Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 88 (1995)

Heft: 1

Artikel: A new look at the Blattengrat unit of eastern Switzerland : Early Tertiary foreland basin sediments from the South Helvetic realm

Autor: Lihou, Joanne C.

DOI: https://doi.org/10.5169/seals-167666

Eclogae geol. Helv. 88/1: 91-114 (1995)

0012-9402/95/010091-25 $1.50 + 0.20/0
Birkhäuser Verlag, Basel

A new look at the Blattengrat unit of eastern Switzerland: Early Tertiary foreland basin sediments from the South Helvetic realm

JOANNE C. LIHOU[1]

Key words: Blattengrat unit, Helvetic, Nummulitic Formation, Early Tertiary, foreland basin

ZUSAMMENFASSUNG

Seit 1960 ist über die Blattengrat Schichtfolge nur noch sehr wenig publiziert worden. Die vorliegende Neuinterpretation der Ablagerungsgeschichte dieser paleogenen Abfolge beruht auf Angaben in der Literatur und auf eigenen Untersuchungen. Die in der Blattengrat Schichtfolge enthaltenen Siliziklastika und Karbonate mit Nummuliten sind paleocaene bis mitteleocaene flachmarine Schelfablagerungen. Sie zeigen bedeutende relative Schwankungen des Meerespiegels (>300 m) an. Faziell ähnliche Ablagerungen im Nordhelvetischen Flysch sind jünger. Ähnlich wie dies Crampton (1992) für den Nordhelvetischen Flysch festgestellt hat, gilt auch für die Blattengrat Schichtfolge, dass die Sedimentation in diesem frühen Stadium eines Vorlandbeckens durch die relativen Meeresspiegelschwankungen, die sich aus den häufigen eustatischen Meeresspiegelschwankungen und der tektonischen Subsidenz zusammensetzen, kontrolliert wird.

ABSTRACT

The Blattengrat unit has received little attention since the 1960s. This study takes advantage of the available literature and complementary new observations by the author to reinterpret its Early Tertiary history. The Nummulitic Formation within the allochthonous Blattengrat unit consists of shallow marine and shelf, mixed siliciclastic and carbonate deposits of Paleocene to mid Eocene age, which show evidence of a large magnitude (>300 m) relative sea level (RSL) change. The mid Eocene Nummulitic Limestone of the autochthonous North Helvetic Flysch (NHF) unit represents younger, time transgressive equivalent deposits to those in the Blattengrat unit. The pattern of RSL changes inferred in the NHF unit was attributed by Crampton (1992) to a eustatic sea level curve superimposed on uniform tectonic subsidence in a foreland basin. Similarly, the pattern of RSL changes in the Blattengrat unit suggests that background tectonic subsidence was accompanied by high frequency eustatic variations, that together controlled sedimentation of the earliest foreland basin deposits.

1. Introduction

The Blattengrat unit is located between the Linth and Rhine valleys within the Canton of Glarus, in eastern Switzerland, where it crops out in two main valleys: Weisstannental, and Sernftal in the district of Elm (Fig. 1). It extends over an area of 20 x 14 km, at elevations of 900 to 2,100 m in Weisstannental, and 1,300 to 2,200 m east of Elm. The Blattengrat unit has a WSW-ENE structural grain, is bounded by thrusts, and forms part of the Infrahelvetic nappe pile, separated from the Helvetic nappes by the Glarus Overthrust

[1] Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR, UK

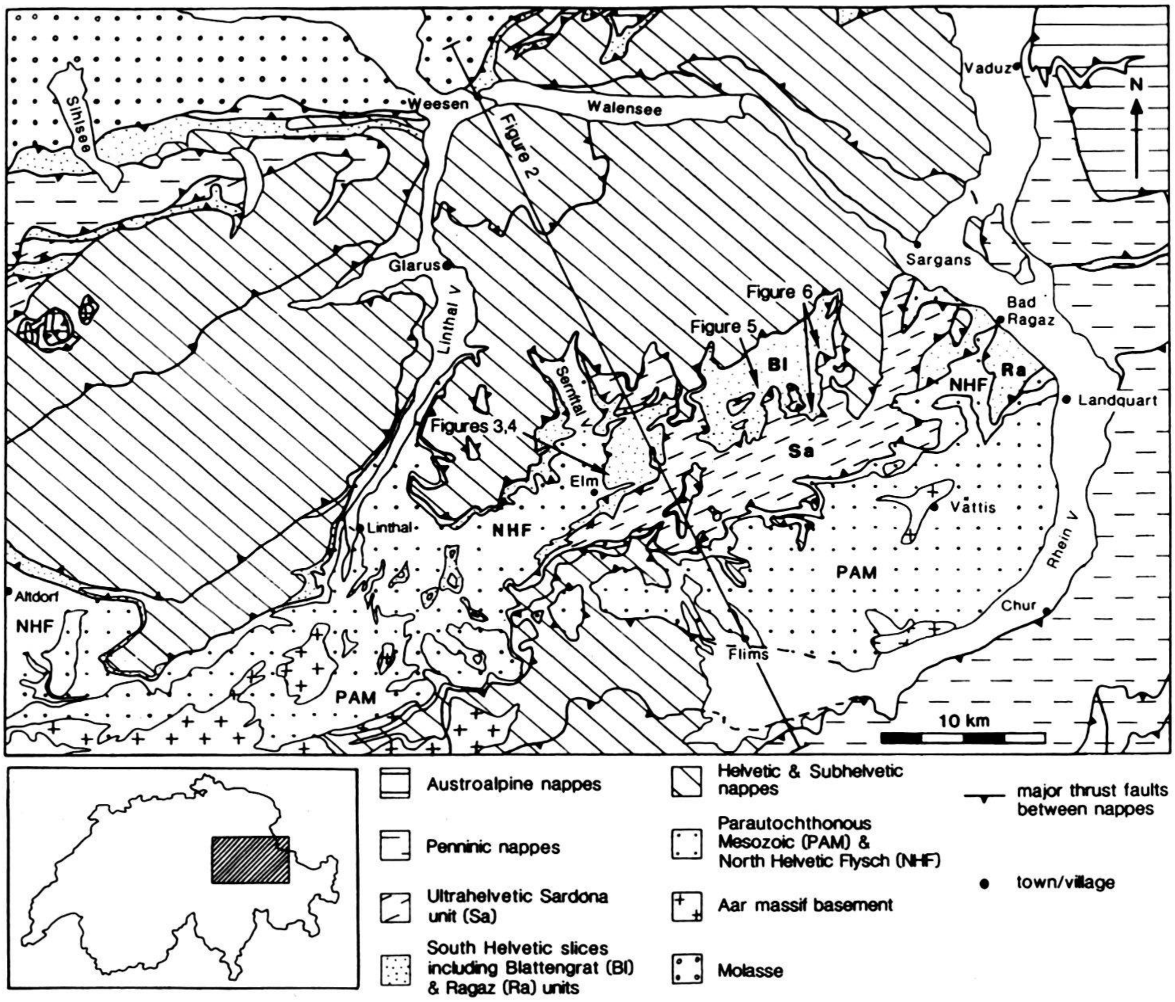


Fig. 1. Tectonic map of the Glarus Alps, adapted from Trümpy (1967) and Spicher (1980), also showing the location of figures 2–6.

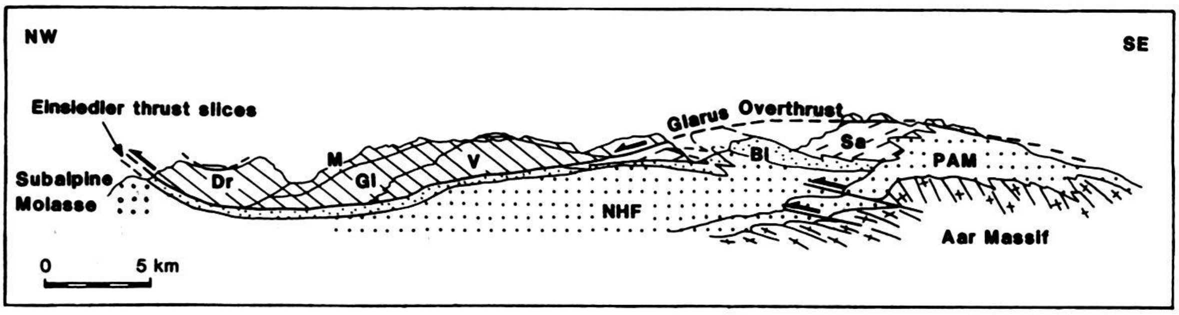


Fig. 2. Simplified structural cross-section through the Glarus Alps, eastern Switzerland, modified from Trümpy (1980) and Pfiffner (1986); key as in figure 1.
Bl – Blattengrat unit; Dr – Drusberg nappe; Gl – Glarus nappe; M – Murtschen nappe; NHF – North Helvetic Flysch; PAM – Parautochthonous Mesozoic; Sa – Sardona unit; V – Verrucano.

Tab. 1. Comparative stratigraphy of the Einsiedler units, from Bisig (1957), Wegmann (1961) & Stacher (1980); zoning of the Nummulitic Limestone member depends on the occurrence of several species of large nummulitids and assilinids. T-transgression surface according to Leupold (1937).

Stratigraphy of the Einsiedler unit	**Stratigraphy of the Blattengrat unit**
Flecken Marl	Flecken Marl
Upper Greensand	Upper Greensand
——— T	——— T
(hematitic infiltration zone)	(hematitic infiltration zone)
Kaufmanni Limestone	Kaufmanni Limestone
Subdistans Limestone	Granulosa Limestone & Marl
Granulosa Limestone	Murchisoni Limestone
Murchisoni Limestone	Middle Greensand
Middle Greensand	
——— T	Batöni Sandstone member
Lithothamnium Lst/echinoderm breccia	——— T
Lower Greensand	Fliegenspitz Formation
——— T	——— T
Amden marls	Amden or Wang marls

(Fig. 2). The allochthonous unit above it, the Sardona unit, consists of deep marine flysch deposits of Late Cretaceous to mid Eocene age (Lihou 1993), whilst it is underlain by the parautochthonous North Helvetic Flysch (NHF) unit, which is composed of mid Eocene shallow marine and shelf deposits (Herb 1988; Crampton 1992) and late Eocene flysch deposits (Sinclair 1989, 1992), that have been attributed to an early north Alpine foreland basin (Allen et al. 1991).

Reconnaissance work on the 'flysch' deposits of the Glarus Alps by Oberholzer (1933) uncovered fundamental stratigraphic differences between the Blattengrat and Sardona units, (the latter being referred to as 'Wildflysch' at this time). In the Sardona unit there is a continuous record of flysch sedimentation from the Late Cretaceous to Early Tertiary, whereas there is a predominance of marl and numerous, structurally repeated, Tertiary Nummulitic Limestone beds in the Blattengrat unit, which are everywhere discordant with the underlying Late Cretaceous marls, an observation that Leupold (1937) attributed to a transgression. Leupold (1937, 1943) interpreted the 'Siderolithic' or 'hematitic infiltration zone' near the top of the Nummulitic Limestone as probable evidence of emersion followed by a second transgression depositing greensand (Tab. 1). He also established links with the Nummulitic Limestone of the Ragaz flysch unit, at Bad Ragaz in the Rhine Valley to the east, and the (Helvetic) Einsiedler thrust slices at Sihlsee to the north (Leupold 1937, 1938, 1943) (Fig. 1, 2, Tab. 1). Similar stratigraphies can be found in thrust slices beneath the Helvetic nappes as far west as Altdorf (Fig. 1), but these are not the focus of this paper.

In both the Blattengrat and Ragaz units, the Nummulitic Limestone member is replaced laterally by a coarse greensand or glauconitic quartzose sandstone, locally called the Batöni or Ragaz/Guschakopf Sandstone, respectively (Leupold 1937; Rüefli 1959).

This sandstone was considered by Leupold (1938, 1943) to be the lateral equivalent of the Sardona Quartzite in the Sardona unit, although the Late Cretaceous marls of the Blattengrat and Ragaz units underlying it bear little resemblance to the relatively coarse clastics of the Infraquartzite Flysch underlying the Sardona Quartzite. In attempting to reconstruct the original relative positions of the various units, Leupold (1938) made the Ragaz unit intermediate between the Blattengrat and Sardona units in a NW-SE-trending profile of the Helvetic shelf. Thus, the Blattengrat unit came to be considered South Helvetic and the Sardona unit Ultrahelvetic in origin.

The history of research into the Blattengrat and Sardona units by Leupold culminated in him supervising three doctoral projects in the area (Bisig 1957; Rüefli 1959; Wegmann 1961), which provided more detailed lithological descriptions and improved micropaleontological dating of the sediments. However, this body of work has received relatively little attention since then, except in review articles such as those of Leupold (1964) and Herb (1988). The present paper draws upon the available literature for the Blattengrat unit and complements it with new personal observations. This has enabled the interpretation of the depositional environments of the Early Tertiary formations and the reconstruction of the facies distribution of the Blattengrat paleogeographic realm through making regional correlations. The history of relative sea level (RSL) changes for the Blattengrat unit are compared with those deduced by Crampton (1992) for the Nummulitic Formation in the NHF unit. Finally, the issue of whether the inferred RSL changes in the Blattengrat unit can be ascribed to a tectonic and/or eustatic control is discussed.

2. Late Cretaceous units

The Late Cretaceous deposits of the Blattengrat unit are represented by the Amden and Wang Formations, which are dominated by marly shales and are the youngest preserved Mesozoic strata in the Helvetic realm (Leupold 1938; Herb 1988). Because of the deformation within the Infrahelvetic Complex, by thrusting along the boundary between these incompetent marls and the competent Tertiary Nummulitic Formation, the marls can be locally absent. They are most severely affected in this way in the region east of Elm, between the Blattengrat ridge on the south side of Chrauchtal (734/201–736/202), and Tschingelschlucht to the south of Ramintal (733/196). Here, the Blattengrat unit is preserved as a series of five thrust slices or 'Schuppen' (Bisig 1957), many of which are internally stretched to the extent that the Nummulitic Formation is boudinaged along numerous minor normal faults parallel to the regional cleavage (Fig. 3.), and the Tertiary Flecken Marl lies directly upon the Late Cretaceous marl. The extent of the deformation decreases to the east so that in Weisstannental, the Blattengrat unit consists of a series of inclined and recumbent folds, whose limbs may be boudinaged or dislocated by thrusts within either the Tertiary or Late Cretaceous marls. The two marls may be differentiated in the field by their colour difference: the Late Cretaceous marls are almost black, whereas the Tertiary marls are light to medium grey when fresh and weather yellow-grey.

The Amden and Wang marls in the Blattengrat unit were dated as Coniacian to Maastrichtian in age using a meagre *Globotruncana* sp. fauna. However, the faunal list given by Wegmann (1961) includes the species *Globotruncana lapparenti lapparenti, Globotruncana lapparenti tricarinata* and *Globotruncana arca*, which would indicate an age of latest Santonian to Maastrichtian, as well as the exclusively Maastrichtian species *Globotruncana*

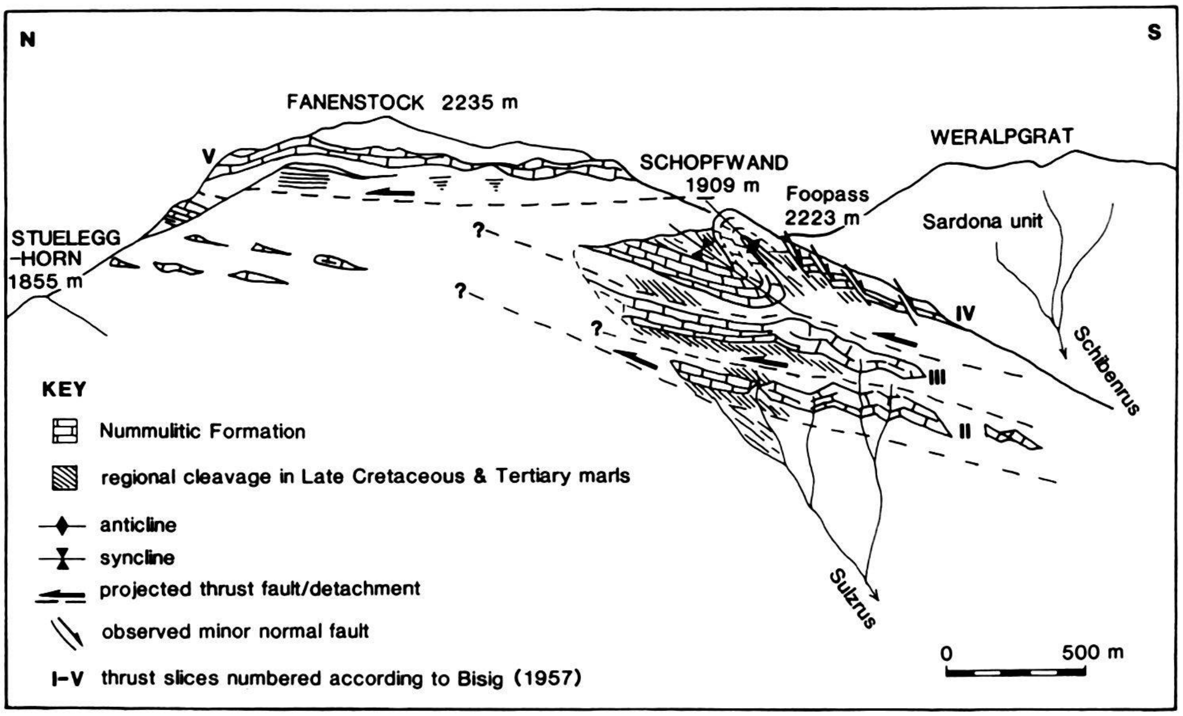
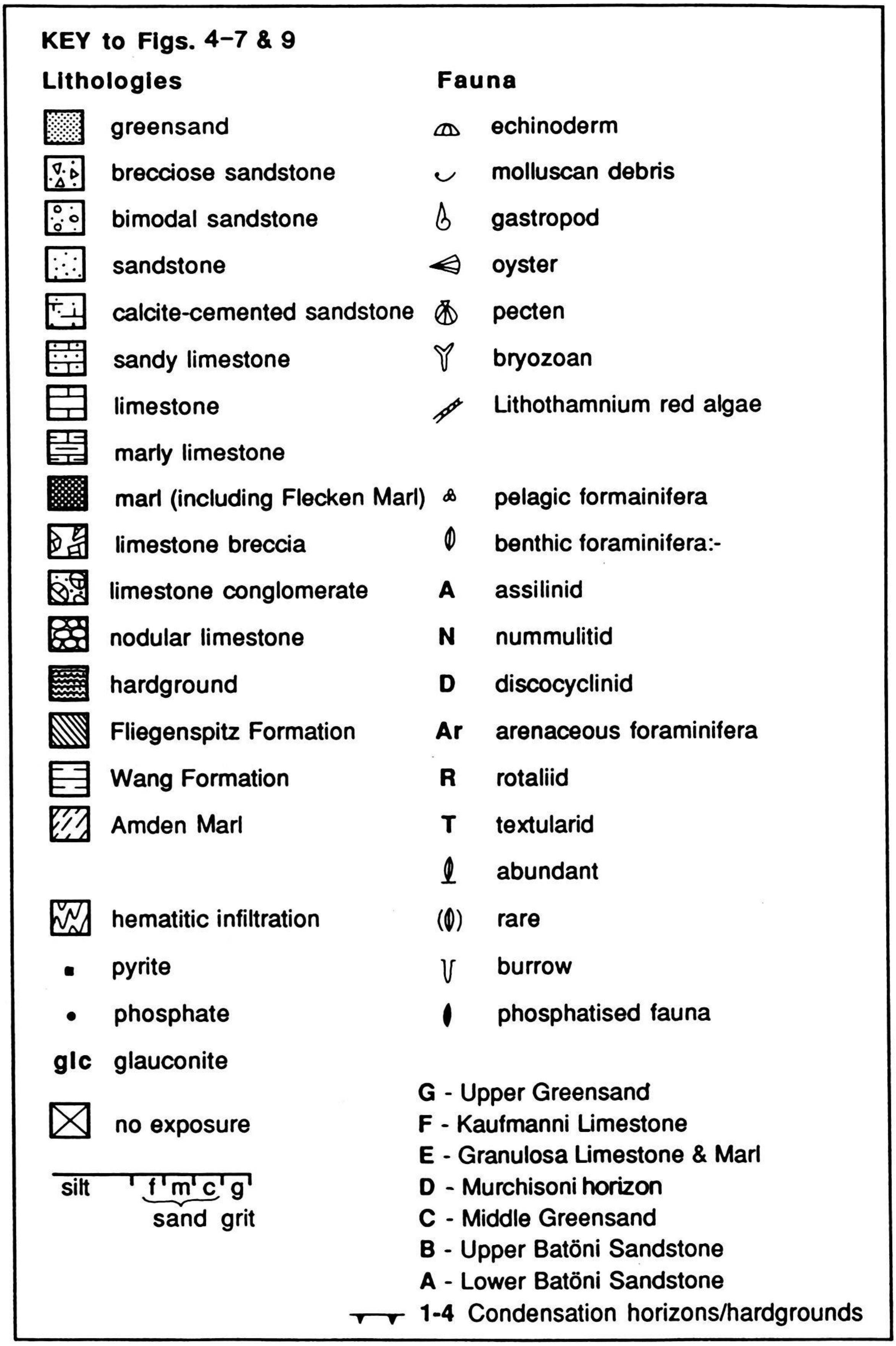


Fig. 3. Field sketches of five thrust slices in the Blattengrat unit northeast of Elm, seen in transverse view from the opposite side of Sernftal looking east; interpretation partly based upon observations by Bisig (1957).

conica and *Globotruncana stuarti* (Caron 1985). Stacher (1980) made an extensive investigation of the stratigraphy, microfacies and micropaleontology of the Wang Formation across Switzerland. He confirmed that in the Blattengrat unit, the transition from the Amden to Wang Formation took place in the late Campanian, and that Wang deposition continued until the middle Maastrichtian. Where the transition between the two formations occurs, there appears to be a gradual horizontal and vertical facies change, so that the lower boundary of the Wang Formation is diachronous, with a south-north younging in the age of the transition (Bisig 1957; Rüefli 1959). The basal beds of the Wang Formation, forming the stratigraphic transition from the Amden Formation, are characterised by an increase in quartz content and grain size (Stacher 1980). In general, the Wang Formation is a dark grey to black, sandy limestone and marl slate, which reaches a maximum thickness of 130 m in the Säntis nappe (Stacher 1980). Stacher (1980) inferred that it was deposited in water depths of 100–800 m on the continental slope in a low energy environment, where periodic, relatively low velocity currents brought in grains of quartz, glauconite, phosphate and heavy minerals, plus some benthic foraminifera from the shelf to the north.

3. Fliegenspitz Formation

This formation is locally preserved at the top of the Wang Formation at Batöni (746/202) and Näserinabach (742/206) in Weisstannental (Stacher 1980). It has a similar appear-


KEY to Figs. 4–7 & 9
Lithologies
greensand
brecciose sandstone
bimodal sandstone
sandstone
calcite-cemented sandstone
sandy limestone
limestone
marly limestone
marl (including Flecken Marl)
limestone breccia
limestone conglomerate
nodular limestone
hardground
Fliegenspitz Formation
Wang Formation
Amden Marl
hematitic infiltration
pyrite
phosphate
glc glauconite
no exposure
silt
f m c g
sand grit
Fauna
echinoderm
molluscan debris
gastropod
oyster
pecten
bryozoan
Lithothamnium red algae
pelagic formainifera
benthic foraminifera:-
A assilinid
N nummulitid
D discocyclinid
Ar arenaceous foraminifera
R rotaliid
T textularid
abundant
rare
burrow
phosphatised fauna
G - Upper Greensand
F - Kaufmanni Limestone
E - Granulosa Limestone & Marl
D - Murchisoni horizon
C - Middle Greensand
B - Upper Batöni Sandstone
A - Lower Batöni Sandstone
1-4 Condensation horizons/hardgrounds

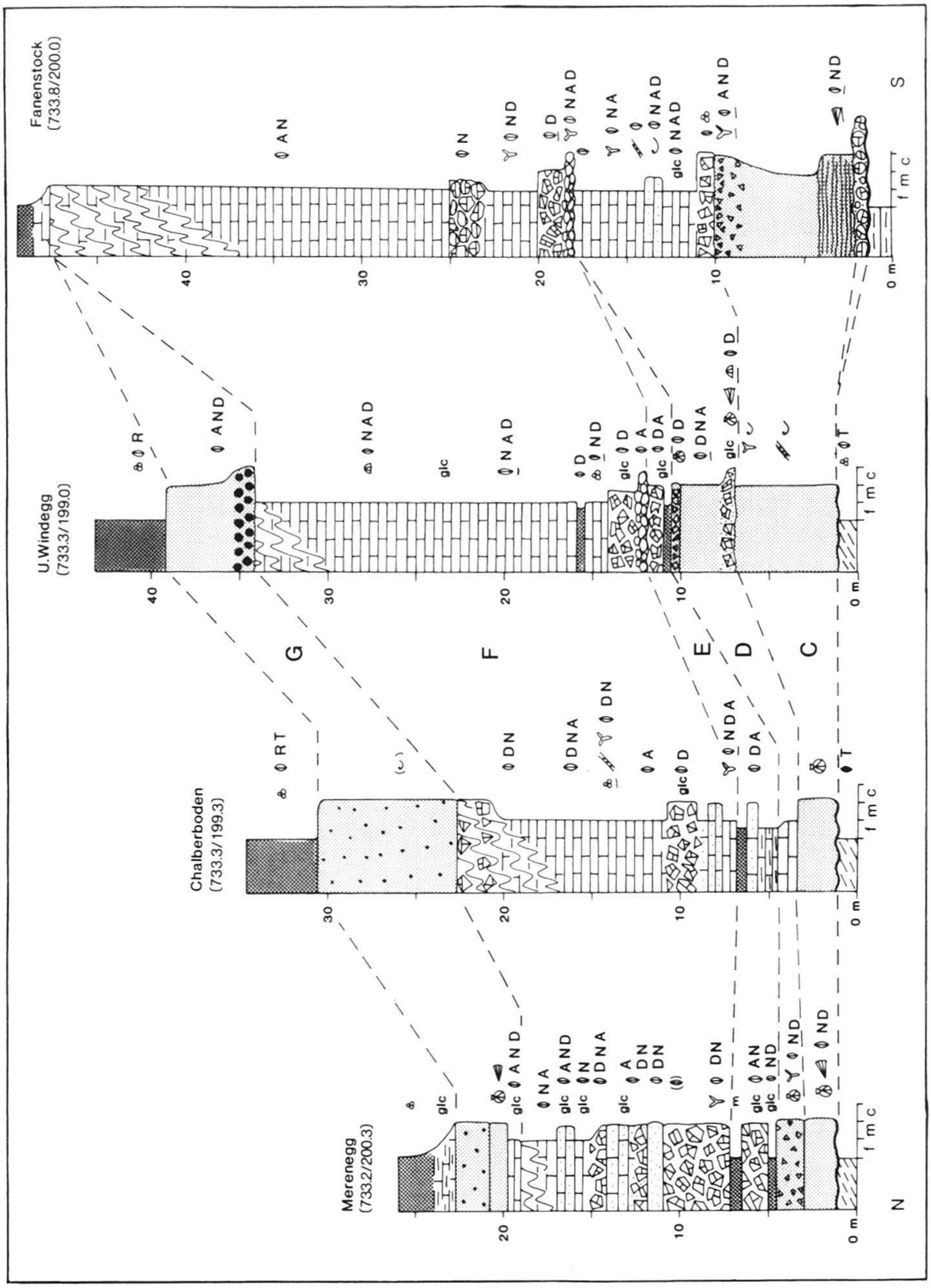


Fig. 4. Stratigraphic profiles through the Nummulitic Limestone member east of Elm, compiled from Bisig (1957).

ance to the Wang Formation, consisting of dark brown to grey-black marls with limestone interbeds. The microfauna is a mixture of reworked Maastrichtian planktonic and benthic foraminifera (e.g., *Globotruncana* sp. and *Lituola grandis*, respectively) and Paleocene planktonic foraminifera; very rare fish teeth were found in a condensation horizon at the top of the Batöni profile (Stacher 1980). At the type locality at Fliegenspitz-Gipfel, where the formation reaches 16 m thickness, planktonic foraminifera from the marl were found spanning the *Globotoralia pusilla pusilla* to *Globotoralia velascoensis* zones (Herb 1988), i.e., P3-6, Thanetian zones (Harland et al. 1989).

Herb (1988) interpreted this unit as being deposited in a detritally-influenced deep neritic environment, at a water depth of 100 m, judging by the mixed planktonic and benthic foraminifera content. He also claimed that it represents the first transgressive deposit across the southern realm of the Helvetic shelf in the Danian/Thanetian, but was subsequently eroded during a regressive phase in the latest Paleocene, so that it remained only in isolated pockets which escaped erosion. Some erosion also took place prior to the deposition of the Fliegenspitz Formation, which Stacher (1980) thought took place in a submarine environment. In Näserinabach the basal surface cuts down to the upper Campanian basal beds of the Wang Formation, but at Batöni, the Fliegenspitz Formation lies on a 75 m thick sequence of the Wang Formation (Stacher 1980), so the erosion probably created an irregular topographic surface.

4. Nummulitic Formation

A thorough investigation of the Nummulitic Formation and its microfauna has already been undertaken by Bisig (1957), Rüefli (1959) and Wegmann (1961). The descriptive stratigraphic profiles contained in their theses are located in figure 1 and reproduced graphically in figures 4 to 6, with amendments to the originals so that grain size and lithology are given priority over stratigraphic zonation. This helps to make facies correlations between profiles more obvious and facilitates interpretations of the depositional environments. Faunal assemblages were reported in sufficient detail to assist with these correlations. The faunal classifications and stratigraphic ranges for the nummulitids and assilinids identified by Bisig (1957), Rüefli (1959) and Wegmann (1961) were cross-referenced against Schaub's (1981) memoir and confirmed that the main development of the Nummulitic Limestone member was during the Ypresian to early Lutetian. A paucity of diagnostic fauna makes precise dating of the Batöni Sandstone member more problematic.

In general, Amden shales are preserved beneath the Tertiary transgressive deposits in the north of the area and beneath the Wang Formation in the south. This south-north increase in stratal gap was a helpful guide when attempting to reconstruct the relative positions of the Nummulitic Limestone facies in the five thrust slices east of Elm.

4.1 Batöni Sandstone member

Oberholzer (1933) discovered during the mapping of Weisstannental that the lateral equivalent of the Nummulitic Limestone member, present in the east of the valley, was a coarse sandstone which he named after its type locality at Batöni in Val Lavtina (745.6/202). The Batöni Sandstone member appears east of gridline 743 according to

Tab. 2. Stratigraphy of the Batöni Sandstone member, from Rüefli (1959).

Calcareous to sandy Nummulitic limestone	
Lithothamnium limestone	→ laterally a glauconitic, sandy echinoderm breccia
Upper Batöni Sandstone	
	(hardground)
Lower Batöni Sandstone	

Rüefli (1959). It consists of two main units, a 10–15 m thick glauconitic quartz sandstone (the Batöni Sandstone proper), which becomes more fossiliferous upwards, and a Nummulite-bearing limestone, which is rich in *Lithothamnium* sp. in places. The general scheme is shown in table 2.

Herb (1988) believed that the Lower Batöni Sandstone was a deep neritic deposit and a relic of a late Paleocene transgressive phase also recorded by the Fliegenspitz Formation. He also drew parallels between the Upper Batöni Sandstone and overlying Lithothamnium Limestone (Tab. 2), and the Lower Greensand and Lithothamnium Limestone of the Einsiedler unit (Tab. 1). He interpreted rapid facies changes in both units as evidence that local sand accumulations were separated from sand-free Lithothamnium Limestone or higher energy bioclastic limestone. He also attributed the lack of Nummulitic Limestone member overlying the Batöni Sandstone member to a regression and period of erosion prior to deposition of the Flecken Marl, i.e., during the lowstand that produced the hematitic infiltration zone at the top of the main Nummulitic (Kaufmanni) Limestone (Fig. 4, 5). It is difficult to see how erosion of strata overlying the Batöni Sandstone member would not entirely remove the Nummulitic Limestone member from the Blattengrat realm. An alternative explanation is proposed in section 7.

At its type locality at Batöni (745.6/202), the sandstone unit forms a 25 m high bluff, lying unconformably atop Late Cretaceous marl and siliceous limestone interbeds of the Wang Formation, capped by 0.5 m of Fliegenspitz Formation (Stacher 1980). The unconformity is often stained red-brown by the weathering out of a dense layer of pyrite nodules within the sandstone immediately above it. In fact, the Batöni Sandstone is characteristically an orange-brown colour due to a high iron oxide content, and the weathering of authigenic pyrite to hematite and limonite. Texturally, it is a coarse quartzose grit with a polymodal grain size distribution: the average grain size is 1–3 mm, but there are also dispersed, indurated pebbles of subangular to rounded quartz, chert and siltstone, as well as occasional phosphatic clasts up to coarse pebble grade within it.

It is rare to see any sedimentary structures within the sandstone, perhaps because of a high degree of bioturbation: fresh surfaces are often mottled by the activity of burrowers. However, fallen boulders of medium-coarse sandstone in Gufelbach north of Batöni sometimes show good parallel stratification, ripple- and convolute-lamination, or 10 cm scale cross-beds, implying deposition by currents. Pebbly sandstones also exhibit cross-

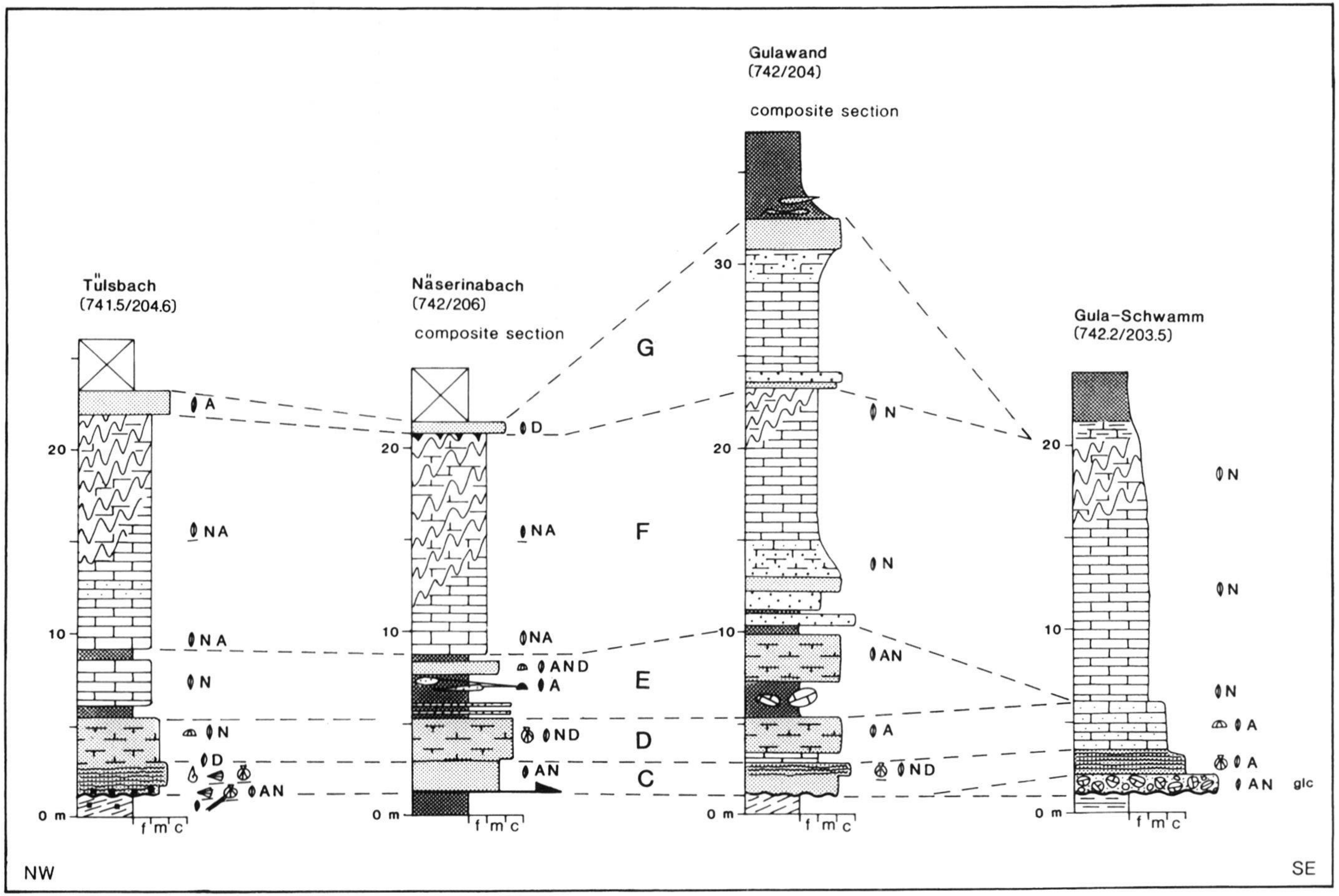


Fig. 5. Stratigraphic profiles through the Nummulitic Limestone member in Weisstannental, compiled from Leupold (1936–42) in Rüefli (1959). For explanation of symbols see p. 96.

bedding and rare coarse-tail grading, and there are examples where they grade into pebbly conglomerates.

Mineralogically, the sandstone is moderately mature, being dominated by monocrystalline quartz that comprises 65–80% of the total lithic grains; the other main constituents are glauconite, sedimentary clasts and muscovite mica. Multi-chambered foraminifera can occasionally be seen in most thin-sections. Some samples were found to be rich in bioclasts, such as echinoderms, bryozoa and discocyclinids.

The intergranular glauconite in the sandstone is probably authigenic, although it is difficult to differentiate between authigenic and resedimented or reworked glauconite (Fischer 1990). Its granular appearance and similar size to the quartz grains could mean that the glauconite was transported along with the quartz, or else that the glauconite has replaced some of the original quartz grains during diagenesis. However, glauconite would abrade much faster than quartz during transport, so their similar sizes are not necessarily an indication of transport (Fischer 1987). In addition, it is difficult to erode entire peloids from a lithified sediment (Fischer 1987), so one would expect resedimented (or allogenic) glauconite peloids to be fragmented and abraded. The glauconite in the Batöni Sandstone usually constitutes 20–26% of the detrital grains, so is equivalent in concentration to some modern sites of glauconite formation (Odin & Matter 1981). Also, it sometimes infills foraminiferal chambers, so may well have formed *in situ*.

The precipitation of glauconite requires slow sedimentation and mildly reducing conditions, forming on the shelf and upper continental slope between 50 and 500 m water depth, but particularly in 200–300 m of water, where the detrital influence is low and winnowing by currents continually redistributes the sediment beyond the shelf edge (Odin & Matter 1981). Granular substrates, especially medium to coarse sands such as the Batöni Sandstone, are the favoured environment for the formation of glauconite because of the stable, semi-confined microenvironment within pore spaces or the interior of grains. Marine transgressions provide granular material that becomes submerged into less turbulent conditions when the zone of sediment accumulation shifts landwards, so that glauconite precipitation follows deposition of the transgressive sand bodies (Odin & Matter 1981). This could be the case for the formation of glauconite in the Batöni Sandstone.

The most informative and thorough profile through the Batöni Sandstone was compiled by Rüefli (1959) at Batöni-Oberlavtina (Fig. 6). Here, the base of the Lower Batöni Sandstone contains globigerinids, which could be reworked from the underlying Late Cretaceous Wang Formation, as with the Fliegenspitz Formation, or else they represent deposition in water depths exceeding 40 m (Brasier 1980). The lower sandstone is also characterised by the presence of arenitic agglutinating foraminifera: *Ammobaculites* sp., *Ammobaculoides* sp., and *Bigenerina* sp., likely to be derived if this was a deep neritic sandstone as Herb (1988) claimed, but from much shallower water, since they inhabit water depths of 0–100 m at the present day (Murray 1991). Agglutinating foraminifera are more common in brackish water where there is less calcium carbonate available for test growth, and small foraminifera in general, favour protected habitats (Ghose 1977), which points to them inhabiting an estuary or lagoon. The foraminifera may then have been carried offshore during storm discharges, to be deposited below the storm wave base in shallower water depths than those suggested by Herb (1988).

An enrichment in coarse arenaceous foraminifera and the coarsening upwards at the

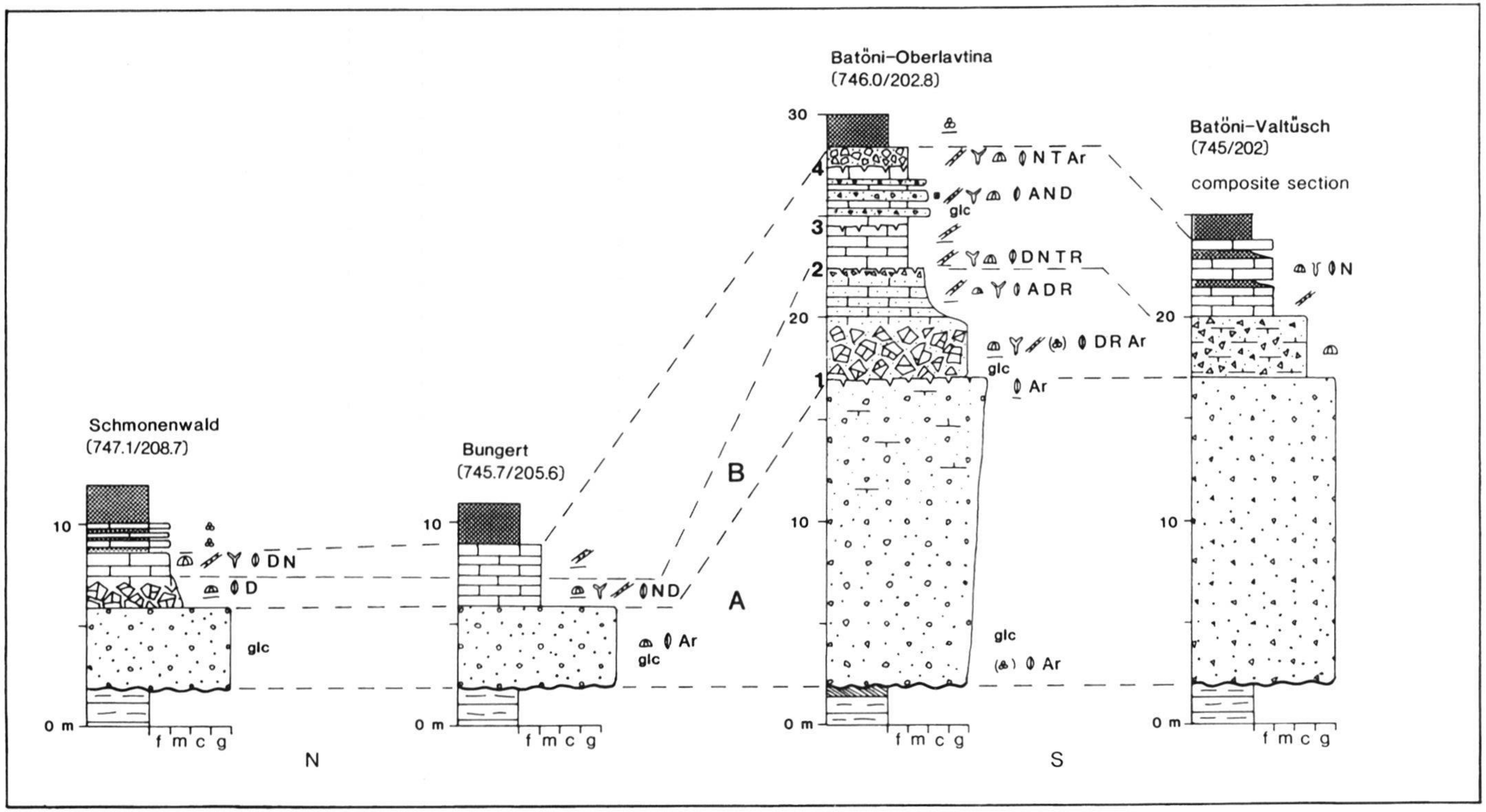


Fig. 6. Stratigraphic profiles through the Batöni Sandstone member in Weisstannental, compiled from Rüefli (1959). For explanation of symbols see p. 96.

top of the Lower Batöni Sandstone (Fig. 6) may have arisen from a period of winnowing removing the finer quartz fraction. This could have been caused by storm-related waves or bottom currents affecting the inner shelf. This period of winnowing was called a 'condensation horizon' by Rüefli (1959); three more 'condensation horizons' appear within the upper half of the Batöni Sandstone, the subsequent ones being preserved as a microfossil breccia, or an algal hardground. The latter is evidence that a hard substrate was colonised by the crustose coralline red algae *Lithothamnium* sp., perhaps forming an algal pavement at shallow water depths in the nearshore environment.

The Upper Batöni Sandstone commences above the first 'condensation horizon' and initially contains detrital *Lithothamnium* sp. and bryozoan fragments, which may have been derived from an algal pavement nearby, but then the sand content decreases markedly and it is overlain by two units of Lithothamnium-rich limestone, separated by a second 'condensation horizon'. Above the third 'condensation horizon', an algal pavement, there is a series of brecciose calcareous sandstone and limestone interbeds. The sand and reworked foraminifera they contain could have been introduced together into deeper water inhabited by thin discocyclinids, during storm events. Glauconite and pyrite were precipitated in the chambers of these foraminifera, suggesting that the overall sedimentation rate was low. The last 'condensation horizon', above the storm-generated beds, is overlain by a thin limestone breccia with a diverse fauna of nummulitids, discocyclinids and textularids, with fragmented bryozoans, echinoderms and Lithothamium red algae, that perhaps represents a lag deposit. The Flecken Marl then begins abruptly above this horizon.

Rüefli (1959) recovered primitive reworked nummulitids from the Lithothamnium-rich limestone at the top of the Upper Batöni Sandstone at Batöni, namely *Nummulites aff. exilis* and *Nummulites aff. nitidus,* which he thought indicated a late Paleocene to basal Eocene age. The equivalent Lithothamnium Limestone that overlies the Lower Greensand in the Einsiedler thrust zone, also contains primitive, basal Eocene (Ilerdian) nummulites (Herb 1988). However, Schaub (1981) dated *Nummulites aff. exilis* and *Nummulites aff. nitidus* as middle Ilerdian and middle Cuisian, respectively. Their revised ages imply that the underlying Lower Batöni Sandstone is at least as old as basal Eocene, possibly even Paleocene in age. The second Lithothamnium limestone overlying the Upper Batöni Sandstone contains the early to middle Cuisian nummulitid *Nummulites aff. murchisoni.* In addition, Rüefli (1959) found Ilerdian and Cuisian nummulitids and assilinids in the brecciose calcareous sandstone beds at the top of the Batöni profile, giving an upper age limit of mid to late Cuisian for the Batöni Sandstone member.

The five packages of sediment separated by 'condensation horizons' are not preserved in the thinner, condensed profiles to the north of the area (Fig. 6), which only record a rapid change to a sand-free environment and then deposition of the Flecken Marl. Rüefli (1959) correlated this zone of reduced thickness with the SW-NE-trending 'Northern Reduction Zone', explained by Leupold (in Rüefli 1959, p. 96) as a pre-Nummulitic swell within the Helvetic shelf removing much of the stratigraphy between the Middle and Upper Greensands in the Einsiedler Nummulitic Formation (Herb 1988 & references therein). Westnorthwestwards, the Batöni Sandstone member disappears, to be replaced by the Nummulitic Limestone member.

4.2 Nummulitic Limestone member

Like the Batöni Sandstone member, the Nummulitic Limestone member was deposited unconformably on Amden and Wang marls. It thickens from 20 m in the northwest to almost 50 m in the south to southeast. In the south(eastern) Gula Schwamm profile, there is a limestone conglomerate present at the base of the Nummulitic Limestone, which consists of pebbles of limestone containing small nummulitids and assilinids in a sandy glauconitic cement (Fig. 5; Leupold 1939, in Rüefli 1959). This conglomerate is equivalent to the basal limestone breccia and quartzite seen in the Fanenstock thrust slice (Fig. 4; Bisig 1957) and may be a lag representing a relic of the Upper Batöni Sandstone. Herb (1988) interpreted the reworked pebbles of Lower Greensand and Lithothamnium Limestone beneath the Middle Greensand in the Einsiedler thrust slices, as relics of an Ilerdian erosion phase.

North of these profiles, the basal unconformity is overlain by the **Middle Greensand**. The greensand east of Elm is 2–6 m thick below the first hardground (Fig. 4), and contains fragmented mollusc shells, usually pectens and oysters, becoming more brecciose upwards as foraminifera such as *Discocyclina pratti, Operculina gigantea, Assilina placentula* and *Nummulites murchisoni* appear, along with bryozoans which colonise firm or hard substrates; this becomes a well-developed hardground in the Upper Windegg profile. In Weisstannental, the greensand unit is less than 2 m thick and consists of a sterile glauconitic sandstone occasionally with phosphate nodules overlain by a hardground of pectens, large oysters and gastropods (Fig. 5). The development of a hardground at the top of the Middle Greensand indicates that there can have been little or no sediment input from the land at this time, or else a lack of accommodation space prevented sand deposition, and the sediment was by-passed further out onto the shelf. The main process operating was winnowing by currents or storm-related waves.

The first hardground in the Nummulitic Limestone marks the base of the **Murchisoni horizon**, named after the common occurrence of *Nummulites murchisoni*, a lower to middle Cuisian nummulite (Schaub 1981). In Weisstannental, the Murchisoni horizon is represented by a calcareous greensand with echinoderm debris, that passes southeastwards into a sandy limestone at Gula-Schwamm (Fig. 5). East of Elm, the same stratigraphic horizon thickens to the south and passes into a limestone-rich facies in the Fanenstock profile (Fig. 4). There, the hardground is overlain by a limestone breccia containing *Operculina* sp. and *Globigerina* sp.; whilst Operculina sp. inhabits a range of water depths (0–130 m) (Murray 1991), globigerinids are rare at depths of less than 40 m, and only abundant above 80–100 m (Brasier 1980). The limestone breccia passes upwards into a glauconitic foraminiferal limestone with very big nummulitids and discocyclinids; the bias towards large B-form nummulitids either arose by winnowing out of smaller A-forms by bottom currents, or selective transport of larger forms during high energy storm events (Crampton 1992). *In situ* faunas are dominated by A-forms in an A:B ratio of 10:1 (Blondeau 1972).

In most profiles, the Murchisoni horizon passes directly into the **Granulosa Limestone and Marl**, which was named after its index foraminifera, *Assilina granulosa*. It consists of two marls of varying thickness (0.2–0.5 m) separated by a brecciated limestone or calcareous greensand. At Lower Sibetsegg (733.7/197.7) (Wegmann 1961) and Näserinabach (Fig. 5), both the limestone and marls contain a fauna of abundant assilinids, small nummulitids and discocyclinids, which implies a water depth of more than 50 m according to Racey (1988). The marls provide good correlation surfaces, in particular the second marl which coincides with the disappearance of *Nummulites murchisoni* at the base of the main Nummulitic Limestone. The lower marl in Näserinabach is much thicker than elsewhere and contains silty lenses with pyritised assilinids and echinoderms, produced by bioturbation within a sediment column that became a reducing environment further down.

At Upper Windegg, there is evidence of a third phase of early cementation in the form of a nodular limestone horizon at the top of the Granulosa Limestone (Fig. 4). The fine sandy limestone nodules and medium-sized assilinids imply that fine material has been winnowed out and the remainder lithified by through-going pore fluids. A similar nodular limestone is present in the Fanenstock profile where there is no marl at all, and is colonised by bryozoans (Fig. 4).

The main Nummulitic Limestone is named after the appearance of *Nummulites kaufmanni*, a thick-walled, globular nummulite, of middle Cuisian age (Schaub 1981), whose robust form enables it to colonise higher energy, shallower water, bank or fore-bank environments (Ghose 1977; Crampton 1992). Other Cuisian foraminifera usually present are *Nummulites distans, subdistans* and *formosus*, plus *Assilina placentula* and *laxispira*, with early Lutetian foraminifera, *Nummulites obesus* and *Assilina spira*, appearing towards the top of the unit. Crampton (1992) associated concentrations of large nummulitids in the Bürgen (Nummulitic) Formation of eastern Switzerland with the development and progradation of a nummulite bank in water depths of 5–20 m; globular types accumulated in the fore-bank area where they would have been exposed to incoming waves and longshore currents which winnowed out small A-forms. East of Elm, the base of the **Kaufmanni Limestone** is everywhere denoted by a glauconitic limestone breccia containing discocyclinids (Fig. 4), which may represent talus deposits associated with the growing nummulite bank, that were subsequently overlain by the main Nummulitic Limestone as the bank prograded southwards.

Within the Kaufmanni Limestone of the Lower Sibetsegg profile (GR 733.7/197.7) (Wegmann 1961), there is a local concentration of alveolinids overlain by a sterile marl; this foraminifera is usually found in protected lagoonal environments (Ghose 1977; Racey 1988). The Alveolina Limestone represents a lateral facies change within the Kaufmanni Limestone, and may correlate with the uppermost glauconitic limestone within the Merenegg profile (Fig. 4) which also contains alveolinids and the encrusting foraminifera *Planorbulina* sp.. The overlying marl at Lower Sibetsegg may correlate with the *Globigerina*-rich horizon within the Chalberboden profile (Fig. 4), which also contains (reworked) alveolinids.

At the top of Kaufmanni Limestone is a **'hematitic infiltration zone'** up to 10 metres thick, which gives the limestone an obvious rust-red colour. The development of hematite staining is associated with oxidising conditions in a subaerial environment, so that the limestone must have become emergent for some time and hence exposed to erosion. Consequently, some of the main Nummulitic Limestone may have been removed. A thin karst with numerous, weathered-out nummulites in the Näserinabach profile (Fig. 5) attests to a period of winnowing of the underlying limestone following hematitisation.

In all sections except Fanenstock (Fig. 4) and Gula-Schwamm (Fig. 5), the hematitic infiltration zone is overlain by a fine glauconitic sandstone, called the **Upper Greensand**. Only in the Merenegg and Gulawand profiles can a gradual transition from a glauconitic limestone to sterile greensand with flecks of phosphate be seen. The biogenic greensand often contains large, early Lutetian assilinids, like *Assilina exponens* and *spira*, which prefer water depths of >50 m (Racey 1988), plus medium-sized discocyclinids like *Discocyclina discus* and small nummulitids. The basal Assilina Greensand of the Bürgen (Nummulitic) Formation in the NHF unit has a very similar fauna (Crampton 1992) and is probably a correlative of the Upper Greensand in the Blattengrat unit. In the Upper Windegg profile, the base of the greensand contains a horizon of phosphatised macrofossils, representing a condensed marine horizon, equivalent to the 'Steinbach Fossilschicht' in the Einsiedler thrust zone. Where the Upper Greensand is absent, at Fanenstock (Fig. 4) and Gula Schwamm (Fig. 5), the hematitic infiltration zone passes directly up into the pelagic Flecken Marl.

5. Flecken Marl

Leupold (1937) began the use of the term 'Flecken Mergel' for the equivalent in the Blattengrat unit of the Globigerina Marl at Einsiedeln, or the normal Helvetic 'Stadschiefer', and subsequent workers adopted the same terminology. Also, the name 'Flecken' was applied to the generally monotonous marl because it has a characteristic 'spotty' appearance on cleavage planes, probably caused by bioturbation. Extensive bioturbation was observed in a polished stream cut at Unter Stich in Weisstannental (738/202) implying that the sediment was oxygenated. The marl is generally accepted to include parts of the Lutetian and Priabonian (Bisig 1957; Rüefli 1959).

The sand content of the Flecken Marl varies between 15 and 30%, being sandiest just above the transition from the Nummulitic Formation (Rüefli 1959). Initially, it is rich in arenaceous foraminifera like textularids, reworked small nummulitids, discocyclinids, and fragments of *Lithothamnium* sp., bryozoa and echinoderms. A similar unit, called the Pecten Beds, can be found in the Bürgen Formation, forming the transition between the underlying Nummulitic Limestone and the overlying Globigerina Marl (Crampton 1992). Initially, it too is rich in fine sand, and there is the same upward decrease in fine sand and silt; the fauna is similar to the Flecken Marl as well, except that pectenids are locally abundant.

Pelagic foraminifera become increasingly abundant up sequence in the Flecken Marl; it is therefore probably also equivalent to the Globigerina Marl of the Bürgen Formation. The planktonic foraminifera in the marls can be used for precise dating of the formation: Rüefli (1959) includes the P17 zonal fossil *Globotoralia centralis* in his faunal list for the Flecken Marl, which suggests an upper age limit as young as the Priabonian/Rupelian boundary, i.e., the Eocene/Oligocene boundary (Harland et al. 1989); whereas the Globigerina Marl is assigned to the *Globigerinatheka semiinvoluta*, or P15 zone (Herb 1988; Harland et al. 1989). It therefore seems that the Flecken Marl is Lutetian to Priabonian in age and consequently spans the age range for both the Pecten Beds and Globigerina Marl of the North Helvetic realm.

6. Intermediate Flysch

Only at the top of the whole Blattengrat unit is the complete Tertiary stratigraphy preserved so as to include the youngest unit, a 30–50 m thick sandstone flysch variously known as the Intermediate, Scheubser or Lavtina Flysch (Leupold 1943, 1966; Rüefli 1959), the Blattengrat Sandstone (Bisig 1957), or more generally referred to as South Helvetic Flysch (Herb 1988). Found only at the top of the uppermost thrust slice at Fanenstock, east of Elm (Bisig 1957), and on Alp Laui (741–2/205–6), Alp Scheubs and Alp Foo (738–9/201) in Weisstannental (Leupold 1943; Rüefli 1959), it forms both a stratigraphic cap and a universal detachment horizon for the Blattengrat Complex, and therefore is rarely preserved. From Bisig's (1957) account of the flysch, it is transitional from the Flecken Marl, the change marked by the appearance of limestone interbeds within the marl, then fine-grained micaceous sandstones, ultimately becoming interbedded micaceous sandstones and siliceous limestones.

The Intermediate Flysch generally consists of thin, interbedded micaceous fine sandstones, sandy limestones and marl. The parallel-laminated medium grey marl contains *Chondrites* traces. Such traces are not restricted to one facies association, but the flysch was probably deposited in water depths equivalent to the Flecken Marl. Sandstones are up to 20 cm thick, but most are less than 10 cm thick; they commonly exhibit parallel-, ripple-, undulose- and convolute-lamination, and can be interpreted as distal sandy turbidites. Grits to fine pebbly conglomerates are locally present and consist of mixed immature detritus deposited as traction carpets beneath sandy turbidites. Quartz is the dominant component, with subordinate dolomite, black mudstone, marl, muscovite and chlorite grains. Volcanic clasts (andesites with a trachytic texture) are relatively common in the coarse fraction. Bioclasts of shallow water large foraminifera, such as *Discocyclina*, and Lithothamnium red algae are also found in the coarse fraction, while planktonic foraminifera, particularly globigerinids, are preserved in the fine fraction.

The planktonic foraminifera may be reworked, since they appear in large concentrations in fine to medium sandstones, rather than in the hemipelagic marl intervals. Bisig's (1957) inference that the flysch was Priabonian in age, from the occurrence of the foraminifera *Heterostegina helvetica* (a characteristic microfossil for the Taveyannaz Sandstone of the North Helvetic Flysch) must therefore be accepted with caution. A Priabonian microfauna including the P17 zonal fossil *Globotoralia centralis* was also recovered by Rüefli (1959) from micaceous sandstones in the Intermediate Flysch as well as the youngest Flecken Marl, from which he concluded (probably incorrectly) that the two units were deposited synchronously.

Rüefli (1959) reasoned that if the Intermediate Flysch was only found in stratigraphic continuity at the top of the Fanenstock thrust slice, which Bisig (1957) had assumed had the most southerly origin, then the Intermediate Flysch may have been deposited to the south of the Flecken Marl and later tectonically superimposed upon it. This was substantiated by his conclusion that, in Weisstannental, the Intermediate Flysch formed a distinct structural unit, sandwiched between the Blattengrat and Sardona units, making it 'intermediate' in the tectonic sense. However, having examined Rüefli's (1959) type sections in Weisstannental, there appears to be a lack of structural deformation at the contact between the Flecken Marl and the overlying Intermediate Flysch, suggesting that they form a conformable succession. Therefore, their apparently comparable ages either mean that they were both deposited within the P17 zone, or that the Intermediate Flysch is in fact younger and has not yet been accurately dated.

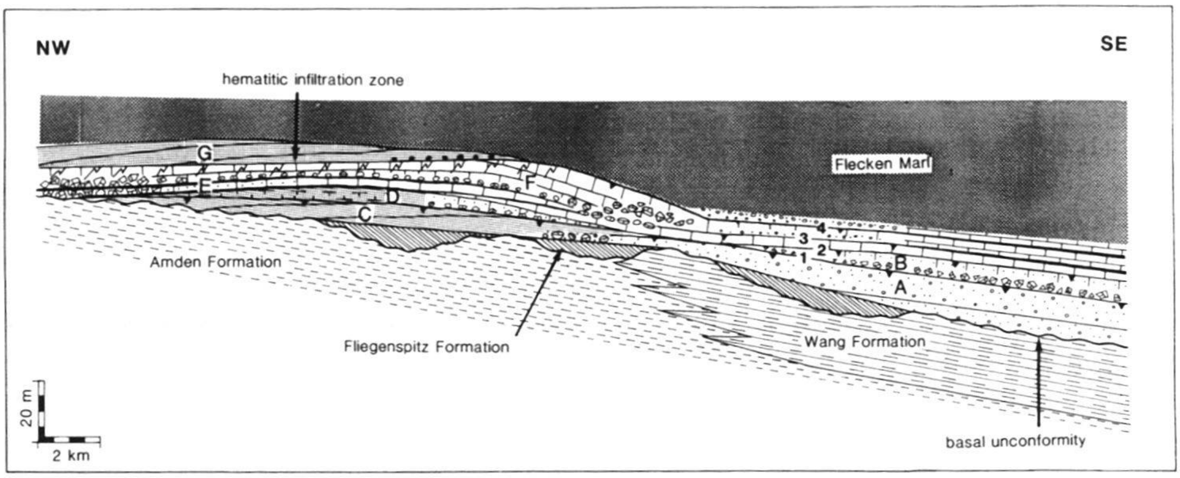


Fig. 7. Schematic reconstruction of the South Helvetic margin.
For explanation of symbols see p. 96.

7. Evidence for relative sea level changes

The Fliegenspitz Formation and the Batöni Sandstone were deposited on a basal unconformity (megasequence boundary) developed during a widespread regression affecting much of the Helvetic shelf (Herb 1988). The chronostratigraphic gap between the underlying Wang Formation and the Fliegenspitz Formation only spans the late Maastrichtian to Danian, which suggests that there was less erosion than elsewhere in the Helvetic realm (Allen et al. 1991). The Wang Formation was deposited in water depths of 100–800 m (Stacher 1980), so that a minimum 100 m RSL fall would be required to erode it just in the foreshore/shoreface environment, and more if it was eroded subaerially. The Fliegenspitz Formation was probably deposited as a thin veneer of muddy sediment on an irregular topography created during this period of erosion (Fig. 7). Some of the material was derived from reworking of the exposed Late Cretaceous formations (Stacher 1980). The Fliegenspitz Formation was only preserved in isolated pockets which escaped erosion by currents or waves acting on the inner shelf during a subsequent minor shoreline regression (Fig. 8).

The Lower Batöni Sandstone was deposited shortly afterwards, during a second transgression of the Helvetic margin. The pattern of a south-north decrease in thickness of the Lower Batöni Sandstone, from approximately 15 m at Batöni to 5 m further north (Fig. 6), could be due to northward onlap of the shelf (Fig. 7). The sandstone coarsens-upwards and is capped by a 'condensation horizon', marking a period of winnowing and non-deposition, probably due to a lack of accommodation space at the end of a shallowing upwards cycle. The increase in water depth and accommodation space, that allowed deposition of the Upper Batöni Sandstone, would have required a rise in RSL (Fig. 9). The progressive switch to carbonate-dominated sedimentation shown by the Upper Batöni Sandstone member could be explained by the RSL rise drowning the source area for siliciclastic material and increasing the area available for carbonate production within the photic zone, thus allowing a switch to a carbonate-dominated shelf, rather than a seg-

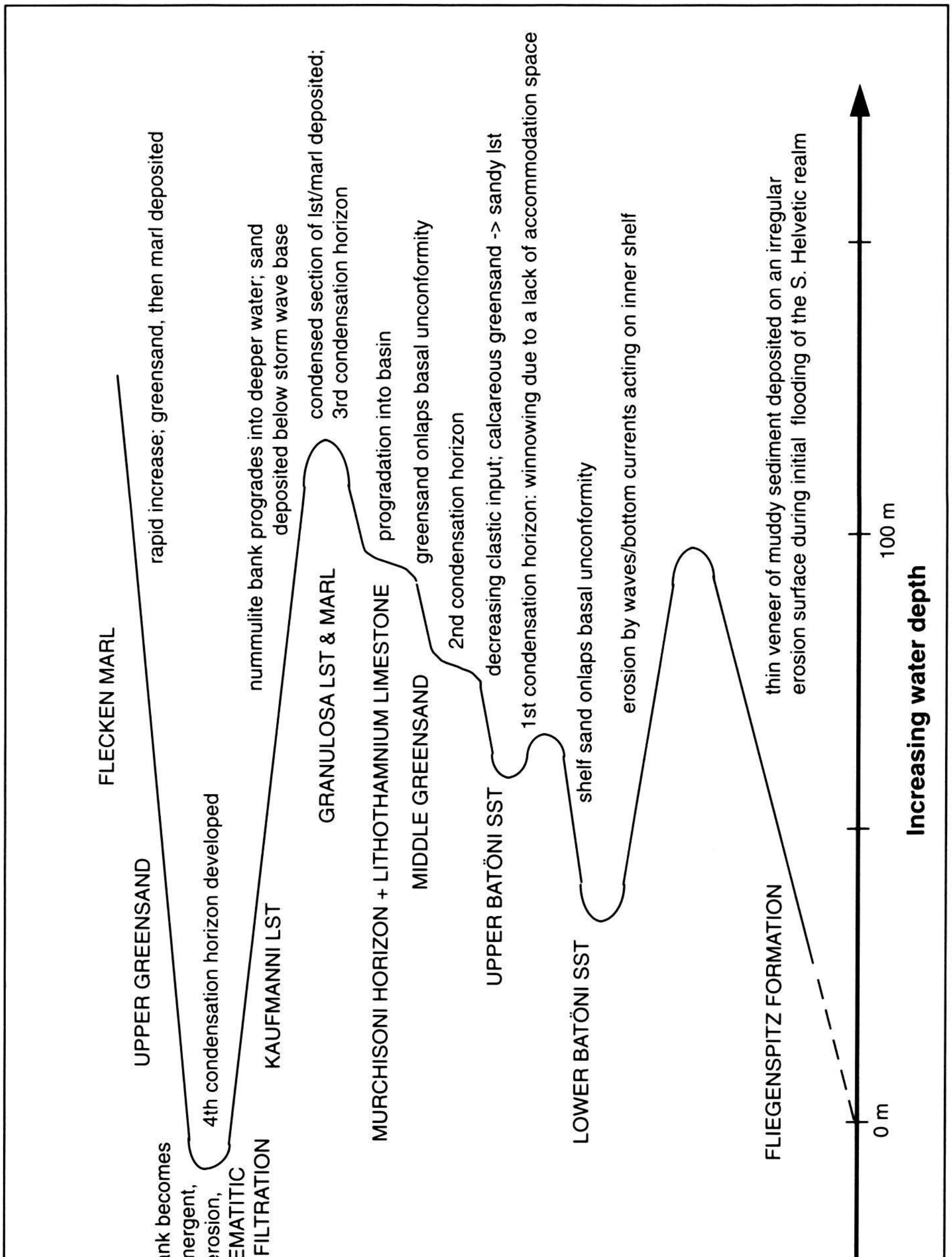


Fig. 8. Schematic representation of the inferred changes in water depth during deposition of the Nummulitic Formation in the Blattengrat unit.

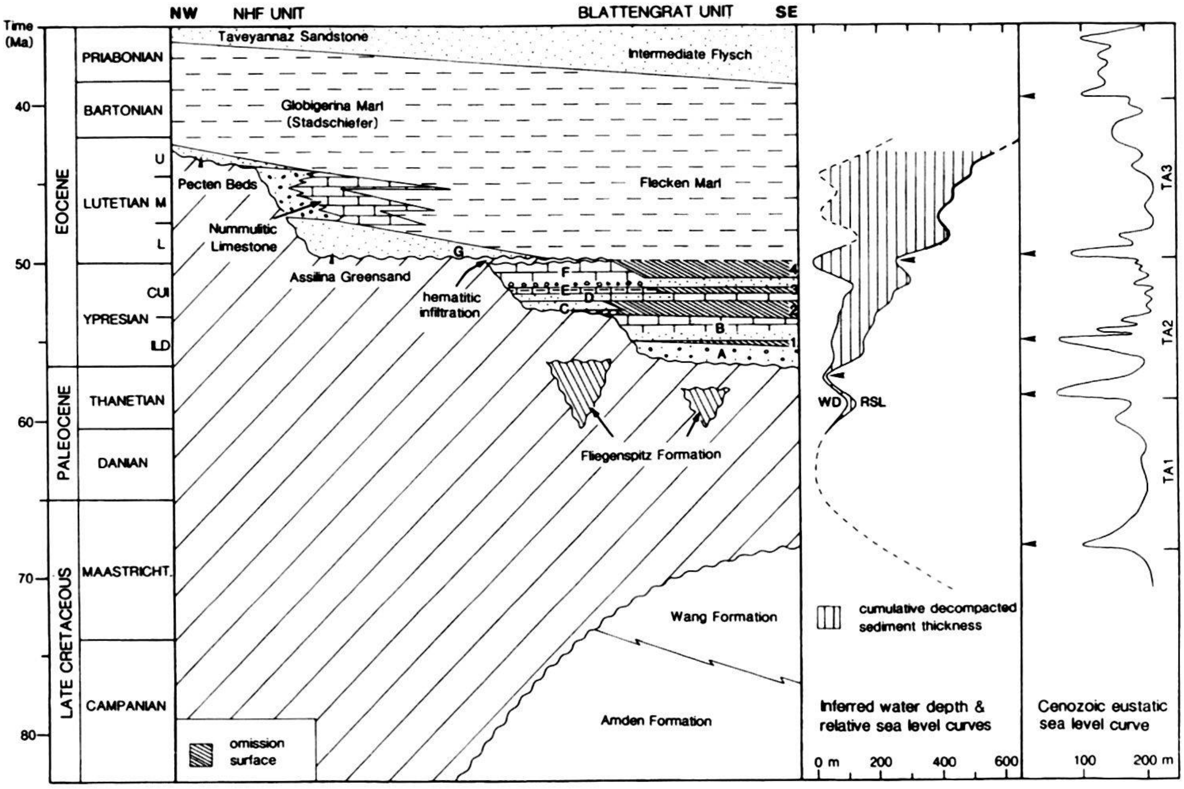


Fig. 9. Diagram of the combined chronostratigraphy and inferred relative sea level (RSL) curves for the Blattengrat and North Helvetic Flysch (NHF) units, in comparison with the Cenozoic eustatic sea level curve of Haq et al. (1988); the chronostratigraphy and RSL curve for the NHF unit (in bold) was taken from Allen et al. (1991) and Crampton (1992, Fig. 8.3), respectively; and the chronology of Harland et al. (1989) was adopted. RSL = (inferred water depth + cumulative, decompacted sediment thickness); parameters for the decompaction were taken from Sclater & Christie (1980), assuming a 6 km overburden prior to erosion of the Helvetic nappes.

regation of sand-dominated and carbonate-dominated facies as suggested by Herb (1988).

As with the Batöni Sandstone member, the first deposit overlying the basal unconformity in the Nummulitic Limestone member is a glauconitic sandstone capped by a condensation horizon. The progressive flooding of the South Helvetic shelf, begun with the deposition of the Batöni Sandstone to the southeast, probably spread further northwest to deposit the Middle Greensand (Fig. 7). The site of sand deposition shifted landward during the RSL rise, and likewise the area of low sediment accumulation moved up the shelf, recorded as the second condensation horizon at the top of the Upper Batöni Sandstone, then in the Middle Greensand as the first hardground (Fig. 7).

The change to carbonate-dominated sedimentation can also be seen in the Nummulitic Limestone member: the Murchisoni horizon shows an increase in the preservation of carbonate material – the greensand is calcareous, and towards the south and southeast, this passes into a bioclastic sandy limestone at Fanenstock and Gula-Schwamm (Fig. 4, 5, respectively). This limestone could be coeval with the sandy Lithothamnium-rich limestone of the Batöni Sandstone member (Fig. 7), and would therefore show downlap onto the second condensation horizon. Progradation of the limestone facies into the basin and downlap onto an omission surface would have arisen during a relative stillstand or slight RSL fall (Fig. 9).

Very little sand was supplied to the area during the deposition of the two marls within the Granulosa Limestone and Marl unit. Marls can be associated with flooding surfaces because they represent a deepening of several tens to hundreds of metres. The preserved fauna within the marls suggests a water depth in excess of 50 m, but it was probably deposited in more than 100 m of water if it was part of an ongoing transgression and the underlying Murchisoni horizon was deposited in ~100 m of water (Fig. 8). The RSL rise in this case was probably in the order of several tens of metres, and represents maximum flooding of the area during a RSL highstand (Fig. 9).

No marl was preserved either in the Fanenstock or Gula-Schwamm profiles, or further southeast in the Batöni Sandstone member, or else it was subsequently removed, so the landward shift of the marl facies at the time when the Granulosa Marl appeared in the Nummulitic Limestone member may have been greater than the width of the Blattengrat realm itself. Rüefli (1959) estimated this width to be 10–15 km, so a backstepping of facies by at least this amount was achieved by a RSL rise of a few tens of metres, implying that the shelf had a very gentle slope.

Subsequently, there was development of a shallow water (5–20 m water depth) nummulitic bank to form the main Nummulitic (Kaufmanni) Limestone. The inferred water depths are much shallower than for the previous marl deposition (Fig. 8), which may mean that the nummulite bank prograded into deeper water. The thickness of the Kaufmanni Limestone is fairly constant across the region, being 15–25 m east of Elm (Fig. 4), and 10–15 m in Weisstannental (Fig. 5), which supports the idea that there was little aggradation and more progradation of the bank basinward. Relative sea level is inferred to have fallen slowly during this period (Fig. 9).

The first nodular horizon at the base of the Kaufmanni Limestone at Fanenstock may correlate with the second condensation horizon at Batöni-Oberlavtina (Fig. 4, 6), formed by a shallow water algal pavement. The limestone breccia at Fanenstock may represent preserved forebank talus deposits buried by the prograding nummulitic bank. Offbank deposits accumulated further offshore in the Batöni Sandstone realm. Storms may have transported sand and fragmented bioclasts periodically into these offshore environments, to form the brecciose calcareous sandstone at Batöni-Oberlavtina (Fig. 6).

Following deposition of the Kaufmanni Limestone, there was regression and subaerial exposure of part of the Blattengrat realm (Fig. 8), so that the limestone was infiltrated by hematite (Fig. 7). This shallowing upwards phase implies that accommodation space was decreasing, with the sedimentation rate exceeding the subsidence rate. No such hematitic staining is found in the Batöni Sandstone member, probably because it remained submerged. There does not appear to be any substantial incision or karstification of the exposed Nummulitic Limestone bank to suggest that there was prolonged exposure. Also, lithostratigraphic correlations (Fig. 7) suggest that there was no deposition in the Batöni Sandstone realm associated with the regression and RSL lowstand.

The Upper Greensand is part of a transgressive systems tract deposited on the exposure surface (Fig. 7). Phosphatised macrofossils at the base of the greensand at Upper Windegg represent a condensed section developed during the rapid increase in water depth (Fig. 8). The microfauna within the greensand indicate that the area was flooded to a depth in excess of 50 m. If the shelf slope was gentle, then the magnitude of this rise would flood a large expanse, including areas previously emergent during the Tertiary. This is supported by the observation that the basal Assilina Greensand in the Bürgen Formation, preserved in the Helvetic autochthon, is very similar to the Upper Greensand and may be its correlative (Fig. 9).

Water levels appear to have continued rising, bringing the Blattengrat realm within the depth range for marl deposition only. The Flecken Marl is generally considered to be a deeper water deposit than the Stadschiefer to the west (Herb 1988). This implies that the transition from Nummulitic Limestone to Flecken Marl involves a drowning of several hundred metres, with the greensand deposited during the early phase of increasing water depth (Herb 1988). Evidence for a continued progressive drowning of the area comes from the fauna in the Flecken Marl immediately overlying the Upper Greensand at Upper Windegg and Chalberboden (Fig. 4): it contains rotaliids and textularids as well as a large proportion of globigerinids, which point to an established connection between lagoonal and open sea environments, by a breaching or drowning of the protected nearshore environment (Ghose 1977). In addition, there is an upward decrease in the sand content of the marl, indicating that it gradually ceased to receive any material from the inner shelf as water depth increased and the Blattengrat realm became more distal from the shoreline. The eventual drowning of the area is inferred to have coincided with a RSL rise (Fig. 9) and any further fluctuations in RSL affecting the Helvetic realm would not have caused facies changes in the Blattengrat realm.

8. Discussion and conclusions

After the regressive phase in the late Maastrichtian-Paleocene that eroded the South Helvetic margin and produced the basal unconformity, the Tertiary strata of the Nummulitic Formation show three main transgressive phases separated by regressive phases (Fig. 8). The first of these was in the late Paleocene (Thanetian) and deposited the Fliegenspitz Formation; the second of these began in the Ilerdian and was responsible for the deposition of the Batöni Sandstone member, continuing into the middle Cuisian, to deposit the Granulosa Limestone and Marl; the final phase began in the early Lutetian, depositing the Upper Greensand and Flecken Marl. The magnitude of the overall RSL change is inferred to be more than 300 m, exhibiting a pattern of relatively rapid rises and stillstands during the transgressive phases (Fig. 9).

A similar pattern of rapid RSL rises and slow falls or stillstands, was inferred for the Bürgen (Nummulitic) Formation by Crampton (1992) (Fig. 9). The estimated magnitude of the cumulative RSL rise in this case was in the order of 250 m (Crampton 1992, Fig. 8.3) but there were no large magnitude RSL falls inferred from the facies. The 2.5–3 Myr reported periodicity in the cycles is within the range (i.e., 1–10 Myr) for the third order sea level cycles of Vail et al. (1977). Crampton (1992) concluded that this pattern was produced by a sinusoidally varying eustatic sea level curve superimposed upon uniform tectonic subsidence in a foreland basin setting.

The Blattengrat unit can be confidently linked to the NHF unit, via the Upper Greensand in the former, and the basal Assilina Greensand in the latter. Hence, I envisage that the Nummulitic Limestone of the NHF unit represents younger time-transgressive equivalent deposits to those in the Blattengrat unit. The pattern of RSL changes in the two units appears to be broadly the same (Fig. 9), implying a common driving mechanism of tectonic subsidence. Approximately 7 Myr is represented by the long wavelength cycle within the Tertiary of the Blattengrat realm that spans the Ilerdian to early Lutetian (Fig. 9), with the second of the two periods of shoreline regression and RSL fall approximately coeval with a postulated, major eustatic sea level fall in excess of 100 m (Fig. 9; TA3 second order supercycle of Haq et al. 1988). The inferred distribution of sedimentary facies and pattern of RSL changes for the Blattengrat unit may have been influenced by the eustatic signal, but tectonic subsidence appears to have been the principal control on the creation of accommodation space in the embryonic foreland basin. This is in accordance with other studies of the Alpine foreland basin that have focused on the younger foreland basin deposits, where tectonic subsidence is inferred to have been the most important control (Homewood et al. 1986; Pfiffner 1986; Sinclair et al. 1991; Sinclair & Allen 1992).

Acknowledgements

This work was undertaken as a part of a D.Phil research project at the University of Oxford, England, supervised by Philip Allen, and funded by a student sponsorship provided by Shell International Petroleum Company Limited. The manuscript was improved by comments from the reviewers Dr. Schwizer and Prof. Luterbacher. The author gratefully acknowledges technical advice from Andy Clarke with drafting figures and help with German translations from Maria Mange and Helene Grunnet-Jepsem.

REFERENCES

Allen, P.A., Crampton, S.L. & Sinclair, H.D. 1991: The inception and early evolution of the North Alpine Foreland Basin, Switzerland. Basin Res. 3, 143–163.

Bisig, W. 1957: Blattengratflysch und Sardonaflysch im Sernftal nördlich der Linie Richetlipass–Elm–Ramintal–Grosse Scheibe. PhD. thesis Univ. Zürich.

Blondeau, A. 1972: Les nummilites. Recherche Science de la Terre, Librairie Vuibert, Paris, France.

Brasier, M.D. 1980: Microfossils. Allen & Unwin, London, England.

Caron, M. 1985: Cretaceous planktonic foraminifera. In: Plankton Stratigraphy (Ed. by Bolli, H.M., Saunders, J.B. & Perch-Nielsen, K.). Cambridge University Press, Cambridge, England, 87–154.

Crampton, S.L.E. 1992: Inception of the Alpine Foreland Basin: Basal unconformity and Nummulitic Limestone. PhD. thesis, Univ. of Oxford (unpublished).

Fischer, H. 1987: Excess K-Ar ages of glauconite from the Upper Marine Molasse and evidence for glauconitization of mica. Geol. Rdsch. 76, 885–902.

– 1990: Glauconite formation: discussion of the terms authigenic, perigenic, allogenic and meta-allogenic. Eclogae geol. Helv. 83, 1–6.

Ghose, B.K. 1977: Paleoecology of the Cenozoic reefal foraminifers & algae – a brief review. Paleogeog. Paleoclimatol. Paleoecol. 22, 231–256.

Hallock, P. 1985: Why are larger foraminifera large? Paleobiology 11, 195–208.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G. & Smith, D.G. (1989): A geologic time scale. Cambridge University Press, Cambridge, England.

Haq, B.U., Hardenbol, J. & Vail, P.R. 1988: Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In: Sea-level Change: an Integrated Approach (Ed. by Wilgus, C.K., Hastings, B.S., Kendall, C.G.ST.C., Posamentier, H., Ross, C.A. & van Wagoner, J.). Soc. Econ. Paleont. Mineral. spec. publ. 42, 71–108.

Herb, R. 1988: Eocene Paläogeographie und Paläotektonik des Helvetikums. Eclogae geol. Helv. 81, 611–657.

Homewood, P., Allen, P.A. & Williams, G.D. 1986: Dynamics of the Molasse basin of western Switzerland. In: Foreland Basins (Ed. by Allen, P.A. & Homewood, P.). Int. Assoc. Sediment. Spec. Publ. 8, 199–217.

LEE, J.J., MCEENERY, M.E. & KAHN, E.G. 1979: Symbiosis and the evolution of larger foraminifera. Micropaleontology 25, 118–140.
LEUPOLD, W. 1937: Zur Stratigraphie der Flyschbildungen zwischen Linth und Rhein. Eclogae geol. Helv. 30, 1–23.
– 1938: Die Flyschregion von Ragaz. Bericht über die Exkursion der Schweizerischen Geologischen Gesellschaft 1938 und Ergebnisse neuer Untersuchungen im Glarner Flysch. Eclogae geol. Helv. 31, 403–428.
– 1943: Neue Beobachtungen der Gliederung der Flyschbildungen der Alpen zwischen Reuss und Rhein. Eclogae geol. Helv. 35, 247–291.
– 1964: Blattengrat Complex. In: Lexique stratigraphique international, vol. 1, fasc. 7c: Alpes suisses et Tessin méridional (Ed. by RUTSCH, R.F.). Congrès géol. int. – Comm. stratigraphie, Centre nat. Rech. sci., Paris, France.
LIHOU, J.C. (1993): The earliest evolution of the North Helvetic foreland basin as recorded by the Sardona unit of eastern Switzerland. Abstr. suppl. to TERRA nova 5, 669.
MURRAY, J.W. 1991: Ecology and Palaeoecology of benthic foraminifera. Longman Scientific & Technical, Harlow, England.
OBERHOLZER, J. 1933: Geologie der Glarneralpen. Beitr. Geol. Karte Schweiz. N.F. 28, Schweiz. Geol. Kommission.
ODIN, G.S. & MATTER, A. 1981: De glauconarium origine. Sedimentology 28, 611–641.
PFIFFNER, O.A. 1986: Evolution of the north Alpine foreland basin in the Central Alps. In: Foreland Basins (Ed. by ALLEN, P.A., HOMEWOOD, P.). Int. Assoc. Sediment. Spec. Publ. 8, 219–228.
RACEY, A. 1988: Nummulitid biostratigraphy & Paleogene peleoenvironments, Sultanate of Oman. PhD. thesis, Univ. of London (unpublished).
RÜEFLI, W.H. 1959: Stratigraphie und Tektonik des eingeschlossenen Glarner Flysches im Weisstannental (St. Galler Oberland). PhD. thesis Univ. Zürich.
SCHAUB, H. 1981: Nummulites et Assilines de la Téthys paléogène. Taxonomie, phylogenèse et biostratigraphie. Schweiz. Paläont. Abhandlungen 104, Basel.
SCLATER, J.G. & CHRISTIE, P.A.F. 1980: Continental Stretching: An Explanation of the Post-Mid-Cretaceous subsidence of the Central North Sea Basin. J. Geophys. Res. 85, 3711–3739.
SINCLAIR, H.D. 1989: The North Helvetic Flysch of Eastern Switzerland: foreland basin architecture and modelling. PhD. thesis, Univ. of Oxford (unpublished).
– 1992: Turbidite sedimentation during Alpine thrusting: the Taveyannaz sandstone of eastern Switzerland. Sedimentology 39, 837–856.
SINCLAIR, H.D. & ALLEN, P.A. 1992: Vertical and horizontal motions in the Alpine orogenic wedge: stratigraphic response in the foreland basin. Basin Res. 4, 215–232.
SINCLAIR, H.D., COAKLEY, B.J., ALLEN, P.A. & WATTS, A.B. 1991:Simulation of foreland basin stratigraphy using a diffusion model of mountain belt uplift and erosion: an example from the Central Alps, Switzerland. Tectonics 10, 599–620.
STACHER, P. 1980: Stratigraphie, Mikrofacies und Mikropaläontologie der Wang-Formation. Beitr. Geol. Karte Schweiz. N.F. 152, Schweiz. Geol. Kommission.
TRÜMPY, R. 1967: Geologischer Führer der Schweiz. Heft 7, Wepf & Co., Basel, Switzerland 649–696.
– 1980: Geology of Switzerland, a Guide-Book. Wepf & Co., Basel, Switzerland.
VAIL, P.R., MITCHUM, R.M.JR., TODD, R.G., WIDMIER, J.M., THOMPSON, S., SANGREE, J.B., BUBB, J.N. & HATLELID, W.G. 1977: Seismic stratigraphy and global change of sea level, parts 1–6. In: Seismic Stratigraphy-Applications to Hydrocarbon Research (Ed. by PAYTON, C.E.). Mem. Assoc. Amer. Petrol. Geol. 26, 49–133.
WEGMANN, R. 1961: Zur Geologie der Flyschgebiete südlich Elm. PhD. thesis Univ. Zürich.

Manuscript received July 15, 1994
Revision accepted December 7, 1994