Hydrocarbon habitat and potential of Swiss and German Molasse Basin : a comparison

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Hydrocarbon habitat and potential of Swiss and German Molasse Basin: A comparison

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ABSTRACT

The Tertiary Molasse Basin north of the Alpine belt and its Mesozoic substratum show a conspicuous vertical and lateral variation in thickness, lithological composition and content of organic matter. This heterogeneity is additionally overprinted by a complex structural and thermal history along the Alpine front.

The estimated hydrocarbon reserves in the German Molasse Basin are 11 million t of oil and 21 billion m^3 of gas. In the Eastern German Molasse area oil was found mainly in the Eocene, gas in the Oligocene and Miocene. In the Western German Molasse area oil has mostly accumulated in Oligocene and gas in the underlying Mesozoic reservoirs. Only one very small gas find in the Jurassic near Finsterwald (Entlebuch) has been made so far in Switzerland although numerous hydrocarbon shows at surface and in wells could be observed.

In the entire Molasse basin a major part of the hydrocarbons have probably been generated below the Alpine overthrust where the most effective kitchen area for the main source rocks, the Oligocene shales in the east and the Toarcian shales in the west is situated. Long migration paths would, however, be required to reach traps in the northern part of the Molasse basin. An alternative source could exist in the coalbearing Permocarboniferous troughs, observed in Western and Northern Switzerland and in the area of Lake Constance. Biogenic gas is common in the Eastern German Molasse Basin.

Structuration of the Tertiary basin fill is complex in the German Molasse but gives way to a gently structured monocline over large parts of the Swiss basin outside the Alpine realm. Though sizeable Mesozoic traps are present in the Swiss basin especially below the overthrusted Molasse, only small uneconomic gas accumulations have been discovered to date. This is primarily due to poor reservoirs and – to a lesser degree – questionable seals.

Measured in number of wells and seismic grid density the Swiss Molasse Basin has a much lower exploration maturity than the South German Molasse. The hydrocarbon potential of the Swiss Molasse Basin is therefore much more difficult to define. New seismic is likely to provide a better understanding of the plays, especially where reservoir information could be gained through geophysical tools. Future development of new plays depends therefore largely on the improvement of geophysical resolution, both for deep structures as well as for reservoir quality.

ZUSAMMENFASSUNG

In der tertiären Molasse nördlich der Alpen liegen in einer Halbschüssel übereinander geschichtet geologische Formationen, gliederbar nach Alter, lithologischer Zusammensetzung, organischem Anteil und Sedimentationsgeschichte, in schwankenden Möglichkeiten und z. T. in komplexer Verbreitung untereinander verzahnt. Die mesozoische Unterlage ist von vergleichbarer vertikaler, aber weniger chaotischer lateraler Heterogenität. Die sedimentäre Vielfalt wird im Bereich der alpinen Front entlang eines schmalbandigen Lineaments von einer komplexen Strukturbildung (gefaltete subalpine Molasse) und flächenhaft als Funktion der regionalen Absenkungsgeschichte zusätzlich thermisch überprägt.

In diesem komplexen Sedimentbecken wurden bis heute etwa 11 Millionen Tonnen Erdöl und etwa 21 Milliarden m^3 Erdgas nachgewiesen. Die Kohlenwasserstoffe werden regional in unterschiedlichen Spei-

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chergesteinen angetroffen. Zwischen München und Salzburg hat sich das Erdöl überwiegend im eozänen Priabon-Sandstein, das Erdgas überwiegend in den darüber liegenden oligozänen bis miozänen Sandsteinen (Chattian (Early Egerian), Aquitanian (Late-Egerian to Eggenburgian), Burdigalian (Ottnangian)) angesammelt. Ein bedeutender Teil des Erdgases ist hier biogenen Ursprungs. In der Molasse nordöstlich des Bodensees wurde das Erdöl im wesentlichen in den oligozänen Bausteinschichten (ca. 2-fache Vorräte wie in der deutschen Molasse östlich Münchens) und das Erdgas in mesozoischen Speichern (vergleichbar ca. ein Viertel der Vorräte) gefunden. Im Vergleich dazu konnte in der Schweiz nur ein kleinerer Gasfund bei Finsterwald (Entlebuch) im Malm nachgewiesen werden (ca. 0,1 Mrd. m^3 Reserven).

Vermutlich entstammt der größere Teil der wirtschaftlich förderbaren thermisch generierten Kohlenwasserstoffe aus dem Bereich unterhalb der alpinen Decken, wo erst das erforderliche zeitabhängige Temperatur- und Druckregime für die tertiären, mesozoischen oder auch permokarbonischen Muttergesteine vorliegt. Bis zu ihren Fangstrukturen im Vorland hatten die Kohlenwasserstoffe z.T. weite laterale Migrationswege zurückzulegen, für den deutschen Teil in einem überwiegend extensionalen tektonischen Regime, für den schweizerischen Teil in einem eher kompressiven. Trotz der in der Schweiz im Vergleich zu Süddeutschland beobachteten minderen Qualität der bekannten Speichergesteine besteht ein mögliches, aber bisher noch wenig exploriertes Kohlenwasserstoffpotential in Malmriffen, in Trägern unterhalb der triadischen Salze und im Bereich der gefalteten Molasse. Voraussetzung für eine erfolgreiche Exploration ist allerdings eine verbesserte Auflösung der Seismik sowohl für tiefere Strukturen wie für Reservoirqualität sowie ein Nachweis für die Wirtschaftlichkeit dieser risikoreichen Ziele.

1. Introduction

In the complex geological region of the Molasse Basin (North Alpine Foreland Basin) approximately 50 oil and gas fields have been discovered to date containing estimated proven reserves of 11 million tons of oil and 21 billion m^3 of gas in the German area (Fig. 1). A similar exploration success has been lacking in Switzerland, al-

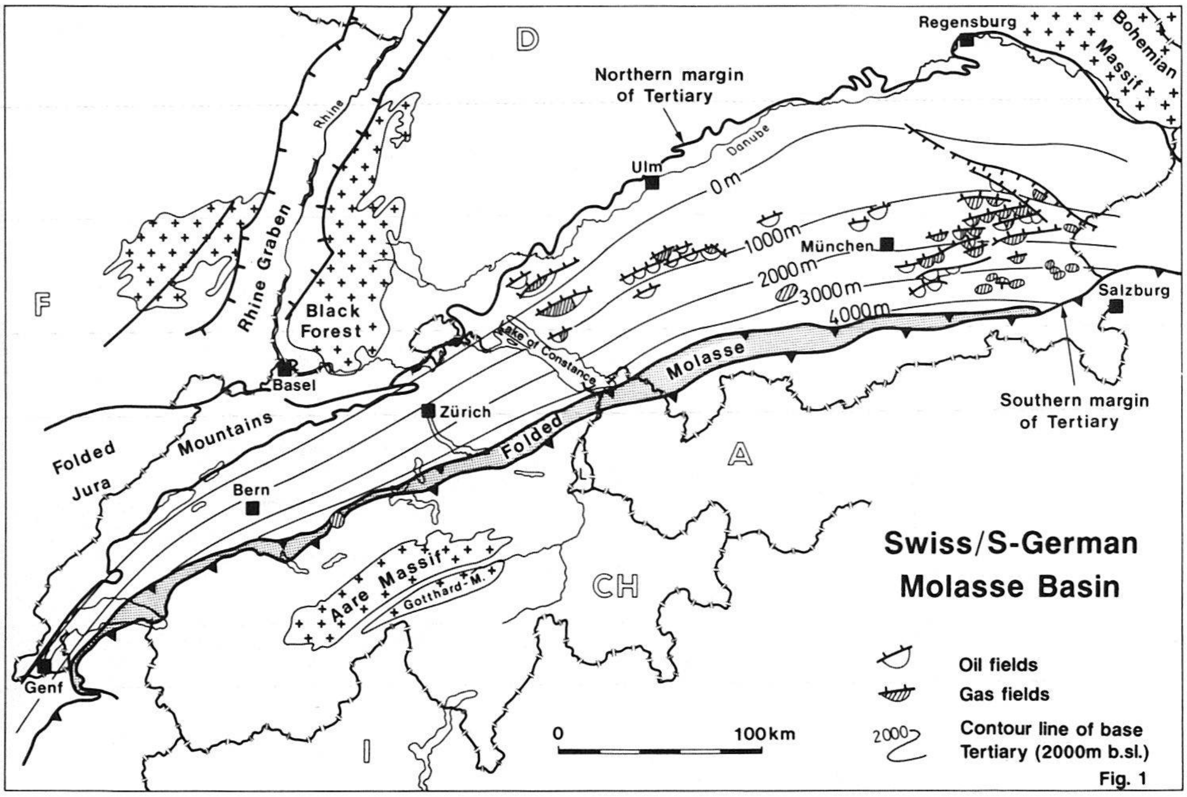

Fig. 1. Swiss/S-German Molasse Basin: oil and gas fields and contour lines of base Tertiary

though numerous and significant hydrocarbon shows have been observed at surface, in tunnels and in wells. The only hydrocarbon producing field in Switzerland is the small Finsterwald gasfield (Vollmayr & Wendt 1987), which produces from Upper Jurassic reservoirs (approx. 0.1 billion m^3 reserves of gas).

In the German Eastern Molasse area between München and Salzburg, oil has been found mainly in reservoirs of Eocene age whereas gas has been found in Oligocenen and Miocene strata. In the German Western Molasse area northeast of Lake Constance oil has mainly accumulated in the Oligocene and gas in the underlying Mesozoic reservoirs (Lemcke 1981, 1988; Bachmann et al. 1987; Schröder 1991).

In this paper the evolution of the North Alpine Foreland Basin, the stratigraphic development, reservoir distribution, source rock maturities and entrapment of hydrocarbons in the Swiss and Southern German Basin will be compared and discussed briefly. A short description of the remaining hydrocarbon potential is added as a conclusion.

2. Development of the Molasse Basin

The Molasse Basin was developed as the flexural depression of the lithosphere that was formed in front of the north- to northwestwards migrating Alpine thrust wedge. The flexural bending of the subsurface has been locally modified by tectonic structuration due to released vertical and horizontal stresses and by their subsequent faulting of the brittle sedimentary and cristalline rocks. The internal thickening of the thrust wedge has been counteracted by erosion of the surface. Sedimentation in the flexural depression generated additional load. These erosional, depositional, migrating and thickening processes acted to redistribute the effective load in a 4-dimensional feedback system (3D-space and time), merging physicalgeological causes and effects, thereby modifying the shape and the volume of the basin with time (see Sinclair et al. 1991).

3. Stratigraphy

The stratigraphy within the Molasse Basin has preserved a quite incomplete record of the filling and sorting processes of the Alpine belt foreland basin system through time. Important products of these processes are the deposition of Tertiary source rocks and reservoir seal pairs as well as the sedimentation of ductile shales providing potential formations for structural detachments. They show major differences between the Swiss and the German Molasse Basin. These factors have subsequently influenced the forming and structuration of parts of the Molasse basin and the trapping of hydrocarbons.

a) Reservoirs

Reservoirs, seals and source rocks are stacked and linked together in the Tertiary Molasse Basin north of the Alpine belt partly in a very complex pattern recognizable due to a dense well and seismic grid. They can be distinguished by their age, lithological composition, organic matter and depositional history. They show variable thickness and partly diffuse lateral extent. The vertical heterogeneity of the underlying Mesozoic layers is of the same order as that of the Tertiary layers. However, their lateral

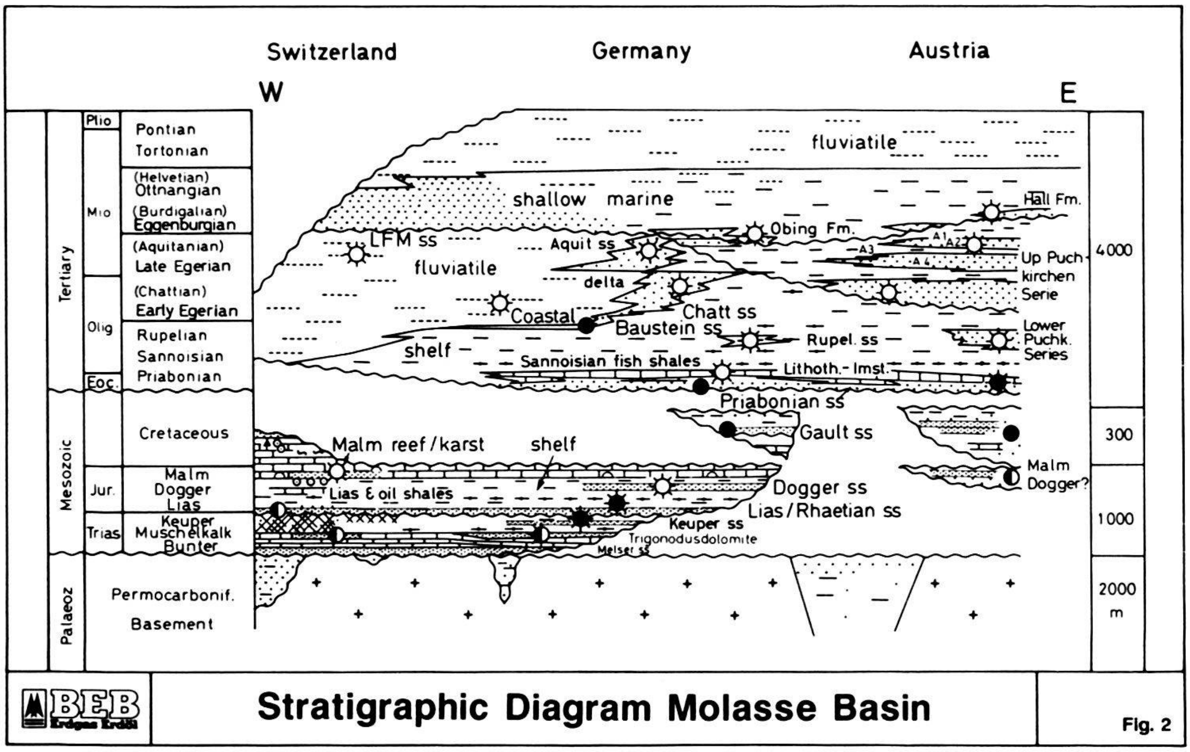

Fig. 2. Stratigraphic diagram of the Swiss/S-German Molasse Basin.

distribution is more homogeneous. Very roughly speaking the Mesozoic strata thickens in southwestern direction indicating a local sedimentary depocenter below the present Folded Jura Mountains in SW-Switzerland. In time the shoreline of the basin migrated southeastwards, controlling the development of reservoir-rock belts (Bachmann et al. 1987).

The absence of well defined reservoir-seal-pairs in the Tertiary of Switzerland is conspicuous (Fig. 2) and is a result of mainly continental deposition (Lemcke 1981, 1988; Betz & Wendt 1983; Bachmann et al. 1987). The areal distribution of Tertiary reservoirs shows this difference between the Swiss and German part of the Molasse Basin clearly. In the German Eastern Molasse the sandstone of Priabonian, Rupelian, Chattian (Early Egerian), Aquitanian (Late Egerian to Eggenburgian) and Burdigalian (Ottnangian) age are superimposed (Fig. 3), however, they all shale out westward towards Lake Constance and are virtually absent in the Swiss part of the Molasse Basin. The Mesozoic reservoirs are Melser sandstone, Trigonodus dolomite (Muschelkalk), Keuper sandstone, the sandstone of Rhaetian/Lias and Dogger and the carbonates of Malm age. They show a concentration in the German Western Molasse Basin northeast of Lake Constance (Fig. 4). In both the Tertiary and the Mesozoic the degree of stacking of reservoirs coincides remarkably with the concentration of oil and gas fields in these areas (Fig. 1). A further significant difference can be derived from porosity and velocity evaluations. The lack of porous reservoirs is one of the major risks of exploration in Switzerland. For a given depth value the porosities recorded in the same formations are much lower on the Swiss side compared to the German side. This observation is supported by the fact that some interval velocities, e.g. for the Dogger (Middle Jurassic),

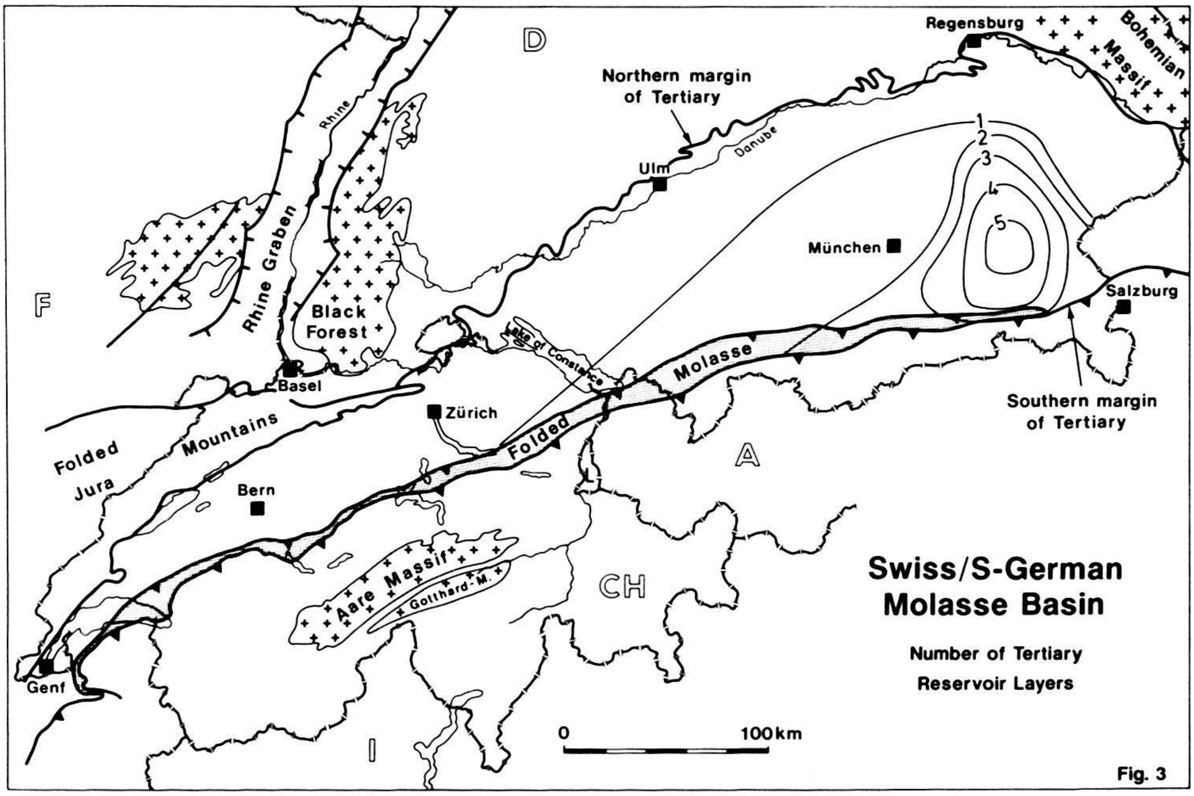

Fig. 3. Number of Tertiary reservoir layers of the Swiss/S-German Molasse Basin.

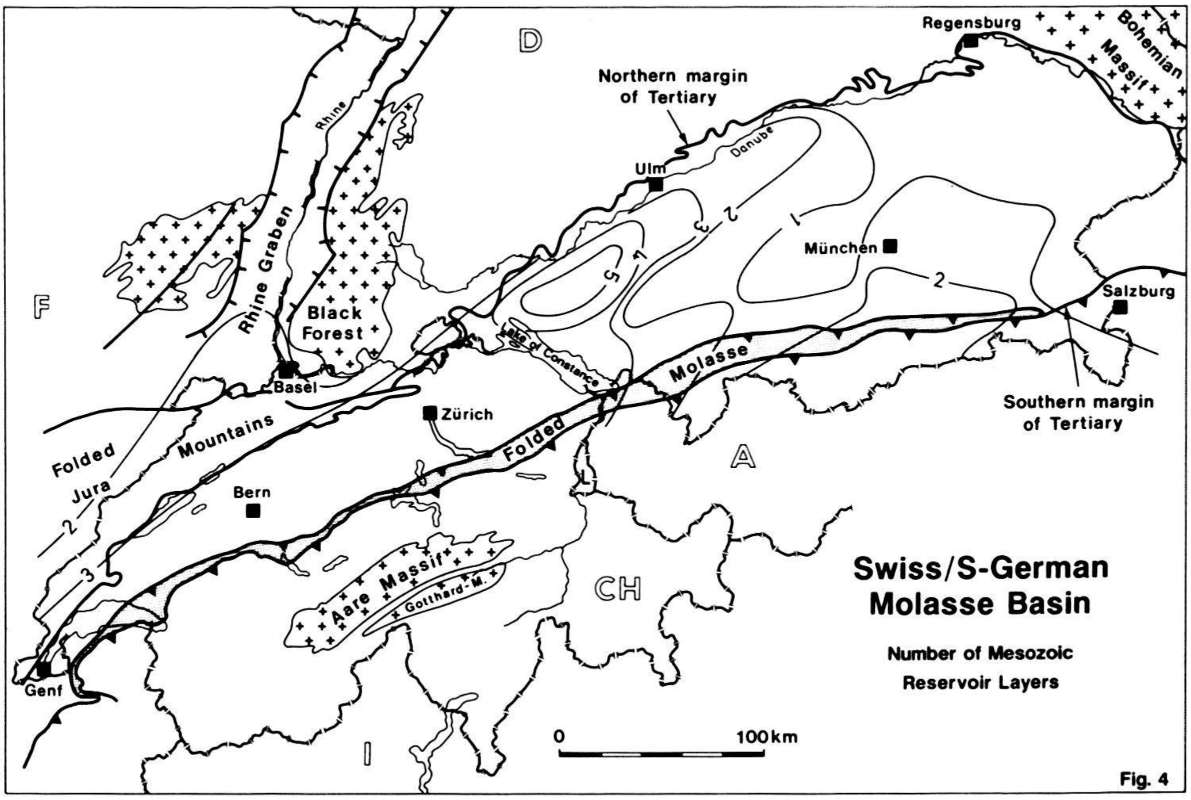

Fig. 4. Number of Mesozoic reservoir layers of the Swiss/S-German Molasse Basin.

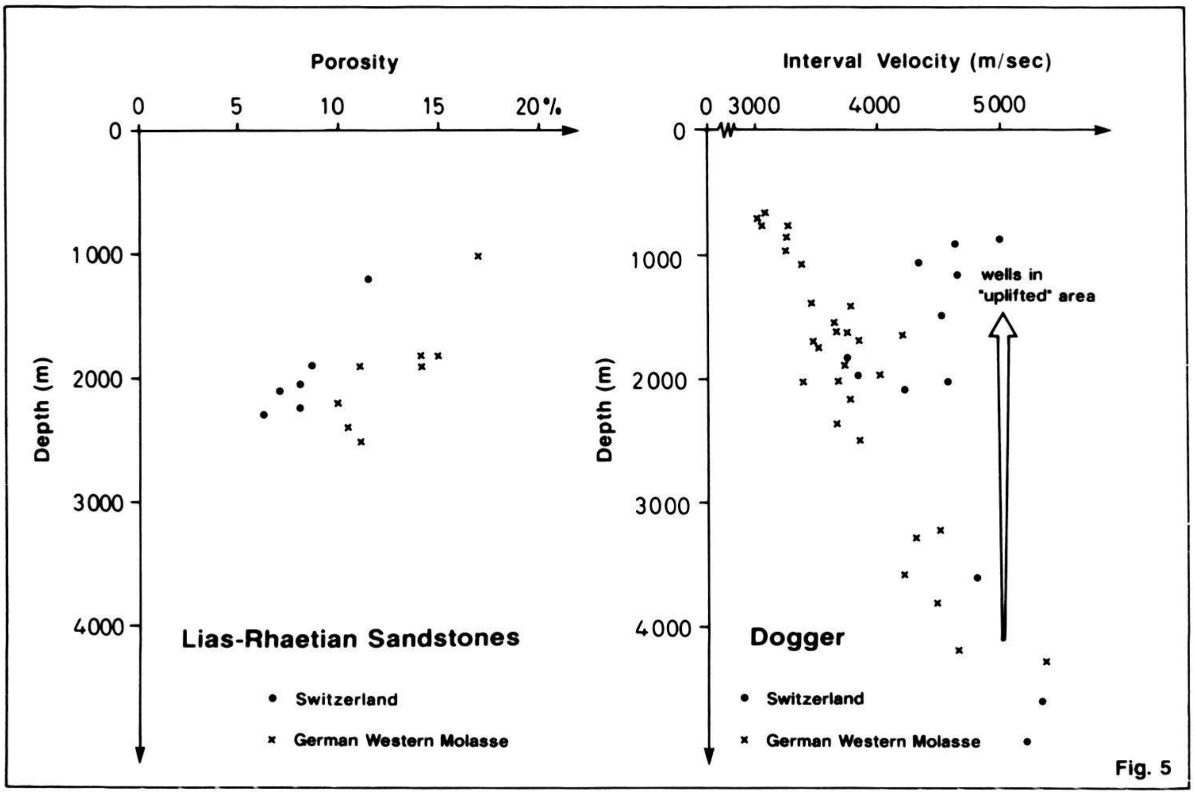

Fig. 5. Swiss/S-German Molasse Basin:
left – *porosity* vs. *depth* of sandstone of Lias/Rhaetian age
right – *Interval velocity* vs. *depth* of the "Dogger" formation (Middle Jurassic)

are much higher in significant wells in Switzerland compared to the bulk of values in Southern-Germany picked for the same depth, hence indicating deeper subsidence. A shift of up to 3000 m downwards for the anomalous Swiss depth values would give corresponding velocities for the Swiss and German sector (Fig. 5). Mapping the depth residuals, an estimate can be given for an assumed post-Jurassic uplift. Based on this evaluation, the area of maximum uplift is interpreted to be located in the SW corner of Switzerland (Fig. 6) approximately coinciding with the depocenter during the Mesozoic. Similar amounts of uplift are given by Lemcke (1974), based on quantitative evaluation of sedimentation and erosion balances of Tertiary sequences.

b) Source Rocks

In the entire Molasse basin the major part of the hydrocarbons has probably been generated below the Alpine overthrust where the most effective kitchen areas for the main source rocks are situated:

- in the West: the Jurassic shales (mainly Lias epsilon (Toarcian)), providing the charge for the Mesozoic reservoirs (Fig. 7),
- in the East: the Oligocene shales (mainly Sannoisian Fish shale), charging the Tertiary reservoirs (Fig. 8).

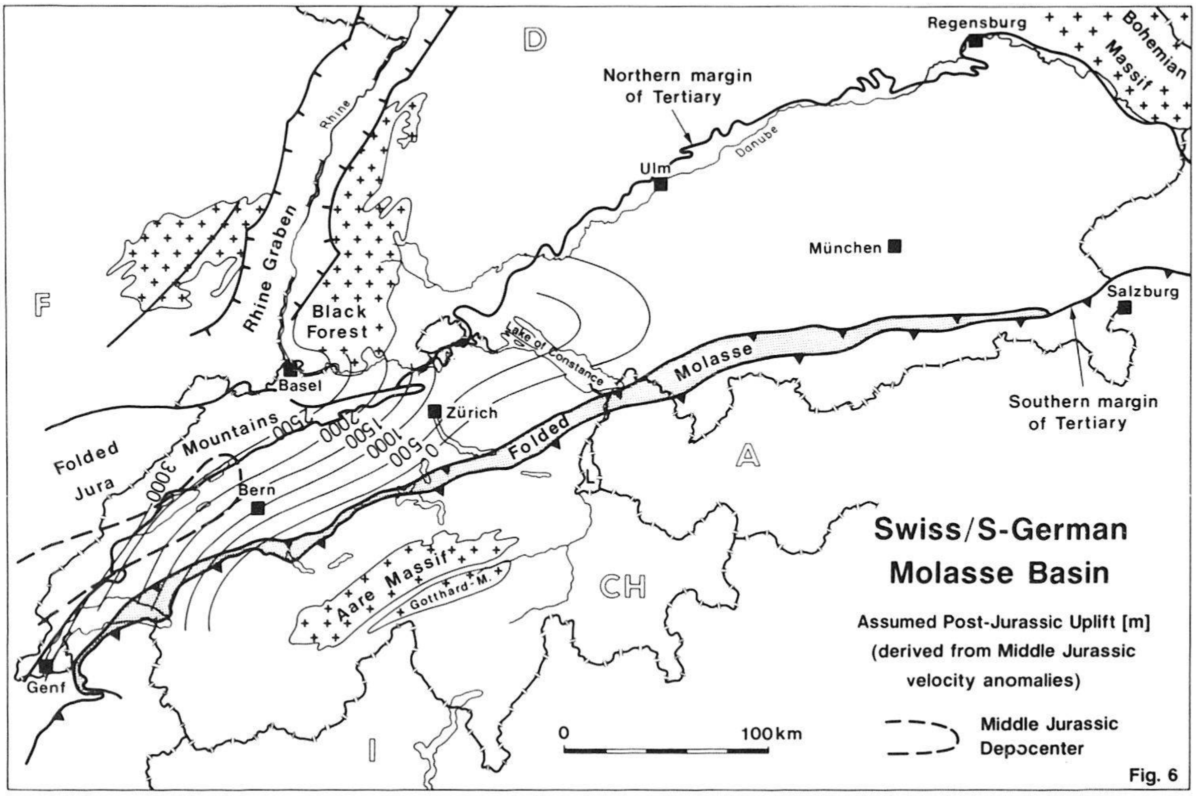

Fig. 6. Swiss/S-German Molasse Basin: assumed Post-Jurassic uplift (m) (derived from Middle Jurassic velocity anomalies)

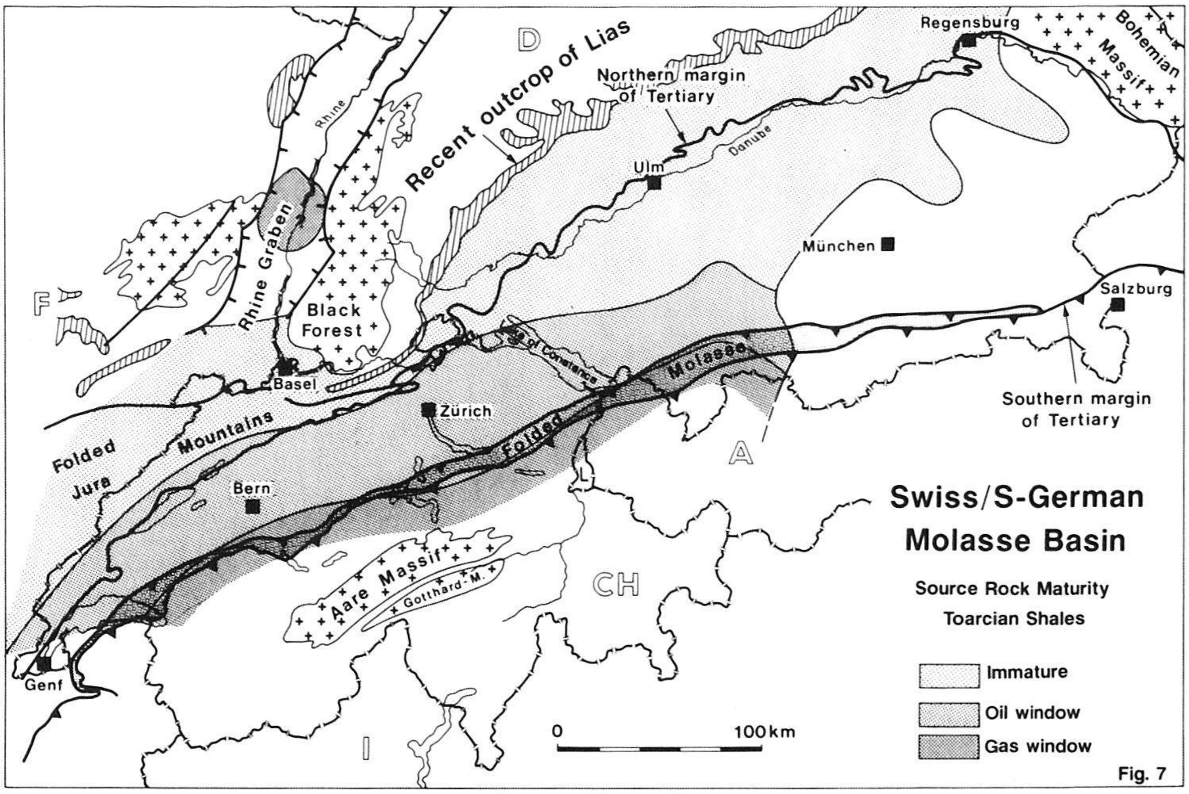

Fig. 7. Swiss/S-German Molasse Basin: source rock maturity of shales of Toarcian age

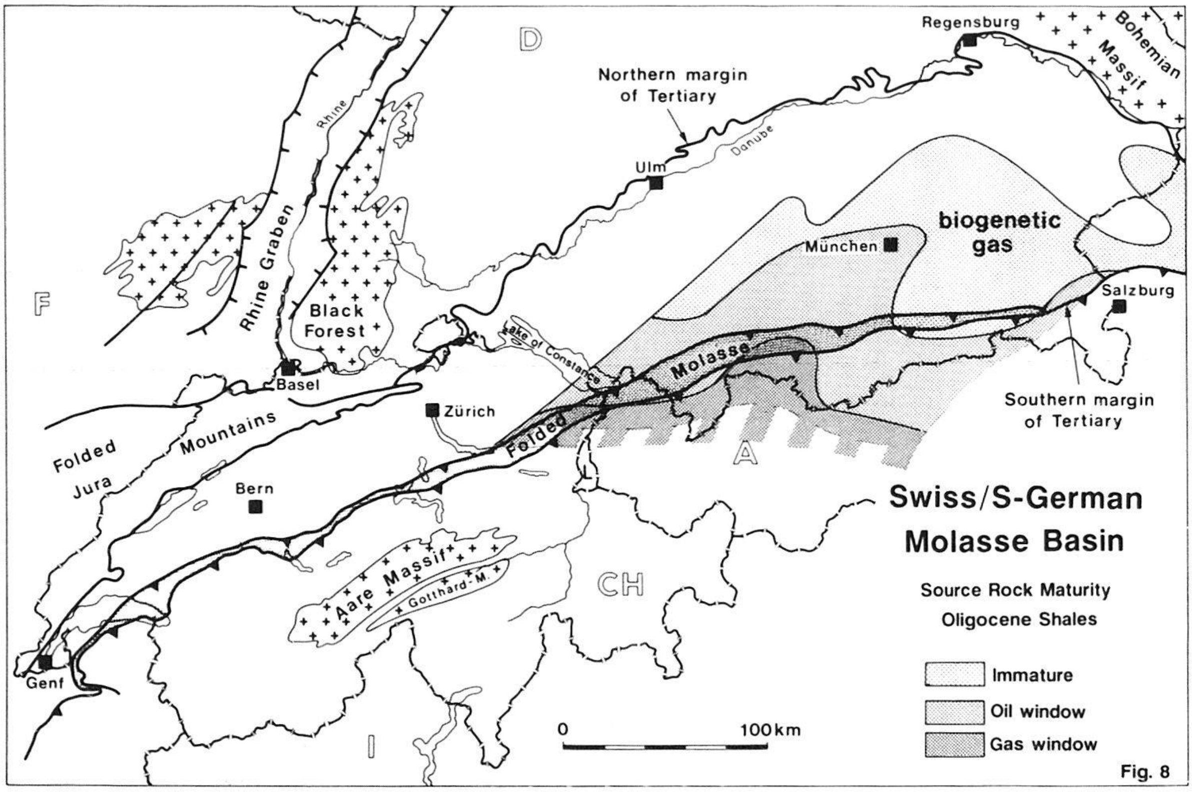

Fig. 8. Swiss/S-German Molasse Basin: source rock maturity of shales of Oligocene age

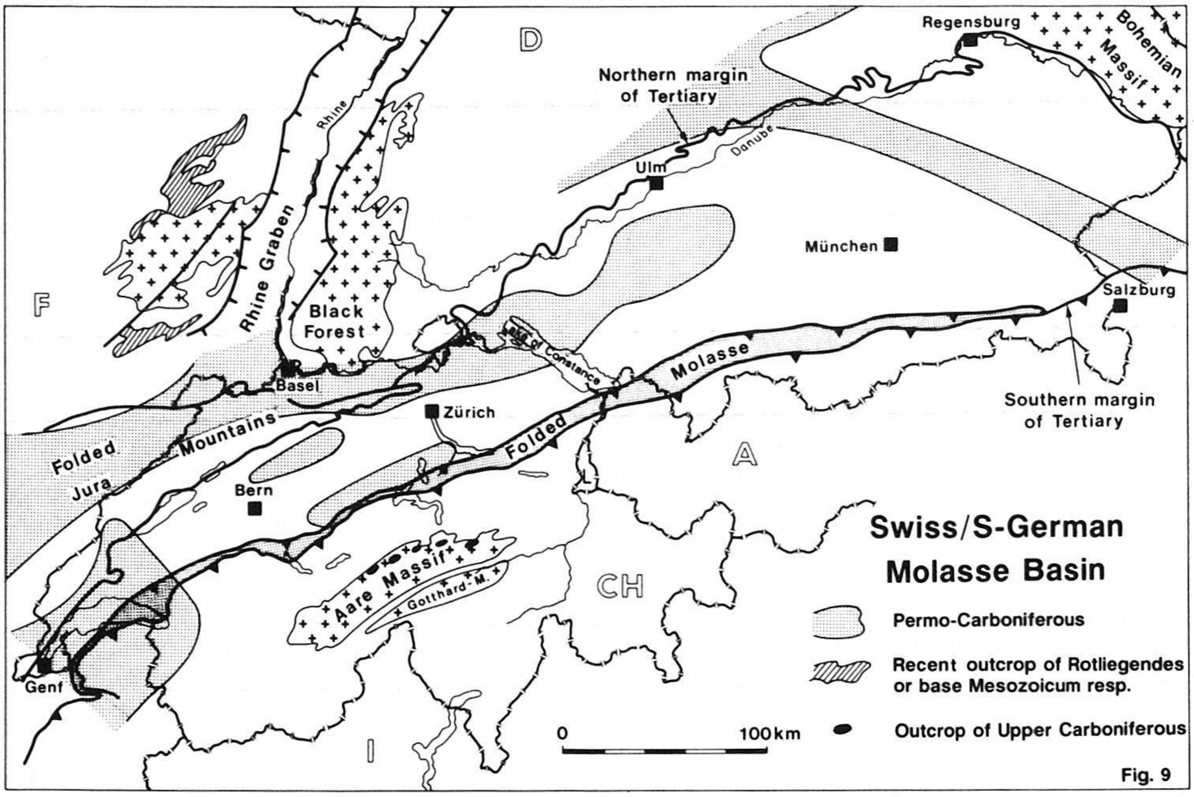

Fig. 9. Swiss/S-German Molasse Basin: sketched Permo-Carboniferous trough system

In both cases long migration paths would, however, be required to reach traps in the northern part of the Molasse basin. Additionally bacterial (biogenetic) gas is common in the German Eastern Molasse basin (Schoell 1977).

An alternative source exists in the coalbearing Permo-Carboniferous troughs, observed in Western and Northern Switzerland and in the area of Lake Constance (Fig. 9) (Kettel & Herzog, 1989). Near the Alpine front coalbearing Carboniferous has been proven to be the gas window (well Entlebuch 1).

4. Entrapment

One of the most significant differences between the Swiss and the Southern German Molasse Basin is the repertoire of structural styles expressed at base Tertiary level. The German part is predominantly governed by an extensional regime, resulting in the development of partly sealing synthetic and antithetic normal faults, running mainly parallel to the basin axis. The Swiss part is dominated by compressional styles, such as folds and inverse faults (Betz & Wendt 1983) (Fig. 10).

The present day internal structuration of the area is the result of many different mainly tectonic forces, acting through time:

Extensional stress was induced by the flexural bending of the crust, predominantly fauling the subsurface of the German Molasse Basin (Bachmann et al. 1987; Bachmann & Müller 1992). Compressional stress was and has been generated by the migrating front of the Alpine thrust belt (Illies & Greiner 1978) subsequently folding and faulting the base of the Swiss Molasse Basin, too. This compressional structuration interfered with the effects of the extensional stress regime of the superimposed crustal bending. Both of these tectonic processes are accompanied by shear force-induced wrench faulting (strike-slip regime). The effects of compressional forces are also recorded in the structuration of the folded Swiss and French Jura Mountains. They also have caused the development of few gentle, partly gas-bearing anticlines of Miocene sands north of the Folded Molasse Belt in Bavaria (Bachmann et al. 1982). Fuchs et al. (1989) explained the structuration of the Jura Mountains as a process mainly governed by underthrusting of the crystalline basement below the sedimentary Molasse basin and the Alpine nappes (acc. to Hsü 1979).

However, neither the "Fernschubhypothese" (Buxtorf 1907) nor the "Gravity Gliding" (Laubscher 1961) fit the theoretical model used by Fuchs et al. In terms of plate tectonics this means that the subduction of the European Plate below the African Plate took place until the main phase of folding of the Jura Mountains was completed (11 million a ago). Horizontal stress in southeast-northwest direction down to base crustal level and perpendicular to the Swiss Alpine front is expressed by the upthrusting of the Po plain Moho on the underthrusting European Moho (Buness et al. 1990; Butler 1990). The German Alpine front area is situated more tangentially to the main stress field. The Tertiary fill of the Molasse Basin appears to the influenced by the vertical and lateral compressional forces in a different way. A different mode of reaction instead of deforming the shape of rocklayers (e.g. by folding), is the compaction of the stressed rockvolumes. This compaction can lead to the building-up of an internal overpressure regime. Overpressures (up to 2.4 bar/10 m), caused by compaction and tectonics, have been observed in the Tertiary at the northern margin of

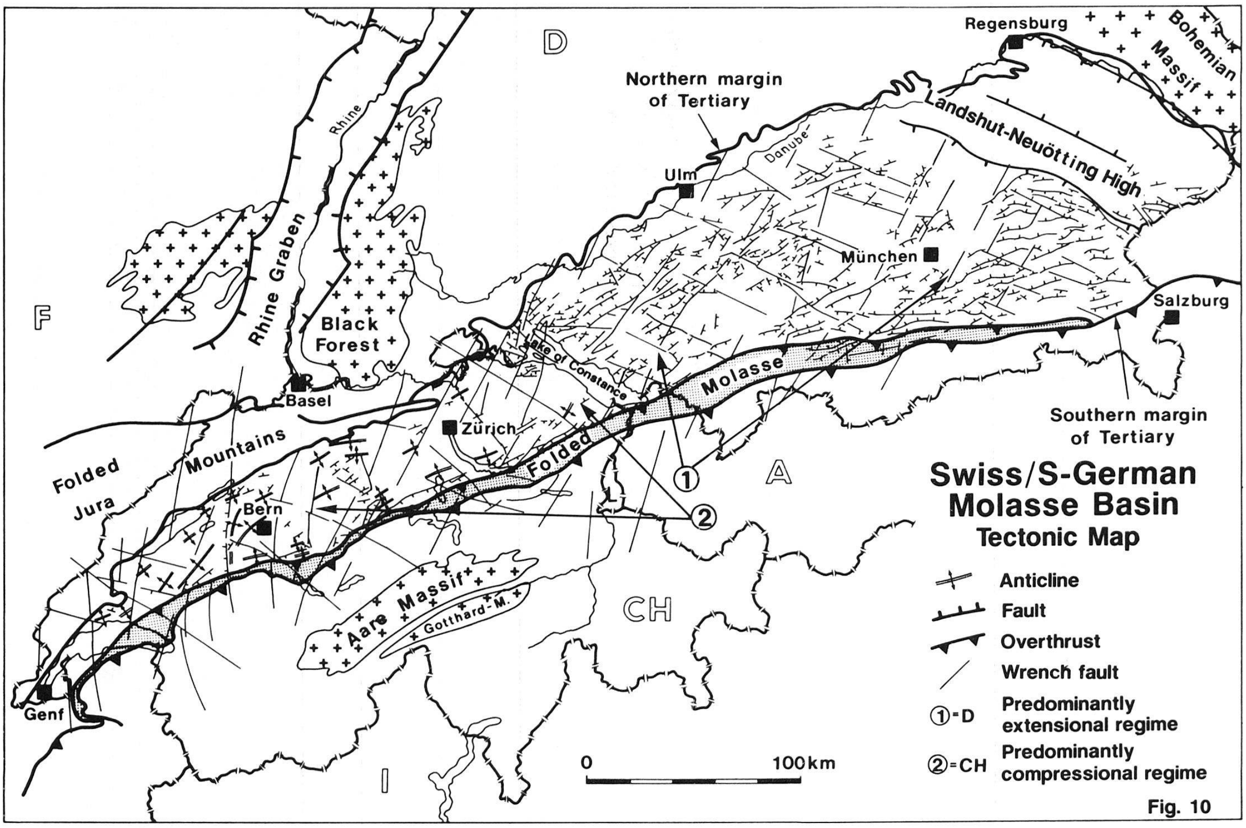

Fig. 10. Swiss/S-German Molasse Basin: sketched tectonic map

the German Alps (Müller et al. 1988), indicating a closed system of fluid filled rocks inbedded in sealing shales. Overpressures of similar order have not been observed in the Tertiary of the Swiss Molasse Basin.

Detachment horizons are required to release some of the above-mentioned forces. In the sedimentary sequence of the Molasse basin Tertiary shale layers (e.g. shales of Rupelian age) in front of the Alpine thrust belt and Mesozoic layers of salt (e.g. Middle Muschelkalk), anhydrite or shale can act as detachment levels. Especially the Mesozoic detachment levels are common in the Swiss subsurface. They have not been activated in the German North Alpine Foreland probably due to the lack of salt layers and due to the different tectonic regime. Within the Alpine belt, fluids such as water, CO2, hydrocarbons(?) or other volatile components released by thermal forces increasing with depth might generate further detachment horizons (Laubscher 1985). Either individually or in a synergetic way, incorporating short-term geological events into long-term processes via selforganization, governed by feedback-mechanisms (see Brink 1984), all the above-mentioned forces and processes have influenced the generation of hydrocarbons within the source rocks, the lateral and vertical migration within porous layers (German Molasse) and along faults (Swiss Molasse?), and the entrapment in different tectonic settings (extensional and compressional regimes) within the North Alpine Molasse Basin.

5. Hydrocarbon Habitat and Potential

Any comparison of the hydrocarbon habitat (Fig. 11) and potential between the South-German and the Swiss Molasse Basin has to be seen against the backdrop of a very different exploration maturity. Both the coverage with modern seismic and the well density are higher by an order of magnitude in Southern Germany. The seismic coverage north of the Lake Constance can be characterized by a mean grid size of 1 km whereas in Switzerland a seismic grid size of approximately 3–5 km has been shot. In the concessions of the German Western Molasse area 1 to 5 wells per 100 km^2 have been drilled. In Swiss concessions a density of 0.1 to 0.2 exploration wells per 100 km^2 is observed, demonstrating the low exploration maturity. In spite of this shortcoming it is evident that the Swiss and German sectors of the Molasse Basin have to be seen as two conspicuously different provinces, characterized by the common mega-geotectonic history of the Alpine orogeny but on the other hand separated by differences in structuration and sedimentation. This separation is expressed at the surface by a topographical depression of regional size running from Lake Constance westwards, and by lineaments of outcrops of different rocks which follow the same megatectonic element along the southern edges of the Black Forest, of the Rhine Graben, and of the Vosges.

Main risks and drawbacks of the Swiss Molasse Play when compared to the German and Austrian sectors are the scarcity of Tertiary reservoir-seal-pairs, the assumed deep burial history in the southwestern area which negatively affects pre-Tertiary reservoir properties and to a lesser degree the higher structural complexity in a compressional/strike-slip regime.

Main assets of the Swiss Molasse Basin are the almost ubiquitous gas charge, supplied most likely by Mesozoic and Permocarboniferous sources, the existence of some

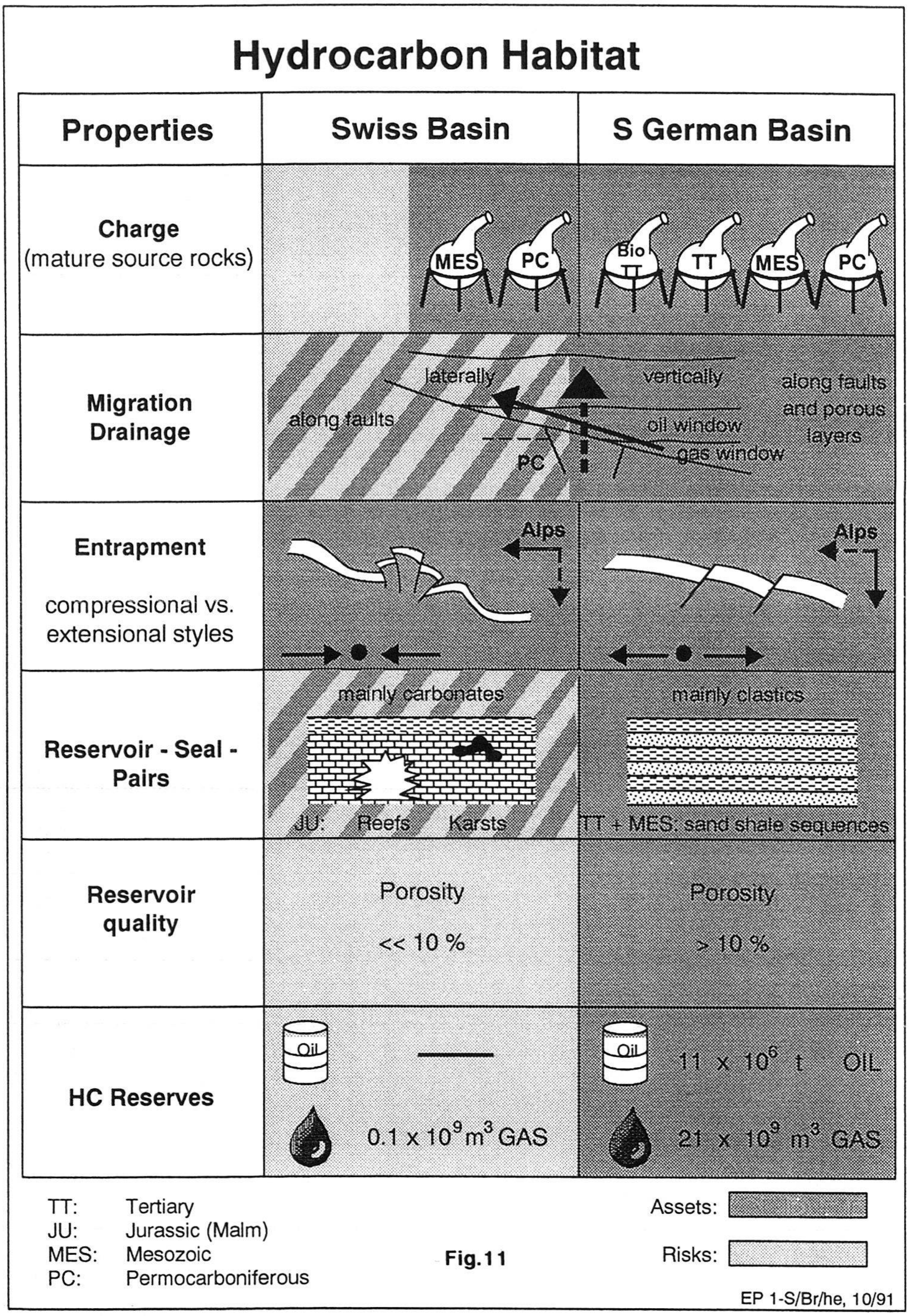

Fig. 11. Hydrocarbon habitat of the Swiss and S-German Molasse Basin

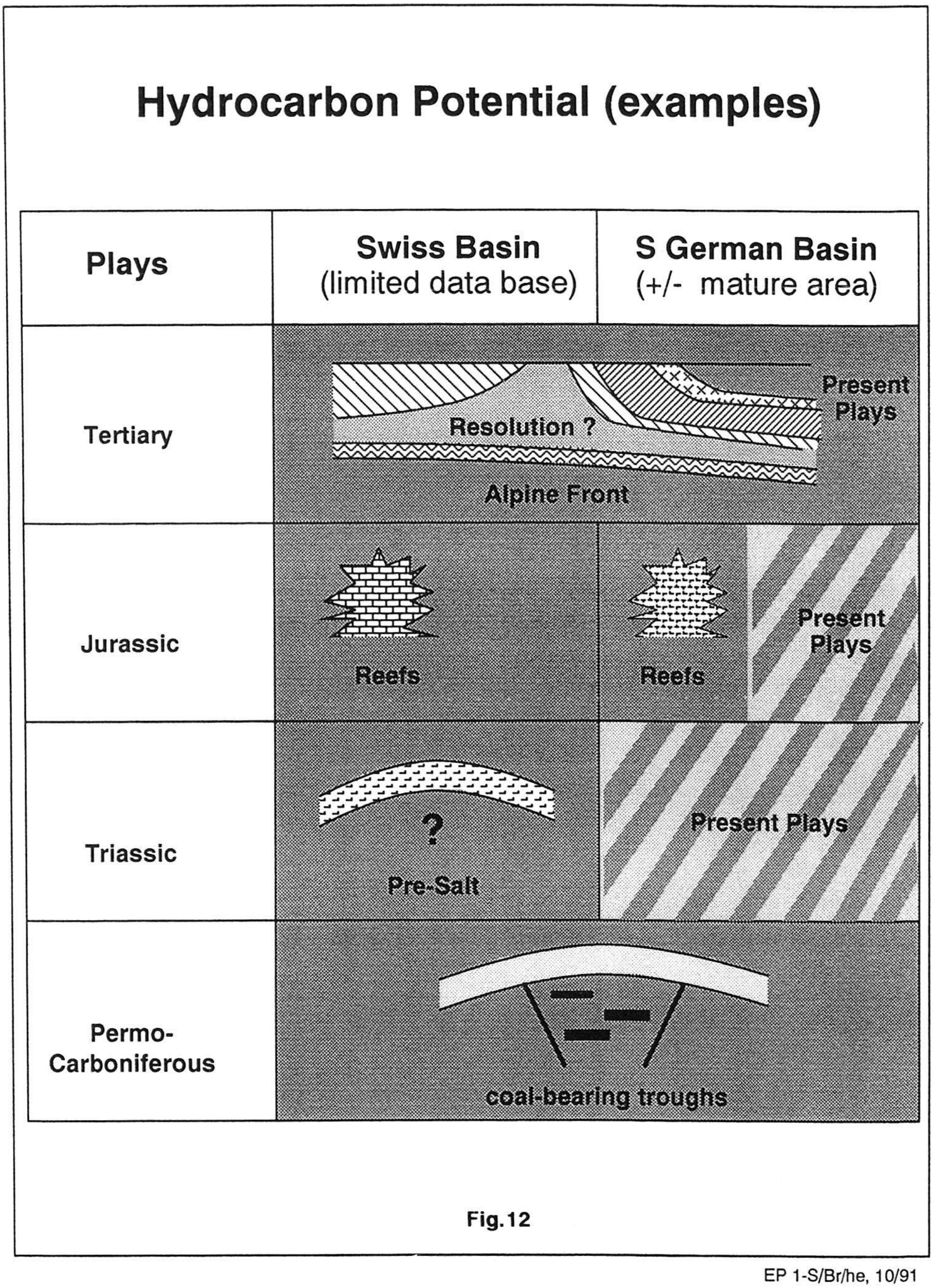

Fig. 12. Hydrocarbon potential (examples) of the Swiss and S-German Molasse Basin

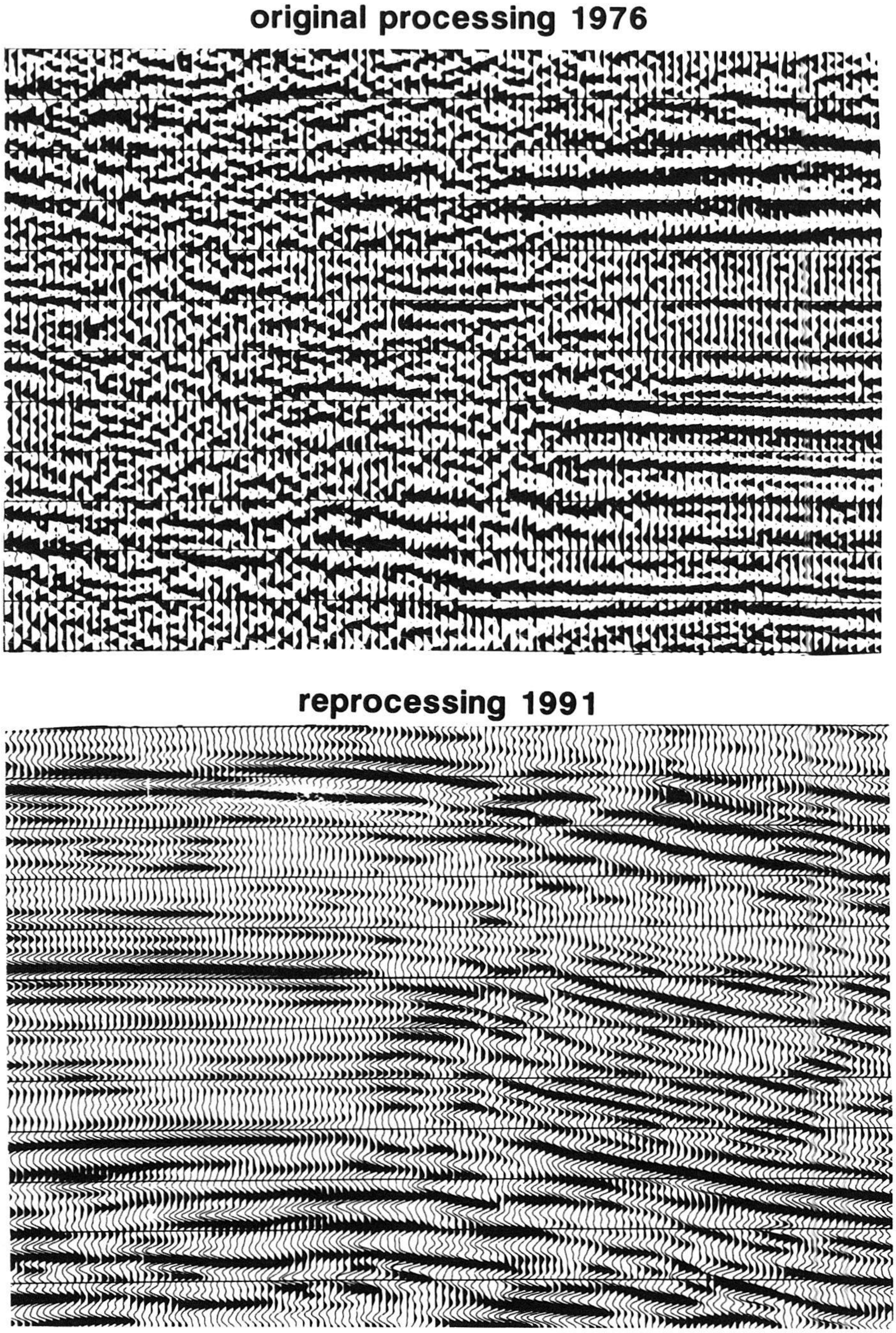

Fig. 13. Improvement by reprocessing of the 1976 seismic line (Swiss Molasse Basin)

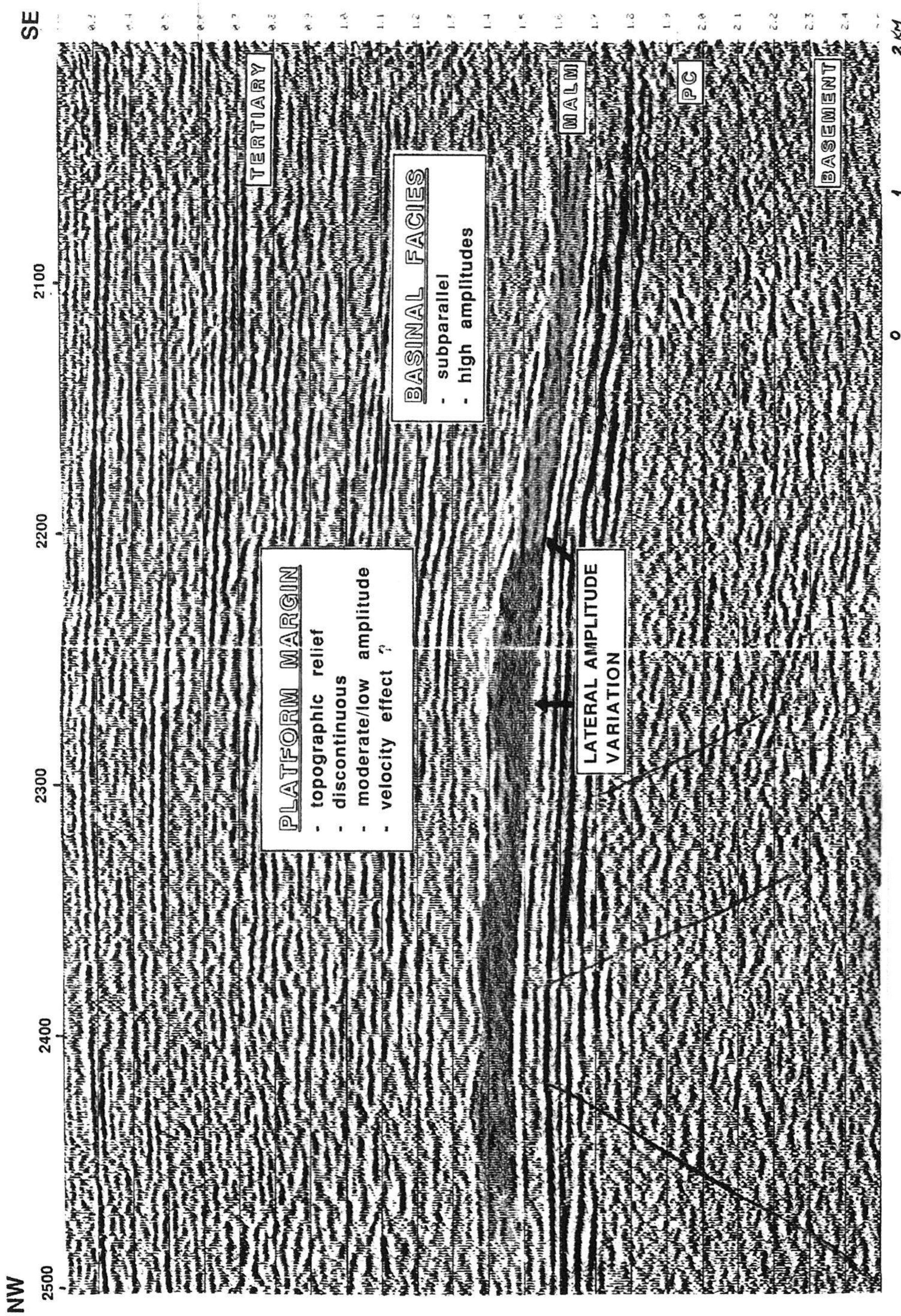

Fig. 14. Seismic expression of a possible reef body (Swiss Molasse Basin)

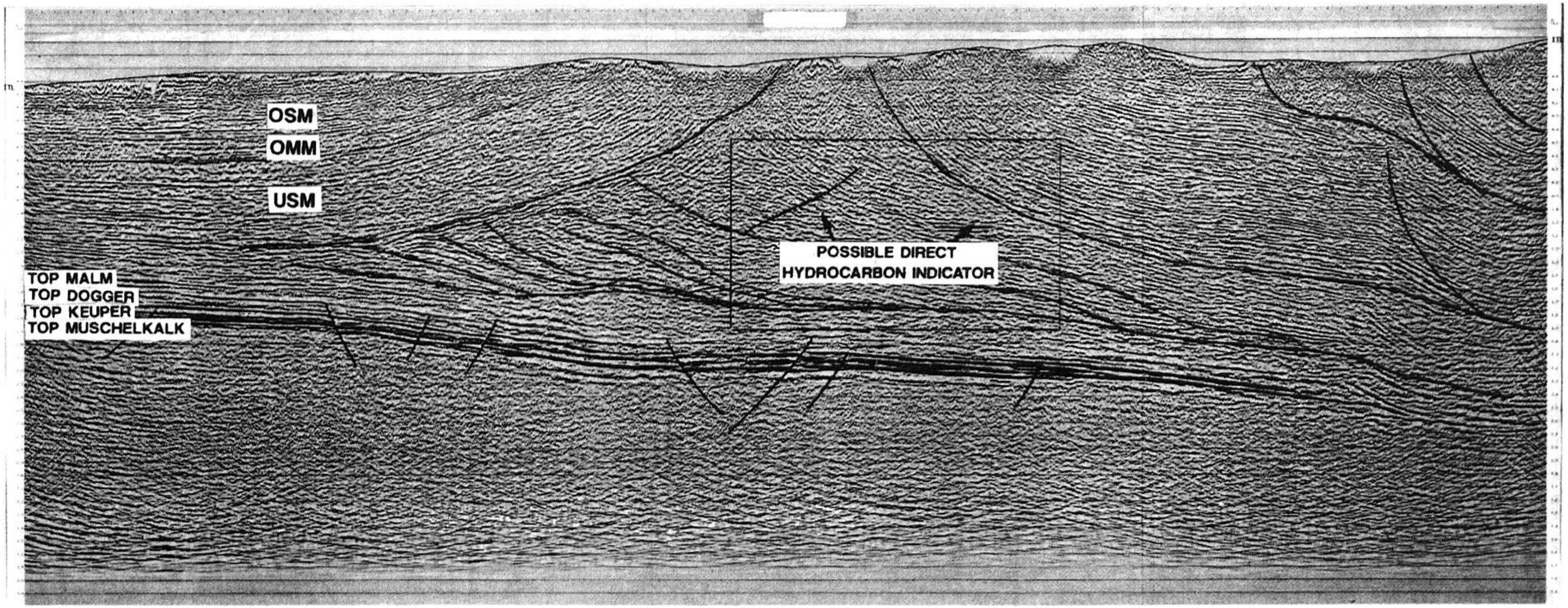

Fig. 15. Seismic line crossing the subalpine triangle zone, showing amplitude anomalies (Swiss Molasse Basin)

large regional sturctures and – in the western part of the Basin – the presence of a regional Triassic evaporite seal (Fig. 12).

Modern seismic and processing techniques will have to play the lead role to a conclusive evaluation of the hydrocarbon potential in the Swiss Molasse Basin. Fig. 13 shows the dramatic improvement achieved by reprocessing of 1976 seismic lines. Higher resolution seismic might allow the recognition of Jurassic reef bodies (Fig. 14), the mapping of targets below the Triassic salt and the unravelling of the subalpine triangle zone (Fig. 15) (see Müller et al. 1988). All these targets could not be properly defined or even recognized on the previously available geophysical data. Possible direct hydrocarbon indications may add an additional tool to the evaluation, especially along the alpine front (Fig. 15). Seismic amplitude anomalies, as they are recorded in the seismic line shown, may be related to hydrocarbon accumulations. While technically a must, the need for good seismic control combined with relatively high drilling costs along the Alpine front will, however, constrain the short term economical possibilities of the industry.

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