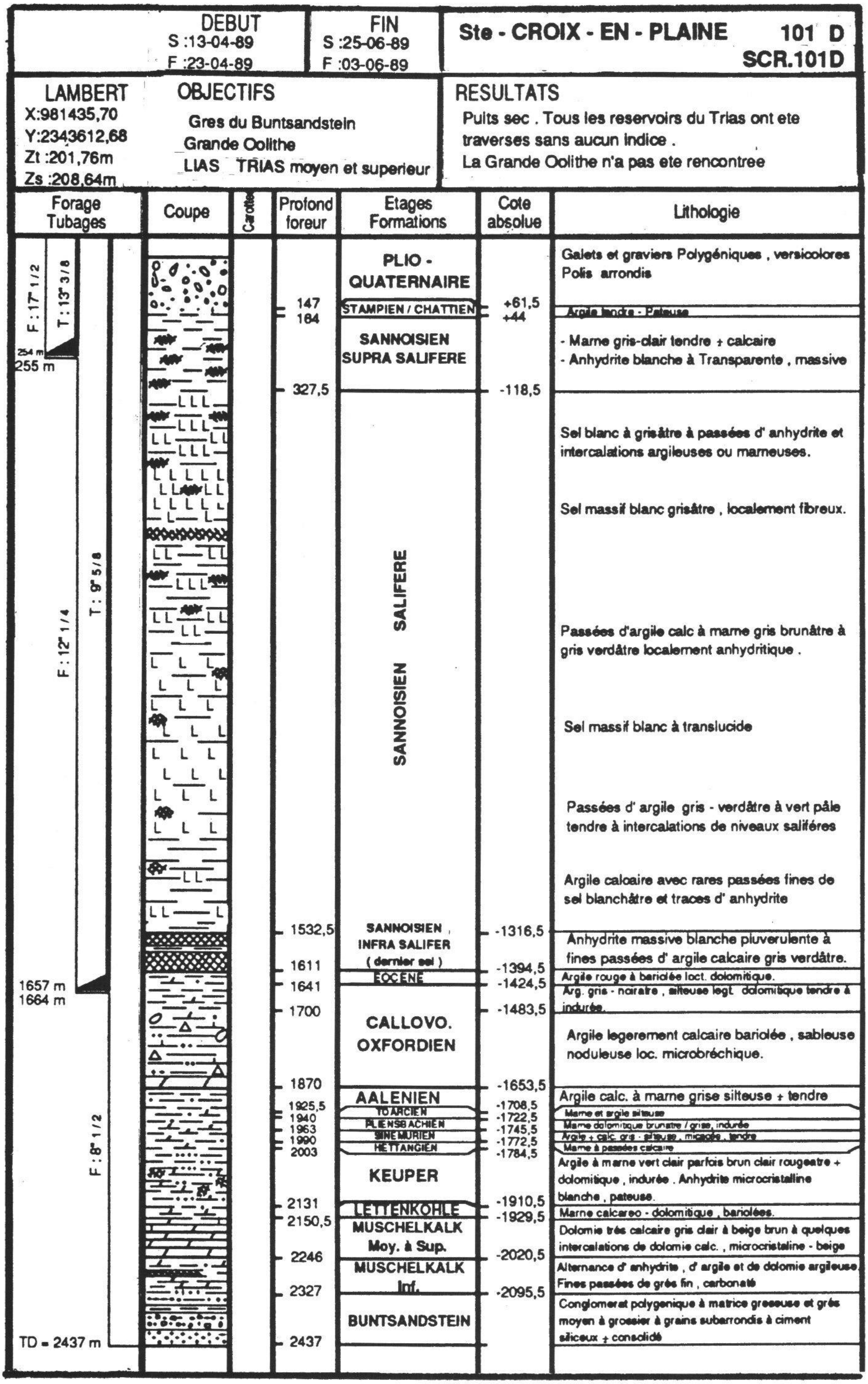

Fig. 28: Ste-Croix-en-Plaine 101 D: Well summary (author: SNEA(P)); well location on Figs. 20, 21.

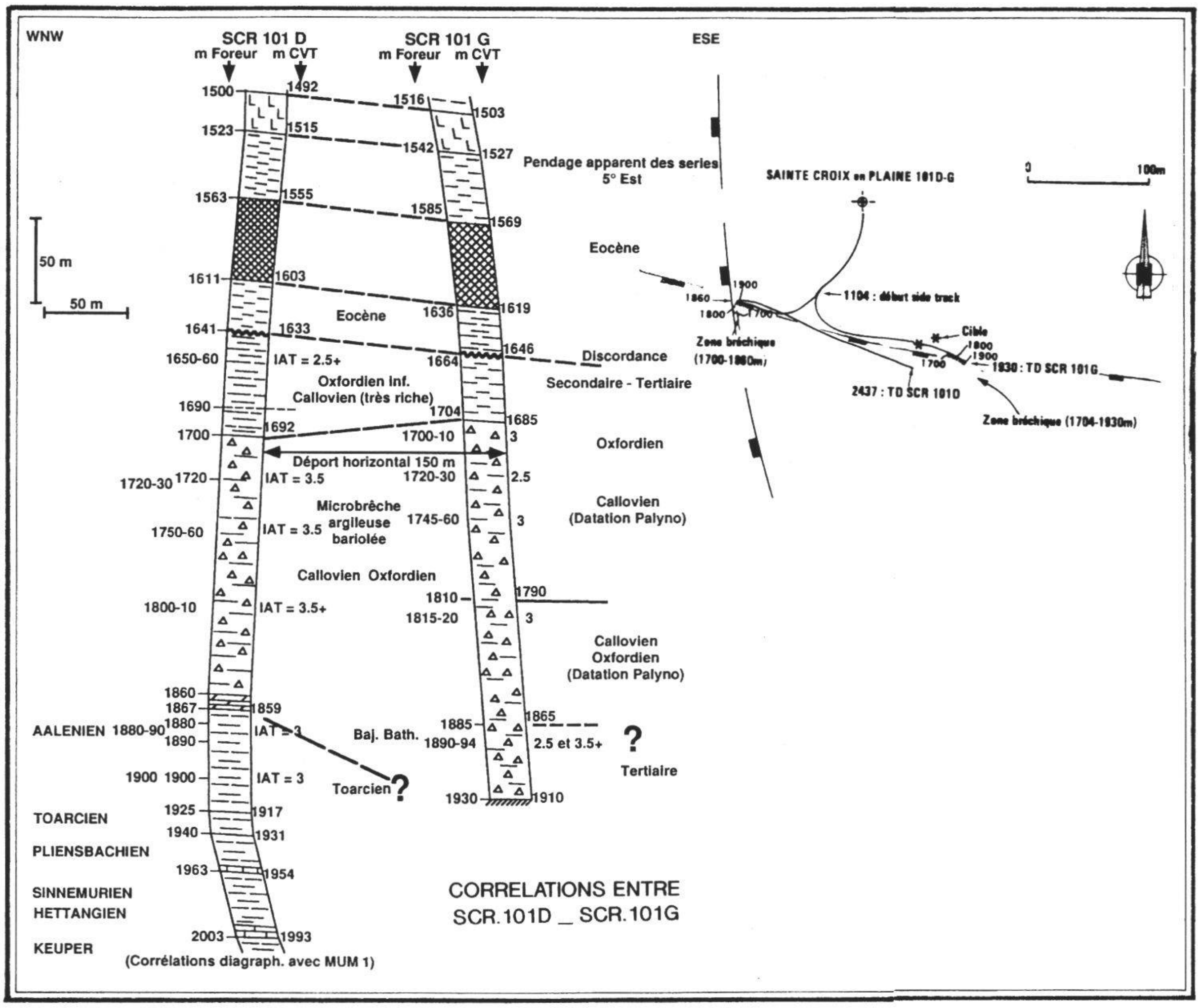

Fig. 29: Correlation between Ste-Croix-en-Plaine 101 D and 101 G (deviation) (author: SNEA(P)).

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 sub-