Discussion of results

Autor(en): **[s.n.]**

Objekttyp: **Chapter**

Zeitschrift: **Bulletin für angewandte Geologie**

Band (Jahr): **4 (1999)**

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

PDF erstellt am: **26.04.2024**

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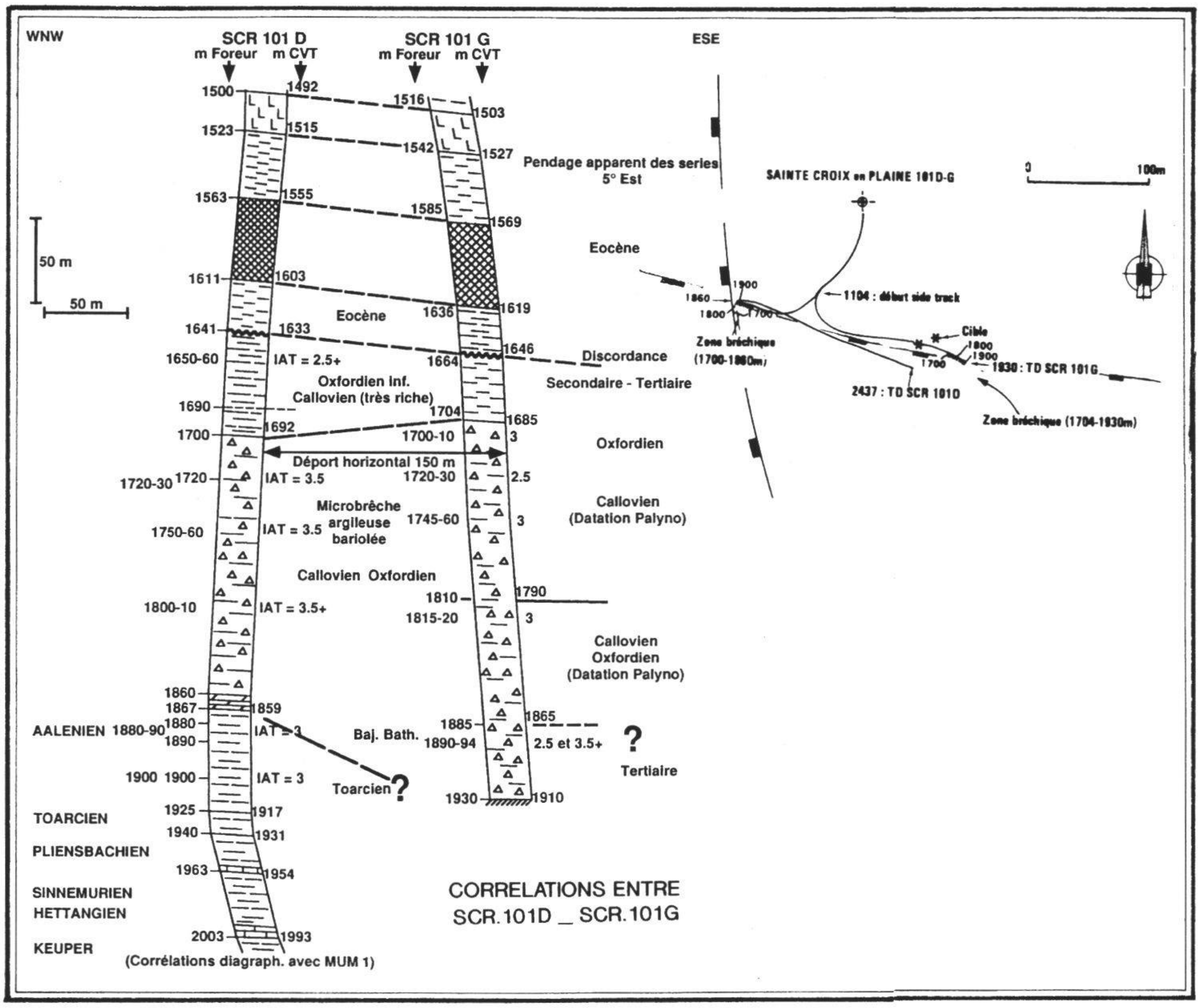

Fig. 29: Correlation between Ste-Croix-en-Plaine 101 D and 101 G (deviation) (author: SNEA(P)).

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

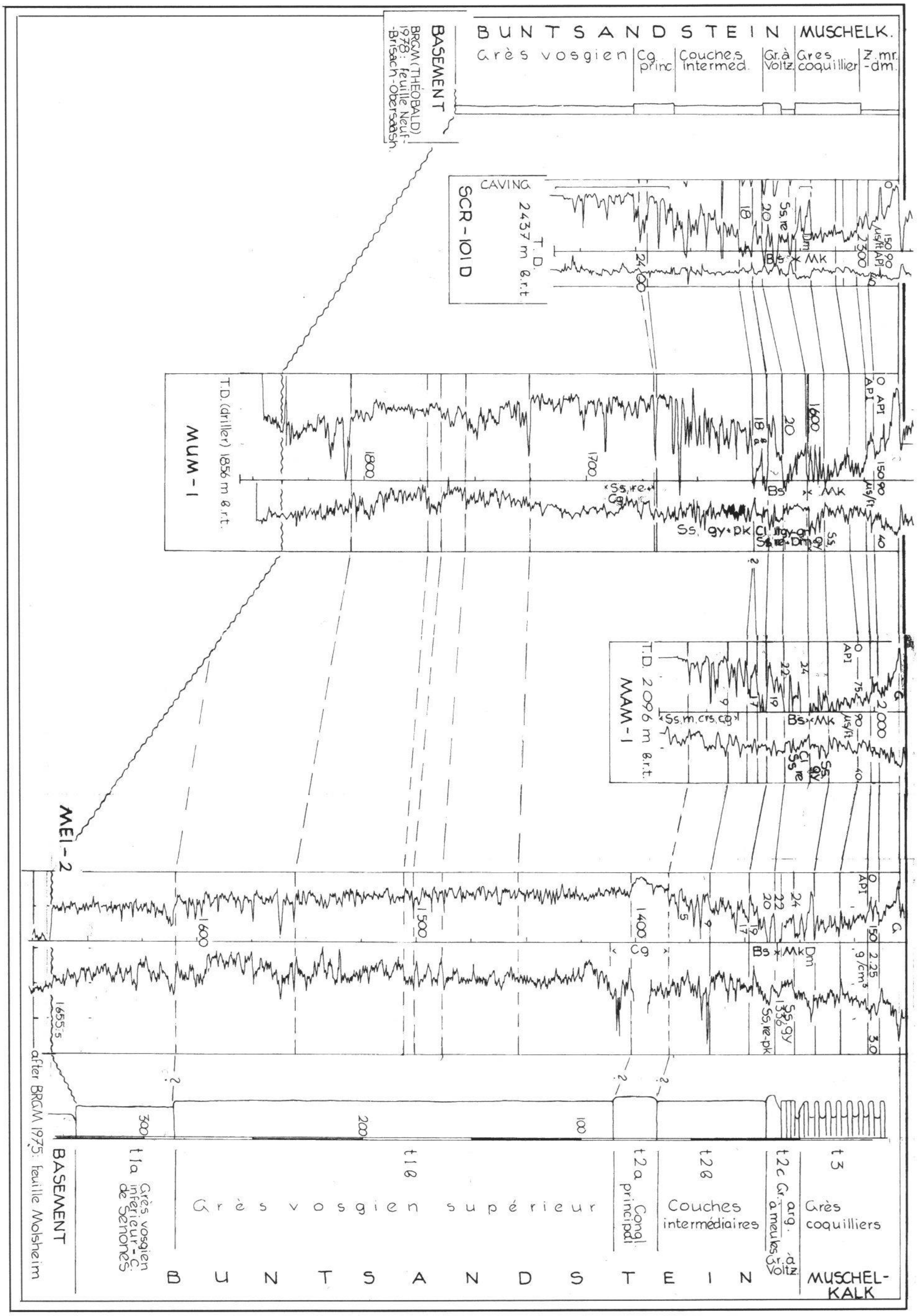

Fig. 30: Log correlation: *Buntsandstein;* Bs/Mk-boundary (indicated along vertical mid-line of logs) and lithologies: from final well logs wells Meistratzheim-2 (MEI-2), Mackenheim-1 (MAM-1), Muntzenheim-1 (MUM-1), Ste-Croix-en-Plaine-101D (SCR-101D); well locations on Figs. 5, 12, 20.

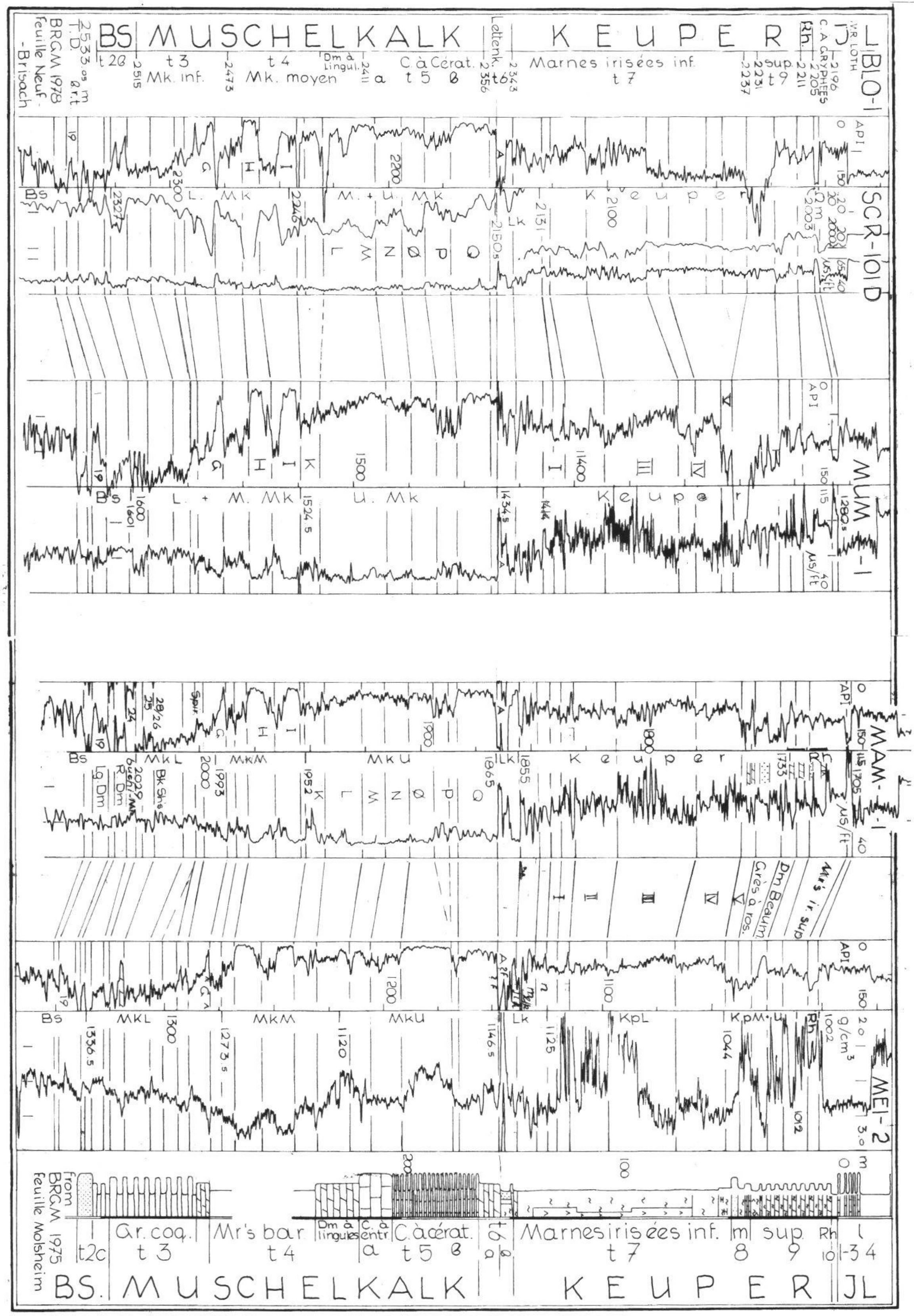

Fig. 31: Log correlation: *Muschelkalk - Keuper;* along vertical midline of logs: stratigraphic units from final well logs; MAM-1: Keuper - M. Muschelkalk acc. to BRGM (1972b); L. Muschelkalk: correlation with GLA 1977: 91, Fig. 7 - Lg. Dm = Liegende Dolomite, R. Dm. = Rauhe Dolomite, Bk.Sh's = shales 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

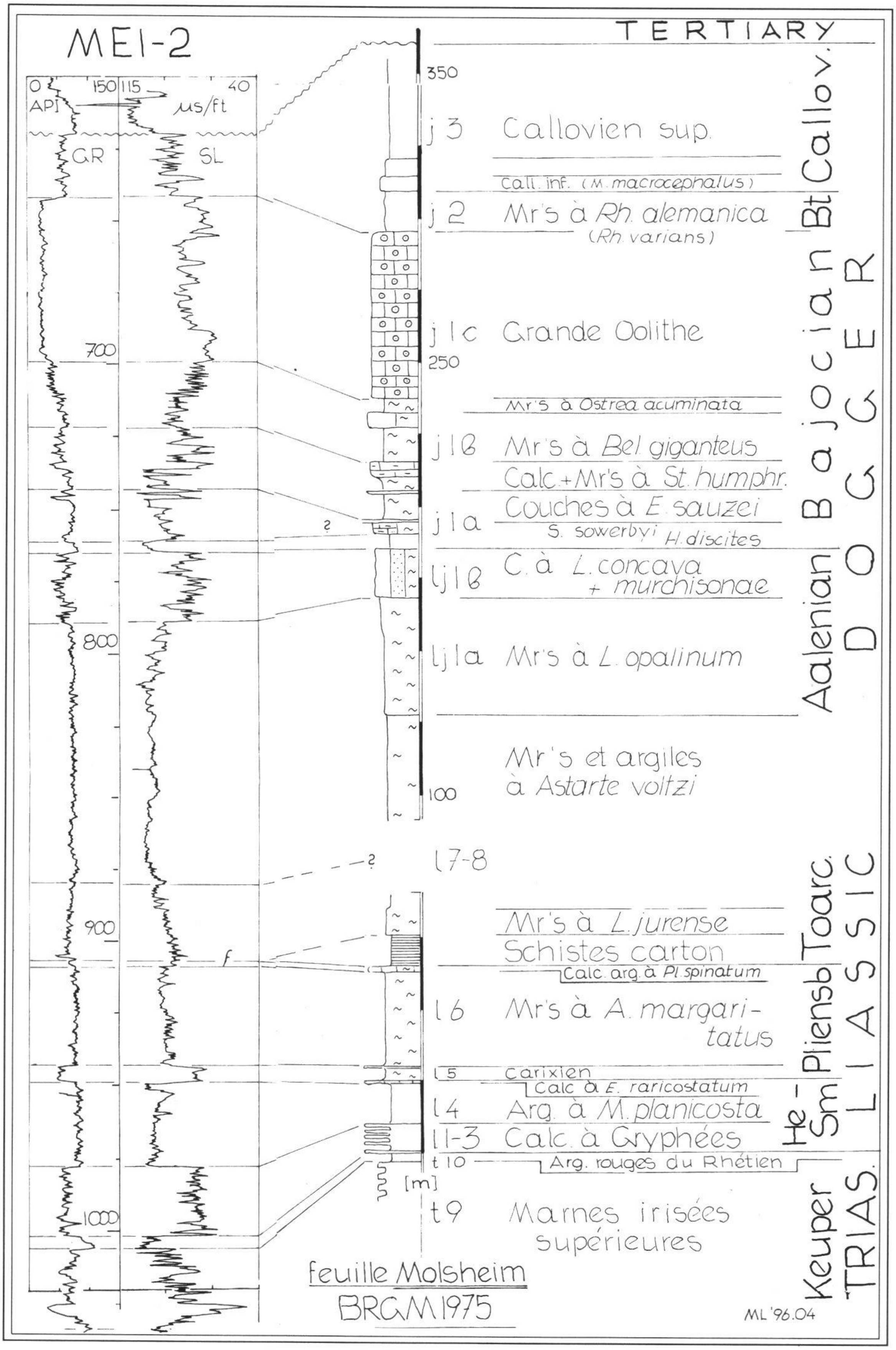

Fig. 32: Correlation gamma ray/sonic log of the *Jurassic* interval of Meistratzheim-2, and a composite surface section from geol. map 1:50'000, sheet Molsheim (BRGM 1975); well location on Fig. 5.

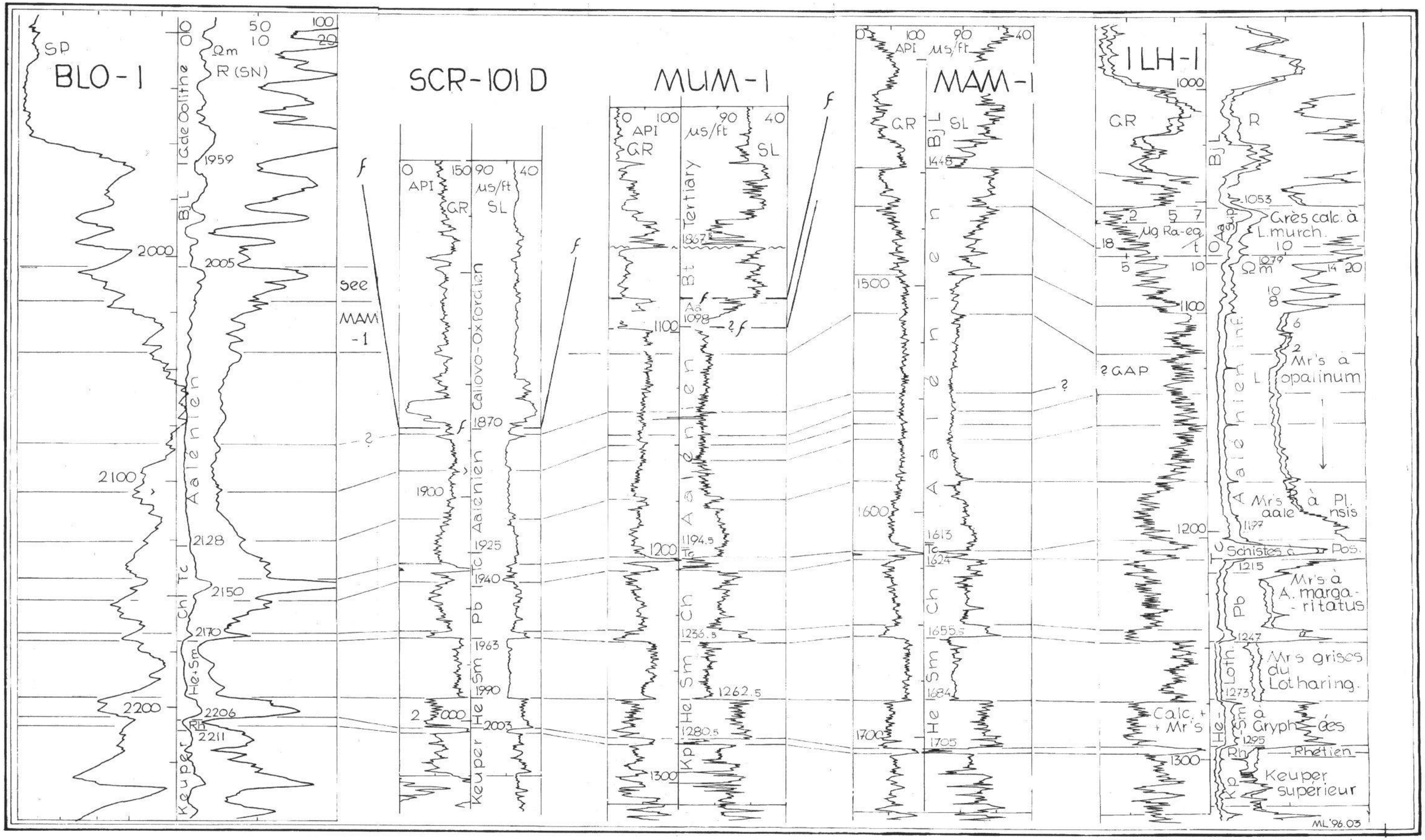

Fig. 33: Log correlation: *Liassic* and *Aalenian;* along vertical mid-line of logs: stratigraphy from final well logs; strat. units in ILH-1 from BRGM 1972b; wells as on Fig. 30, and Blodelsheim-1 (BLO-1), Illhæusern-1; well locations on Figs. 5, 12, 20.

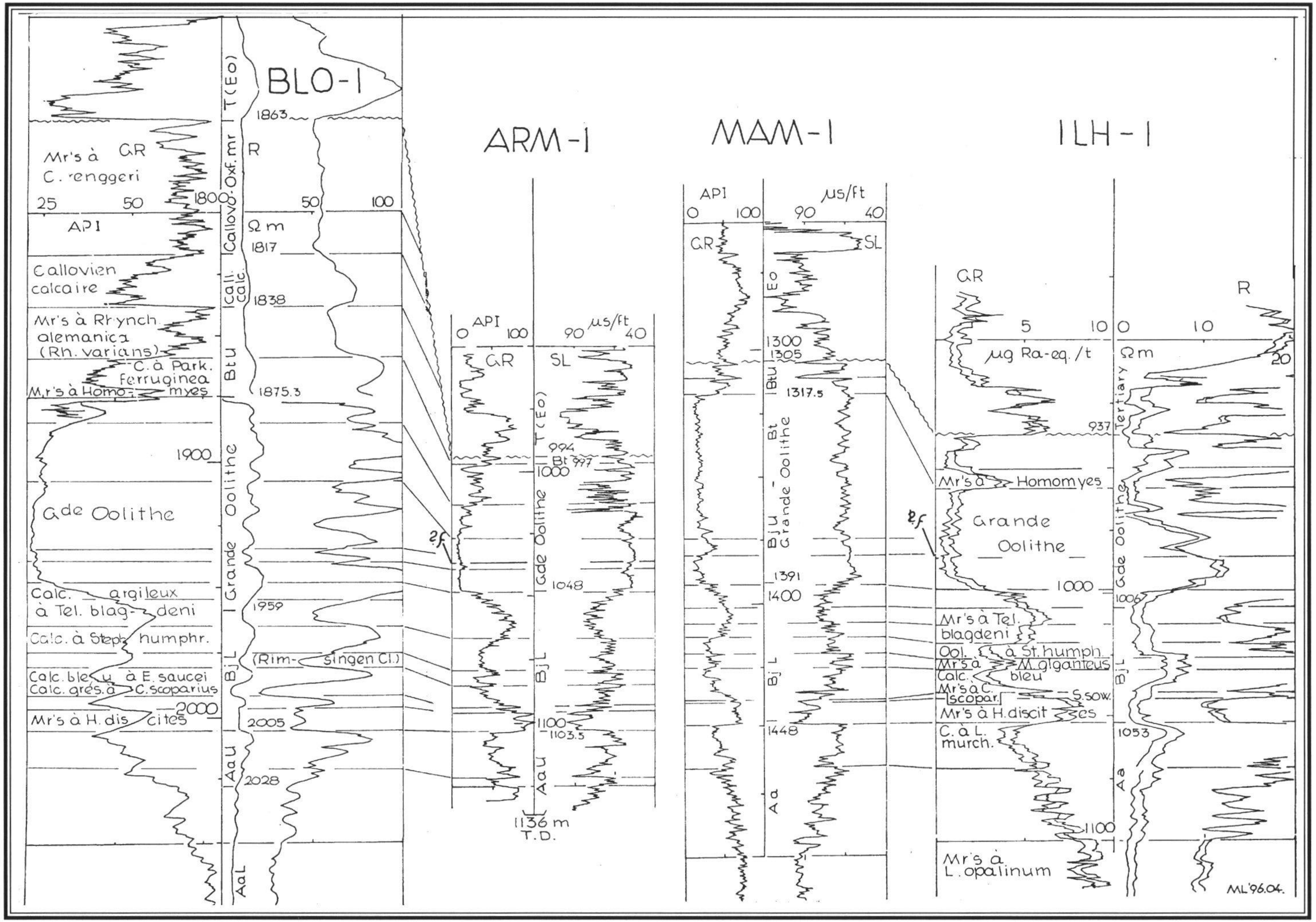

Fig. 34: Log correlation: *Bajocian-Bathonian* to *base Tertiary* unconformity; along vertical mid-line of logs: stratigraphy from final well logs; strat. subdivision in ILH-1 and BLO-1 acc. to BRGM 1972b and 1978; wells Illhæusern-1 (ILH-1), Mackenheim-1 (MAM-1), Artzenheim-1 (ARM-1, Blodelsheim-1 (BLO-1);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

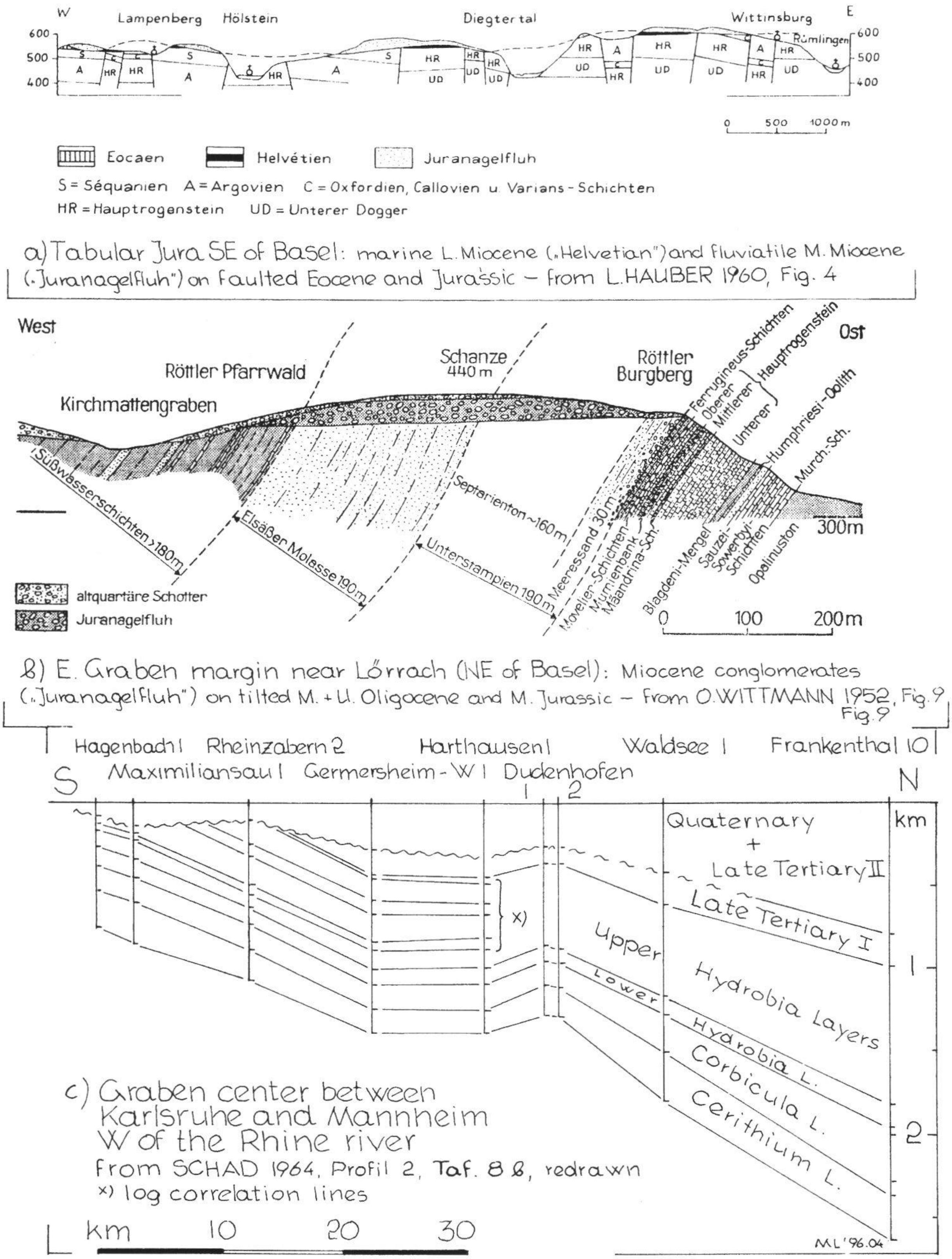

Fig. 35: The Neogene unconformity in the S. Rhine Graben: Structural cross sections:
a) Tabular Jura SE of Basel: marine L. Miocene ("Helvetian") and fluviatile M. Miocene ("Juranagelfluh") on faulted Eocene and Jurassic.- From Hauber (1960: Fig. 4).
b) Eastern graben margin near Lörrach (NE of Basel): 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;

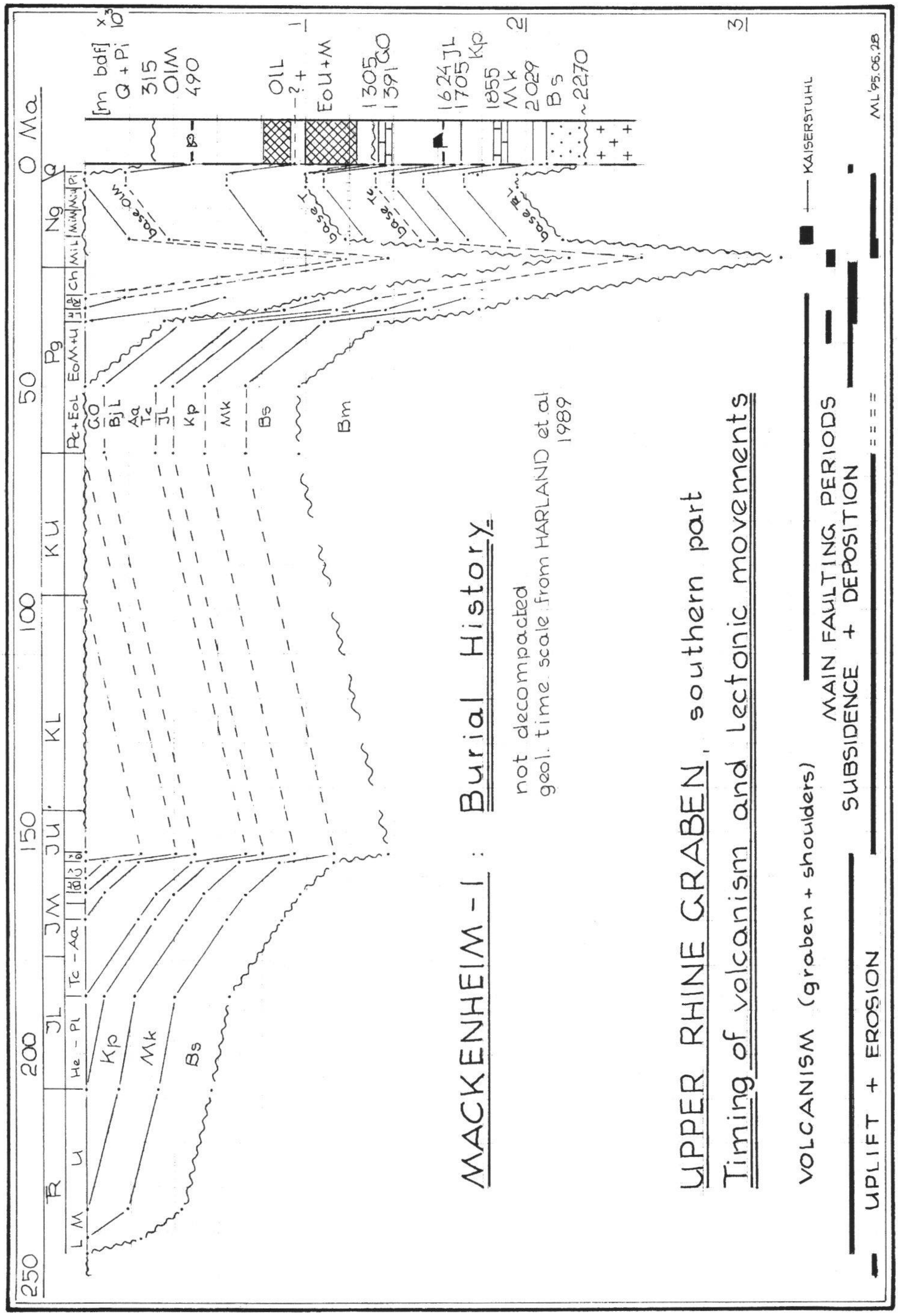

Fig. 36: Mackenheim-1: Burial graph.

- 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 (∅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.

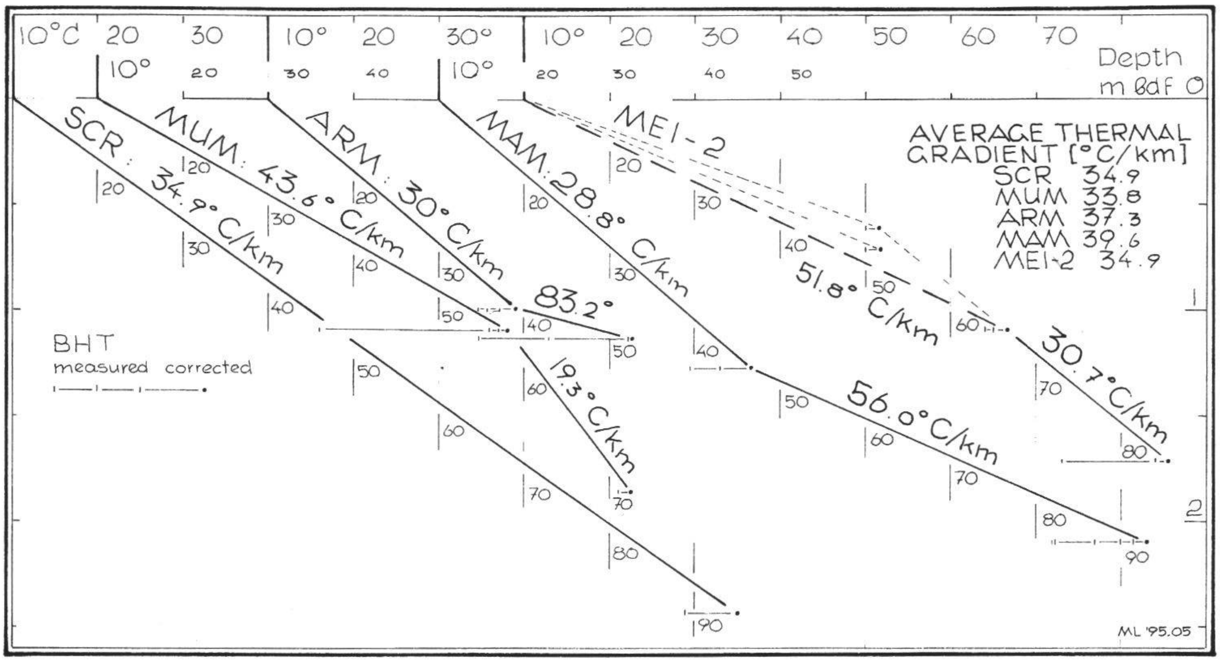

Fig. 37: Temperatures and temperature gradients in the wells drilled.

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.