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# Tectonic style and pressure distribution at the northern margin of the Alps between Lake Constance and the River Inn

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With 10 figures


## Zusammenfassung

Die von der Erdöl- und Erdgasindustrie im Bereich des Alpennordrandes durchgeführten Untersuchungsarbeiten brachten neue Ergebnisse zum tektonischen Bau. So stellt sich in zwei N-S-Profilen nördlich von Hindelang (Bayern) und über die Tiefbohrung Sulzberg 1 (Vorarlberg) die Stirn der Faltenmolasse als Triangelzone dar, wie sie von JONES (1982) aus den Foothills der Rocky Mountains beschrieben wird.

Tiefbohrungen auf Erdöl und Erdgas haben verbreitet überhydrostatische Porendrücke mit Gradienten bis 2,5 bar/10 m angetroffen. Es wurden Druckprofile aus den Bohrungen Sulzberg 1, Hindelang 1, Staffelsee 1, Miesbach 1 und Bromberg 1 nach stratigraphisch-lithologischen Gesichtspunkten analysiert, regionaltektonisch zugeordnet und interpretiert. Es zeigt sich, daß die Überdrücke in der Vorlandmolasse durch Kompaktion entstanden sind, während diejenigen unter den Decken tektonische Ursachen haben.

## Abstract

Hydrocarbon exploration in the Molasse basin and the Alpine thrust belt has provided new information on the tectonic structure of the foreland margin of the overthrust belt. Two N-S cross-sections show the front of the Folded Molasse as a so-called Triangle Zone in the area north of the Hindelang 1 well (Bavaria) and the Sulzberg 1 well (Vorarlberg). The Triangle Zone was described and defined by JONES (1982) for the Alberta Foothills in Canada.

Oil and gas wells commonly encountered overpressured zones with pressure gradients up to 2.5 bar/10 m. The pressure profiles from the Sulzberg 1, Hindelang 1, Staffelsee 1, Miesbach 1 and Bromberg 1 wells were analysed stratigraphically and lithologically with respect to the tectonics of the region. It can be concluded that the overpressures in the Foreland Molasse were caused by compaction, where those within the thrust belt were caused by tectonics.

## Résumé

Les travaux d'exploration entrepris par l'industrie du pétrole dans le bassin molassique et dans la bordure septentrionale des Alpes ont conduit à de nouveaux résultats en ce qui concerne les structures tectoniques de cette région. Dans deux profils nord — sud établis dans la région, respectivement au nord de Hindelang (Bavière) et au nord de Sulzberg (Vorarlberg), le front de la molasse plissée se présente comme une »zone triangulaire« du type défini par JONES (1982) dans les Foothills d'Alberta au Canada.

Des forages pétroliers profonds ont fréquemment recontré des pressions interstitielles hyperhydrostatiques avec des gradients pouvant atteindre 2,5 bars / 10 m.

Les profils de pression relevés dans les sondages de Sulzberg 1, Hindelang 1, Staffelsee 1, Miesbach 1 et Bromberg 1 ont été analysés au point de vue stratigraphique et lithologique et placés dans le cadre tectonique de la région. Il en résulte que les surpressions dans la molasse d'avant-pays (Vorlandmolasse) sont dues à la compaction et que celles des formations recouvertes par les nappes sont d'origine tectonique.

## Краткое содержание

При исследованиях, проведенных в регионе северного альпийского края по инициативе нефте- и газопромышленных фирм, установили новые данные о тектоническом строении этого региона. Так в двух профилях, простирающихся один с севера на юг севернее Hindelang / Бавария /, а другой через глубинную скважину Sulzberg 1 / Vorarlberg / передний фронт моляссовых складок представляет собой треугольник, подобный описанному Jones' ом в 1982 году в Foothills Скалистых гор.

Сверхглубокие скважины при проспекции на нефть и газ натолкнулись на широко распространенные сверхвысокие давления в порах пород с градиентом до 2,5 бар/10 м. Профили буровых скважин проанализировали с точки зрения стратиграфии и литолигии, классифицировали по региональной тектонике и провели интерпретацию. Выяснилось, что сверхдавления в моляссах предгорья появились в результате уплотнения, а в покровном чехле –в следствие тектонических процессов.


## Introduction

In the early days of hydrocarbon exploration in the Molasse, several exploratory wells were drilled in the Alpine Thrust Belt (Fig. 9).

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At the same time, drilling activity was moved southwards, accompanied by extensive seismic surveys. A series of key wells were completed in the Folded Molasse, as well as in the upper nappes such as the Helvetikum and Kalkalpin (BACHMANNet al. 1981: Fig. 1, Tab. 1; MÜLLER 1985).

Drilling and geophysical surveys on the northern margin of the Alps confirmed some of the generally accepted interpretations, but also produced some new aspects. Two new interpretations will be presented in this paper.

### 1. Tectonic Structure of the Thrust Front, as seen in the Folded Molasse in the Sulzberg 1 Well

The Folded Molasse Zone with its overthrust and imbricate structure is part of the Alpine thrust belt (MÜLLER 1984: Fig. 1 + 2). We therefore define the northern margin of the Alpine thrust belt at the fault

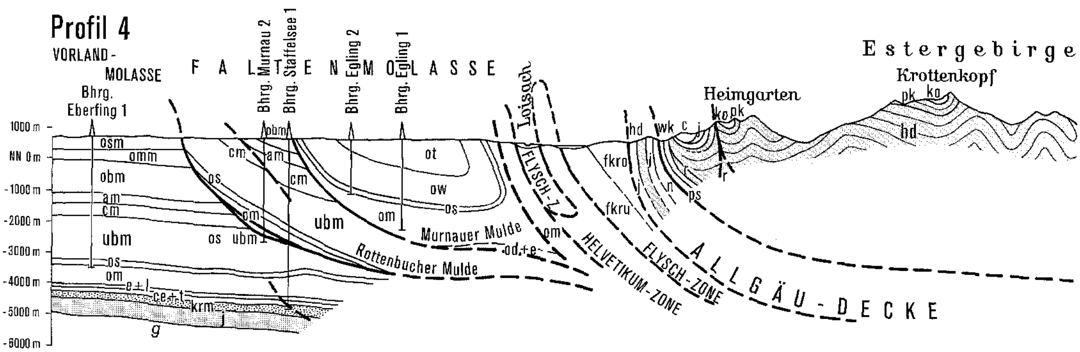


Fig. 1. N-S cross-section through the northern Alpine margin near Murnau from DOBEN & SCHWERD (1981: Taf. 6) after MÜLLER (1970, 1978).

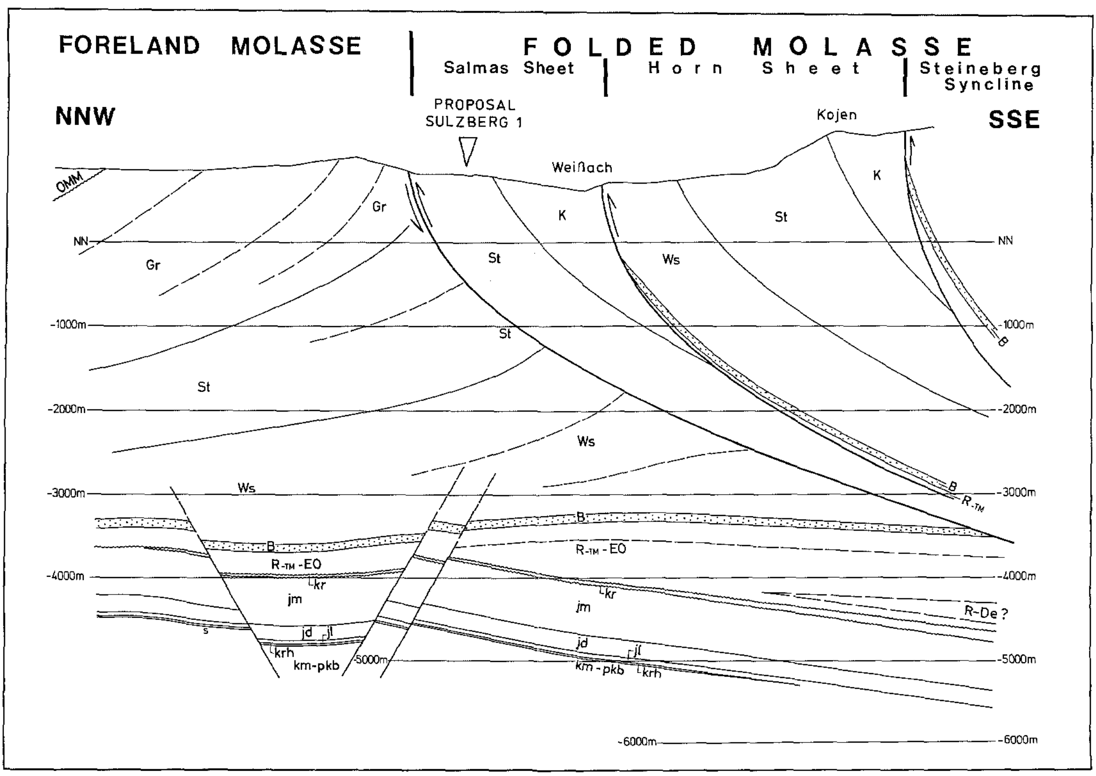


Fig. 2. NNW-SSE cross-section through the Sulzberg 1 well. The main overthrust was expected at a depth of 1300 m. NN = sea level

which separates the allochthonous Folded Molasse from the autochthonous Foreland Molasse. This conception has the advantage of clearly separating the allochthonous and autochthonous regions, whereas the older interpretation places the northern margin of the Alpine Thrust Belt at the thrust plane between the Helvetikum and the Molasse or between the Flysch and the Molasse, i.e. within the allochthonous nappes. The question of where the northern margin appears at the surface will be dealt with at the end of this section 1.

Since most overthrusts dip subvertically to vertically at the surface, a geological cross section was constructed as shown in Fig. 1.

The assumption of a steeply dipping overthrust was used in the geological model for site proposal for the Sulzberg 1 well location (Fig. 2). This was not contradicted in any way by the interpretation of the seismic section (Fig. 3 upper profile), which showed the main thrust at a depth of 0.6 seconds (appr. 1300 m). In actual fact, the fault separating the allochthonous and autochthonous Molasse was penetrated at a depth of over 4000 m. Since this result was not compatible with the initial drilling concept, new ideas as to the tectonic evolution and structure of the thrust zone had to be developed.

A new interpretation was found in the model developed for the foreland margin of the Canadian Rocky Mountains by JONES (1982) and others before him (DAHLSTROM 1970, BALLY et al. 1966). Extensive hydrocarbon exploration has made this area one of the best studied thrust belts in the world. This model is based on the development of an »ideal«, so-called Triangle Zone (Fig. 4). This zone is formed by a wedge-like stack of blind thrust slices being thrust between well defined upper and lower detachments into the foreland of the Rocky Mountains (Fig. 5).

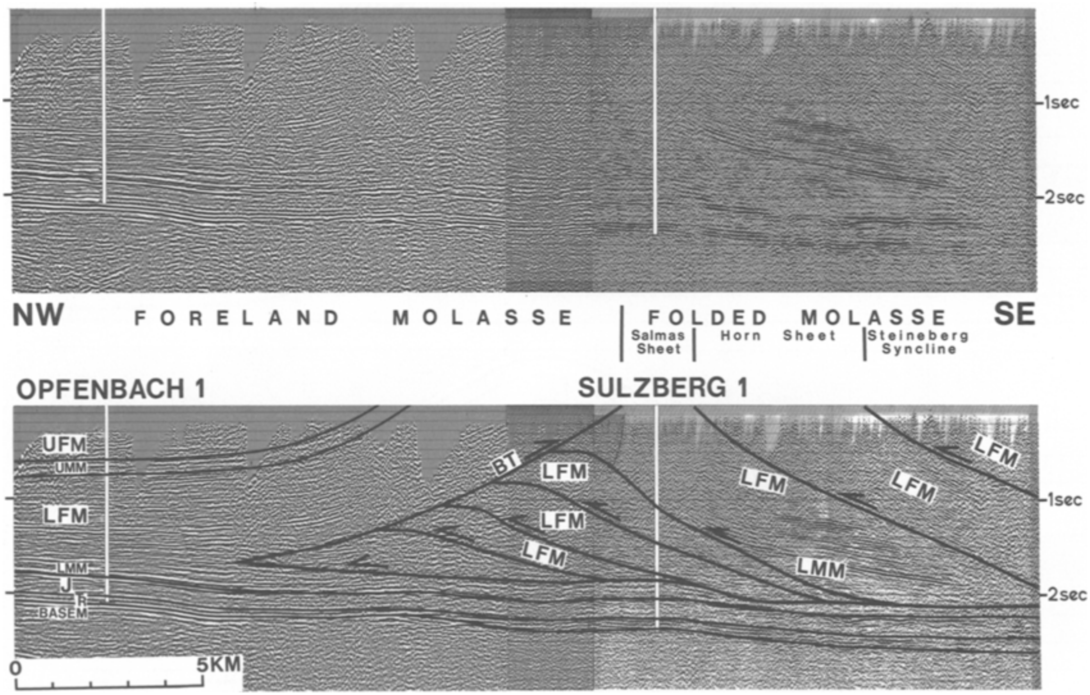


Fig. 3. Top: Not interpreted section . It was assumed that the seismic reflection of the overthrust fault which surfaces to the northwest of the location would be met in the well at a depth of 0.6 seconds.
Bottom: Interpreted section. On the right are the geologically mapped imbricate thrust sheets of the Molasse. Below the Salmas sheet are the three thrust slices found in the Sulzberg 1 well. Below these and to the NW there is a fourth thrust slice. On the left are the upper detachment forming a backthrust (BT) and the »Aufgerichtete« (Uptilted) Foreland Molasse.

UFM = Upper Freshwater Molasse
UMM = Upper Marine Molasse
LFM = Lower Freshwater Molasse
LMM = Lower Marine Molasse
J = Jurassic
TR = Triassic

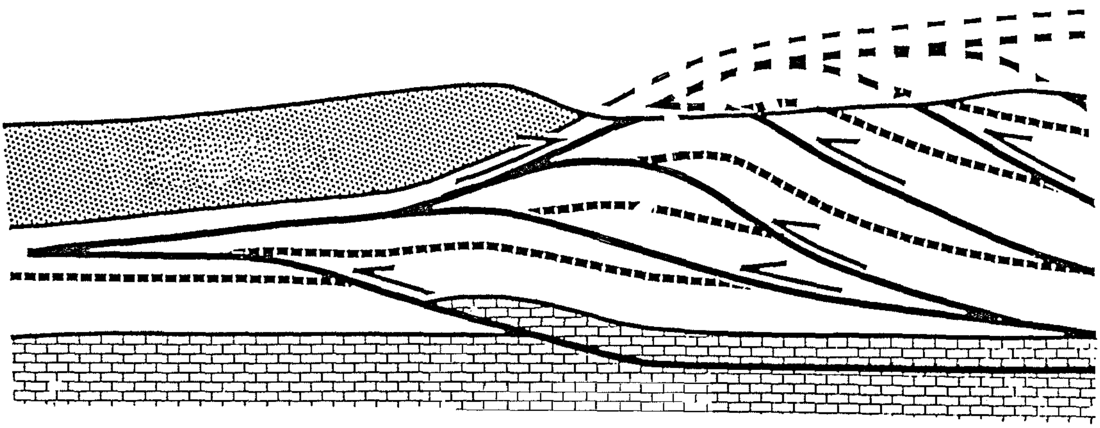

Fig. 4. The »ideal« Triangle Zone (after JONES 1982: Fig. 16). Note the lateral movement of the blind slices toward the left and the anticlinial uplift above.

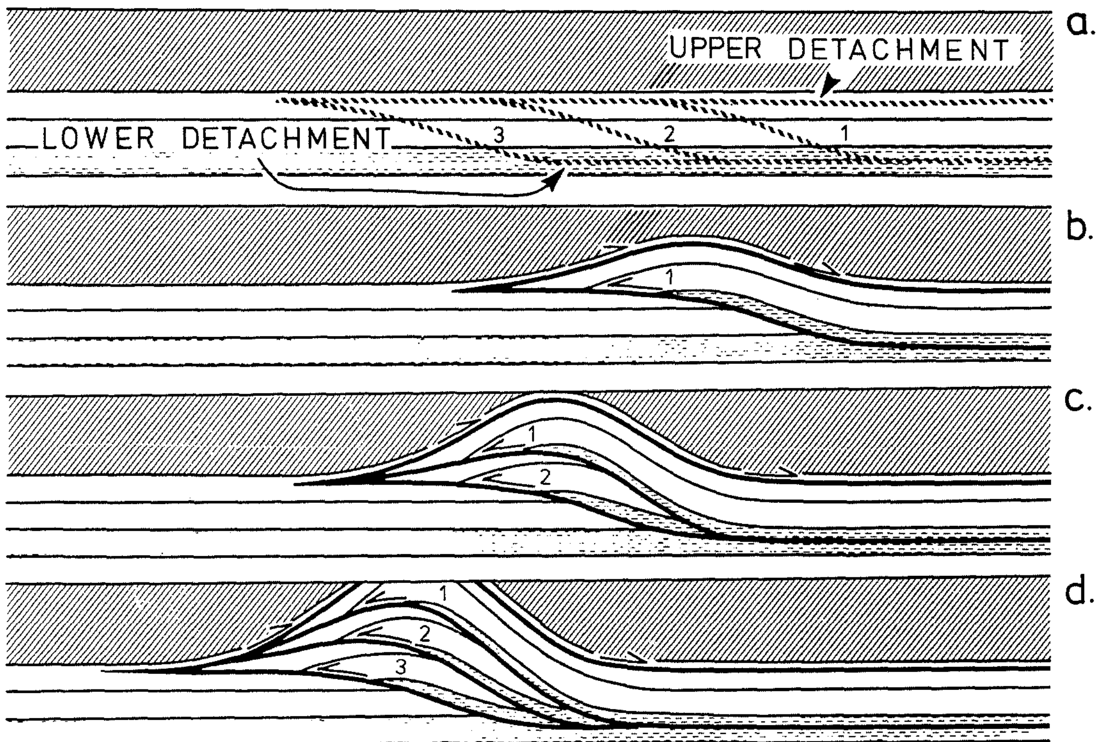


Fig. 5. Simulation of the development of a Triangle Zone (after JONES 1982: Fig. 17).

Tectonic analysis of the data obtained from the Sulzberg 1 well making use of JONES' model led to reconstruction of the structure as shown in Figure 6. The remaining question was whether this reconstruction was compatible with existing seismic data. Figure 3 shows a comparison of the interpreted and uninterpreted seismic sections which have the same orientation as Figure 6. It is possible to divide the allochthonous substratum beneath the Salmas sheet into four thrust slices, of which the three higher slices have been proved in the Sulzberg 1 well. Additionally, the wedge, which is thrust into the autochthonous Foreland Molasse can be depicted with both the upper and lower detachments. This seismic interpretation supports the geological interpretation and demonstrates the validity of the JONES model for the Vorarlberg region.

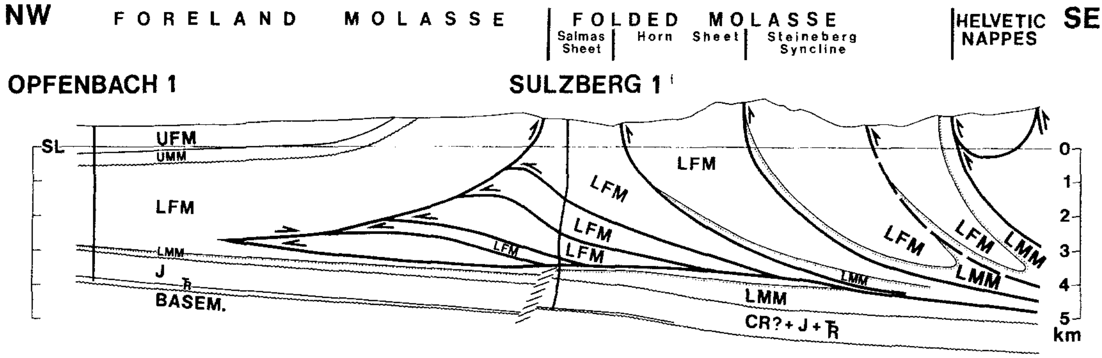


Fig. 6. NW-SE cross-section of the Alpine Margin using the JONES model. Based on surface mapping and data from the Sulzberg 1 well.

Figure 7 shows the striking similarity of the structure in the Alberta Foothills to that of the Alpine margin in Vorarlberg. Analysis of additional seismic sections showed that this structural interpretation could well be characteristic of other sections of the Alpine margin. Figure 8 illustrates this with an example of a N-S cross-section north of the Hindelang 1 well. In this section the thrust slices of the overthrust front which are thrust into the autochthonous Molasse are clearly recognisable, as shown in Figure 7. The thrust consists of a wedge bounded above and below by the upper and lower detachments. The imbricated thrust sheets of the Folded Molasse and Helvetic Flysch, together with the higher nappes of the Helvetikum, Flysch and Kalkalpin, overly one another successively southwards.

The exact location of the northern margin of the Alpine tectonic region can be identified at the northernmost limit of the blind thrust slices i.e. of the northerly directed thrust wedge (Fig. 3, 6 and 8). This point at which the upper and lower detachments separate the »Aufgerichtete Molasse« (Uptilted Molasse) from the underlying older Molasse is clearly recognisable seismically, but cannot be located at all without the help of geophysics. For practical reasons it is therefore recommended that the northern margin be taken as the outcrop of the backthrust at the surface (Fig. 3: BT).

The northern extent of the buried thrust wedge can be estimated as roughly equal to the width of outcrop of the Uptilted Foreland Molasse.

## 2. The Pore Pressure Distribution in the Northern Parts of the Thrust Zone and Adjacent Foreland, and its Interpretation

The deep wells drilled for hydrocarbon exploration and completed in the Molasse and Alpine thrust zone often met overpressured zones. Figure 9 shows isolines of the maximum pressure gradients measured in these wells. The increase in overpressure from north to south towards the Alpine thrust belt, as well as the similar trend of the isolines and of the northern Alpine margin is clearly recognisable. The highest known pressures encountered in this region reached a value of 2.5 bar/10 m (Hindelang 1 well).

Let us look at a few wells (Fig. 10) with regard to the pressure characteristics found in them. The well locations are shown in Figure 9.

The Bromberg 1 well, drilled through the Autochthonous Foreland Molasse and the underlying Mesozoic formations was abandoned in the Crystalline Basement. Hydrostatic pore pressures remained normal down to the Middle Oligocene/Lower Oligocene boundary. Thereafter, the pore pressure increased in three stages reaching a maximum pressure gradient of 1.95 bar/10 m. In this particular case it is assumed that the pressure would have fallen to a relatively normal value in upper part of the Cretaceous. Similar overpressures and increases in pressure were also encountered in other wells drilled in the Foreland Molasse.

The Miesbach 1 well also encountered overpressured zones. These were observed after drilling through the base of the thrust pile, i.e. at a similar stratigraphic level as in the Bromberg 1 well. The increase in pressure reached a comparable level to that in the Bromberg 1 well. The high pressure, however, continued into the Lower Cretaceous and only fell on approaching the Malm.

In the Staffelsee 1 well overpressure was encountered in the Oligocene sands of the Autochthonous Molasse. In this case, the pressure gradient rose to 1.65 bar/10 m. The maximum observed was 2.2 bar/10 m, just above the base of the Molasse.

The overpressured zones in the Sulzberg 1 well were first encountered in the lower beds of the Allochthonous Folded Molasse and reached a maximum value of 2.33 bar/10 m in the basal parts of the Autoch-

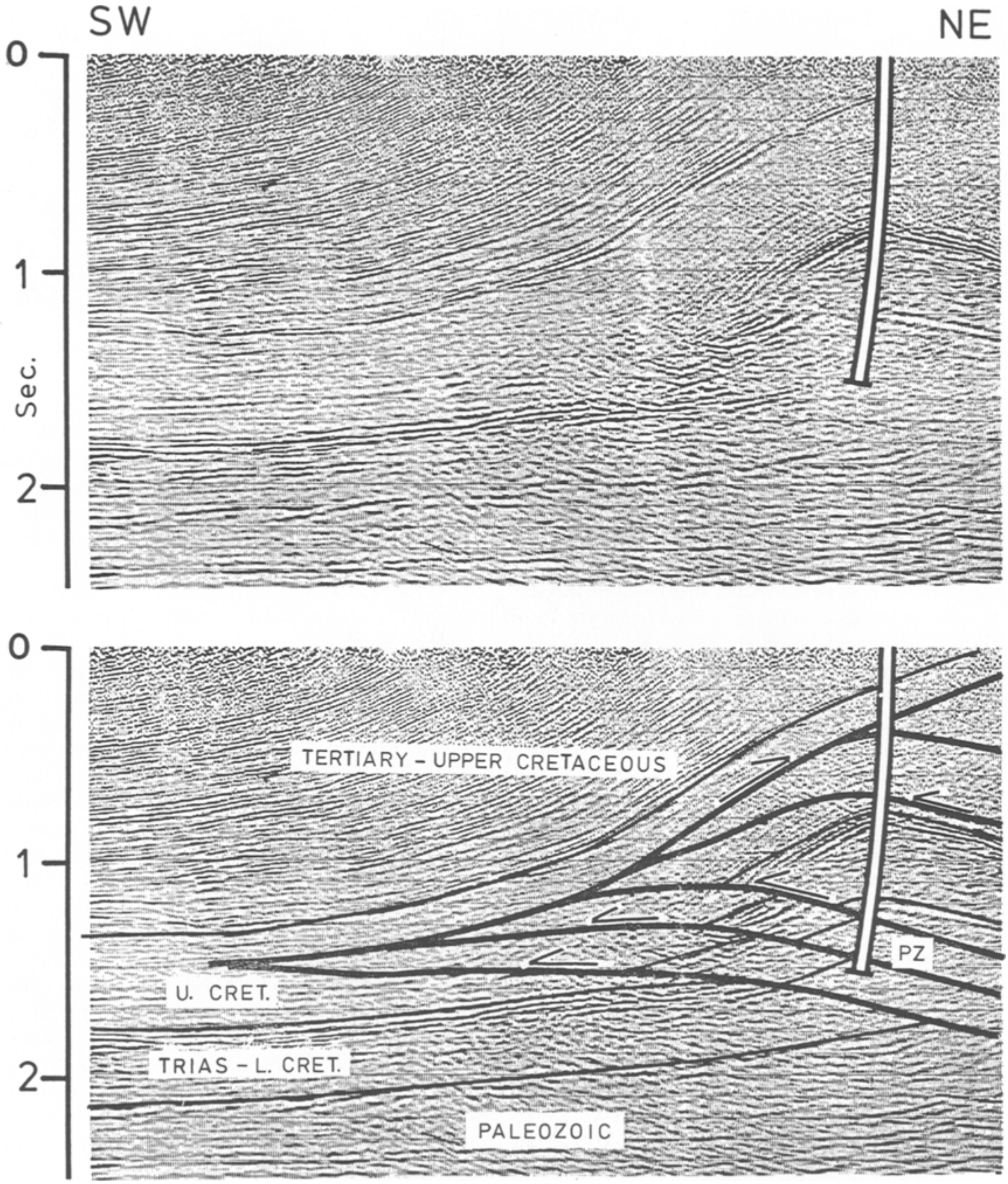


Fig. 7. The Findley Structure on the margin of the Rocky Mountains in N. Alberta (after JONES 1982: Figs. 14–15). The upper diagram is not interpreted. Note the lower interpreted diagram is similar to that of the cross-section through the Sulzberg 1 well (see Fig. 3).

thonous Molasse. However, in contrast to the Bromberg 1 well, the pressure remained high (2.2 bar/10 m) even in the Mesozoic formations.

Finally, in the Hindelang 1 well the overpressures first appeared in the lower Helvetikum. Then pressure increased rapidly in the Helvetic Flysch, a nappe between the Helvetikum and the Molasse nappes. The pressure gradients encountered in this well reached the highest values, with a maximum of 2.5 bar/10 m.

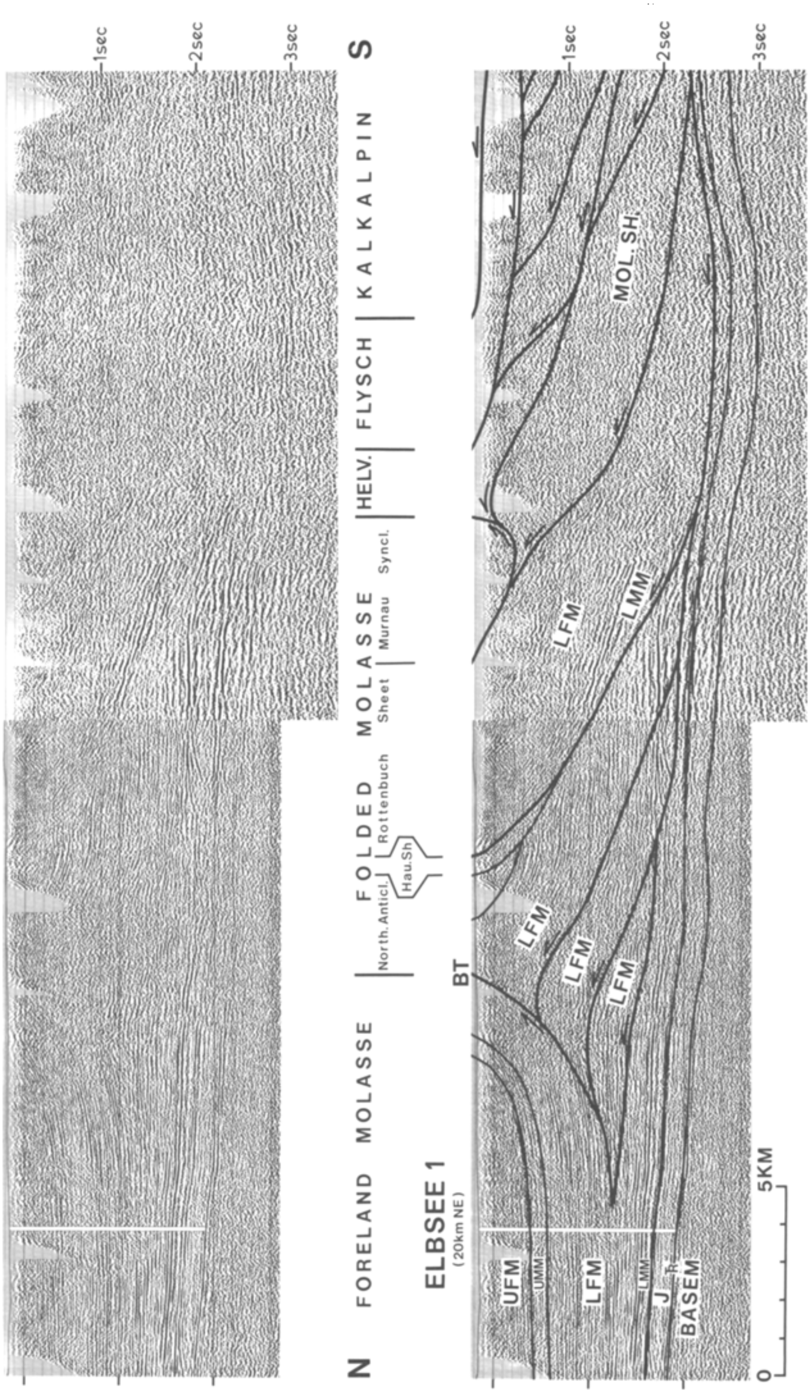


Fig. 8. Top: Cross-section to the north of Hindelang. The upper and lower detachments are clearly discernable south of the Elbsee 1 well.
Bottom: Several thrust slices can be seen in the Triangle Zone. (c.f. Figs. 3 and 7).
Surface Geology after SCHWERD(1983)
Hau. Sh. = Hauchenberg (thrust) sheet.
For further abbreviations, see fig. 3.

In the Bromberg 1 well, which is used here as the representative well of the Foreland Molasse, the overpressure profile shows high pressure zones in Lower Oligocene sands mostly limited to isolated sand lenses in a very rapidly sedimented, deeply buried basin. It can be assumed in this case that the overpressured zones were caused by compaction pressures, i.e. »fossil« overpressures. On account of the rapid sedimentation, this overpressuring is as might be expected, limited to certain lithofacies in the Molasse.

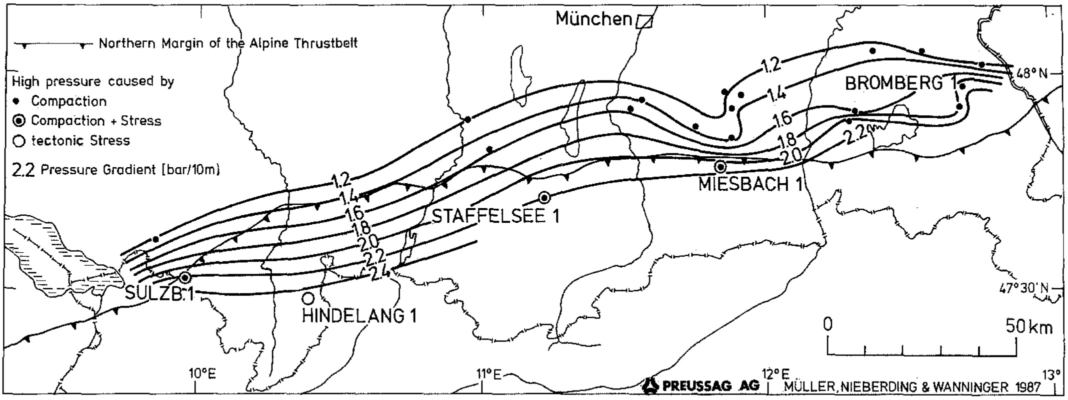


Fig. 9. Pressure-gradient isoline map of the distribution of overpressures. These values are based on the specific gravity of the drilling fluids used in each well.

In the Staffelsee 1 and Miesbach 1 wells, the overpressured zones first appear in the Oligocene sand lenses, as in the wells drilled in the Foreland Molasse. However, the overpressured zones continue below the base of the Molasse and well into the Mesozoic formations.

We believe that in the wells near the front of the thrust zone, overpressuring results from a combination of tectonic pressure and compaction pressures.

The overpressured zones in the Hindelang 1 and Sulzberg 1 wells, however, are most probably purely of tectonic origin. These overpressured zones here are restricted to discrete tectonic units, which are sealed and have no contact with the surface. They are distributed throughout thick sequences comprising a range of lithologies.

Figure 9 shows the regional distribution of the overpressured zones. This plot is based on the specific gravity of drilling fluids used in each well. Although a considerable number of wells have been drilled in this area, the northern limit of the hydrostatic overpressured region cannot be drawn in exactly. This is due to the fact that the specific gravity of the drilling fluid used is always adjusted to produce pressures well in excess of the pore pressure. A possible northern limit to the region has been suggested by LEMCKE (1979: Fig. 1).

The pressure-gradient isoline trend shows higher overpressures in the eastern Alpine Foreland than in the western region. These observations correlate with the rate at which the Molasse Basin sank. The total thickness of the beds in the west is about 3700 m, with approximately 100 m Lower Oligocene, whilst the total thickness in the east approaches 4400 m (measured in the Endorf 2 well), with something like 2000 m of Lower Marine Molasse. Information on the regional thickness variations is given by LEMCKE (1973: Appendix 2, Fig. 1; 1984 Fig. 10). As has already been indicated, there is a direct association between the rate of sedimentation and the high pressure zones of the Lower Marine Molasse, particularly those in the Lower Oligocene.

The rate of subsidence was at its greatest in the south of the region, where the highest compaction pressures are found. The fact that the overpressured zones in the overthrust region owe their origins to tectonic stress is evidenced by the similar trend of the pressure-gradient isolines and the northern Alpine margin. The difference between the regions which are largely compaction-pressure influenced and those regions in which the overpressures are stress generated can be shown by comparing the western and eastern parts of Figure 9. In the west, south of the thrust front, the compaction pressure is small in comparison with the steep increase of the stress-generated overpressure, whereas in the east, even the very thick Lower Oligocene Molasse shows exceptionally high compaction pressure gradients.

The mechanics of overpressured zones due to tectonic stress is discussed by GRETENER (1981), who emphasises the close relationship between sediment thickness, pore pressures, the processes of overthrusting and associated isostatic movements. GREINER & LOHR (1980) demonstrate the mutual influence of tectonic stress and seismic velocities. Their ideas on velocity distribution closely approach our own conclusions shown in Figure 9. Here, in the wells drilled through the nappes, we meet a situation characterised both by »fossil« overpressures and by pressure build up of recent age. GREINER & LOHR (1980: p. 10 ff) argue, on the basis of observations in mines, stress measurements

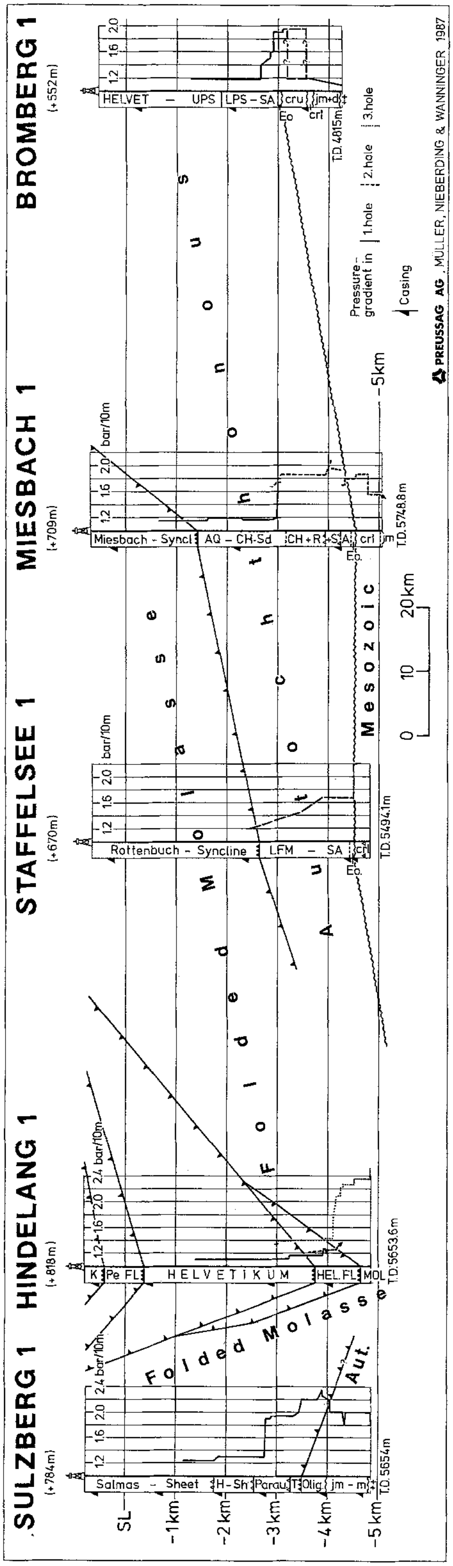


Fig. 10. Pore pressure gradients from the wells on either side of northern Alpine margin (obtained from the specific gravity of the drilling fluids used in each well and from overpressure predictions for the Hindelang 1 and Sulzberg 1 wells).

Tectonic units

| | | |
|---|---|---|
| K | = | Kalkalpine Zone |
| Pe Fl | = | Penninic Flysch |
| Hel. Fl | = | Helvetic Flysch |
| Mol. | = | Molasse |
| H-Sh | = | Hauchenberg Sheet (Molasse) |
| Parau | = | Parautochthonous Sheet (Molasse) |
| T | = | Tectonic slice (Molasse) |

Stratigraphic units:

| | | |
|---|---|---|
| Helvet | = | Helvetian (M. Miocene) |
| Aq | = | Aquitanian (L. Miocene) |
| Ch | = | Chattian (U. Oligocene) |
| UPS/LPS | = | U/L Puchkirchen-Formation (L. Miocene to Oligocene) |
| LFM | = | L. Freshwater Molasse (Oligocene) |
| R | = | Rupelian (M/L Oligocene) |
| Sa | = | Sannoisian (L. Oligocene) |
| Eo | = | U. Eocene |
| cru/crl | = | U/L Cretaceous |
| jm+d | = | Malm + Dogger (Jurassic) |
| m | = | Muschelkalk (M. Triassic) |

and study of the distribution of seismic velocities that the tectonic pressures are of recent origin. The overpressures in the thrust zone are further proof that the process of overthrusting is still continuing today.

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