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Thermal Diagenesis in the Swiss Molasse Basin:
Implications for Oil Generation

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Thermal diagenesis in the Swiss molasse basin: implications for oil generation¹

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Clay mineral transformations during burial are indicators of the degree of diagenesis of sediments. Diagenetic zonations in numerous wells of the Swiss molasse basin are defined by the disappearance of smectite and (or) the appearance of either corrensite or irregular 2:1 mixed layers. The maximum level attained in the thickest molasse sections corresponds to organic matter maturation suitable for hydrocarbon generation. Reconstructed on the basis of the clay mineral transformation data, a burial history of the basin is proposed.

Les transformations subies par les minéraux argileux lors de l'enfouissement constituent des indices du degré de diagenèse des sédiments. Les zonations diagenétiques dans de nombreux puits du bassin molassique suisse sont définies par la disparition des smectites et (ou) par l'apparition soit de la corrensite ou d'interstratifiés irréguliers du type 2:1. Les transformations maximales atteintes dans les coupes les plus épaisses de la molasse correspondent à une maturation de la matière organique suffisante pour engendrer des hydrocarbures. L'histoire de l'enfouissement des sédiments dans le bassin est retracée à l'aide de renseignements obtenus sur la transformation des minéraux argileux.

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Introduction

The degree of burial diagenesis can be determined by studying organic matter and clay mineral transformations, particularly with reference to changes of 2:1 layer silicates. In the case of the molasse basin of Switzerland (Figs. 1, 2), where the smectite is an important constituent of the sediment, our purpose is to set up a zonation of the diagenesis based on the transformation pathway of smectite to illite.

The mineralogical aspects of diagenesis in sedimentary basins have been discussed by various authors, for example, Weaver (1960), Burst (1969), Dunoyer de Segonzac (1964, 1968, 1969), Perry and Hower (1970, 1972), Heling and Teichmüller (1974), Foscolos *et al.* (1976), and Kübler (1980).

The major first step in the process of "illitization" is the transformation of smectite to interstratified 2:1 layer silicates. This transformation has been correlated with the onset of the oil window and with a vitrinite reflectance value of approximately 0.5% of R_o (in oil), (see Fig. 3; Héroux *et al.* 1979; Kübler *et al.* 1979a; Kübler 1980). In the Sverdrup Basin (Arctic Islands) the level of smectite transformation has been correlated with the onset of the organic extract increase, and with a

vitrinite reflectance value of 0.5% of R_o (Powell *et al.* 1978). But where the organic matter is woody-herbaceous, significant hydrocarbon generation does not occur below a vitrinite reflectance value of 0.7% of R_o . The changes in both clay minerals and organic matter are attributed to the heat effect encountered during burial. Besides this indicator, the crystallinity index of illite is another criterion useful in the study of stepwise burial (Kubler 1964, 1967, 1968).

In this study mineralogical investigations have been used to set up a diagenetic scheme for the Swiss molasse basin in order to deduce the subsidence history and to predict the hydrocarbon generation potential from possible source rocks in this part of Switzerland.

Samples

Molasse is a succession of rather immature clastic deposits ranging from shales to conglomerate. To this allochthonous sediment were sporadically added autochthonous deposits such as lacustrine limestone and coal. The molasse deposits are Tertiary in age. The oldest rocks are of Rupelian age (middle Oligocene) and overlie the Mesozoic series with a major unconformity. The top of the molasse section is an erosional surface. The youngest known rocks belong to the Tortonian (Upper Miocene), although younger rocks (up to Pliocene) may have existed prior to erosion. The clastic deposits were mostly derived from erosion of the Alpine orogen (Fig. 2), and were deposited in alternating shallow marine and fluvio-terrestrial (freshwater) environments.

The average composition of the molasse deposit rock, based on X-ray diffraction analyses of 2088 samples

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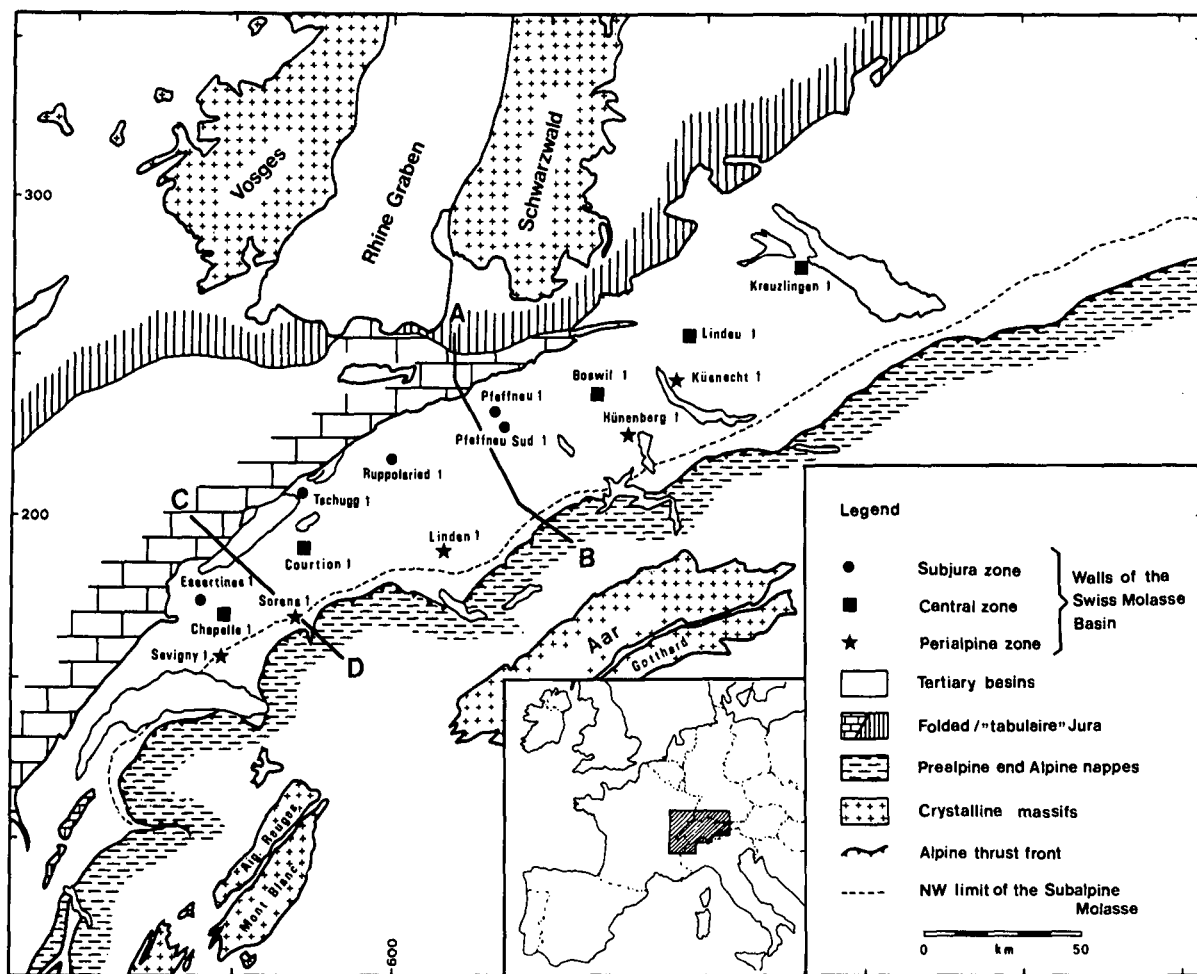


FIG. 1. Well locations and tectonic setting in the Swiss molasse basin. Cross sections A-B, C-D: see Fig. 2.

from 18 wells (Monnier 1979), is as follows:

Mineral	Percentage
Quartz	27.3±7.2%*
K-feldspar	4.5±3.2
Plagioclase	14.8±8.0
Calcite†	20.0±7.1
Dolomite	6.2±5.6
Total	72.8‡

*One standard deviation.

†Includes one limestone sample. The balance of carbonate occurrence is as debris and cement.

‡The balance of 27.2% is attributed to the clay mineral content.

conforms to a feldspathic sandstone with a calcareous-argillaceous cement, namely, a macigno after the definition of Cayeux (1929) (Bersier 1958). The mineral concentration varies over a narrow range with small changes in the amount of argillaceous, feldspathic, quartzose, and carbonate components. This average composition defines the chemical environment, which indicates ions available from non-clay minerals during clay transformation.

From 15 drilled wells through the molasse section (Fig. 1) 1500 samples, mostly cuttings, were selected for X-ray diffraction determination of the clay fraction. For eight of the wells the sampling interval was 20 m, but it was 10 m in the Linden 1 and Küsnacht 1 wells, and 50 m in the remaining five wells (Hünenberg 1, Boswil 1, Pfaffnau Sud 1, Pfaffnau 1, Essertines 1).

Experimental

Based upon the average composition, the molasse

From each sample a carbonate-free oriented clay

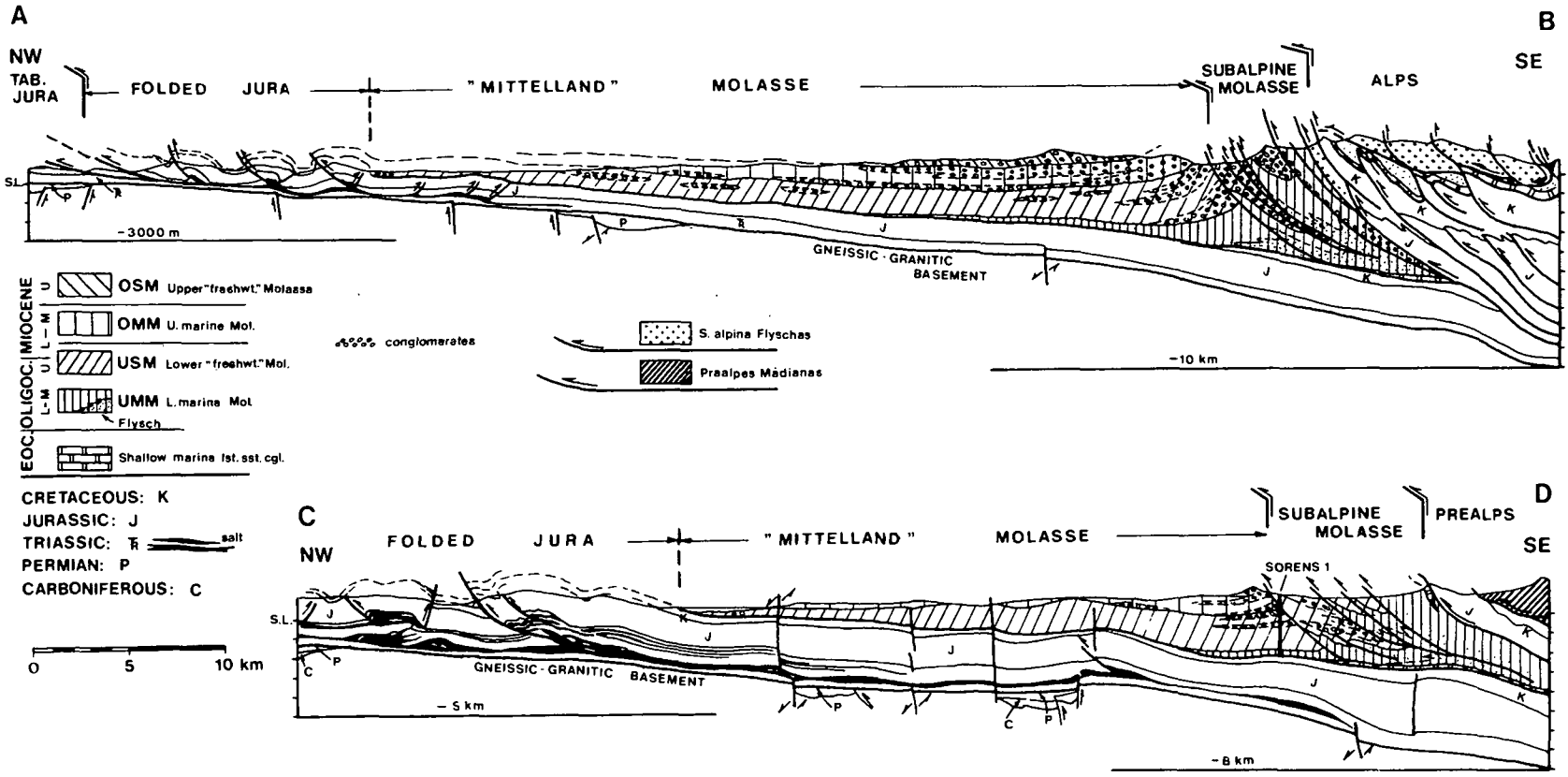


FIG. 2. Cross sections through the Swiss molasse basin. Location: see Fig. 1. (Simplified after D. Rigassi 1978, in Weidmann 1979.)

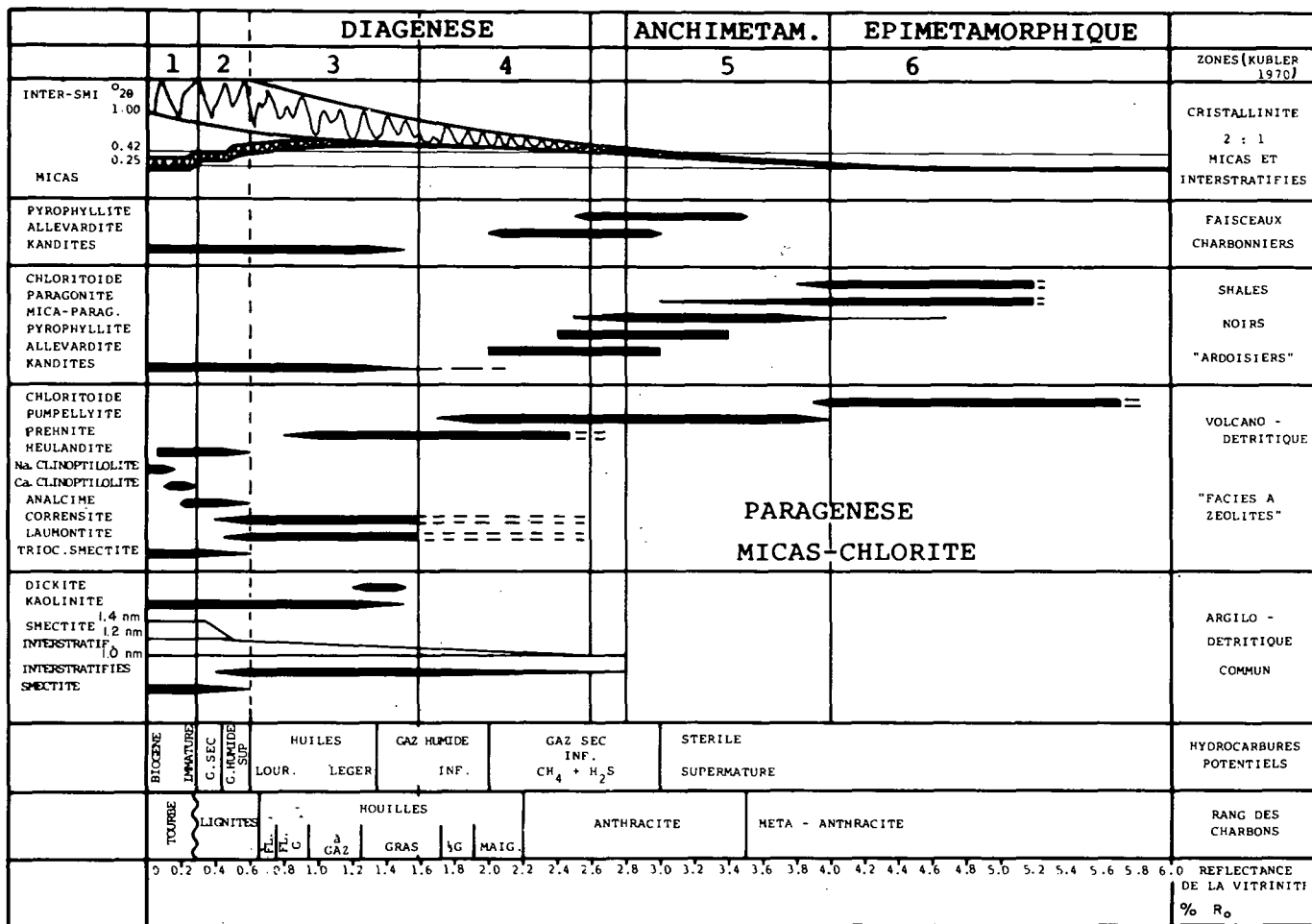


FIG. 3. Table comparing mineral associations, zones of hydrocarbon potential, and vitrinite reflectances (after Kübler *et al.* 1979b).

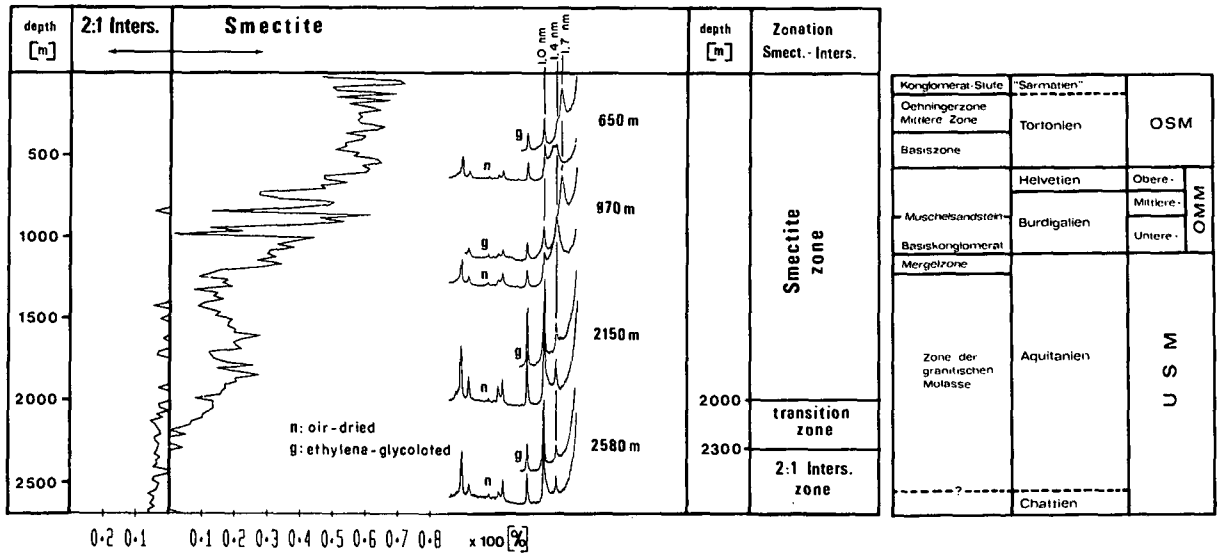


FIG. 4. Smectite disappearance (right-hand axis), 2:1 mixed layers (left-hand axis) in Künsnacht 1 well, and lithostratigraphic column (after Büchi *et al.* 1965).

fraction ($<2.0 \mu\text{m}$) was analyzed by X-ray diffraction after air drying and then after ethylene-glycol saturation. A Philips diffractometer was used with a vertical goniometer, $\text{CuK}\alpha$ radiation, slits $1^\circ - 0.2 \text{ mm} - 1^\circ$, speed of $(2^\circ 2\theta)/\text{min}$, and chart speed of 1200 mm/h .

The concentration of phyllosilicate was obtained by measuring the heights of the following peaks on the ethylene-glycol saturated sample: smectite = 1.73 nm ; illite = 1.0 nm ; corrensite $\approx 1.55 \text{ nm}$; kaolinite-chlorite = 0.716 nm . For the irregular 2:1 mixed layers, the height of the plateau above the background between 1.0 and 1.4 nm was taken.

The ratio kaolinite/chlorite was obtained from the ratio of the heights of the 0.357 and 0.354 nm peaks in the air-dried samples. The peaks represent the 002 and 004 peaks for kaolinite and chlorite, respectively. The sharpness index (width at half-height of the 1.0 nm peak (Kübler 1964) was measured on air-dried samples (IAN) and after ethylene-glycol saturation (IAG).

Minor minerals (goethite, pyrite, feldspar, quartz, etc.) were present but are not discussed.

Mineral composition of the fine fraction ($<2.0 \mu\text{m}$)

The fine clay fraction is composed of smectite, mixed layers, illite-mica, and chlorite; some samples have corrensite. Corrensite was detected in the western part of the basin (see wells Savigny 1, Chapelle 1, Courtion 1, Fig. 1). Kaolinite, which is present in the Bavarian part of the molasse basin (Füchtbauer 1964; Monnier 1979) and the High Rhine and the Rhondanian Basins (Sittler 1965), was never encountered in the Swiss part of the molasse basin. This absence of kaolinite confirms similar observations of Kübler (1970). As a result,

kaolinite cannot be used as an index of diagenesis (Dunoyer de Segonzac 1969) in this basin.

Smectite disappearance

The specific pathways of smectite disappearance encountered in wells of the Swiss molasse basin will be discussed by following the changes in three wells, namely, Künsnacht 1, Linden 1, and Courtion 1 (Figs. 4, 5, 6).

Künsnacht 1 (Fig. 4)

The content of smectite in this well is roughly 60% at 600 m and decreases with burial. At 2300 m smectite disappears. The trend is modulated by variations assigned to lithological effects. The high content of smectite between 1000 and 1200 m, for instance, is related to a marly formation called "Mergelzone" of Aquitanian age as defined by Büchi *et al.* (1961, 1965).

At 2000 m, interstratified clays appear consistently in the clay section of the well (Fig. 4). However, the beginning of the illitization process occurs at 600 m where the peak attributed to smectite begins to broaden and decrease in height. This change is due to the disordering caused by the increase of non-swelling interstratified layers.

Linden 1 (Fig. 5)

In this well, the trend of smectite disappearance is similar to that of Künsnacht. However, the top of the well is already within the decreasing trend of smectite, which implies that the zone of smectite stability is absent. This suggests that an important part of the molasse section, about 600 m, is missing; this is also indicated by stratigraphic evidence. Smectite disappears at about

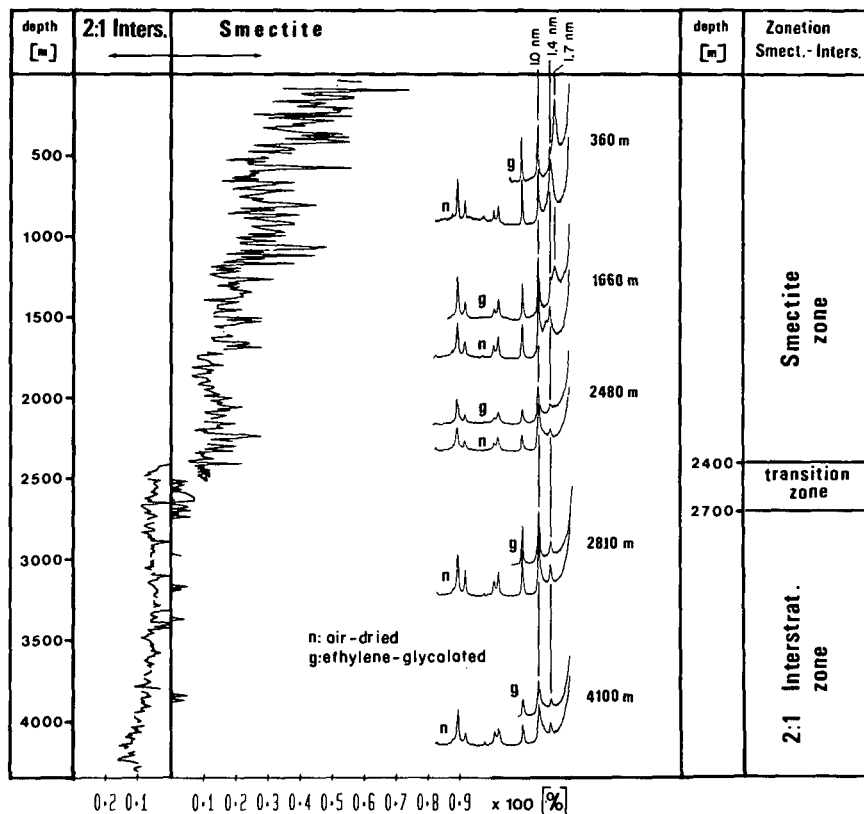


FIG. 5. Smectite disappearance (right-hand axis) and 2:1 mixed layers (left-hand axis) in Linden 1 well.

2700 m depth, which is 400 m deeper than in Künsnacht 1 well. However, the disappearance of smectite in Linden 1 well takes place 1000 m below that of Künsnacht 1 well, if one considers the additional 600 m of eroded section. The transitional zone in which both smectite and mixed layers are present (Fig. 5) is 300 m thick as in Künsnacht (Fig. 4).

The reappearance of significant amounts of smectite in some levels of the mixed-layer zone could be due to caving or to undercompaction, which can retard clay diagenesis by preventing water expulsion (Rumeau and Sourisse 1972).

Courtion 1 (Fig. 6)

In this well, a different pathway of mineral changes is observed. In the lower part of the molasse section where the smectite has not completely disappeared some corrensite, as defined by Lippmann (1954), is encountered. The upper zone, to a depth of 810 m, looks like the other wells, and shows a decrease of smectite with burial. Below this depth corrensitic bands appear and smectite is correspondingly absent. Between these bands, smectite concentration ranges between 15 and 30% of the clay fraction. At 1000 m depth 2:1 mixed layers appear in association with smectite, but never

when corrensite is present. Therefore, the mineral changes follow in part an evolution pathway towards chlorite (chloritization) via regular interstratification to yield corrensite, and in part the pathway towards illite (illitization). The pathway of a diagenetic transformation to corrensite will be discussed below.

Illite crystallinity with respect to smectite transformation

The crystallinity index of Kübler (1964) (width at half-height of the 001 illite peak) has been measured in all the studied wells of the molasse basin. The measurements have been made from X-ray diffractograms of both air-dried and ethylene-glycol saturated specimens. The results from samples of the Künsnacht 1, Linden 1, and Sorens 1 wells will be considered in connection with the transformation of smectite during molasse diagenesis.

Linden 1 (Fig. 7)

Several zones based on crystallinity indices can be defined with increasing depth:

(a) A zone of inherited crystallinity, where the index value is around $0.3^\circ 2\theta$ for both air-dried and glycolated samples, suggesting a high level of diagenesis (Anchi-

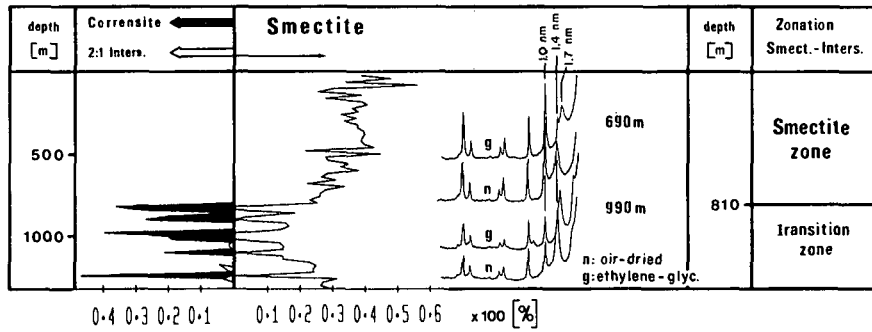


FIG. 6. Smectite disappearance and appearance of corrensite in Courtion 1 well.

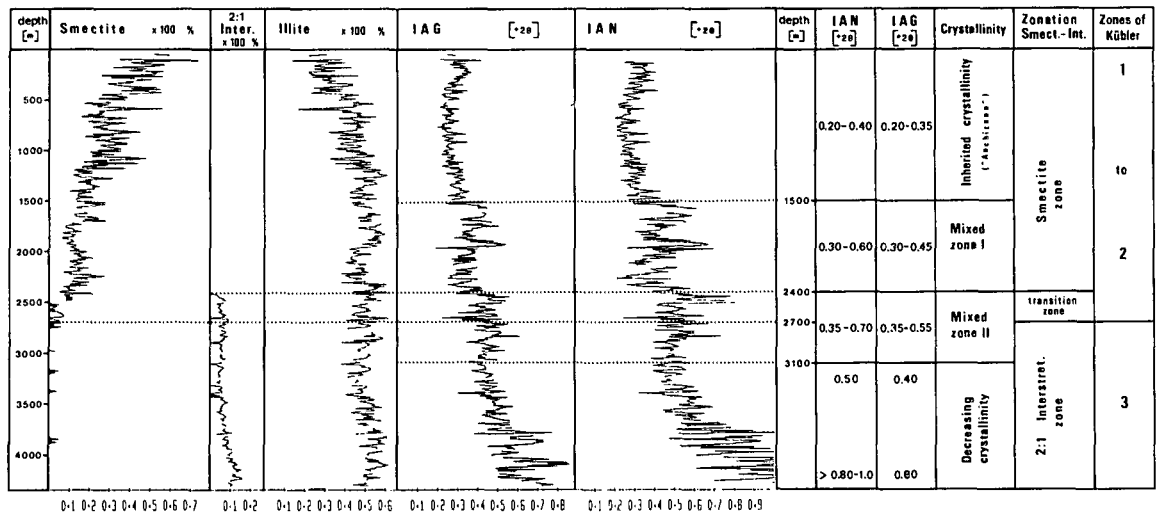


FIG. 7. Mineral changes and illite crystallinity in Linden 1 well.

zone). An explanation for this is that source rock material contributed a substantial amount of mica.

(b) A mixed zone I, where the higher indices may be assigned to either inheritance or the first effects of diagenesis.

(c) A mixed zone II, where mixed layers appear and the Kübler index varies widely, indicating the onset of the transition zone (overlap between smectite and mixed-layer zones).

(d) An increasing index zone of crystallinity, encountered at the depth of 3140 m. The index increases with burial from 0.5° 2θ to 1.0° 2θ for an air-dried sample and 0.4° 2θ to 0.8° 2θ for glycolated samples. At this depth diagenesis erases the crystallinity of inherited detrital micas. In terms of smectite evolution, the two upper zones are in the smectite stability zone and the two lower zones coincide with the mixed-layer part of the section.

Sorens 1 (Fig. 8)

The crystallinity index is around 0.3° 2θ for both air-dried and ethylene-glycol saturated specimens along

the whole section. These values are typical for the Anchizone of metamorphism and apparently do not change by diagenesis. The X-ray diffractograms (Fig. 9) of the mixed-layer zone show a shoulder on the low angle side of the 1.0 nm peak. However, this secondary peak does not reach the half-height of the diffraction peak and therefore does not influence the crystallinity index measurement. As a matter of fact, the amount of newly formed illite is not sufficient to influence the crystallinity index derived from the detrital micas. Thus, the crystallinity indices in the Sorens 1 well are a function of the relative concentration of both weathered micas and newly formed illite or mixed-layer illite-chlorite.

Küsnacht 1 well (Fig. 10)

In the upper portion (0-1150 m) of the Küsnacht 1 well, there is a wide variation in the crystallinity index of the ethylene-glycol saturated specimens, ranging from 0.25° 2θ to 0.6° 2θ. The crystallinity index of the air-dried samples is greater than 0.7° 2θ because of the presence of smectite. Between 1170 and 1460 m the

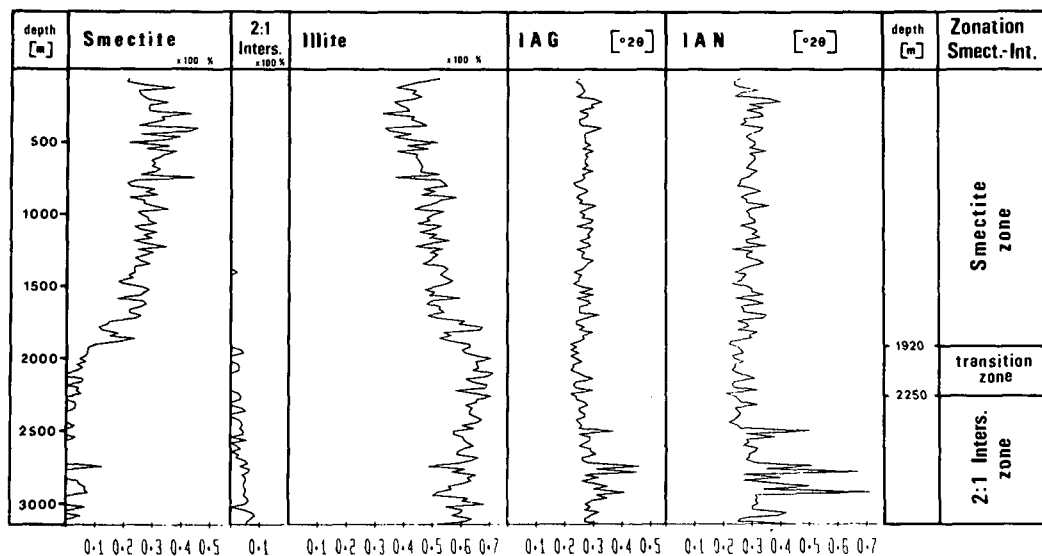


FIG. 8. Mineral changes and illite crystallinity in Sorens 1 well.

crystallinity index of both glycolated and air-dried specimens is constant at $0.25^\circ 2\theta$ because of the presence of mica. The same was observed in the Sorens 1 and Linden 1 wells. Below a depth of 1460 m the crystallinity index increases and varies in the case of the glycolated samples between $0.25^\circ 2\theta$ and $0.60^\circ 2\theta$ and in the case of air-dried samples between $0.25^\circ 2\theta$ and $0.45^\circ 2\theta$. This variability is due to the presence of expandable 2:1 layer silicates. Below a depth of 2000 m the range of crystallinity index in the glycolated and air-dried samples is limited by the presence of mica.

The results from the three wells show the variability of crystallinity indices that exist in the Swiss molasse. The index cannot always be used to characterize the level of diagenesis in all cases. In the upper zone of diagenesis, the so-called smectite zone, the index reflects the detrital origin of the clay fraction and the inheritance of mica crystallinity. In the zone where mixed-layer silicates predominate the index can be of some significance because of the presence of newly formed illite. Thus, there is a threshold proportion of illite to mica where the crystallinity index becomes of some value. In the Sorens and Künsnacht wells this threshold has not been reached, but in the Linden 1 well it has.

Mineral changes during diagenesis in the Swiss molasse basin

The concentration of smectite with burial in Savigny 1, Chapelle 1, Courtion 1, Sorens 1, Linden 1, Hünenberg 1, and Künsnacht 1 wells has been summarized in Fig. 11. In the same figure the presence of 2:1 mixed layers and corrensite has also been reported.

Corrensite appears only in the western part of the

Swiss molasse, namely, in the wells Savigny 1, Chapelle 1, Courtion 1, and Sorens 1, whereas the illitization process is characteristic of the eastern part (Linden 1, Hünenberg 1, and Künsnacht 1 wells). Clay mineral diagenesis in the Swiss molasse basin can be divided in three belts: the Subjura belt, the Central belt, and the Perialpine belt. These belts have the following characteristics.

(1) The Subjura belt shows no decrease of smectite concentration with burial (Essertines 1, Tschugg 1, Ruppolsried 1, Pfaffnau 1, and Pfaffnau Sud 1 wells, Fig. 1).

(2) The Central belt (Fig. 1) of the basin shows a decrease in smectite followed by the appearance of corrensite (Chapelle 1 and Courtion 1 wells, Fig. 11).

(3) The Perialpine belt, in which rapid subsidence yielded a very thick section (Fig. 1), shows smectite decreases with burial and is replaced by mixed layers (Künsnacht 1, Hünenberg 1, Linden 1, Sorens 1, and Savigny 1 wells, Fig. 11).

Origin of corrensite

The origin of corrensite in the western part of the Swiss molasse can be attributed either to inheritance from the source rock or to diagenesis.

The possibility of having inherited corrensite in the section is discarded because very few alpine rocks could have supplied this regular mineral (an interstratified, montmorillonite-chlorite silicate). Corrensite occurs in Grés de Taveyannaz and the Liassic Formation of the Median Prealps. However, neither of these formations was eroded during the deposition of that portion of the molasse in which corrensite occurs (M. Weidmann, personal communication, 1979). As a result, corrensite

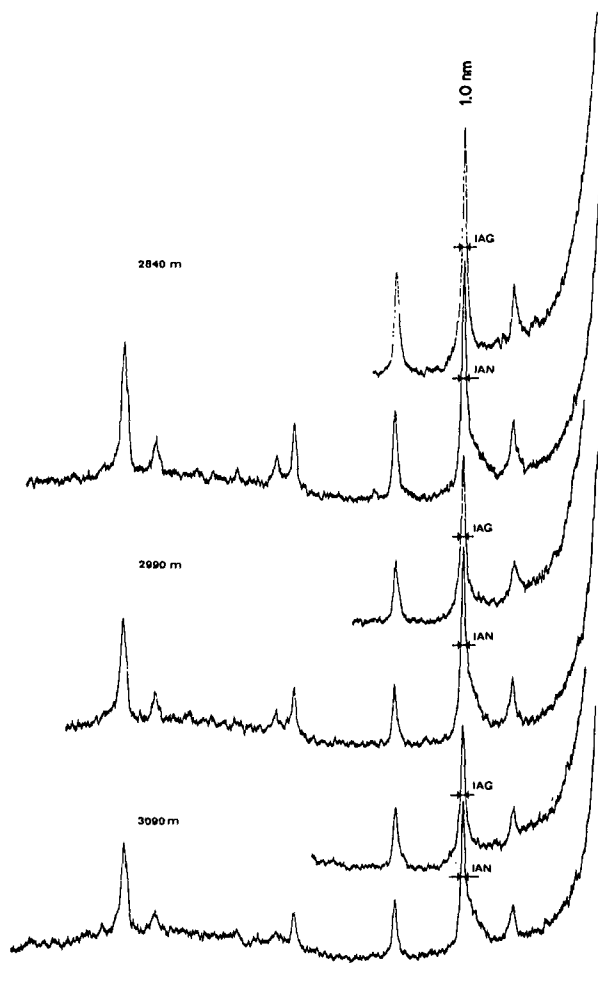


FIG. 9. Crystallinity measurement in some diffractograms of Sorens 1 samples.

in the Swiss molasse should be attributed to diagenesis. Corrensite is a typical mineral that occurs in diagenetic environments: it has not been found in Recent sediments (Kübler 1973). This regularly interstratified clay disappears in the lower zone of metamorphism. This disappearance is related to the advance of greenschist facies conditions. There are three environments of deposition with which diagenetic corrensite is associated (Kübler 1973): the evaporitic facies; the carbonate facies; and the volcanic and volcano-detrital facies.

In the Chapelle 1 and Savigny 1 wells, corrensite occurs below an evaporitic facies, the "Anhydrite Bröckchen" formation (Lemcke 1959, 1963). It seems that only below the anhydrite level are both the critical temperatures and the magnesium-rich-potassium-poor solutions present for the formation of corrensite.

In the Courtion 1 section (Fig. 6), corrensite appears along with interstratified smectite-illite. This indicates

that the transformation of smectite to a 2:1 mixed-layer silicate occurs parallel with the transformation of smectite to a regular interstratified smectite-chlorite, that is, corrensite. This implies that, although the presence of a mixed-layer clay is a function of temperature, the kind of mixed layer is a function of the ions at disposal during the transformation process. In Sorens 1 well the presence of corrensite is roughly 1000 m below the delineation zone where discrete smectite disappears and mixed layers appear.

Burial history assessment and oil potential of the Swiss molasse

Numerous authors, Weaver (1960), Dunoyer de Segonzac (1968, 1969), Burst (1969), Perry and Hower (1972), Rumeau and Sourisse (1972), Foscolos *et al.* (1976), Powell *et al.* (1978), and Kübler *et al.* (1979a,b) have showed that the smectite disappearance and the appearance of mixed layers are related to catagenetic effects during burial (Fig. 3). The geothermal gradient is the relationship between temperature and depth. These clay transformations form an irreversible record of the thermal diagenesis. That is, this fingerprinting is not modified by subsequent uplifting movement. Thus, the delineation outlined by the onset of the transition zone from smectite to mixed layers expresses an isopaleotemperature surface.

From organic petrography and organic geochemistry investigations, it is known that vitrinite reflectivity increases with heat and that oil and gas are generated at elevated temperatures. These processes are also influenced by the geothermal gradient. Oil and gas models proposed by Sokolov (1965), Vassoevich *et al.* (1970, 1974), and Tissot *et al.* (1971, 1974) are calibrated on a vitrinite reflectance scale (Teichmüller 1971; Hood and Castaño 1974). From this, the principal oil generation starts at a reflectance level of about 0.5% of R_o .

The correlation between the onset of the principal oil generation zone (oil window) at a level of 0.5% of R_o and the disappearance of smectite is emphasized by many authors, such as Rumeau and Sourisse (1972), Heling and Teichmüller (1974), Powell *et al.* (1978), Kübler *et al.* (1979b), and Kübler (1980). Héroux *et al.* (1979) have compiled and correlated in a chart the major thermal maturation indicators. In this chart the appearance of neofomed corrensite and 2:1 mixed-layer silicates and the disappearance of smectite coincide with a vitrinite reflectance value of about 0.5% of R_o and with the upper limit of the oil window. In all the above-mentioned catagenetic transformations, a temperature-time integral must be considered (Lopatin 1971; Connan 1974; Cornelius 1975). However, in the Swiss molasse, all areas of the basin were exposed to heat during the Tertiary for similar periods of time. Thus, the time factor may be neglected for burial reconstruction and oil and gas generation discussed below.

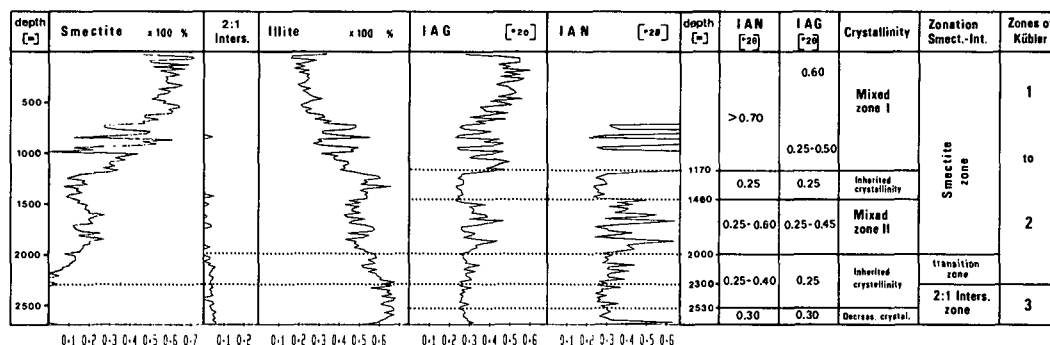


FIG. 10. Mineral changes and illite crystallinity in Künsnacht 1 well.

Burial reconstruction

The following is an attempt to evaluate the depositional history of the Swiss molasse basin on the basis of clay mineral diagenesis. Maturation indicators can be correlated with absolute depth only where the maximum depth of burial is known. The Künsnacht 1 well has been used as a reference for burial depth since it has the most complete section, extending up to rocks of Tortonian age. Thus, the depth of the transition zone at 2000 m in the Künsnacht 1 well is taken as the depth of burial required to attain this level of diagenesis.

In the Subjura zone, which includes the wells Essertines 1, Tschugg 1, Ruppolsried 1, Pfaffnau 1, and Pfaffnau Sud 1, and those of the eastern central part, like Boswil 1, the burial is not more than 2000 m because the transition zone of discrete smectite to mixed-layer clays is never attained. From Fig. 11 it is concluded that in the western central part, which includes the wells of Chapelle 1 and Courtion 1, the depths of the transition zone are 1190 and 810 m, respectively. In the Perialpine part, which includes the wells of Savigny 1, Sorens 1, Linden 1, Hünenberg 1, and Künsnacht 1, the depth of the transition zone is around 2000 m, with a maximum of 2400 m depth encountered in Linden 1.

Reconstructing the burial of Linden 1, it is noted that the transition zone is 400 m deeper than that of Künsnacht 1 (Fig. 11). In addition at least 600 m of late Tertiary sediments of Tortonian age is encountered in Künsnacht 1 well (Figs. 4, 11). Therefore, the transition zone of smectite to mixed layers in Linden 1 is buried at least 1000 m deeper than that of Künsnacht. This implies that the paleogeothermal gradient is lower than that of Künsnacht. In the Hünenberg 1 well where the molasse section is almost as complete as in Künsnacht 1, the depth of the transition zone also indicates a lower paleogeothermal gradient, but not as low as in the Linden 1 case. Some vitrinite reflectance measurements in Künsnacht 1 and Hünenberg 1 wells reported by Rybach and Bodmer (1980) confirm lower paleogeothermal conditions in Hünenberg 1 well (0.008% of $R_d/100$ m in terms of vitrinite reflectivity gradient) than in Künsnacht 1 well

(0.005% of $R_d/100$ m). The reflectance measurements range from 0.4 to 0.6% of R_m . Rybach and Bodmer (1980) have noted as well that the current gradient is also lower in Hünenberg (22.7°C/1000 m) than in Künsnacht (26.8°C/1000 m).

In both Sorens 1 and Savigny 1 wells the depth of transition from discrete smectite to mixed-layer silicates is about the same. However, the autochthonous sediment in these two wells is covered by the Subalpine molasse thrust, which is 500 m thick in Sorens 1 and 900 m thick in Savigny 1. If it is assumed that the sediment of the Subalpine molasse thrust has not affected the diagenesis of the underlying autochthonous series, then, in comparison with Künsnacht 1 well, 600 m of sediments is missing in Sorens 1 and 1050 m of sediments is missing in Savigny 1. In the remaining two wells of the western part of the molasse basin, that is, Chapelle 1 and Courtion 1, the depth of the transition from smectite to mixed layers is of the same order of magnitude as in Sorens 1 and Savigny 1 wells (Fig. 11). This implies that the genesis of both regular (corrensite) and irregular interstratified 2:1 layer silicates took place at about the same level in all wells of the western part of the molasse basin and that the Subalpine molasse thrust in Savigny 1 and Sorens 1 did not affect the thermal diagenesis of the layer silicates. Similarly Kübler (1967, 1968), in studying the diagenetic mineral transformation in the North Pyrenees, observed that sediments underlying a major thrust block (4500 m thick) were catagenetically unaffected by additional thrust burial and still contained smectite, whereas the thrust block did not.

The clay minerals of the thrust molasse are smectite, illite, micas, chlorite, and very few mixed layers. The paucity of mixed layers indicates that these sediments were never extensively buried prior to thrusting.

From the foregoing discussion the burial history of the Swiss molasse basin as deduced from the mineral changes can be summarized as follows.

(1) In the Perialpine part of the basin, sedimentation occurred to a sufficient thickness to cause the disappearance of smectite and the appearance of mixed-layer

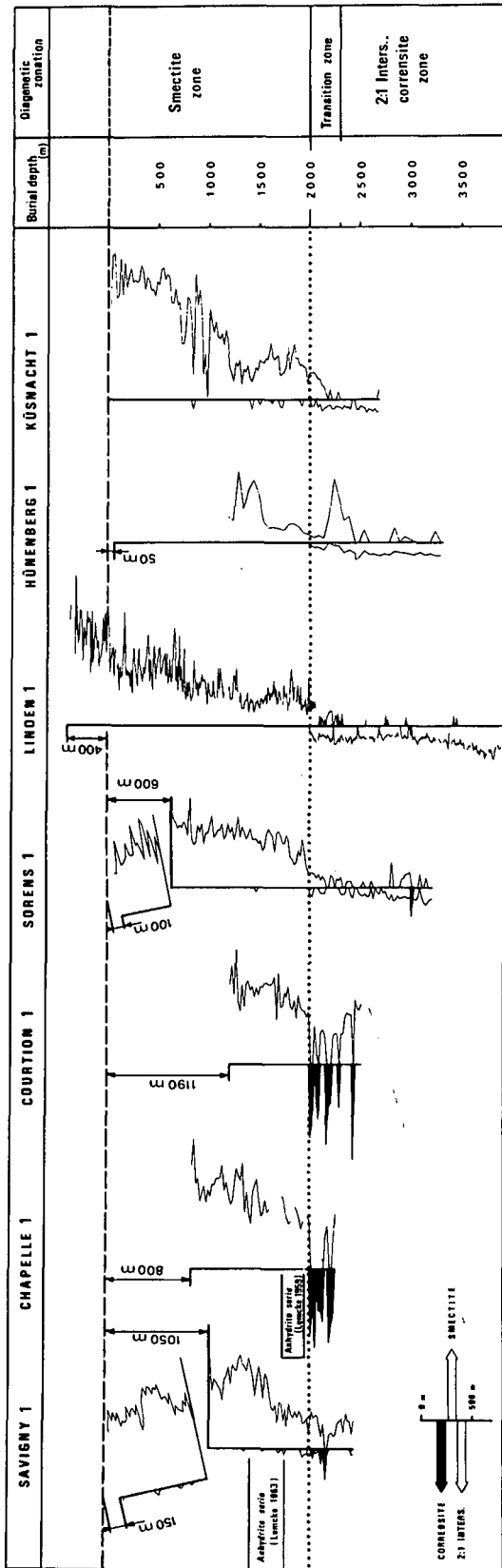


FIG. 11. Estimation of burial using the onset of the transition zone with Küsnacht 1 well as reference.

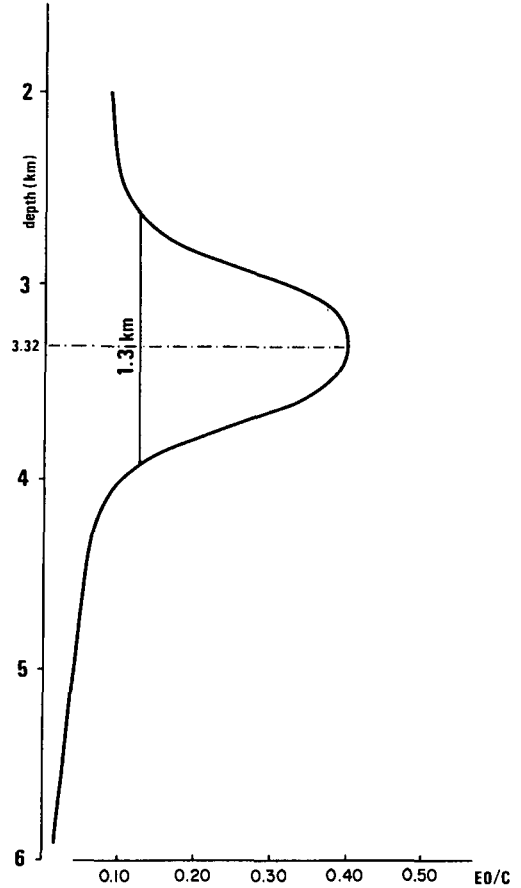


FIG. 12. Variation of the organic extract/organic carbon ratio versus depth in the southwest Aquitaine Basin (after Le Tran *et al.* 1974). The oil window is 1.3 km thick.

silicates. In the Linden 1 area, faster subsidence and a low geothermal gradient resulted in the formation of a deep transition zone (below 3400 m depth).

(2) Erosion (uplift) resulted in the removal of the late Tertiary molassic series in the western part.

(3) Thrusting of the Subalpine molasse took place.

The succession of events that is recognizable from the clay transformation is consistent with the timing of the northwest Subalpine thrust of Tortonian (Late Miocene) age (after Trümpy 1978), and also with the range of ages of the sediments on the actual erosion surface. In order to have a sufficient sedimentary section to bring about the diagenetic changes observed in the Savigny 1, Chapelle 1, and Courtion 1 wells, it is necessary to assume that the sedimentation continued beyond the time of the deposition of the surface rocks and probably at least to the end of the Miocene. The same was also concluded by Laubscher (1974) and Lemcke (1974). The sediments were then eroded to the level of Aquitanian rocks in the Savigny 1 well, to early Burdigalian rocks in Sorens 1, and to about middle Burdigalian rocks in Linden 1. The age relationships of the surface sediments

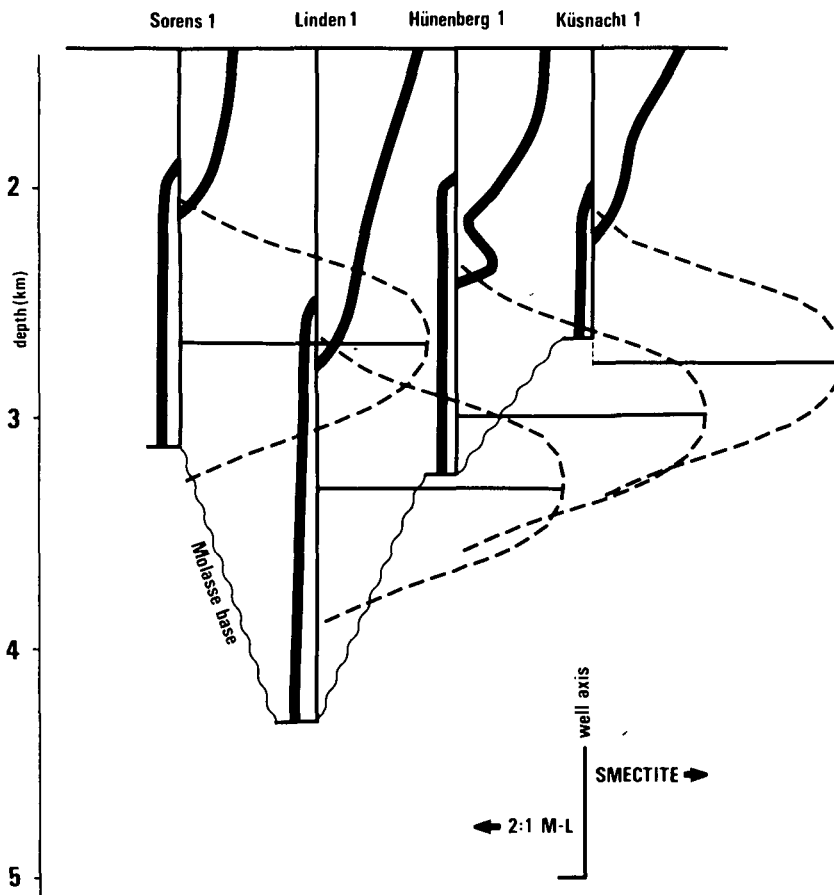


FIG. 13. Position of Aquitaine oil window (dashed line) in the Swiss molasse wells based upon disappearance of smectite (right-hand axis) and appearance of 2:1 mixed layers (M-L) (left-hand axis).

of the molasse basin are the same as those observed in the thrust, in which the top stratigraphic levels follow the same trend: younging to the east. This implies that the major erosional stage took place before the Subalpine molasse thrust.

Potential oil-window location in respect to the Tertiary thermal diagenetic cycle in the Swiss molasse basin

In order to locate an oil window in the Tertiary molassic series and underlying Mesozoic strata smectite disappearance has been used because no organic geochemical and only a few organic petrographical data are available.

Among several oil-window patterns (Albrecht and Ourisson 1969; Tissot *et al.* 1971; Le Tran *et al.* 1974), the Aquitaine Basin is chosen as a model for the Swiss molasse. Figure 12 shows that between the upper and lower limits of the oil window there is 1300 m of sediment. The maximum generation of oil should take place 650 m below the top of the oil window, which is 3320 m from the Earth's surface. Similar thicknesses of oil window have been observed in the Douala and Paris Basins; however, the burial depths are different. Thus

the clay mineral data have been combined with the thickness model to derive the depth of the oil window in the wells of the Swiss molasse basin (Fig. 13).

In Essertines 1, Tschugg 1, Ruppolsried 1, Pfaffnau 1, and Pfaffnau Sud 1 of the Subjura zone, the smectite does not disappear. The degree of sediment diagenesis is not sufficient to cause the maturation of the organic matter. Thus, the oil window is expected to be deeper in the Mesozoic strata. Some oil shows have been found close to the Tertiary–Mesozoic contact, indicating that oil migration took place from below. At Essertines, the oil shows in Lower Jurassic rocks could occur within the oil window.

In the Chapelle 1 and Courtion 1 wells of the Central zone, smectite begins to decrease and is replaced by corrensite. This trend cannot be detected in the other wells of this zone (Boswil 1, Lindau 1, and Kreuzlingen 1). Therefore, in the central part of the basin, even if sedimentary sections are thicker than in the Subjura zone, the maturation of the organic matter is not sufficient to cause oil generation.

In the Perialpine zone, the smectite disappearance level is very obvious in the wells of Sorens 1, Linden 1,

Hünenberg 1, and Küsnacht 1. In Savigny 1 the smectite transformation is incomplete but it is inferred to be completed slightly below the base of the well. Applying the Aquitaine model to the four wells, Linden 1, Hünenberg 1, Sorens 1, and Küsnacht 1 (Fig. 13), the conclusion is that diagenesis during the Tertiary resulted in optimum conditions for oil generation within the molasse. In Küsnacht, the oil window should be located at the Mesozoic–Tertiary contact (Fig. 13). As a matter of fact no hydrocarbon was found in the molasse itself. It must be deduced therefore that the organic matter for oil generation was missing or that trapping conditions did not exist. Underneath the molasse, in the Mesozoic strata, the level of catagenesis would have particularly been suitable for gas generation.

Southeast of the Perialpine part, below the Subalpine thrust block (assuming it did not influence the thermal diagenetic level of the autochthonous underlying series as previously discussed for the mineral transformations), conditions for oil generation may exist in the molasse and even underneath, in the Mesozoic strata.

Conclusion

In the Swiss molasse basin, it has been observed that during burial smectite disappears with the formation of interstratified minerals. Two pathways of smectite transformation have been emphasized, one towards an irregular 2:1 mixed-layer silicate, the other towards corrensite. The corrensite formation in the southwest province of the basin (in the Savigny 1, Chapelles 1, Courtion 1, and Sorens 1 wells) implies that magnesium is supplied by an Mg-rich sedimentary environment and that an adequate temperature is provided by thermal diagenesis (Kübler 1973). The presence of anhydrite-bearing rocks close to corrensite horizons is evidence of a suitable environment. The irregular 2:1 mixed-layer formation in the remaining part of the basin (northeast province) is a classical pathway. However, it differs from the Douala Basin where the transformation follows successive steps of regular interstratification from smectite to illite (Dunoyer de Segonzac 1964). This could be attributed to the high carbonate content (average calcite content 20%) of the molasse.

Reconstructing the burial history of the molasse basin, one must assume a depositional subsidence and an uplift scheme, which is different for the western and eastern provinces. The deposition probably affected the basin everywhere until at least the end of the Miocene or the beginning of the Pliocene. The basin was then uplifted while the Subalpine molasse was being thrust along the Alp border and the Jura Mountains were building. However, the southwest province seems much affected by the uplift. The same was also concluded by Lemcke (1974) and Laubscher (1974) using other geological data.

The clay mineral changes, especially smectite transformation, show that the Swiss molasse, which is located in the Perialpine region, reaches the third diagenetic zone as defined by Kübler *et al.* (1979b) (see Fig. 3). This zone is the mature zone. Hydrocarbon generation is possible in this region, but because no oil shows were found, it must be assumed that organic matter was missing or it was inadequate, or it was oxidized before burial, or the hydrocarbons migrated and were never trapped. Therefore, oil recovery should be more favourable underneath the molasse, northwest of the Perialpine part. In the Perialpine part, the molasse substratum is at a higher level of maturation, which can be correlated with gas generation. Southeast of the Perialpine part, gas and even oil recoveries may be possible from the sections underlying the molasse below the Subalpine thrust block.

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