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The Structural Development of Areas of Tertiary Sedimentation in Switzerland

by CARL WIEDENMAYER (Standard Oil Company N. J.) [1]

I. Introduction

Switzerland has been combed over for many years now by its geologists with comparatively small funds available for their difficult task. The work has, as a whole, been well coordinated and we can justly be proud of the professional achievement.

There are many problems which remain to be solved. We should compare the exploration work performed in Switzerland with that of other countries where Geology finds more industrial application and where much of the exploratory effort is encouraged and financed particularly by the Petroleum industry. Much of the geological surveying in Switzerland has been carried out single-handed, by individuals and not by corporations. Much of our future exploration will have to be coordinated with geophysical studies. It will require team work and more substantial financing. The fact that Switzerland did not share in the benefit of being explored by reliable petroleum companies of good standing is partly attributable to the antiquated cantonal mining laws.

Our geologists have done good work in stratigraphical and structural geology; but have they scratched deep enough? When trying to make a synthesis of the geological work done in the past or which is still in the course of development, we must admit that we are still confronted with many questions and particularly such as cannot be answered by surface geology only. We know well the mountains but have not explored sufficiently the basins. The petroleum geologist knows that the riches of this earth, as far as they are associated with sedimentary rocks, are located in basin areas.

The principal aim of this paper is to elucidate the stratigraphical conditions of the Tertiary basin of Switzerland and the development by successive stages of this „Swiss Molasse Basin". It is a difficult task, and it is hoped that this description may encourage further research.

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1) Published with the permission of the Producing Coordination Departement of Standard Oil Company (N. J.).

II. General Remarks on Problems of Stratigraphy

a) Alpine Flysch

There has been published very recently by Jean Tercier, professor for geology, University of Fribourg, an article on the Flysch in the Alpine sedimentation (lit. 47).

The points brought out under this topic constitute a brief summary of the salient features of that paper and are specially interesting when studying also the sub-or perialpine Flysch sediments as a possible source rock for oil and gas.

The word „Flysch“ was first introduced by the Swiss geologist Bernhard Studer in 1827. This term has since been applied to so many various rocks that it has become difficult to give an accurate definition. One attribute for such a designation of a sedimentary series remains, however, generally accepted: it does not apply to a formation of a determined age but to a sedimentary series of a particular facies and appearance.

The Flysch is generally referred to as a sedimentary series closely associated with orogenetic developments. More specifically it antedates the paroxysmal or final stage of mountain building. In the Alps it coincides with the final stage of sedimentation in a geosynclinal area in which the mountain ranges are already lined up and in which some erosion has already set in. Thrusting may have already been initiated but sedimentary troughs still existed between the early ranges, and the piling up in „Decken“ thrusts of the early chains had still not taken place.

Several successive „foredeeps“, troughs or more or less wide basins have probably developed in front of the staggered primordial Alpine ranges. The sedimentation here was not necessarily contemporaneous. There developed probably a repeated upheaval or thrusting in decreasing amplitude from south towards the north (in the Alps) and consequently also a successive alteration of the depth of the primordial foredeeps or troughs. There was also the interference of the early Vindelician swells persisting through out the orogenetic movements, and also this accounts for a differentiation of the Flysch sediments.

Fundamental characters of the Flysch are the following:

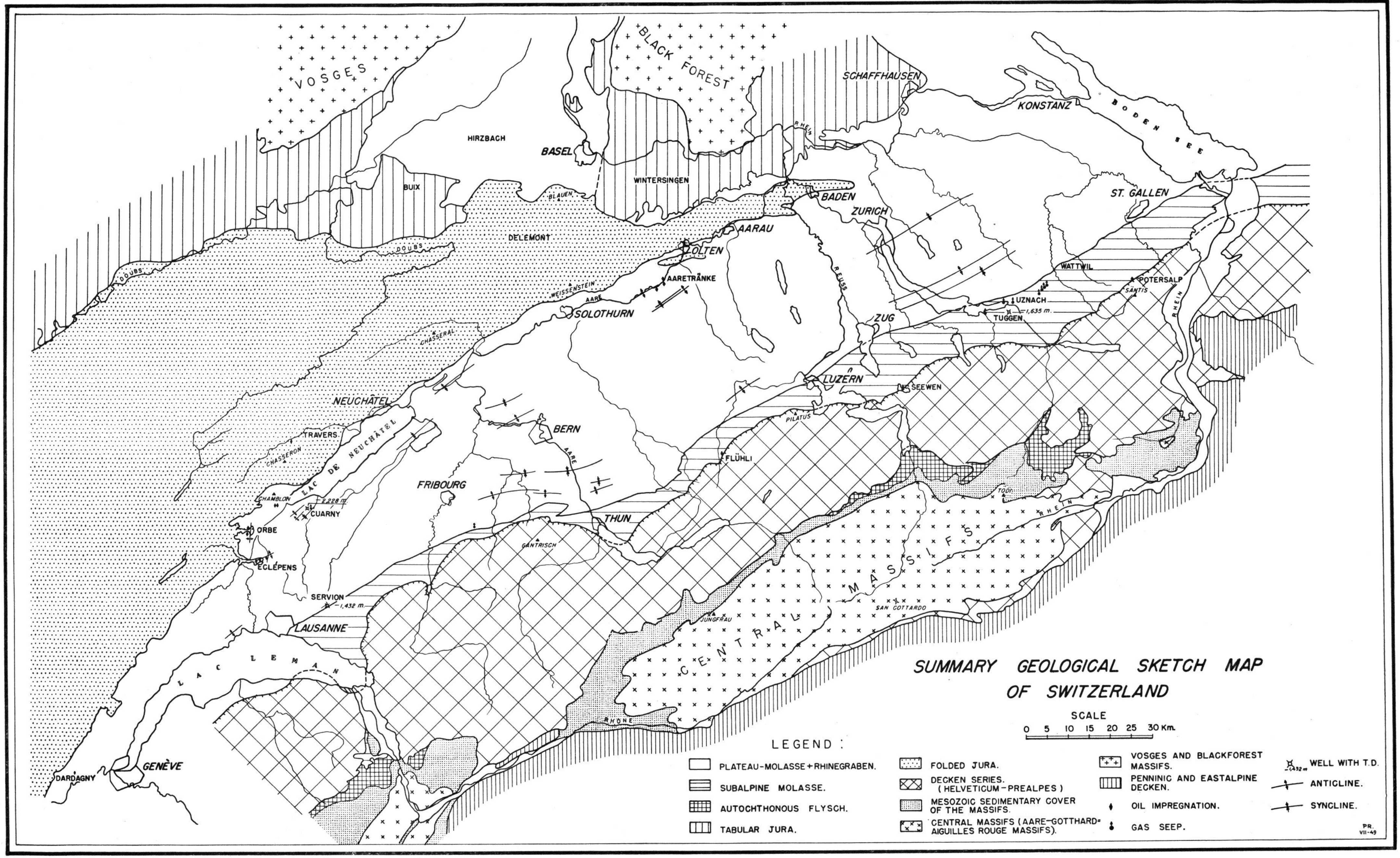
— It corresponds essentially to detritic or terrigenous sediments with very subordinate organogenic constituents, and results in more or less regular alternation of sandstone, micaceous shale, with occasional intercalations of conglomerate or of lime;

— On the whole it is a thick sedimentary sequence with lithologic characteristics usually not adapted for further subdivision;

— It is constituted exclusively of marine sediments, laid down partly in a neritic environment and partly in a bathyal environment;

— Its area of sedimentation belongs to steep troughs irregularly outlined and in front of cordillera ranges of mobile belts.

It may be added that the Flysch, in contrast to Molasse facies, is always characterized by a rapid alternation in innumerable cycles, rapidly and monotonously succeeding each other, of sandstone (and to a minor extent of


SUMMARY GEOLOGICAL SKETCH MAP
OF SWITZERLAND
SCALE
0 5 10 15 20 25 30 Km.
LEGEND:
PLATEAU-MOLASSE + RHINEGRABEN.
SUBALPINE MOLASSE.
AUTOCHTHONOUS FLYSCH.
TABULAR JURA.
FOLDED JURA.
DECKEN SERIES. (HELVETICUM-PREALPES)
MESOZOIC SEDIMENTARY COVER OF THE MASSIFS.
CENTRAL MASSIFS (AARE-GOTTHARD-AIGUILLES ROUGE MASSIFS).
VOSGES AND BLACKFOREST MASSIFS.
PENNINIC AND EASTALPINE DECKEN.
OIL IMPREGNATION.
GAS SEEP.
WELL WITH T.D.
ANTICLINE.
SYNCLINE.
PR. VII-49
VOSGES
BLACK FOREST
SCHAFFHAUSEN
KONSTANZ
BODEN SEE
HIRZBACH
BASEL
BUIX
WINTERSINGEN
BLAUEN
RHEIN
BADEN
ZURICH
ST. GALLEN
DELEMONT
DOUBS
AARAU
OLTEN
AARETRÄNKE
WEISSENSTEIN
AARE
SOLOTHURN
REUSS
ZUG
WATTWIL
UZNACH
TUGGEN
1,635 m.
POTERSALP
SÄNTIS
CHASSERAL
LUZERN
SEEWEN
PILATUS
NEUCHÂTEL
TRAVERS
CHASSERON
LAC DE NEUCHÂTEL
BERN
FLÜHLI
FRIBOURG
CHAMBLON
2,228 m.
CUARNY
ORBE
THUN
GANTRISCH
TÖDI
ECLÉPENS
SERVION
1,432 m.
LAUSANNE
JUNGFRAU
SAN GOTTARDO
CENTRAL MASSIFS
LAC LEMAN
RHÔNE
GENÈVE
DARDAGNY

conglomerate and breccias), sandy shale, shale and marly lime. Large outcrops of comparatively little disturbed Flysch are usually characterized by excellent stratification. The rocks are practically always micaceous. Usually the sandstone and calcareous sandstone are glauconitic.

Organogenic limestones are not too rare, but they occur in single beds or lenses only. They contain usually large foraminifera *(Orbitolina, Nummulites, Assilina, Discocyclina,* etc.) and *Lithothamnium algae.*

Crossbedding and ripplemarks are absent.

The expression „calcareous Flysch“ of the French geologists and others refers to monotonous series of alternations of argillaceous and marly lime with shale. The limes contain *Chondrites* and *Fucoidites,* traces of mud-dwellers. According to Tercier, this type of sedimentation is not typical of the Flysch facies proper.

Some of the continuous Flysch sections can be measured in thickness up to 1500 meters without much change in the overall lithologic character.

Subdivisions can usually be made in the sandstone on the basis of macroforaminifera: *Orbitolina* and *Siderolites* for Cretaceous Flysch; *Nummulites, Assilina, Discocyclina* and more rarely *Operculina* for Tertiary Flysch. But many of those larger foraminifera are certainly reworked. Other fossils are practically absent. The orogenetic events of Alpine structure and the Flysch sedimentation were closely associated and passed through different phases, not equally developed in various areas, and therefore it is difficult to determine the period of Flysch sedimentation.

In some cases it set in as a normal succession to the Maestrichtian (Wang-Beds of the eastern „Helveticum“ Alps), in other cases the Flysch was initiated after the deposition of Middle Eocene beds („Globigerina marls“).

Tercier compares the Flysch type sediments with the sedimentations recently studied by Reville and Shepard off the southern California coast (A. A. P. G. Bulletin 1939, p. 245) and by Ph. H. Kuenen („The Snellius Expedition“, vol. V, part 3, section I, Leiden 1943) in the East Indian Archipelago.

b) Flysch and Molasse

For a comparison[2], only the Flysch of the northern (Helveticum) Alps can be used. This is the area to the north of the Aar-Massif. Other Flysch types, which are associated with higher „Decken“ elements and which originally had been laid down in inter-alpine troughs, have no direct association with the Molasse deposits.

As stated before, the Flysch is composed essentially of detritic (clastic) sediments. The Molasse is constituted exclusively of such sediments, with exception of some intercalated calcareous freshwater sediments. The frequent alternation of sandstone and shale may be observed only in the older Molasse subdivisions of Rupelian and Chattian (Oligocene).

2) For comparison see also the paper: Flysch and Molasse, by A. J. Eardley and Max G. White, Bull. Geol. Soc. of America, vol. 38, No. 11, Nov. 1947, published shortly before Terciers's paper, but which could not be studied by Tercier previous to the publication of his paper.

The Molasse displays lithological units most of which are much larger and more conspicuous than those observed in the Flysch. Notable are particularly the extremely thick and massive deposits of conglomerate close to the Alps and of thick Molasse-sands in the central portion of the Molasse Basin.

The Molasse shows, similarly as does the Flysch, great thicknesses of sediments in the order of 4000—6000 meters in the areas adjacent to the Alps. But those are terrestrial and near-to-shore deposits. Great deltaic fans were laid down in subaerial conditions, and on the edge under freshwater or brackish water, with successive periods of submergence. The subsidence could only intermittently keep pace with the volume of sedimentation. To accomplish differentiation of substages is even more difficult in this entire succession than in the Flysch sediments.

Whereas the Flysch belongs to a strictly marine sedimentation, the Molasse, beyond the great conglomerate fans, shows a recurrence or predominance of freshwater deposition with an interfingering of marine sediments. The restricted marine intercalations are characterized by shallow water faunal associations.

Strong crossbedding and pronounced depositional dips, together with frequent ripple marks, are in the Molasse sediments.

The Molasse was deposited on a foreland or over an already filled foredeep. Its deposition occurred partly after the „Decken"-thrusts were initiated and partly after the „Decken" reached their final implacement also to the north of the Aar-Massif.

One of the great Alpine orogenetic movements is known to have occurred, apparently in successive phases, during Oligocene time. This ended the sedimentation in the properly Alpine environment and initiated the peri-Alpine Molasse deposition. Still, the change in the type of sedimentation was not abrupt. Where the lower Molasse sediments of Rupelian age can be observed, they display a definite affinity to some of the Lower Oligocene Flysch of the northern Alps (Helveticum structural province). The Rupelian shale with *Meletta* fish-scales of the Entlebuch near Flühli (between Lake of Lucerne and Lake of Thun) already have much in common with the Oligocene Flysch slate of the Canton of Glarus in the autochthonous zone of the Alps.

Similarly it could be observed in the Val d'Illiez, 23 kilometers to the south of Montreux on Lake of Geneva (Lac Leman), that the Molasse sediments succeed the Flysch without interruption (no unconformity could be traced so far in the Swiss Alps, which is in contrast to A. F. de Lapparent who, in southern France, has postulated a general angular unconformity between the Stampian Molasse and the underlying marine „Nummulitique" in Etude géologique dans les régions provençales et alpines entre le Var et la Durance; Bull. Carte Géol. de France, No. 198, 1938).

The Flysch of the autochthonous sedimentary sequence, to the north of the Aar-Massif, is not directly to be associated with the Flysch of the northern Alps pertaining to the Helveticum „Decken" thrusts and, naturally, much less with the Flysch of the higher „Decken" sequence. This autochthonous Flysch, which consists of the „Altdorfer Sandstone", the „Taveyannaz Sandstone" and a characteristic „Roofing slate" („Dachschiefer") sequence, is placed into the time interval from Uppermost Eocene to the Lower Oligocene. It antedates, therefore, directly the Molasse sediments. And also for the geographical distribution it represents the filling of a migrating or incipient foredeep which developed temporarily, in front of the Aar-Massif.

The early alpine orogenetic movements of major scale, which fall in the interval between the deposition of the Flysch and the initiation of the Molasse sedimentation, render it difficult to make a clearcut distinction between the two realms of sedimentation. It is also difficult to give a composite stratigraphical column for the entire fill of the Molasse basin in which the autochthonous Upper Eocene deposits north of the Massifs have to be included. The northward extension of the Upper Eocene-Lower Oligocene sequence in the Molasse basin is entirely a matter of speculation.

c) Development of the Molasse Basin

It is not intended to repeat in this paper a general description of the stratigraphy of the Molasse Basin. But it may be useful to give a brief review of the development of this sedimentary area. We give herewith the subdivisions in a summary form:

Upper Lacustrine Molasse	Sarmatian? Tortonian	Miocene
Upper Marine Molasse	Helvetian Burdigalian	Miocene
		Transgression
Lower Lacustrine Molasse	Aquitanian Chattian	Oligocene
Lower Marine Molasse	Rupelian	Oligocene
Flysch Sediments (Autochthonous, N of the Aarmassif)	Sannoisian	Oligocene
	Priabonian	— Upper Eocene

The Middle and Lower Eocene are not included in this section. They belong essentially to the inner-Alpine environment and with it to the realm of the Mediterranean Thethys, a large geo-synclinal feature. The area now occupied by the Molasse Basin was then a shelf which extended from the then unfolded Jura to the Aar-and Gotthard massifs. A northward extension of the sea, advancing from SE towards NW, associated with a down-buckling or the forming of an initial foredeep, is documented by the sedimentation of the thick Upper Eocene-Lower Oligocene sandstone-shale of the autochthonous Flysch.

With the sedimentation of the Rupelian formation the direct influence of the Tethys came to an end and the irregular spread of the Oligocene seas over some of the continental area of Europe was initiated.

The Lower Marine Molasse was laid down in a shallow sea which was open to the east, and which, at least for a certain period of time, also connected with the graben of the Rhine valley, where similar deposits have been encountered, and with a similar fossil fauna. As regards lithology the Rupelian has still a certain affinity to the Flysch sediments. This Rupelian which is subdivided in „Grisiger-Mergel“ and „Horwer Sandstein“ near Lucerne is found well developed also in the Bregenzer-Wald, western Austria, where the series is known under „Bausteinzone“.

The upper Marine Molasse starts usually with a clear transgression, but without an angular unconformity, of the Burdigalian.

Near the Jura this series is properly marine, and it becomes a partly brackish water sediment towards the Alps. The Helvetian corresponds to a more typically marine deposition. It is part of the large regional Vindobonian transgression which covered large areas of continental Europe. Extended conglomerate fans of terrestrial deltas restricted the width of this sea in some portions of the Swiss Molasse Basin. It appears that there is more direct faunistic connection with the Vienna-Pannonian-Black sea environment than with the Mediterranean.

It is worthy of note that within the area of the Molasse Basin there has never been any comparatively deep sea, except for the Flysch sediments. The Helvetian sea bottom had probably a maximum depth of 50 to 100 meters. The Molasse sediments consist prevailingly of sands and conglomerates. In the intervening shale and clay beds no diagnostic fauna of foraminifera could ever be discovered.

At the close of the Miocene the Molasse Basin had not only been filled up and become the realm of freshwater and practically piedmont deposition, but it appears that its surface was also elevated close to 1000 meters. Very little is known about the drainage pattern at the beginning of the Pliocene. But we know that strong erosion was active at this stage, particularly to the south of the Molasse Basin.

The strongest Alpine movements, which have also most strongly affected the Jura environment (second phase of folding of the Jura chains), occurred in Pliocene time, that is at the end of the Molasse deposition. Those movements reduced the original Tertiary basin of Switzerland to parctically half its size, as far as the structurally comparatively undisturbed portion is concerned.

III. Geological History and Structure

(See Plate 1: Summary Geological Sketch Map of Switzerland)

a) Remarks on the Structure of the Rhine Valley Graben

The interpretation of the structural conditions of this large and impressive Graben have been the subject of many studies since Elie de Beaumont postulated, about 100 years ago, the graben faulting between Black Forest and Vosges Mountains.

The opinions regarding the direction of forces responsible for the graben are still divided, and this is an indication that outcrops are far from conclusive as a whole.

E. de Beaumont, E. Suess, H. Cloos and others believe in essentially vertical movements produced by sinking on one side and uplifting on the other, while van Wervecke, Bubnoff, Quiring and others, believe in differential horizontal movements of continental areas acting in opposite directions.

Within the graben detailed observations have been possible by shafts and wells in the Pechelbronn area and in the Potassium saltmine area of Mulhouse-Buggingen and finally by exploratory wells drilled for oil in the Altkirch-Hirtzbach area. These observations justify the following conclusions:

— The internal graben of Dammerkirch, probably together with the main graben feature, started to develop in the Eocene. There is no indication that any movements took place in the Mesozoic.

— Faulting in southern Alsace continued in Oligocene time.

— Faulting, characteristically produced by lateral E-W tension, was particulary strong in post-Oligocene time. It produced some uplifted or tilted horsts within the graben, but there is no indication of renewed subsidence of the graben in its general form as a sedimentary trough.

While there is sufficient indication for vertical movements between the faultblocks, there is, on local exposures to the south of the Rhine Valley Graben, also evidence of horizontal shifting along some of the faults which extend into the folded Jura mountains. The faults in the Burgerwaldkette (folding axis of the Forêt de la Montagne) are of pre-Stampian age and the folding, too, is here pre-Stampian. Those pre-Stampian (Middle Oligocene) tear-faults have also been traced in the folded Jura chains of Switzerland, and here too they are associated with a horizontal shift between the faultblocks, which later influenced the folding trend.

Some of those secondary faults of the Graben must reach the crystalline basement, and this is certainly the case for the large faults of the Graben. Some observers describe horizontal striation on the main faults where those are exposed.

By looking at the grain of the various continental pre-Permian European land areas it seems certainly not exluded that the crystalline basement, below the Jurassic and Upper Trias cover formations, may have experienced not only vertical but also horizontal movements in a later phase produced by differential tension.

Such features are also pertinent for the explanation of the structural development of the folded Jura system to the south of the Black Forest Massif, the Rhine valley graben and the Vosges mountains.

This old central European Massif (Vosges and Black Forest) of the Armorican-Variscan orogeny was peneplained and afforded little elevation in the time when the epicontinental Mesozoic seas covered much of the European area. It has probably never been entirely covered by the Jurassic seas, which showed the widest spread.

We believe that this Massif extended also southwards under the Jurassic sea and produced a swell extending between the Black Forest and the Alpine Aarmassif, which was the cause of shallow water and slow deposition throughout the Jurassic period and which ended in an emergence in Lower Cretaceous time.

In Tertiary time the Black Forest and the Vosges drifted apart. And the separation and subsequent differential movement of this basement complex made themselves felt not only in the orogeny of the folded Jura ranges but also below the Molasse basin.

This will, undoubtedly, constitute a very interesting subject for future geophysical research in the realm of the Swiss Molasse Trough. To date only some very sketchy and preliminary information is available.

b) General Remarks on the Structural Conditions of the Jura Mountains

1. Eastern Tabular Jura

This corresponds to the Mesozoic cover which dips away very gradually from the Black Forest Massif. Proceeding from north towards south, one may observe a succession of Permian, Trias, Jurassic and Tertiary, with different escarpments of the various units, particularly of the Dogger and Malm subdivisions.

The western limit of this tabular system is given by the eastern fault of the Rhine valley graben near Basel. Northeastwards it continues to surround the eastward inclined peneplain of the basement dipping away from the Black Forest, and it merges into the Suabian plateau. To the NW of Schaffhouse it is expressed in the tabular mountain of the Randen. Due eastward the tabular Jura disappears under the Tertiaries, between the Laegern fold, the Rhine and the Lake of Constance, and continues under the Basin of Munich.

The portion of the tabular Jura between Basel and the Aarriver, affluent of the Rhine, is characterized by pre-Miocene block-faulting and graben-faulting and a peneplanation which occurred before and during the deposition of the marine Burdigalian-Helvetian sediments, and, therefore, before the folding of the Jura chains in this general vicinity. This Tabular Jura area was later covered by still younger sediments of the Tortonian freshwater molasse.

This Tabular Jura, in time previous to the main Jura folding period, constituted the northern extension of the Tertiary Basin of the peri-Alpine environment.

2. Western Tabular Jura

To the west of Rhine valley graben and beyond the northernmost marginal chains of the folded Jura there remained comparatively undisturbed a portion of the Tabular Jura. It forms the characteristic landscape of the Ajoie region (Elsgau near Porrentruy) and extends northward to the Vosges mountains. And in this direction progressively lower formations are exposed, down to the Buntsandstein or Lower Trias which is here transgressive over the Crystalline of the Vosges.

In a general way the western Tabular Jura of the Ajoie is connected with the wide extension of the Mesozoic sediments in the Paris Basin and eastern France. If any separation is to be inferred, it must be attributed to more or less strong NS and NNE-SSW trending normal faults formed in pre-Miocene time.

On the outer margin of the arch of the folded Jura mountains, to the north of Dôle and in an area of about 4 by 10 kilometers, there is an occurrence of granite, gneiss and micashist which is referred to as the „Massif of Serre“. It is surrounded by sediments of the Permian, Trias, and Jurassic and is bounded by faults.

Between the Massif of Serre, the southern slope of the Vosges and the principal ranges of the folded Jura mountains a burried belt of Carboniferous had been inferred from subsurface information as a possible extension of the St. Etienne Carboniferous basin towards NE. A society was formed in Switzerland during the first world war for exploring the coal production possibilities. It was calculated that the Carboniferous section containing the St. Etienne coal would be reached in the Ajoie at a depth not exceeding 1000 m.

The well of Buix, near Porrentruy, gave an excellent section of the horizontal Mesozoic sediments, from the Oxfordian to the top of the Permian. It reached the depth of 1052.75 m. and was abandoned in April 1919. At this time it was calculated that owing to an unexpected increase in thickness of the Lias and the Muschelkalk, the Carboniferous could not be encountered at less than 1500 meters.

3. The Folded Jura

This mountain system is composed of folded beds of the Mesozoic, with Tertiary sediments only in the synclines. It presents itself in the shape of a crescent. The inner arch has an extension of about 340 km. The greatest width between the Lake of Neuchâtel and Besançon, is approximately 65 km.

The folded Jura mountains are considered a textbook example of folding and it is not our intention to give a further description beyond some of the most significant aspects. It will be important to discuss further the mountain building forces and the geologic history of those ranges.

Walter H. Bucher in his famous book on „The Deformation of the Earth's Crust“, Princeton 1941, gives considerable space to the explanation of the structural conditions of the Jura mountains.

It is very clear that in the northeastern portion of the Jura chains the folding does not extend down to the base of the comparatively thin sedimentary series. The sedimentary mantle is sheared off along the anhydrite and rocksalt containing sections of the Lower Muschelkalk and to a lesser extent in the gypsiferous Keuper section. The plastic salts have acted as a lubricant on which the Jura folds slid northwards leaving the Lower Trias and the Permian, where present, in place together with the Crystalline basement. This seems, at a first glance, to imply that the basement has not been moved.

Practically all students of the structural framework of the Jura mountains have agreed until lately that the mountain building force came from the Alps. We may specify that, although the Jura folding is connected with the Alpine orogeny, the connection is not very simple. There is no indication of continuous propagation of orogenetic forces northward, and the

Molasse Basin area shows no impressive folds in the Mesozoic. Such would be revealed also in the Molasse sediments, because the main orogenetic forces which raised the Jura folds occurred late in the Tertiary.

This push, almost superficial, from the Alps is also inconsistent with professor Bucher's „Law 28: In arcuate orogenetic belts the convex side of the arc exhibits the greater amount of overfolding and thrusting and the stronger marginal folding".

This law does not apply in all details to the structural features of the Jura mountains.

On a discussion the writer has had with his friend, prof. L. Vonderschmitt, at the Basel University, it was revealed that the theory regarding the orogeny of the Jurassic arc is being revised. It is held that where immense mountain-building forces, like those of the Alps, were displayed, it is not likely that a marginal and superficial crustal movement took place all by itself. The shearing off along salthorizons depends also on the amount of salt present. And it is not likely that the salt plays the same part over the entire extension of the Jura mountains, of which the southern chains are linked with the Alps. It must also be considered that the folding of the Jura mountains is a process which started in Oligocene time and finished with the Tertiary era.

Since the writer's discussion with prof. Vonderschmitt there has come to hand new evidence tending to prove that the Crystalline basement extending from the Black Forest and the Vosges southwards was directly affected by the Alpine orogeny by tending to move southwards and becoming involved in the mobile belt.

The central Alpine Massifs of the Aar and the Gotthard are much moved and appear uprooted. This is indicated by the general gravimetric picture.

All this would imply that the comparatively thin Mesozoic-Tertiary sedimentary mantle (from Middle Muschelkalk upwards, and in the western Jura possibly from Keuper or the Aalenian upwards) was moved more passively towards the north, as some sort of a backwash, while the basement was moved towards the southeast („Einschluckungstheorie") where it became partly absorbed into the gigantic Alpine orogenesis.

The westernmost „marginal" Jura folds seem to be the oldest folds which have been formed, and the folding advanced progressively towards south to a line where the movement of the basement and the shearing above the salthorizons were compensated or offset by other movements.

It may be interesting to review the historical development of the Jura folding as it has been studied, particularly to the south and southwest of Basel in 1920—1925. In this respect we may refer to the description of the basin of Delémont and the vicinity of Movelier by Hans Liniger (Lit. 33). This description refers to the portion of the folded Jura mountains to the SW of Basel, that is in the southern prolongation of the Rhine valley graben, which is an area particularly adapted for the study of the successive structural events which led to the building of the Jura mountains.

Eocene — Not subdivided, period of terrestrial and locally of lacustrine deposition. Regional drainage towards south.

Development of slight swells through gentle folding running in NNE-SSW direction and extending from the Delémont Basin into the southern Rhine valley graben area. Generally low topographical relief and scarce erosion. Calcareous dry land plateau over most of northern Switzerland.

Oligocene — Troughout this time the regional drainage was towards north.

a) Sannoisian = Lower Oligocene. Lake and river deposits. The oblique NNE-SSW folds became more accentuated. Interior Jura-basins subsided in accordance with the sinking down of the Rhine valley graben. Development of NNE-SSW faults.

b) Lower Stampian = Lower Middle Oligocene. Advance and transgression of the Stampian sea extending from the Basin of Paris (faunistic associations) and from the Rhine valley gulf. The oblique swells and lows became still more accentuated.

c) Upper Stampian = Upper Middle Oligocene. Rapid deposition of „Alsacian Molasse" and extension of the sea across the area now occupied by the Jura folds. Connection with the Swiss Molasse area through the „Raurachische Senke". Persistence of the oblique swells while the Rhine valley graben and its southern extension must have experienced a conspicuous subsidence.

d) Aquitanian = Upper Oligocene. Lake deposits near Delémont (freshwater fauna), fossil mammals in the southwestern Jura. Probably period of emersion throughout the Jura region.

Miocene — a) Burdigalian = Lower Miocene. Some marine fossiliferous sandstones, now as remnants in some of the synclines within the folded Jura (Chaux-de-Fonds, Court, Tavannes). This marks a northward transgression of the Miocene from the Swiss Molasse Basin. It did not reach the northern and western areas of what is now the folded arc and had no more connection with the Rhine valley graben. Regional drainage towards south.

The northern and westernmost ranges, at this time, started to buckle.

b) Middle Miocene (Helvetian, approx. = Lower Vindobonian). Further transgression of the sea northwards, somewhat beyond the Burdigalian sea. The previously elevated and slightly warped or folded Jura had become mildly peneplained and the Middle Miocene sediments (conglomerates and sands) rest on formations of different age. A slight erosional and angular unconformity is locally observable (eastern part of Delémont Basin). A Helvetian marine shell breccia fills out the grabens in the eastern tabular Jura.

c) Tortonian = Upper Miocene (Upper Vindobonian). Known only as freshwater deposits in the Jura environment. Period of uplifting. First principal phase of Jura folding. Uplifting of the Vosges mountains, followed by strong fluvial erosion and deposition of local deltaic fans of sands and pebbles in some low areas within the Jura. The southward drainage still more accentuated. In consequence of this the Jura folds became peneplained particularly in the west into what has been called the pre-Pontic Peneplain.

Pliocene — Rivers flowing from north to south spread gravel deposits over northern and western Jura peneplain and drained into the Molasse Basin. No traces of Pliocene deposits were left in this latter environment, because such have been removed subsequently by the strong diluvial erosion.

The second principal phase of Jura folding is to be placed into a period following this gravel deposition, that is into Middle or Upper

Pliocene time. The old peneplain became strongly warped, the folds of the Jura became more accentuated and considerable overthrusting developed at this time in the north-eastern Jura.

Quaternary — This was a phase of erosion. From the southern and youngest Jura folds was removed the Molasse mantle. Many epigenetic valleys crossing the Jura folds developed in this time. The erosion of the Molasse, in the subjurassic zone, was greatest at the time when the Rhone glacier spread over the western and northern Molasse Basin area, connecting with the Rhine glacier. The Rhine and Rhone systems of drainage came into existence in early Quaternary time.

In conclusion it can be said that the Jura folds were formed a long time after the deposition of the formations of which they are constituted. The folds grew slowly at first, with successive and long periods of emergence and denudation. The principal folding movement occurred in two phases: Upper Miocene and Middle or Upper Pliocene, and the last one was probably responsible for the final detachement and gliding of most of the Mesozoic mantle along the salt bearing formations of the Middle Triassic.

The mechanism of folding may be somewhat different in the westernmost Jura ranges, and the Mesozoic stratigraphic section here is more complete and of greater thickness.

c) General Remarks on the Structural Conditions of the Swiss Molasse Basin

1. The Subjurassic Belt

This is a zone which extends from Geneva to the eastern end of the Jura folds, north of Zürich. It is characterized by scarce and intermittent exposures of the older Molasse formations with comparatively moderate thickness.

Before the great erosion, effected by the glaciation of the Quaternary time, this area was filled with more Tertiary deposits which must have formed a peneplain with elevations between 800—900 meters.

During Eocene time the Mesozoic basement was already slightly warped and became eroded slowly in a realm of arid dry-land. In western Switzerland the basement is formed by Lower Cretaceous (Urgonian = Barremian). On some of the uplifts the Urgonian has been removed by erosion, and its debris are found merely in large sinkholes, associated with Bolus clay, a ferruginous caliche, and with fine quartz sands, whereas the surface is formed by Hauterivian (Chamblon Dome, west of Yverdon). Farther towards northeast the basement is formed by the Malm limestone.

Lower Oligocene (Sannoisian = Lattorfian) sediments are practically missing in the subjurassic belt except at Oberdorf near Solothurn. They were removed by erosion in Middle Oligocene time. The same applies also to the Lower-Middle Oligocene (Lower Stampian = Rupelian).

In western Switzerland it is the Upper Stampian (= Chattian) which overlaps on the basement, and in the vicinity of Aarburg-Aarwangen the lowest formations exposed above the basement are assigned to the Middle Stampian.

All those Oligocene formations of the subjurassic zone have been deposited in lacustrine environments. Fossil faunas consist of vertebrates and fresh-water Molluscs. It is difficult to compile dependable aggregate stratigraphical sections, not only owing to the lack of good fossils and key beds, but also because the exposures are poor and disconnected.

Some lateral changes in the sediments may be observed locally which must have been produced through warpings of the irregular surface of the basement.

It is considered very probable that the Lower Stampian (Rupelian), which occurs on the Alpine border as a marine-brackish water sediment, is present immediately south-east of the subjurassic belt and that it is overlapped in a slightly angular unconformity by the lacustrine Upper-Stampian.

A marked subsidence must have occurred with the deposition of the Aquitanian. Its thickness increases very rapidly in a south-easterly direction.

From those brief remarks on the stratigraphy it should be evident that it will be difficult to make further deductions on the structural development of the subjurassic belt in a historical sense.

The detailed surface exploration in western Switzerland and the subsurface information gained at Cuarny, together with the detailed investigations in the Aare valley near Wangen and Aarburg, indicate that some folding of the Jura continues under the Molasse Basin, at least within the marginal subjurassic belt. The folding is, however, generally of lesser amplitude and the anticlines are shorter and nearly of domal or brachy-anticlinal type.

The following structures belonging to this belt are enumerated as they appear from west to east.

Name	Location	Remarks
Mormont Anticline (Urgonian on crest)	Between Yverdon and Morges	7 km. long, faulted to SW, gradual plunge towards ENE; cross-faulting; approx. symmetrical in the Talent River valley; max. dip 20—25^0 towards south.
Chamblon Dome (Hauterivian on crest)	3 km. W of Yverdon	2,5 km. long; faulted; well exposed; max. dip ca. 40^0 towards north.
Chevressy-Cuarny structure; (Small Urgonian exposure on crestal area).	2,7 km ESE of Yverdon	Approx. 2,5 km. long; faulted; asymmetric; mostly under Molasse cover. Max. dip 40—35^0 towards south.
Several Molasse folds: Mörigen, Büttenberg and others	South and east of Bienne (Biel)	Poorly defined for lack of adequate exposures; no Mesozoic exposed.
St. Verena structure	North-east of Soleure (Solothurn)	Slightly folded; northward upthrusted Kimeridgian and Upper Sequanian.

Name	Location	Remarks
Wynau anticline	10 km. south-west ot Aarburg	Brachy-anticline; Middle Stampian exposed on the crest; essentially brachy-anticline. Max. dip 40^{0} towards south, 36^{0} towards north.
Born anticline	Between Aarburg and Olten	Strong Jurassic anticline, exposing Kimeridgian to Argovian (Malm); 13 km. long; max. dip 85^{0} toward south, 18^{0} toward north.

Compared with the long and pronounced folds of the arc of the Jura mountains this is a very poor crop of structures, and it is evident that the large scale folding ends along the inner border of the arc in almost a straight line. This fairly sharp line may be compared in a regional sense to a large and consistent flexure. From the texts known to the writer, it has never been particularly explained. But it may mark the limit along which the Upper Triassic-Jurassic-Cretaceous sedimentary mantle has been folded after the shearing off along the salthorizons. This would postulate for the few subjurassic brachy anticlinal folds a different mechanism whereby the salt has shown little or no flowage while there has still resulted a detachement from the basement.

The comparatively sharp dying out of the Jura folding towards the Molasse basin is to be explained, in the opinion of the writer, not by absence of salthorizons but possibly by an unknown feature in the Hercynian basement.

The Jura folds which converge eastward into the Laegern fold and finally seem to die out into the eastern Molasse basin must have a causal connection with the mechanism of the basement. This latter may have here remained more stable.

Some other sort of a suture seems also to interfere and may cross the basin in E-W direction extending into the southeastern area of the Lake of Constance. It is quite probable that the sharp line which is marked by the Lomont-Mont Terri-Laegern anticlinal trend continues eastward. A detailed gravimetric study would obviously help to solve those problems.

The marginal flexure on the inner side of the Jura arc and the „Lomont-Laegern Line" are entirely theoretic features at present, but their study would be of much practical importance for outlining the Swiss Molasse Basin and for a possible separation from the Munich Basin. It may even involve a differentiation of sedimentary environment. It is anticipated that the marginal flexure is a young feature while the E-W line could have come into existence at an earlier stage of the Jura folding.

It should be added here that the northeastern subjurassic belt shows some peculiar structural features inasmuch as some of the Jura folds display a characteristic virgation with noses plunging eastward under the Molasse sediments. But, owing to scarce exposures, this belt could never be studied in detail sufficient to elucidate the relation between the Molasse sediments and the plunging Jura structures.

2. *Central Portion of the Molasse Basin (Plateau Molasse)*

There is little to be said regarding the structural conditions of this portion. It is practically unfolded or else contains only small folds difficult to outline, particularly owing to the lack of mappable finer stratigraphical subdivisions. The dips on those structures are very shallow, and, in the absence of known angular unconformities in deeper formations, it cannot be anticipated that any much more pronounced folding is present at greater depth.

If our theory is correct that the crystalline basement was moved towards the Alps, we may assume that some shearing took place also here, but due to a greater overburden of Molasse sediments there developed little noticeable folding in the Mesozoic mantle and the Molasse sediments.

The Mesozoic formations are burried from 2000 to 6000 meters in the central portion of the basin.

The most recent views regarding the sedimentary realms in which the freshwater Molasse was deposited may be summed up as follows, according to prof. R. Rutsch of Berne:

„Large bodies of freshwater lakes which persisted for long periods provided for the deposition of freshwater limes and, on the edge, for marl, shale and peat. But there were also extended dryland areas with favourable enough conditions to support a flora and a fauna of all kinds of Vertebrates. In the course of repeated subsidence those land areas became temporarily submerged and the products of weathering together with remnants of terrestrial plant and animal life became imbedded in the sediments. Emergence must have followed usually after a comparatively short time so that no freshwater fauna of any importance could develop. Emergence and brief periods of submergence must have succeeded each other many times."

The best known structures in the central portion of the Molasse basin are very gentle and are briefly described in the following list:

Name	Location	Remarks
Morges anticline	On the north shore of Lake of Geneva	About 4 km. long; in Chattian; vicinity of subjurassic belt.
Frienisberg syncline	Approx. 12 km. NNW of Berne	Approx. 5 km. long; in Burdigalian.
Wohlen anticline	Approx. 5 km. W of Berne	Approx. 9 km. long; in Aquitanian
Albligen syncline	Approx. 12 km. SW of Berne	Approx. 6 km. long; in Burdigalian
Belpberg syncline	Approx. 11 km. SE of Berne	Approx. 25 km. long; in Helvetian; eastern extension not well defined

Name	Location	Remarks
Schwarzenburg-Riggisberg anticline	Approx. 23 km. S of Berne	Approx. 23 km. long; in Burdigalian-Helvetian plunging towards east. Possibly two cores in echelon
Kurzenberg anticline	Approx.17 km. SSE of Berne	Approx. 4 km. long; in Helvetian
Diessbach syncline	Approx. 18 km. SSE of Berne	Approx. 4 km long; in Helvetian
Falkenfluh anticline	Approx. 19 km. SSE of Berne	Approx. 6 km. long; in Burdigalian and Aquitanian; overturned and partly upthrust
Entlebuch anticline	Approx. 16 km. W of Lucerne	Approx. 9 km. long; in Burdigalian, Helvetian and Tortonian
Wädenswil-Schnebelhorn syncline	Approx. 15 km. S of Zürich	Approx. 30 km. long; in Tortonian
Rothen-Käpfnach anticline	Approx. 12 km. S of Zürich	Approx. 40 km. long; in Tortonian
Uetliberg-Schauenberg syncline	West of Zürich, extending towards ENE	Approx. 40 km. long; in Tortonian; poorly defined, very shallow

3. *The Subalpine Molasse Belt*

This Molasse belt which responds essentially to a structural terminology is very characteristic of the Swiss Molasse Basin. It comprises a series of very particular schuppen-structures which are only locally derived from recumbent and faulted anticlinal structures.

It would be going too far to try to give in a brief chapter a description of the stratigraphic and structural features, and we wish, instead, to refer to the attached graphic material. Still it will be important to keep in mind the great thickness of the involved sediments, which is greatest whenever the sediments are presented in the conglomeratic facies of the sub-Alpine river fans. The thickness is given below for the different localities:

Age	Locality	Thickness in meters
Aquitanian	Gäbris; SE of St. Gall. Hohe Rone; E of Zug	1200 approx. 1500—2000
Chattian (Upper Stampian)	Bulle; S of Fribourg Blumenschuppe; E of Thun Rigi; E of Lucerne Speer; E of Southend of Lake of Zürich	approx. 3000 approx. 3500 approx. 3000 approx. 2400

Rupelian (Lower Stampian)	Bulle; S of Fribourg Fluehli; SW of Lucerne (Hilferenzone) Lucerne Toggenburg Valley (Ct. St. Gall.)	minimum 275 approx. 1100 approx. 1400 minimum 700

Because of the abnormal structural contacts in schuppen segments, none of those formations are ever exposed in complete sequences.

It cannot be established in which portion of Switzerland the thickness was originally greatest. No attempt should be made to use the thickness indicated for any isopach-study.

It should be noted that, with few exceptions, the Miocene formations which occur immediately to the north of the Subalpine Belt do not participate in this schuppen structure, but are clearly separated from Oligocene upthrust formations. This is in spite of the fact that the upthrusting definitely took place at the close of the Miocene and within a short lapse of time. Emphasis must be placed on lateness of this structural movement to the north of the Alps, after the sedimentation of the thick Oligocene and Miocene had proceeded regularly and without noticeable break.

In order to size up the events responsible for the development of the Subalpine Belt, we shall try to analyze the successive structural-stratigraphic phases:

a) in Upper Tortonian or Sarmatian time, when the first principal folding phase of the Jura occurred, the deposition of the Alpine piedmont deposits was halted. There developed an erosion of a pronounced longitudinal valley by a strong drainage system, directed probably towards the east, with ensuing captation of the Miocene rivers which had emptied northward into the basin. This valley extended along the foot of the Central Massifs, and this erosion antedates the final implacement of the Helveticum „Decken“ and the other northernmost „Decken“ elements.

b) In Pontian (early Pliocene) time there was a general uplifting of the Subalpine Molasse associated with imbrication and thrusting. This process has been linked to the movement and up-rooting of the Central Massifs. Renewed erosion attacked the Miocene and even Oligocene piedmont fans and the crests of the Subalpine mountains. Deposits from this Pontian erosion must have been laid down in a trough now covered by „Decken“ elements of the eastern Helveticum Alps, but there are no observations supporting this assumption.

c) For the close of the Pliocene and early Pleistocene time a northward sliding of the Helveticum „Decken“ is postulated, with ensuing abutment against the partly eroded Subalpine Molasse ranges. This movement produced the final structural pattern of the Subalpine Molasse schuppen. The Peri-Alpine erosional valley has in consequence been filled entirely by the Helveticum and Ultra-Helveticum „Decken“ masses.

Those above described extremely complicated structural developments have been studied, partly in great detail, within the last 40 years. And it is evidently impossible to give any clear account of the sedimentary realm in which the sediments of the Subalpine Molasse Belt were laid down. It is not permissible to construct any isopach maps from the fragmentary sections exposed. We can merely anticipate that the greatest sedimentary fill for the Molasse, including Oligocene and Miocene, must be placed into a belt which is now entirely uprooted, as for intance at the Rigi mountain. At the close of the Tertiary system much of this basin filling had been removed so that even the Oligocene stages of sediments had been opened to erosion.

4. *Early Tertiary Deposits in the Realm of the Northern Alps*

It has been stated before, when the terms „Flysch“ and „Molasse“ were discussed, that it is extremely difficult to compile a clear summary stratigraphy for the formations which are older than Rupelian, that is, for the Lower Oligocene or the Sannoisian (= Lattorfian) and the Eocene. Those formations are already involved in the „Decken“-Structures or are covered by them. The autochthonous thick Lower Oligocene and Upper Eocene are found in a belt where the deep engulfment („Einschluckung“) of the early Tertiary sediments, possibly even under the Crystalline Massifs, has to be assumed in accordance with the newest theories on Alpine structure.

Even though the knowledge of the Lower Tertiary stratigraphy in the Alps still shows large gaps, the fragmentary observations give some indications on the early development of the sedimentary basin to the north of the Alps.

Lower Oligocene (Sannoisian) which is apparently transitional with Upper Eocene (Priabonian) is represented in the autochthonous sections of the northern Alps by thick deposits of sandstone and shale, which, in the western Swiss Alps, are known as the Taveyannaz Sandstone and, in great part, correlate with the Altdorfer Sandstone to the north of the Aar-Gotthard Massifs.

Below this sandstone-shale section there is found, also in fragmentary exposures, a thick series of *Globigerina* marls or slates, which is placed essentially into the Upper Eocene (Priabonian).

There is little Middle Eocene and no Lower Eocene present in this Upper Eocene-Lower Oligocene sedimentary area to the north of the Swiss Alpine Massifs (autochthonous and parautochthonous Flysch).

The Eocene section is, howewer, much more complete in the „Decken“ units. Middle Eocene (Lutetian) and even Lower Eocene (Ypresian) and locally some Paleocene are known in stratigraphic profiles of the Helveticum „Decken“, particularly in the Flysch of Einsiedeln. This indicates that in the internal zones of the Alps, which means before the Alps had been formed, some sea existed with a much more regular succession of sedimentation. This observation is valid even for the Mesozoic sections, because formations which must definitely be attributed to the Maestrichtian, Campanian, Senonian and Turonian were found associated with and underlying the Tertiary Flysch sections of the Helveticum Alps.

In consequence of all this it may be questioned whether a well defined „foredeep“ ever existed to the north of the Alps over any substantial period of time. It appears that much shifting of the basin axis occurred, at short intervals, throughout the Tertiary era. The bulk of the Molasse deposition was laid down on a foreland, and, with advancing time, those sediments became what may even be termed ‚piedmont deposits' (Tortonian time).

The fact is that a deeper portion of the Swiss Tertiary basin, with prevailingly marine sedimentation, existed in late Eocene to early Oligocene time within the area now occupied by the northern Alps. „Decken" movements from above and a process (still theoretical) of engulfment from below, or swallowing into greater depths, have affected those early Tertiary sediments and have contorted and metamorphosed the beds to such an extent that they retain no practical value for the generation or accumulation of oil.

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