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Paleogene of the Eastern Alps

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Contents

Facies and basin development of the Oligocene in the Lower Inn Valley, Tyrol/Bavaria

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Abstract: The sedimentary succession of the Oligocene in the Inn Valley is subdivided into the following formations and members: 1) the basal unit of the Oligocene transgressing unconformably over the Triassic to Cretaceous bedrock is termed the Häring Formation. The Lengerergraben Mb. contains conglomerates and sandstones deposited in fan deltas that interfinger with the bituminous marls of the Bergpeterl Mb. 2) deep marine calcareous marls form the Paisslberg Fm., contemporary to littoral carbonates termed Werlberg Mb. Rapid deepening from limnic to deep marine conditions (ca. 1000m) is recorded by the Häring to Paisslberg Formations. 3) The Paisslberg Fm. is overlain by the turbiditic Unterangerberg Fm. as the clastic input rises. 4) A major sea level fall combined with increasing clastic input causes establishment of limnofluviatile conditions (Oberangerberg Fm.) in the basin at the begin of the Chattian. Subsidence histories and the subdivision into marine Rupelian and limnofluviatile Chattian closely correlate to the western Molasse basin.

The Molasse deposits on top of the Alpine orogenic wedge record the tectonic development during the Oligocene. Early Rupelian NW-directed shortening is replaced by sinistral activity of the Inntal shear zone, caused by orogen-parallel extension in more internal parts of the orogen during the Oligocene/Miocene. The Inntal shear zone delimited eastward moving blocks in the south against stable blocks in the north. Orogen-parallel extension compensated for vertical growth of the orogen due to (Insubric) backthrusting, which in turn was a response to accretion of material from the lower plate in the Western Alps. Topographic growth of the orogen adjacent to the Periadriatic line caused an increase of erosion and coarse clastic sedimentation of the western Molasse basin and the Oberangerberg Fm.

Zusammenfassung: Die oligozäne Sedimentabfolge wird erstmals in Formationen und Subformationen unterteilt. 1) Die Häring-Fm. transgrediert diskordant auf den prä-känozoischen Untergrund. Konglomerate und Kalksandsteine gehören zur Lengerergraben-Sbfm., die mit den Bitumenmergeln der Bergpeterl-Sbfm. verzahnt. 2) Die tiefmarinen Mergel ("Zementmergel") werden als Paisslberg-Fm. bezeichnet, das litorale Äquivalent mit Karbonaten als Werlberg-Sbfm. Die Häring- und Paisslberg-Fm. zeichnen eine rapide Abtiefung von limnischen zu tiefmarinen (ca. 1000 m) Verhältnissen auf. 3) Durch Zunahme des klastischen Eintrags in den Sedimentationsraum geht die turbiditische Unterangerberg-Fm. aus der Paisslberg-Fm. hervor. 4) Eine starke Meeresspiegelabsenkung kombiniert mit einem weiteren Anstieg des klastischen Eintrags führt zum

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Auffüllen des Beckens und Ablagerung der grobklastischen limnofluviatilen Oberangerberg-Fm. mit dem Beginn des Chattium. Eine gemeinsame Subsidenzgeschichte und die ähnliche lithostratigraphische Entwicklung mit tiefmarinen Sedimenten im Rupelium (= Untere Meeresmolasse) und limnofluviatilen Sedimenten im Chattium (= Untere Süßwassermolasse) sprechen dafür, das Unterinntaler Tertiär als Teil der Molasse auf dem alpinen Orogenkeil zu interpretieren.

Die oligozänen Sedimente zeichnen die tektonische Geschichte des Orogenkeils im Oligozän auf. NW-SE orientierte Verkürzung wird im späten Rupelium von sinistraler Bewegung an der Inntal-Scherzone abgelöst. Die sinistrale Scherung spiegelt orogen-parallele Extension im zentralen Bereich der Alpen wieder, die durch Akkretion von Material der Unterplatte in das alpine Orogen und die damit verbundene Rücküberschiebung und Krustenverdickung an der Insubrischen Linie ausgelöst wurde. Dabei grenzt die Inntal-Scherzone nach Osten wandernde Blöcke im Süden von "stabilen" Blöcken im Norden ab. Die Krustenverdickung am Südrand der Ost- und Westalpen führte auch zur Hebung und dadurch zu starker Erosion, was durch grobklastische Sedimentation in der Oberangerberg-Fm. und im westlichen Molassebecken überliefert ist.

Keywords: Northern Calcareous Alps, Stratigraphy, Inntal Shear Zone, Brittle Deformation, Evolution of the Alpine Orogeny

Contents

1. INTRODUCTION

In the Lower Inn Valley area a nearly complete stratigraphic record of synorogenic deposits from the Early Cretaceous to the Late Oligocene on top of the Northern Calcareous Alps is present. The synorogenic sediments record changes in environment and in the tectonic regime during a period of intense tectonic activity that was characterized by continental collision between the Adriatic microplate (upper plate) and the European (lower) plate during the Eocene (e.g., FRISCH, 1979). During neoalpine shortening the Austroalpine units belonging to the upper plate were transported for a considerable distance over the Penninic units, which belonged to an ocean formerly separating the two plates. The maximum age for extinction of the Penninic ocean is constrained by the age of the youngest flysch deposits (Early Eocene; EGGER, 1992: Rhenodanubian Flysch; RUDOLPH, 1982: Engadine Window). The European Helvetic margin was overthrusted after the Middle Eocene (HAGN et al., 1981), and from the Oligocene until the Middle Miocene the Alpine nappes overthrust the Molasse basin (STEININGER et al., 1991; review in DECKER & PERESSON, 1996). In the internal parts of the orogen Oligocene and Miocene postcollisional convergence led to backthrusting, exhumation along the southern margin of the Western Alps during the Oligocene (SCHMID et al., 1996; HURFORD et al., 1989) and exhumation of the Tauern Window in the Miocene (SELVERSTONE,1988; BEHRMANN, 1990) in the Eastern Alps, accompanied by lateral extrusion of rocks from the Central Alps towards the east (RATSCHBACHER et al., 1991; PERESSON & DECKER, 1997). In the earliest Oligocene the peripheral foreland basin (Molasse basin) formed north of the Alpine orogen (STEININGER et al., 1991) due to loading by the nappes. The source area of clastics deposited in the basin changed as a consequence of the tectonic reorganisation of the Alpine orogenic wedge (see above).

1.1. Study area and geological setting

The study area comprises the Lower Inn Valley between Kramsach and Reit im Winkel in the eastern part of the Tyrol and the southernmost part of Germany (Figs. 1, 2). The Oligocene sediments are preserved in a syncline-anticline system over 50 km lateral extent along the Inntal shear zone, which is a major fault system in the Eastern Alps with approximately 40 km offset (ORTNER, 1996). In the investigated area, the Inntal shear zone separates two nappe units of the Northern Calcareous Alps, the Inntal nappe/ Tirolic unit to the south and the Lechtal nappe/Bajuvaric unit to the north in the structurally lower position.

Paleogene sedimentation in the investigated area starts with a turbiditic succession, which represents part of the synorogenic Late Cretaceous to Middle Eocene Gosau Group. Late Eocene (Priabonian) deposits represent a complete sedimentary cycle with terrestrial to shallow marine deposits (Oberaudorf beds). After a short period of erosion and/or non-deposition, Oligocene sedimentation started with limnofluviatile deposits. The depositional realm rapidly subsided to pelagic conditions, but fluviatile sedimentation started again in the Late Oligocene. Because of the many similarities with deposits in the Molasse basin, the Oligocene of the Lower Inn Valley was also termed "Inneralpine Molasse" (FUCHS, 1976, 1980). The Oligocene of the Lower Inn Valley was previously studied by several authors (MOJSISOVICS, 1869; DENINGER, 1901; DREGER, 1902;

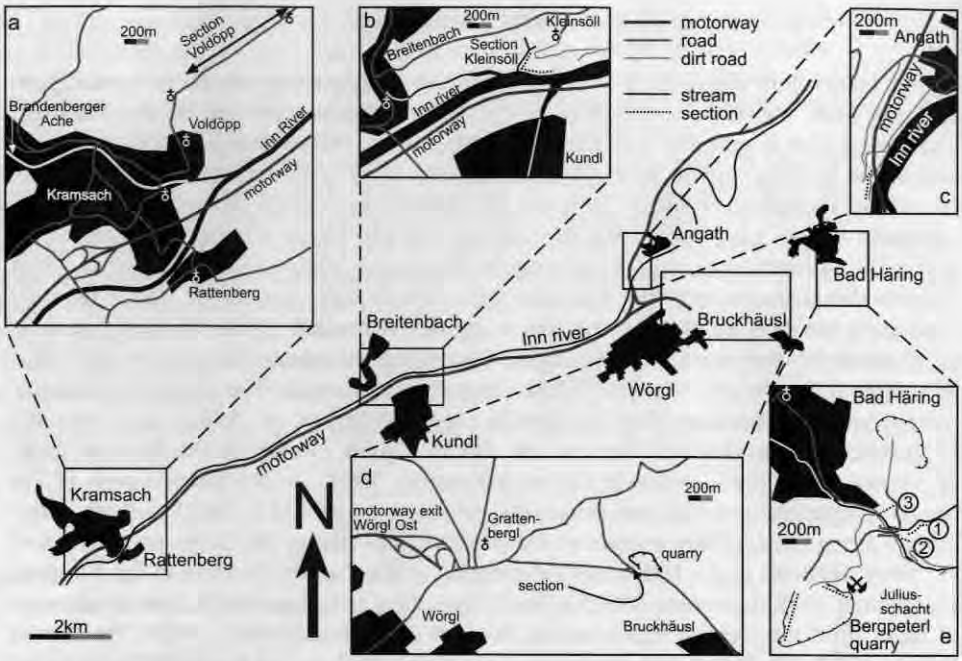

Fig. 1: Geographical sketch map of the study area with position of the new type sections of the Oligocene sediments of the Lower Inn Valley. a) Location of the type section of the Oberangerberg Fm., b) Location of the reference section for the Unterangerberg Fm. (Höllgraben section), c) Location of the type section of the Unterangerberg Fm., d) Location of the type section of the Werlberg Mb., e) Location of type sections in the Häring area: Häring Fm.: 1 ... type section of the Lengerergraben Mb., Juliusschacht ... type section of the Bergpeterl Mb., Bergpeterl quarry ... type section of the Paisslberg Fm.

SCHLOSSER, 1910; AMPFERER, 1922; HEISSEL, 1951, 1956; SCHNABEL & DRAXLER, 1976; HAGN et al., 1981; STINGL & KROIS, 1991; KROIS, 1992; ORTNER & SACHSENHOFER 1996; GRUBER, 1997), especially the basal part which was of economic interest because of a thick coal measure, which was mined from the 18th century to the 1950ies.

1.2. Methods and scope of the study

Our results are based on detailed mapping of the Oligocene and underlying rocks on a scale 1:10.000 and the analysis of selected stratigraphic sections. Reconstruction of basin geometries was aided by the analysis of microstructures in sediments, that were deformed before lithification (soft sediment deformation; PETIT & LAVILLE, 1987). The sedimentary history of the Oligocene in the Inn Valley is compared to the Alpine Molasse basin, and changes in depostional style in the Inn Valley and in the Molasse are linked to the tectonic history of the Eastern and Western Alps.

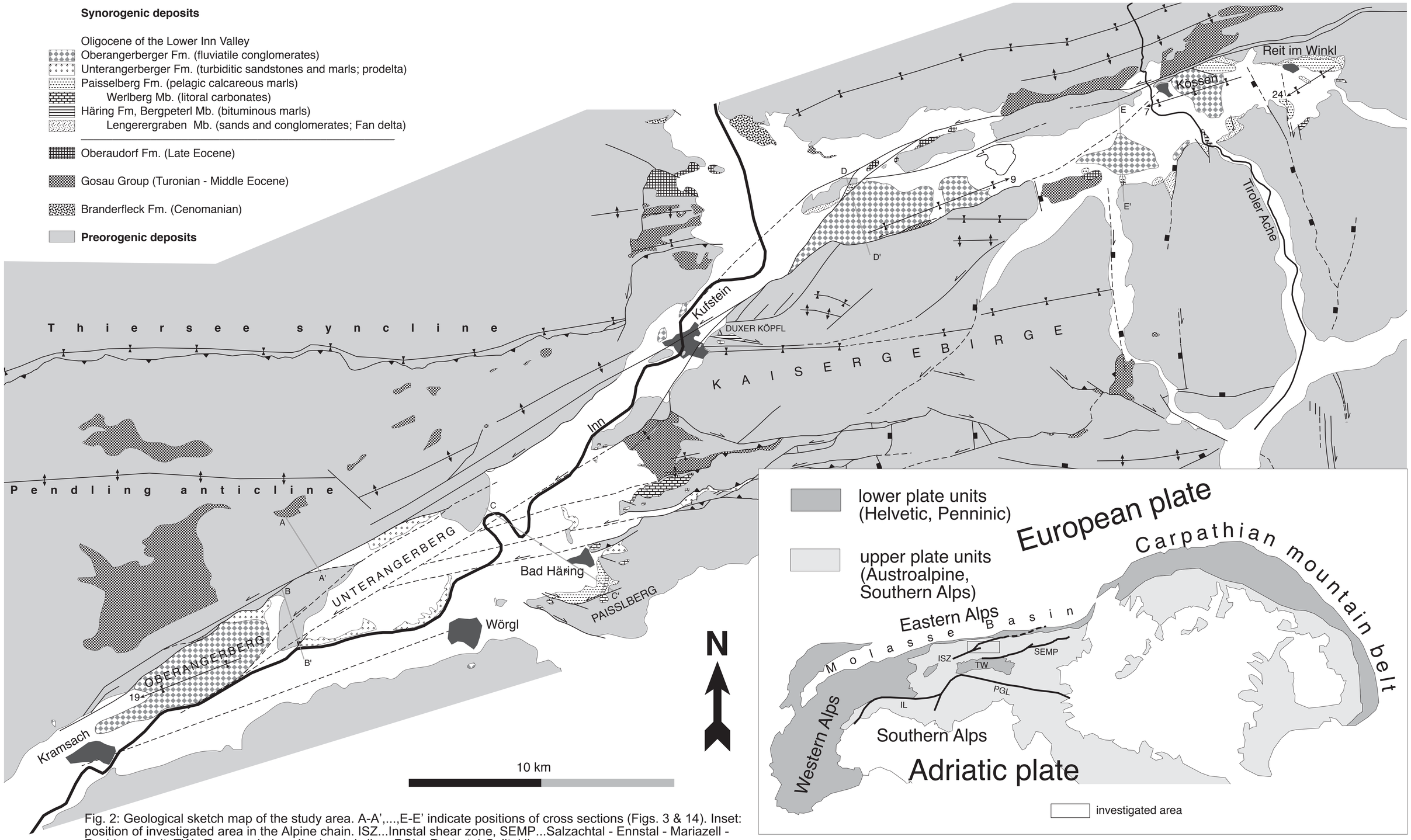

Fig. 2: Geological sketch map of the study area. A-A',...,E-E' indicate positions of cross sections (Figs. 3 & 14). Inset: position of investigated area in the Alpine chain. ISZ...Innstal shear zone, SEMP...Salzachtal - Ennstal - Mariazell - Puchberg fault, TW...Tauern window, IL...Insubric line, PGL...Pustertal-Gailtal line

2. LITHOSTRATIGRAPHY AND FACIES

2.1. Häring Formation

The Häring Fm. transgresses unconformably onto Triassic to Late Eocene rocks. Pre-Oligocene and Oligocene tectonics and erosion produced a highly differentiated relief, leading to facies differentiation and local non-sedimentation of the Häring Fm. The restricted occurrence of the Häring Fm. in the type locality was known since long time due to coal prospection activities (e.g., SCHULZ & FUCHS, 1991). Stratigraphically and facially similar sediments occur in some places from the type locality in the SW as far as Reit im Winkl in the NE.

The name of the formation was introduced by FLURL (1813), who described the "Steinkoleschichten von Häring" from their type locality south of the health-resort Bad Häring. The best and most wide-spread outcrops are located at the northern flank of the Paisslberg (Figs. 1, 2). Two quarries and the galleries of a now abandoned coal mine give insight into the complex facies development of the Häring Fm. Further subsurface data on the areal distribution originate from boreholes (AMPFERER, 1922; HEISSEL, 1951; FRITZ, 1971; SCHULZ & FUCHS, 1991) and seismics (HEISSEL, 1951). Outcrops of the Häring Fm. extend along the northern front of the Kaisergebirge mountain chain. Only small occurrences exist in the north of the Inn Valley at the localities Breitenbach and Schindler (AMPFERER, 1922; HEISSEL, 1956; HAMDI, 1969; SCHNABEL & DRAXLER, 1976; STINGL, 1990).

The subdivision by FLURL (1813) was maintained by most authors (AMPFERER, 1922; HEISSEL, 1951; 1956; LÜHR, 1962; OEXLE, 1978; STINGL & KROIS, 1991; KROIS, 1992; ORTNER & SACHSENHOFER, 1996), most of them including the "Zementmergel-Serie" into the Häring Fm. The last classification was given by STINGL & KROIS (1991) and KROIS (1992), comprising a "basal series", "coal and bituminous marls" and the "Zementmergel". The data on thicknesses, facies development, and the wide spatial distribution require the exclusion of the "Zementmergel" from the Häring Fm. and the constitution of an individual formation (Paisslberg Fm., this study).

Facies development of the Häring Fm. – as demonstrated by STINGL & KROIS (1991) and KROIS (1992) – clearly shows the possibility to separate two members. The former socalled "Basisserie" (basal series) comprises local coarse clastic wedges and is introduced here as "Lengerergraben Member", named after the best outcrops in the type locality south of Bad Häring. The coal measures and bituminous marls in the hanging wall are classified as "Bergpeterl Member", named after the occurrence in the "Bergpeterl" quarry south of Bad Häring. The first author who described an interfingering of bituminous marls (Bergpeterl Mb.) and basal conglomerates (Lengerergraben Mb.) in the coal mine was HEISSEL (1951). STINGL & KROIS (1991) observed the same feature at the surface in the Lengerer Graben valley.

The facially different conglomerates in the Kohlenbach section south of Kössen have always been included in the Häring Fm. A discussion of their stratigraphic and paleogeographic position is given below (section 2.1.1).

2.1.1. The conglomerates of the Kohlenbach section

South of Kössen, a nearly 150 m thick succession of conglomerates with thin intercalations of mudstones, which is overlain by thick calcareous marls, crops out in the

Kohlenbach valley. The stratigraphic position of the conglomerates has been always disputed. BODEN (1931) considered them as a very local development of unknown age, while AMPFERER (1933) assigned the clastics to Gosau conglomerates (Late Cretaceous), and the marls to the Early Cretaceous. Based on the occurrence of terrestrial gastropod remains LINDENBERG (1962) compared the limnofluviatile sediments with coarse clastics of the Late Eocene Oberaudorf Fm. He argued for a sediment supply from the N. In 1965, he revised his age classification and dated the conglomerates into the Oligocene. WOLETZ (in HEISSEL, 1956) and SCHNABEL & DRAXLER (1976) analysed the heavy mineral content of the clastics and found a large amount of chromian spinells, obviously originating from a northern source. The first detailed sediment-petrographic description of the "Häringer Schichten" in the Kohlenbach outcrop was given by ALLERSMEIER (1981). The pebble composition is dominated by nearly 100% of Late Jurassic to Early Cretaceous rocks from a Middle Penninic source, Triassic rocks from the Northern Calcareous Alps are nearly completely absent. This fact and the high chromite content, together with unequivocal transport directions from the N allow a clear distinction from the Häring Fm. ALLERSMEIER compares the Kohlenbach section with the Oberaudorf Fm. and discusses a Late Eocene age. The lithologic differences to sediments of the Häring Fm. (Lengerergraben Mb.) in the immediate neighbourhood supports this interpretation.

2.1.2. Lengerergraben Member

The newly established "Lengerergraben Member" includes the clastic sediments of the previously socalled "Basisserie" of the Häring Fm. The type locality is situated in the Lengerergraben valley between the mountains Pölven in the E and Paisslberg in the W. The lithological development can best be studied in the Schuhreissergraben at the western slope of the Pölven mountain (type section: Fig. 3, section 1). The outcrops are accessible ca. 1.1 km SE of the center of the village Bad Häring (ÖK 90, Bl. Kufstein, coordinates 47°30'12"N/12°8'00"E).

A comprehensive description of the lithostratigraphy and facies is given by STINGL & KROIS (1991). The Lengerergraben Mb. is characterized by the three facies associations (STINGL & KROIS, 1991):

Facies A consists of massive, coarse-grained breccias and conglomerates, resting on a rugged erosional bedrock relief. These locally developed clast-supported sediments reach an overall thickness of up to 5 m and bed thicknesses between 0.5 and 1 m. They show structureless and chaotic textures, and consist solely of locally derived pebbles (Lower Triassic sandstones and Middle Triassic carbonates). The clastics are interpreted as proximal sediments of a small alluvial fan filling topographic lows and were transported mainly as cohesive debris flows with a small amount of fine-grained carbonatic matrix.

Facies B comprises a succession of coarse-grained to fine-grained stratified conglomerates. In the type locality they show bed thicknesses of up to 0.5 m. Graded beds, cross-bedded sets, imbricated clasts in the coarse-grained parts and additional flaser bedding and horizontal lamination in the finer-grained parts point to sedimentation from density-modified grain flows or as stream flow deposits in a channel network of fluvial origin. Horizontal lamination, dewatering structures, and load casts in intercalated lenticular sandstone bodies indicate rapid deposition. Rarely bioturbation is visible.

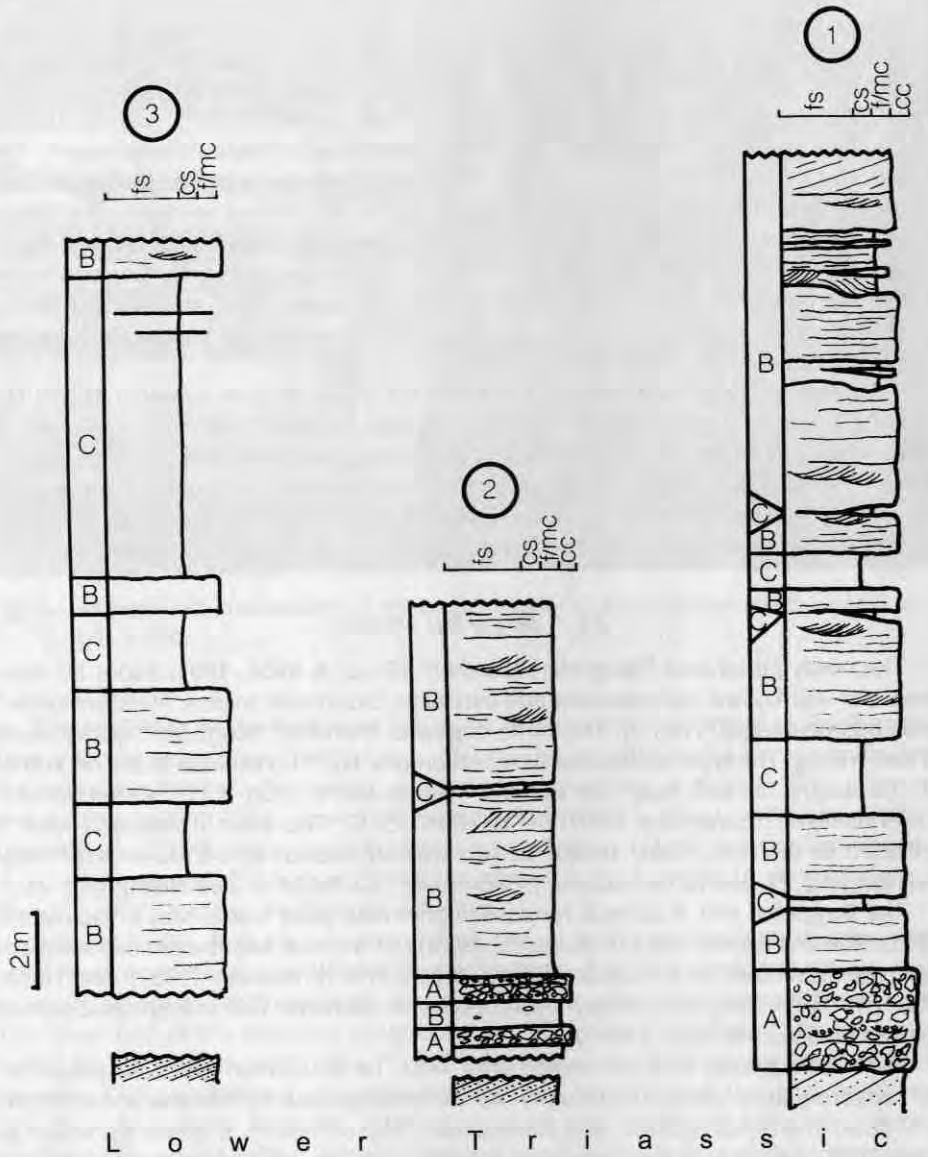

Fig. 3: Type section (1) of the Lengerergraben Mb. in the Schuhreißergraben valley. Sections 2 (Lengerergraben valley) and 3 ("Burg") illustrate the lateral facies changes in transport direction. A, B, C refer to the facies associations of Stingl & Krois (1991). For location see Fig.1.

Facies C (fine- to medium-grained carbonate sandstones and calcareous marls) shows horizontal lamination with graded bedding and rare ripple bedding. The sandstones are organized into coarsening- and thickening-upward sequences. The lower parts are fine-grained, laminated, and show a higher bituminous content (with pyrite concretions). The upper parts reach bed thicknesses of up to 5 cm and are less bituminous. Shell fragments and small plant remains are rare. HEISSEL (1951: p. 211) mentioned the finding of a single foraminifer and therefore deduced a marine environment. The sandstones may be interpreted as turbidite-like sediments deposited in shallow water.

Intensive interfingering of facies B and C and some textural evidences for shear-strength lowering in the conglomerates due to water entrainment in a standing water body allow the recognition of an at least partly subaquatic fan delta body (STINGL & KROIS, 1991). The overall lithologic development points to a shallow water, near-shore environment. The increase of total thickness and the increasing content of facies C towards the N indicate basin deepening towards the N or NW.

The Lengerergraben Mb. reflects a sedimentary evolution from subaerial alluvial fan deposits through fan delta conglomerates to carbonate sandstones of the prodelta area in shallow water at the mouth of a small fluvial system originating from the S. All occurrences of the Lengerergraben Mb. (type locality and some occurrences north of the Kaisergebirge mountain chain) are characterized by a solely locally derived clast spectrum of mainly Middle Triassic carbonates, which have been supplied from a southern source.

2.1.3. Bergpeterl Member

The newly introduced "Bergpeterl Member" (STINGL & KROIS, 1991: Facies D) comprises the well known coal measures and laminated bituminous marls ("Häringer Kohle" and "Bitumenmergel"; Fig. 4). The name originates from the "Bergpeterl" quarry south of Bad Häring. The type locality and type section (see Fig. 5) is situated in the NE corner of the quarry, in and near the socalled "Juliusschacht" (ÖK 121, Neukirchen am Großvenediger, coordinates 47°30'01"N/12°07'35"E). The main distribution area is restricted to this area. Some smaller occurrences are located at the Duxer Köpfl near Kufstein (Fig. 2), and in the socalled "Fleckmulde" northeast of Bad Häring (Fig. 2).

The Bergpeterl Mb. is famous for its well preserved plant fossils (VON ETTINGSHAUSEN, 1853). The distribution and the economic aspects of the coal and the bituminous marls have been discussed by MOJSISOVICS (1869), SANDER (1921), AMPFERER (1922), and HEISSEL (1951, 1956). A comprehensive synopsis of historic, economic and petrographic aspects is given by SCHULZ & FUCHS (1991).

The subbituminous coal was mined until 1954. Its distribution area runs parallel to the Lengerergraben valley. The channel-like body wedges out to the sides and to the N. A detailed macropetrographic and microscopic characterisation is given by SCHULZ & FUCHS (1991). A thin carbonaceous clay horizon forms the base of the coal seam. The coal measure reaches thicknesses from 1 to 10 m, with an average of 4 m.

The bituminous marls and carbonate sandstones show a wider distribution than the coal seam, but are also restricted to the area around Bad Häring and the above mentioned small occurrences. Thicknesses reach up to 15 m, with a maximum of 20 m. Petrographic details are described by SANDER (1921), SANDER (in AMPFERER, 1922), HRADIL (1925, 1953), and SCHULZ & FUCHS (1991).

Fig. 4: Laminated bituminous marls of the Bergpeterl Mb. in the Bergpeterl quarry. Length of scale = 20cm.

The sediments of the Bergpeterl Mb. have always been interpreted as limnic-palustrine deposits (e.g., LÜHR, 1962; OEXLE, 1978). The arguments for the environmental reconstruction are not unequivocal, as pointed out by STINGL & KROIS (1991). High ash and sulphur contents (e.g., FLORES & ETHRIDGE, 1981; HUNT & HOBDAY, 1984) and high B contents (up to 290 ppm), as reported by JANDA & SCHROLL (1959), may be indicative for a marine environment. However, low contents in Cl, Br, J, and K (AUGUSTIN-GYURITS & SCHROLL, 1992) point to fresh water influence.

Paleontological data are not unequivocal, too. Graded coquinas with undetermined small bivalves and bryozoan detritus in the bituminous carbonate sandstones are characteristic. SCHLOSSER (1925) reported terrestrial (?) gastropods from the bituminous marls. The upper part of the sequence contains foraminifers (OEXLE, 1978) and coralline algae. From the uppermost part, LÜHR (1962) described charophyte oogonia. SCHNABEL & DRAXLER (1976) mentioned coccolithophorids from the base of the coal beds, and hystrichosphaerideans from the bituminous marls and therefore deduced a marine environment. Additionally, GRUBER (1995) reported oolites with a slightly bituminous matrix from the Peppenau locality in the NE of the Pölven mountain.

The sedimentological evidence indicates rapid deposition of the plant bearing carbonatic sandstones to clayey marls. Horizontal lamination, graded beds, slumping, and ripple marks point to sedimentation as distal turbidites. It seems likely that the bituminous marls and carbonate sandstones (STINGL & KROIS, 1991: facies D) correspond to a more distal facies compared to the carbonate sandstones of the Lengerergraben Mb.

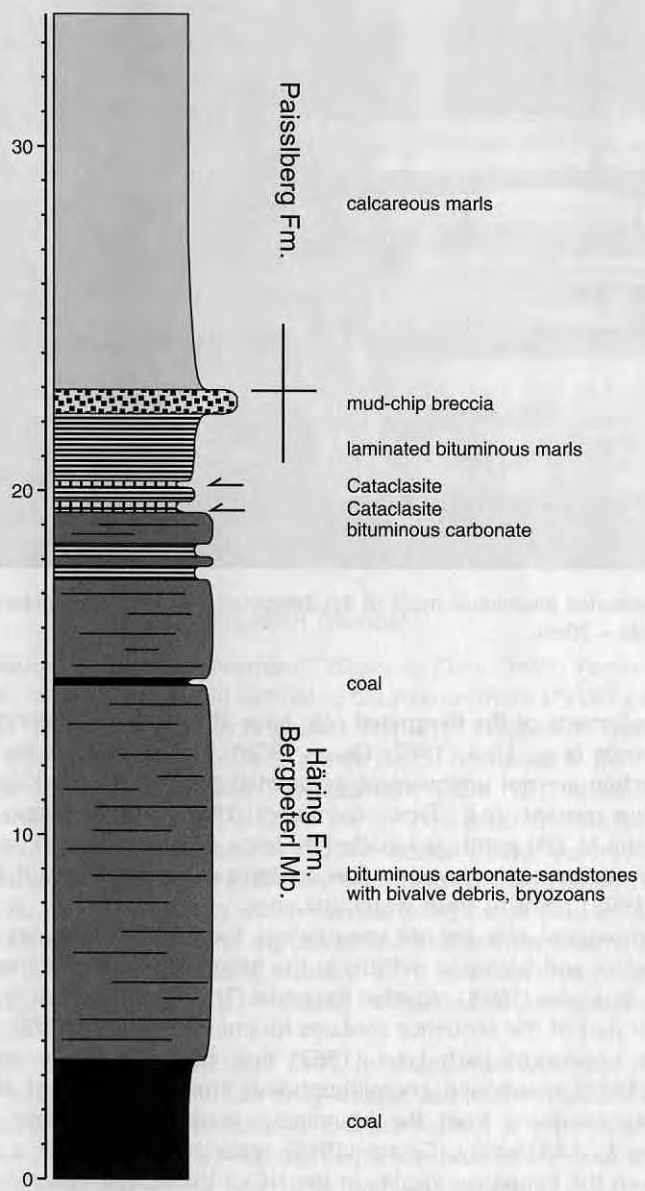

Fig. 5: Type section of the Bergpeterl Mb. in the Juliusschacht in the Bergpeterl quarry. For location see Fig. 1.

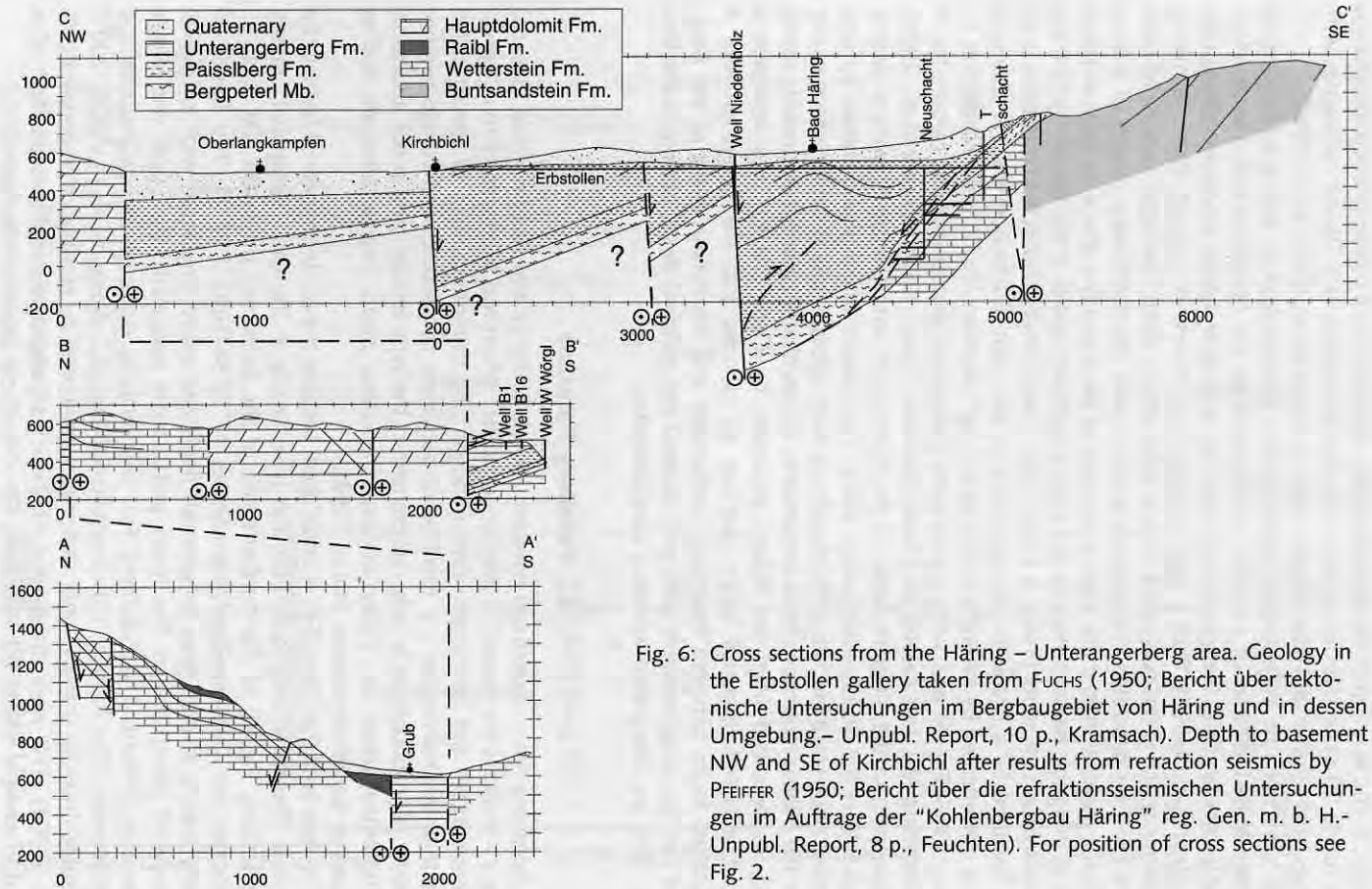

Fig. 6: Cross sections from the Häring – Unterangerberg area. Geology in the Erbstollen gallery taken from Fuchs (1950; Bericht über tektonische Untersuchungen im Bergbaugebiet von Häring und in dessen Umgebung.– Unpubl. Report, 10 p., Kramsach). Depth to basement NW and SE of Kirchbichl after results from refraction seismics by Pfeiffer (1950; Bericht über die refraktionsseismischen Untersuchungen im Auftrage der "Kohlenbergbau Häring" reg. Gen. m. b. H.- Unpubl. Report, 8 p., Feuchten). For position of cross sections see Fig. 2.

(facies C). The very top of the Bergpeterl Mb. is marked by a coarse-grained fossiliferous layer (up to 20 cm in thickness), with reworked intraclasts, rare Triassic carbonates with borings, and small mud chips (Heissel 1956; Stingl & Krois, 1991; Krois, 1992).

In summary, the petrographic, geochemical, paleontological, and sedimentological data are more indicative of a marine environment for the Bergpeterl Mb. The development from a fan delta (Lengerergraben Mb.) to a shallow marine succession (Bergpeterl Mb.) seems more likely than a rapid change from terrestrial through limnic to marine conditions which is not supported by any sedimentary data. The large amount of plant debris must be deposited in nearshore areas around the distributary mouth of a river, supplying material from the S. High input rates of plant remains, and slow sedimentation rates of inorganic particles may be the most important control in the formation of these carbonaceous sediments (Stingl & Krois, 1991). Additionally, restricted conditions were also favoured by a circulation barrier north of the main distribution area. A structural high is documented by subsurface data (well "Ag": Ampferer, 1922; well "Niederholz I": Heissel, 1956; Fig. 6) and surface data from Osterndorf [autochthonous carbonates of the Werlberg Mb. (see below) on Triassic bedrocks: Oexle, 1978; Nebelsick et al., 2001]. Backstepping of the different facies of the Häring Fm. onto Triassic bedrock is directly observable in the Schuhreissergraben valley. This coastal onlap is also shown by very coarse-grained scarp breccias with bituminous marly groundmass in the limestone quarry W of the Pölven mountain. Small occurrences of freshwater carbonates (possibly spring tufas), as described from the Pölven mountain by Oexle (1978), may represent a correlative lateral terrestrial facies, and can be included into the Bergpeterl Mb. A transitional facies between freshwater carbonates and bituminous marls of the Bergpeterl Fm. are conglomerates with well rounded and polished clasts, present in the Dux area. They are interpreted as beach conglomerates.

2.2. Paisslberg Formation

The Paisslberg Fm. – distributed between Häring in the W and Reit im Winkl (Bavaria) in the E – includes the former "Zementmergelserie" which was subdivided into a "Lower Zementmergel" and an "Upper Zementmergel" by the intercalation of the so called "Lithothamnienkalkbreccie", a fossiliferous sequence of breccias and conglomerates. However, this subdivision is only represented at the type locality, and is not applicable for the entire Lower Inn Valley, because the coarse clastic intercalations are neither unique nor contemporaneous (Krois, 1992).

The new term Paisslberg Fm. is introduced, because the old terms cannot formally be accepted. The name originates from the type locality in the vast "Bergpeterl" quarry (type section: Fig. 7) at the northern side of the Paisslberg mountain (ÖK 121, Bl. Neukirchen am Großvenediger, coordinates 47°29'54"N/12°7'24"E). The formation consists mainly of dark grey to greenish marls and marly limestones with an overall thickness of about 200 m. The lower part is more carbonatic, the upper one shows higher clay content. The Paisslberg Fm. also includes coarse limestone breccias and conglomerates (the former "Lithothamnienkalkbreccie"; Nebelsick et al., 1996, 2001) and autochthonous shallow water carbonates mentioned by Heissel (1951) and Nebelsick et al. (2001). The wide distribution of these carbonates allows the separation of a mapable member within the Paisslberg Fm. (Werlberg Member, see below).

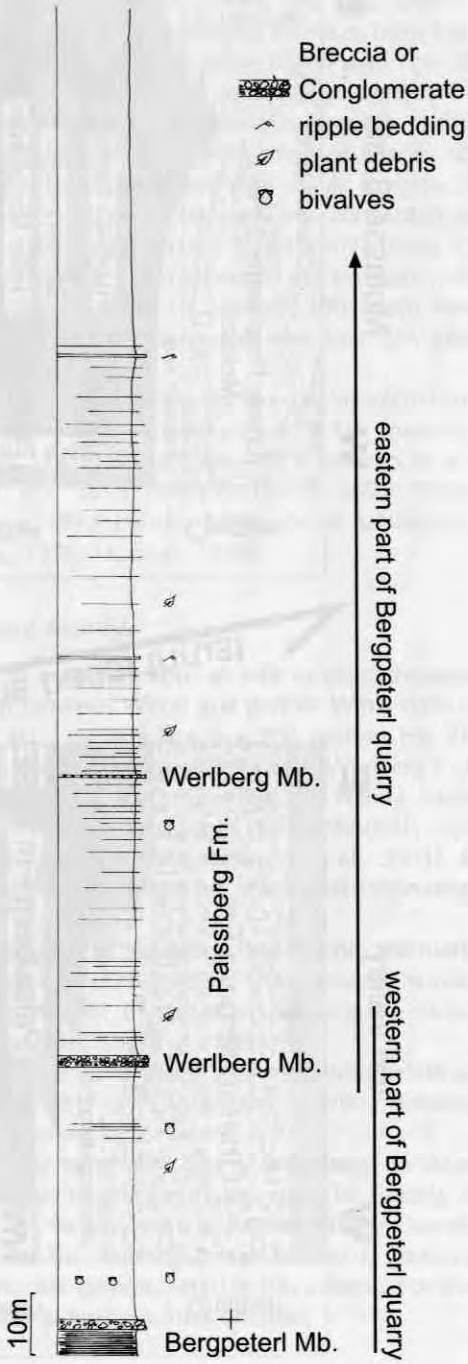

Fig. 7: Type section of the Paisslberg Fm. in the Bergpeterl quarry (with intercalations of carbonate breccias of the Werlberg Mb., see chapter 2.2.1.). For location see Fig. 1.

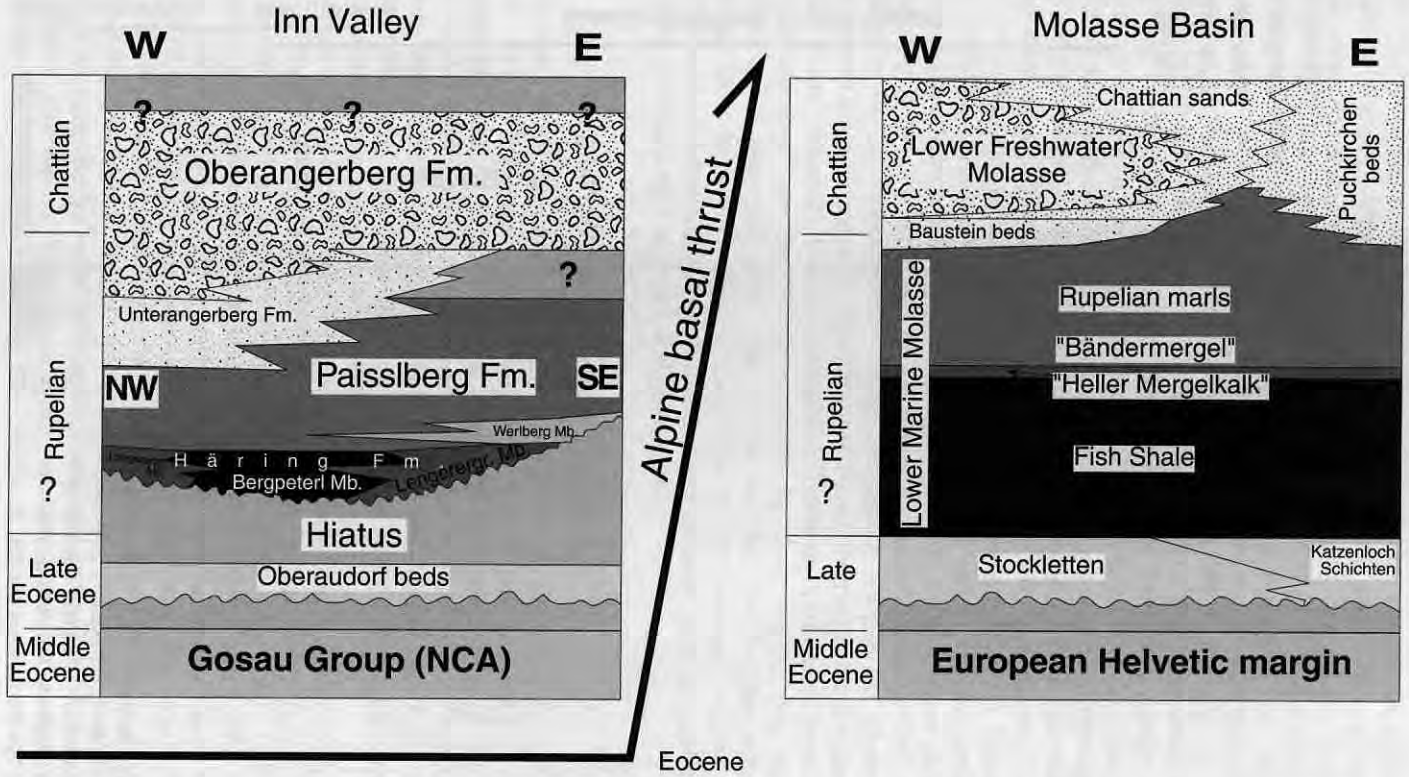

Fig. 8: left side: Lithostratigraphy of the Oligocene in the Inn Valley (modified from ORTNER, 1996); right side: Facies development of the Oligocene of the German Molasse Basin (modified from BACHMANN & MÜLLER, 1991).

The overall development indicates a transgressive trend within the marly sediments. As deduced from the increasing abundance of planktic foraminifera (LÜHR, 1962; LINDENBERG, 1965; CICHA et al., 1971; HAGN et al., 1981) sedimentation depth increases from 50–200 m in the lower part to 200–600 m (possibly up to 1000 m) in the higher part. LÖFFLER (1999) also inferred water depths from the lower neritic to the upper bathyal zone from the analysis of mollusc faunas. The deepening of the sedimentation area responds to the combination of sea level rise and tectonic subsidence. The intercalation of coarse- to fine-grained debris flows and slumping horizons in the marls may result from local tectonic movements (KROIS, 1992). Rapid sea level rise combined with low sedimentation rates at the southern shelf may be responsible for the abundance of glauconite (KROIS et al., 1991). The increasing ratio of benthic vs. planktic foraminifera in the topmost part of the Paisslberg Fm. ("Knollenmergel"; LINDENBERG, 1965; HAGN et al., 1981) indicates not only a regressive trend, but also restricted conditions possibly due to freshwater influence (HAGN et al., 1981).

The Paisslberg Fm. includes abundant micro- and macrofossils (e.g., nannoplankton: SCHNABEL & DRAXLER, 1976; LÖFFLER, 1999; coralline algae: NEBELSICK et al., 2001; foraminifera: LÜHR, 1962; LINDENBERG, 1965; HAGN et al., 1981; SCHERBACHER, 1999; NEBELSICK et al., 2001; SCHERBACHER et al., this volume; corals: REIS, 1889; molluscs: DREGER, 1892, 1902, 1904; DENINGER, 1901; SCHLOSSER, 1923; SCHACHL, 1939; LÖFFLER, 1999; LÖFFLER & NEBELSICK, this volume; palynology: SCHNABEL & DRAXLER, 1976; HOCHULI, 1978).

2.2.1. Werlberg Member

Carbonates within the Paisslberg Fm. occur in autochthonous as well as allochthonous settings. Autochthonous carbonates crop out between Wörgl and Reit im Winkl (OEXLE, 1978; GRUBER, 1995, 1997; NEBELSICK et al., 2001; LÖFFLER & NEBELSICK, this volume; Fig. 2).

The autochthonous facies delineates the southern margin of the basin (Werlberg S of Bad Häring, Bergpeterl quarry), or rims isolated horsts surrounding the Häring basin (Osterndorf NE of Bad Häring). It consists of pale limestones with lithoclasts and biogenics (coralline algae, foraminifera, corals, bryozoans etc.: NEBELSICK et al., 2001). A remarkable feature are isolated rounded boulders of bioeroded limestones originating from a pebbly or rocky shore.

Allochthonous carbonates occur as isolated or bundled debris flows within the marls of the Paisslberg Fm. (Figs. 7, 8; "Lithothamnienkalkbreccie"). They contain heavily bioeroded Middle Triassic lithoclasts as well as a lot of bioclasts reflecting the facies distribution in adjacent shallow water regions (NEBELSICK et al., 2001).

The widespread distribution and thicknesses of up to 8 m warrant the designation as "Werlberg Mb.". First mentioned by HEISSEL (1951) as "Litoralfazies", further detailed descriptions are given by KROIS (1992) and NEBELSICK et al. (2001).

The type region is situated to the W of the Bergpeterl quarry (Werlberg). A short section E of the village Brugger Mühle at the beginning of the road to Gasteig is designated as type section (Fig. 9; ÖK 121, Bl. Neukirchen am Großvenediger, coordinates 47°29'53"N/12°5'50"E). The results of the working group around J. NEBELSICK regarding the carbonates of the Werlberg Mb. are demonstrated in this volume. For this reason the authors refer to this paper (LÖFFLER & NEBELSICK, this volume).

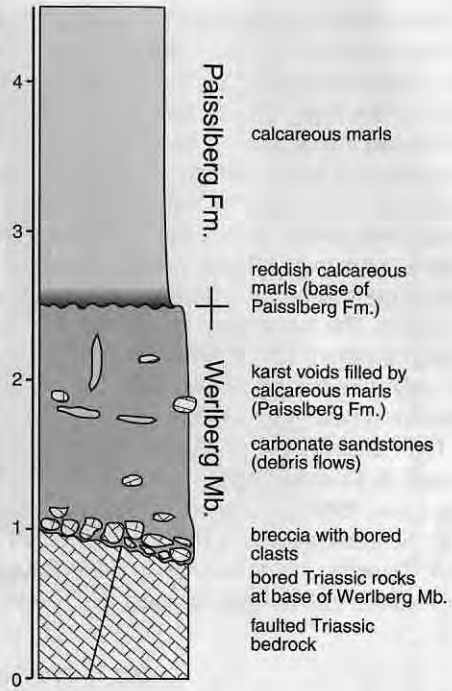

Fig. 9: Type section of the Werlberg Mb. NW of the village Bruckhäusl at the beginning of the road to Gasteig. For location see Fig. 1.

2.3. Unterangerberg Formation

SCHLOSSER (1895) introduced the name "Angerberg Schichten". He differentiated only between the coarse conglomerates, sandstones and marls at the top of the Tertiary sediments (Angerberg Schichten), while the conglomerates, carbonates, and finer clastics S of the Lower Inn Valley were included in the "Häringer Schichten". The first to distinguish between "Zementmergel" (now: Paisslberg Fm.) and "Unterangerberger Schichten" on the one hand, and "Unterangerberger" and "Oberangerberger Schichten" on the other hand, was HEISSEL (1951). In 1965 LINDENBERG maintained the term "Unterangerberger Schichten", but included it in the Häring Fm. again. SCHNABEL & DRAXLER (1976) also retained the term "Unterangerberger Schichten". They referred to the flyschoid charakter of these sediments at the Unterangerberg as well as to their terrigenous-siliciclastic composition, which distinguishes them from the "Zementmergel".

The Unterangerberg Fm. is clearly distinguished from the Paisslberg Fm. by its silty to sandy siliciclastic content and some fine-grained conglomerates (Fig. 10). It evolves from the Paisslberg Fm. by an increasing amount of sand-sized detritus (quartz, micas, etc.). For this reason the lower boundary is not very sharp. It is conventionally fixed with the first striking occurrence of siliciclastics (exposed for example in the locality Glaurachgraben south of the river Inn, AMPFERER, 1922). The upper boundary is drawn at the base of

Fig. 10: Sand-mud couplets in a turbidite sequence from the Unterangerberg Fm. (Glaurachgraben). The sand layers mostly include the Bouma Ta to Tb division, in some cases the Tc division is present. Length of hammer = 20 cm.

the first coarse-grained conglomeratic unit of the Oberangerberg Fm. (see below), called the "Höllgrabenkonglomerat" (MOUSSAVIAN, 1983, 1984; KROIS et al., 1991; KROIS, 1992; Fig. 11).

The typical development of the Unterangerberg Fm. can be studied in 3 sections. Section "Kleinsöll" in the W is situated in the Höllgraben valley south of the village Kleinsöll and at the adjacent northern river banks of the Inn (ÖK 120, Wörgl, coordinates 47°28'48"N/11°59'12"E). It displays the development of the upper part up to the Höllgraben conglomerate (base of the Oberangerberg Fm.), and is designated as reference section for the upper boundary of the Unterangerberg Fm. (Fig. 11). To the E, section "Innufer" (ÖK 120, Wörgl, coordinates 47°29'30"N/12°3'00"E) and type section "Angath" (Fig. 12; ÖK 89, Angath, coordinates 47°30'00"N/12°3'30"E) show a more distal facies of the deeper parts of the formation, but without reaching the base. Despite the wide distribution, also recorded in drill holes (e.g., AMPFERER, 1922; HEISSEL, 1956), no complete section exists. Therefore, thickness data differ widely. KÖVECS (1964, cit. in MOUSSAVIAN, 1983) estimated 500 to 700 m overall thickness from the outcrops along the Inn river banks. HAGN et al. (1981) mentioned 190 m for their "marine Häring beds" (i.e., Häring Fm. + Paisslberg Fm. + Unterangerberg Fm.). The above mentioned sections represent a combined thickness of about 120 m without reaching the base. From outcrop and subsurface data an estimated thickness of about 300 m for the Unterangerberg Fm. seems to be plausible (KROIS, 1992).

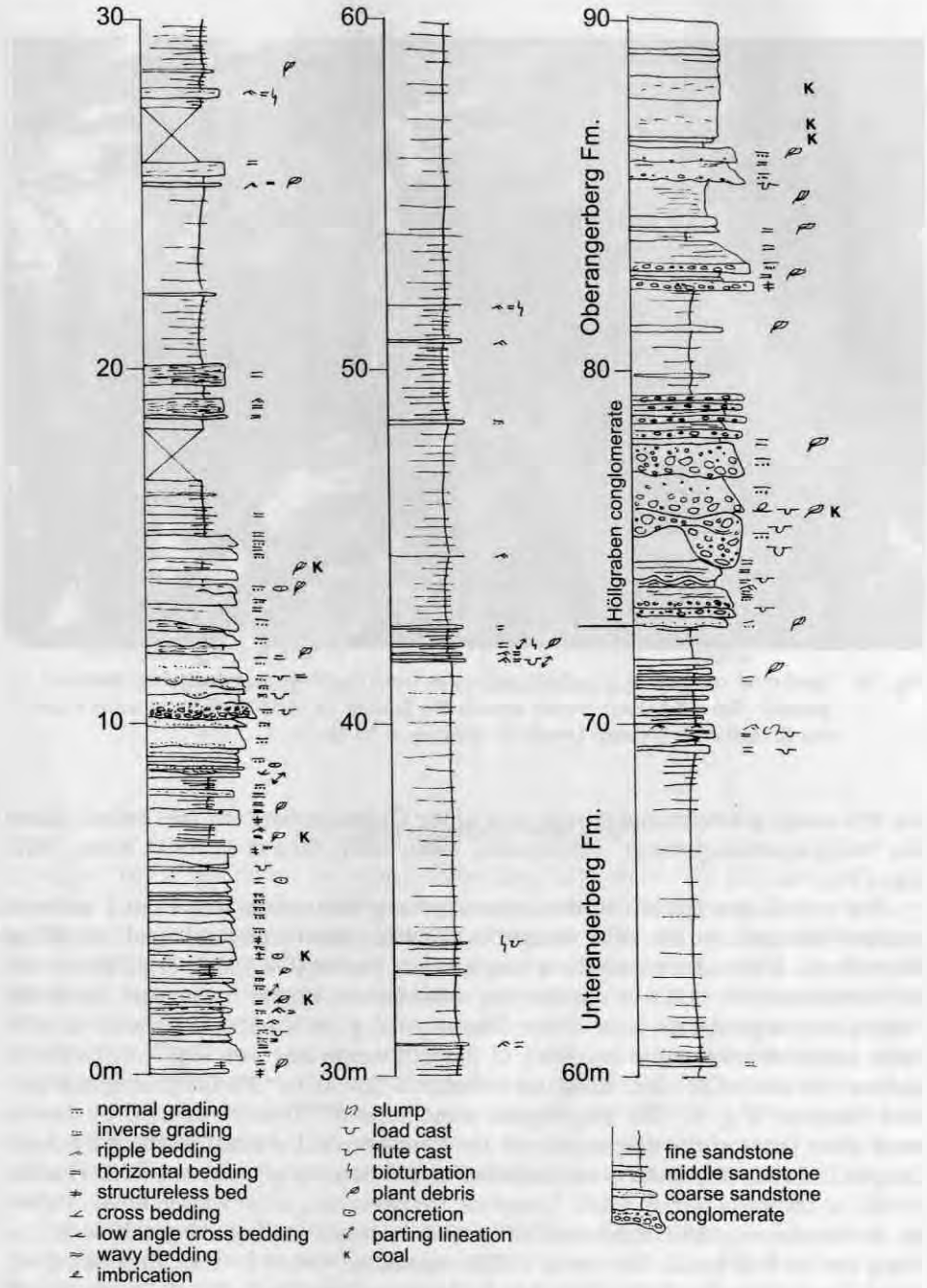

Fig. 11: Section Kleinsöll: Reference section for the upper boundary of the Unterangerberg Fm., and the base of the Oberangerberg Fm. (Höllgraben conglomerate). For location see Fig. 1.

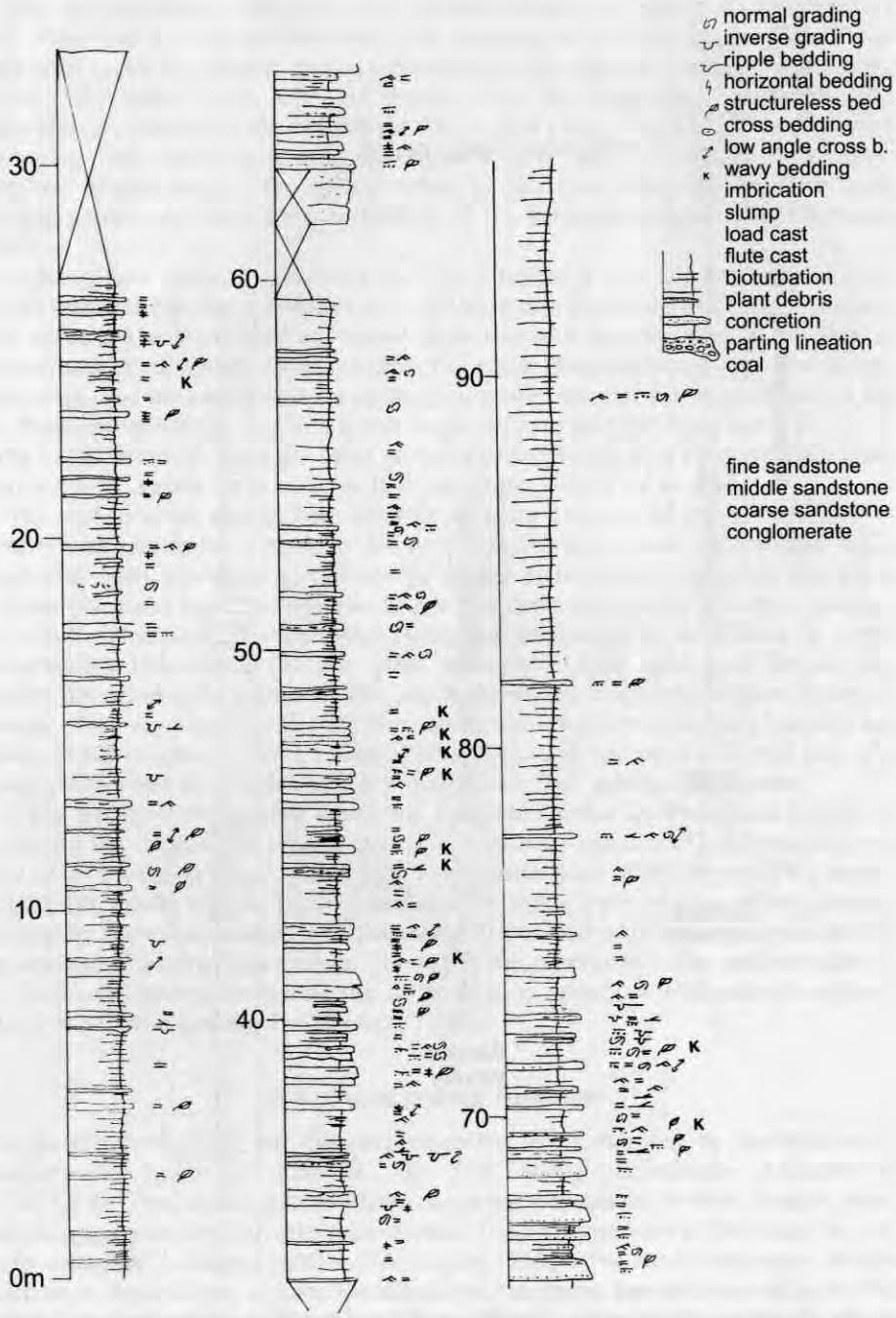

Fig. 12: Section Angath: Type section of the Unterangerberg Fm. For location see Fig. 1.

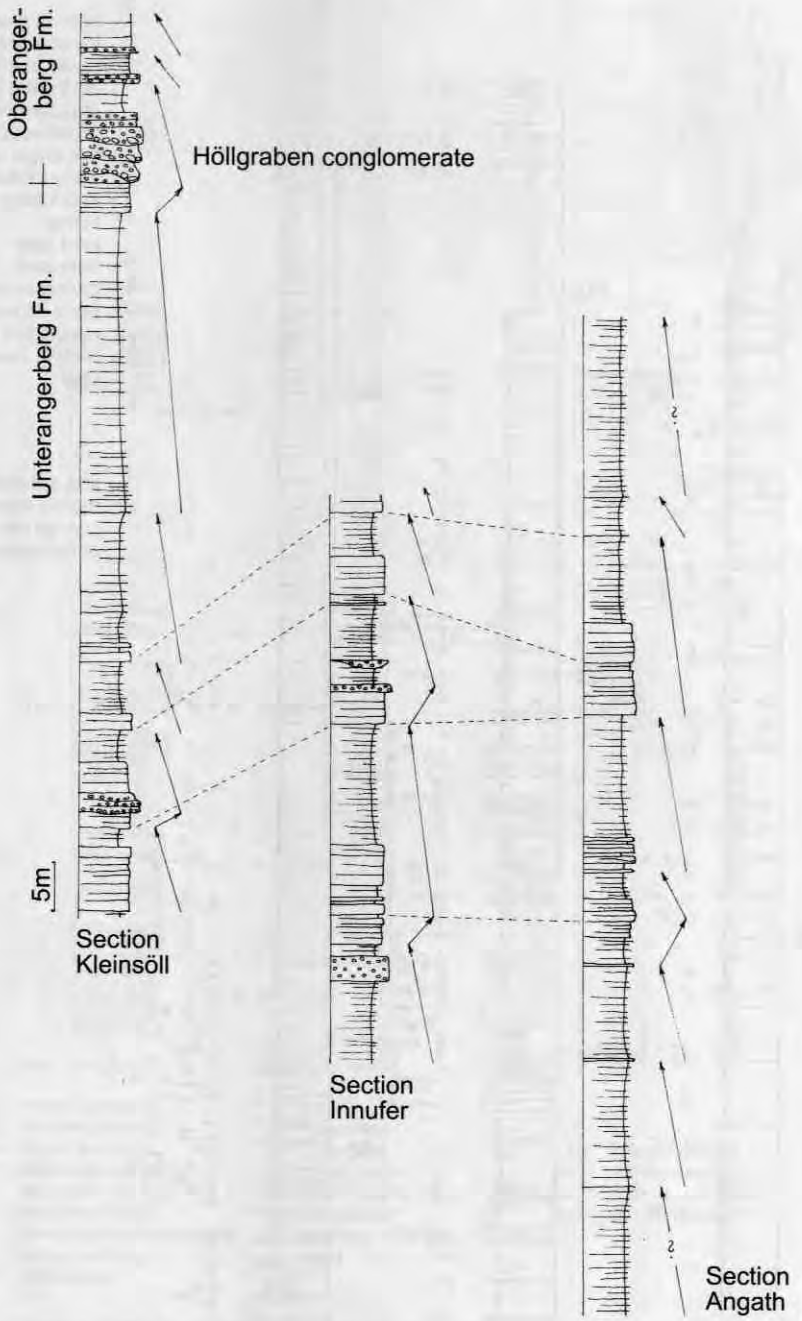

Fig. 13: Correlation of the sections Kleinsöll, Innufer, and Angath (Unterangerberg Fm.), based on cycle stacking pattern and lithologic criteria. For location of the sections see Fig. 1.

The Unterangerberg Fm. consists of sandstone-marl (or mudstone)-interbeddings with some fine-grained conglomerates, all arranged in fining-upward cycles. These small-scale cycles are stacked to fining-upward and thinning-upward large-scale cycles, reaching thicknesses from 1 to 20 meters. Only few large-scale coarsening- and thickening-upward cycles are intercalated. The overall trend in cycle stacking displays a coarsening- and thickening-upward development from base to top of the Unterangerberg Fm., culminating in the sedimentation of the Oberangerberg Fm. The cyclic stacking pattern also allows the correlation of the individual sections (Fig. 13; KROIS, 1992).

Bedding type (graded, horizontal and ripple bedding) and sedimentary structures (typical sole marks) point to turbiditic sedimentation on a small submarine fan. The large-scale cycles can be interpreted as channel fills or levees of suprafan lobes in the distal to mid-fan area (KROIS, 1992; ORTNER, 1996). The entire Unterangerberg Fm. represents a coarsening- and thickening-upward megacycle, which indicates the progradation of the fan. Transport directions vary in a broad range, with an average trend from NW to SE, partly to NE. Although there are some vectors pointing to the N, a main sediment input from the S, as argued by SCHNABEL & DRAXLER (1976), cannot be verified.

The clast spectrum derives from different sediment sources. The fine-grained conglomerates and sandstones consist of different types of high-grade metamorphic clasts originating from crystalline complexes W of the sedimentation area, of low-grade metamorphic rocks from the Paleozoic Greywacke Zone, and diverse Mesozoic carbonates from the Northern Calcareous Alps. Heavy mineral spectra are dominated by garnet and staurolite (SCHNABEL & DRAXLER, 1976). Glauconite, plant debris and bioclasts are present throughout the sequence. The poorly developed foraminiferal fauna shows an increase of the abundance of benthic forms towards the top and indicates a Rupelian age (HAGN, 1960; LINDENBERG, 1965; HAMDI, 1969). A striking feature is the total lack of a typical deep-water ichnofacies, which is assigned to high sedimentation rates.

Cycle arrangement, bedding types, and grain size distribution throughout the Unterangerberg Fm. indicate the progradation and/or lateral migration of a submarine fan in front of an advancing fluvial system (Fig. 21). In distal parts of the system the Unterangerberg Fm. grades into the higher Paisslberg Fm. In the topmost parts of the Unterangerberg Fm. a regressive trend with shallowing of the sedimentation area is indicated by the increase of benthic foraminifera. The regression culminates in the sedimentation of the first coarse-grained conglomerates of the mid- to upper fan (Höllgraben conglomerate of the Oberangerberg Fm.; ORTNER, 1996).

2.4. Oberangerberg Formation

The lower boundary of the Oberangerberg Fm. is represented by the Höllgraben conglomerate (south of Kleinsöll, ÖK 120, Wörgl, coordinates 47°28'48"N/ 11°59'12"E). This coarse-grained clastic sequence consists of m-thick trough cross-bedded conglomerates with intercalated marls. The clast spectrum is dominated by Late Cretaceous and Paleogene pebbles (MOUSSAVIAN, 1983). The marls exclusively contain redeposited foraminifera of Late Cretaceous to Paleogene age and nannofossils from reworked Eocene sediments (HAMDI, 1969). Near Reit im Winkl horizons with *Polymesoda* ("Cyrenenschichten": HAGN et al., 1981) are intercalated. While cross-bedded con-

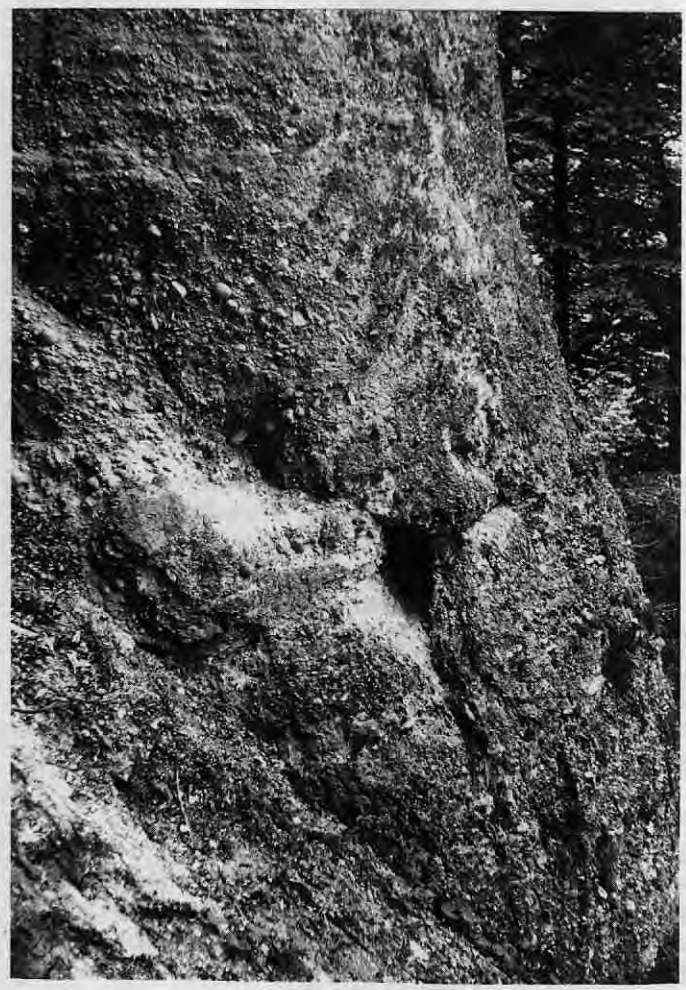

Fig. 14:
Fluviatile conglomerates from the Oberangerberg Fm. (Mühlbach gorge). Coarse trough cross-stratification is visible in the upper left of photograph. Outcrop height = 4 m.

glomerates are interpreted as submarine channel fills in the mid- to upper fan area, poorly stratified to structureless conglomerates represent submarine debris flows. The sequence of the Höllgraben conglomerate points to a transition from the mid-fan area to the upper fan and consists of an interfingering of channel fills, debris flows, and fine-grained unchannelized slope sediments (Ortner, 1996).

Structureless conglomerates at the locality Hermannsquelle near Kufstein consist solely of well rounded and polished beach pebbles. Marly interlayers show caliche-like concretions. The sequence develops into typical fluvial conglomerates, and is interpreted as fluvially reworked beach sediment (Ortner, 1996).

The type area of the formation is the Oberangerberg between Kramsach in the W and Breitenbach in the E. The northern part of the Oberangerberg displays a similar, but slightly

more distal development of the clastic succession. In the Mühlbach gorge NW of Ramsau (ÖK 50, Bl. 120 Wörgl, 47°29'20"N/11°57'12"E) a 90 m thick coarsening-upward section is exposed (Ortner, 1996), which displays an interlayering of cross-bedded sandstones to conglomerates (Fig. 14). This clastic sequence is interpreted as delta plain of an advancing fluvial system. Fine-grained overbank deposits in inter-channel areas contain abundant plant remains.

Typical sediments of the Oberangerberg Fm. are exposed in the southern part of the Oberangerberg. Section Voldöpp (ÖK 50, Bl. 120 Wörgl, coordinates 47°27'12"N/ 11°54'36") displays the best outcrops, and is designated as type section for the Oberangerberg Fm. (Fig. 15). The coarse conglomerates of a slightly sinuous, braided river system (Krois & Stingl, 1991) indicate perennial high energy runoff. The main facies elements are channel fills with longitudinal bars and large-scale ripples. The scarcity of overbank fines (levees, crevasse splays and floodplain deposits, mud-filled abandoned channels) supports the model of a highly mobile channel system. Transport directions derived from imbricate clasts and cross-bedding are oriented from NW-W to SE-E.

Biostratigraphic dating of the Oberangerberg Fm. is not unequivocal. Rare mammal remains (*Rhonzotherium cadibonense* Roger: Schlosser, 1910; Zöbelein, 1955), charophytes, and terrestrial gastropod remains point to Chattian age. Plant fossils (*Cinnamomum* cf. *scheuchzeri and C.* cf. *spectabila* Heer) indicate an Oligocene to Miocene age (Hamdi, 1969). Only the

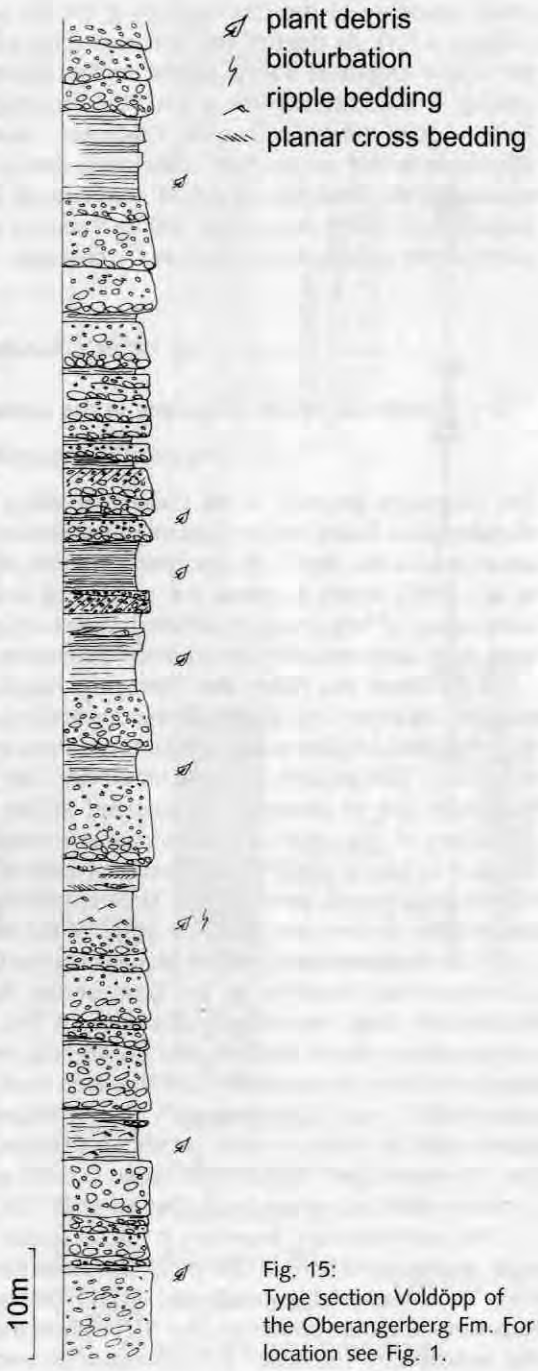

Fig. 15:
Type section Voldöpp of the Oberangerberg Fm. For location see Fig. 1.

sequence stratigraphic interpretation of the succession provides some evidence for the lower boundary of the Oberangerberg Fm. to be near the base of the Chattian (see Chapter 3.1.1). As the first pebbles from rocks of the Bernina, Err, and Julier nappes in the Upper Engadine Valley appear in the Aquitanian of the Molasse zone, and are lacking in the Oberangerberg Fm., the erosional upper boundary of the Inn Valley Tertiary must still be within the Oligocene. Modelling of the thermal history of the Oligocene based on vitrinite reflectance data in the Häring – Oberangerberg area resulted in the prediction of a total thickness of 1300m of eroded sediment (ORTNER & SACHSENHOFER, 1996). More than 1000m thickness of the Oberangerberg Fm. is preserved north of the Kaisergebirge (section Durchholzen, Fig. 23, D–D').

3. PALEOGEOGRAPHY

3.1. Correlation of the Oligocene in the Lower Inn Valley to the Molasse Basin

3.1.1. Sequence stratigraphic interpretation

The Oligocene deposits of the Lower Inn Valley were considered to be a part of the Molasse basin based on the similarities in lithostratigraphy (FUCHS, 1976, 1980; FREUDENBERGER & SCHWERD, 1996). A description in terms of sequence stratigraphy (VAN WAGONER et al., 1988) allows to show the relation of sedimentation to relative sea level. The comparison of sequences in different basins indicates whether a common relative sea level ruled sedimentation or sequence development was independent.

In the Lower Inn Valley, the Häring and Paisslberg Fms. onlap onto the basin margin towards the south (Fig. 8) and during deposition of these formations, the basin subsided from terrestric/shallow water conditions to deep marine conditions (LÜHR, 1962; HAGN et al., 1981). This pattern is characteristic for the transgressive part of sequences. The maximum rate of deepening is recorded in the upper part of the Paisslberg Fm. by deposition of glauconite and an increase in fossil content (KROIS, 1992; Fig. 16). The increase in clastic input in the overlying part of the Paisslberg Fm. and the general coarsening upward trend in the Unterangerberg Fm. indicates progradation of the sedimentary system and therefore onset of the high stand systems tract.

In the Molasse basin, the first sequence in the Oligocene reaches from the Priabonian *Lithothamnium* limestone to the base of the Baustein beds (latest Rupelian) or the Puchkirchen beds, respectively (BACHMANN & MÜLLER, 1991; ZWEIGEL et al., 1998). The transgressive systems tract includes the shallow marine basal sands and *Lithothamnium* limestone (early transgression) and the deep marine condensed "Fischschiefer", "Heller Mergelkalk" and "Bändermergel" (late transgression). The highstand deposits are represented by Rupelian marls, which are characterized by clinoforms and downlap onto the "Bändermergel" on a seismic scale, indicating an eastward prograding delta during a relative stillstand of sea level (ZWEIGEL et al., 1998).

The most important boundary in the succession of the Lower Inn Valley is the change from marine conditions in the partly contemporaneous Paisslberg and Unterangerberg Fms. to limnofluviatile conditions in the Oberangerberg Fm. approximately at the Rupelian – Chattian boundary (Fig. 8). While in the western part of the Lower Inn Valley the sedimentary succession is continuous, showing a transition from the deep marine

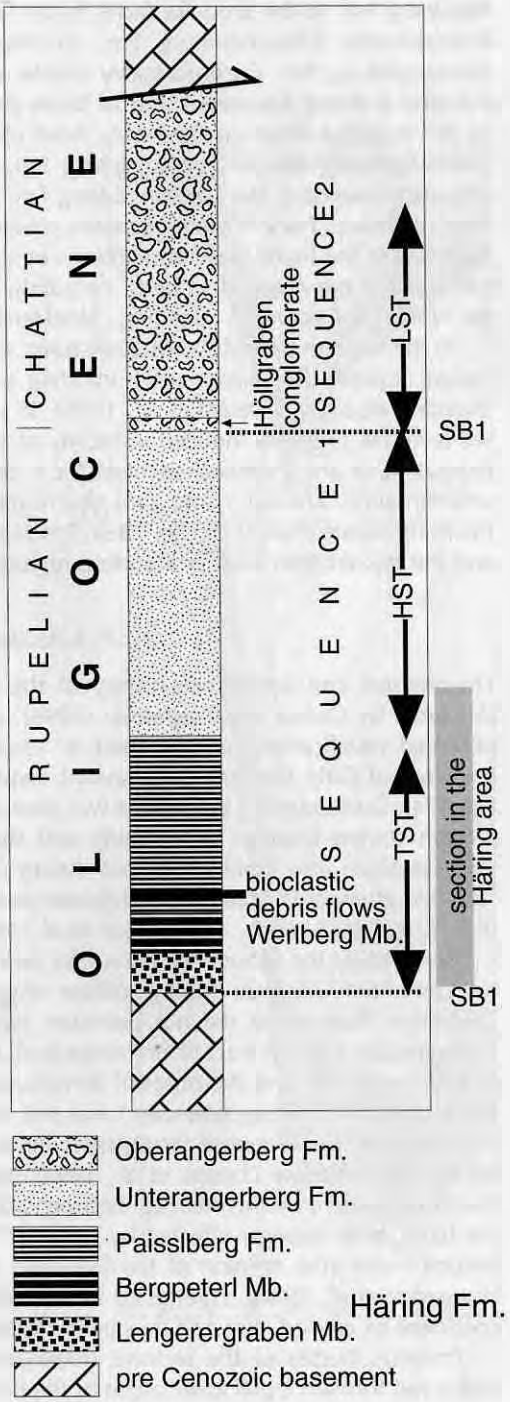

Fig. 16:
Sequence stratigraphic interpretation of the Oligocene in the Inn Valley (modified from KROIS et al., 1991).
LST.... lowstand systems tract,
TST.... transgressive systems tract, HST... highstand systems tract.

Paisslberg Fm. to the prodelta facies in the Unterangerberg Fm. and to the deltaic and limnofluviatile Oberangerberg Fm., in the eastern part fluviatile deposits of the Oberangerberg Fm. unconformably overlie marls of the Paisslberg Fm. (Fig. 8). This indicates a strong basinward shift of facies zones possibly triggered by the sea level fall at the Rupelian-Chattian boundary (HAQ et al., 1988). The contact of Paisslberg or Unterangerberg Fm. – Oberangerberg Fm. is therefore interpreted to be a type 1 sequence boundary, the Oberangerberg Fm. forming the lowstand systems tract of the next sequence. Thick fluviatile deposits covered large parts of the Northern Calcareous Alps east of the Inntal shear zone (FRISCH et al., 1998). Remnants of these sediments are preserved in the Augenstein beds, frequently found on large elevated karst plateaus of the Northern Calcareous Alps (e.g., Winkler-Hermaden, 1950; Stingl, 1990).

In the western part of the Molasse basin, coastal deposits (Baustein beds) onlap deep marine deposits (Rupelian marls), indicating a sea level fall and subsequent deposition of lowstand deposits (Zweigel et al., 1998). In the eastern part of the Molasse basin, the sea-level fall probably induced instability at the southern shelf and triggered turbiditic deposition of the Puchkirchen beds (l.c.), causing a strong basinward shift in clastic sedimentation. The submarine fans (Puchkirchen beds) were supplied with debris from the rising Alpine chain (Lemcke, 1984; Frisch et al., 1998). The base of the Baustein beds and the Puchkirchen beds is therefore regarded to be a type 1 sequence boundary.

3.1.2. Subsidence curves

The thermal and subsidence history of the Oligocene in the Lower Inn Valley was simulated by ORTNER & SACHSENHOFER (1996). Subsidence curves in accordance with the observed coalification indicate rapid or accellerating subsidence throughout the Oligocene and Early Miocene (Aquitanian) combined with a low heat flow (70 mW/m^2; Fig. 17a). Subsequently, subsidence was slow until the Middle Miocene, when uplift and erosion started because of thrusting and shearing along the Inntal shear zone. The Molasse basin also rapidly subsided during Oligocene and Early Miocene and slowly subsided afterwards. Uplift in the Molasse basin started much later in the Late Miocene (Fig. 17b; ZWEIGEL et al., 1998; JACOB et al., 1982; HOMEWOOD et al., 1986).

Remarkably the subsidence curves for both the Molasse basin and the Oligocene of the Lower Inn Valley do display uniform or even increasing subsidence throughout the Oligocene. Subsidence did not decrease, when the basin stopped becoming deeper (transgressive systems tract of first sequence), but started to fill (high stand systems tract of first sequence), and the onset of limnofluviatile conditions (sequence boundary near the Rupelian – Chattian boundary) was not related to uplift.

Therefore, the sequence stratigraphic development in the Molasse basin is generally controlled by eustasy (ZWEIGEL et al., 1998), but the transgressive-regressive cycles were mainly dependent on the interplay between accomodation space and sediment input into the basin, both strongly affected by tectonics. Accomodation space was created by the flexural event after collision of the European and Adriatic plates in Eocene times (e.g., HOMEWOOD et al., 1986), as reflected by the subsidence curve. Sediment input was mainly controlled by erosion rates and thus by the tectonic history of internal parts of the orogen.

Previous studies of the tectonic development of the Oligocene in the Lower Inn Valley put forward a pull apart origin of the basin (ORTNER, 1996; ORTNER & SACHSENHOFER,

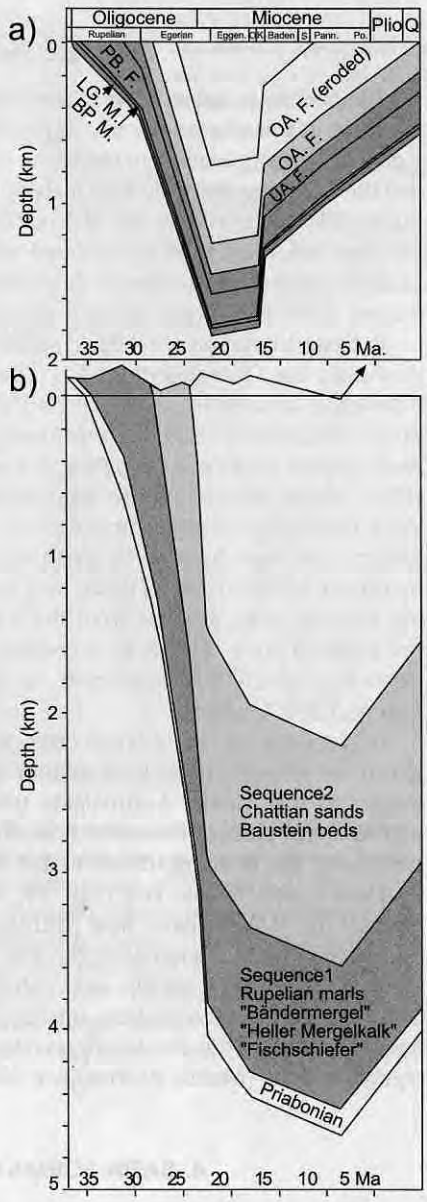

Fig. 17:
a) Subsidence curve for the Oligocene in the Lower Inn Valley redrawn from ORTNER & SACHSENHOFER (1996).Timescale after STEININGER et al. (1988/89) for Oligocene sediments and STEININGER et al. (1990) for Miocene sediments. b) Subsidence curve for a well SSE of Munich in the Molasse basin simplified from ZWEIGEL et al. (1998). Absolute ages taken from Harland et al. (1990) and STEININGER et al. (1985). Minor differences between the curves due to differences in time scales. Abbreviations: BP. M. = Bergpeterl Mb., LG. M. = Lengerergraben Mb., PB. F. = Paisslberg Fm., UA. F. = Unterangerberg Fm., OA. F. = Oberangerberg Fm.

1996). However, the open marine facies of the Paisslberg Fm. is not in accordance with a local basin, and the overall similarities in subsidence and sequence development between the Molasse basin and the Oligocene of the Lower Inn Valley rather calls for a genetic link between the two depositional areas.

3.2. Provenance studies

Phyllite pebbles in debris flows in the Unterangerberg Fm. document the erosion of crystalline rocks in a nearby source area as phyllites cannot be transported far and give evidence for a drainage system eroding to crystalline rocks nearby. In contrast, in the Lengerergraben Mb. and the Paisslberg Fm. only local material from the underlying units were redeposited. Clastic material derived from the Alps also reached the Molasse basin in sandy submarine fans (Fig. 18), that are interpreted to represent predecessors of the large fans developing from the Chattian onwards (Freudenberger & Schwerd, 1996). This first clastic input indicates increased erosion in the central part of the Alps during the Early Oligocene.

Better information is available about the catchment area of the paleo-Inn River which deposited the Oberangerberg Fm. The clast composition is dominated by Triassic and Paleogene carbonates, as well as dark dolomites, possibly from the Northern Greywacke Zone (Moussavian, 1983; Krois & Stingl, 1991). High-grade metamorphic rocks from the Austroalpine basement, phyllites and other pebble types are subordinate. Mair et al. (1992, 1996) describe rare andesite and dacite clasts in the Oberangerberg Fm. suggesting a headwater of the supplying river in the Ortler and Reschenpaß region. The river system must have been an orogen-parallel precursor of the recent Inn River, as supposed by Lemcke (1984). Skeries (1988) and Skeries & Troll (1991) observed the first "typical" Inn material (e.g., granites from the Julier region) in the Aquitanian (Early Miocene) of the Molasse zone. This is in accordance with Hantke (1984, 1987), who argues for a paleo-Inn, which first connected to the upper Engadin valley during the latest Oligocene/Early Miocene.

Provenance studies of latest Oligocene/Miocene conglomerates at the southern margin of the Molasse basin indicate that the paleo-Inn river had its source at the southern margin of the Middle Austroalpine units west of the Tauern Window or even in the northernmost parts of the western Southern Alps (Brügel, 1998; Frisch et al., 1998, 1999). Therefore, the drainage divide in the latest Oligocene was located in the area of the Pustertal-Gailtal/Tonale line (Fig. 19; Frisch et al., 1998, 1999). The paleo-Inn river reached the Molasse basin near Salzburg and fed the Chiemgau fan, which is part of the Puchkirchen beds, a submarine fan into the eastern Molasse basin (Fig. 8). The development of the Inn River system was controlled by the Inntal shear zone. North of the orogen parallel paleo-Inn River system, smaller fans at the mouth of minor rivers into the Molasse basin developed (Pfänder, Hochgrat, Nesselburg fans). Only the Hochgrat fan cut into the crystalline units (Middle Austroalpine Silvretta nappe; Brügel, 1998; Frisch et al., 1999).

4. BASIN FORMATION AND DEFORMATION

Basin formation and deformation were influenced by processes at two scales: 1) Evolution of the Alpine orogenic wedge and its foreland basin (Molasse basin) and 2) shearing

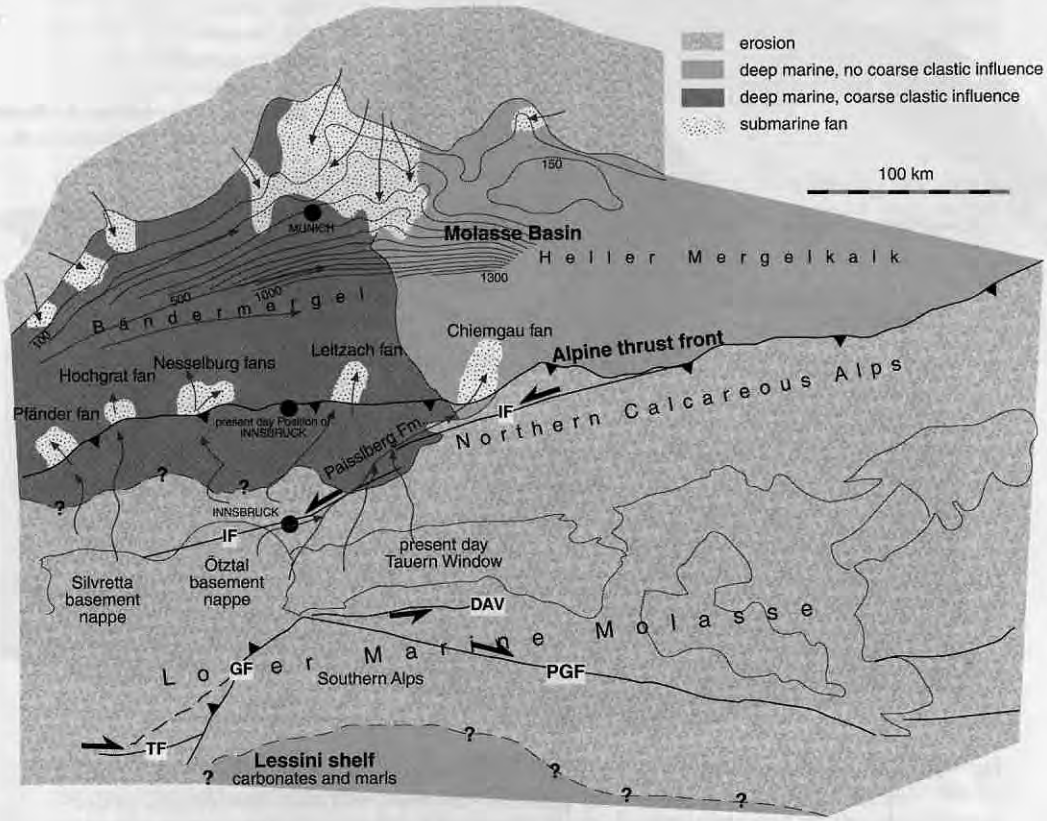

Fig. 18: Paleogeographical sketch of the Eastern and Southern Alps during the Middle Rupelian, at the transition from transgressive to highstand systems tract in Molasse Basin ("Heller Mergelkalk" = condensed section). Isolines in northern part of Molasse basin indicate increase of thickness of Rupelian deposits to the south. Alpine nappes are taken back to a possible Rupelian position following FREUDENBERGER & SCHWERD (1996). Major active faults at approximately 33 Ma: IF... Inntal shear zone (this study), TF... Tonale fault, GF... Giudicarie fault, DAV...Defreggen-Antholz-Vals line, PGF...Pustertal-Gailtal fault (MANCKTELOW et al., 1999). Most of the area of the Alpine orogen was subject to erosion. Generally, during the Early Oligocene the sedimentary cover of the central Alpine basement units was eroded.

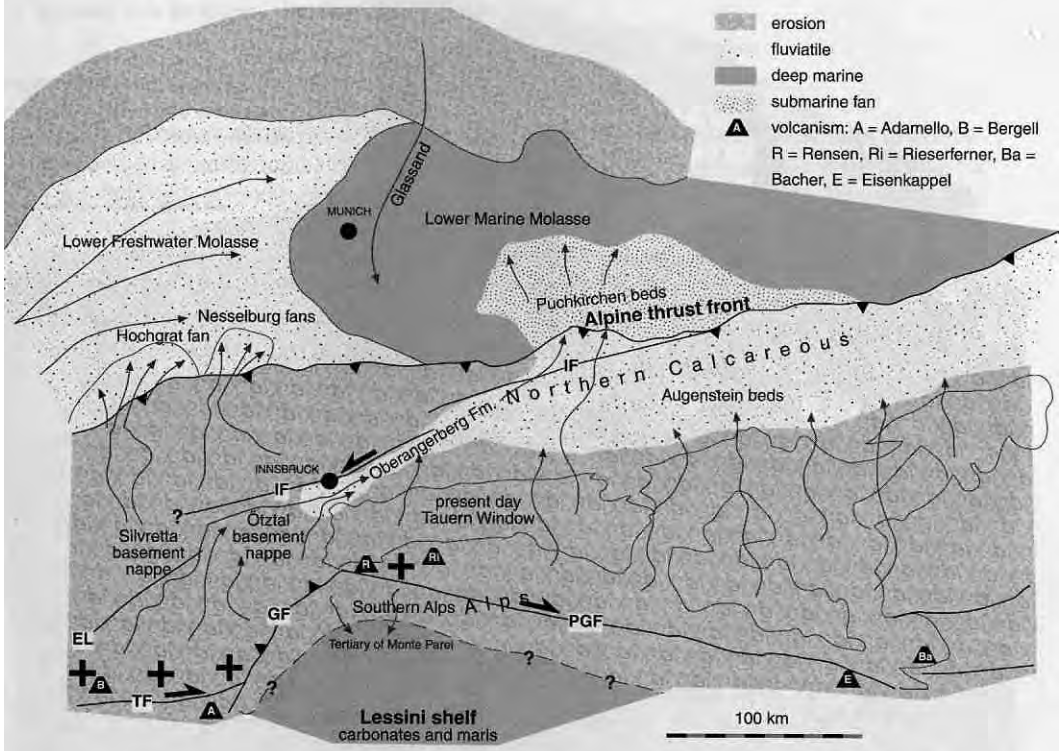

Fig. 19: Paleogeographical sketch of the Eastern and Southern Alps during the Chattian. Alpine thrust front drawn at present day position. Periadriatic volcanics were eroded, as documented by pebbles in Oberangerberg Fm. and Molasse basin. The western part of the Molasse basin was filled, the eastern part remained a deep marine basin. The Augenstein beds were deposited east of the Inntal fault on top of the Northern Calcareous Alps (Frisch et al., 1998). + indicates uplift. Major active faults at approximately 25 Ma: IF...Inntal shear zone (this study), EL...Engadine line (Schmid & Froitzheim, 1993), TF...Tonale fault, GF...Giudicarie fault, PGF...Pustertal-Gailtal fault (Schmid et al., 1989). Southern Alps drawn following Luciani (1989) and Keim & Stingl (2000).

along the Inntal fault. In the following paragraphs, local deformation is shortly discussed on the base of analysis of brittle fault planes and depositional geometries, and regional deformation is evaluated on the base of current models for the development of continental collision zones. A detailed survey of brittle deformation in the investigated area will be published elsewhere (compare ORTNER, 1996; ORTNER & SACHSENHOFER, 1996; PERESSON & DECKER, 1997).

4.1. Shearing

Synsedimentary faulting can be reconstructed throughout the Oligocene. The faults below are thought to shape local topography in the area, but they cannot account for the overall subsidence of the basin.

4.1.1. Early Rupelian (D1)

Scarp breccias in the Bergpeterl Mb. of the Häring Fm. (Fig. 20) are bound to WNW-ESE trending faults. Neptunian dykes in Mesozoic rocks underlying Oligocene sediments, which are filled by redeposited carbonates (Werlberg Mb.) and calcareous marls (Paisslberg Fm.) trend in the same direction (Fig. 21a). In a few locations fault planes are sealed by carbonates of the Werlberg Mb. (Fig. 21b). Analysis of the sealed fault planes and comparable planes indicates NW-SE directed shortening accomodated by dominant WNW-trending dextral strike-slip faults and conjugated N-S trending sinistral strike-slip faults (Fig. 21c).

Vertical offset across dextral faults is in the range of a few tens of meters. Along the faults, elongate depressions with half graben geometry formed, filled by bituminous marls (e.g., Dux area; Fig. 2; Fig. 21).

4.1.2. Late Rupelian (D2)

The Unterangerberg Fm. was locally deformed prior to lithification. This led to formation of pseudoductile structures in the sediments (Fig. 22). The Unterangerberg is cut by several shear zones with top SW displacement. In the hanging wall of the shear zones decametric, SW-verging folds developed. In an early stage of folding, layer parallel shortening led to the formation of cuspate-lobate folds at the interface of sandstone and marl layers with contrasting competence. Increasing shortening formed sets of conjugate ramp faults in sandstone beds (Fig. 22), sometimes with hydroplastic slickensides (Fig. 23a), that often disappear within the bed. Near a major branch of the Inntal shear zone, a vertical E-W trending shear zone with sinistral sense of shear was observed (Fig. 23b). All these features of Late Rupelian deformation can be integrated into a model of overall sinistral shearing along ENE-trending faults (Fig. 23c). Along branches of the Inntal shear zone, thrusts connected to the strike-slip faults led to top SW displacements of several 100m.

On a larger scale, the Paisslberg and Unterangerberg Formations successively buried the evolving topography. During sedimentation of the lower part of the Paisslberg Fm., the basin margin, or uplifted portions of fault blocks with (half-) graben geometry carried carbonate buildups (Werlberg Mb.). Debris flows transported material from these buildups into the basin (allochthonous carbonates of the Werlberg Mb.). Continued

Fig. 20: Scarp breccia in the Bergpeterl Mb. of the Häring Fm. south of Bad Häring. Spaces between blocks of bedrock (Wetterstein limestone) are filled by a matrix of bituminous marls. Lenght of scale: 1m.

shearing increased the half-graben relief, resulting in large thicknesses of the Paisslberg Fm. adjacent to the faults, as documented by the outcrops in the Häring mine and the well Niedernholz (Fig. 6). Lateron, the local topography was completely covered by the Paisslberg and Unterangerberg Fms.

4.1.3. Chattian

During the Chattian, the river system depositing the Oberangerberg Fm. transported debris from the western part of the central Alps to the Chiemgau fan west of Salzburg at the southern margin of the Molasse basin, guided by the Inntal fault. Conglomerates of the Augenstein beds, which are interpreted to represent redeposited remains of the Oberangerberg Fm. (Ortner & Sachsenhofer, 1996) are only found south of the Inntal shear zone, indicating that the Northern Calcareous Alps north of the shear zone formed a topographic barrier constraining the course of the paleo-Inn River (Fig. 19). Therefore, continued (?sinistral) activity of the Inntal fault zone throughout the Chattian is probable.

4.1.4. Post-Oligocene deformations

The main effect of post-Oligocene deformation was folding of the Paleogene deposits with WSW-trending axes (D3). Large scale folds several km in wavelength formed (e.g.,

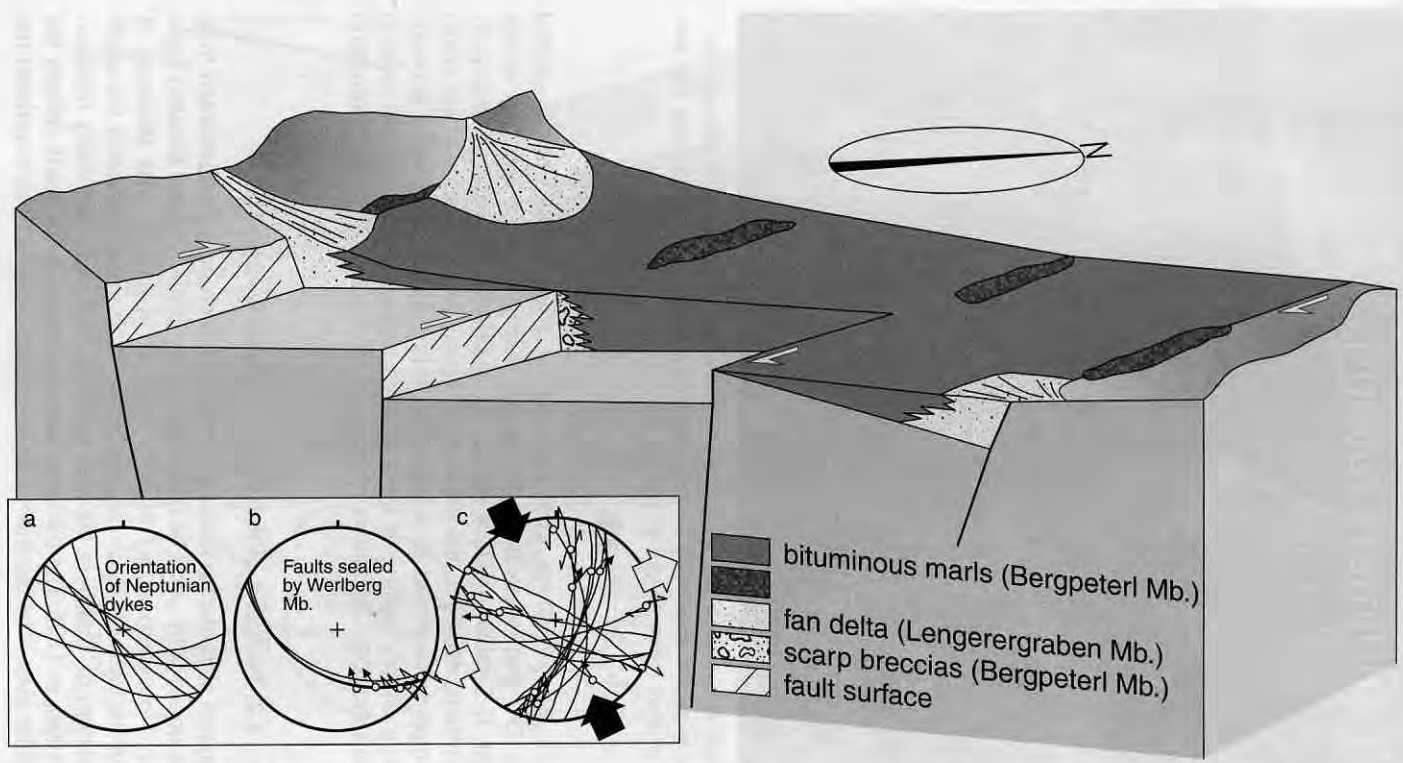

Fig. 21: Block diagram of the Inntal area during deposition of the Häring Fm. WNW-trending dextral faults dissected the area and formed half-graben shaped small restricted basins. Inset: a) Orientation of neptunian dykes filled by flowstones and debris from Werlberg Mb., b) WNW-trending dextral faults sealed by the Werlberg Mb. of the Paisslberg Fm., c) brittle fault plane data set compatible with a) and b) indicating NNW-SSE directed compression.

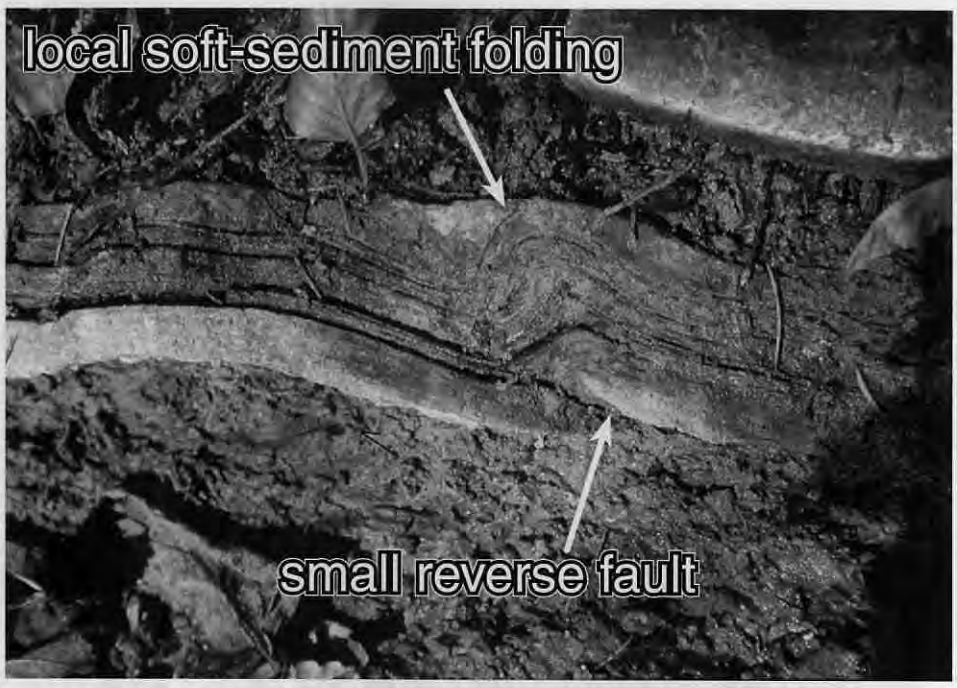

Fig. 22: Soft sediment deformation structures in a sandstone bed of the Unterangerberg Formation. Layer-parallel shortening is compensated by folding of the sandstone bed and formation of small ramps. Width of photograph = 0.5 m.

cross section E – E', Fig. 24). These folds were cut by a set of ENE-striking, sinistral transpressive faults (D4) that reactivate faults formed during D2. In a late stage of this deformational event, N-S-striking oblique normal faults developed, which are interpreted to represent antithetic riedels to the Inntal fault zone. Dextral normal offset across these mostly east-dipping faults led to west-plunging fold axes in Oligocene deposits. Normal faults striking slightly oblique to the Inn Valley overprinted quaternary rocks in the area west of Kufstein (D5). They were responsible for Quaternary graben formation in the Inn Valley.

4.2. Evolution of the Alpine orogenic wedge

Flexure of the European plate due to loading by the Alpine orogen is documented from the Early Oligocene onwards by onset of rapid subsidence in the Molasse foreland basin (Jacob et al., 1982; Homewood et al., 1986; Zweigel et al., 1998). The thickness of Rupelian deposits in the Molasse basin (isolines in Fig. 18) increases towards the south and reaches a maximum of 1300m in the area north of the Lower Inn Valley (Freudenberger & Schwerd, 1996, p. 172). The thickness increases towards the south reflects the flexural bending of the plate. The Northern Calcareous Alps, that actively overthrust the

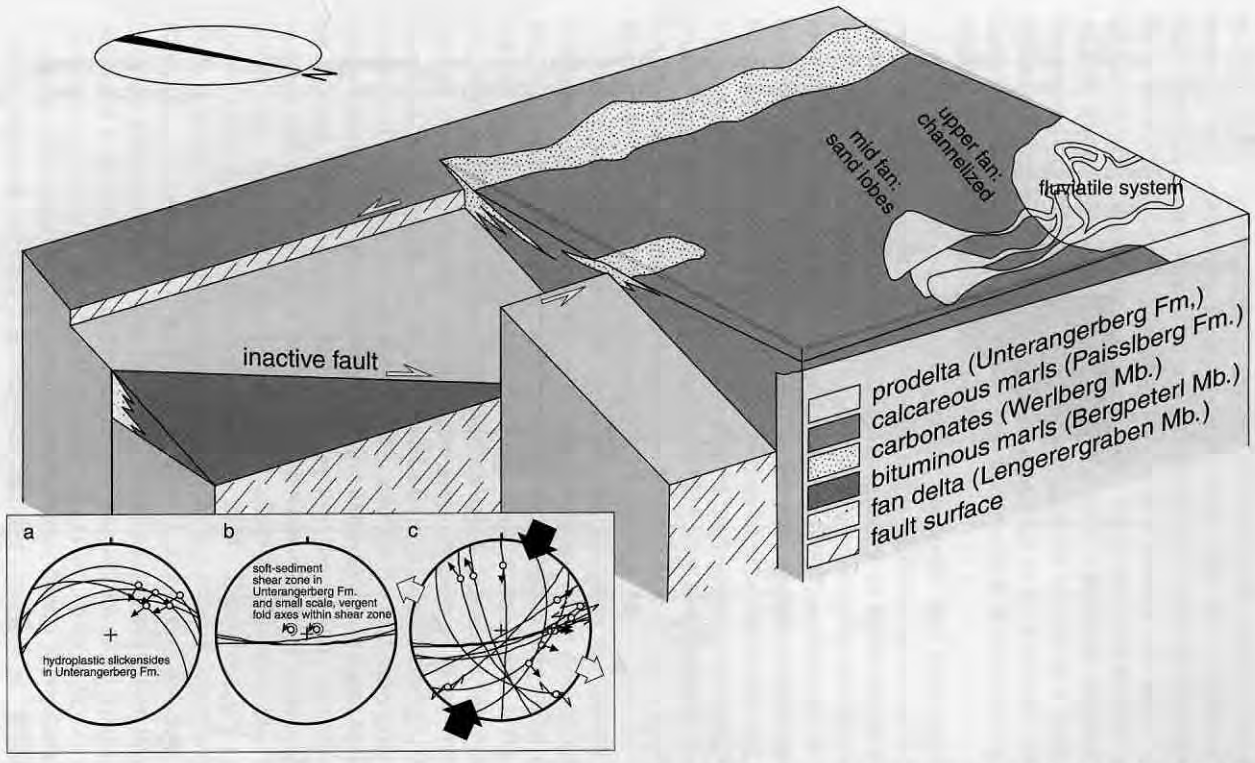

Fig. 23: Block diagram of the Inntal area during deposition of the Paisslberg and Unterangerberg Formations. Werlberg Mb. rims the southern margin of the basin and isolated horsts inside the basin. Fault blocks between active sinistral faults show half graben geometry. From the west, a fluviatile system approaches, with the Unterangerberg Fm. in a prodelta position. Inset: a) Top SW reverse faults with hydroplastic slickensides indicating activity before final lithification interpreted as guided movements parallel to major ENE-trending faults, b) shear planes in pseudoductile shear zone (great circles) and small scale fold axes with vergence of folds indicating a sinistral shear sense, c) brittle fault plane data set compatible with b) indicating NNE-SSW compression.

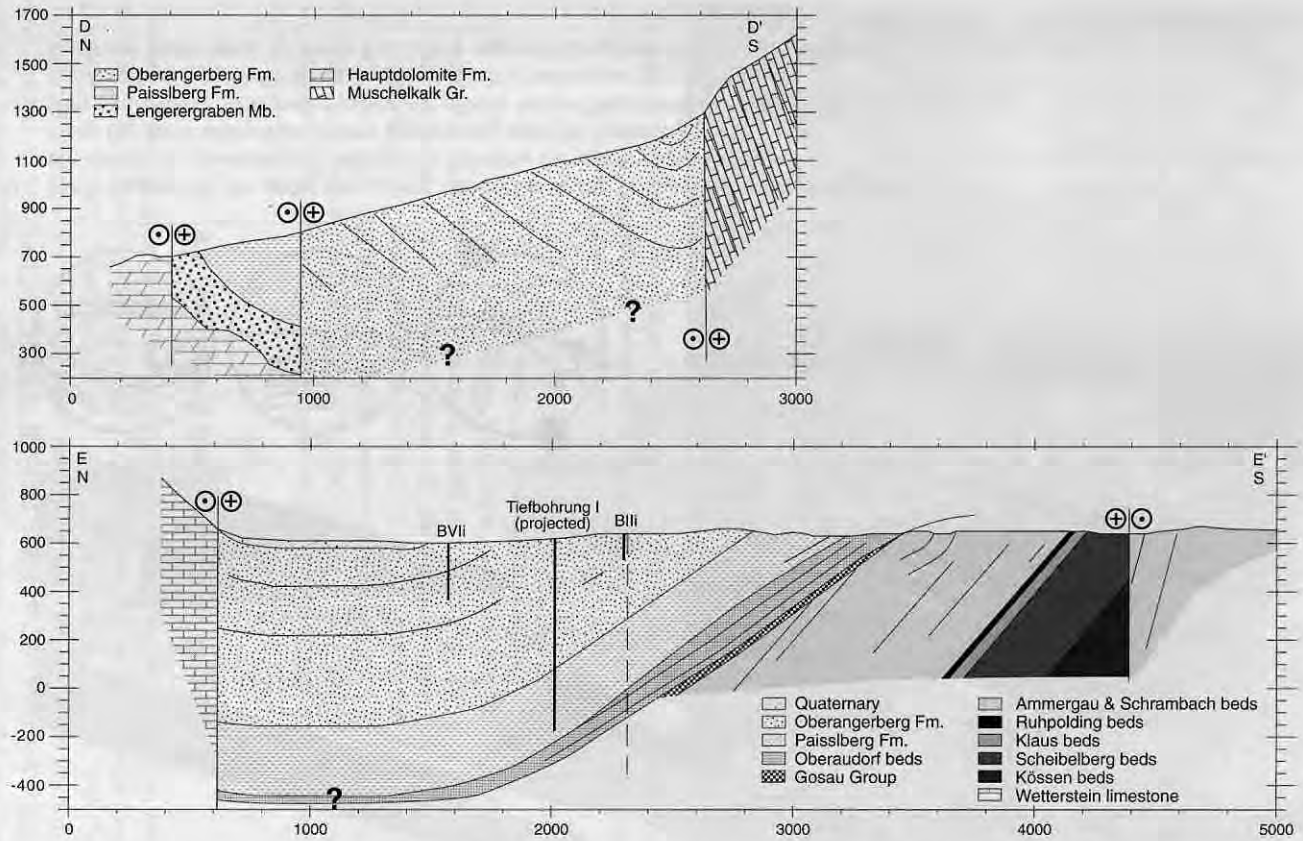

Fig. 24: Cross sections from the eastern part of the Oligocene in the Inn Valley. For position of cross sections see Fig. 1. Section D-D' redrawn from Ortner (1996). Information from wells Tiefbohrung I, BVIi and BIIi in section E-E' taken from Schulz & Fuchs (1991).

Molasse basin during this time span, were partly incorporated into the Molasse basin, as documented by Rupelian deep marine deposits in the Inn Valley area. The littoral Werlberg Mb. of the Paisslberg Fm. in the Lower Inn Valley area formed the southern margin of the Molasse basin in the earliest Oligocene. Further subsidence led to back-stepping of sedimentary facies to the south onto the crystalline basement of the Northern Calcareous Alps. This is documented by carbonate boulders belonging to the Bergpeterl Mb. and the Werlberg Mb. found several km south of the present day exposures of Paleogene rocks (PIRKL, 1961). Therefore, considerable parts of the western part of the Eastern Alps were covered by Early Oligocene deposits. Previous authors interpreted the depositonal realm of the Paisslberg Fm. to be a fjord-like inlet from the Molasse basin into the Northern Calcareous Alps (e.g., SCHLOSSER, 1910). However, the open-marine, pelagic character of the foraminiferal assemblage (HAGN et al., 1981) instead suggests a broad embayment.

As the litho- and sequencestratigraphic similarities and comparable subsidence histories point to a (genetic) connection between Molasse basin and the Oligocene in the Lower Inn Valley, the factors causing transgression in the Rupelian should be related to processes in the Alpine subduction. A general scheme for the development of Alpine-type foreland basins was proposed by SINCLAIR (1997) and SINCLAIR & ALLEN (1992). After initial subsidence due to loading by the orogenic wedge, a deep water basin is created by flexure of the lower plate, filled by turbidites (underfilled basin). The encroaching thrust wedge is dominantly deep marine as well, comparable to conditions during the preceding oceanic subduction (SINCLAIR, 1997). This early stage of foreland basin evolution corresponds to the Early Oligocene of the Alpine Molasse basin that was filled by deep water sediments (Lower Marine Molasse; Fig. 18).

The ongoing subduction of light buoyant European continental margin led to the "clogging" of the subduction zone and formation of an oblique backthrust along the Insubric line (SCHMID et al., 1996). This process possibly was aided by break-off of the oceanic slab from the subducted European crust (BLANCKENBURG & DAVIES, 1995). Insubric thrusting marks a transition from predominantly horizontal movements in the Alpine orogen to predominantly vertical movements (SINCLAIR & ALLEN, 1992). Erosion in the rapidly uplifting regions north of the Insubric line accelerated (e.g., JÄGER & HANTKE, 1984; HURFORD et al., 1989; SCHMID et al., 1989), and for the first time large amounts of coarse clastic material were shed into the intra and extra-Alpine Molasse basins (Lower Freshwater Molasse: Molasse basin; Oberangerberg Fm.: Inn Valley). The depositional state of the western part of the Molasse basin changed from underfilled (Flysch stage in the sense of RICCI LUCCHI, 1986) in the Early Oligocene to overfilled (Molasse stage in the sense of RICCI LUCCHI, 1986) in the Late Oligocene (SINCLAIR, 1997). The more eastern parts of the Molasse basin received much debris from the rising western Alps by axial transport (LEMCKE, 1984; FREUDENBERGER & SCHWERD, 1996), but east of Munich, deep sea sedimentation prevailed until the Middle Miocene (Figs. 8 & 19). Therefore, the eastern part of the Molasse basin remained in an underfilled depositional state (HOMEWOOD et al., 1986), going along with a decreasing amount of backthrusting along the eastern continuation of the Insubric line, the Pustertal-Gailtal line south of the Tauern Window (NEMES & NEUBAUER, 1996). East of the Tauern Window, no back-thrusting was recorded (FODOR et al., 1998).

In the Western Alps, European basement was involved in Alpine orogeny (internal massivs accreted to the orogen during the Early Oligocene; SCHMID et al., 1996). In the

Eastern Alps, the European plate was completely subducted, except for some very small slices of Helvetic sediments lined up along the thrust front. These differences in collisional history might be an effect of strong coupling across the collisional boundary in the Western Alps, and weak coupling in the Eastern Alps, perhaps due to oblique collision. Accretion of the internal massivs and onset of backthrusting during the Early Oligocene (SCHMID et al., 1996; Fig. 8c & d), leading to thickening of the crust probably resulted in Top E extension at the western margin of the Austroalpine (Turba normal fault, Niemet-Beverin E-W extension; NIEVERGELT et al., 1996; SCHMID et al., 1996), because material moved away from contracting regions in the west to less contracting regions in the east, also documented by decompression in Penninic units of the present day Tauern Window (SELVERSTONE, 1985, 1988; BEHRMANN, 1990).

4.3. Interpretation of brittle deformations

NW-directed shortening during Early Rupelian (D1) possibly reflects northward translation and concurrent counterclockwise rotation of the Adriatic microplate (PERESSON & DECKER, 1997). Shortening was replaced by orogen-parallel extension during the Rupelian (see above). Central Alpine units moving towards the east in the Late Rupelian (contemporaneous to Niemet-Beverin/Turba extension) were delimited to the north by sinistral faults like the Inntal shear zone (D2; Fig. 8).

Post – Oligocene deformations in the area are mainly the effect of the formation of the Southalpine Indenter with its tip south of Innsbruck. Before the Middle Miocene, the area experienced mainly folding as documented in Oligocene sediments (D3). However, shortening in the meridian of Innsbruck led to backthrusting and uplift of the Tauern Window, and to major orogen-parallel extension, leading to eastward movement of Central Alpine units (RATSCHBACHER et al., 1991; FÜGENSCHUH et al., 1997). Again, eastward moving blocks were delimited to the north by ENE-trending sinistral faults. The Inntal shear zone was reactivated (D4). Graben formation in the Inn Valley (D5) during the Quaternary might be an effect of adjustment of the Alpine wedge to isostatic uplift in its central parts.

5. CONCLUSIONS

Formations following the international stratigraphic guide (SALVADOR, 1994) are defined for the first time for the inner-Alpine Molasse in the Lower Inn Valley. The Oligocene in the Lower Inn Valley is interpreted to be a part of the Molasse basin overlying the frontal Austroalpine nappes. In a general scheme for the development of Alpine-type foreland basins (SINCLAIR, 1997), a first evolutionary stage is the underfilled basin with deep marine flysch-type sediments. In the Inn Valley, subsidence of the underfilled basin is recorded by the Lengerergraben and Bergpeterl Mbs. of the Häring Fm. followed by the Paisslberg Fm. with the Werlberg Member. Proximal conglomerates and sandstones of the Lengerergraben Mb. interfinger with the distal bituminous marls of the Bergpeterl Mb. These formations fill a local relief created by synsedimentary faulting (dextral slip along WNW-striking faults). The Paisslberg Fm. records rapid deepening of the depositional realm from some 200m in the lower part to about 1000m in the uppermost part,

as documented by the fossil content in the calcareous marls. The contemporaneous littoral carbonates of the Werlberg Mb. stepped considerably back to the south. The Unterangerberg Fm. interfingers with the Paisslberg Mb. and represents a sandy turbidite fan in prodelta position to a distant fluvial system. Soft sedimentary deformation in the Unterangerberg Fm. documents initial activity of the ENE-trending, sinistral Inntal shear zone. The Oberangerberg Fm. was deposited by an orogen-parallel fluvial system guided by the Inntal shear zone, with its headwater in the Reschenpass region. Rapid subsidence continued during its deposition. The depositional state of the Molasse basin west of Munich and its embayment in the area of the Lower Inn Valley changed from underfilled to filled or overfilled and was dominanted by continental conditions, however, east of Munich the Molasse basin continued to be underfilled.

The cause for this transition is mainly the tectonic history of the western margin of the Eastern and the eastern part of the Western Alps. Accretion of European crust into the Alpine wedge and Insubric backthrusting led to thickening of the wedge and orogen-parallel extension. Major orogen-parallel faults like the Inntal shear zone delimited the eastward moving crystalline blocks against the stable thrust belt of the Northern Calcareous Alps and guided the drainage system from the Western into the Eastern Alps. Thickening of the crust predominantly at the southern margin of the Western Alps led to high topography (JÄGER & HANTKE, 1984) and enhanced erosion and brought coarse clastics into the Molasse basin.

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